Distributed Systems

CS425/ECE428

Feb 22 2022

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Acknowledgements: Indy Gupta and Nikita Borisov

Logistics

- HW2 is due tomorrow.
- HW3 has been released.
  - Due on March 7th, Monday.
  - *You can only use up to 24hours of the total 48hours grace period provided for late submissions.*

Today's agenda

- Wrap up Mutual Exclusion
  - Extending Maekawa's algorithm to break deadlocks.
- Leader Election
  - Chapter 15.3

Recap: Mutual exclusion in distributed systems

- Classical algorithms for mutual exclusion in distributed systems.
  - Central server algorithm
  - Ring-based algorithm
  - Ricart-Agrawala Algorithm
  - Maekawa Algorithm

Maekawa Algorithm: Actions

- state = Released, voted = false
- enter() at process P*i*:
  - state = Wanted
  - Multicast Request message to all processes in V*i*
  - Wait for Reply (vote) messages from all processes in V*i* (including vote from self)
  - state = Held
- exit() at process P*i*:
  - state = Released
  - Multicast Release to all processes in V*i*

Maekawa Algorithm: Actions (contd.)

- When P*i* receives a Request from P*j*:

  if (state == <u>Held</u> OR voted = true)

  queue Request

  else

  send Reply to P*j* and set voted = true

- When P*i* receives a Release from P*j*:

  if (queue empty)

  voted = false

  else

  dequeue head of queue, say P*k*

  Send Reply *only* to P*k*

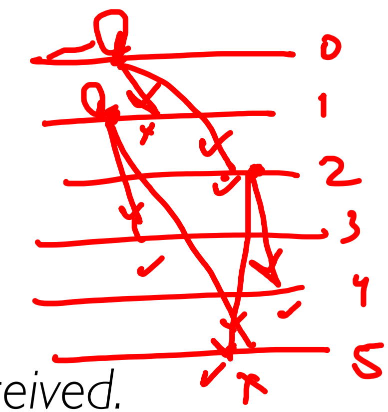
  voted = true

Analysis: Maekawa Algorithm

- Safety:
  - When a process P*i* receives replies from all its voting set V*i* members, no other process P*j* could have received replies from all its voting set members V*j*.
- Liveness
  - Not satisfied. Can have deadlock!
- Ordering:
  - Not satisfied.

Breaking deadlocks

- Maekawa algorithm can be extended to break deadlocks.
- Compare Lamport timestamps before replying (like Ricart-Agrawala).
- But is that enough?
  - *System of 6 processes {0,1,2,3,4,5}. 0,1,2 want to enter critical section:*
    - V_0= {0, 1, 2}: 0, 2 send reply to 0, but 1 sends reply to 1;
    - V_1= {1, 3, 5}: 1, 3 send reply to 1, but 5 sends reply to 2;
    - V_2= {2, 4, 5}: 4, 5 send reply to 2, but 2 sends reply to 0;
  - Suppose (L1, P1) < (L0, P0) < (L2, P2).
  - *Deadlock can still happen based on when messages are received.*
    - P5 receives P2's request before P1's, and replies back to P2 first.
- ***We need a way to take back the reply.***



Breaking deadlocks

- Say Pi's request has a smaller timestamp than Pj.
- If Pk receives Pj's request after replying to Pi, send fail to Pj.
- If Pk receives Pi's request after replying to Pj, send inquire to Pj.
- If Pj receives an inquire and at least one fail, it sends a relinquish to release locks, and deadlock breaks.

Breaking deadlocks

- *System of 6 processes {0,1,2,3,4,5}. 0,1,2 want to enter critical section:*
    - V_0= {0, 1, 2}: 0, 2 send reply to 0, but 1 sends reply to 1;
    - V_1= {1, 3, 5}: 1, 3 send reply to 1, but 5 sends reply to 2;
    - V_2= {2, 4, 5}: 4, 5 send reply to 2, but 2 sends reply to 0;
- Suppose (L1, P1) < (L0, P0) < (L2, P2).
- P2 will send fail to itself when it receives its own request after P0.
- P5 will send inquire to P2 when it receives P1's request.
- P2 will send relinquish to V_2. P5 and P4 will set "voted = false". P5 will reply to P1.
- P1 can now enter CS, followed by P0, and then P2.

Mutual exclusion in distributed systems

- Classical algorithms for mutual exclusion in distributed systems.
  - Central server algorithm
    - Satisfies safety, liveness, but not ordering.
    - O(1) bandwidth, and O(1) client and synchronization delay.
    - Central server is scalability bottleneck.
  - Ring-based algorithm
    - Satisfies safety, liveness, but not ordering.
    - Always uses bandwidth, O(N) client and synchronization delay
  - Ricart-Agrawala algorithm
    - Satisfies safety, liveness, and ordering.
    - O(N) bandwidth, O(1) client and synchronization delay.
  - Maekawa algorithm
    - Satisfies safety, but not liveness and ordering.
    - O($\sqrt{N}$) bandwidth, O(1) client and synchronization delay.

Today's agenda

- Wrap up Mutual Exclusion
  - Extending Maekawa's algorithm to break deadlocks.
- Leader Election
  - Chapter 15.3
- Goal:
  - What is leader election in distributed systems?
  - How do we elect a leader?
  - To what extent can we handle failures when electing a leader?

Why Election?

- Example: Your Bank account details are replicated at a few servers, but one of these servers is responsible for receiving all reads and writes, i.e., it is the leader among the replicas
  - What if servers disagree about who the leader is?
  - What if there are two leaders per customer?
  - What if the leader crashes?

    Each of the above scenarios leads to inconsistency

More motivating examples

- The root server in a group of NTP servers.
- The master in Berkeley algorithm for clock synchronization.
- In the sequencer-based algorithm for total ordering of multicasts, the "sequencer" = leader.
- The central server in the "central server algorithm" for mutual exclusion.
- Other systems that need leader election: Apache Zookeeper, Google's Chubby.

Leader Election Problem

- In a group of processes, elect a *Leader* to undertake special tasks
  - And *let everyone know* in the group about this Leader
- What happens when a leader fails (crashes)
  - Some process detects this (using a Failure Detector!)
  - Then what?
- Focus of this lecture: Election algorithm. Its goal:
  1. Elect one leader only among the non-faulty processes
  2. All non-faulty processes agree on who is the leader

Calling for an Election

- Any process can call for an election.
- A process can call for at most one election at a time.
- Multiple processes are allowed to call an election simultaneously.
  - All of them together must yield only a single leader
- The result of an election should not depend on which process calls for it.

Election Problem, Formally

- A run of the election algorithm must always guarantee:
  - **Safety**: For all non-faulty processes *p*:
    - *p* has elected:
      - (q: a particular non-faulty process with the *best attribute value*)
      - or Null
  - **Liveness**: For all election runs:
    - election run terminates
    - & for all non-faulty processes *p*: *p*'s elected is not Null
- At the end of the election protocol, the non-faulty process with the best (highest) election attribute value is elected.
  - Common attribute : leader has highest id
  - Other attribute examples: leader has highest IP address, or fastest cpu, or most disk space, or most number of files, etc.

System Model

- *N* processes.
- Messages are eventually delivered.
- Failures may occur during the election protocol.
- **Each process has a unique id.**
  - Each process has a unique attribute (based on which Leader is elected).
  - If two processes have the same attribute, combine the attribute with the process id to break ties.

Classical Election Algorithms

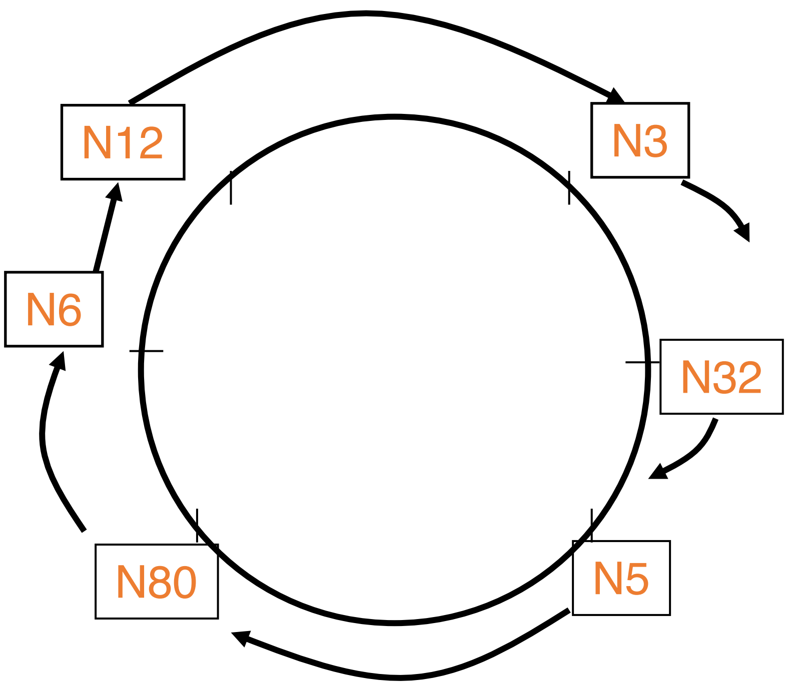
- Ring election algorithm
- Bully algorithm

Classical Election Algorithms

- **Ring election algorithm**
- Bully algorithm

Ring Election Algorithm

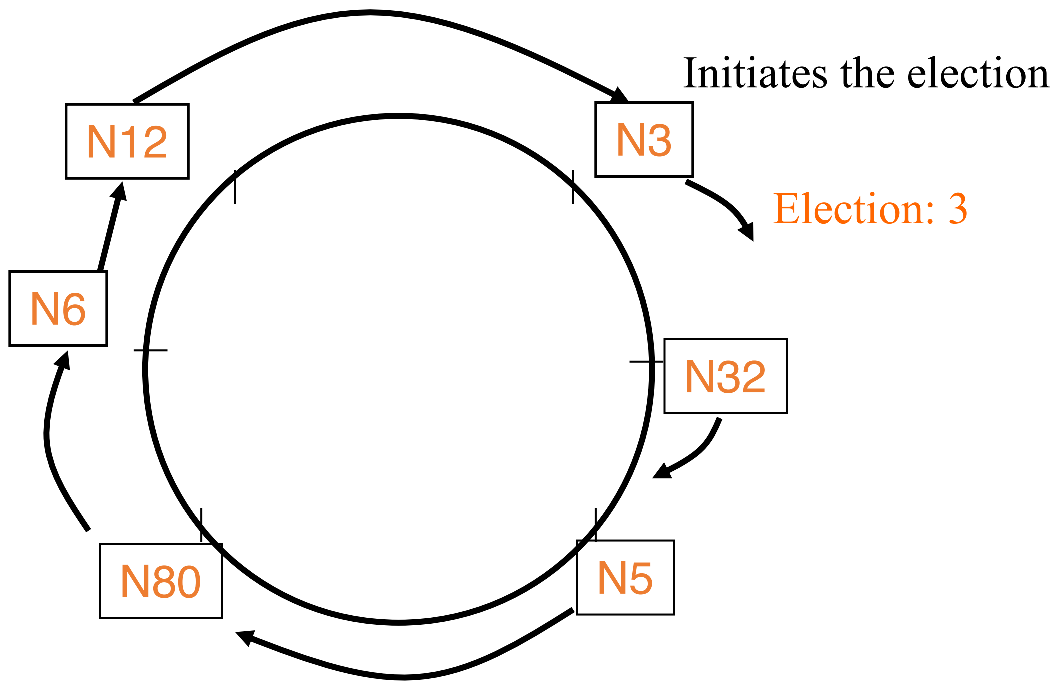
- *N* processes are organized in a logical ring
  - All messages are sent clockwise around the ring.



