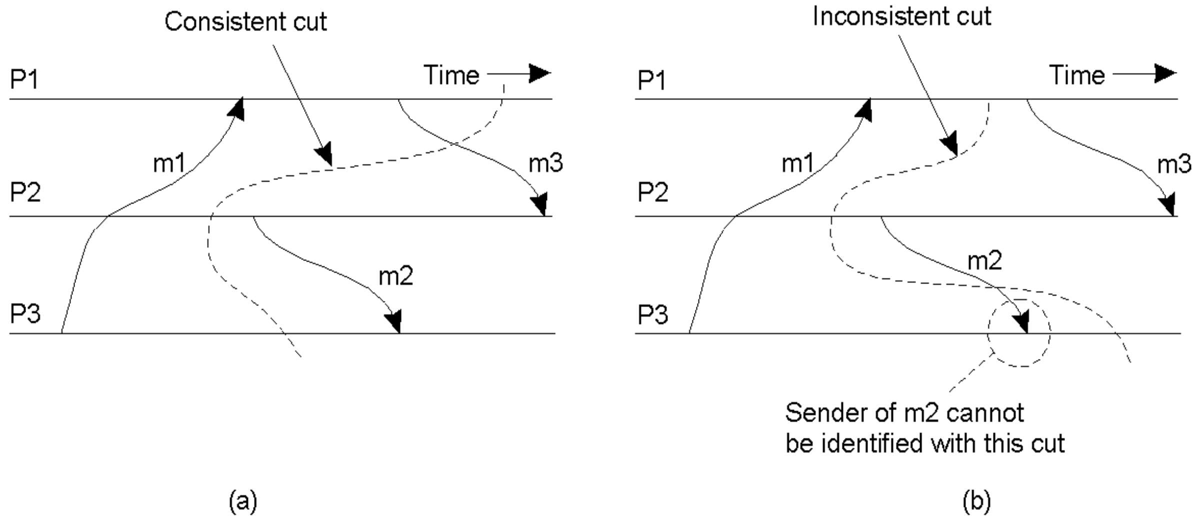
Today: More Classical Problems

- Termination Detection
- Leader election
- Mutual exclusion

Global State

- Global state of a distributed system
  - Local state of each process
  - Messages sent but not received (state of the queues)
- Many applications need to know the state of the system
  - Failure recovery, distributed deadlock detection
- Problem: how can you figure out the state of a distributed system?
  - Each process is independent
  - No global clock or synchronization
- Distributed snapshot: a consistent global state

Global State (1)



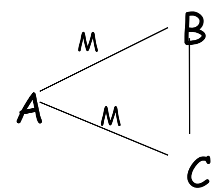
a) A consistent cut
b) An inconsistent cut

Distributed Snapshot Algorithm

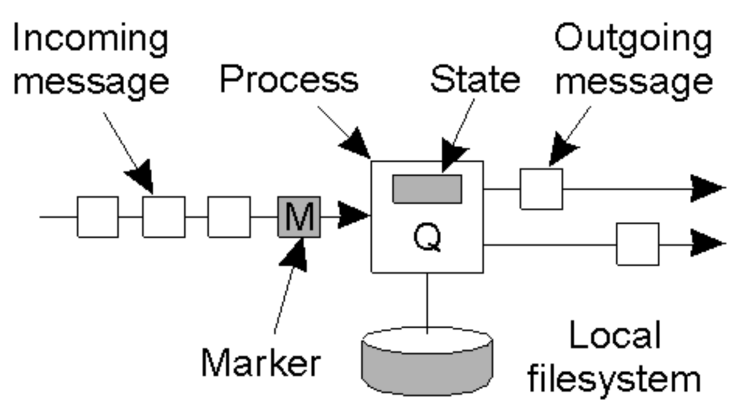
- Assume each process communicates with another process using unidirectional point-to-point channels (e.g, TCP connections)
- Any process can initiate the algorithm
  - Checkpoint local state
  - Send marker on every outgoing channel
- On receiving a marker
  - Checkpoint state if first marker and send marker on outgoing channels, save messages on all other channels until:
  - Subsequent marker on a channel: stop saving state for that channel

Distributed Snapshot

- A process finishes when
  - It receives a marker on each incoming channel and processes them all
  - State: local state plus state of all channels
  - Send state to initiator
- Any process can initiate snapshot
  - Multiple snapshots may be in progress
    - Each is separate, and each is distinguished by tagging the marker with the initiator ID (and sequence number)



