Distributed Systems

CS425/ECE428

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Today's agenda

- Mutual Exclusion (contd)
  - Chapter 15.2

- Leader Election
  - Chapter 15.3

Mutual exclusion in distributed systems

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

Recap: Messages in RA Algorithm

- enter() at process Pi
  - set state to Wanted
  - multicast "Request" <Ti, Pi> to all other processes, where Ti = current Lamport timestamp at Pi
  - wait until all other processes send back "Reply"
  - change state to Held and enter the CS
- On receipt of a Request <Tj, j> at Pi (i ≠ j):
  - if (state = Held) or (state = Wanted & (Ti, i) < (Tj, j))

    // lexicographic ordering in (Tj, j), Ti is Lamport timestamp of Pi's request

    add request to local queue (of waiting requests)

    else send "Reply" to Pj
- exit() at process Pi
  - change state to Released and "Reply" to all queued requests.

Analysis: Ricart-Agrawala's Algorithm

- Safety
  - Two processes P*i* and P*j* cannot both have access to CS.
- Liveness
  - Worst-case: wait for all other (*N-1*) processes to send Reply.
- Ordering
  - Requests with lower Lamport timestamps are granted earlier.

Analysis: Ricart-Agrawala's Algorithm

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  - Two processes P*i* and P*j* cannot both have access to CS.
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Analysis: Ricart-Agrawala's Algorithm

- Bandwidth:
  - 2*(*N-1*) messages per enter operation
    - *N-1* unicasts for the multicast request + *N-1* replies
  - Up to *N-1* unicasts for the multicast release per exit operation
- Client delay:
  - one round-trip time
- Synchronization delay:
  - one message transmission time
- *Client and synchronization delays have gone down to O(1).*
- *Bandwidth usage is still high. Can we bring it down further?*

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's Algorithm: Key Idea

- Ricart-Agrawala requires replies from *all* processes in group.
- Instead, get replies from only *some* processes in group.
- But ensure that only one process is given access to CS (Critical Section) at a time.

Maekawa's Voting Sets

- Each process P*i* is associated with a *voting set* V*i* (subset of processes).
- Each process belongs to its own voting set.
- *The intersection of any two voting sets must be non-empty.*

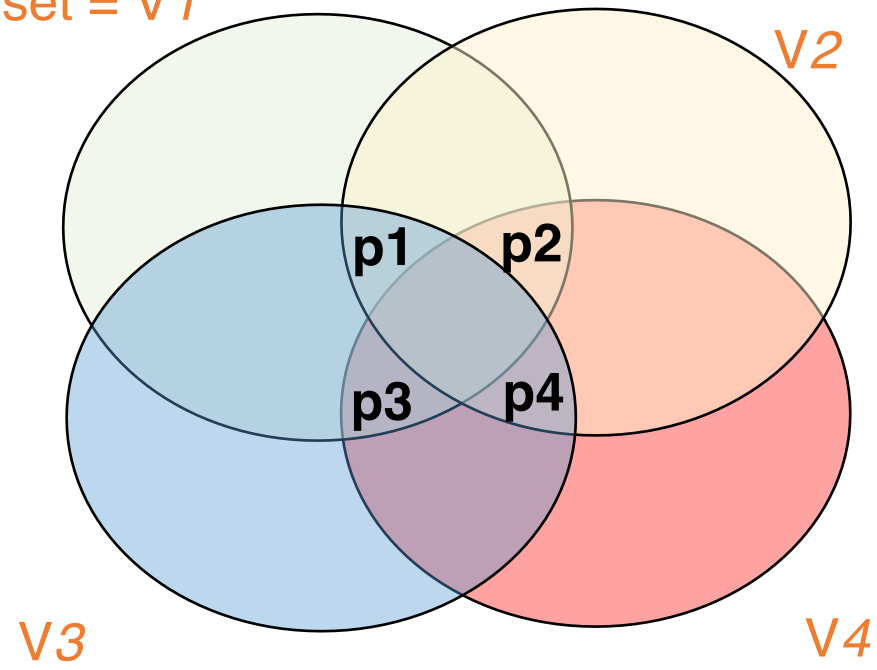
A way to construct voting sets

One way of doing this is to put N processes in a √N by √N matrix and for each Pi, its voting set Vi = row containing Pi + column containing Pi.

Size of voting set = 2*√N-1.

p1	p2
p3	p4

P*1*'s voting set = V*1*



Maekawa: Key Differences From Ricart-Agrawala

- Each process requests permission from only its voting set members.
  - Not from all

- Each process (in a voting set) gives permission to at most one process at a time.
  - Not to all

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*

Actions (contd.)

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

  if (state == Held 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

Size of Voting Sets

- Each voting set is of size *K*.
- Each process belongs to *M* other voting sets.
- Maekawa showed that *K*=*M*=*approx.* $\sqrt{N}$ works best.

Optional self-study: Why $\sqrt{N}$?

