CSE 421/521 - Operating Systems
Spring 2018

Lecture - XXIII

Distributed Systems - II

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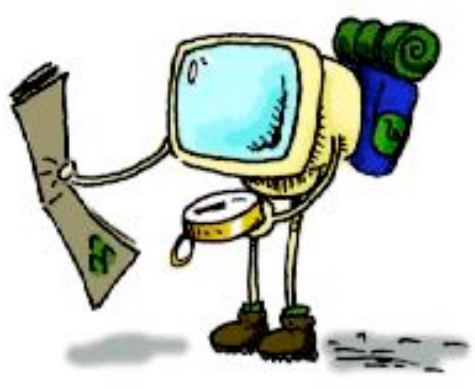
Roadmap

- Distributed Ordering
- Distributed Mutual Exclusion
- Distributed Deadlock Prevention
- Distributed Deadlock Detection



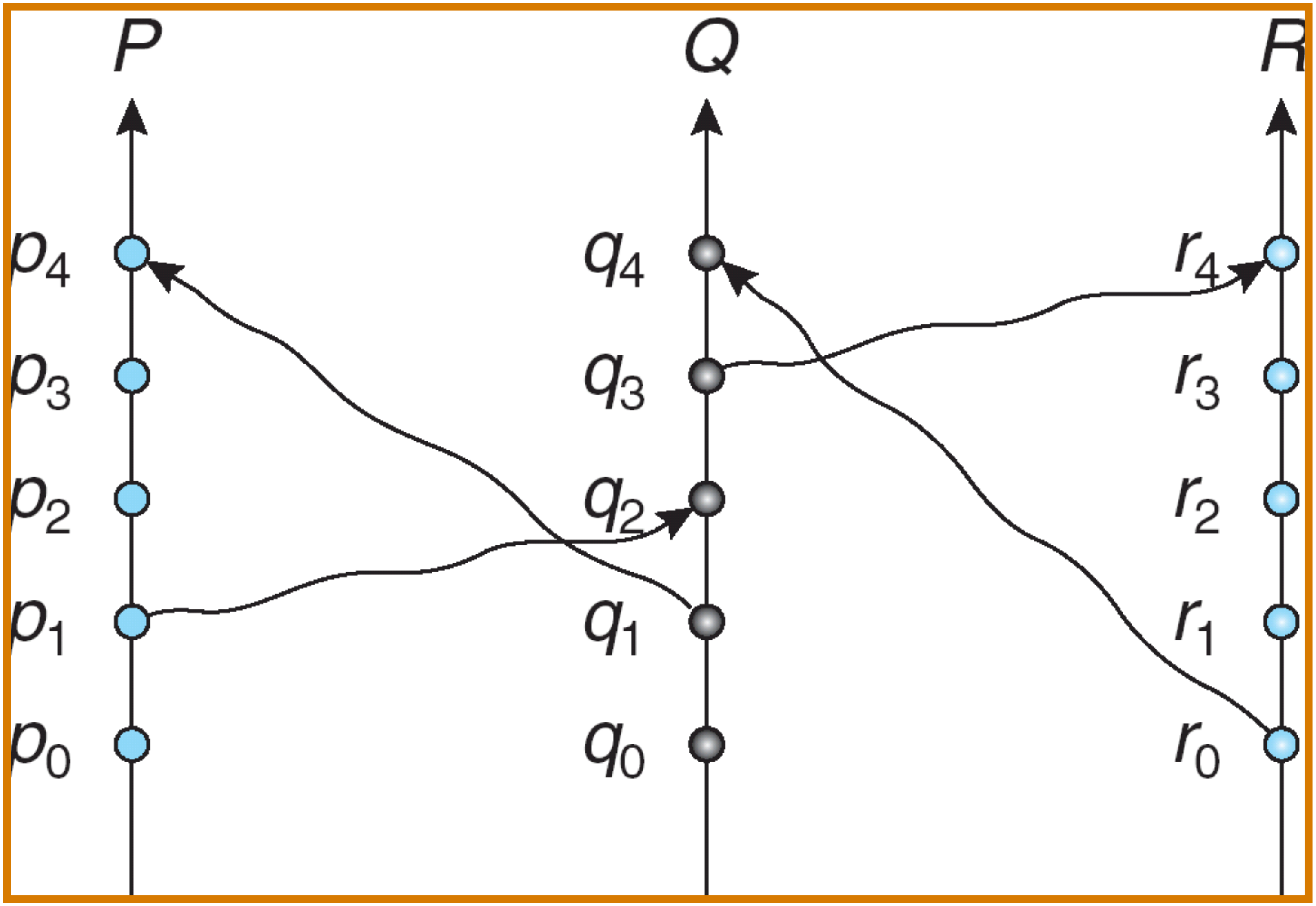
Distributed Event Ordering

- Ordering events and achieving synchronization in centralized systems is easier.
  - We can use common clock and memory
- What about distributed systems?
  - No common clock or memory
  - *happened-before* relationship provides partial ordering
  - How to provide total ordering?

Happened Before Relation

- Happened-before relation (denoted by $\rightarrow$)
  - If *A* and *B* are events in the same process (assuming sequential processes), 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 $A \rightarrow C$
  - If two events A and B are not related by the $\rightarrow$ relation, then these events are executed concurrently.