Ring Election Protocol (basic version)

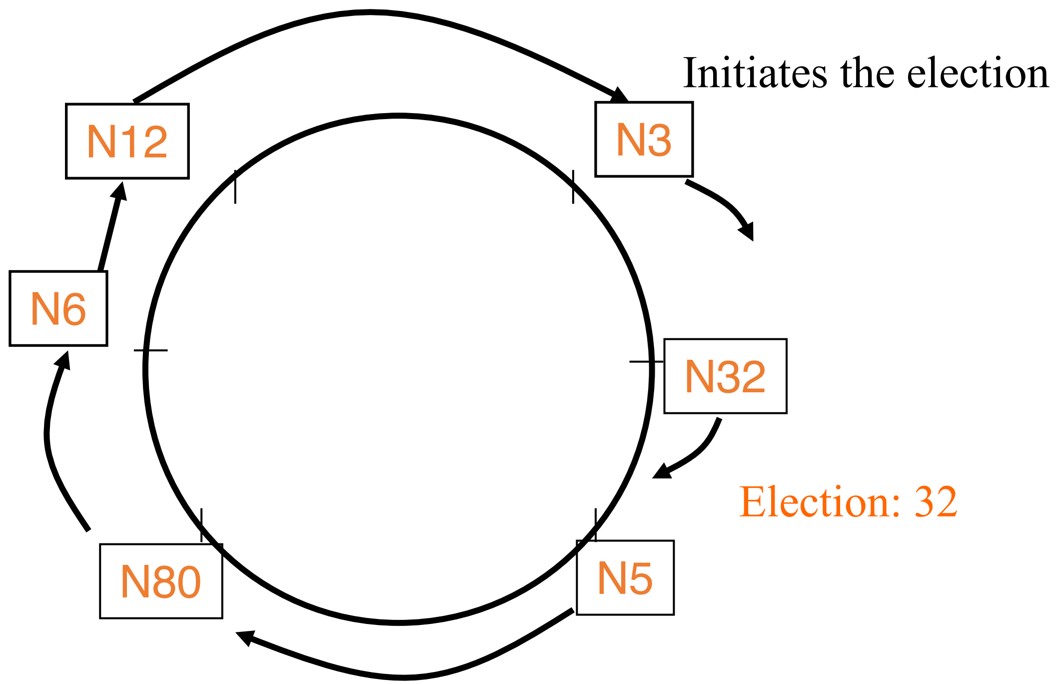
- When Pi start election
  - send election message with Pi's $<attr_i, i>$ to ring successor.
- When Pj receives message (election, $<attr_x, x>$) from predecessor
  - If $(attr_x, x) > (attr_j, j)$:
    - forward message (election, $<attr_x, x>$) to successor
  - If $(attr_x, x) < (attr_j, j)$
    - send (election, $<attr_j, j>$) to successor
  - If $(attr_x, x) = (attr_j, j)$: Pj is the elected leader (why?)
    - send elected message containing Pj's id.
- elected message forwarded along the ring until it reaches the leader.

Ring Election: Example



Goal: Elect highest id process as leader

Ring Election: Example



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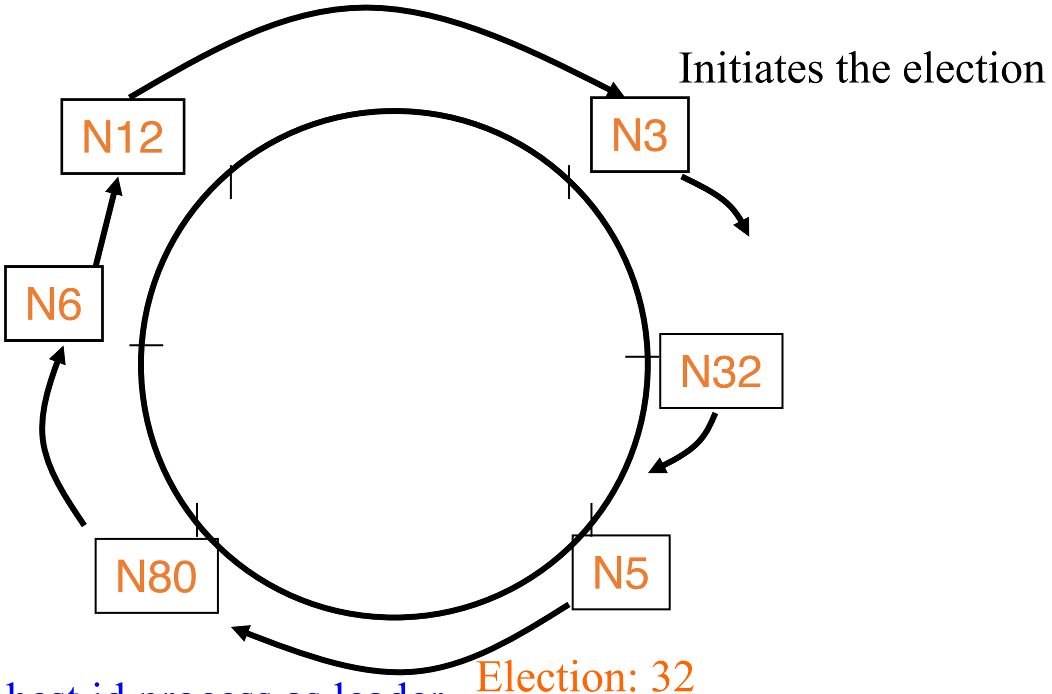

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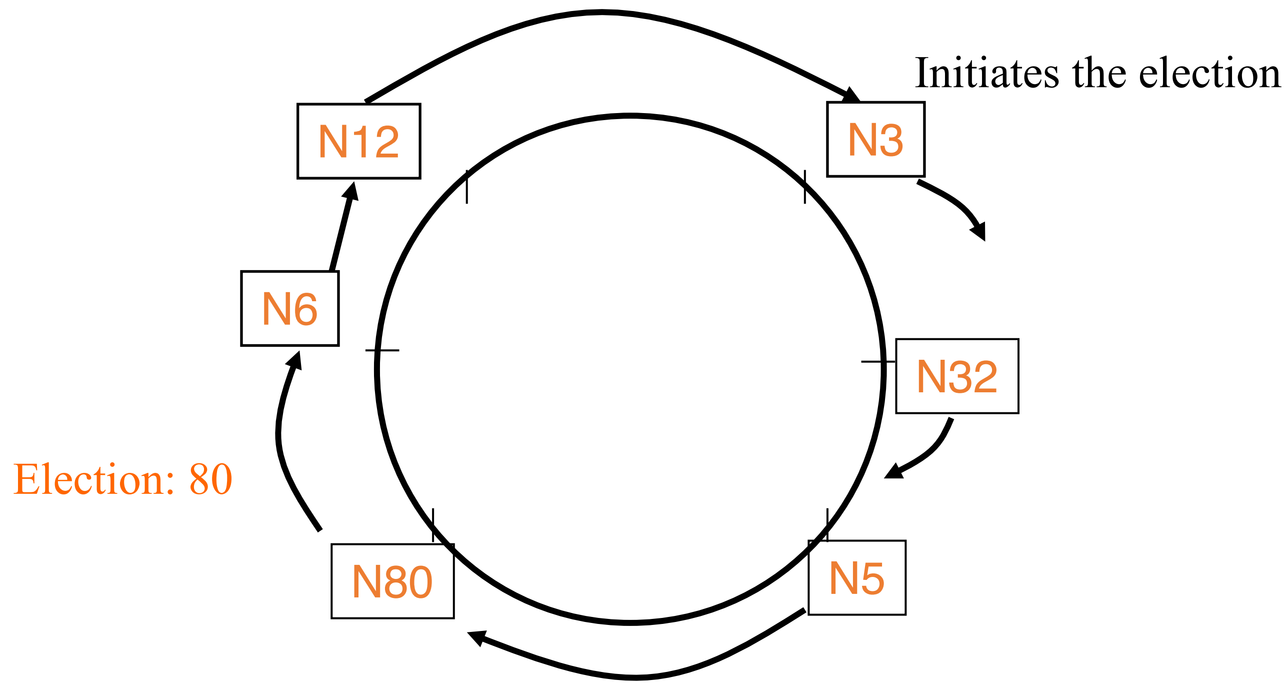

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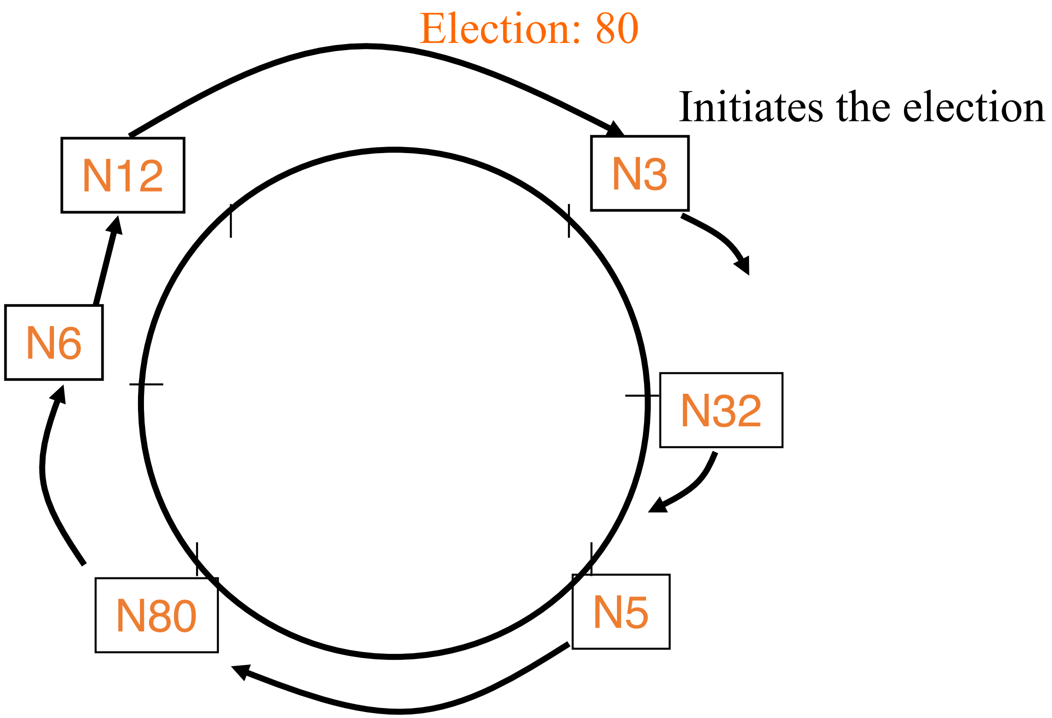

