Distributed Systems

CS425/ECE428

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Acknowledgements: Indy Gupta and Nikita Borisov

Logistics

- HW1 is due today!
- HW2 has been released.
  - you should be able to solve the first question already.
  - you should be able to solve Q2 and Q3 after today's class (hopefully), and the remaining questions by the end of this week.
- Midterm 1 next week!

Today's agenda

- **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?

Examples of leader election?

- 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.

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

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

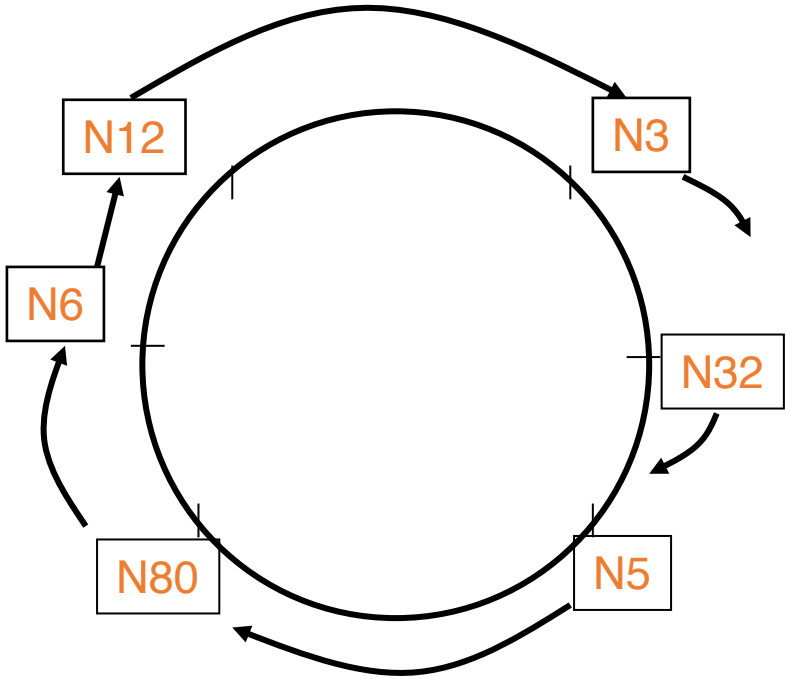
- Ring election algorithm
- Bully algorithm

Classical Election Algorithms

- Ring election algorithm
- Bully algorithm

Ring Election Algorithm

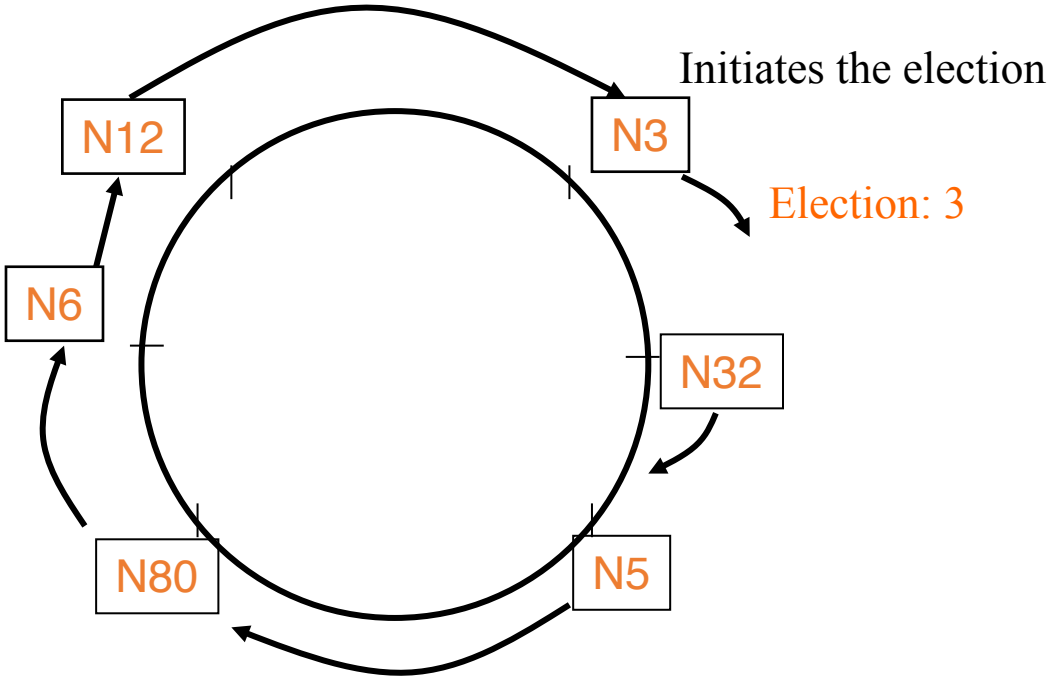
- *N* processes are organized in a logical ring
  - All messages are sent clockwise around the ring.



Ring Election Protocol (basic version)

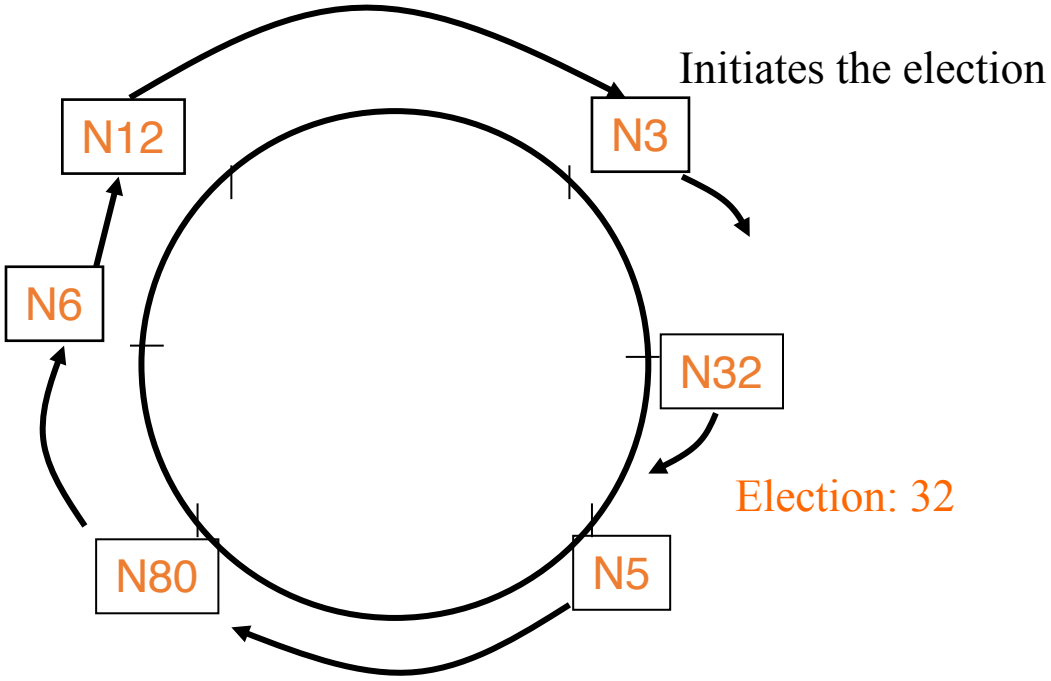
- When Pi start election
  - send election message with Pi's <$attr_i$, i> to ring successor.
- When Pj receives message (election, <$attr_x$, x>) from predecessor
  - If ($attr_x$, x) > ($attr_j$, j):
    - forward message (election, <$attr_x$, x>) to successor
  - If ($attr_x$, x) < ($attr_j$, j)
    - 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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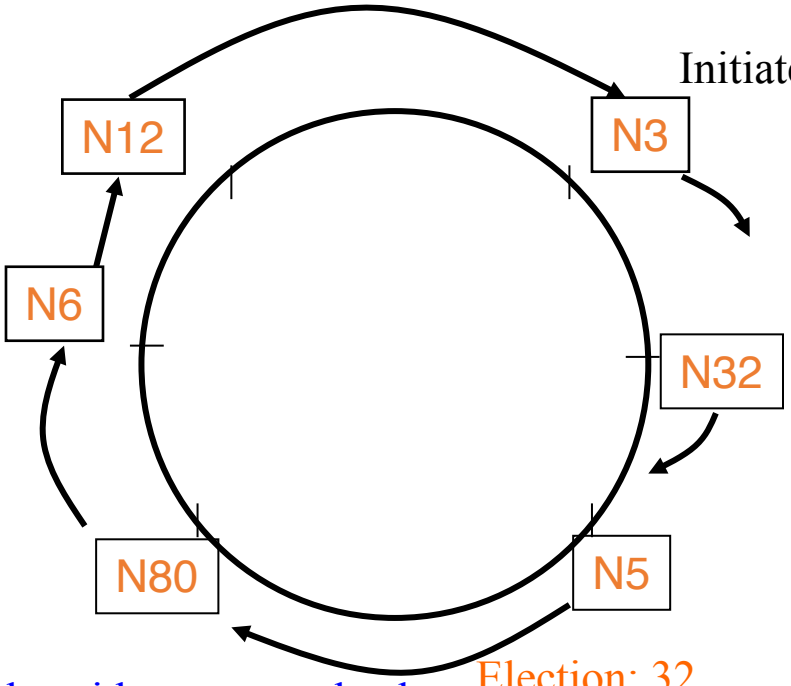