Relative Time for Three Concurrent Processes

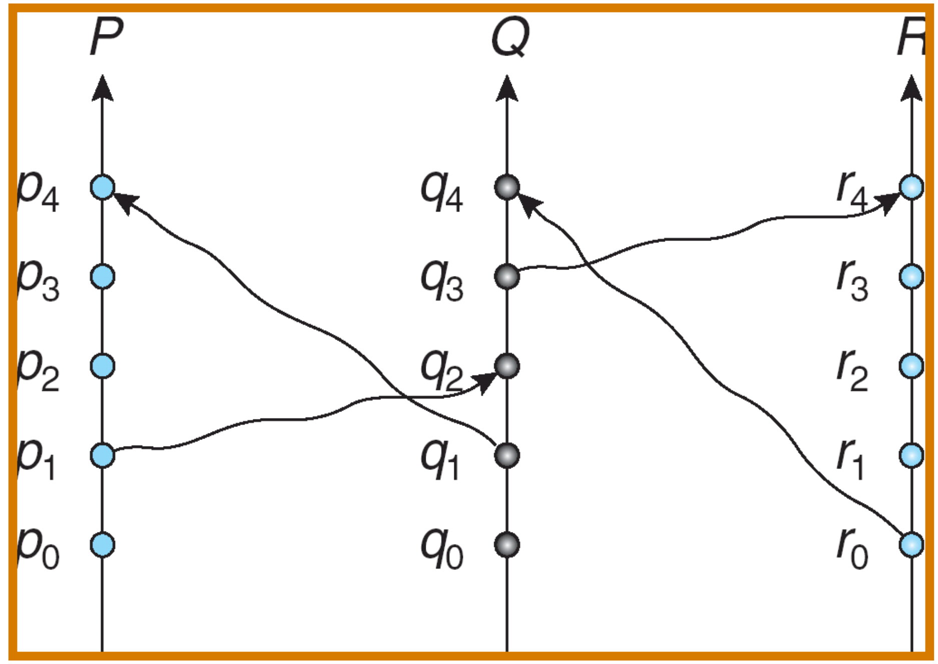


Which events are concurrent and which ones are ordered?

Exercise

Which of the following event orderings are true?

(a) p0 --> p3 :
(b) p1 --> q3 :
(c) q0 --> p3 :
(d) r0 --> p4 :
(e) p0 --> r4 :



Which of the following statements are true?

(a) p2 and q2 are concurrent processes.
(b) q1 and r1 are concurrent processes.
(c) p0 and q3 are concurrent processes.
(d) r0 and p0 are concurrent processes.
(e) r0 and p4 are 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, define a **logical clock**
  - 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
  - Assume A sends a message to B, $LC_1(A)=200$, $LC_2(B)=195$ --> $LC_2(B)=201$
- If the timestamps of two events A and B are the same, then the events are concurrent
  - We may use the process identity numbers to break ties and to create a total ordering

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 different approaches to ensure the mutual exclusion of processes in their critical sections

1. 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 it 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: ***request***, ***reply***, ***release***
- Single point of failure! -> would need a new coordinator to be elected..

2. 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 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 requests

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 first)
    - Otherwise, the reply is deferred
  - Example: P1 sends a request to P2 and P3 (timestamp=10)
    P3 sends a request to P1 and P2 (timestamp=4)

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, and notifying all processes if a process fails

==> More suitable for small, stable set of coordinating processes

3. 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**
- Unidirectional ring guarantees freedom from starvation
- Two types of failures
  - Lost token – election must be called
  - Failed processes – new logical ring established

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
- The coordinator is always the process with the highest priority number. When a coordinator fails, the algorithm must elect that active process with the largest priority number
- Two algorithms, the bully algorithm and a ring algorithm, can be used to elect a new coordinator in case of failures

1. 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.)

- 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

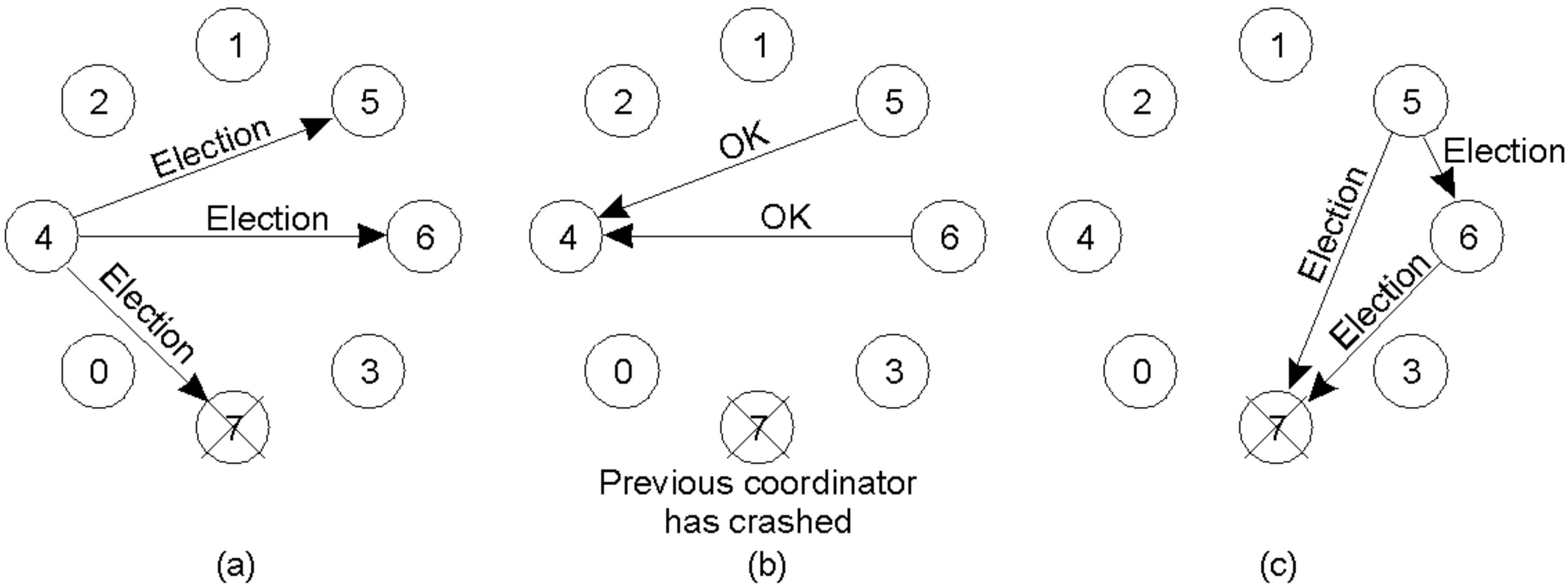
Bully Algorithm (Cont.)

