Distributed Systems

09. Consensus: Mutual Exclusion & Election Algorithms

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Process Synchronization

Techniques to coordinate execution among processes

- One process may have to wait for another
- Shared resource (e.g. critical section) may require exclusive access

Mutual exclusion

- Examples
  - Update a fields in database tables
  - Modify a file
  - Modify file contents that are replicated on multiple servers
- Easy to handle if the entire request is atomic
  - Contained in a single message; server can manage mutual exclusion
- Needs to be coordinated if the request comprises multiple messages or spans multiple systems

Centralized Systems

Achieve mutual exclusion via:

- Test & set in hardware
- Semaphores
- Messages (inter-process)
- Condition variables

Distributed Mutual Exclusion

Goal:

Create an algorithm to allow a process to request and obtain exclusive access to a resource that is available on the network.

Required properties:

Safety: At any instant, only one process may hold the resource

Liveness: The algorithm should make progress; processes should not wait forever for messages that will never arrive

Fairness: Each process gets a fair chance to hold the resource: bounded wait time & in-order processing

Assumption

Assume there is agreement on how a resource is identified

- Pass the identifier with requests
- e.g., *lock("printer")*
  lock("table:employees"),
  lock("table:employees;row:15")

…and every process can identify itself uniquely

We'll just use *request(R)* to request exclusive access to resource *R*.

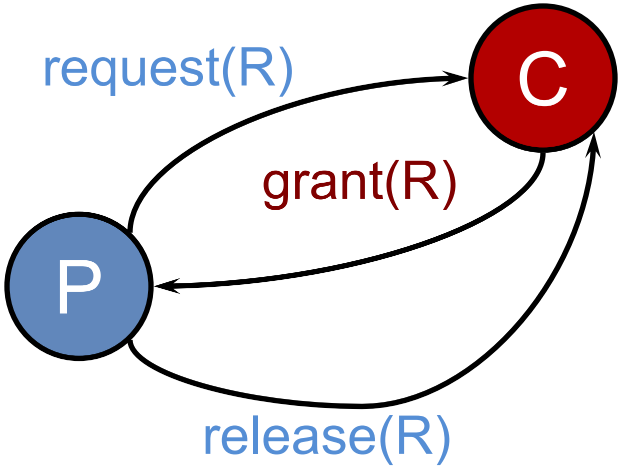
Categories of algorithms

- Centralized
  - A process can access a resource because a central coordinator allowed it to do so
- Token-based
  - A process can access a resource if it is holding a token permitting it to do so
- Contention-based
  - An process can access a resource via distributed agreement

Centralized algorithm

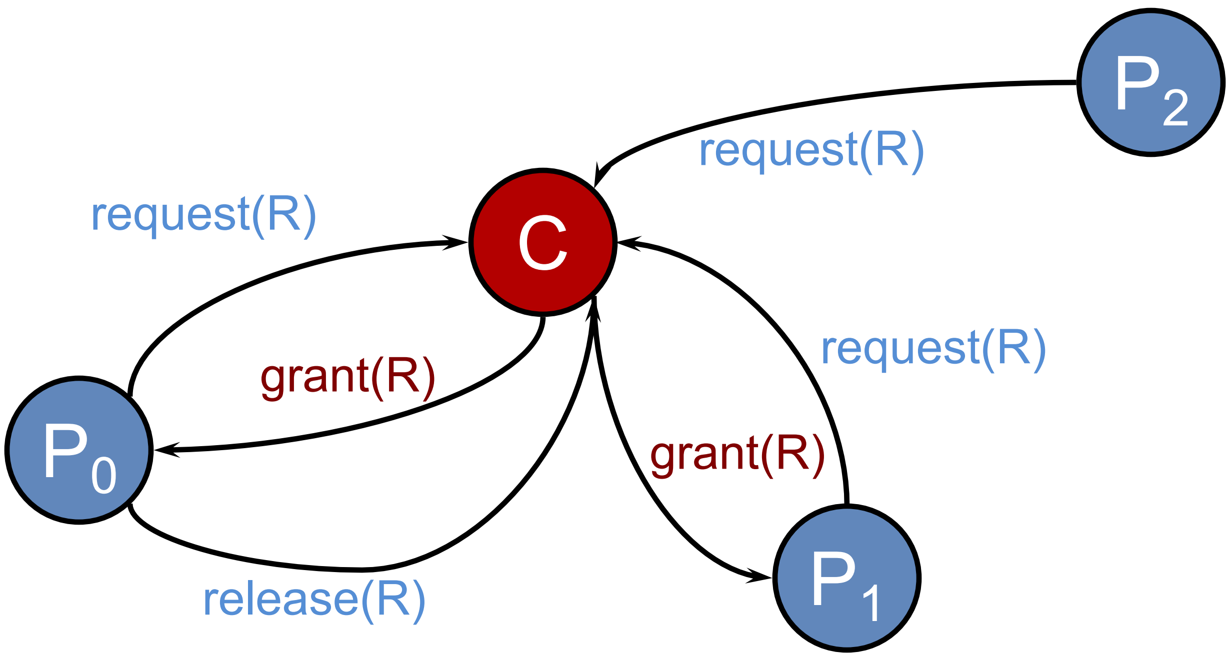
- Mimic single processor system
- One process elected as coordinator

1. **Request** resource
2. Wait for response
3. **Receive grant**
4. *access resource*
5. **Release resource**



Centralized algorithm

- If another process claimed resource:
  - Coordinator does not reply until release
  - Maintain queue
    - Service requests in FIFO order



Centralized algorithm

Benefits

- Fair: All requests processed in order
- Easy to implement, understand, verify
- Processes do not need to know group members – just the coordinator

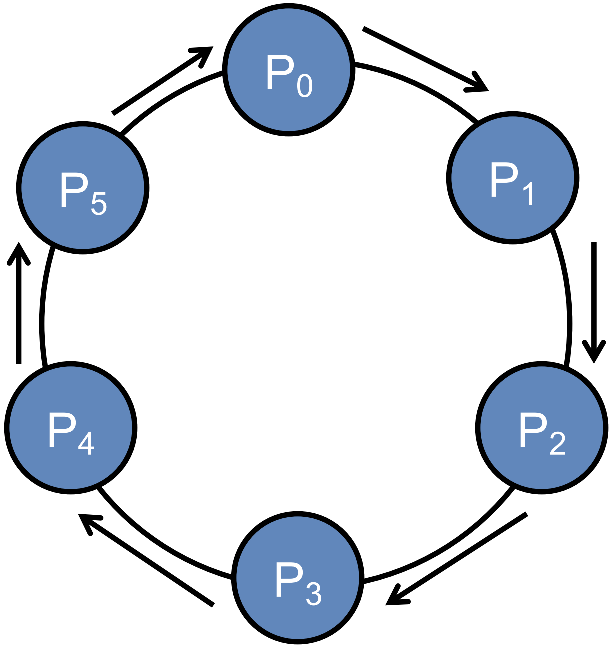
Problems

- Process cannot distinguish being blocked from a dead coordinator – single point of failure
- Centralized server can be a bottleneck