- Let each voting set be of size *K and* each process belongs to *M* other voting sets.
- Total number of voting set members (processes may be repeated) = *K*N*
- But since each process is in *M* voting sets
  - *K*N = M*N => K = M* (1)
- Consider a process P*i*
  - Total number of voting sets = members present in P*i*'s voting set and all their voting sets = *(M-1)*K + 1*
  - All processes in group must be in above
  - To minimize the overhead at each process (*K*), need each of the above members to be unique, i.e.,
    - *N = (M-1)*K + 1*
    - *N = (K-1)*K + 1* (due to (1))
    - *K* ~ $\sqrt{N}$

Size of Voting Sets

- Each voting set is of size *K*.
- Each process belongs to *M* other voting sets.
- Maekawa showed that *K*=*M*=*approx.* $\sqrt{N}$ works best.
- Matrix technique gives a voting set size of $2*\sqrt{N}-1 = O(\sqrt{N})$.

Performance: Maekawa Algorithm

- Bandwidth
  - $2K = 2\sqrt{N}$ messages per enter
  - $K = \sqrt{N}$ messages per exit
  - Better than Ricart and Agrawala's ($2*(N-1)$ and $N-1$ messages)
  - $\sqrt{N}$ quite small. $N \sim 1$ million => $\sqrt{N} = 1K$
- Client delay:
  - One round trip time
- Synchronization delay:
  - 2 message transmission times

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*.
  - V*i* and V*j* intersect in at least one process say P*k*.
  - But P*k* sends only one Reply (vote) at a time, so it could not have voted for both P*i* and P*j*.

Liveness

- Does not guarantee liveness, since can have a *deadlock*.
- *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;
- Now, 0 waits for 1's reply, 1 waits for 5's reply, 5 waits for 2 to send a release, and 2 waits for 0 to send a release. Hence, deadlock!

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.
    - Constant bandwidth usage, 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

- **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 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
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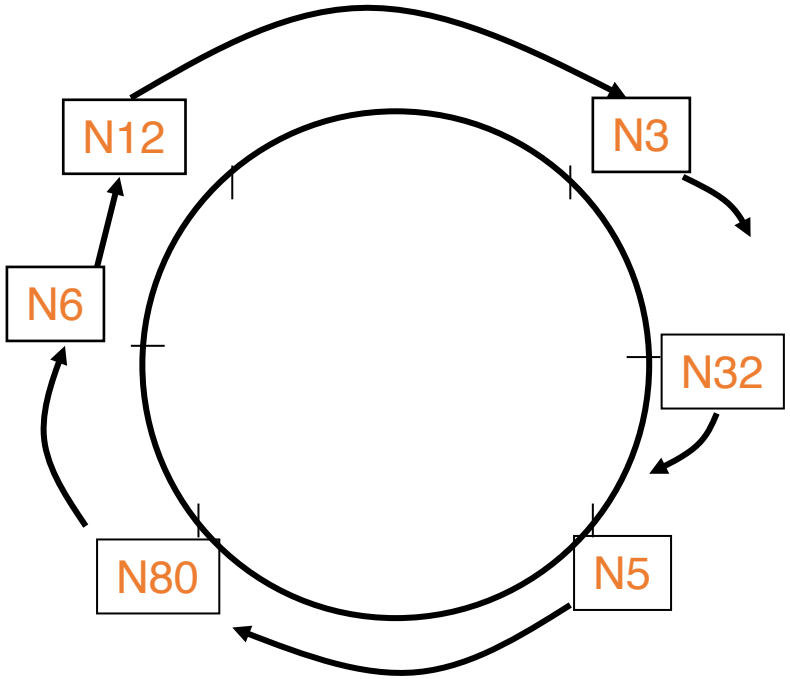
Ring Election Algorithm