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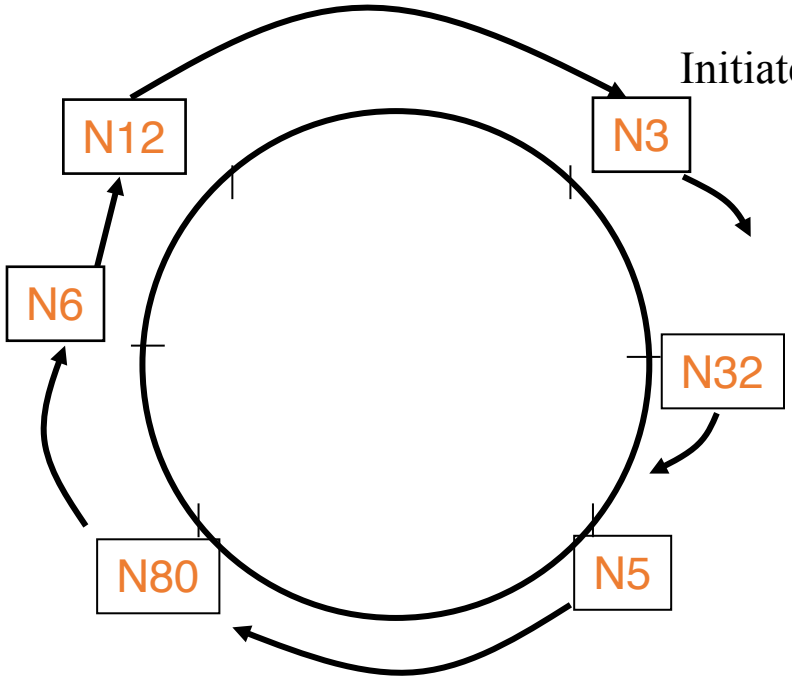
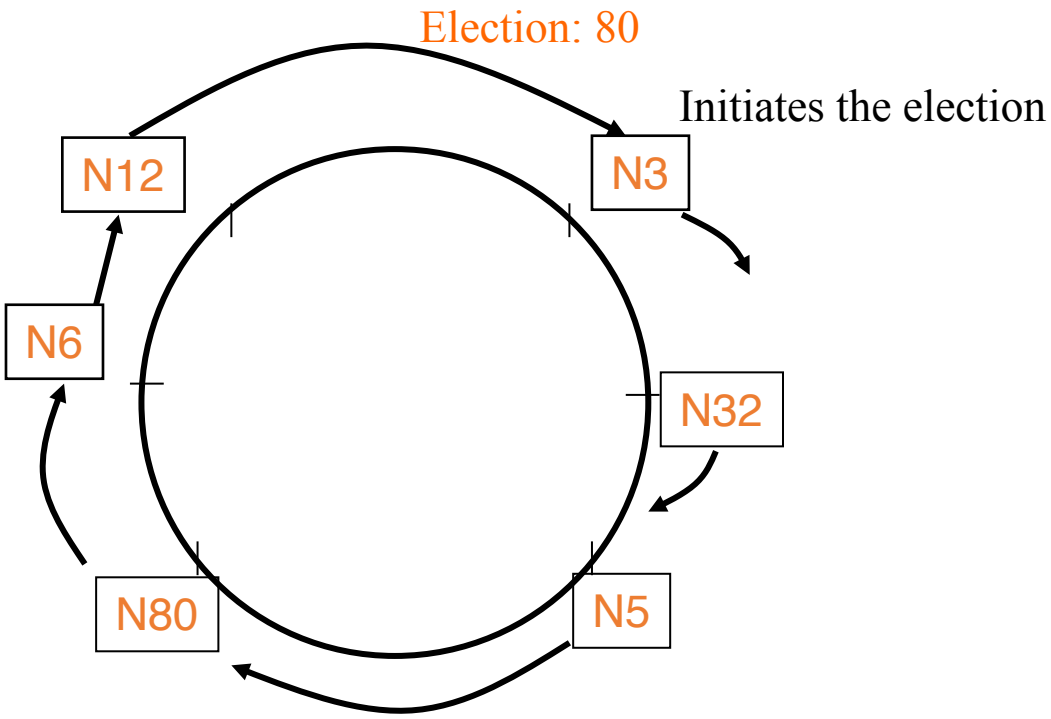
Ring Election: Example



Election: 80

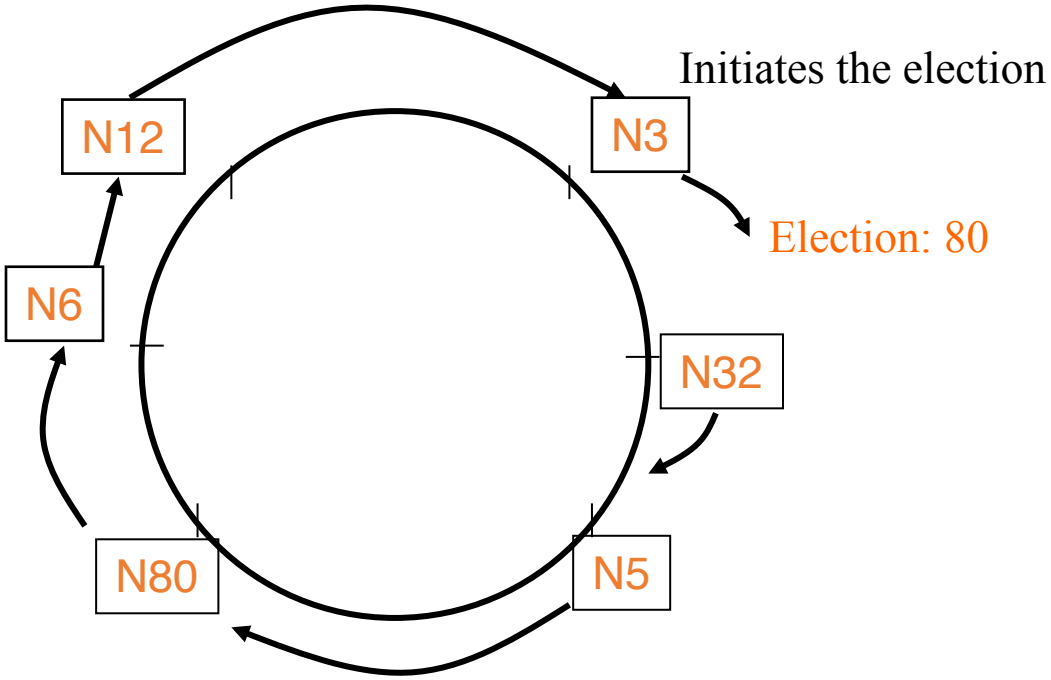
Goal: Elect highest id process as leader

Ring Election: Example



Goal: Elect highest id process as leader

Ring Election: Example



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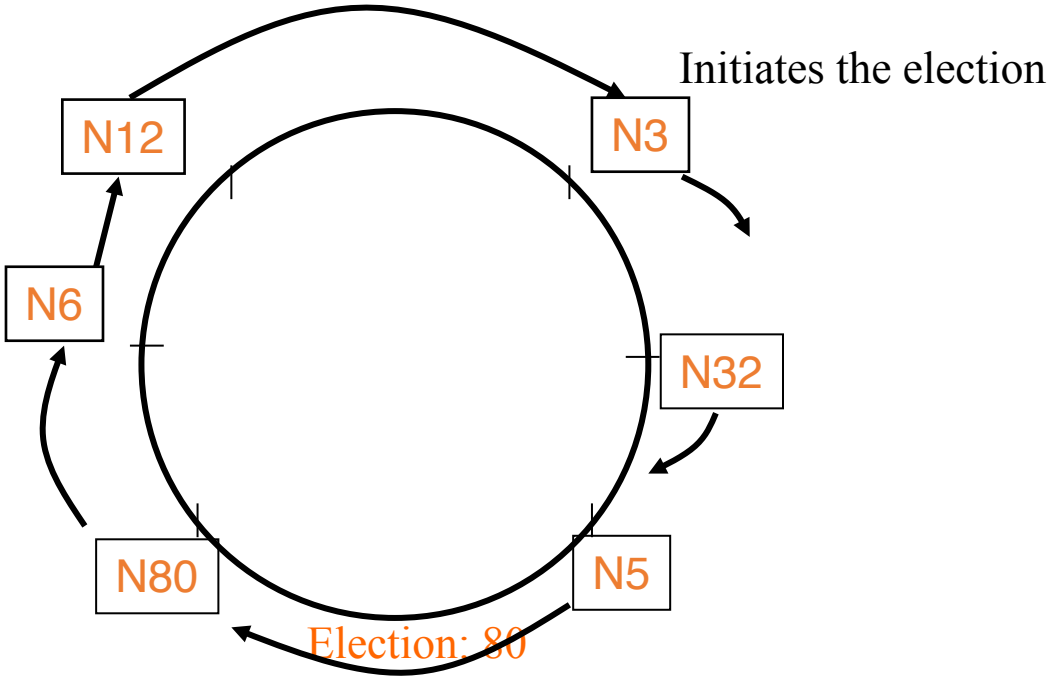
Ring Election: Example