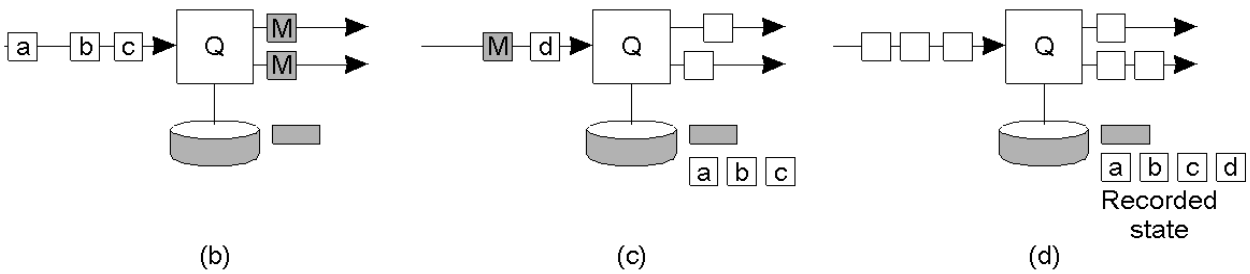
Snapshot Algorithm Example



(a)

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

Snapshot Algorithm Example



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

Termination Detection

- Detecting the end of a distributed computation
- Notation: let sender be *predecessor*, receiver be *successor*
- Two types of markers: Done and Continue
- After finishing its part of the snapshot, process *Q* sends a Done or a Continue to its predecessor
- Send a Done only when
  - All of *Q*'s successors send a Done
  - *Q* has not received any message since it check-pointed its local state and received a marker on all incoming channels
  - Else send a Continue
- Computation has terminated if the initiator receives Done messages from everyone

Election Algorithms

- Many distributed algorithms need one process to act as coordinator
  - Doesn't matter which process does the job, just need to pick one
- Election algorithms: technique to pick a unique coordinator (aka *leader election*)
- Examples: take over the role of a failed process, pick a master in Berkeley clock synchronization algorithm
- Types of election algorithms: Bully and Ring algorithms

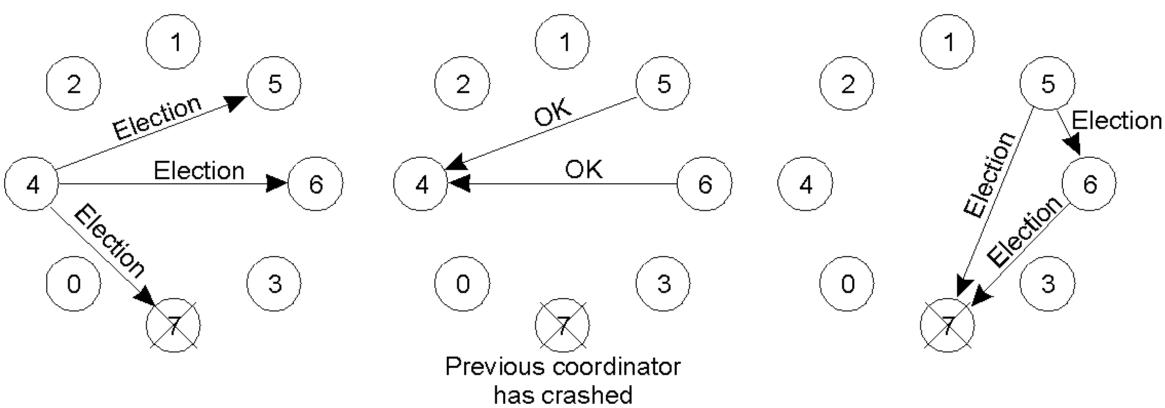
Bully Algorithm

- Each process has a unique numerical ID
- Processes know the Ids and address of every other process
- Communication is assumed reliable
- *Key Idea*: select process with highest ID
- Process initiates election if it just recovered from failure or if coordinator failed
- 3 message types: *election, OK, I won*
- Several processes can initiate an election simultaneously
  - Need consistent result
- $O(n^2)$ messages required with n processes

Bully Algorithm Details

- Any process *P* can initiate an election
- *P* sends *Election* messages to all process with higher Ids and awaits *OK* messages
- If no *OK* messages, *P* becomes coordinator and sends *I won* messages to all process with lower Ids
- If it receives an *OK*, it drops out and waits for an *I won*
- If a process receives an *Election* msg, it returns an *OK* and starts an election
- If a process receives a *I won*, it treats sender an coordinator