- 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

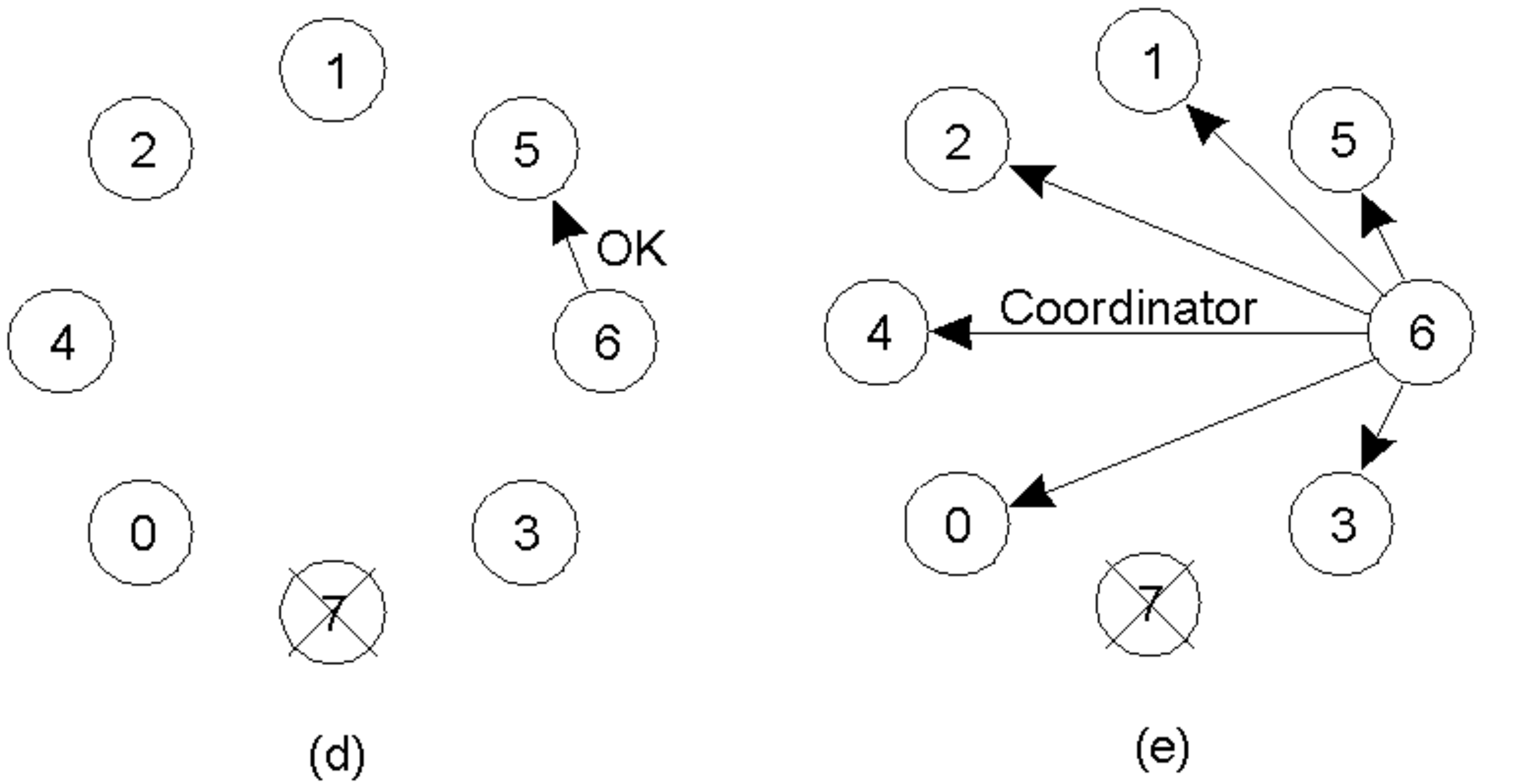
- If there are no active processes with higher numbers, the recovered process forces all processes with lower number to let it become the coordinator process, even if there is a currently active coordinator with a lower number

The Bully Algorithm (Example)



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

The Bully Algorithm (Example)



Bully Algorithm Analysis

- Best case
  - The node with second highest identifier detects failure
  - Total messages = N-2
    - One message for each of the other processes indicating the process with the second highest identifier is the new coordinator.
- Worst case
  - The node with lowest identifier detects failure. This causes N-1 processes to initiate the election algorithm each sending messages to processes with higher identifiers.
  - Total messages = $O(N^2)$