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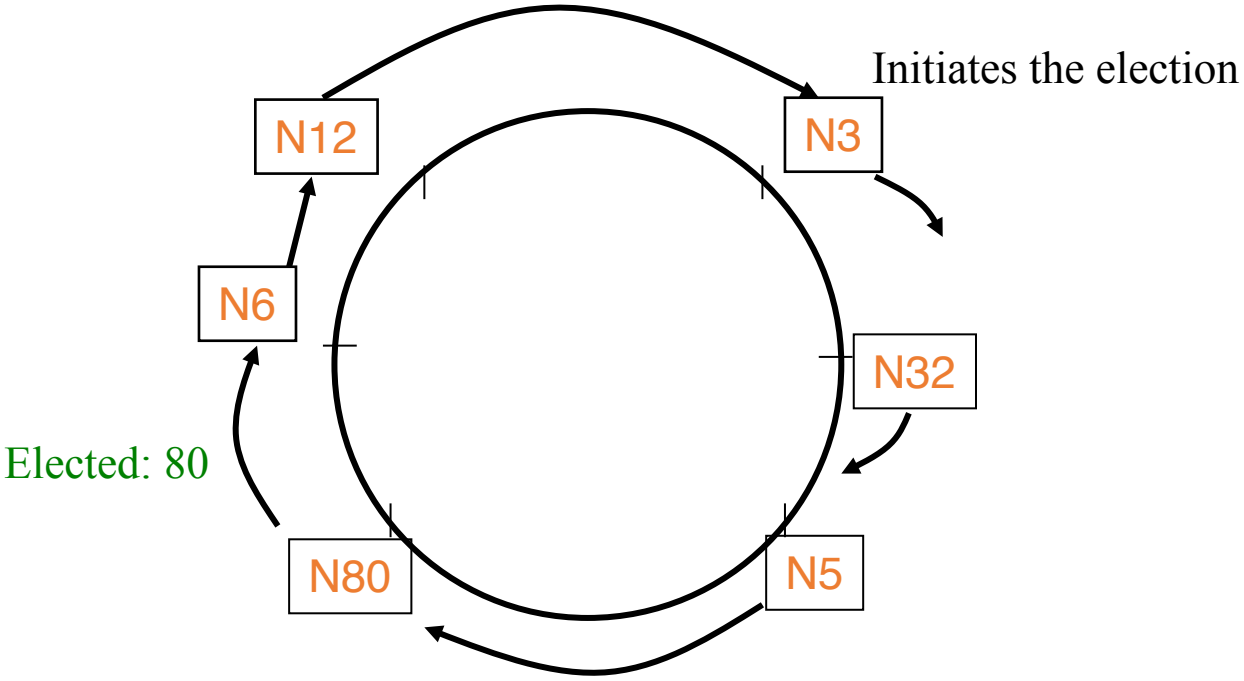
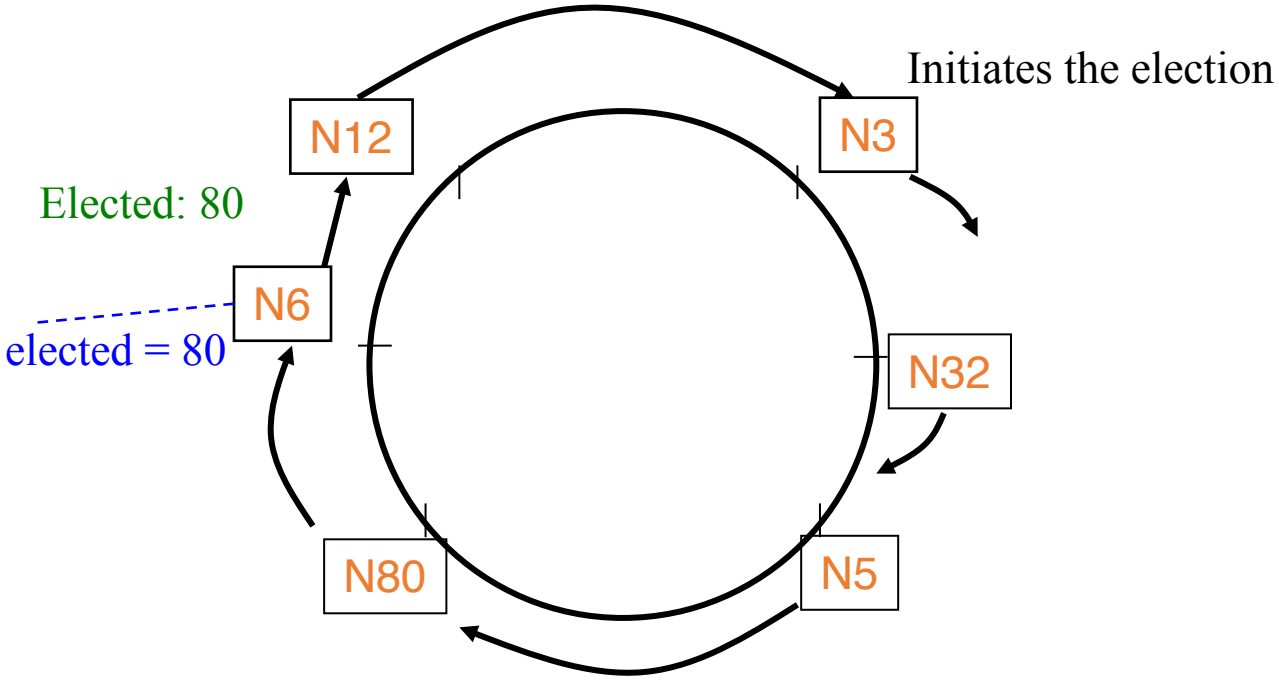
Ring Election: Example



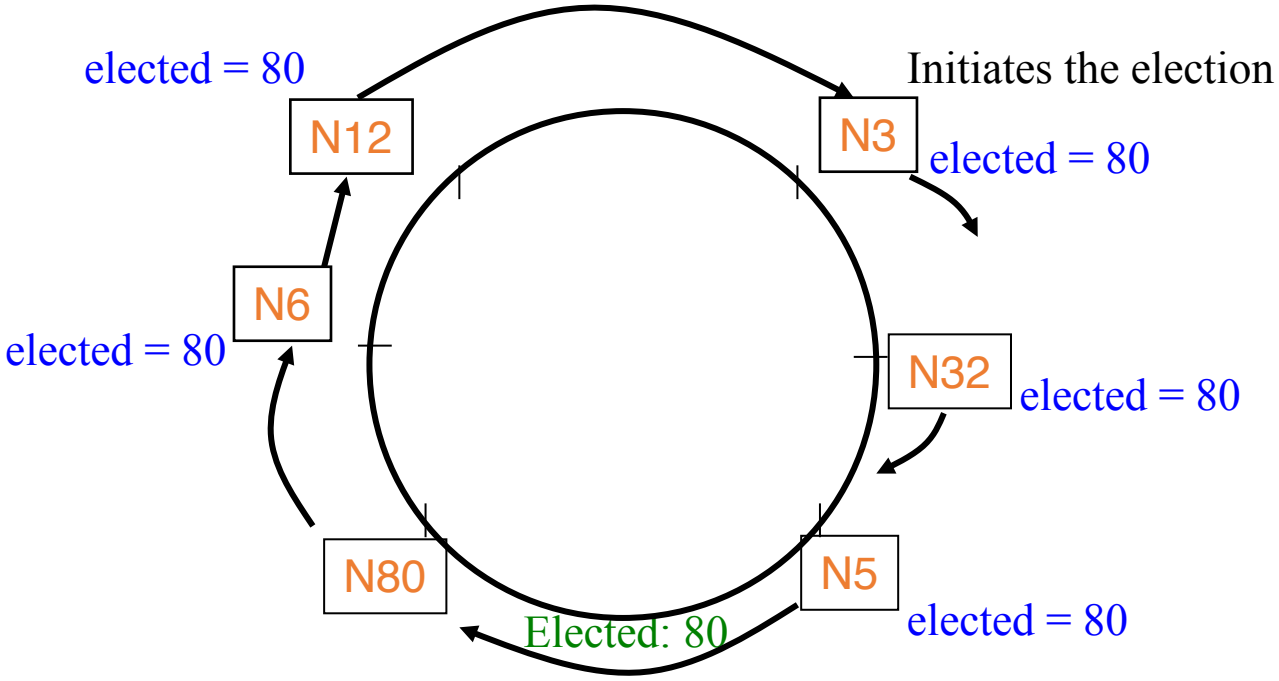
Goal: Elect highest id process as leader

Ring Election: Example



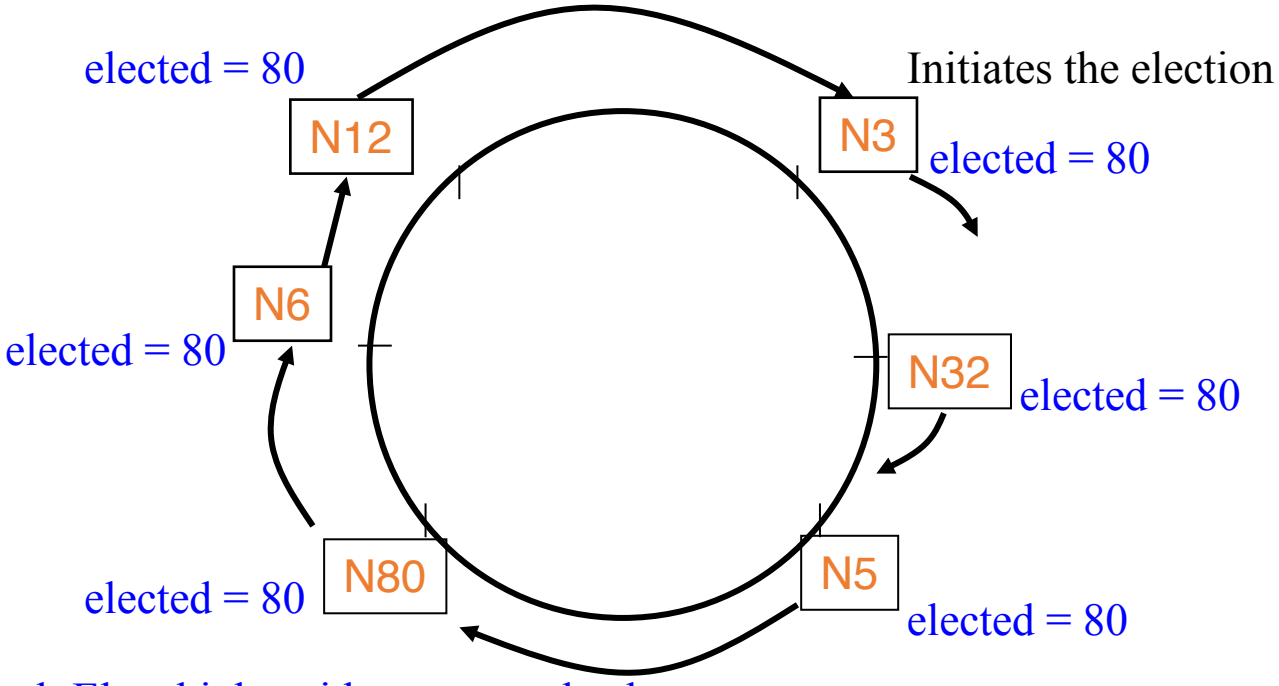
Goal: Elect highest id process as leader

Ring Election: Example



Goal: Elect highest id process as leader

Ring Election: Example



Goal: Elect highest id process as leader

Ring Election Protocol (basic version)

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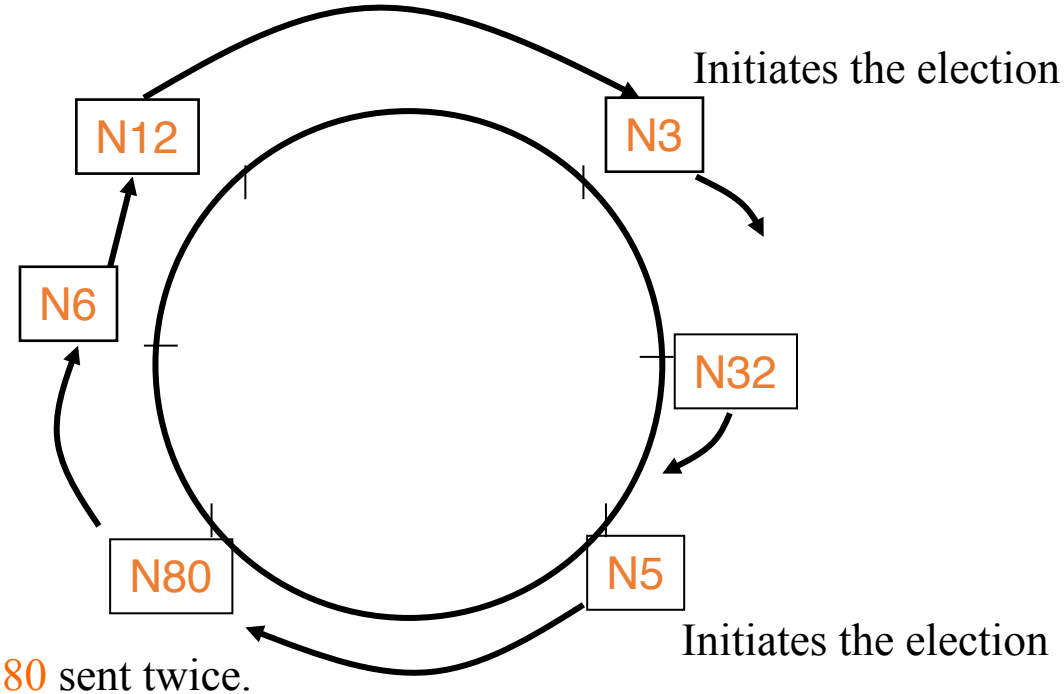
- When Pj receives message (election, $<attr_x, x>$) from predecessor
  - If $(attr_x, x) > (attr_j, j)$:
    - forward message (election, $<attr_x, x>$) to successor
  - If $(attr_x, x) < (attr_j, j)$
    - send (election, $<attr_j, j>$) to successor
  - If $(attr_x, x) = (attr_j, j)$: Pj is the elected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

What happens when multiple processes call for an election?

