Distributed Systems

ECE428

Lecture 10

Adopted from Spring 2021

Today's agenda

- Mutual Exclusion
  - Chapter 15.2
- Leader Election
  - Chapter 15.3

Problem statement for mutual exclusion

- *Critical Section* Problem:
  - Piece of code (at all processes) for which we need to ensure there is <u>at most one process</u> executing it at any point of time.

- Each process can call three functions
  - enter() to enter the critical section (CS)
  - AccessResource() to run the critical section code
  - exit() to exit the critical section

Mutual exclusion in distributed systems

- Processes communicating by passing messages.

- Cannot share variables like semaphores!

- *How do we support mutual exclusion in a distributed system?*

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

System Model

- Each pair of processes is connected by reliable channels (such as TCP).
- Messages sent on a channel are eventually delivered to a recipient, and in FIFO order.
- Processes do not fail.
  - Fault-tolerant variants exist in literature.

Analysis of Central Algorithm

- Safety – at most one process in CS
  - Exactly one token
- Liveness – every request for CS granted eventually
  - With *N* processes in system, queue has at most *N* processes
  - If each process exits CS eventually and no failures, liveness guaranteed
- Ordering:
  - FIFO ordering guaranteed in order of requests received at leader
  - Not in the order in which requests were sent or the order in which processes enter CS!

Analyzing Performance

Three metrics:

- Bandwidth: the total number of messages sent in each *enter* and *exit* operation.
- Client delay: delay incurred by a process at each enter and exit operation (when *no* other process is in CS, or waiting)
  - *We will focus on the client delay for the enter operation.*
- Synchronization delay: the time interval between one process exiting the critical section and the next process entering it (when there is *only one* process waiting). Measure of the *throughput* of the system.

Analysis of Central Algorithm

- Bandwidth: the total number of messages sent in each *enter* and *exit* operation.
  - 2 messages for enter
  - 1 message for exit
- Client delay: delay incurred by a process at each enter and exit operation (when *no* other process is in, or waiting)
  - 2 message latencies (1 round-trip, request + grant) on enter.
- Synchronization delay: the time interval between one process exiting the critical section and the next process entering it (when there is *only one* process waiting)
  - 2 message latencies (release + grant)

Limitations of Central Algorithm

- The leader is the performance bottleneck and single point of failure.