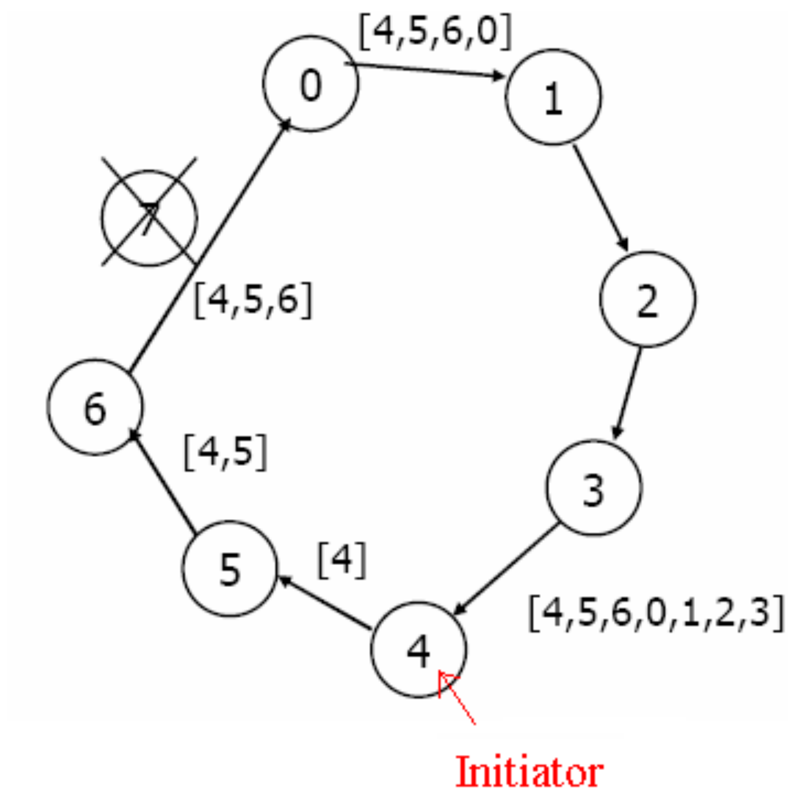
2. Ring Algorithm

- 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, it 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:
  - 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)*
  - If $i \neq j$, the message dos not contain P_i
    - P_i adds j to its active list and forward message to the right
  - 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 largest number in the active list to identify the new coordinator process

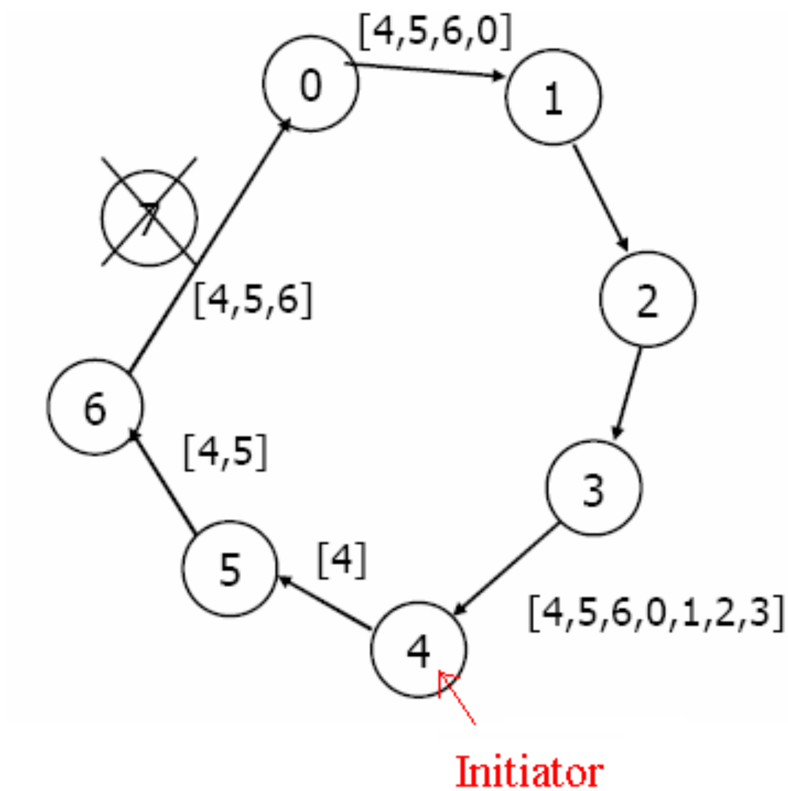
Ring Algorithm (Example)



Initiation:

1. Process 4 sends an ELECTION message to its successor (or next alive process) with its ID

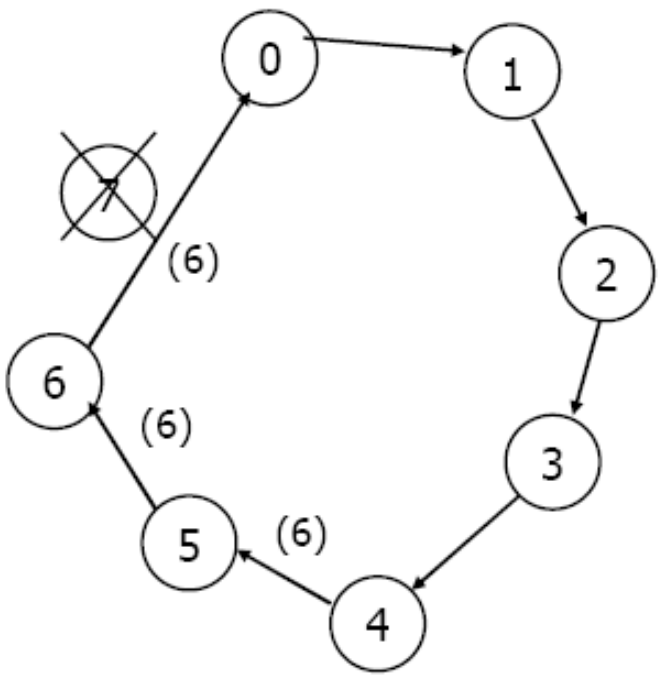
Ring Algorithm (Example)



Initiation:

2. Each process adds its own ID and forwards the ELECTION message

Ring Algorithm (Example)



Leader Election:

3. Message comes back to initiator, here the initiator is 4.
4. Initiator announces the winner by sending another message around the ring

Ring Algorithm Analysis

- At best 2(N-1) messages are passed
  - One round for the ELECTION message
  - One round for the COORDINATOR
  - Assumes that only a single process starts an election.
- Multiple elections cause an increase in messages but no real harm done.