Ring Election: Example

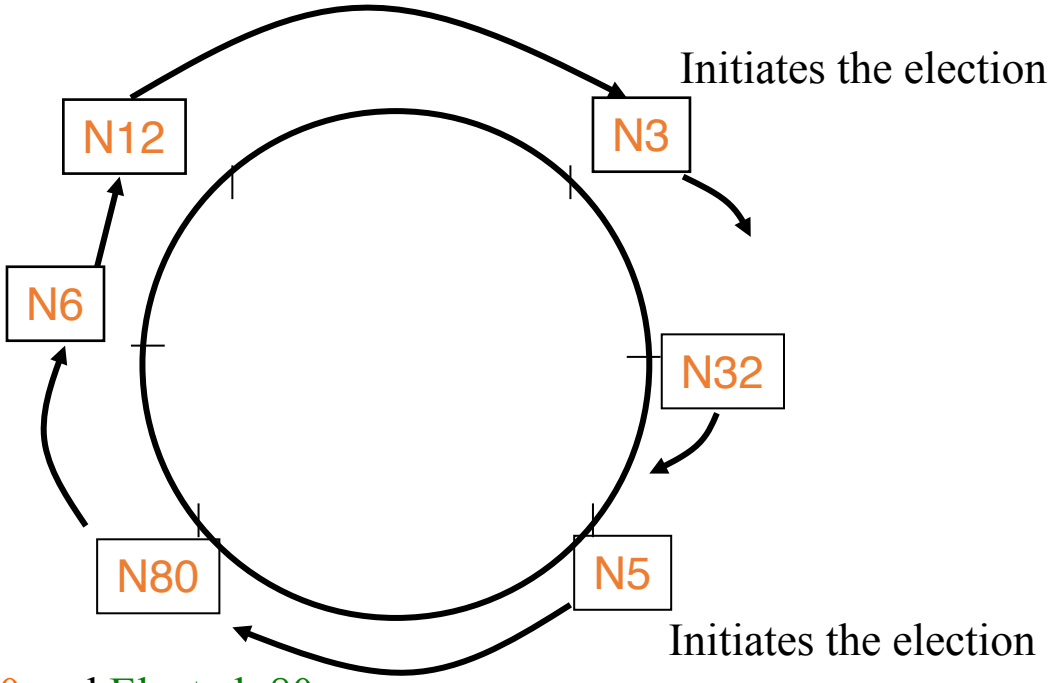


Election: 80 sent twice.
Elected: 80 also sent twice.

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

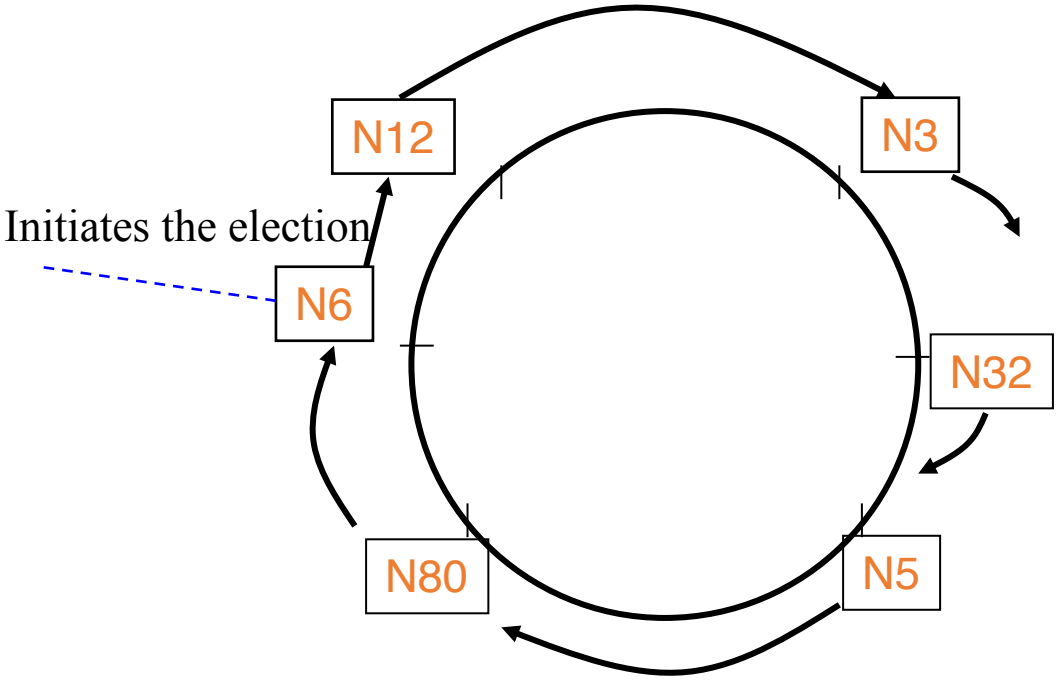


Election: 80 and Elected: 80
sent only once.

Performance Analysis

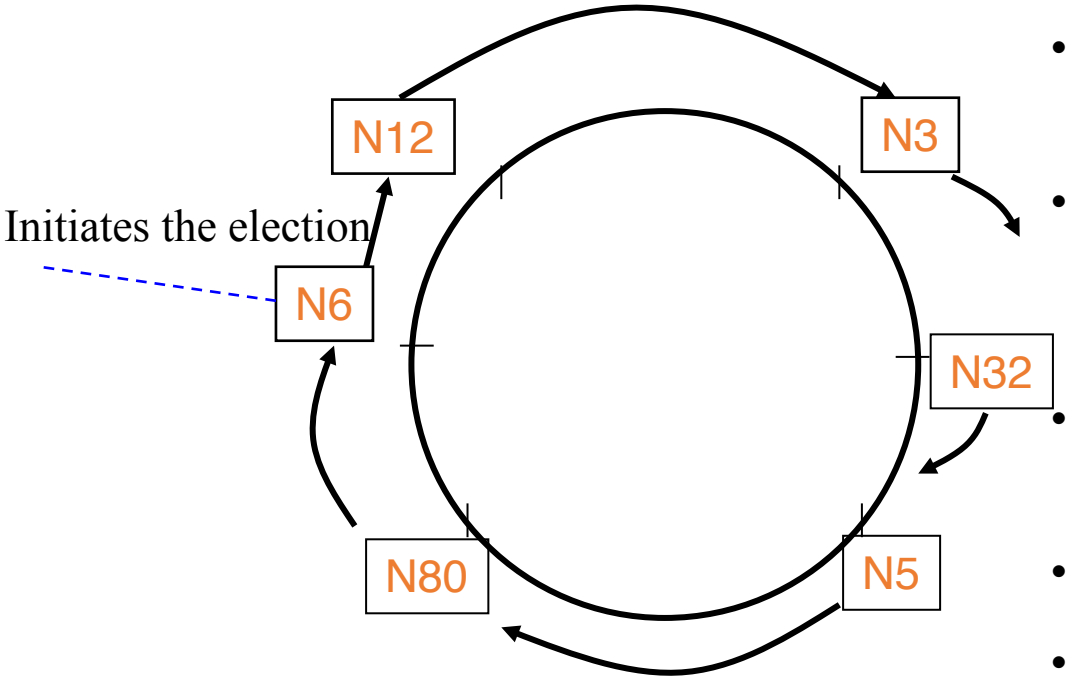
- Let's assume no failures occur during the election protocol itself, and there are *N* processes.
- Let's also assume that only one process initiates the algorithm
- **Bandwidth usage:** Total number of messages sent.
- **Turnaround time:** The number of serialized message transmission times between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

Worst-case



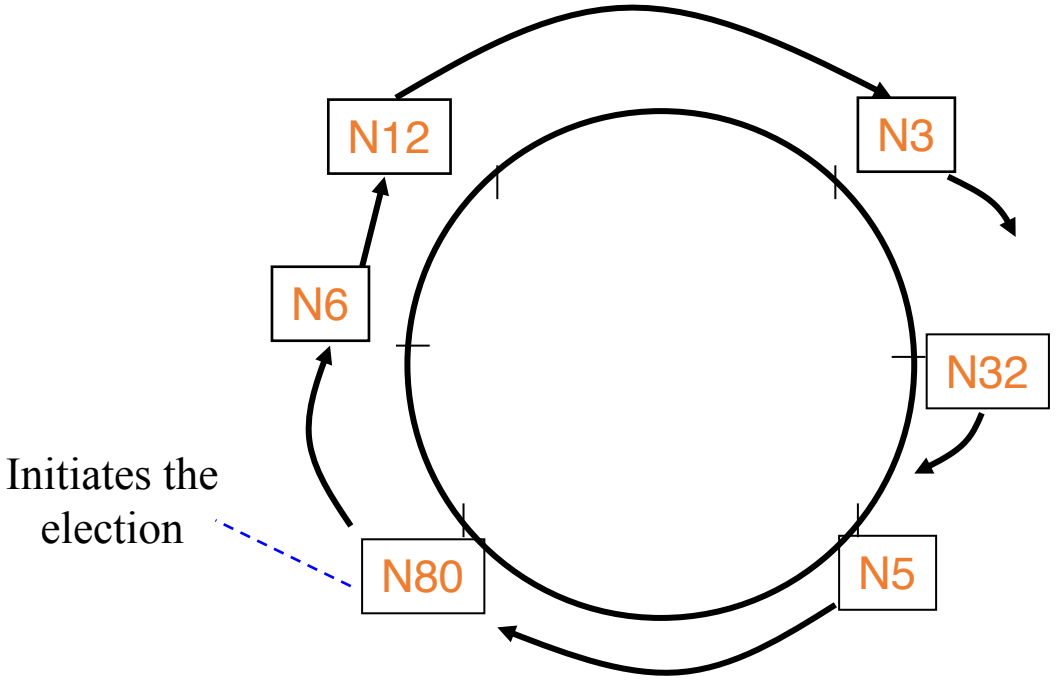
When the initiator is the ring successor of the would-be leader.