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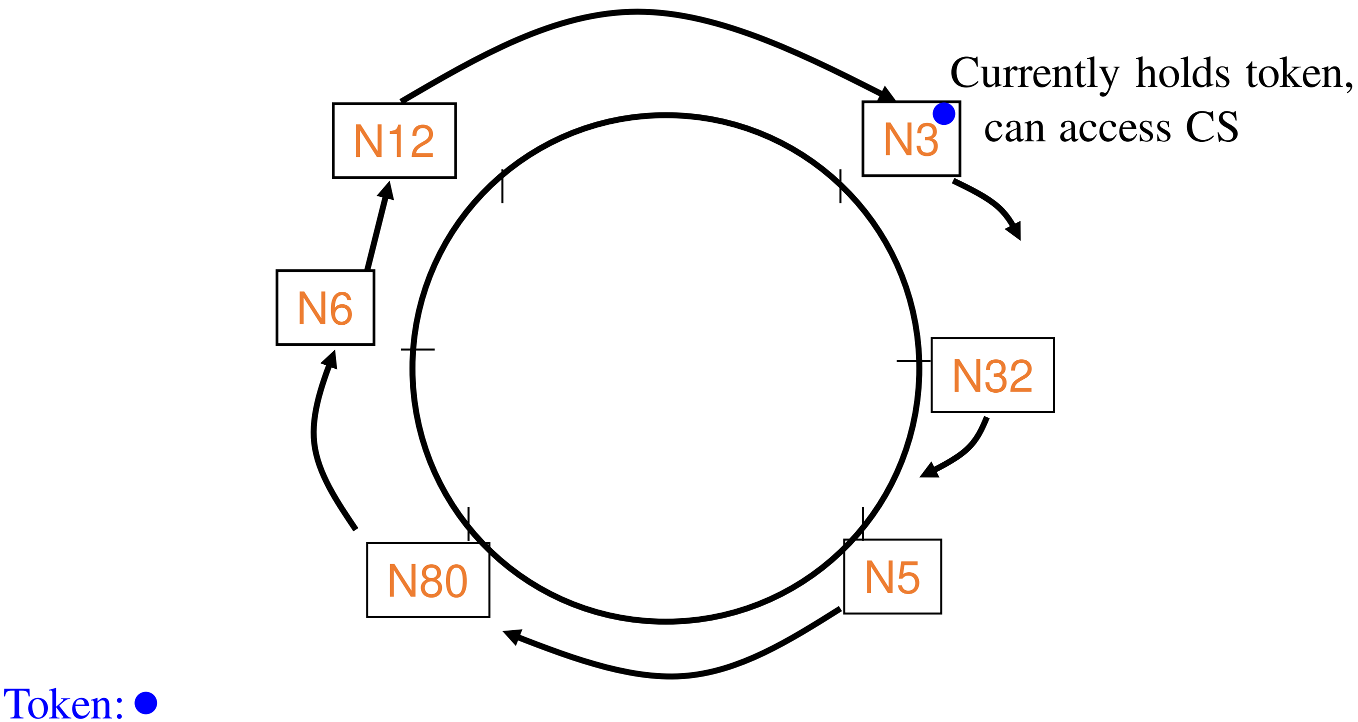
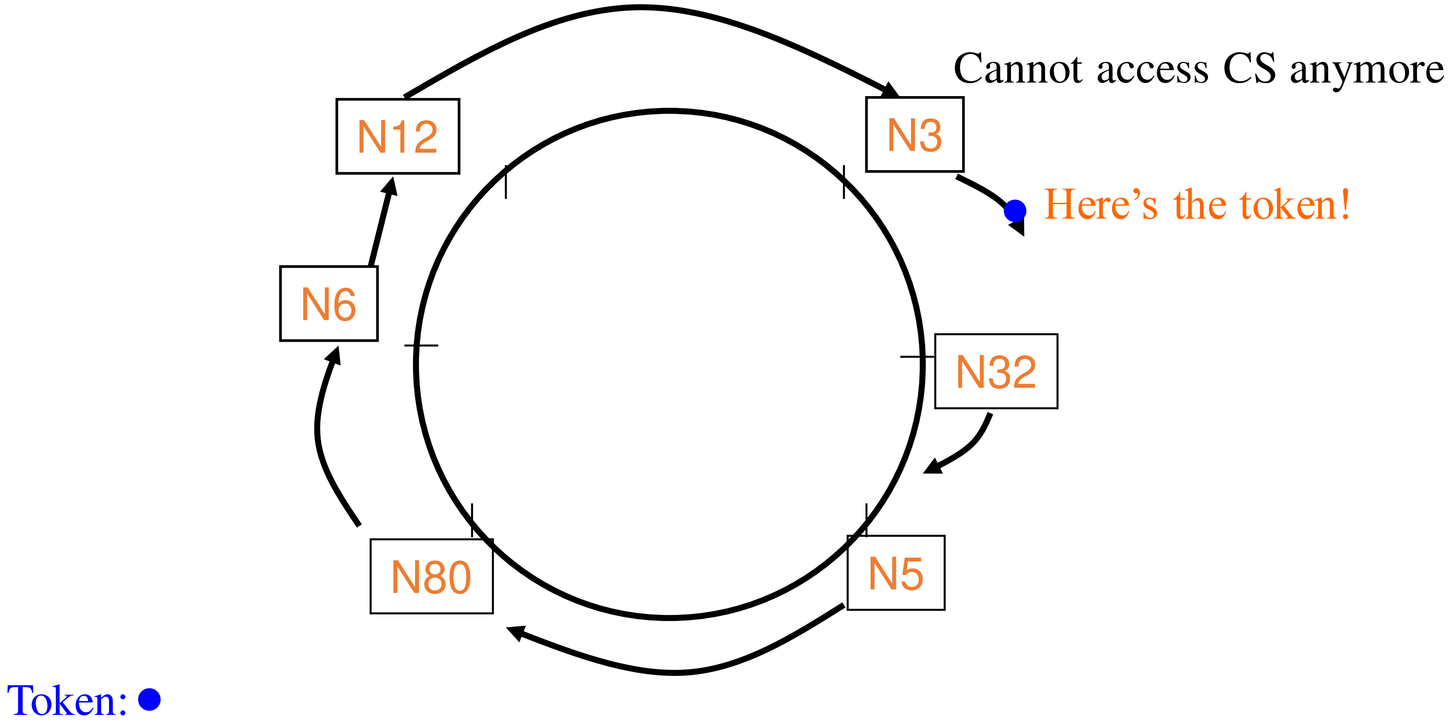
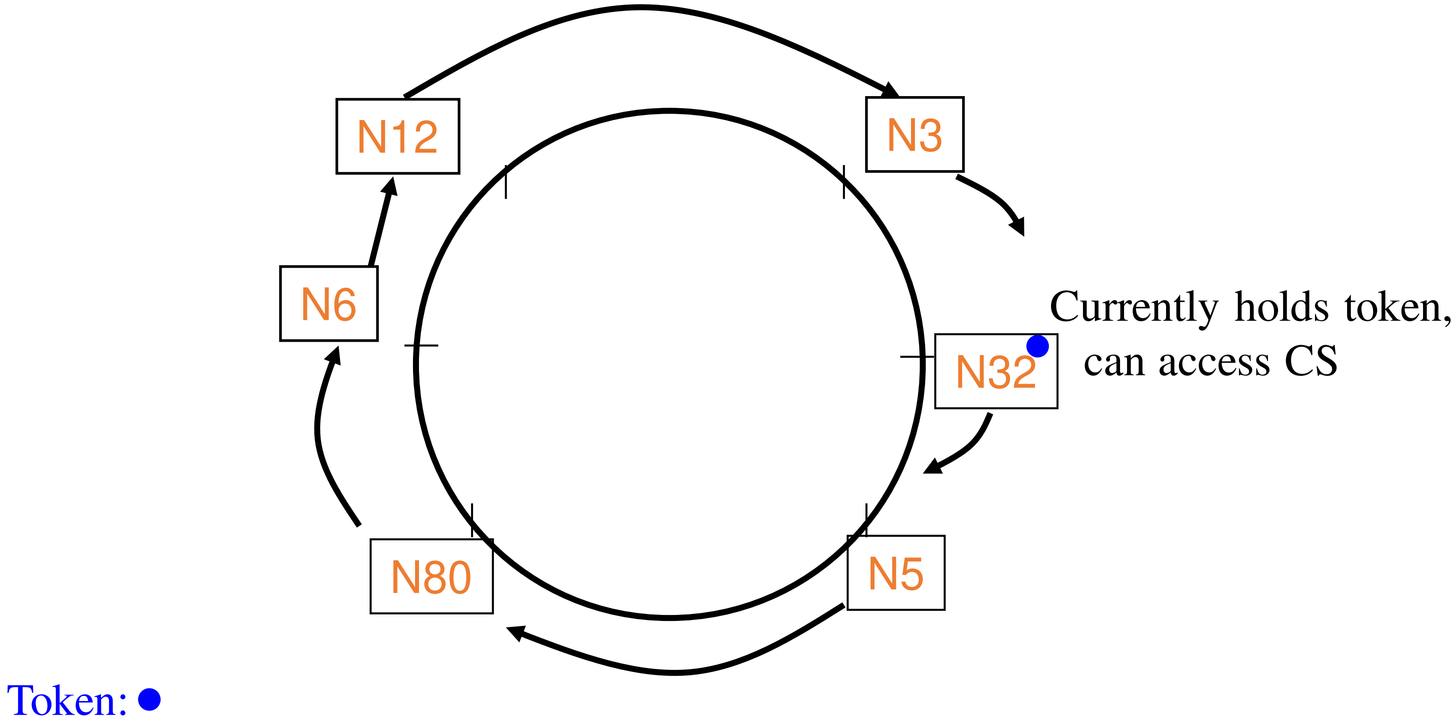
Ring-based Mutual Exclusion