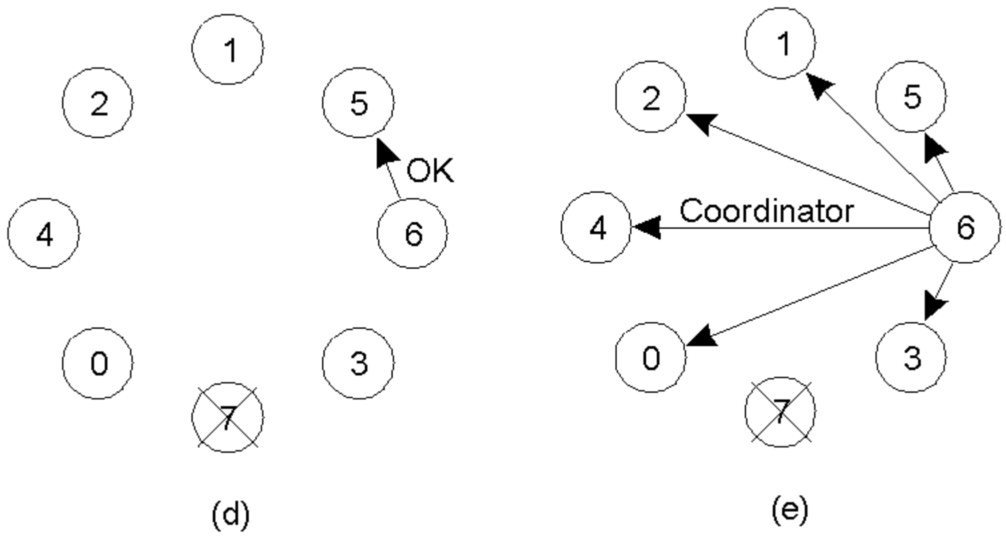
Bully Algorithm Example



(a) (b) (c)

- 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

Bully Algorithm Example



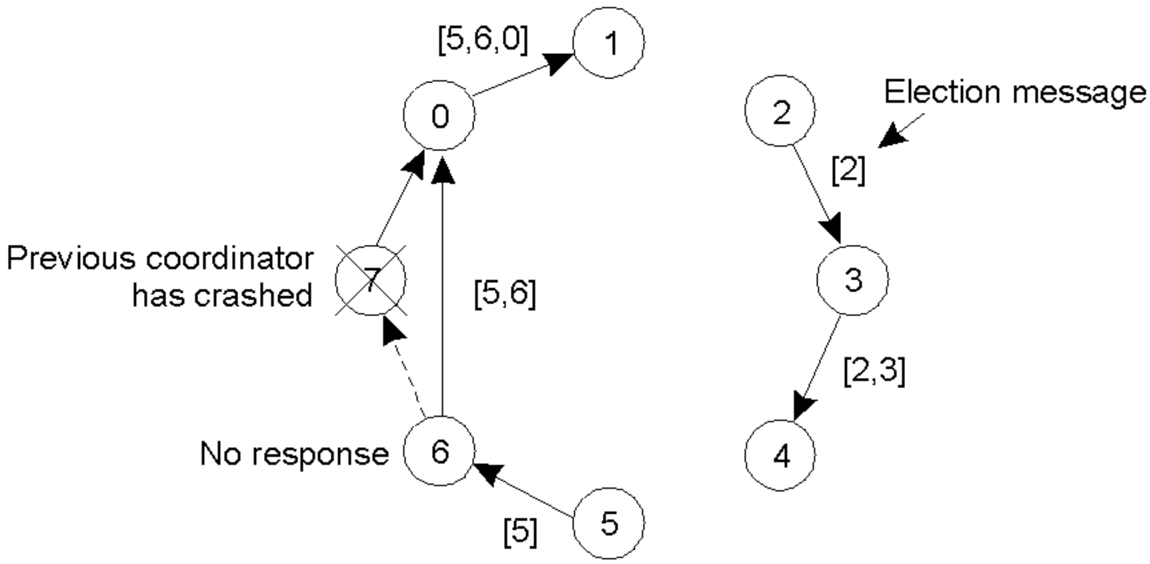
d) Process 6 tells 5 to stop

e) Process 6 wins and tells everyone

Ring-based Election

- Processes have unique Ids and arranged in a logical ring
- Each process knows its neighbors
  - Select process with highest ID
- Begin election if just recovered or coordinator has failed
- Send *Election* to closest downstream node that is alive
  - Sequentially poll each successor until a live node is found
- Each process tags its ID on the message
- Initiator picks node with highest ID and sends a coordinator message
- Multiple elections can be in progress
  - Wastes network bandwidth but does no harm