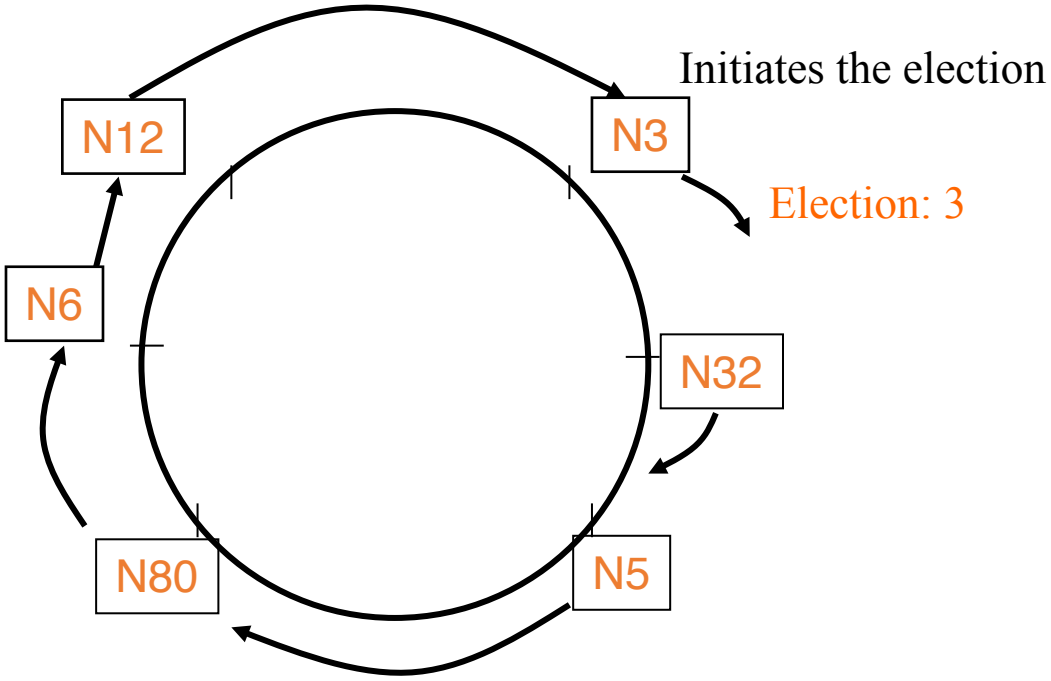
- *N* processes are organized in a logical ring
  - All messages are sent clockwise around the ring.



Ring Election Protocol (basic version)

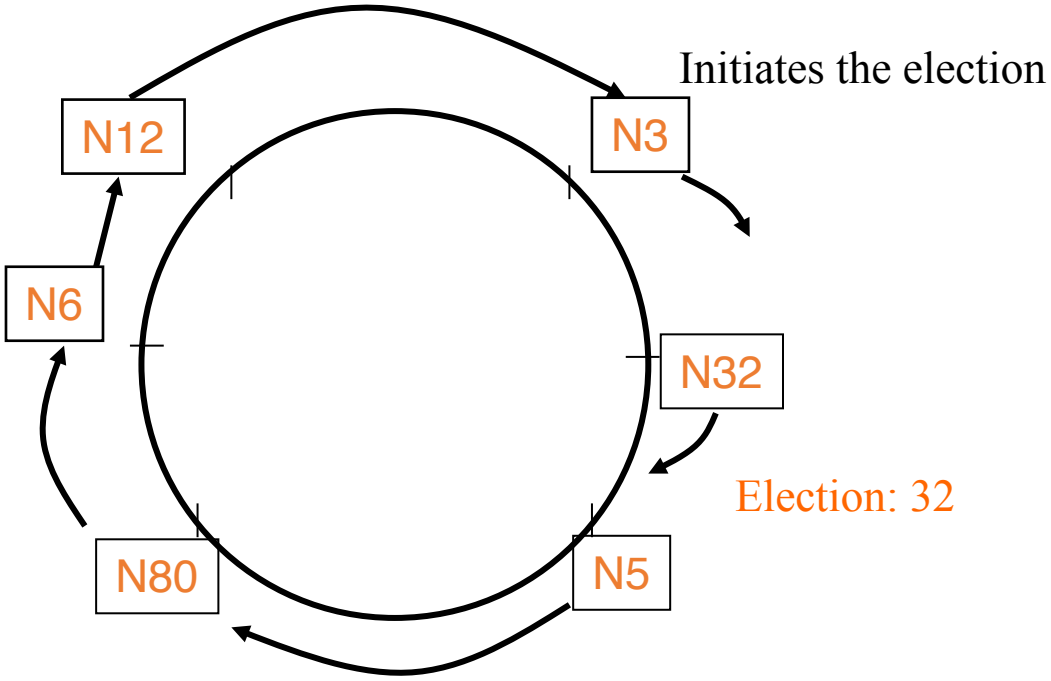
- When Pi start election
  - send election message with Pi's <$attr_i$, i> to ring successor.
- When Pj receives message (election, <$attr_x$, x>) from predecessor
  - If ($attr_x$, x) > ($attr_j$, j):
    - forward message (election, <$attr_x$, x>) to successor
  - If ($attr_x$, x) < ($attr_j$, j)
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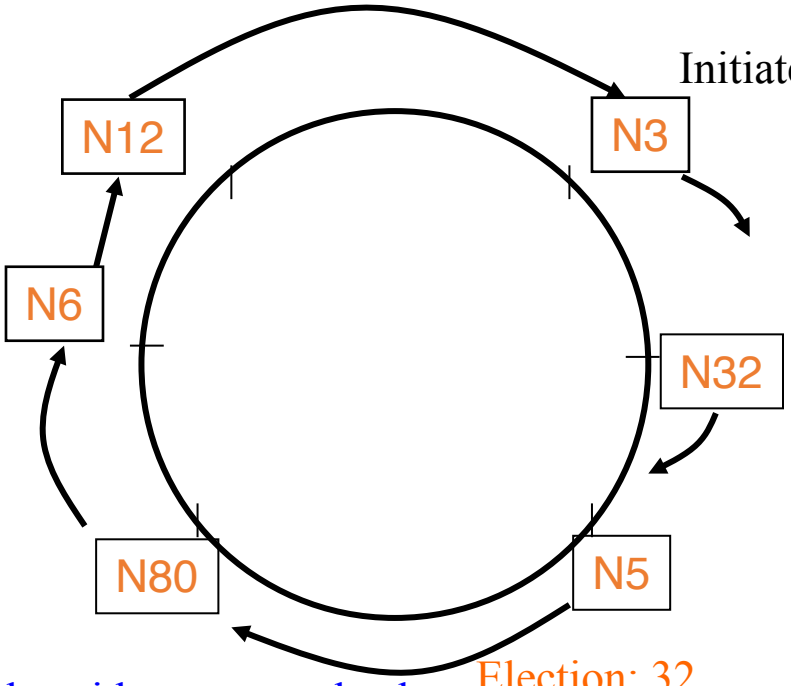