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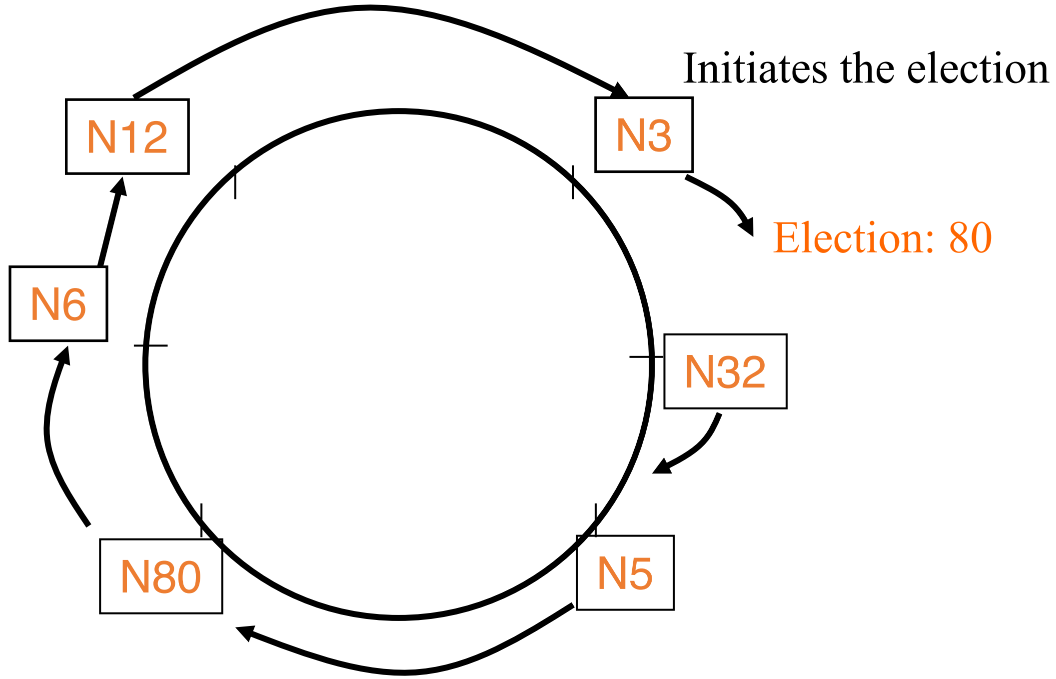

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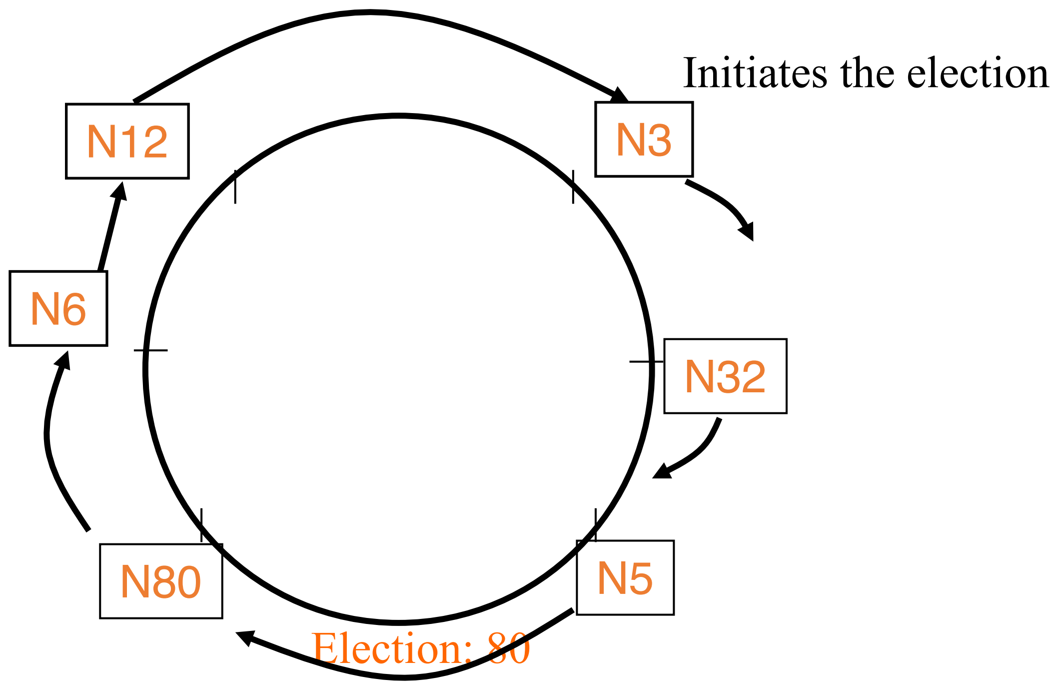

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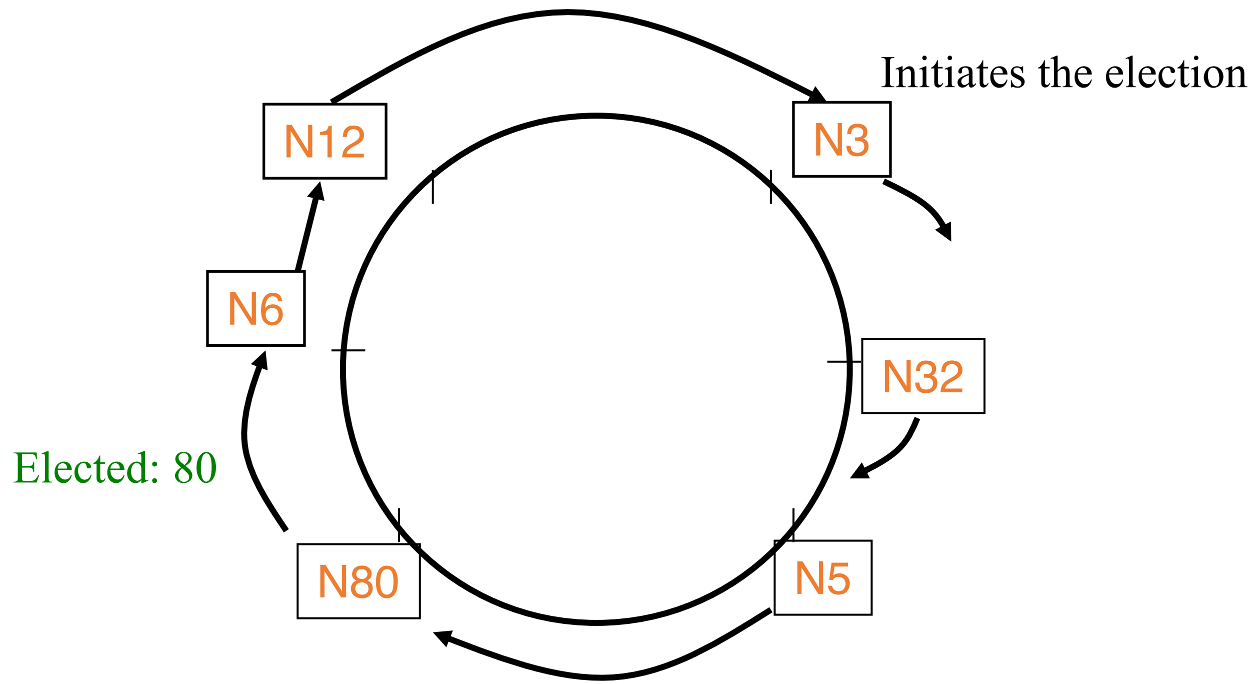

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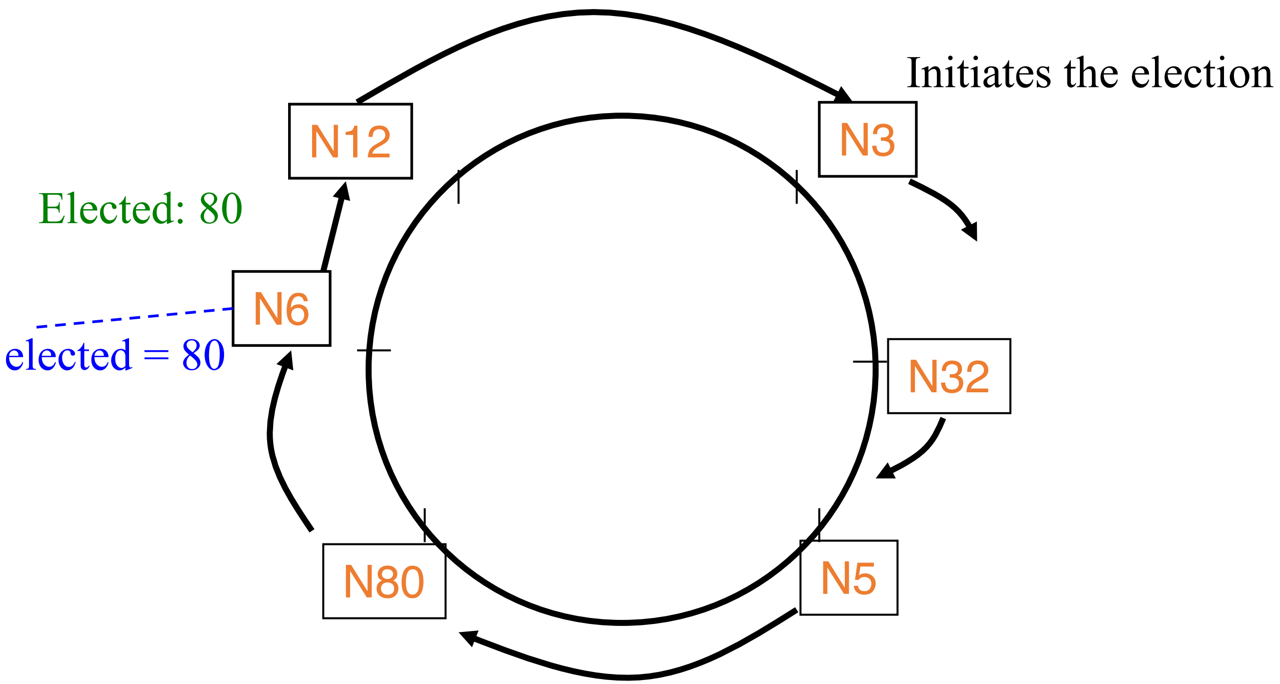