Worst-case



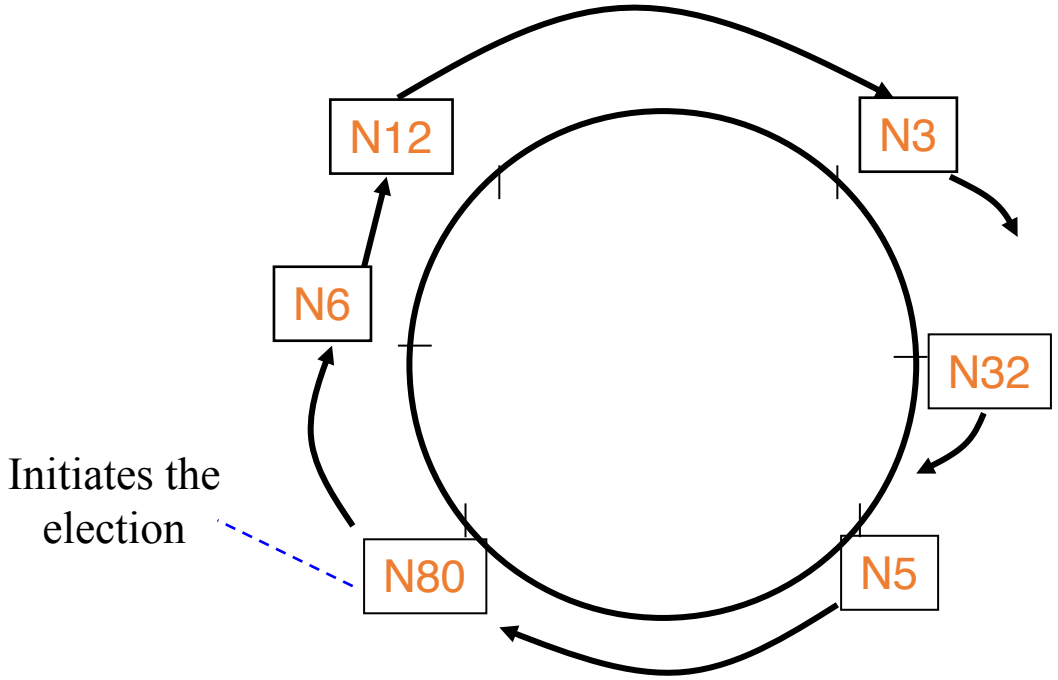
- (N-1) messages for Election message to get from N6 to N80.
- N messages for Election message to circulate around ring without message being changed.
- N messages for Elected message to circulate around the ring
- **No. of messages: (3N-1)**
- **Turnaround time: (3N-1) message transmission times**

Best-case



When the initiator is the would-be leader.

Best-case



When the initiator is the would-be leader.

No. of messages: 2N

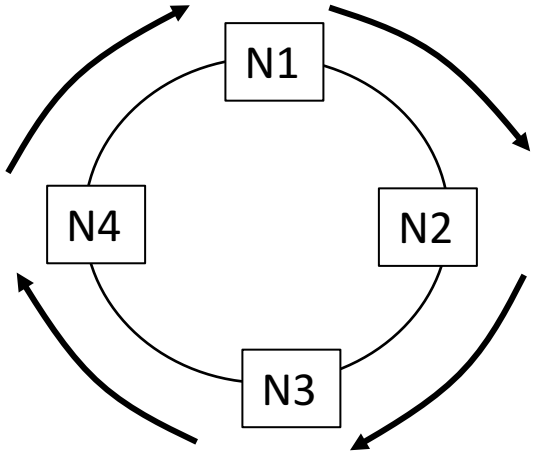
Turnaround time:
2N message transmission times

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

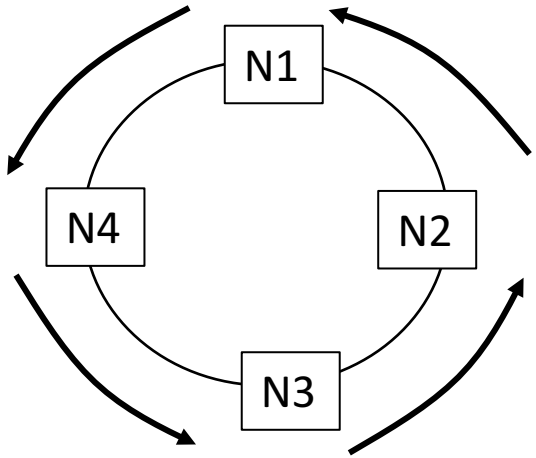
- Let's assume no failures occur during the election protocol itself, and there are *N* processes.
- When each process initiates the algorithm?
  - O(N) messages in best-case.



- 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.
- ….

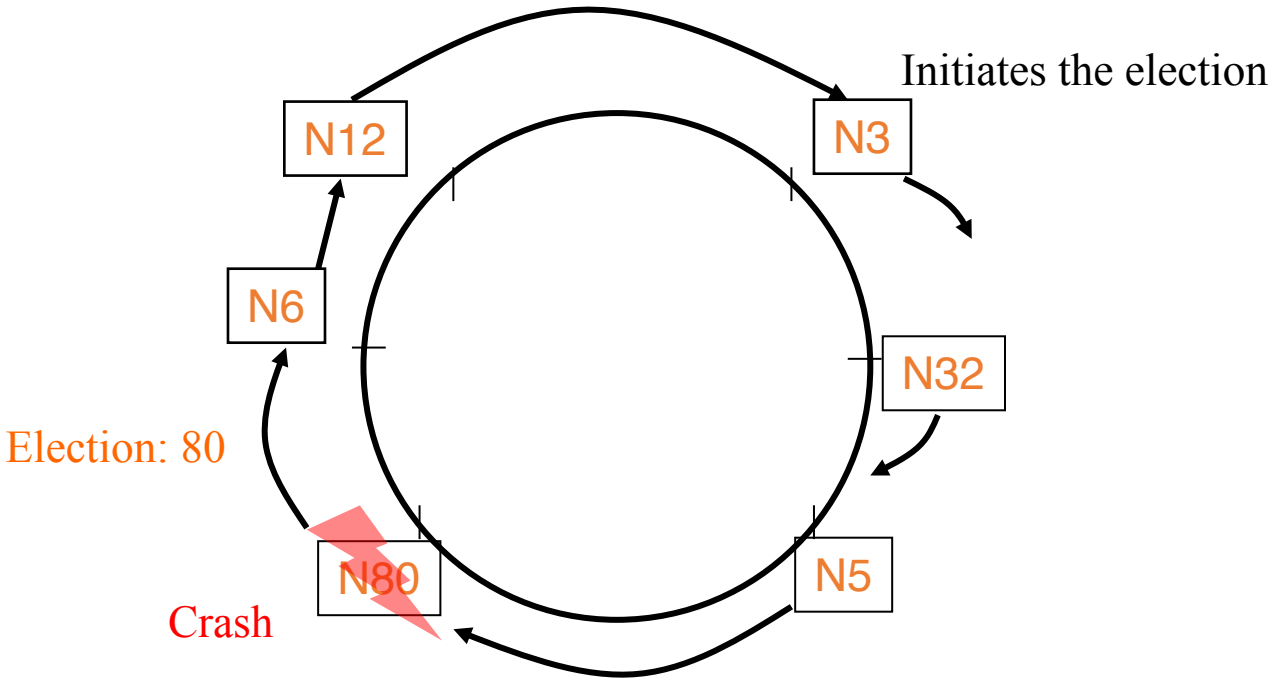
Performance Analysis

- 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.