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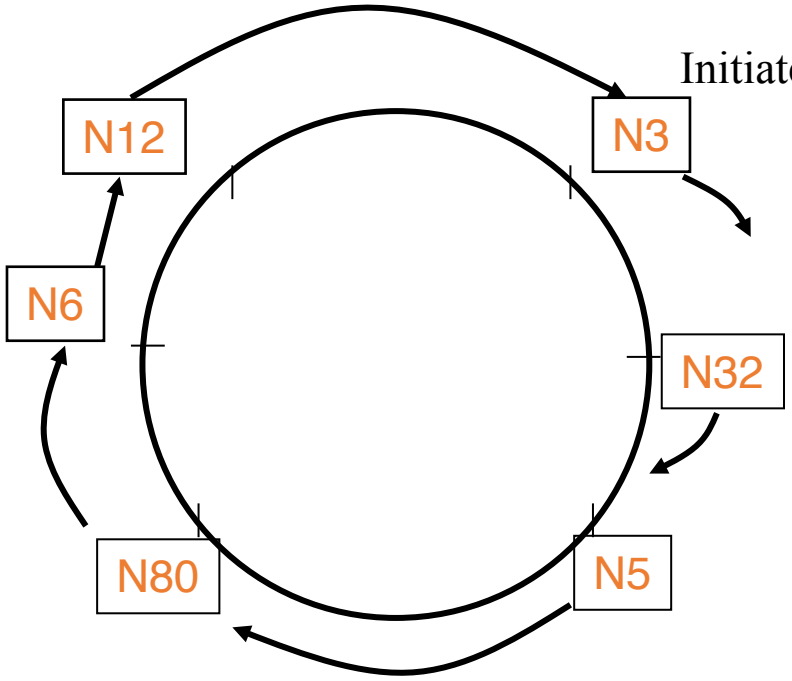
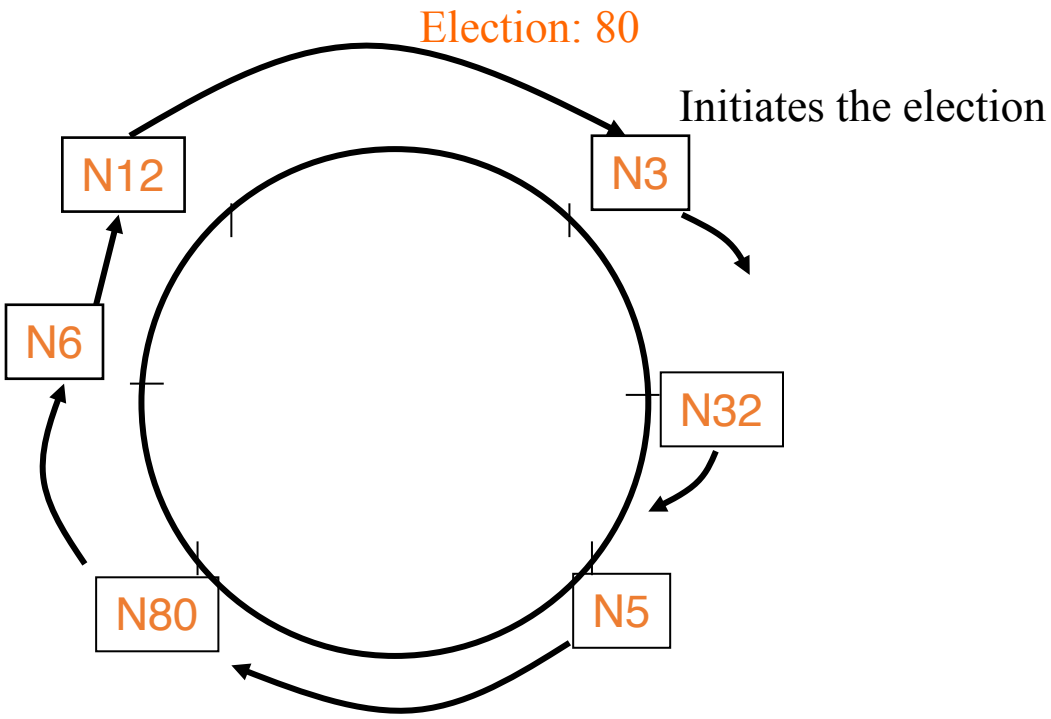