Distributed 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

- Timestamp-ordering deadlock-prevention

  =>unique Timestamp assigned when each process is created

  1. wait-die scheme -- non-preemptive
  2. wound-wait scheme -- preemptive

1. Prevention: Wait-Die Scheme

- non-preemptive approach
- 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 - releases resources)

- Example: Suppose that processes P_1, P_2, and P_3 have timestamps 5, 10, and 15 respectively
  - if P_1 request a resource held by P_2, then P_1 will wait
  - If P_3 requests a resource held by P_2, then P_3 will be rolled back

- The older the process gets, the more waits

2. Prevention: Wound-Wait Scheme

- Preemptive approach, counterpart to the wait-die

- 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
- The rolled-back process eventually gets the smallest timestamp.

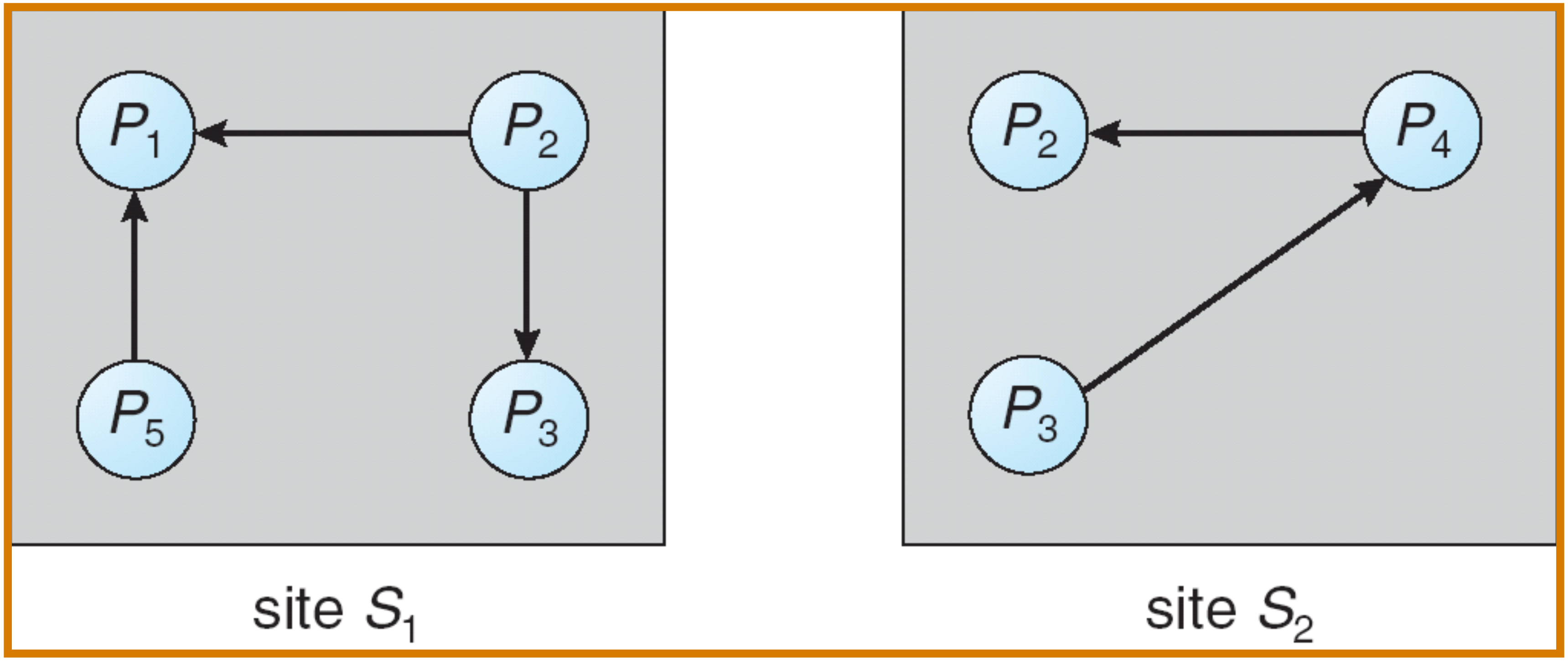
Comparison

- Both avoid starvation, provided that when a process is rolled back, it is not assigned a new timestamp

- In wait-die, older process must wait for the younger one to release its resources. In wound-wait, an older process never waits for a younger process.