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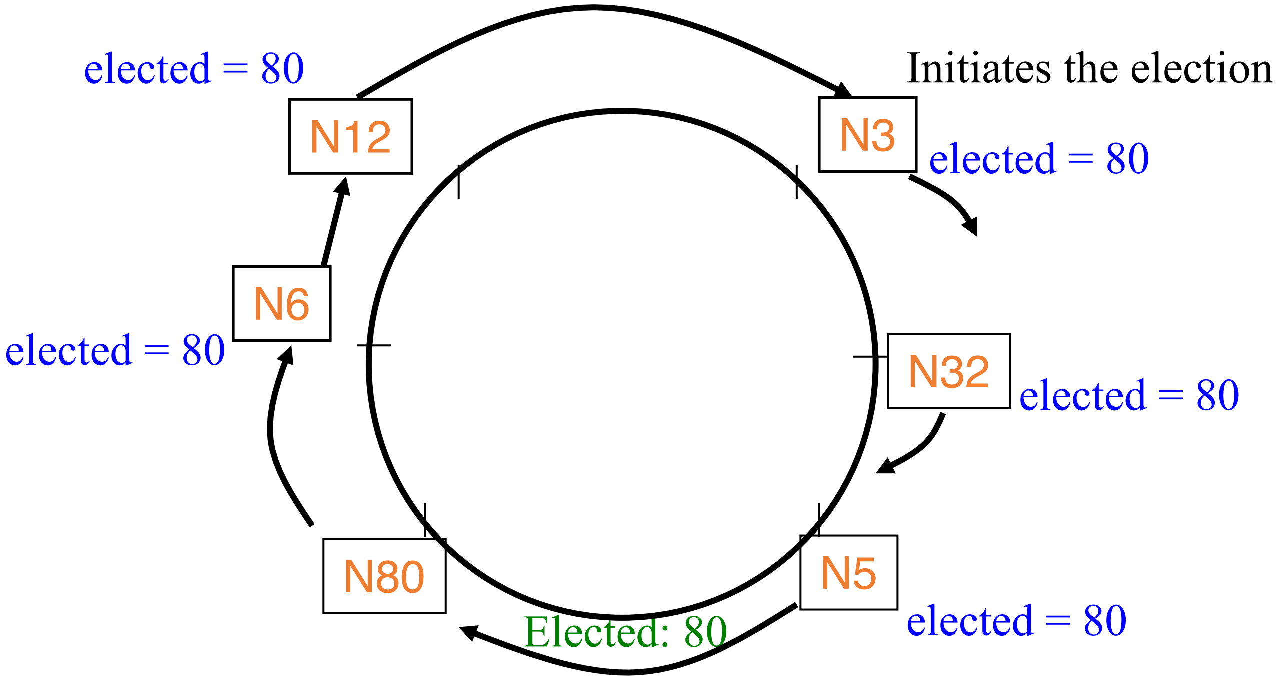
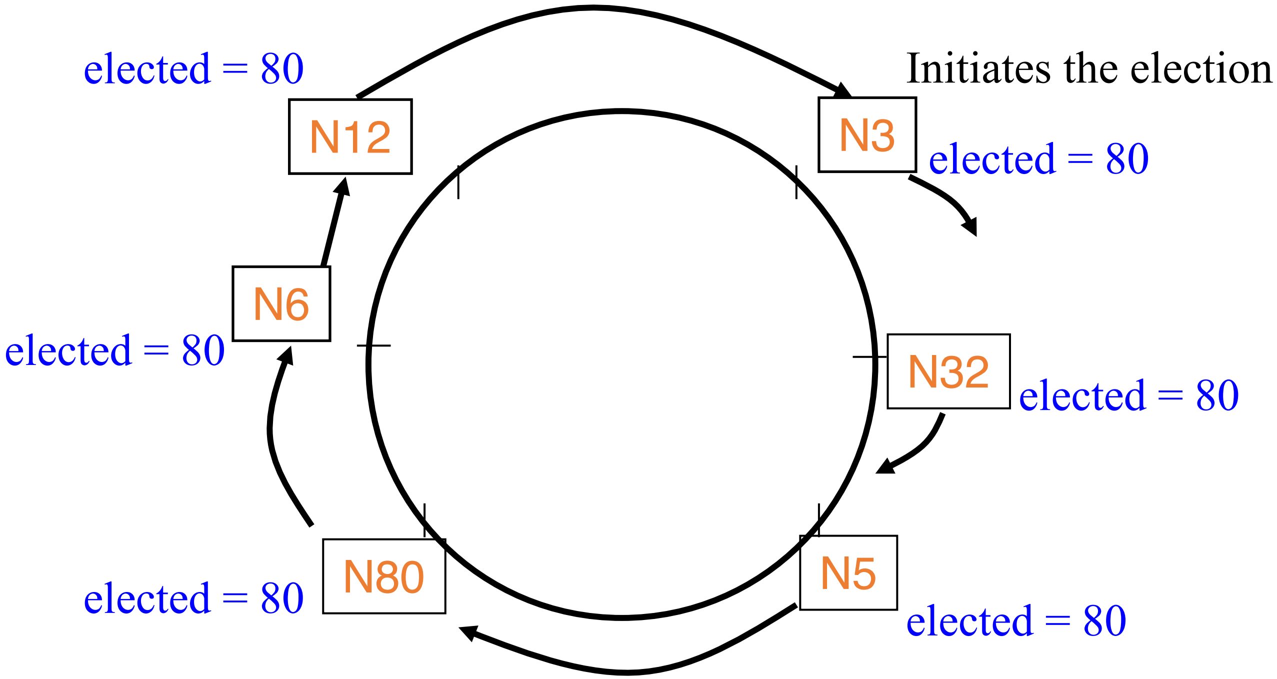


Goal: Elect highest id process as leader

Ring Election: Example



Goal: Elect highest id process as leader

Ring Election Protocol (basic version)

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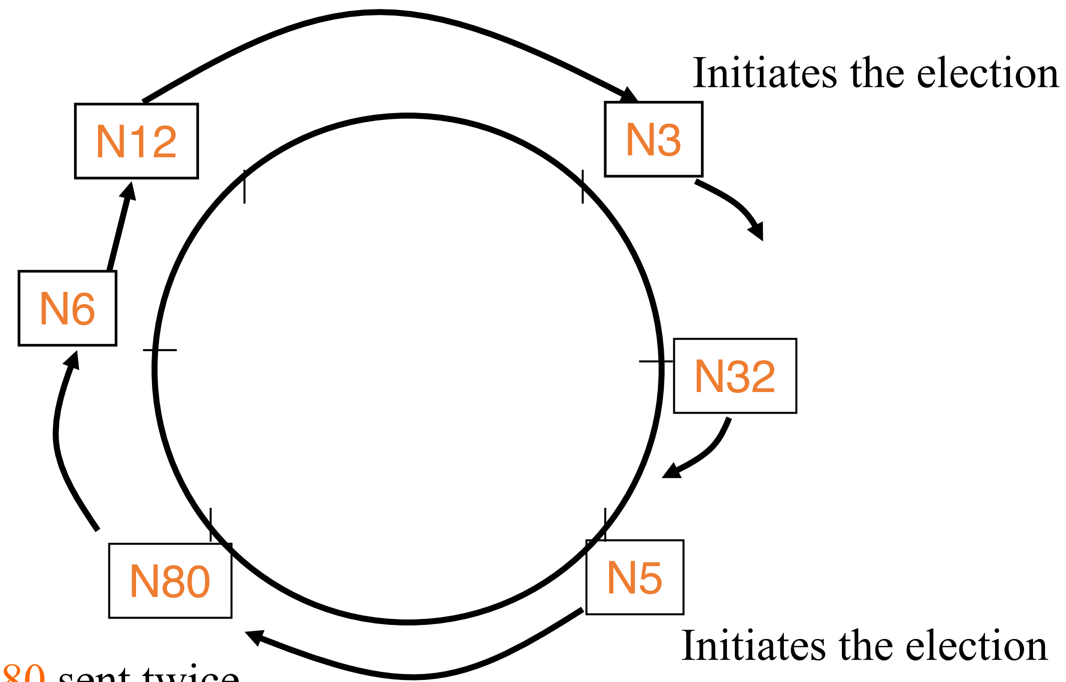
  - If $(attr_x, x) < (attr_j, j)$
    - send (election, $<attr_j, j>$) to successor
  - If $(attr_x, x) = (attr_j, j)$: Pj is the elected leader (why?)
    - send elected message containing Pj's id.
- elected message forwarded along the ring until it reaches the leader.

What happens when multiple processes call for an election?

Ring Election: Example

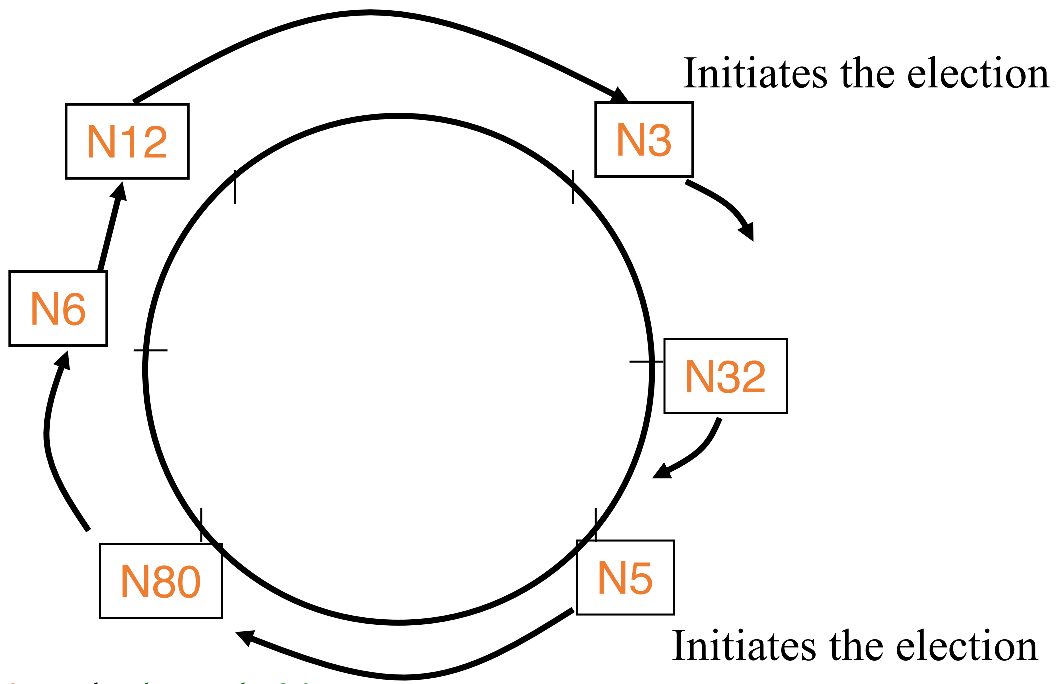


Election: 80 sent twice.
Elected: 80 also sent twice.

Ring Election Protocol [Chang & Roberts'79]

- When Pi start election
  - send election message with Pi's $<attr_i, i>$ to ring successor.
  - set state to participating
- When Pj receives message (election, $<attr_x, x>$) from predecessor
  - If $(attr_x, x) > (attr_j, j)$:
    - forward message (election, $<attr_x, x>$) to successor
    - set state to participating
  - If $(attr_x, x) < (attr_j, j)$
    - If (not participating):
      - send (election, $<attr_j, j>$) to successor
      - set state to participating
  - If $(attr_x, x) = (attr_j, j)$: Pj is the elected leader (why?)
    - send elected message containing Pj's id.
- elected message forwarded along the ring until it reaches the leader.
  - Set state to not participating when an elected message is received.

Ring Election: Example

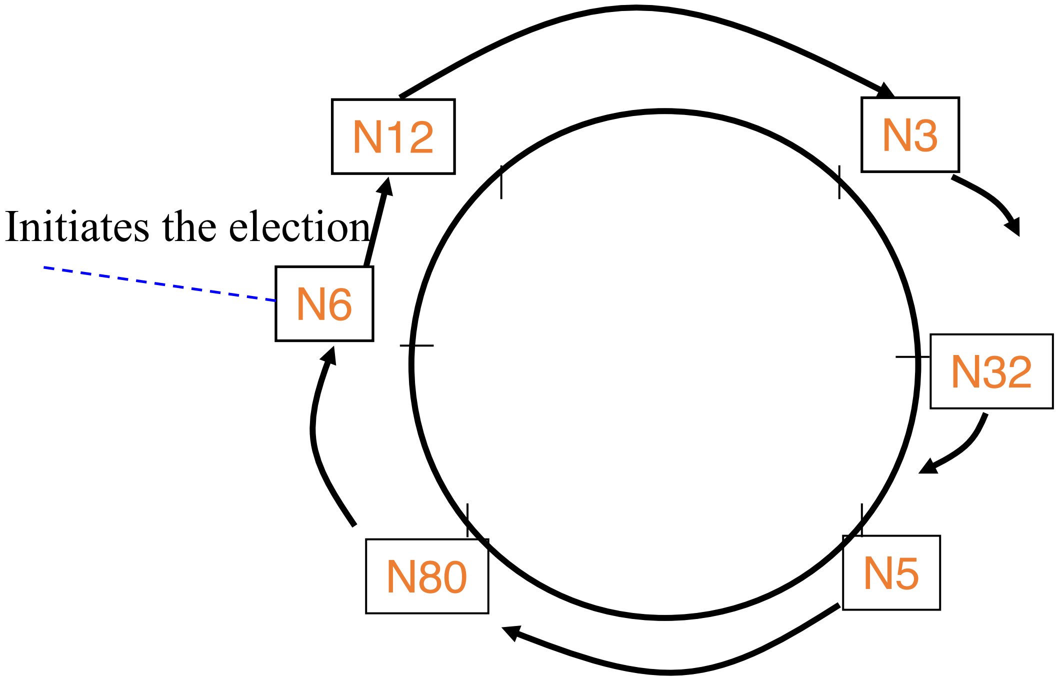


Election: 80 and Elected: 80
sent only once.