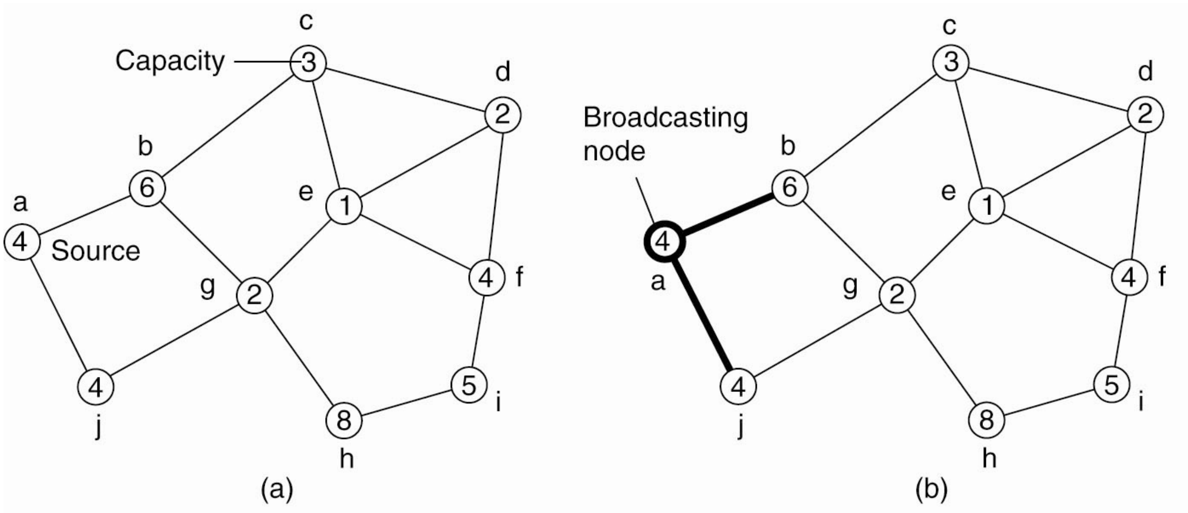
A Ring Algorithm



Comparison

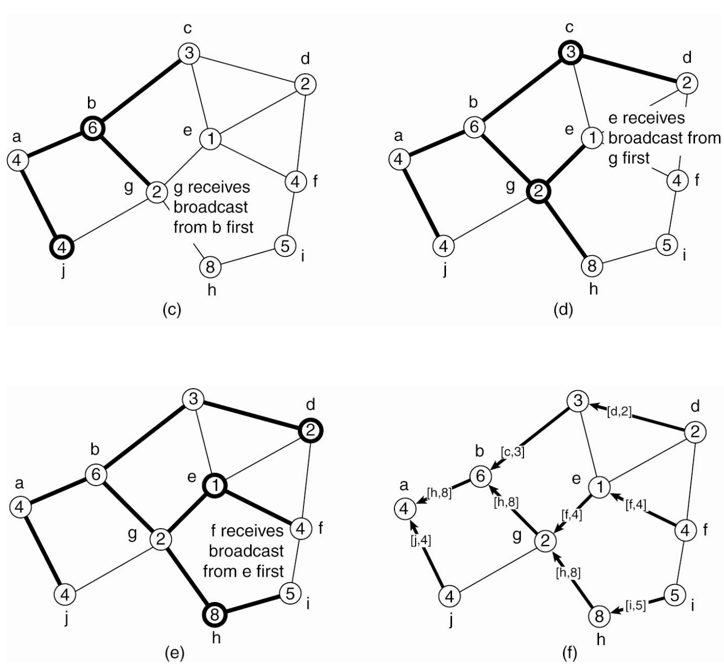
- Assume *n* processes and one election in progress
- Bully algorithm
  – Worst case: initiator is node with lowest ID
    - Triggers n-2 elections at higher ranked nodes: $O(n^2)$ msgs
  – Best case: immediate election: n-2 messages
- Ring
  – 2 (n-1) messages always

Elections in Wireless Environments (1)



- Election algorithm in a wireless network, with node a as the source. (a) Initial network. (b)–(e) The build-tree phase

Elections in Wireless Environments (2)