Token Ring algorithm

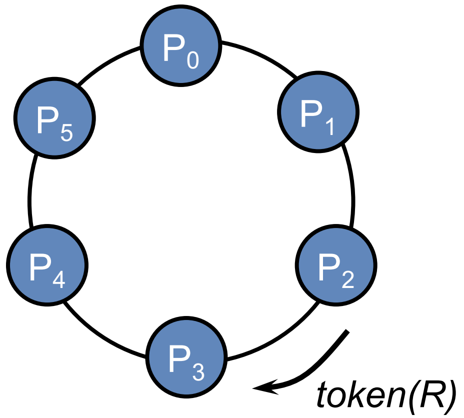
Assume known group of processes

- Some ordering can be imposed on group (unique process IDs)
- Construct logical ring in software
- Process communicates with its neighbor

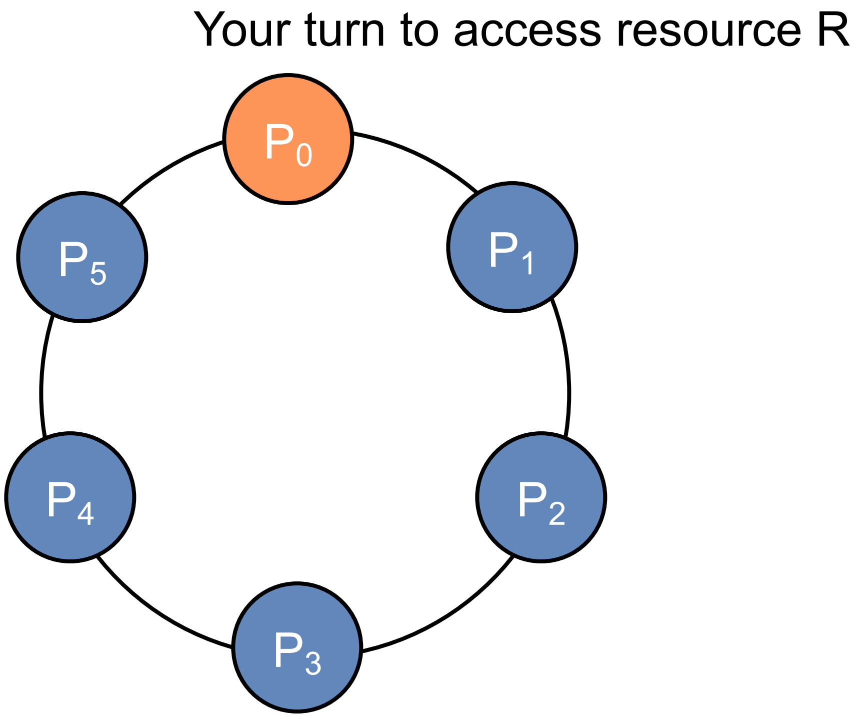


Token Ring algorithm

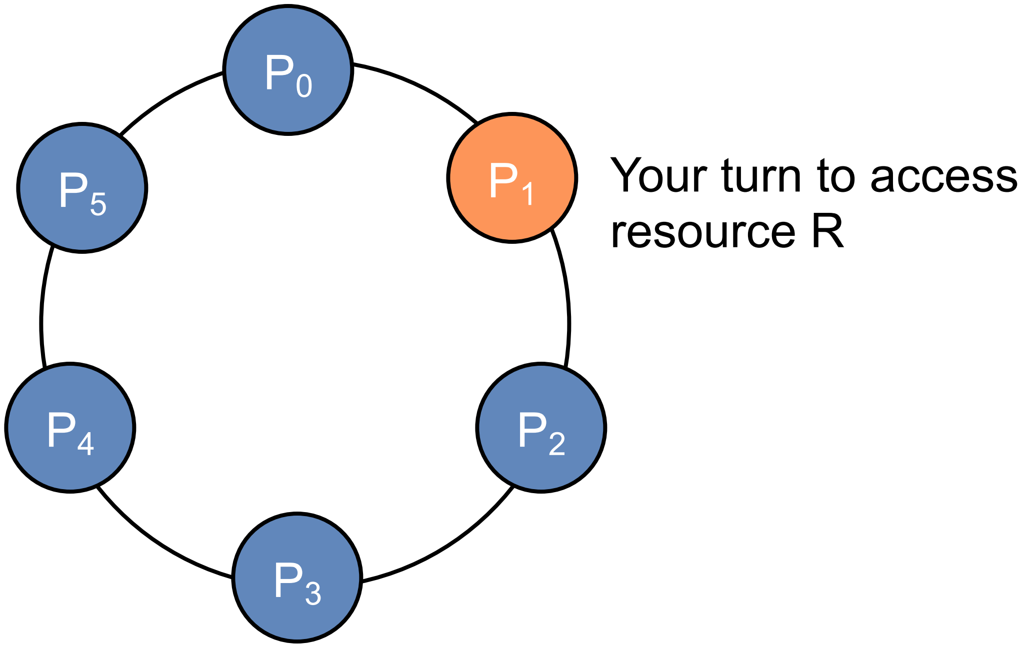
- Initialization
  - Process 0 creates a token for resource R
- Token circulates around ring
  - From P_i to $P_{(i+1)}$mod N
- When process acquires token
  - Checks to see if it needs to enter critical section
  - If no, send ring to neighbor
  - If yes, access resource
    - Hold token until done