Performance Analysis

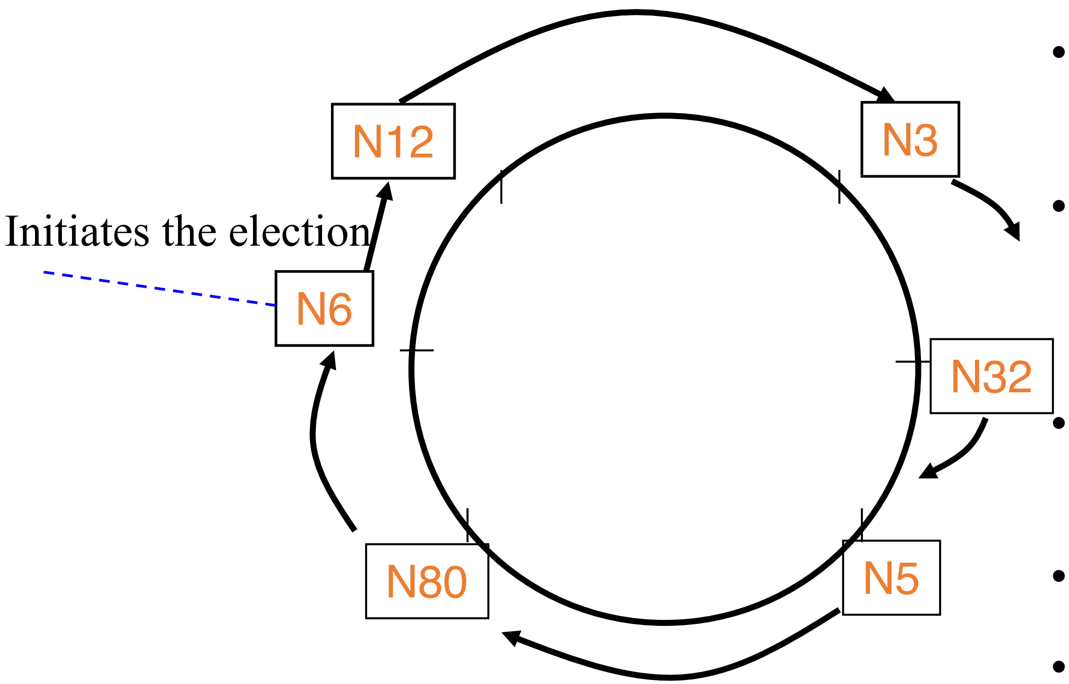
- Let’s assume no failures occur during the election protocol itself, and there are *N* processes.
- Let’s also assume that only one process initiates the algorithm
- **Bandwidth usage:** Total number of messages sent.
- **Turnaround time:** The number of serialized message transmission times between the initiation and termination of a single run of the algorithm.

Worst-case



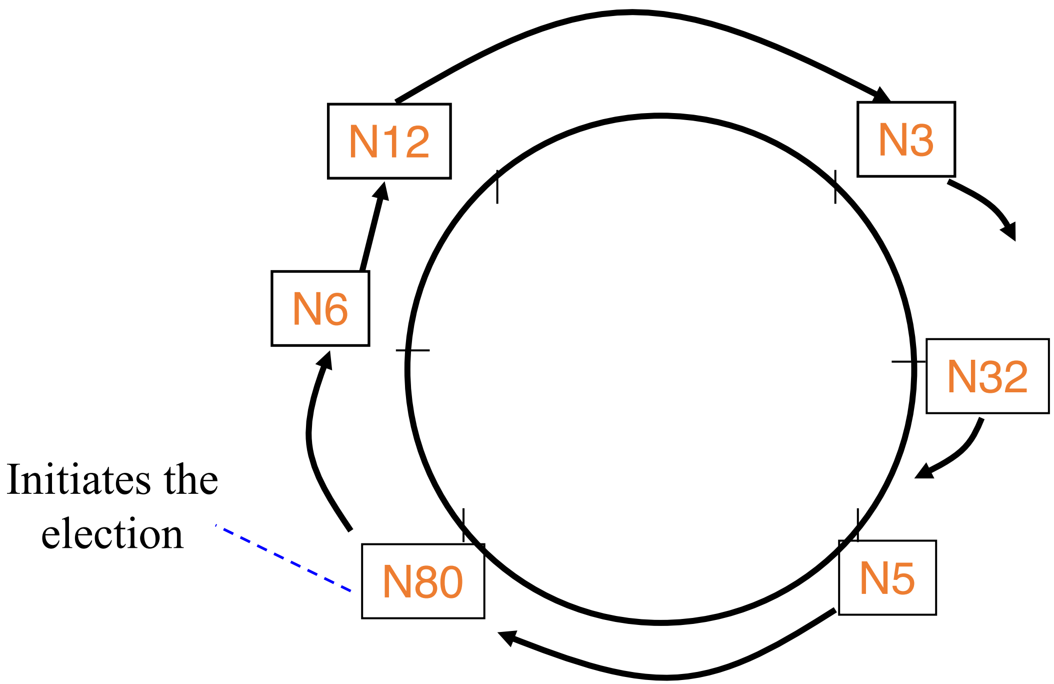
When the initiator is the ring successor of the would-be leader.

Worst-case



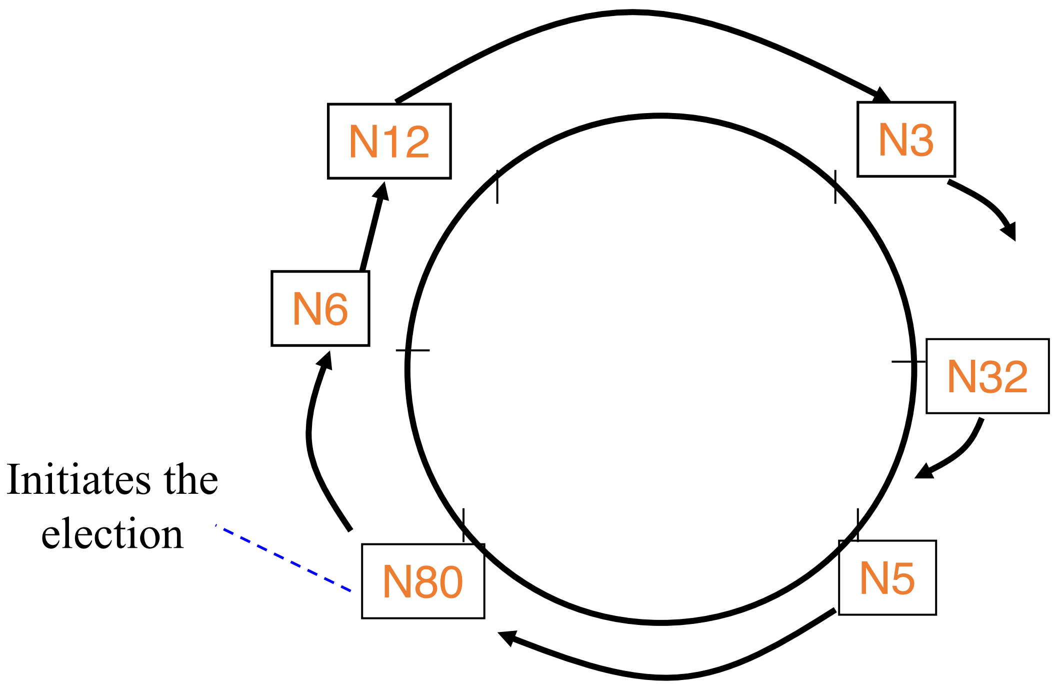
- (N-1) messages for Election message to get from N6 to N80.
- N messages for Election message to circulate around ring without message being changed.
- N messages for Elected message to circulate around the ring
- **No. of messages: (3N-1)**
- **Turnaround time: (3N-1) message transmission times**

Best-case



When the initiator is the would-be leader.

Best-case



When the initiator is the would-be leader.

No. of messages: 2N

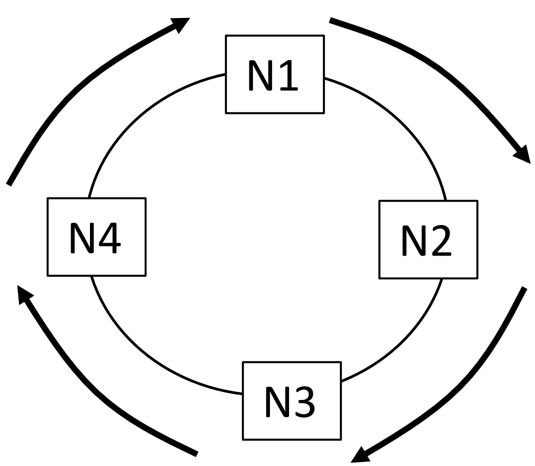
Turnaround time:
2N message transmission times

Performance Analysis

- Let's assume no failures occur during the election protocol itself, and there are *N* processes.
- Let's also assume that only one process initiates the algorithm
- Bandwidth usage (total number of messages)
  - O(N): Worst case = 3N -1; Best case = 2N.
- O(N) turnaround time.

Performance Analysis

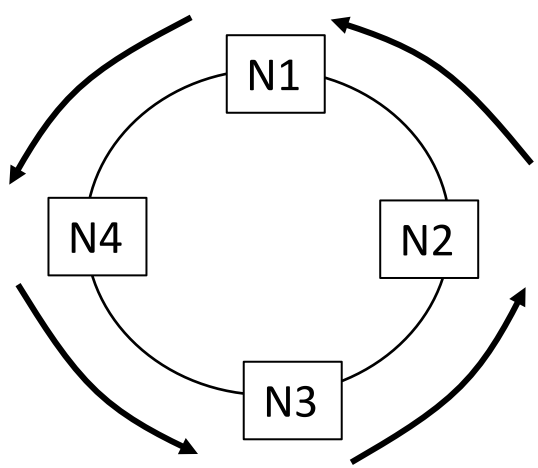
- Let's assume no failures occur during the election protocol itself, and there are *N* processes.
- When each process initiates the algorithm?
  - O(N) messages in best-case.



- N election messages generated at the start of algorithm.
- Only one survives, and completes a full round.
  - N-1 more messages.
- One round for the elected message
  - N messages.
- Total: 3N-1 messages

Performance Analysis

- Let's assume no failures occur during the election protocol itself, and there are *N* processes.
- When each process initiates the algorithm?
  - O(N) messages in best-case.
  - $O(N^2)$ in worst-case.



- N election messages generates at the starts of algorithm.
- N - 1 survive the next time step.
- N – 2 survive the next time step.
- ….

Performance Analysis

- Let's assume no failures occur during the election protocol itself, and there are *N* processes.
- When each process initiates the algorithm?
  - O(N) messages in best-case.
  - O(N^2) messages in worst-case.
  - O(N) turnaround time.