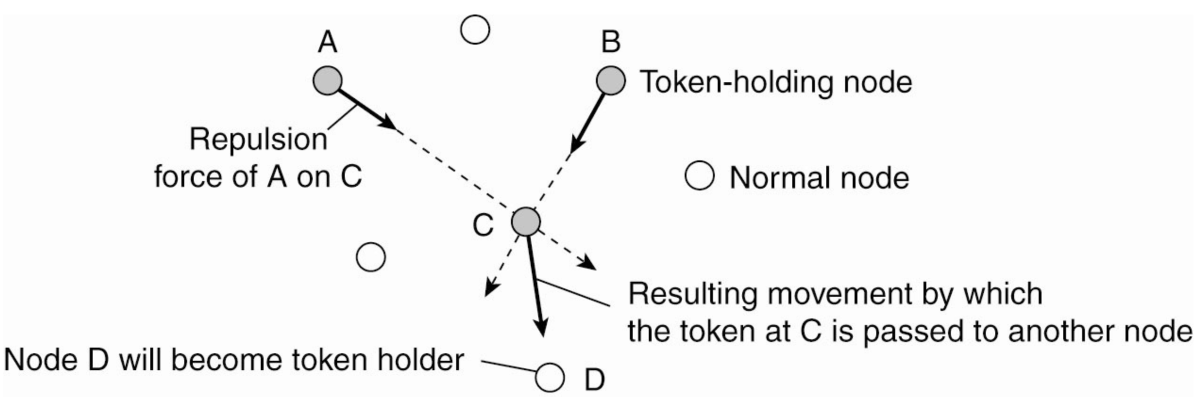


Elections in Large-Scale Systems

- Requirements for superpeer selection:

1. Normal nodes should have low-latency access to superpeers.
2. Superpeers should be evenly distributed across the overlay network.
3. There should be a predefined portion of superpeers relative to the total number of nodes in the overlay network.
4. Each superpeer should not need to serve more than a fixed number of normal nodes.

Elections in Large-Scale Systems (2)



- Moving tokens in a two-dimensional space using repulsion forces.

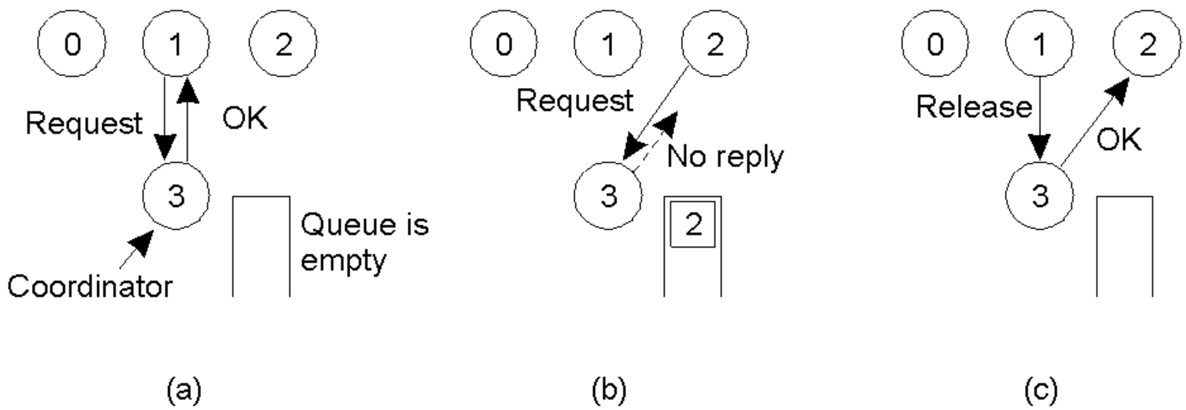
Distributed Synchronization

- Distributed system with multiple processes may need to share data or access shared data structures
  - Use critical sections with mutual exclusion
- Single process with multiple threads
  - Semaphores, locks, monitors
- How do you do this for multiple processes in a distributed system?
  - Processes may be running on different machines
- Solution: lock mechanism for a distributed environment
  - Can be centralized or distributed

Centralized Mutual Exclusion

- Assume processes are numbered
- One process is elected coordinator (highest ID process)
- Every process needs to check with coordinator before entering the critical section
- To obtain exclusive access: send request, await reply
- To release: send release message
- Coordinator:
  - Receive *request*: if available and queue empty, send grant; if not, queue request
  - Receive *release*: remove next request from queue and send grant

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

Properties

- Simulates centralized lock using blocking calls
- Fair: requests are granted the lock in the order they were received
- Simple: three messages per use of a critical section (request, grant, release)
- Shortcomings:
  - Single point of failure
  - How do you detect a dead coordinator?
    - A process can not distinguish between “lock in use” from a dead coordinator
      - No response from coordinator in either case
  - Performance bottleneck in large distributed systems