Election: 80

Goal: Elect highest id process as leader

Ring Election: Example



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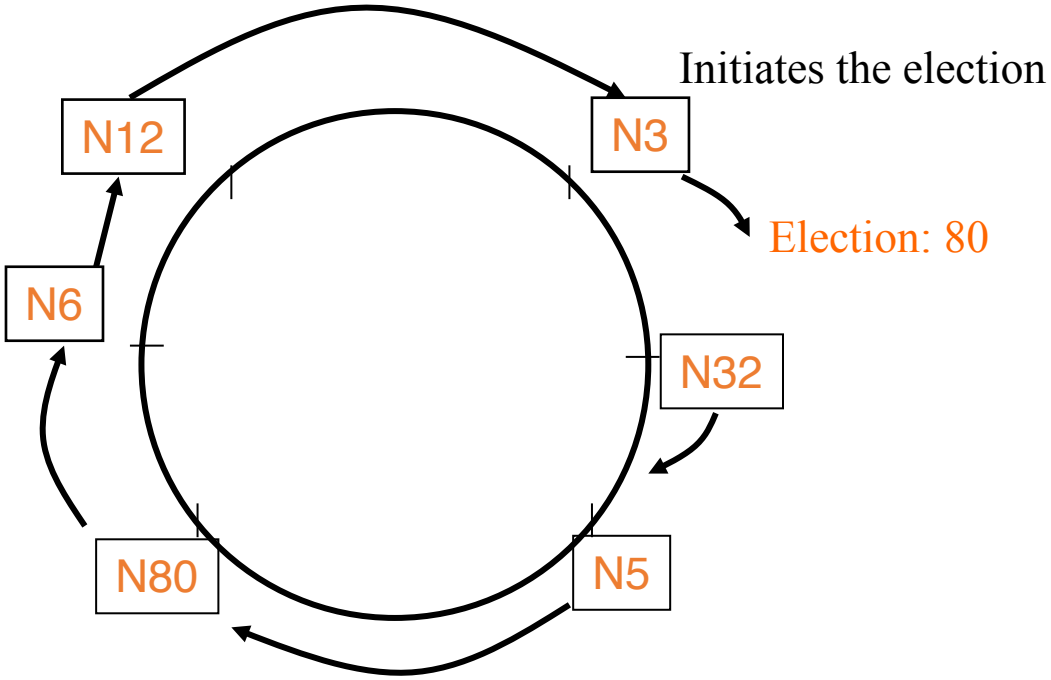
Ring Election: Example



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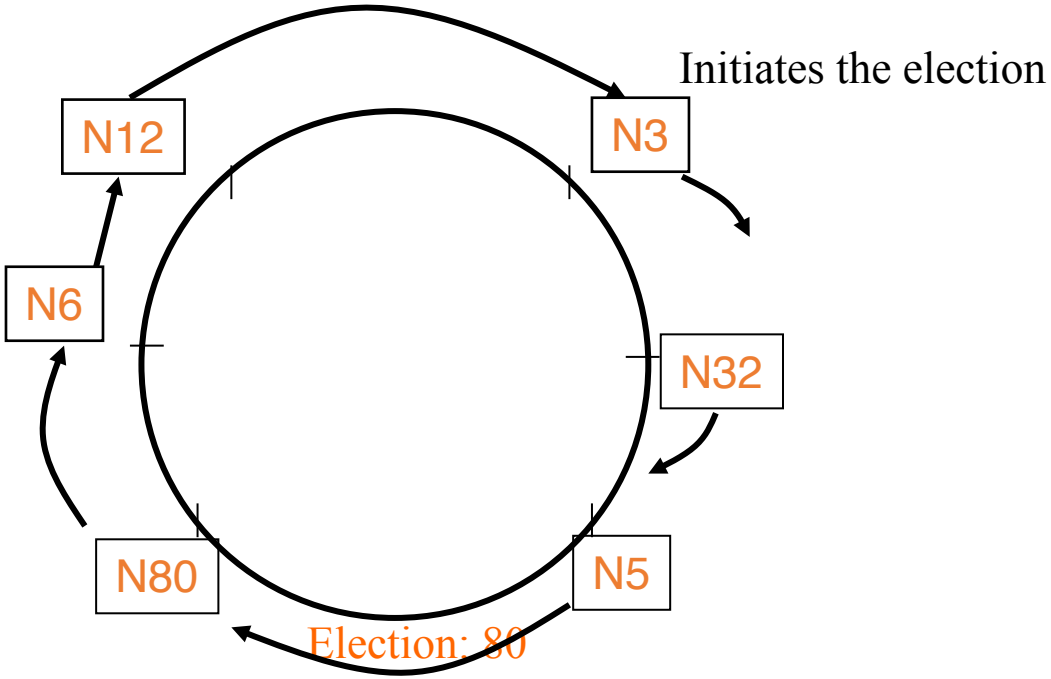