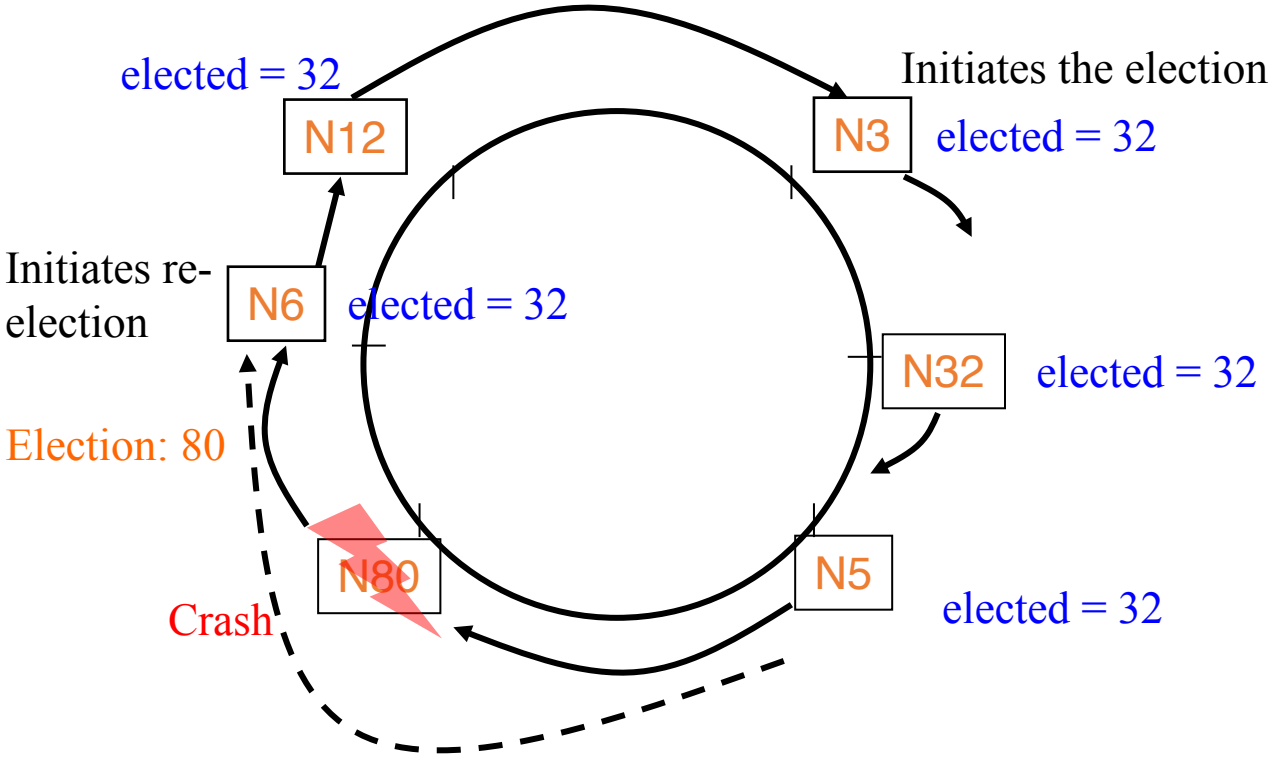
Handling Failures



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.
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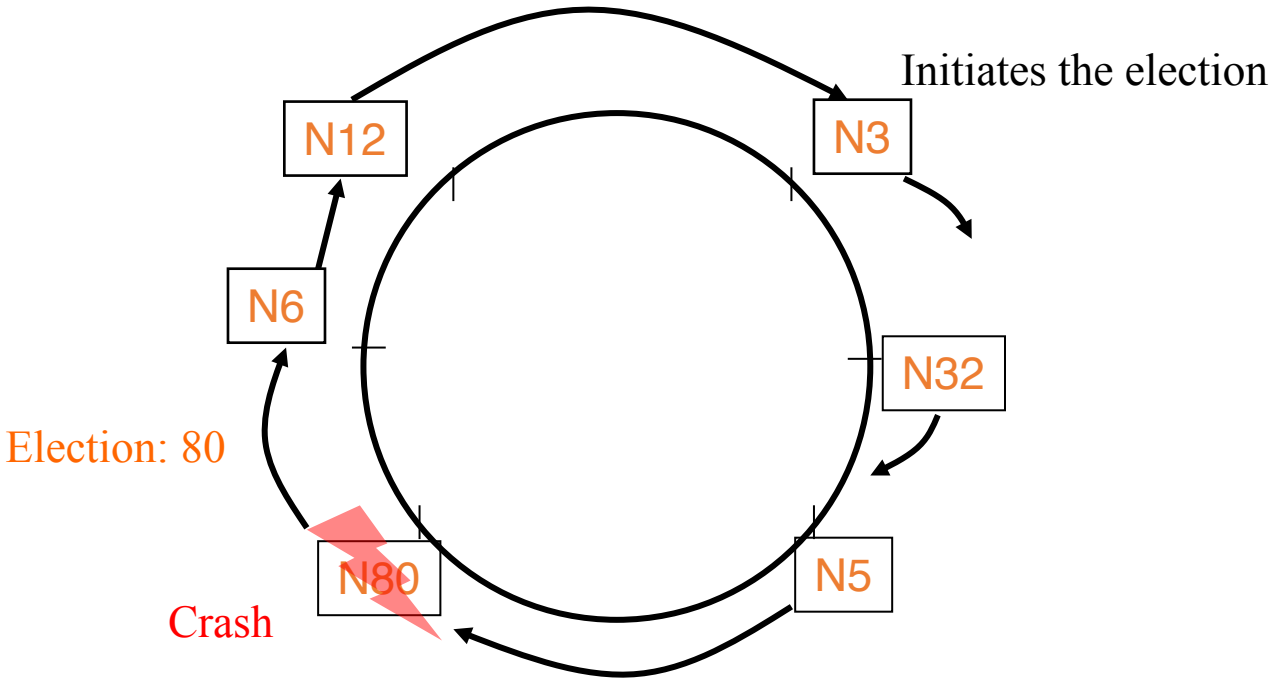
- But failure detectors cannot be both complete and accurate.
  - Incomplete FD => N80's failure might be missed .

What happens if a process failure is undetected?



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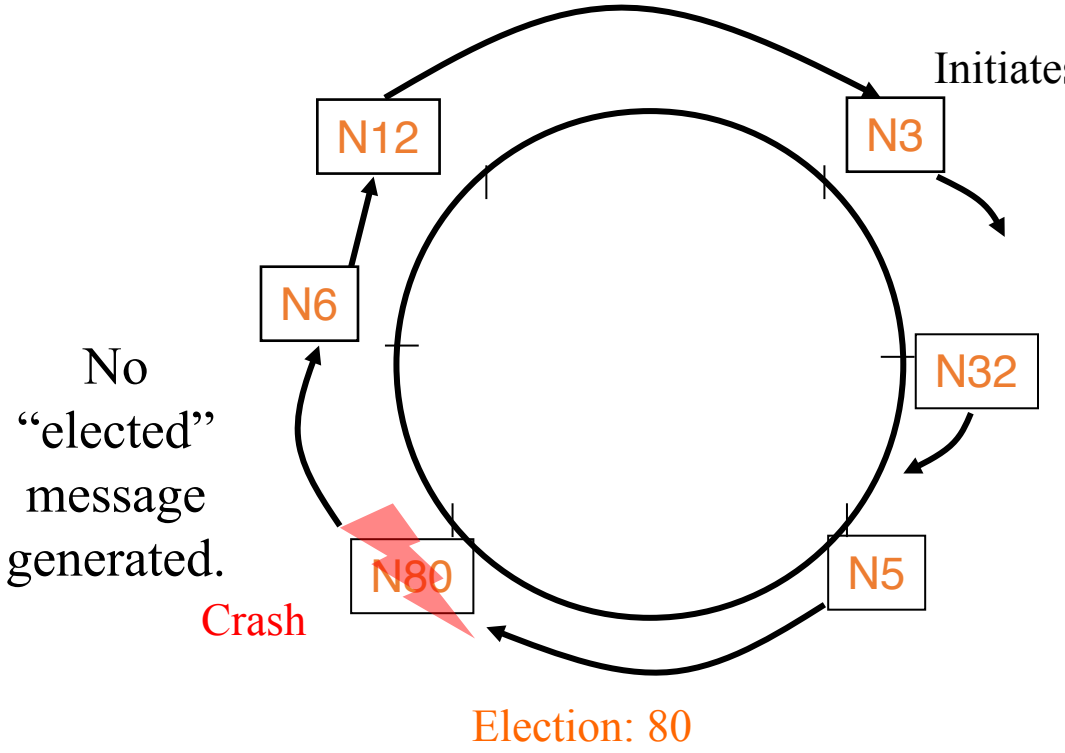


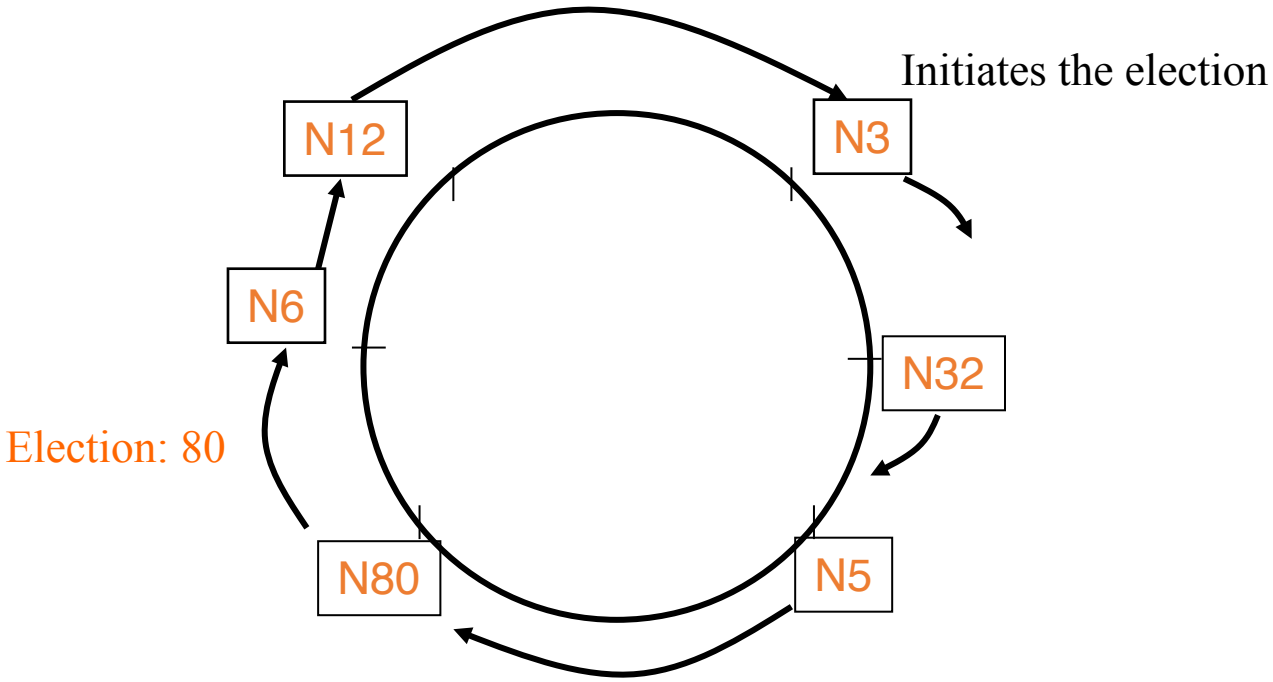
Algorithm does not terminate.

Liveness violated.

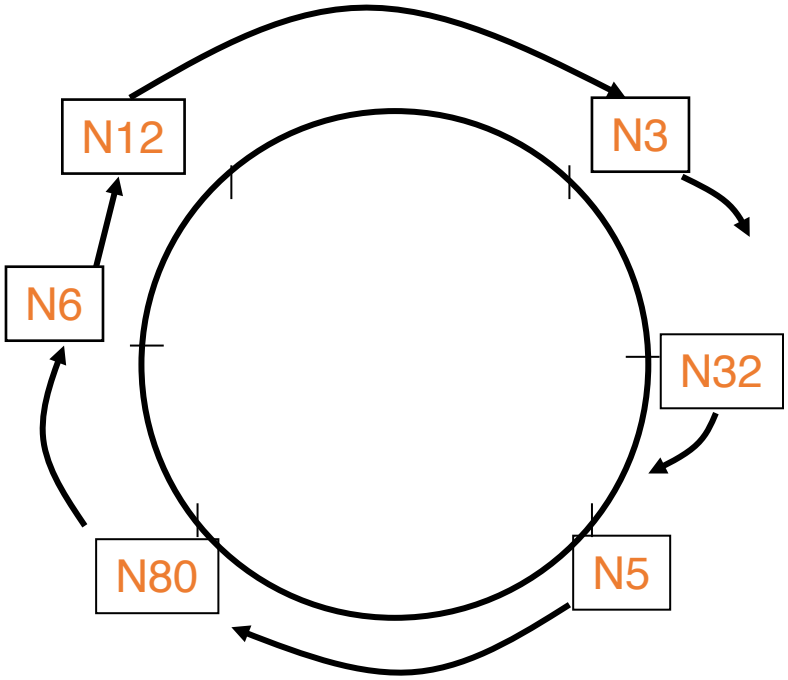
Handling failures

- 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?