Ring-based Mutual Exclusion



Ring-based Mutual Exclusion



Ring-based Mutual Exclusion

- *N* Processes organized in a virtual ring
- Processes send message to their successor in ring
- Exactly 1 token
- enter()
  - Wait until you get token
- exit() // already have token
  - Pass on token to ring successor
- If receive token, and not currently in enter(), just pass on token to ring successor

Analysis of Ring-based algorithm

- Safety
  - Exactly one token
- Liveness
  - Token eventually loops around ring and reaches requesting process (we assume no failures)
- Ordering
  - Token not always obtained in order of enter events.

Analysis of ring-based algorithm

- Bandwidth
  - Per enter, 1 message at requesting process but up to *N* messages throughout system.
  - 1 message sent per exit.
  - *Constantly consumes bandwidth even when no process requires entry to the critical section (except when a process is executing critical section).*

Analysis of ring-based algorithm

- Client delay:
  - Best case: just received token
  - Worst case: just sent token to neighbor
  - 0 to *N* message transmissions after entering enter()
- Synchronization delay between one process' exit() from the CS and the next process' enter():
  - Best case: process in enter() is successor of process in exit()
  - Worst case: process in enter() is predecessor of process in exit()
  - Between 1 and (*N-1*) message transmissions.

Can we improve upon O(n) client and synchronization delays?

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Ricart-Agrawala's Algorithm

- Classical algorithm from 1981
- Invented by Glenn Ricart (NIH) and Ashok Agrawala (U. Maryland)

- No token.
- Uses the notion of causality and multicast.
- Has lower waiting time to enter CS than Ring-Based approach.

Key Idea: Ricart-Agrawala Algorithm

- enter() at process P*i*
  - multicast a request to all processes
    - Request: <T, P*i*>, where T = current Lamport timestamp at P*i*
  - Wait until *all* other processes have responded positively to request
- Requests are granted in order of causality.
- <T, P*i*> is used lexicographically: P*i* in request <T, P*i*> is used to break ties (since Lamport timestamps are not unique for concurrent events).

Messages in RA Algorithm

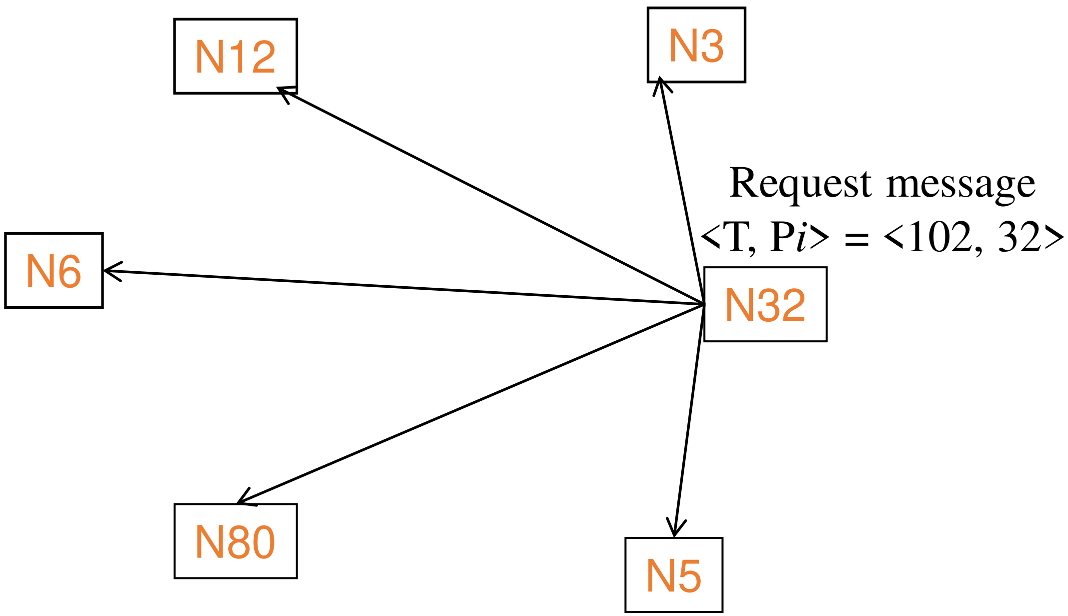
- enter() at process Pi
  - set state to Wanted
  - multicast "Request" <Ti, Pi> to all other processes, where Ti = current Lamport timestamp at Pi
  - wait until all other processes send back "Reply"
  - change state to Held and enter the CS
- On receipt of a Request <Tj, j> at Pi (i ≠ j):
  - if (state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

