Distributed Systems

CS425/ECE428

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Acknowledgements for some of the materials: Indy Gupta and Nikita Borisov

Logistics

- HW1 is due on Monday. HW2 will be released on Monday.

- Please see CampusWire post #126 on Midterm 1:
  - Feb 27-29. Make reservations on PrairieTest (starting Feb 15th).
  - Syllabus includes everything upto and including Multicast.
  - We will release some practice questions over PrairieLearn by next week.
  - CBTF does not allow cheatsheets – we will provide an abridged version of slides on PrairieLearn.
  - CBTF will provide scratch papers and calculator.
  - Please checkout CBTF rules – new rule on bathroom usage!

Today's agenda

- **Mutual Exclusion**
  - Chapter 15.2
- **Leader Election** (if time)
  - Chapter 15.3

Recap: 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

Recap: 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?*

Recap: 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: System Model

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

Mutual exclusion in distributed systems

- Our focus today: Classical algorithms for mutual exclusion in distributed systems.
  - Central server algorithm
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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

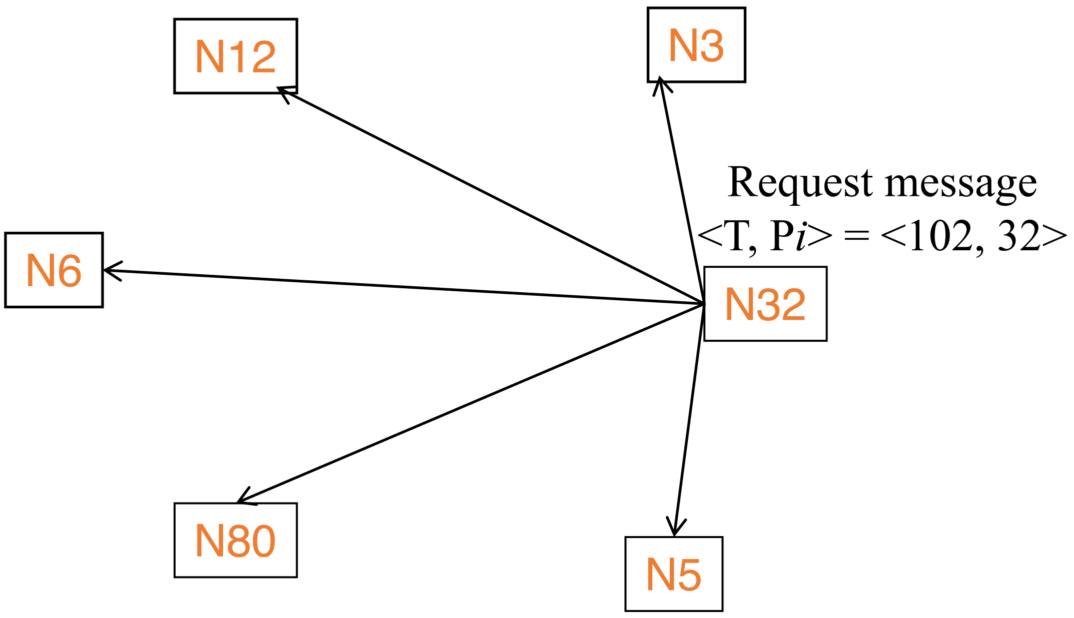
- enter() at process Pi
  - set state to Wanted
  - multicast "Request" <Ti, Pi> to all other processes, where Ti = current Lamport timestamp at Pi
  - wait until all other processes send back "Reply"
  - change state to Held and enter the CS
- On receipt of a Request <Tj, j> at Pi (i ≠ j):
  - if (state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

Example: Ricart-Agrawala Algorithm



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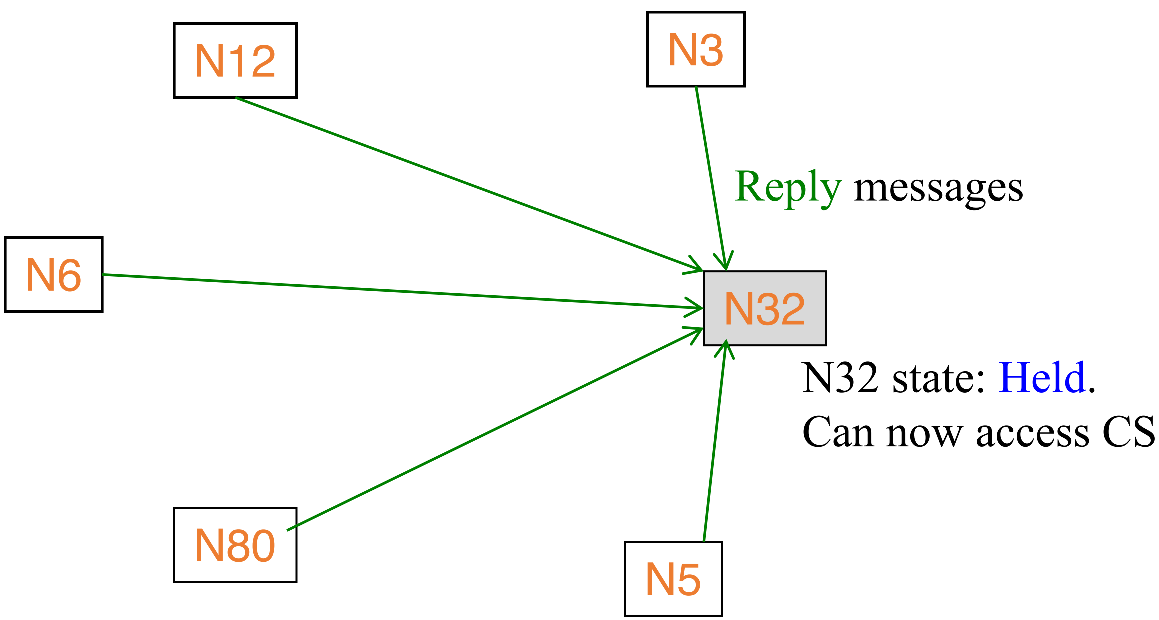