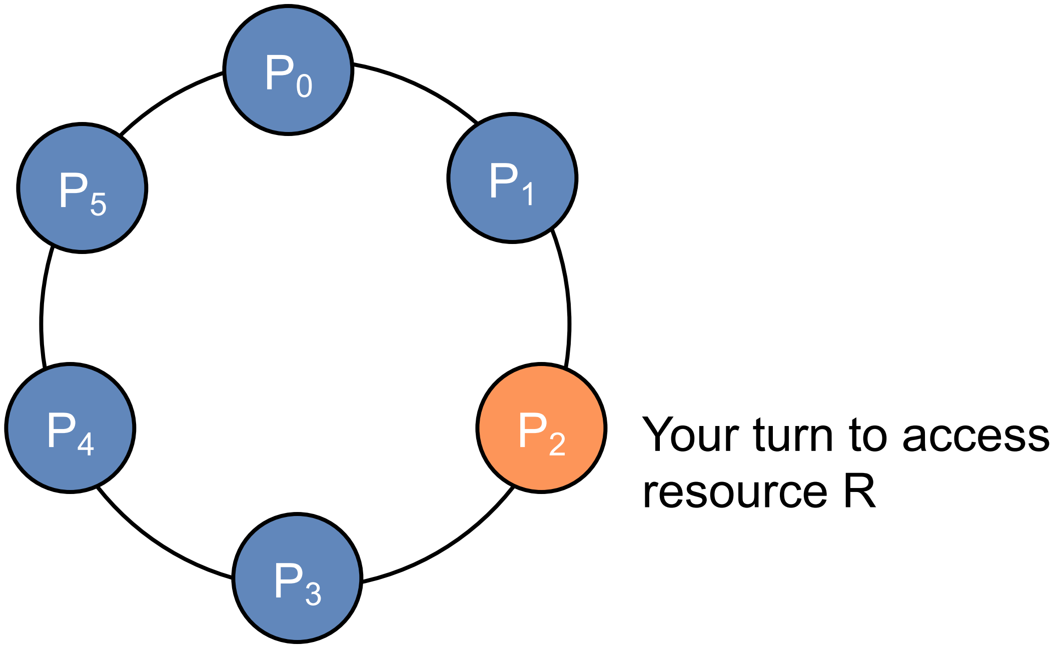
Token Ring algorithm



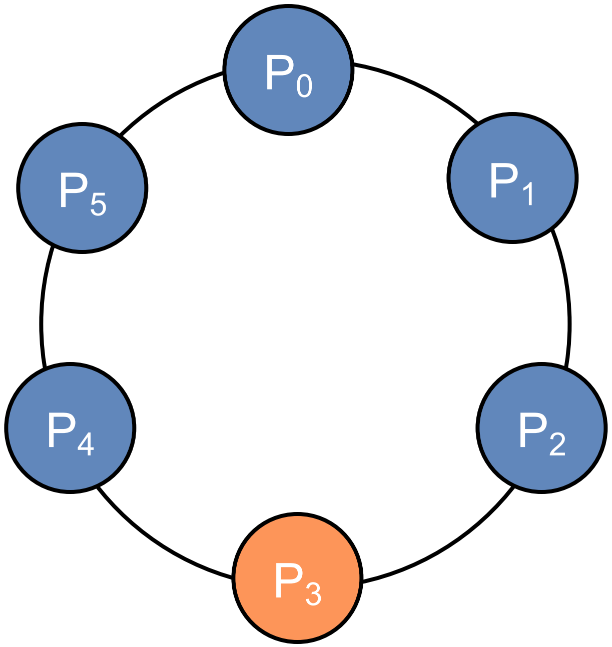
Token Ring algorithm



Token Ring algorithm

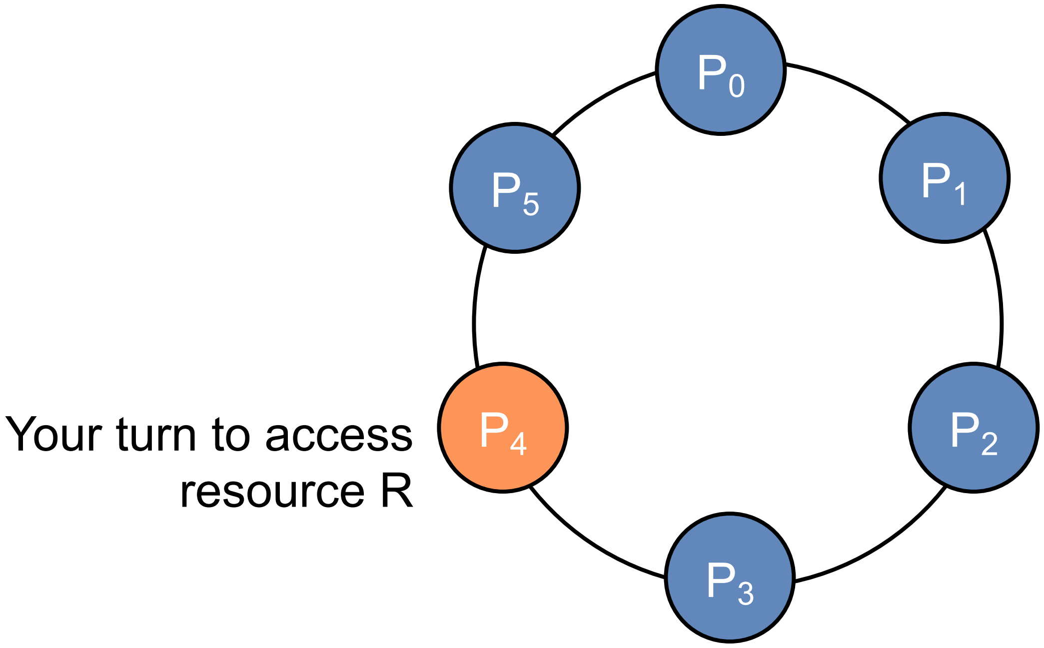


Token Ring algorithm

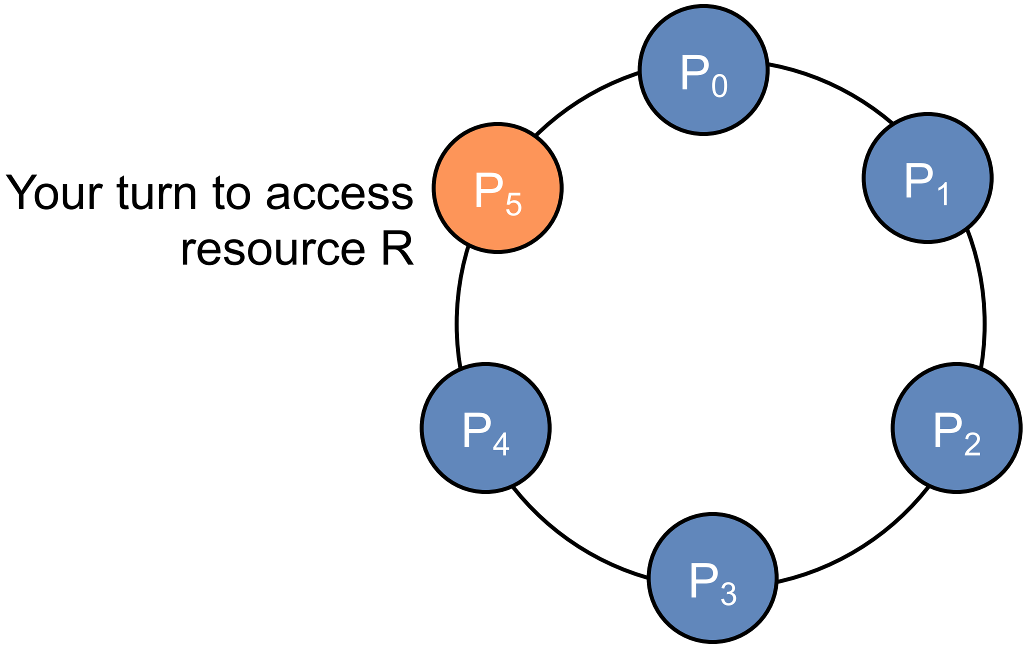


Your turn to access resource R

Token Ring algorithm

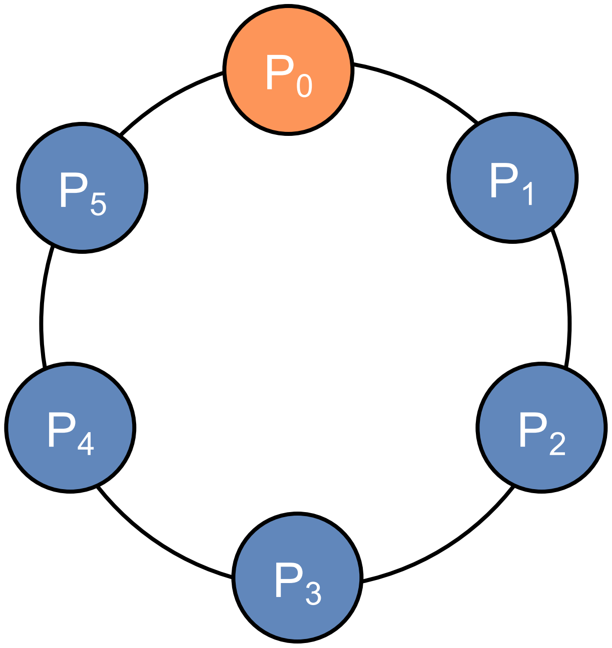


Token Ring algorithm

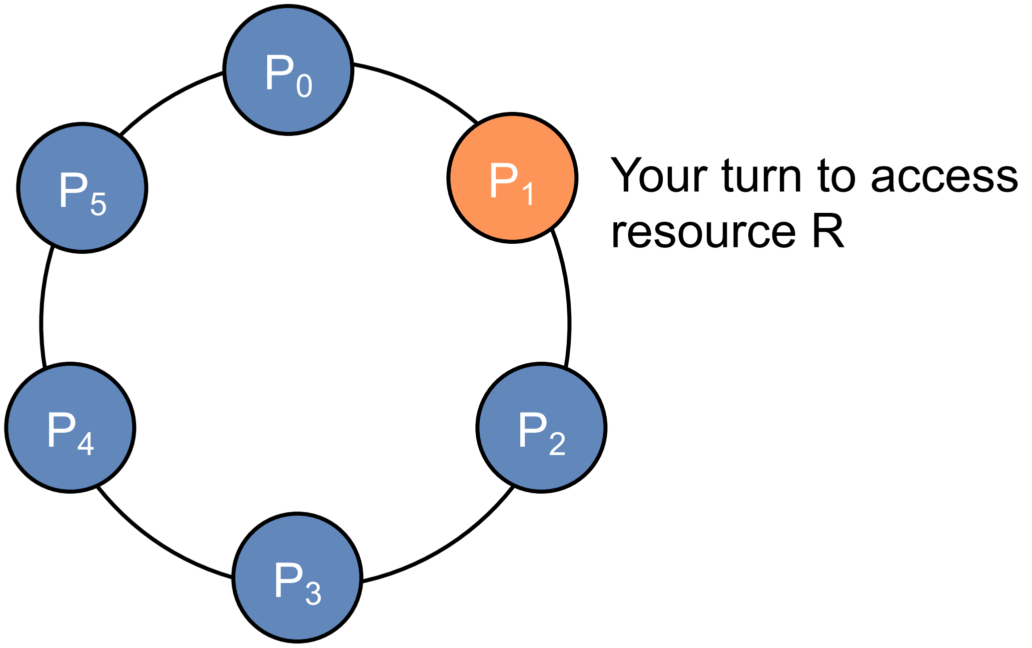


Token Ring algorithm

Your turn to access resource R



Token Ring algorithm



Token Ring algorithm summary

- Only one process at a time has token
  - Mutual exclusion guaranteed
- Order well-defined (but not necessarily first-come, first-served)
  - Starvation cannot occur
  - Lack of FCFS ordering may be undesirable sometimes
- Problems
  - Token loss (e.g., process died)
    - It will have to be regenerated
    - Detecting loss may be a problem
      (*is the token lost or in just use by someone?*)
  - Process loss: what if you can't talk to your neighbor?

Lamport’s Mutual Exclusion

Distributed algorithm using reliable multicast and logical clocks

- Each process maintains request queue
  - Queue contains mutual exclusion requests
- Messages are sent reliably and in FIFO order
  - Each message is time stamped with totally ordered Lamport timestamps
    - Ensures that each timestamp is unique
    - Every node can make the same decision by comparing timestamps
- Queues are sorted by message timestamps

Lamport's Mutual Exclusion

Request a critical section:

- Process P_i sends *request(i, T_i)* to all nodes
  … and places request on its own queue
- When a process P_j receives a request:
  - It returns a timestamped *ack*
  - Places the request on its request queue

Lamport time

Enter a critical section (accessing resource):

- P_i has received ACKs from everyone
- P_i's request has the earliest timestamp in its queue

Release a critical section:

- Process P_i removes its request from its queue
- sends *release(i, T_i)* to all nodes
- Each process now checks if its request is the earliest in its queue
  - If so, that process now has the critical section

Process	Time stamp
P_4	1021
P_8	1022
P_1	3944
P_6	8201
P_{12}	9638

Sample request queue
Identical at each process

Lamport's Mutual Exclusion

- *Performance*
  - *3(N-1)* messages per critical section
  - *(N-1) Request* msgs + *(N-1) Reply* msgs + *(N-1) Release* msgs
- *N* points of failure