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

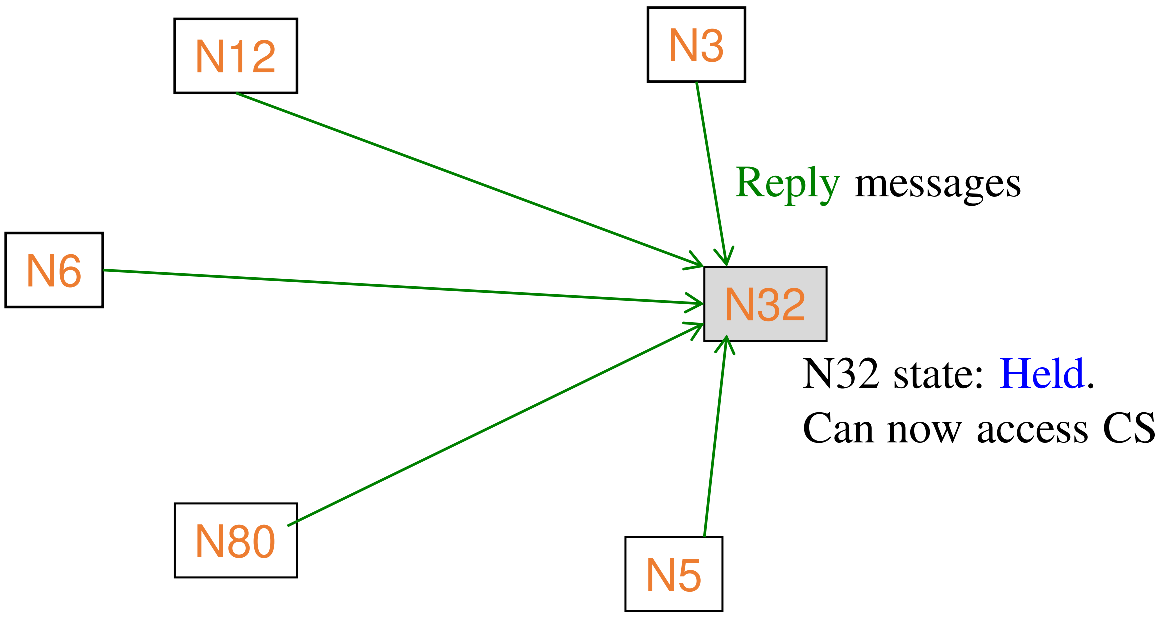
    add request to local queue (of waiting requests)

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

Example: Ricart-Agrawala Algorithm



Example: Ricart-Agrawala Algorithm



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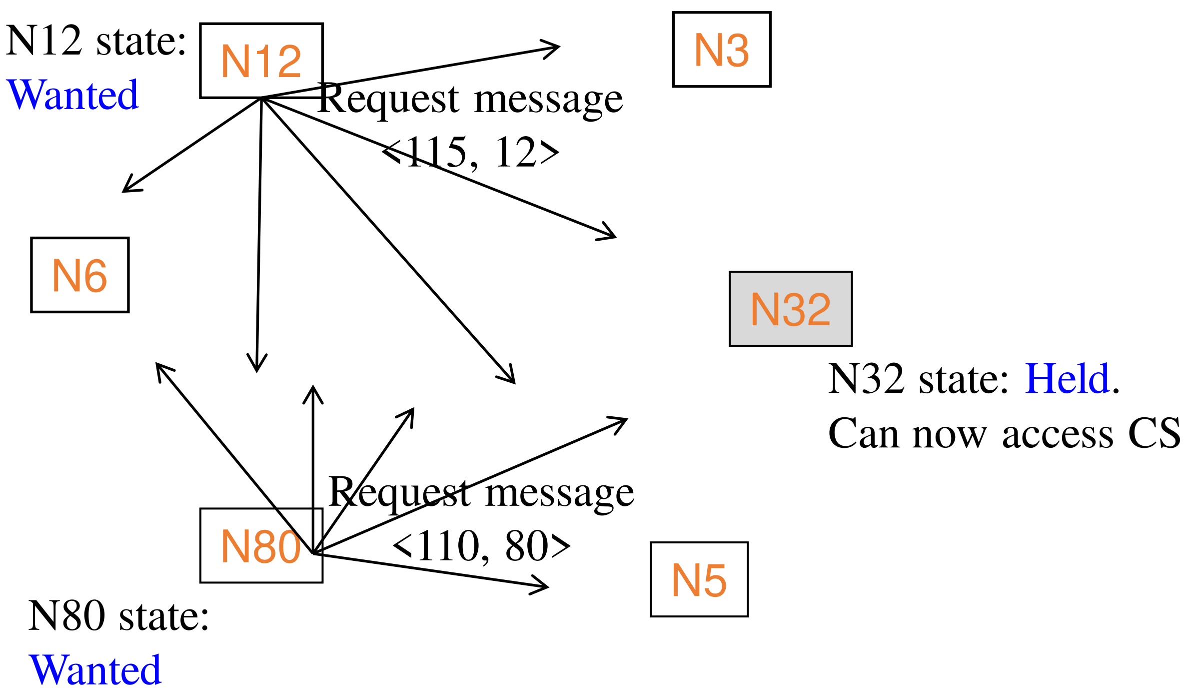