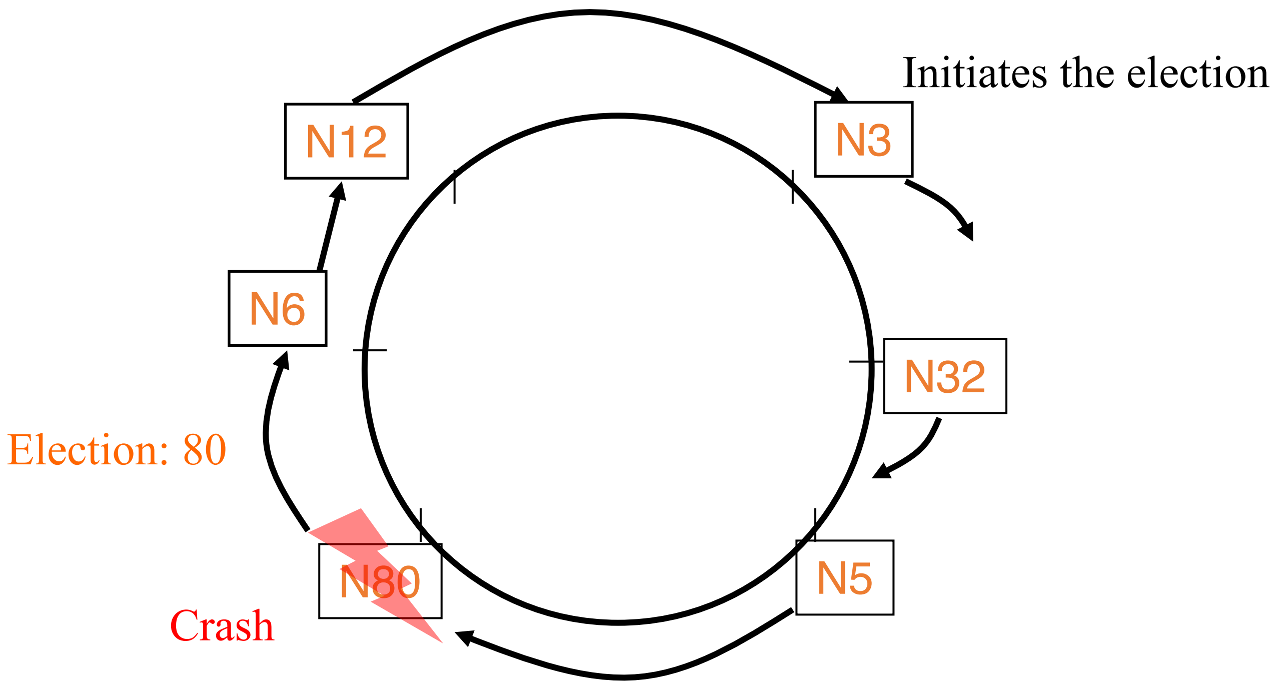
Correctness

- Assuming no process fails.

- Safety:
    - Process with highest attribute elected by all nodes.

- Liveness:
    - Election completes within 3N – 1 message transmission times.

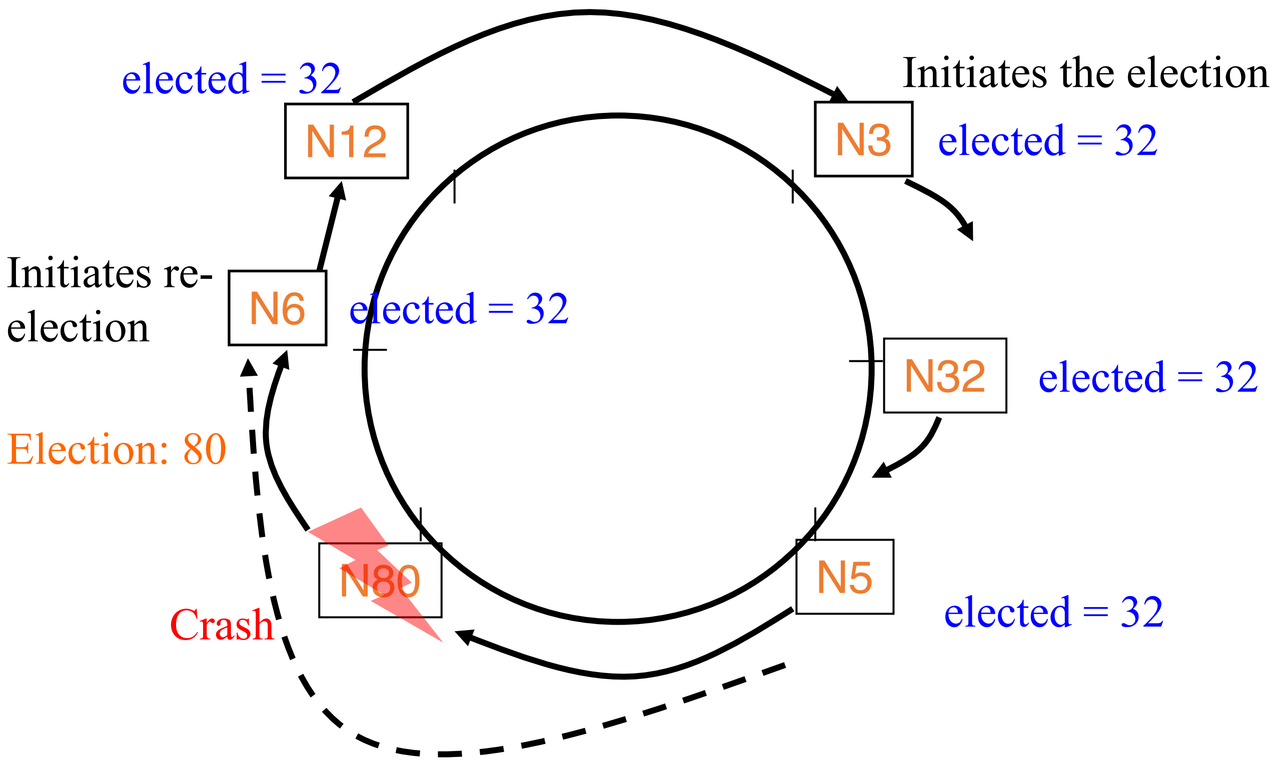
Handling Failures



Handling failures

- Use the failure detector.
- A process can detect failure of N80 via its own local failure detector:
  - Repair the ring.
  - Stop forwarding Election:80 message.
  - Start a new run of leader election.

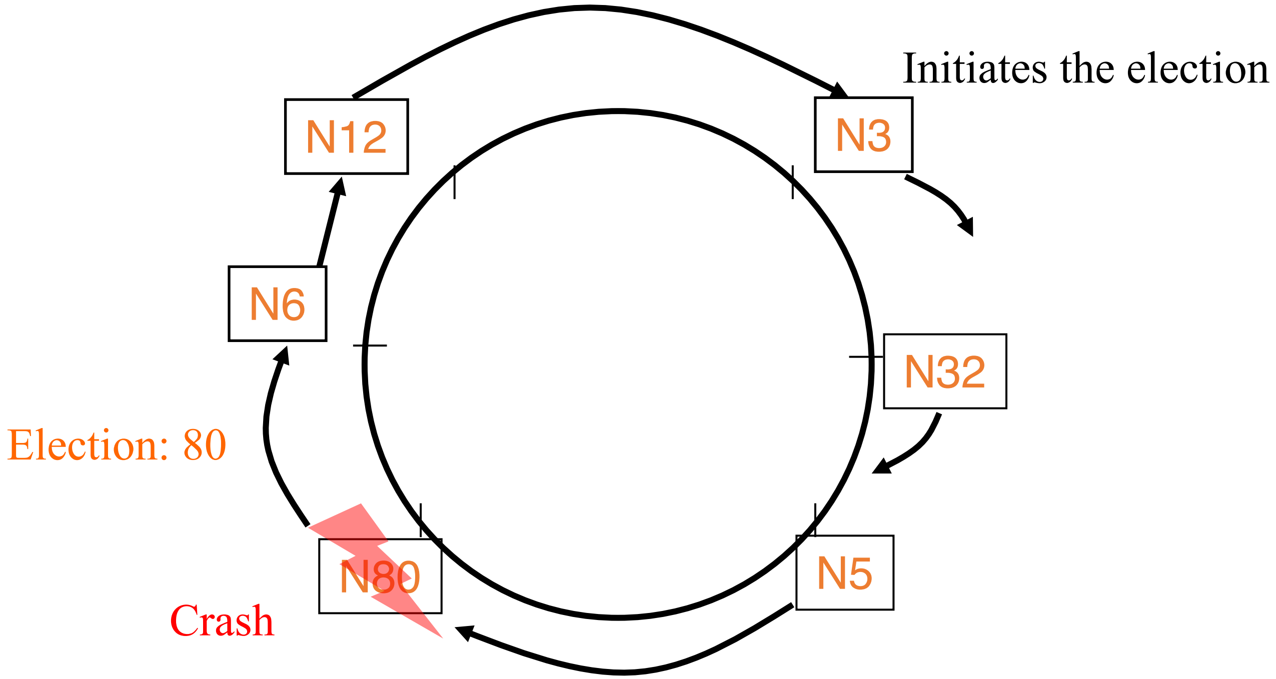
Handling Failures



Handling failures

- Use the failure detector.
- A process can detect failure of N80 via its own local failure detector:
  - Repair the ring.
  - Stop forwarding Election:80 message.
  - Start a new run of leader election.
- But failure detectors cannot be both complete and accurate.
  - Incomplete FD => N80's failure might be missed .

What happens if a process failure is undetected?



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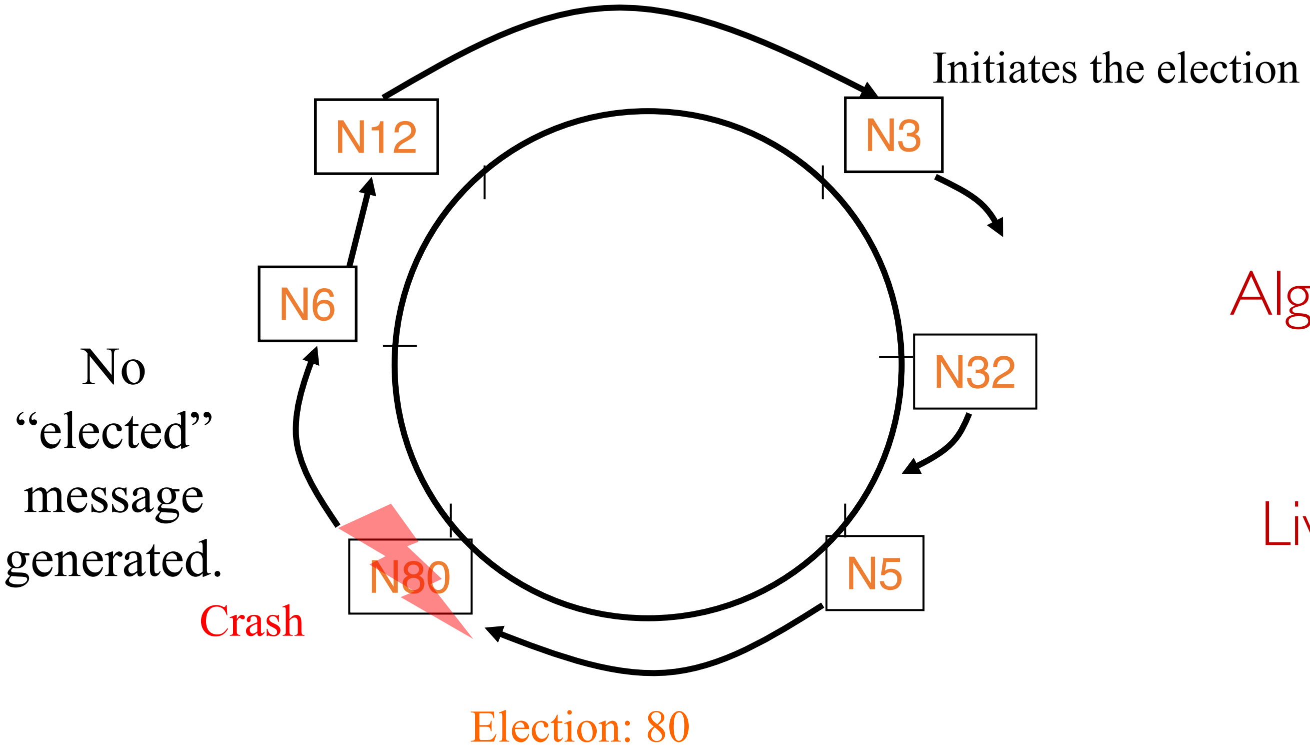