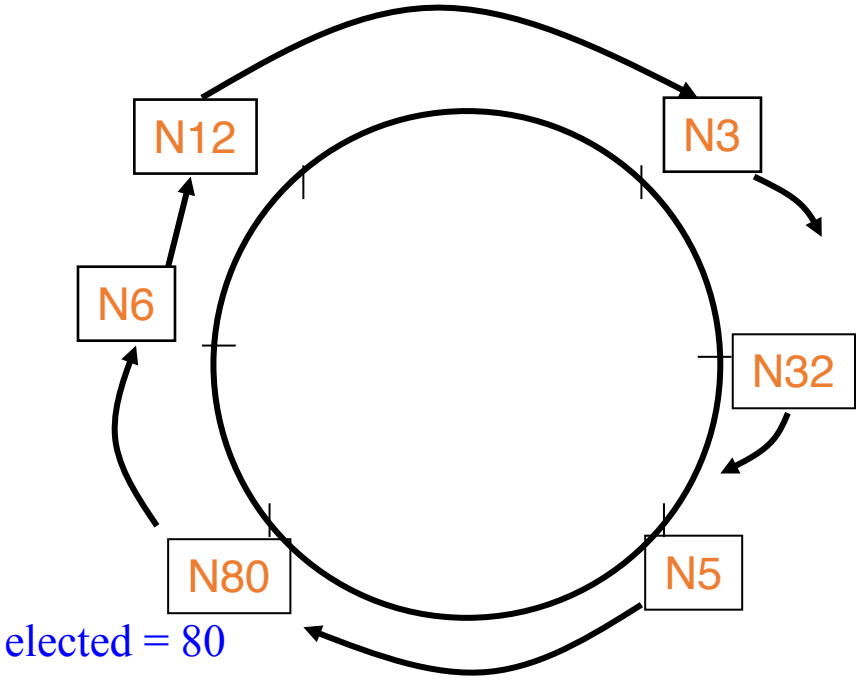


What can happen if an alive process is detected as failed?



Election: 80

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



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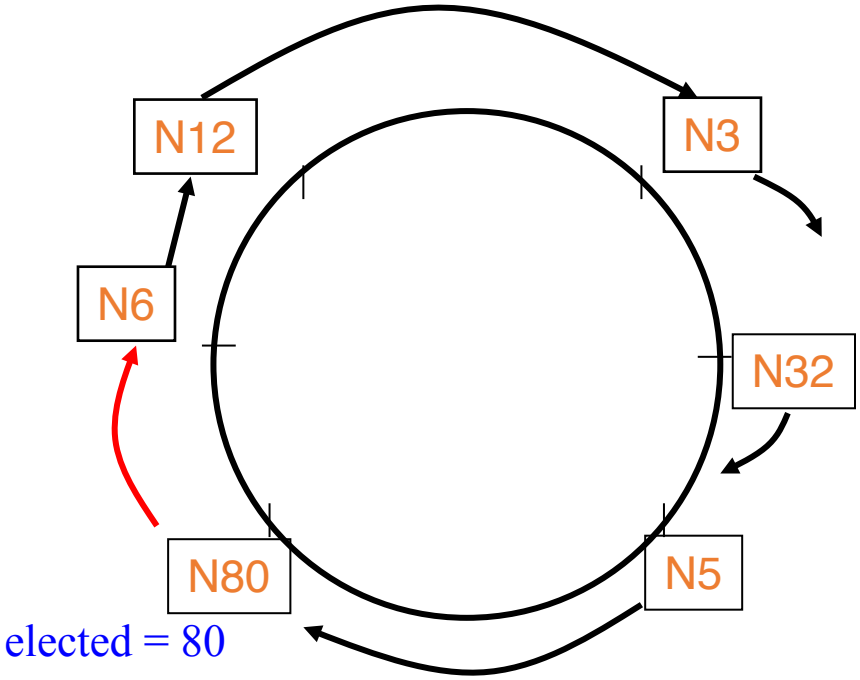

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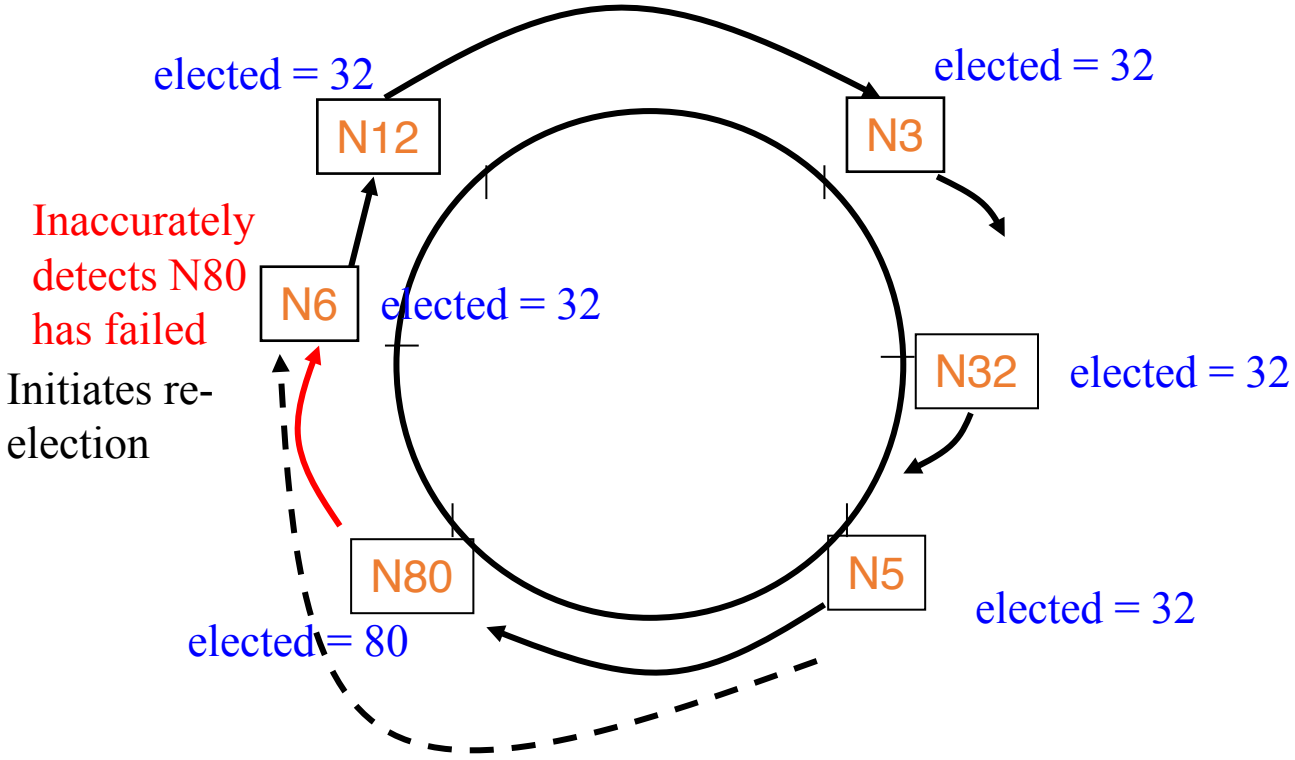


Safety has been violated.

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

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~~
    - ~~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

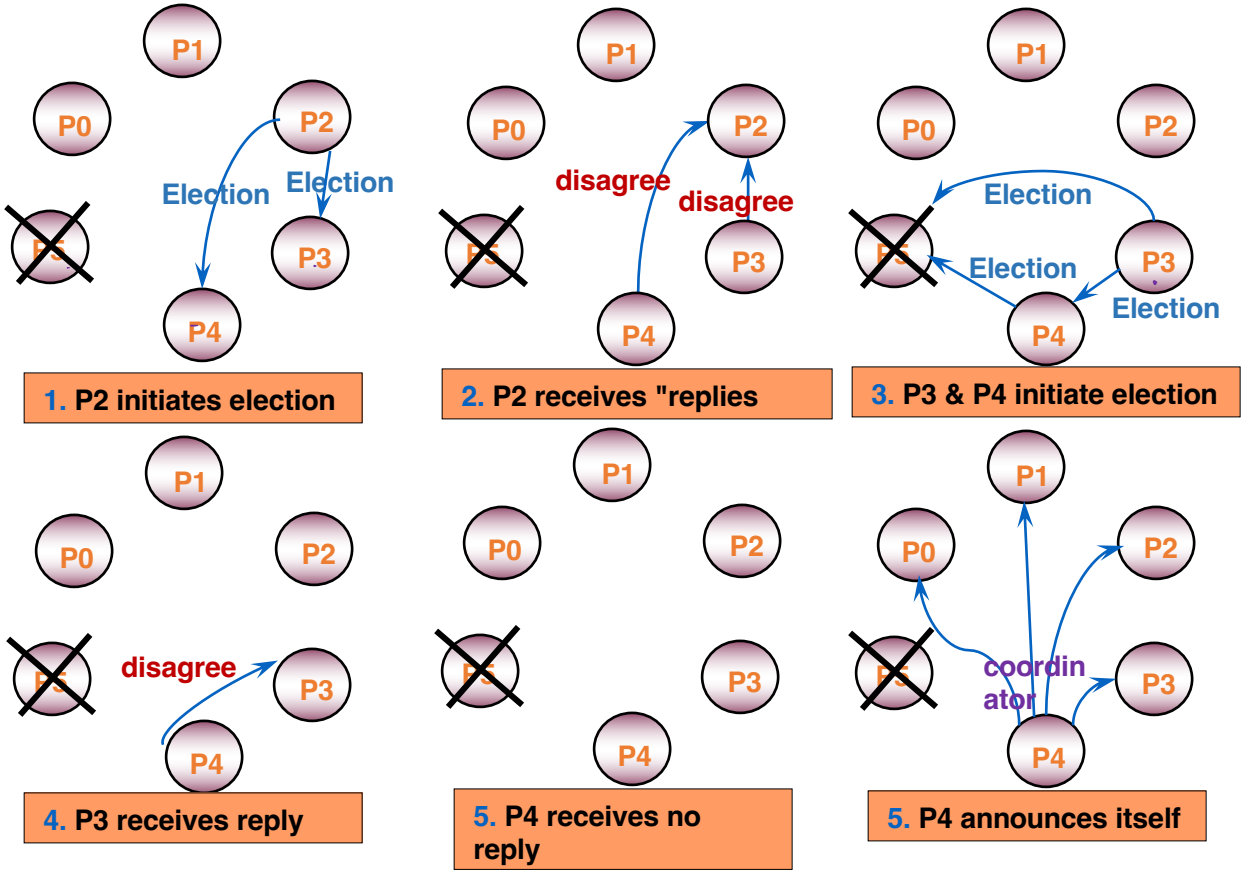
- When a process wants to initiate an election
  - **if** it knows its id is the highest
    - it elects itself as coordinator, then sends a *Coordinator* message to all processes with lower identifiers. Election is completed.
  - **else**
    - it initiates an election by sending an *Election* message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