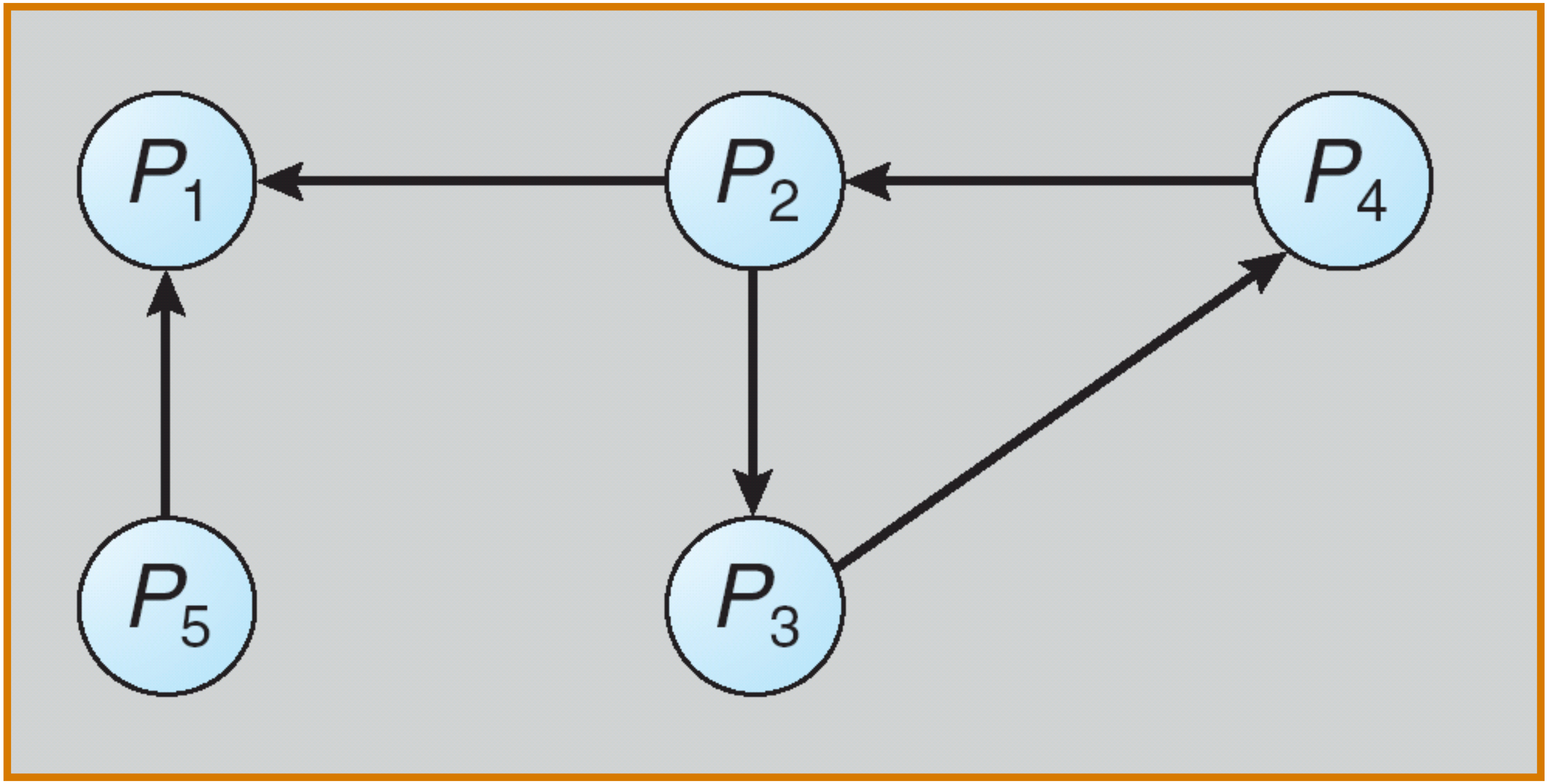
- There are fewer roll-backs in wound-wait
  - Assume Pi is younger than Pj
  - **Wait-Die:**
    - Pi->Pj; Pi dies, requests the same resources; Pi dies again...
  - **Wound-Wait:**
    - Pj->Pi; Pi wounded. requests the same resources; Pi waits..