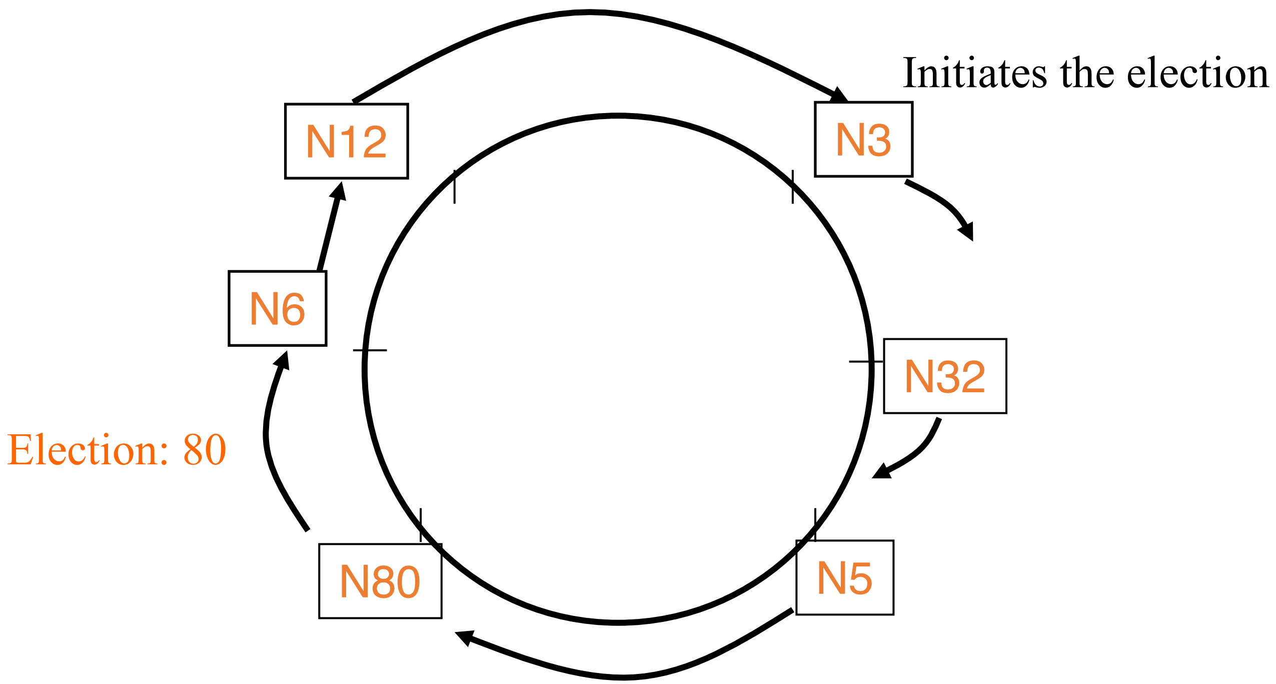
Algorithm does not terminate.

Liveness violated.

Handling failures

- Use the failure detector.
- A process can detect failure of N80 via its own local failure detector:
  - Repair the ring.
  - Stop forwarding Election:80 message.
  - Start a new run of leader election.
- But failure detectors cannot be both complete and accurate.
  - Incomplete FD => N80's failure might be missed
    - violation of liveness.
  - Inaccurate FD => N80 mistakenly detected as failed

What can happen if an alive process is detected as failed?



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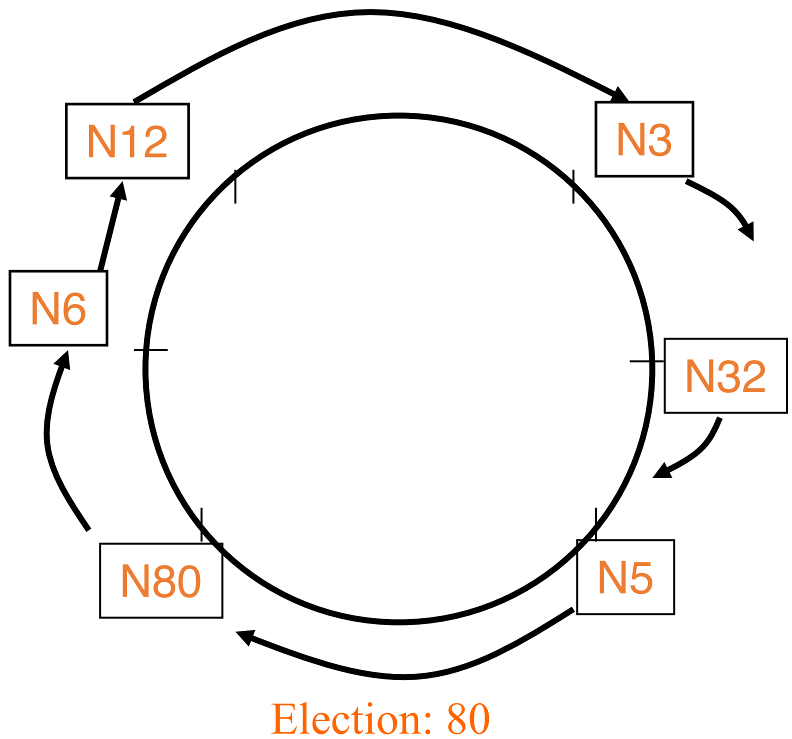
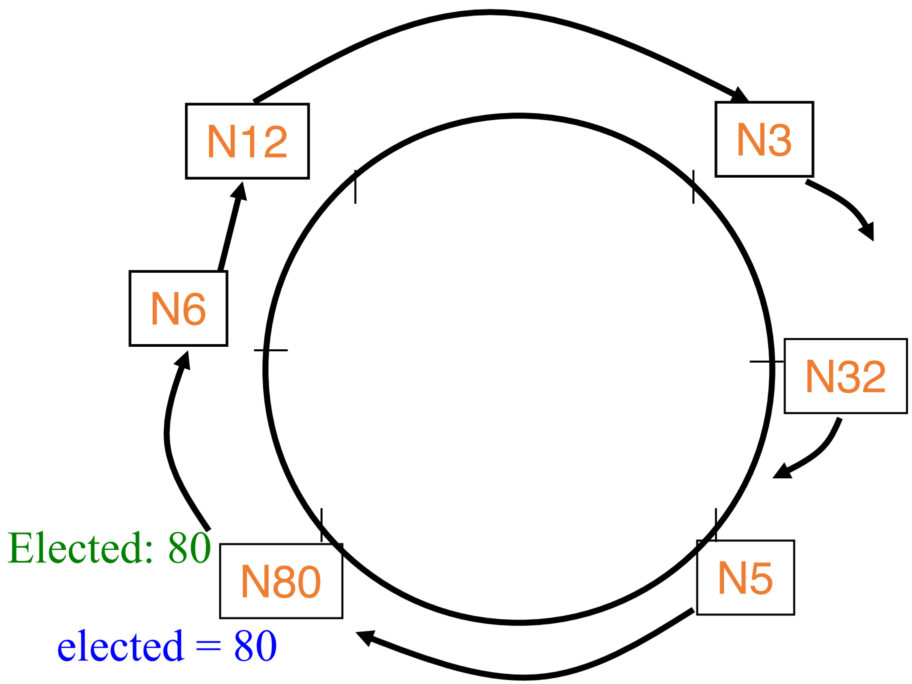


What can happen if an alive process is detected as failed?



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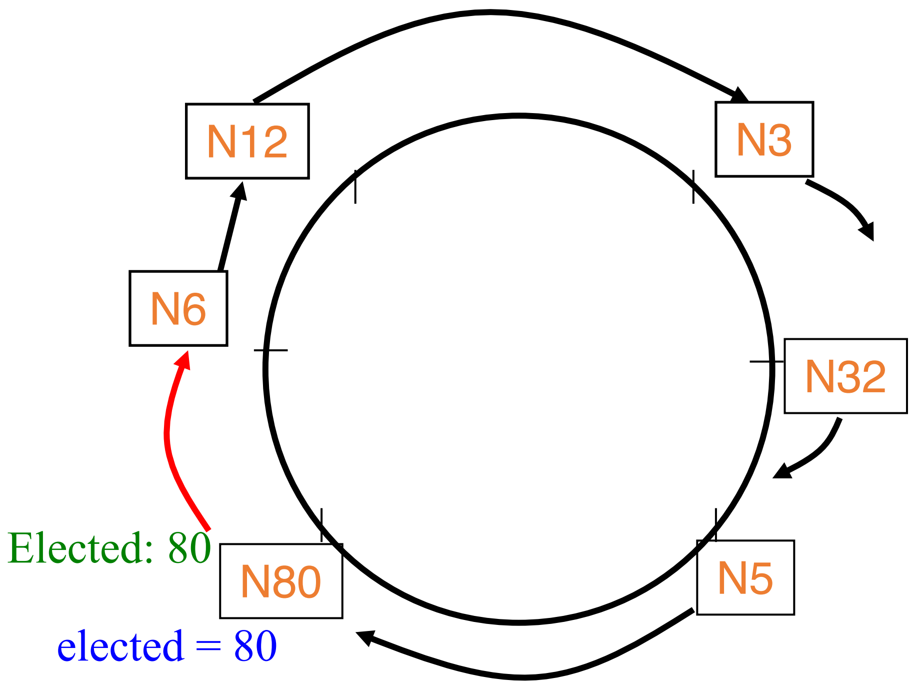

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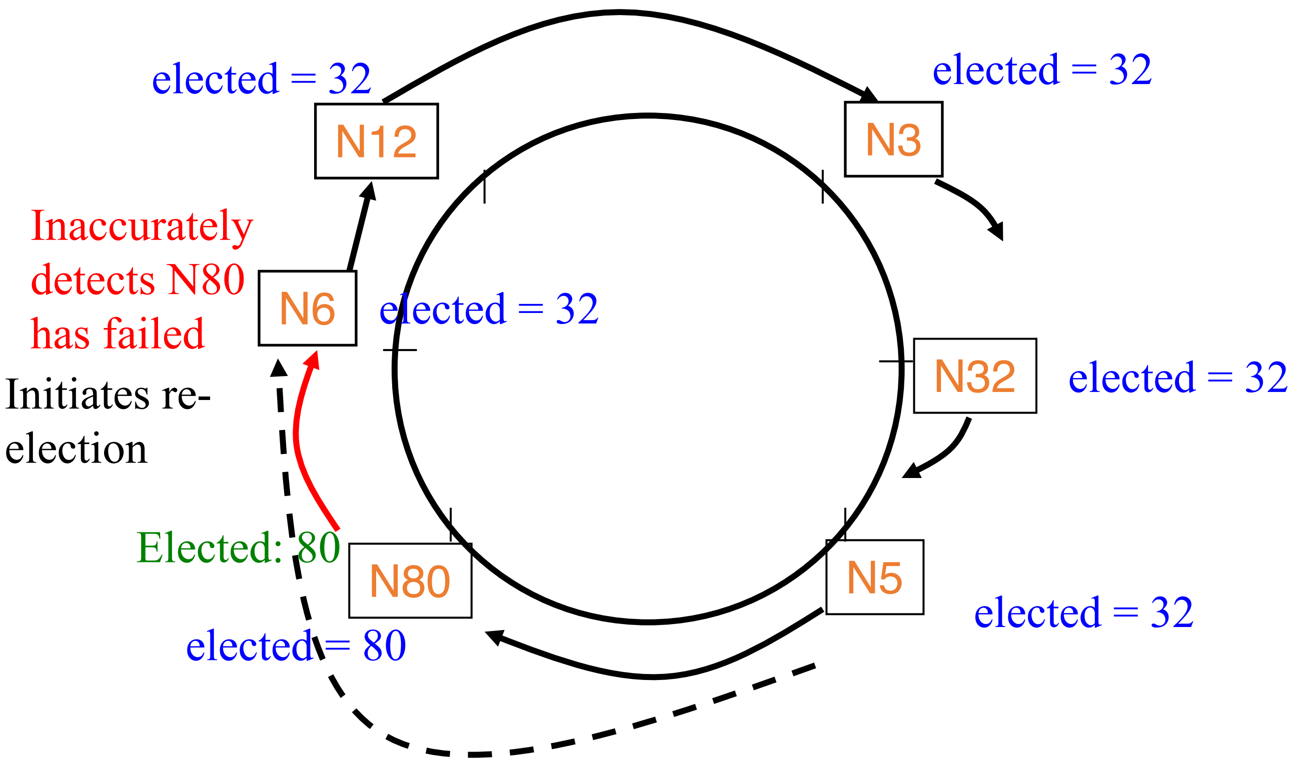

Safety has been violated.