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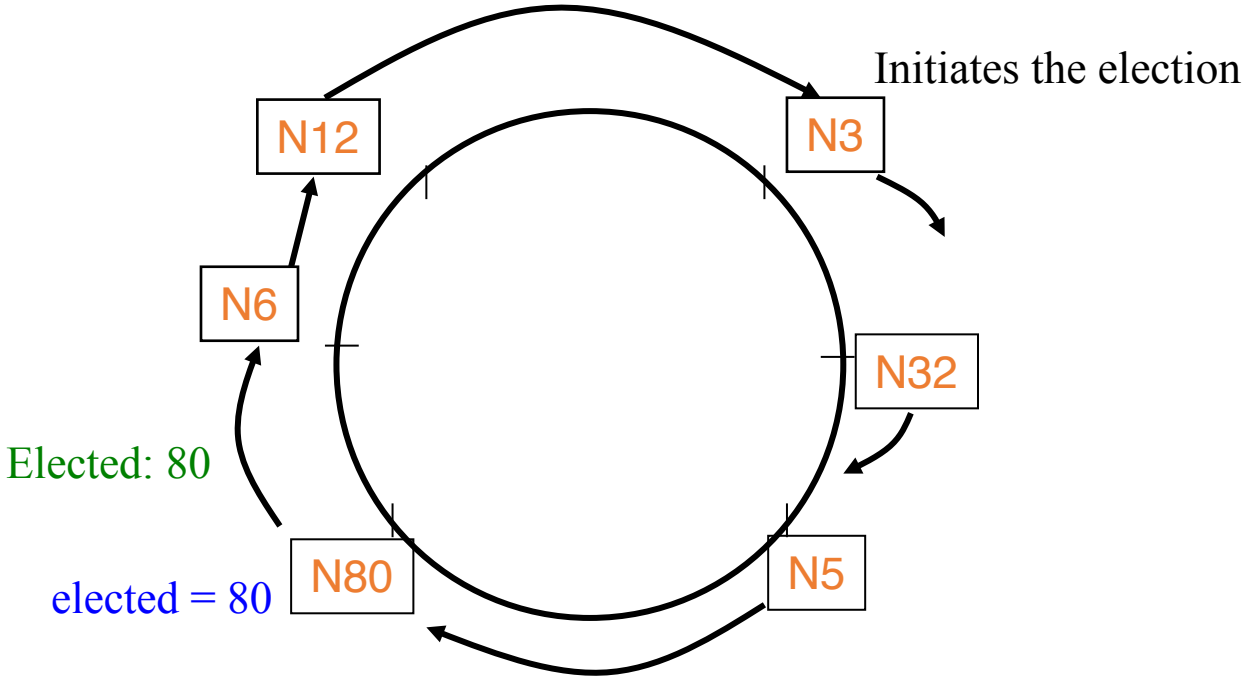
Ring Election: Example



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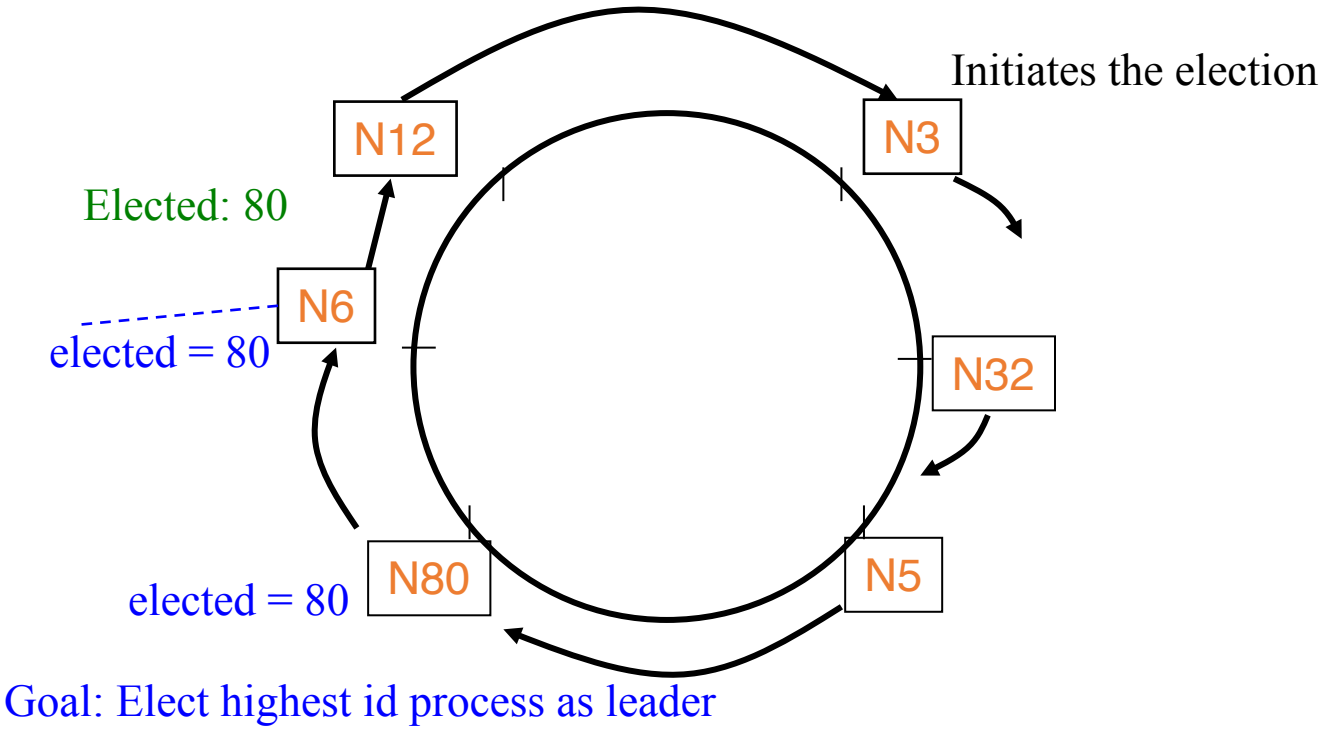
Ring Election: Example