Distributed Deadlock Detection



Two Local Wait-For Graphs

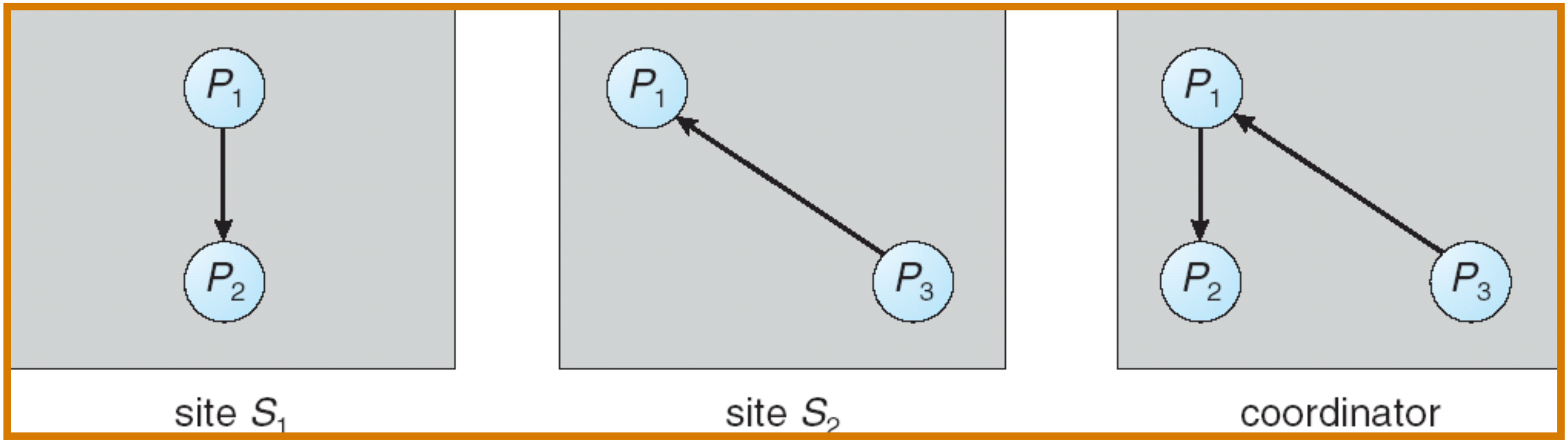
Global Wait-For Graph



1. 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

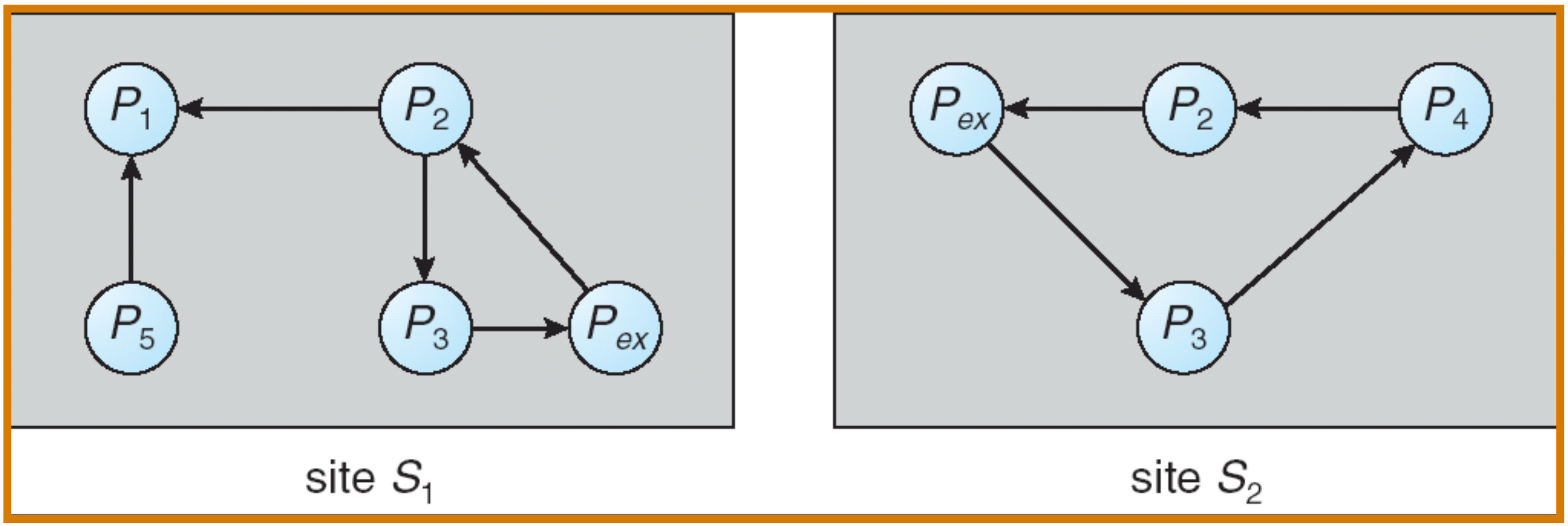
Local and Global Wait-For Graphs



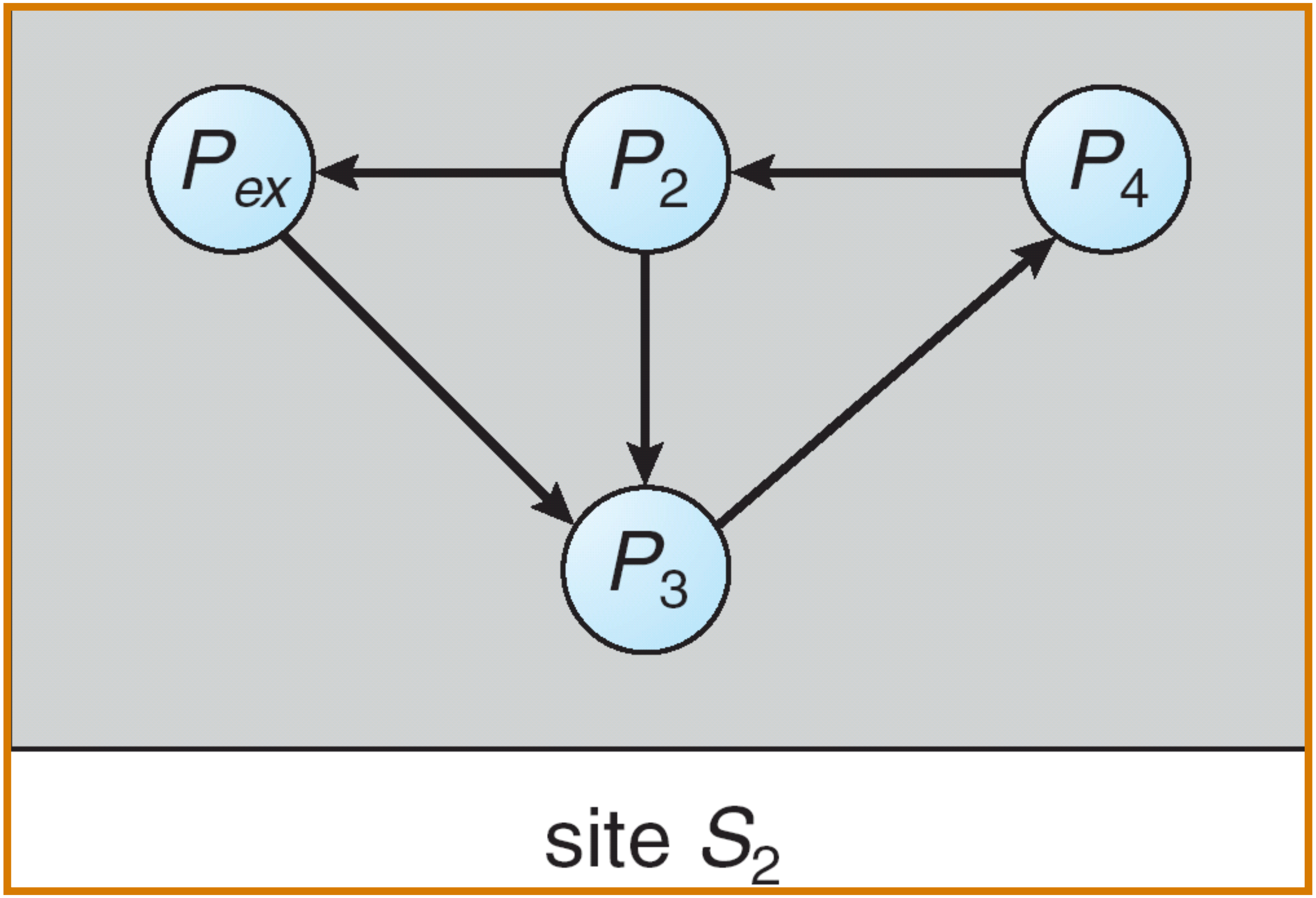
2. Fully Distributed Approach

- 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
  - $P_i \to P_{ex}$ exists if P_i is waiting for a data item at another site being held by any process
- 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