- Not great … but demonstrates that a fully distributed algorithm is possible

Ricart & Agrawala algorithm

Another distributed algorithm
using reliable multicast and logical clocks

- When a process wants to enter critical section:
  1. Compose message containing:
     - Identifier (machine ID, process ID)
     - Name of resource
     - Timestamp (e.g., totally-ordered Lamport)
  2. Reliably multicast request to all processes in group
  3. Wait until everyone gives permission
  4. Enter critical section / use resource

Ricart & Agrawala algorithm

- When process receives request:
  - If receiver not interested:
    - Send OK to sender
  - If receiver is in critical section
    - Do not reply; add request to queue
  - If receiver just sent a request as well: (*potential race condition*)
    - Compare timestamps on received & sent messages
    - Earliest wins
    - If receiver is loser, send OK
    - If receiver is winner, do not reply, queue it
- When done with critical section
  - Send OK to all queued requests

Ricart & Agrawala algorithm

- *Performance*
  - *2(N-1)* messages per critical section
  - *(N-1) Request* msgs + *(N-1) Reply* msgs
- Not great either
  - *N* points of failure
  - A lot of messaging traffic
  - Also demonstrates that a fully distributed algorithm is possible

Lamport vs. Ricart & Agrawala

Lamport

- Everyone responds (acks) … always – no hold-back
- *3(N-1)* messages
  - Request – ACK – Release
- Process decides to go based on whether its request is the earliest in its queue

Ricart & Agrawala

- If you are in the critical section (or won a tie)
  - Don't respond with an ACK until you are done with the critical section
- *2(N-1)* messages
  - Request – ACK
- Process decides to go if it gets ACKs from everyone

Election algorithms

Elections

- Purpose
  - Need to pick one process to act as coordinator

- Processes have no distinguishing characteristics

- Each process has a unique ID to identify itself

Bully algorithm

- Select process with largest ID as coordinator

- When process P detects dead coordinator:
  - Send ***election*** message to all processes with higher IDs
    - If nobody responds, **P wins** and takes over
    - If any process responds, P's job is done
  - Optional: Let all nodes with lower IDs know an election is taking place

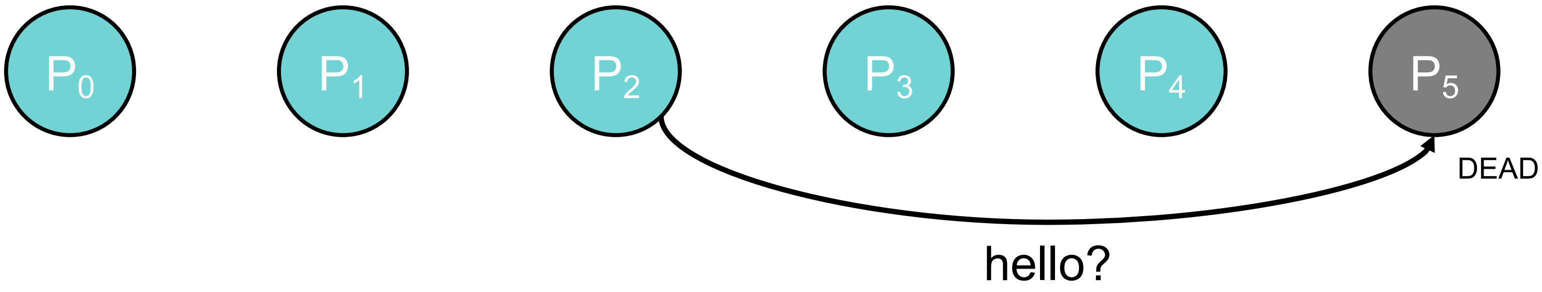
- If process receives an election message
  - Send ***OK*** message back
  - Hold election (unless it is already holding one)