Fixing for failures

- Use the failure detector.
- A process can detect failure of N80 via its own local failure detector:
  - Repair the ring.
  - Stop forwarding Election:80 message.
  - Start a new run of leader election.
- But failure detectors cannot be both complete and accurate.
  - Incomplete FD => N80's failure might be missed
    - violation of liveness.
  - Inaccurate FD => N80 mistakenly detected as failed
    - new ring will be constructed without N80.
    - a process with lower attribute will be selected.
    - violation of safety.

Classical Election Algorithms

- Ring election algorithm
- **Bully algorithm**

Bully algorithm

- Faster turnaround time than ring election.
- Explicitly build in the notion of timeouts into the algorithm.
- Let's assume (for simplicity of exposition) that the attribute based on which leader is elected is the process id.
- Before discussing Bully algorithm, let's first discuss a simpler (related) algorithm…..

Multicast-based algorithm

- Start an election
  - Multicast <election, my ID> to all processes
  - If receive <agree> from all processes, then elected
    - Multicast <coordinator, my ID>
  - If receive <disagree> from any process
    - Give up election

- Receive <election, *ID*> from process *p*
  - If ID > my ID
    - Send <agree> to *p* (unicast)
  - If ID < my ID
    - Send <disagree> to *p*
    - Start election (if not already running)
- What about failures?

Multicast-based algorithm

- Start an election
  - Multicast <election, my ID> to all processes
  - If receive <agree> from all processes or timeout, then elected
    - Multicast <coordinator, my ID>
  - If receive <disagree> from any process
    - Give up election
- Receive <election, *ID*> from process *p*
  - If ID > my ID
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  - If ID < my ID
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    - Start election (if not already running)
- Can we improve on this?

Multicast-based algorithm

- Start an election
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  - If ~~receive <agree> from all processes or~~ timeout, then elected
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  - If receive <disagree> from any process
    - Give up election

- Receive <election, *ID*> from process *p*
  - ~~If ID > my ID~~
    - ~~Send <agree> to *p* (unicast)~~
  - If ID < my ID
    - Send <disagree> to *p*
    - Start election (if not already running)
- Can we improve on this?

Bully Algorithm

- All processes know other process' ids.
- Do not need to multicast election to all processes.
- Only to processes with higher id.

Bully Algorithm

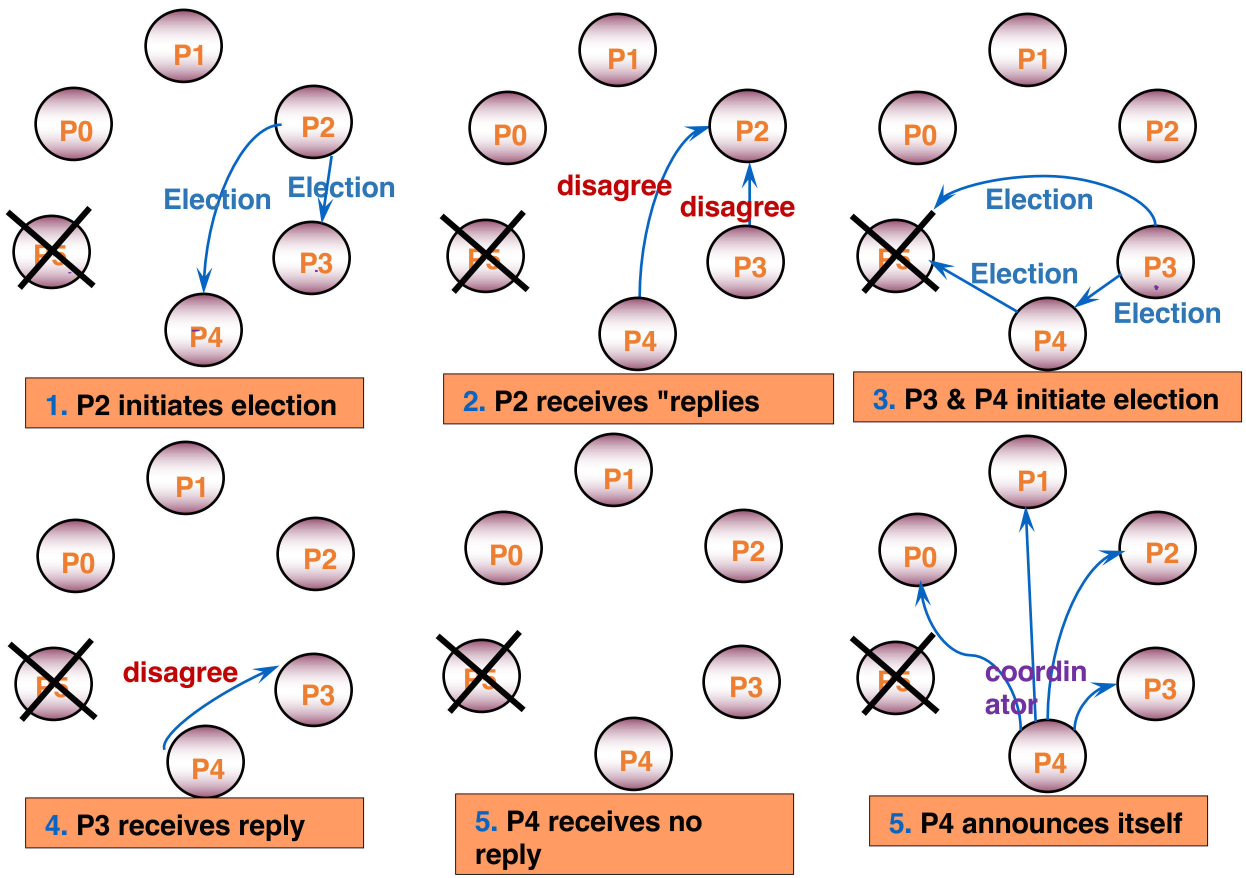
- When a process wants to initiate an election
  - **if** it knows its id is the highest
    - it elects itself as coordinator, then sends a *Coordinator* message to all processes with lower identifiers. Election is completed.
  - **else**
    - it initiates an election by sending an *Election* message
    - (contd.)

Bully Algorithm (2)

  - **else** it initiates an election by sending an *Election* message
    - Sends it to only processes that have a *higher id than itself*.
    - **if** receives no answer within timeout, calls itself leader and sends *Coordinator* message to all lower id processes. Election completed.
    - **if** an answer received however, then there is some non-faulty higher process => so, wait for coordinator message. If none received after another timeout, start a new election run.
- A process that receives an *Election* message replies with *disagree* message, and starts its own leader election protocol (unless it has already done so).

Bully Algorithm: Example

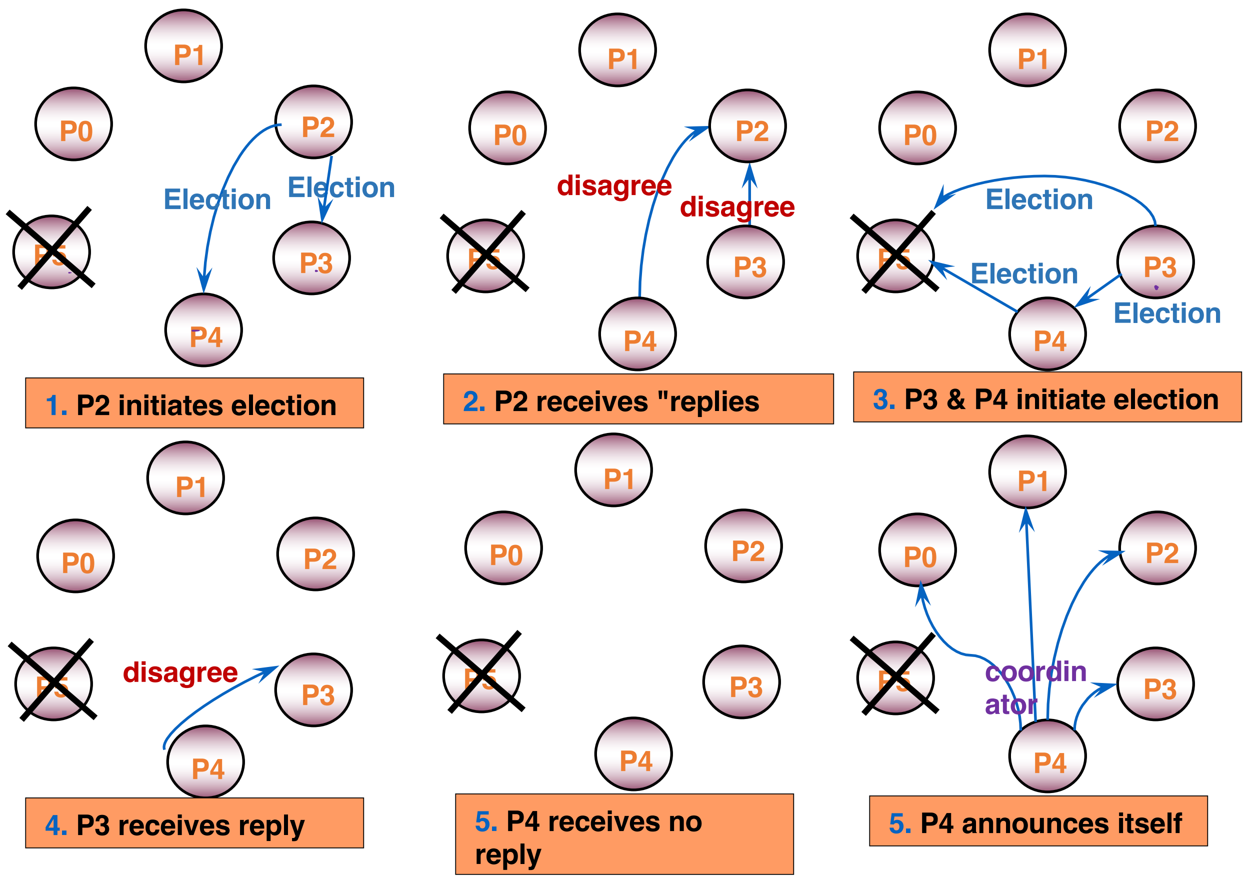
P2 initiates election after detecting P5's failure.



What if P4 fails after step 3?

Bully Algorithm: Example

P2 initiates election after detecting P5's failure.



What if P4 fails after step 4?

Bully Algorithm (2)

- **else** it initiates an election by sending an *Election* message
  - Sends it to only processes that have a *higher id than itself*.
  - **if** receives no answer within **timeout**, calls itself leader and sends *Coordinator* message to all lower id processes. Election completed.
  - **if** an answer received however, then there is some non-faulty higher process => so, wait for coordinator message. If none received after another **timeout**, start a new election run.
- A process that receives an *Election* message replies with *disagree* message, and starts its own leader election protocol (unless it has already done so).

Next class: how to set timeouts and analyze Bully algorithm.