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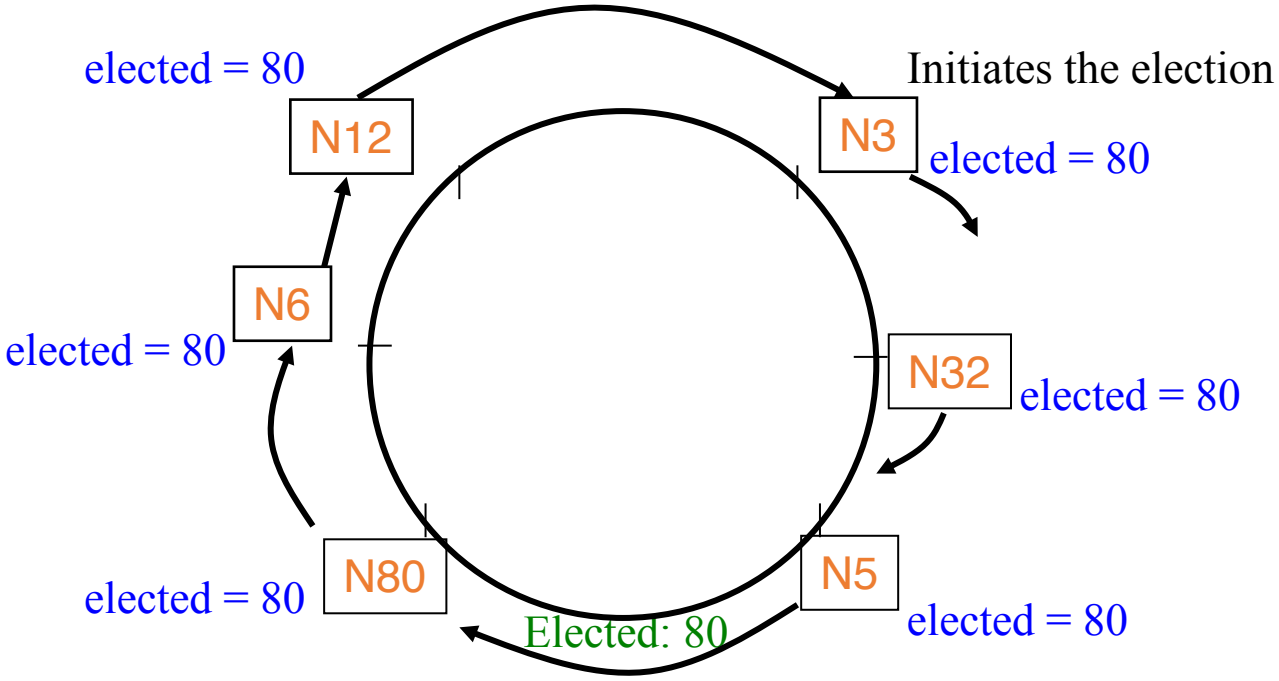
Ring Election: Example