Bully algorithm

- A process announces victory:
  - Sends all processes a message telling them that it is the new coordinator

- If a dead process recovers
  - It holds an election to find the coordinator

Bully algorithm

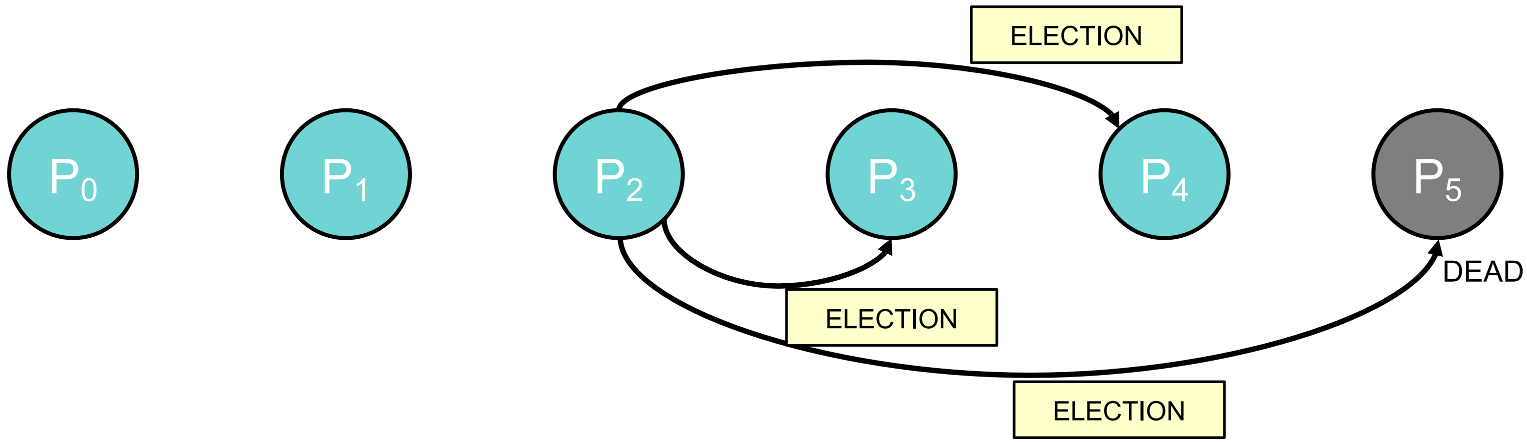


Rule: highest # process is the leader

Suppose P_5 dies

P_2 detects P_5 is not responding

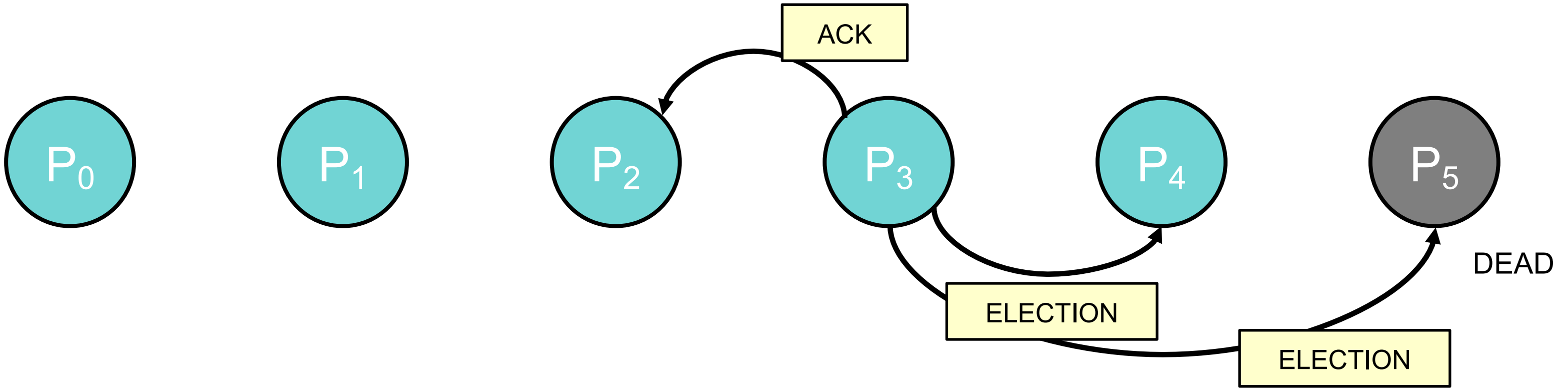
Bully algorithm



P_2 starts an election

Contacts all higher-numbered systems

Bully algorithm



Everyone who receives an ELECTION message responds

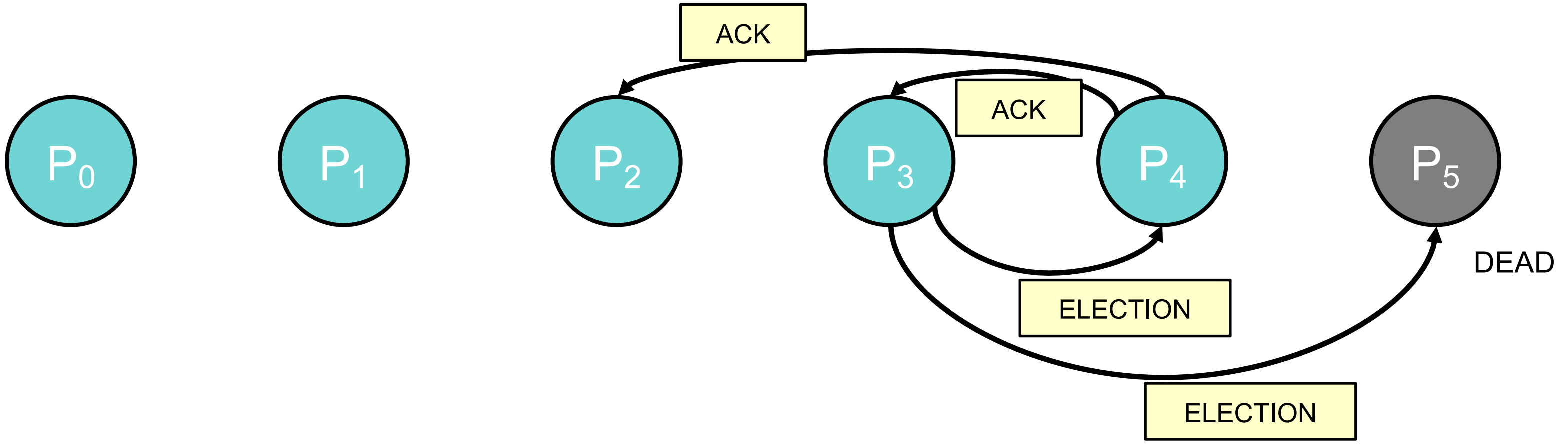
… and holds their own election, contacting higher # processes