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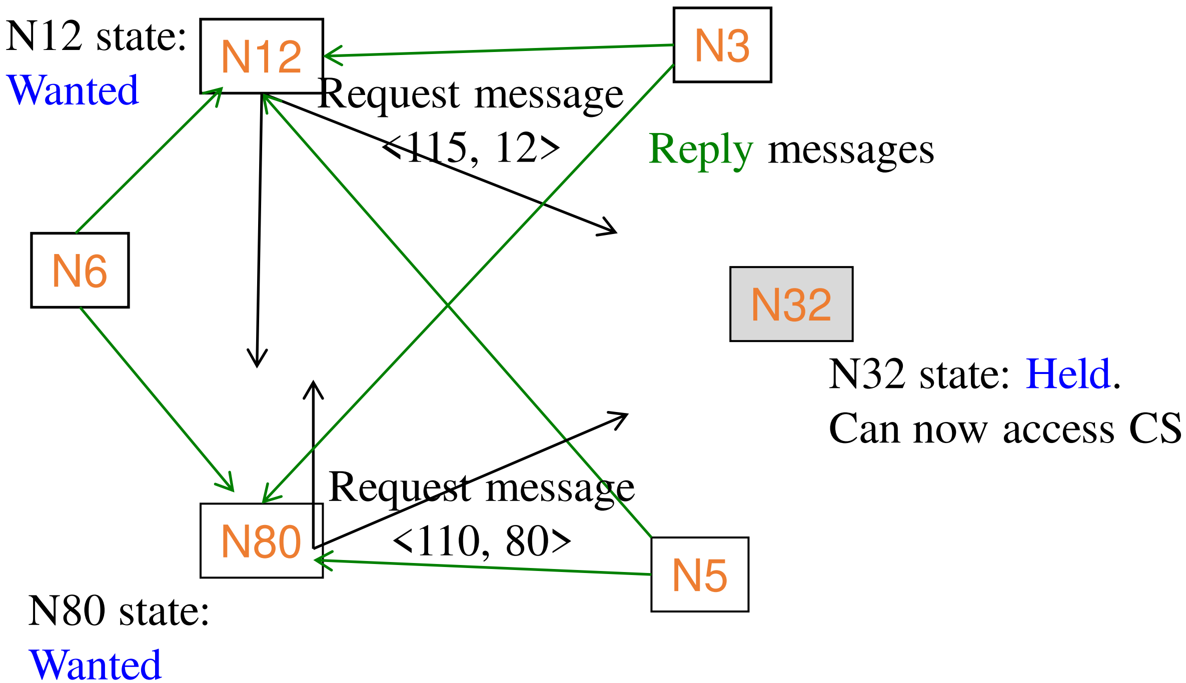

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