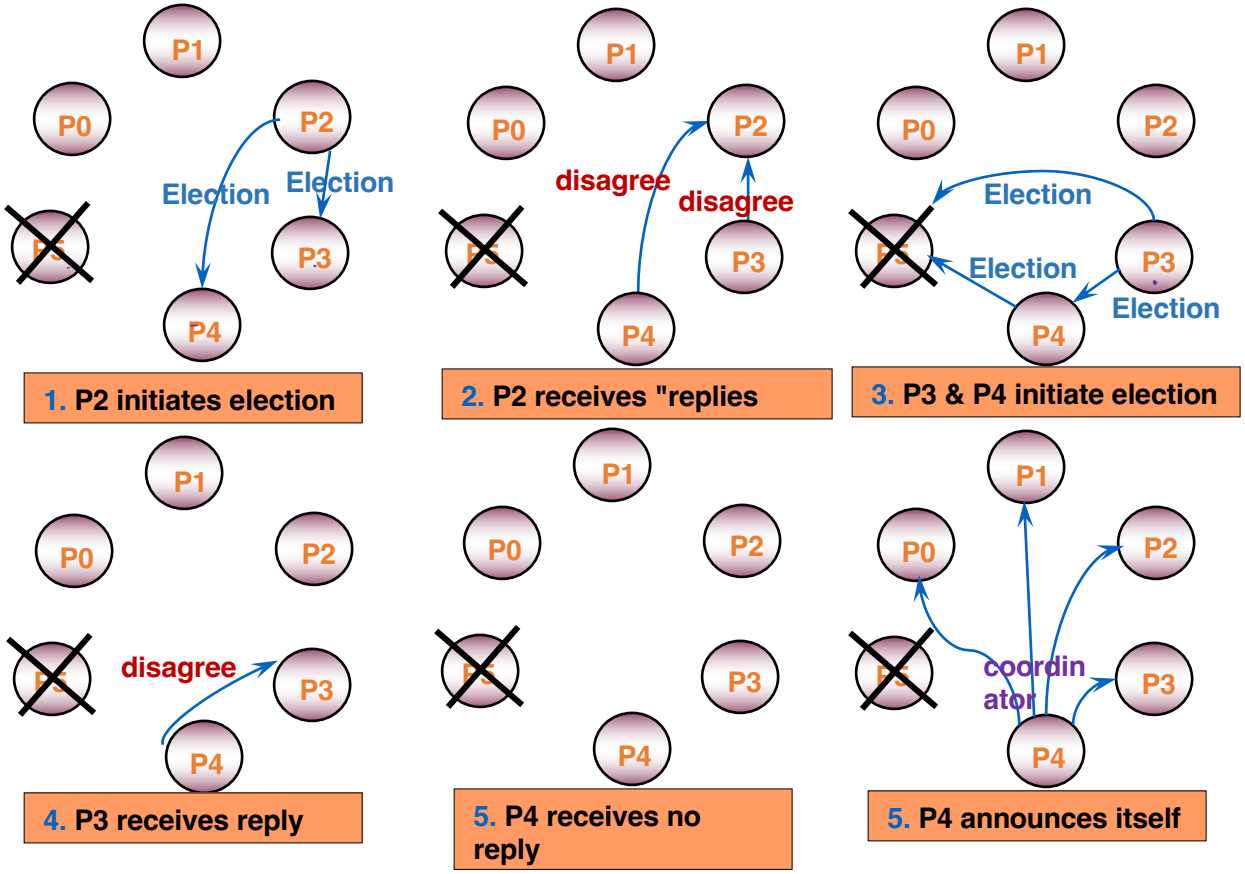
P2 initiates election after detecting P5's failure.



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).

Timeout values

- Assume the one-way message transmission time (T) is known.

- First timeout value (when the process that has initiated election waits for the first response)
  - Must be set as accurately as possible.
    - If it is too small, a lower id process can declare itself to be the coordinator even when a higher id process is alive.
  - What should be the first timeout value be, given the above assumption?
    - 2T + (processing time) ≈ 2T

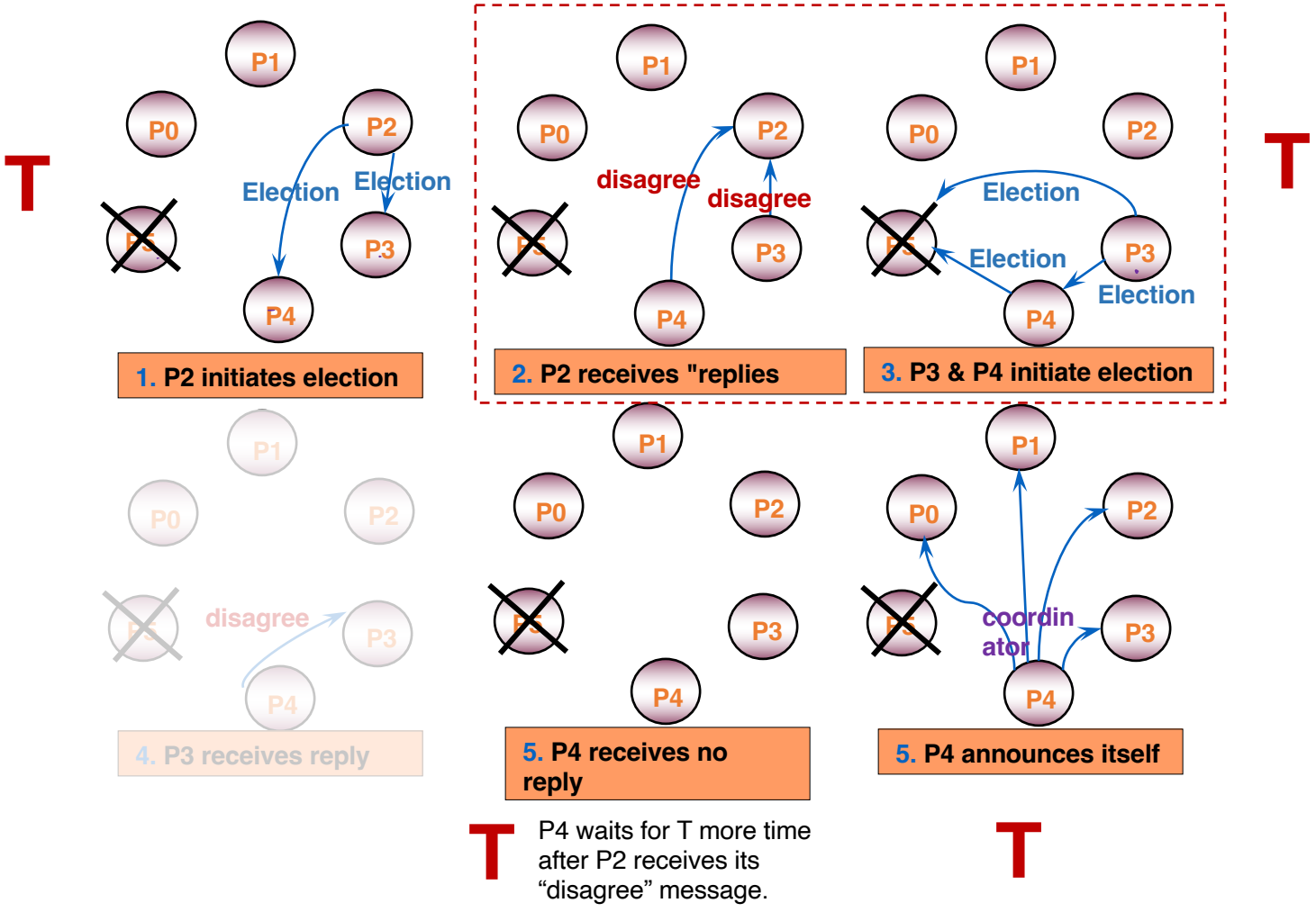
- When the second timeout happens (after 'disagree' message), election is re-started.
  - A very small value will lead to extra "Election" messages.
  - A suitable option is to use the worst-case turnaround time.

Performance Analysis

- Best-case
  - Second-highest id detects leader failure
    - Highest remaining id initiates election.
  - Sends (N-2) Coordinator messages
  - Turnaround time: 1 message transmission time (T)
- Worst-case: For simplicity, assume no failures after a process calls for election.
  - Turnaround time: 4 message transmission times (4T)
    - if any lower id process detects failure and starts election.

Bully Algorithm: Example

P2 initiates election after detecting P5's failure.



Analysis

- Best-case
  - Second-highest id detects leader failure
    - Highest remaining id initiates election.
  - Sends (N-2) Coordinator messages
  - Turnaround time: 1 message transmission time
- Worst-case: For simplicity, assume no failures after a process calls for election.
  - Turnaround time: 4 message transmission times
    - if any lower id process detects failure and starts election.
    - Election + (disagree & Election) + (Timeout – T) + Coordinator
  - When the process with the lowest id in the system detects failure.
    - (N-1) processes altogether begin elections, each sending messages to processes with higher ids.
    - i-th highest id process sends (i-1) election messages
    - Number of Election messages

      $= N-1 + N-2 + \ldots + 1 = (N-1)*N/2 = O(N^2)$

Correctness

- In synchronous system model:
  - Set timeout accurately using known bounds on network delays and processing times.
  - Satisfies safety and liveness.

- In asynchronous system model:
  - Failure detectors cannot be both accurate and complete.
  - Either liveness and safety is violated.

Why is Election so hard?

- Because it is related to the consensus problem!

- If we could solve election, then we could solve consensus!
  - Elect a process, use its id's last bit as the consensus decision.

- But (as we will see in next class) consensus is impossible in asynchronous systems, so is election!

Summary

- Leader election is an important problem in distributed system.
  - Crucial for implementing any centralized algorithm.
- Two classical algorithms:
  - Ring election algorithm and Bully algorithm
- Hard to guarantee correctness in an asynchronous system with failures.