Example: P_3 receives the message from P_2

Responds to P_2

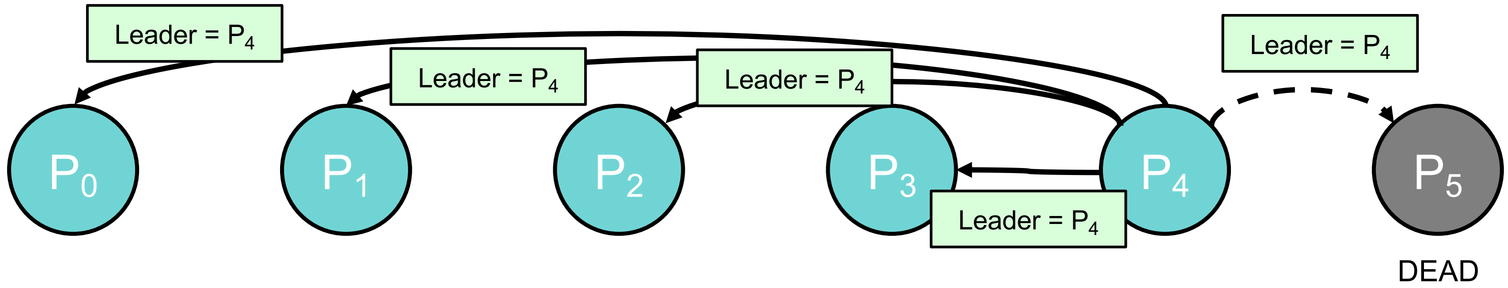
Sends ELECTION messages to P_4 and P_5

Bully algorithm



P_4 responds to P_3 and P_2's messages
… and holds an election

Bully algorithm



Nobody responds to P_4

After a timeout, P_4 declares itself the leader

Ring algorithm

- Ring arrangement of processes
- If any process detects failure of coordinator
  - Construct election message with process ID and send to next process
  - If successor is down, skip over
  - Repeat until a running process is located
- Upon receiving an election message
  - Process forwards the message, adding its process ID to the body

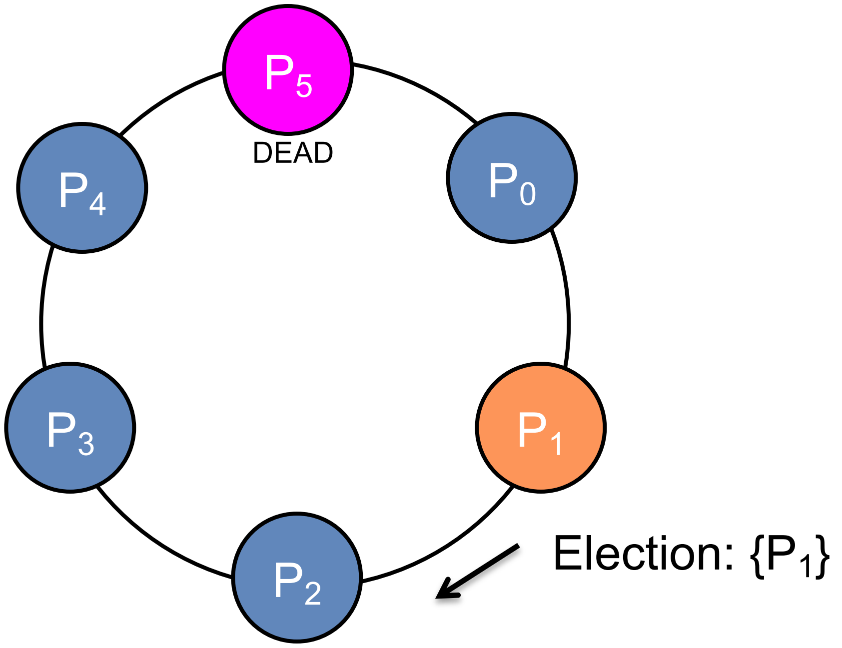
Ring algorithm

Eventually message returns to originator

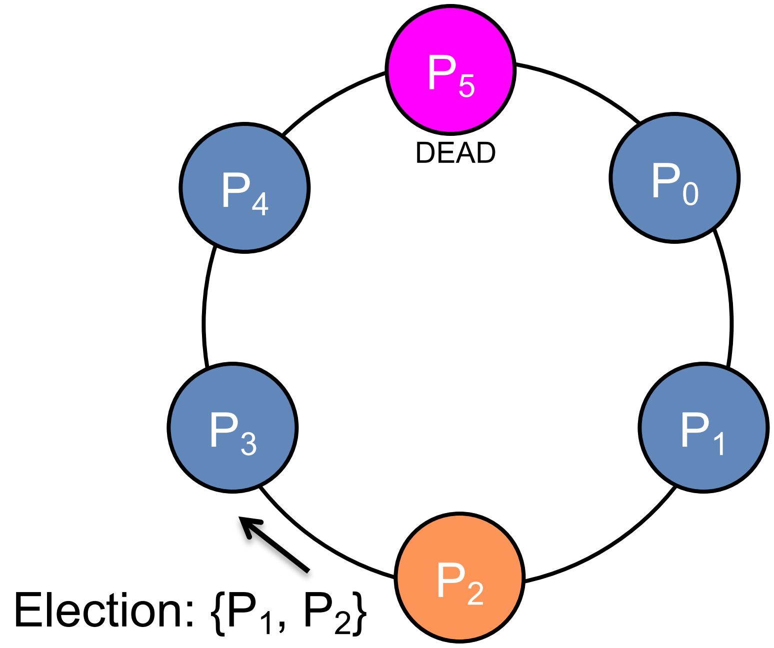
- Process sees its ID on list
- Circulates (or multicasts) a **coordinator** message announcing coordinator
  - E.g. highest numbered process

Ring algorithm

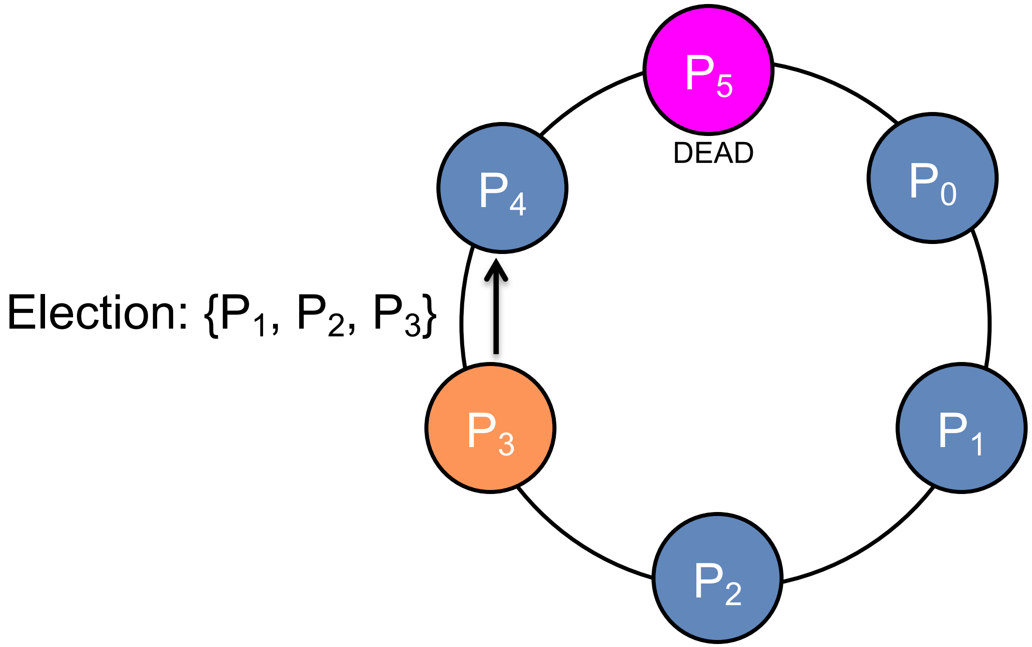
Assume P_1 discovers that the coordinator, P_5, is dead
P_1 starts an election