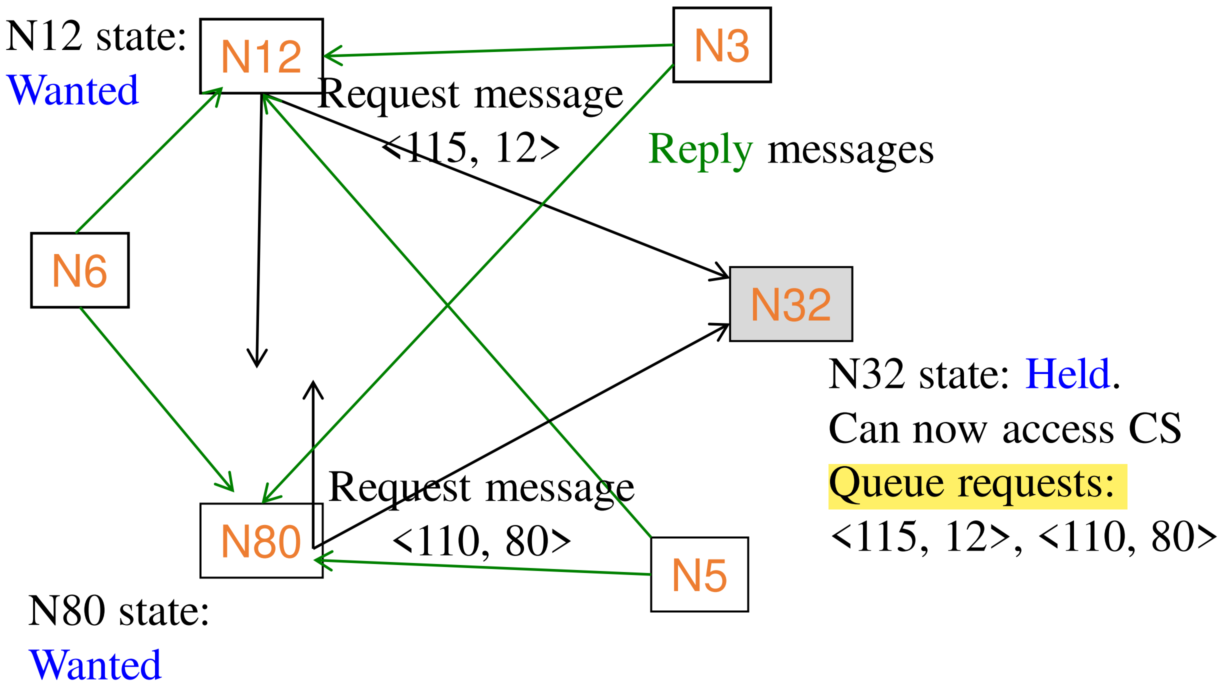
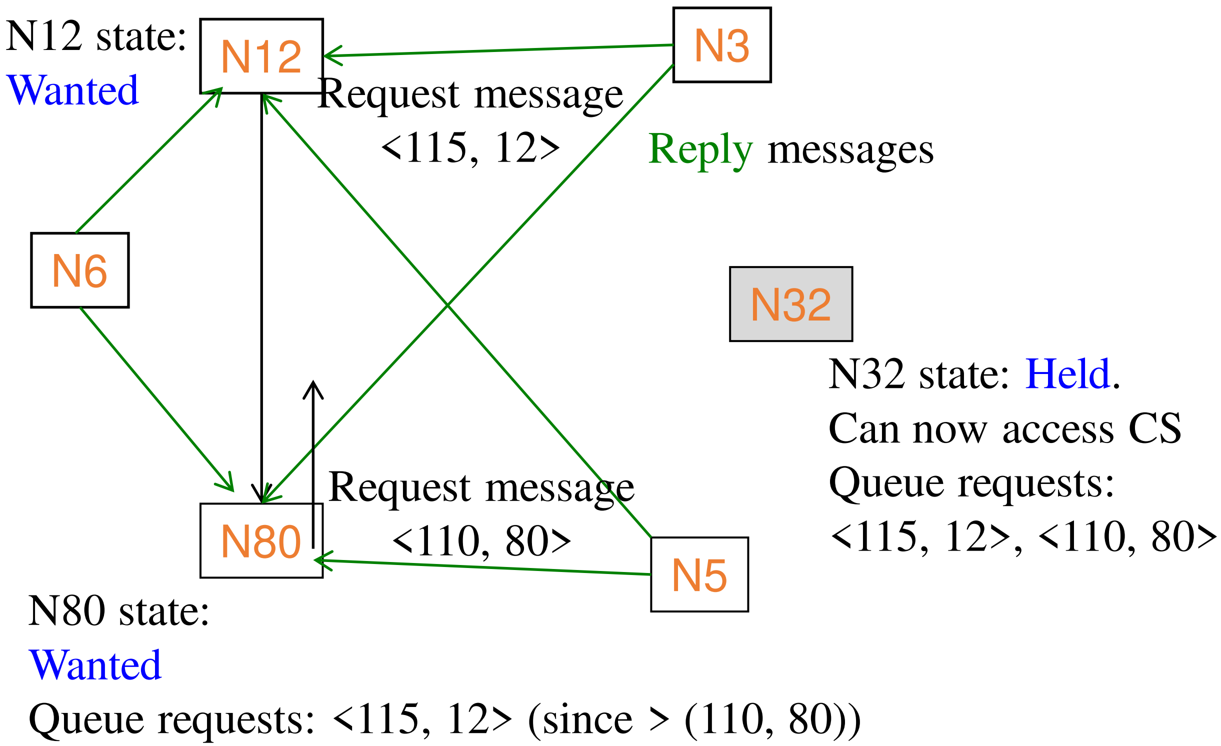
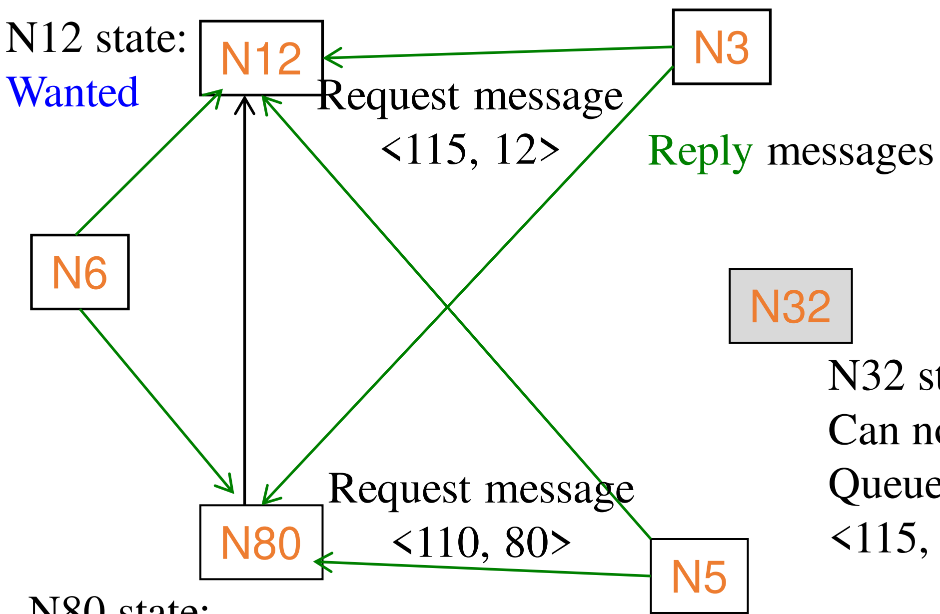