  - To ascertain whether a deadlock does exist, a distributed deadlock-detection algorithm must be invoked

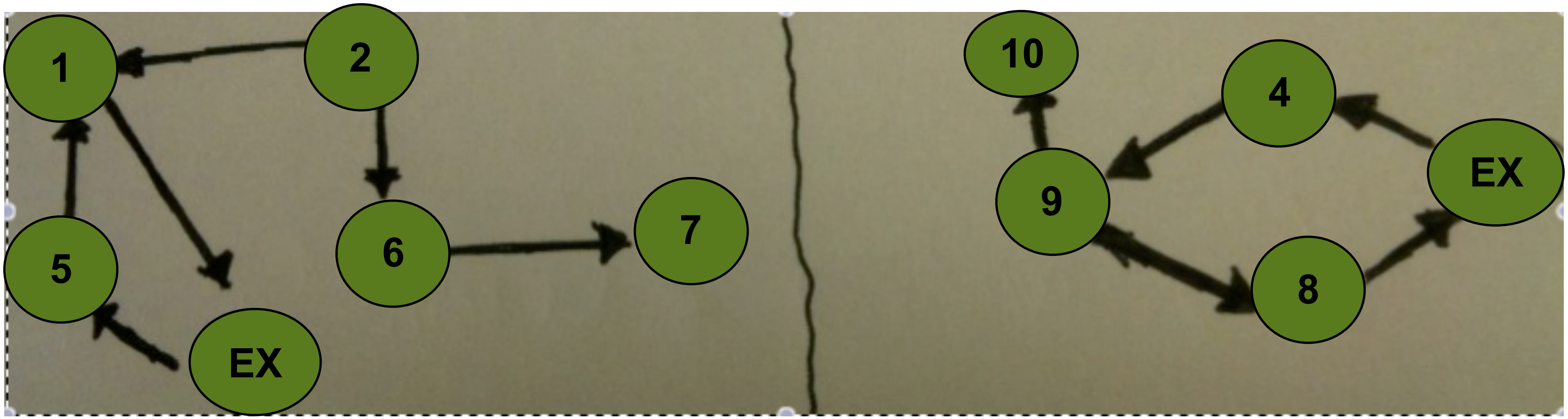
Augmented Local Wait-For Graphs



Augmented Local Wait-For Graph in Site S2

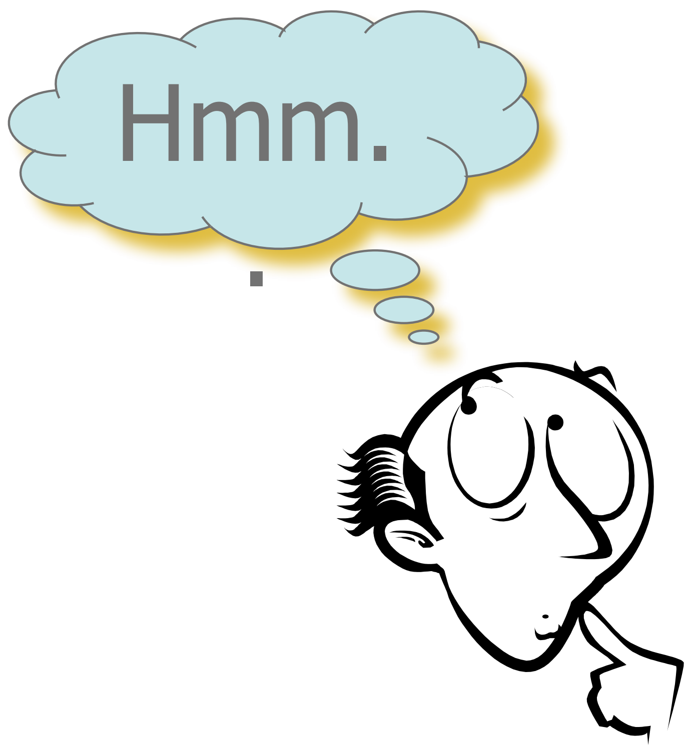


Exercise



Considering the above local wait-for graphs at sites S1 and S2, is the system D in a deadlocked state? If so, which processes are involved in the deadlock? Show how you would check the existence of a deadlock.

Any Questions?



Acknowledgements

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