Ring algorithm



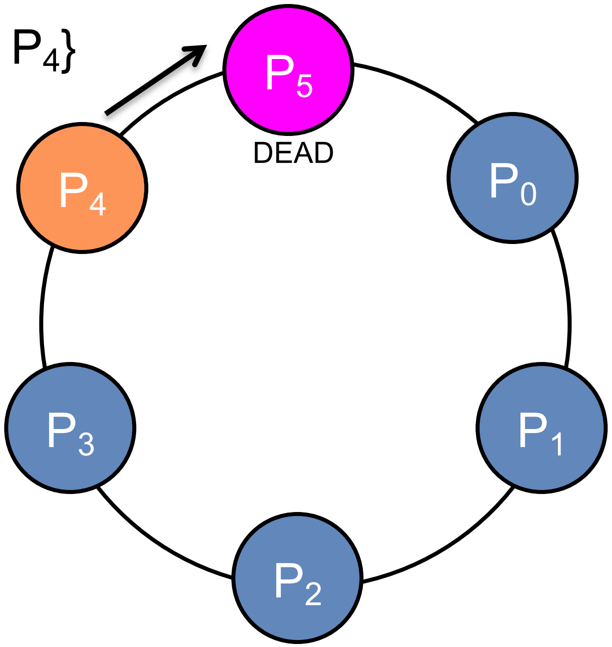
Ring algorithm



Ring algorithm

Election: {P_1, P_2, P_3, P_4}

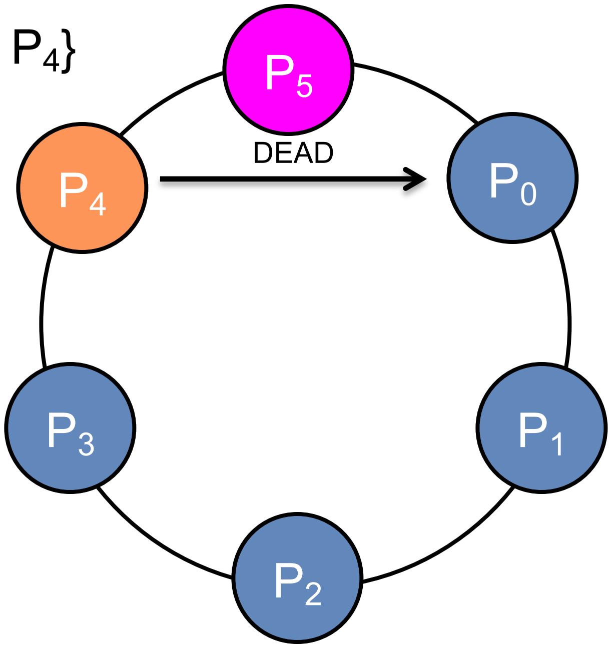
Fails: P_5 is dead



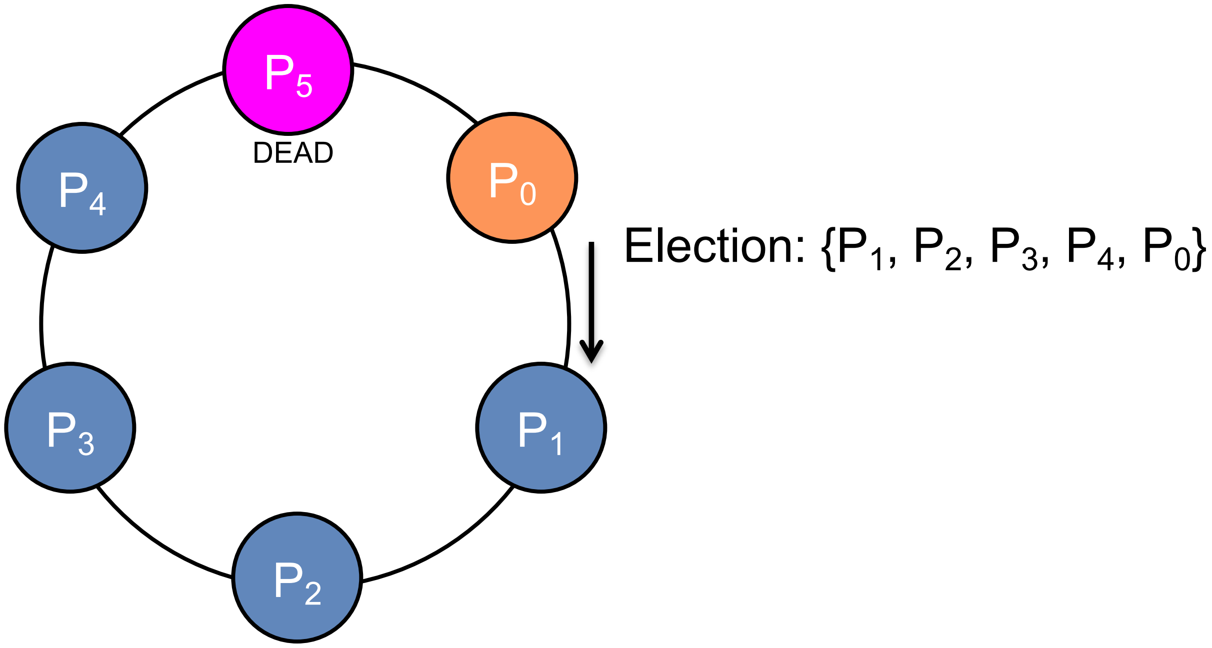
Ring algorithm

Election: {P_1, P_2, P_3, P_4}

Skip to P_0



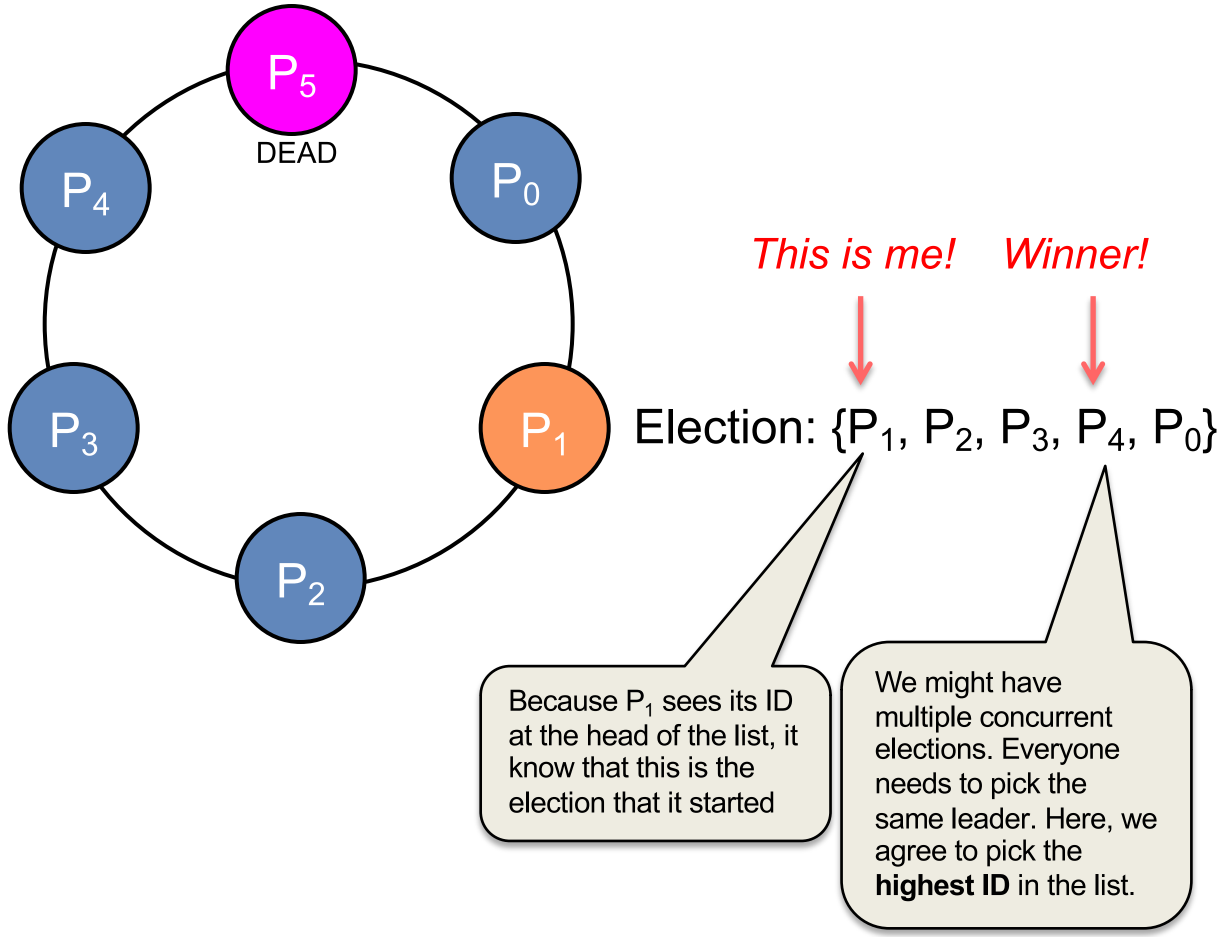
Ring algorithm



Ring algorithm

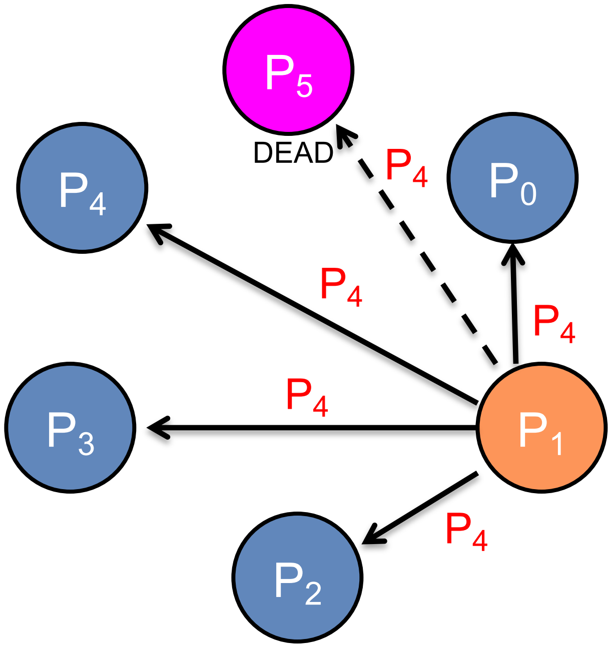
P_2 receives the election message that it initiated

P_2 now picks a leader (e.g., lowest or highest ID)



Ring algorithm

P_1 announces that P_4 the new coordinator to the group



Chang & Roberts Ring Algorithm

Optimize the ring

- Message always contains _one_ process ID
- Avoid multiple circulating elections
- If a process sends a message, it marks its state as a *participant*

Upon receiving an election message:

If PID(message) > PID(process)