Example: Ricart-Agrawala Algorithm



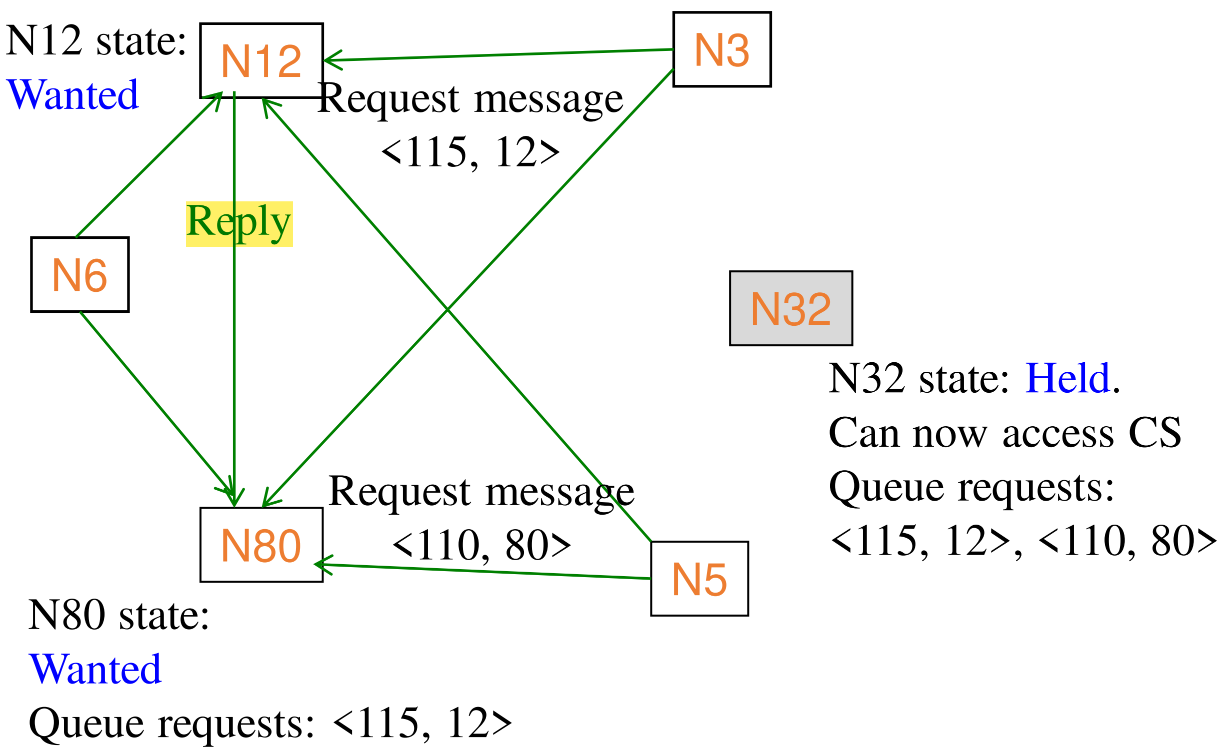
Example: Ricart-Agrawala Algorithm



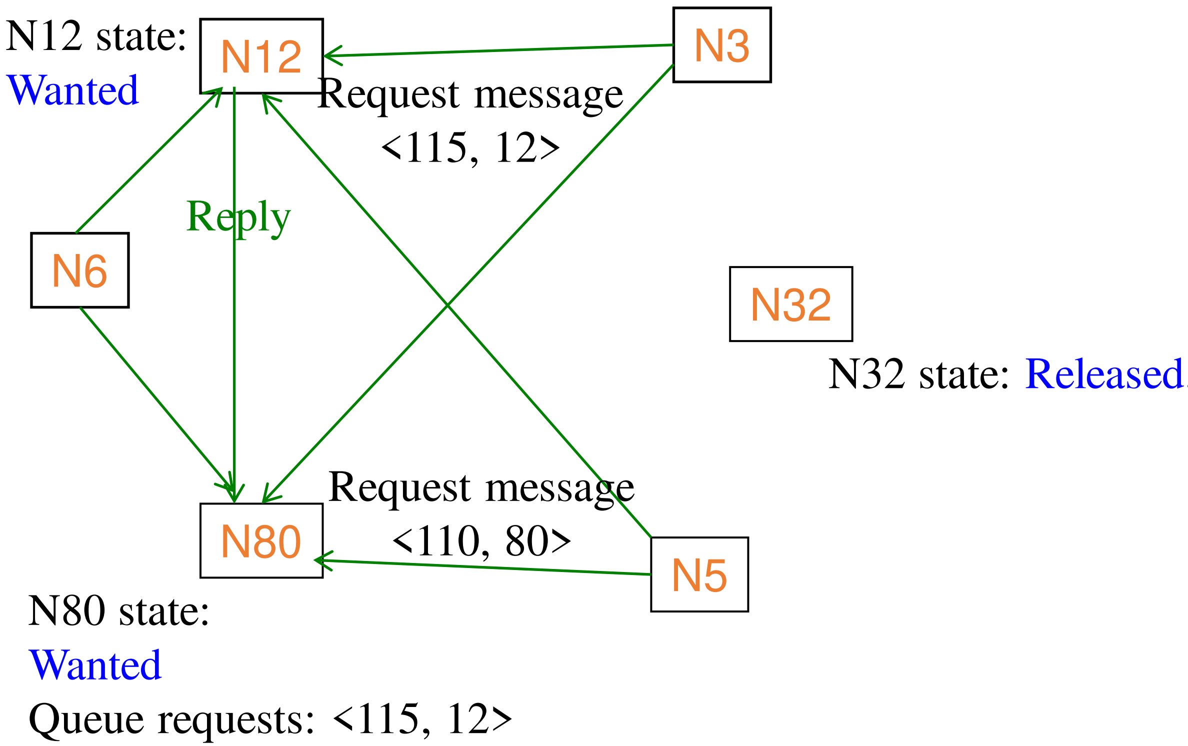
N32 state: Held.
Can now access CS
Queue requests:
<115, 12>, <110, 80>

N80 state:
Wanted
Queue requests: <115, 12> (since > (110, 80))