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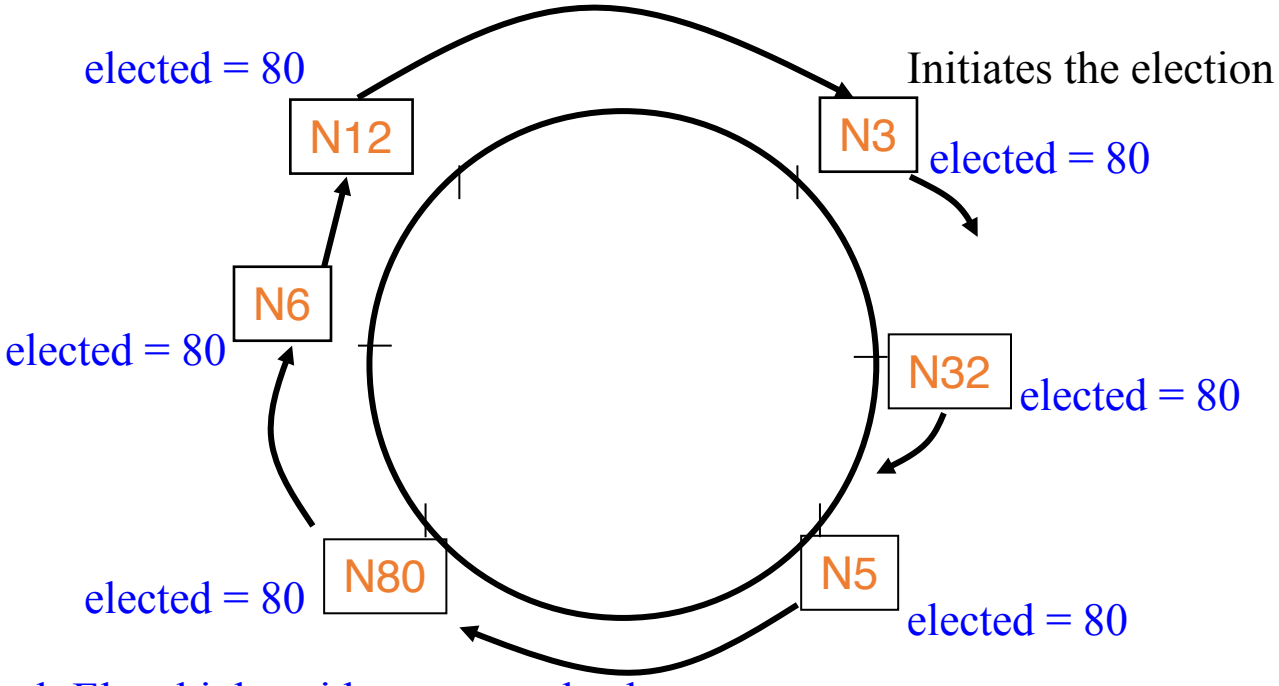
Ring Election: Example



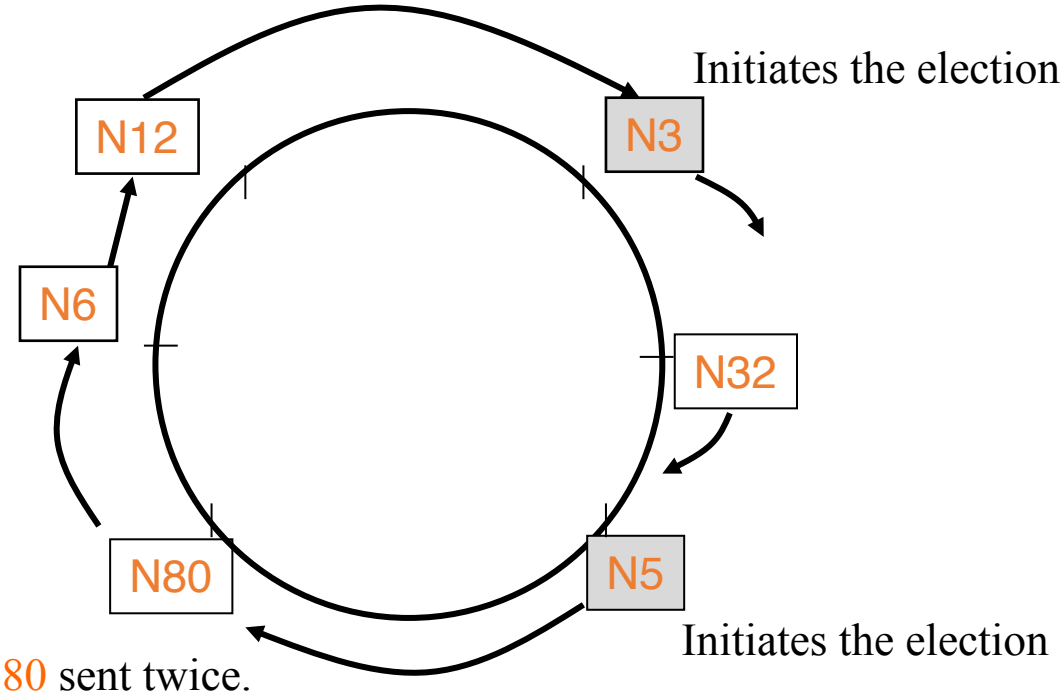
Goal: Elect highest id process as leader

Ring Election 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.

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