forward the message – *higher ID will always win over a lower one*

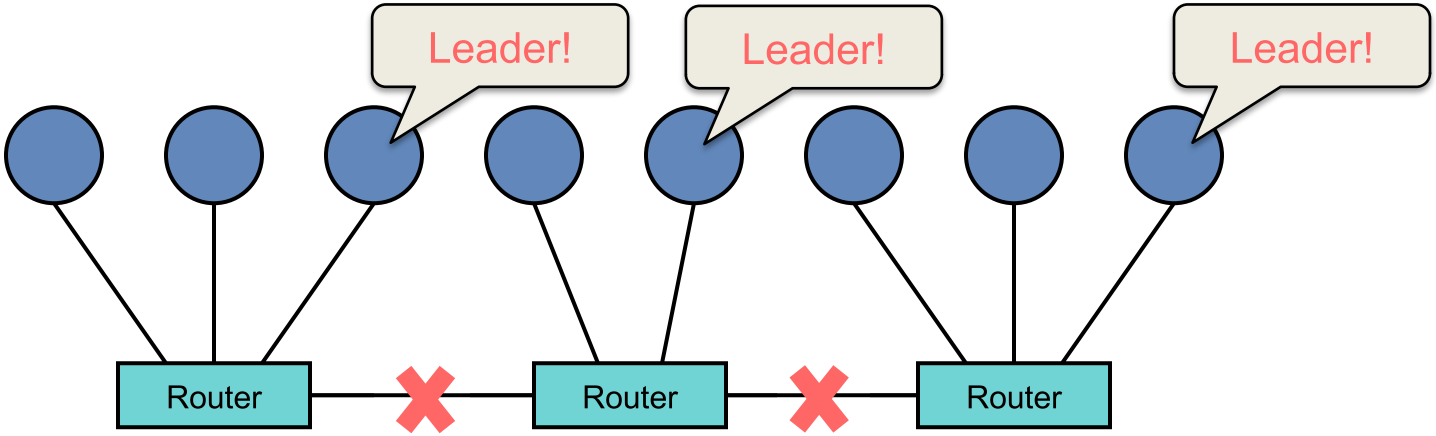
If PID(message) < PID(process)
replace PID in message with PID(process)
forward the new message – *we have a higher ID number; use it*

If PID(message) < PID(process) AND process is *participant*
discard the message – *we're already circulating our ID and ours is higher*

If PID(message) == PID(process)
the process is now the leader – *message circulated: announce winner*

Network Partitions: Split Brain

- Network **partitioning** (segmentation)
  - **Split brain**
  - Multiple nodes may decide they're the leader



- Dealing with partitioning
  - Insist on a majority → if no majority, the system will not function
  - Rely on alternate communication mechanism to validate failure
    - Redundant network, shared disk, serial line, SCSI
- We will visit this problem later!

The End