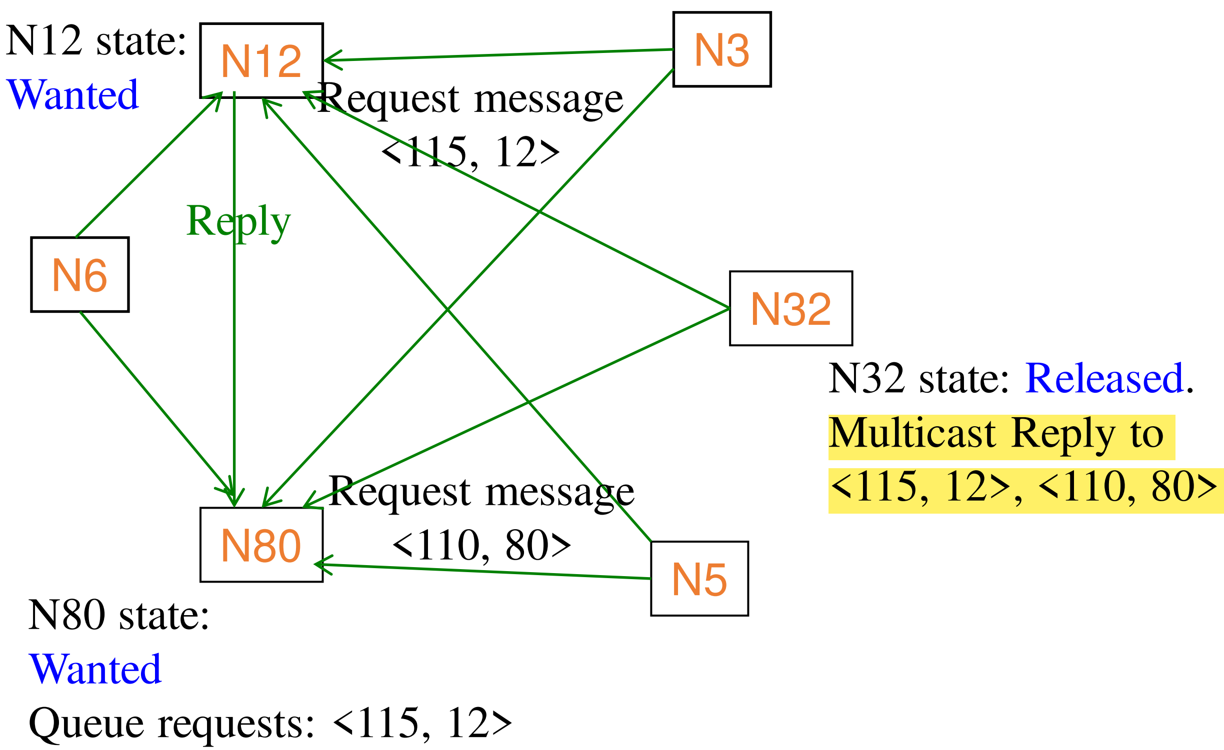
Example: Ricart-Agrawala Algorithm



Example: Ricart-Agrawala Algorithm

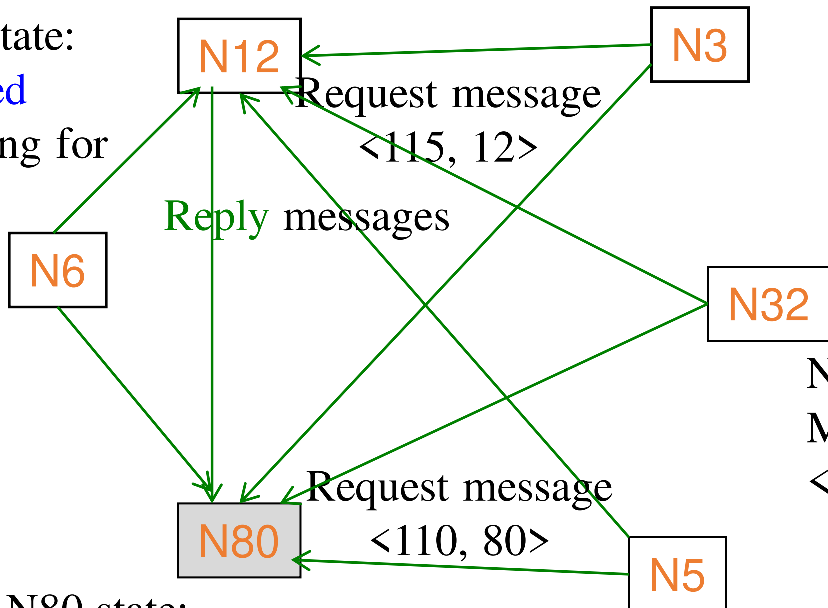


Example: Ricart-Agrawala Algorithm



Example: Ricart-Agrawala Algorithm

N12 state:
Wanted
(waiting for
N80's
reply)



N32 state: Released.
Multicast Reply to
<115, 12>, <110, 80>

N80 state:
Held. Can now access CS.
Queue requests: <115, 12>

Analysis: Ricart-Agrawala Algorithm

- Safety
  - Two processes P*i* and P*j* cannot both have access to CS
    - If they did, then both would have sent Reply to each other.
    - Thus, (T*i*, *i*) < (T*j*, *j*) and (T*j*, *j*) < (T*i*, *i*), which are together not possible.
    - What if (T*i*, *i*) < (T*j*, *j*) and P*i* replied to P*j*'s request before it created its own request?
      - But then, causality and Lamport timestamps at P*i* implies that T*i* > T*j* , which is a contradiction.
      - So this situation cannot arise.

Analysis: Ricart-Agrawala 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 Algorithm

- Bandwidth:
  - 2*(*N-1*) messages per enter operation
    - *N-1* unicasts for the multicast request + *N-1* replies
    - Maybe fewer depending on the multicast mechanism.
  - *N-1* unicasts for the multicast release per exit operation
    - Maybe fewer depending on the multicast mechanism.
- 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

- Our focus today: 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.*

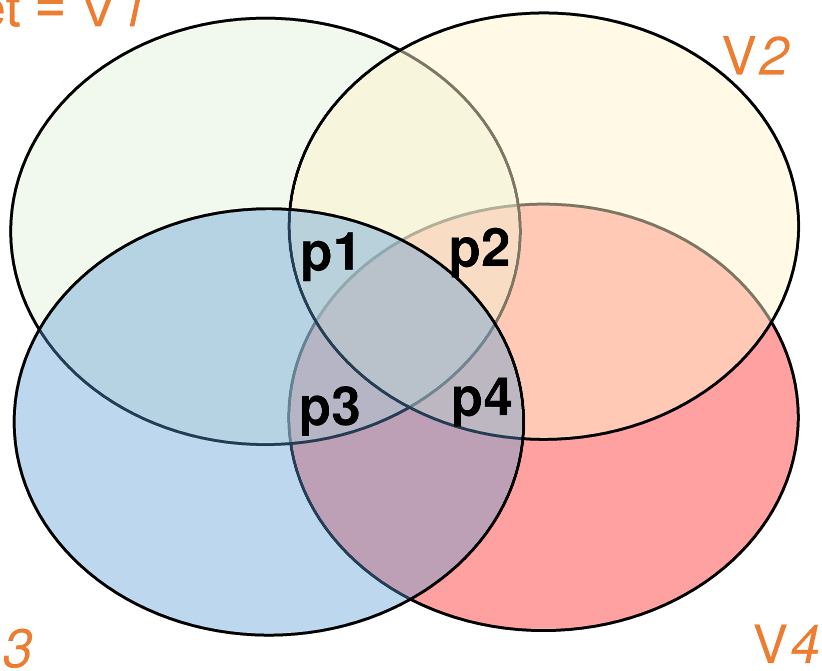
A way to construct voting sets

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

Size of voting set = $2*\sqrt{N}-1$.

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 == <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

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
  - $K*N = M*N \Rightarrow K = M$ (1)
- Consider a process Pi
  - Total number of voting sets = members present in Pi'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))
    - $K \sim \sqrt{N}$

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 ~ 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.

Next Class

- How can we extend Maekawa's algorithm to break deadlock?