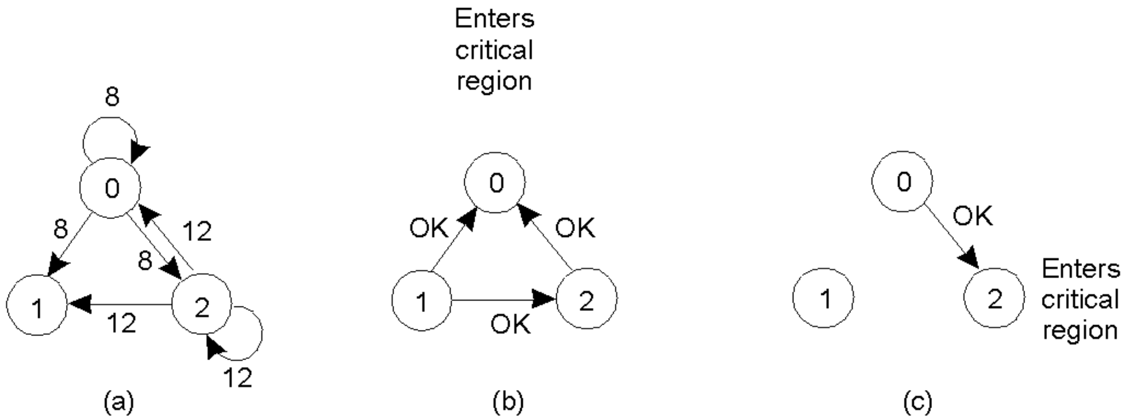
Decentralized Algorithm

- Use voting
- Assume n replicas and a coordinator per replica
- To acquire lock, need majority vote $m > n/2$ coordinators
  - Non blocking: coordinators returns OK or "no"
- Coordinator crash => forgets previous votes
  - Probability that k coordinators crash $P(k) = {}^{m}C_{k}\, p^{k}\, (1-p)^{m-k}$
  - Atleast 2m-n need to reset to violate correctness
    - $\sum_{2m-n}{}^{n}P(k)$

Distributed Algorithm

- [Ricart and Agrawala]: needs 2(n-1) messages
- Based on event ordering and time stamps
  - Assumes total ordering of events in the system (Lamport's clock)
- Process *k* enters critical section as follows
  - Generate new time stamp $TS_k = TS_k+1$
  - Send *request(k,TS_k)* all other *n-1* processes
  - Wait until *reply(j)* received from all other processes
  - Enter critical section
- Upon receiving a *request* message, process *j*
  - Sends *reply* if no contention
  - If already in critical section, does not reply, queue request
  - If wants to enter, compare TS_j with TS_k and send reply if $TS_k<TS_j$, else queue (recall: total ordering based on multicast)

A Distributed Algorithm

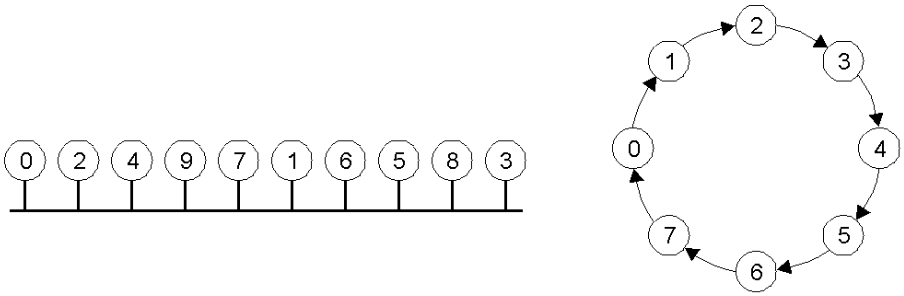


a) Two processes want to enter the same critical region at the same moment.
b) Process 0 has the lowest timestamp, so it wins.
c) When process 0 is done, it sends an OK also, so 2 can now enter the critical region.

Properties

- Fully decentralized
- *N* points of failure!
- All processes are involved in all decisions
  - Any overloaded process can become a bottleneck

A Token Ring Algorithm



(a) (b)

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

- Use a token to arbitrate access to critical section
- Must wait for token before entering CS
- Pass the token to neighbor once done or if not interested
- Detecting token loss in non-trivial

Comparison

Algorithm	Messages per entry/exit	Delay before entry (in message times)	Problems
Centralized	3	2	Coordinator crash
Decentralized	3mk	2m	starvation
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 four mutual exclusion algorithms.