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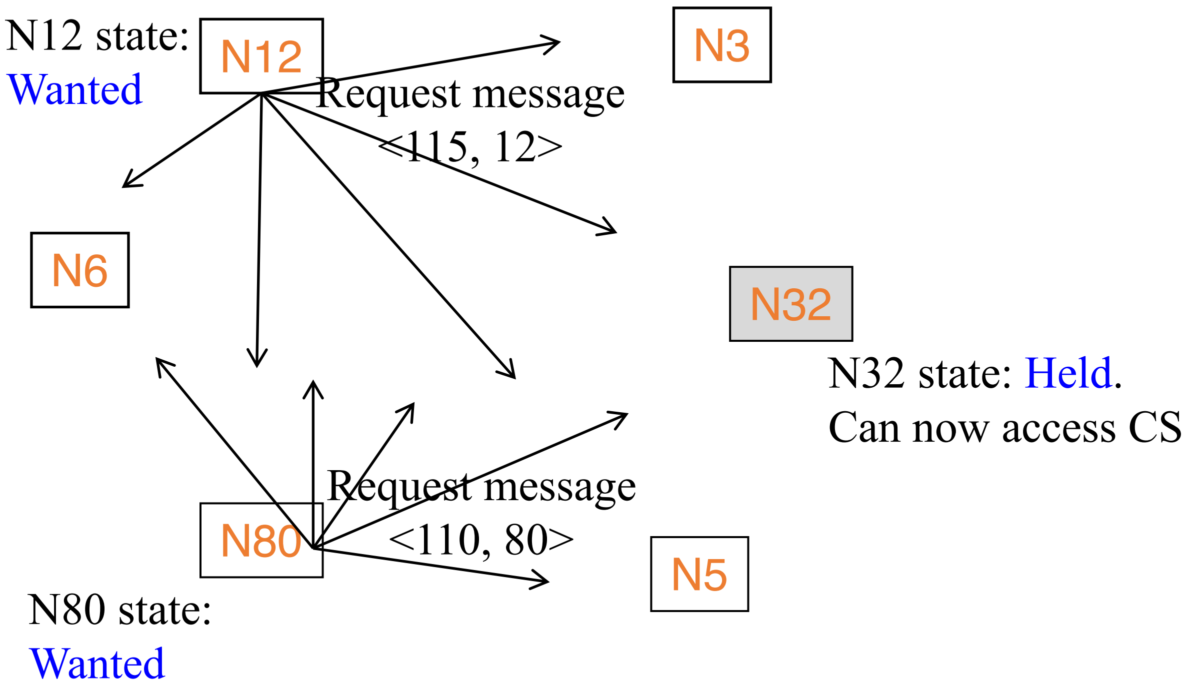

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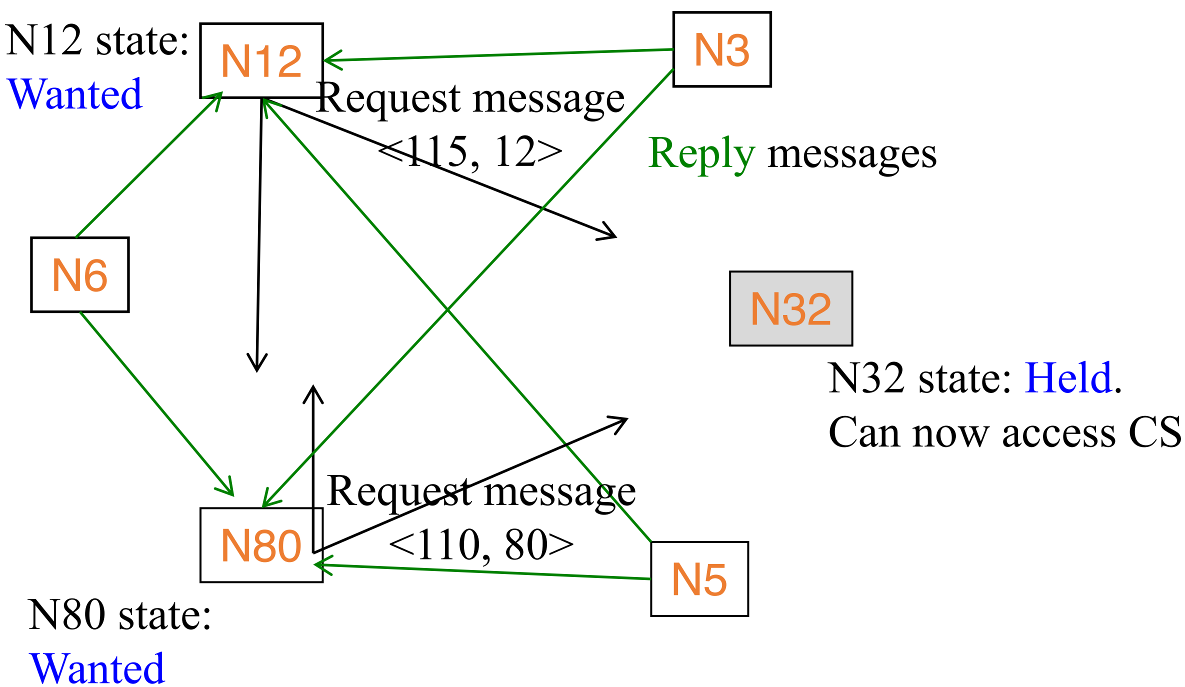

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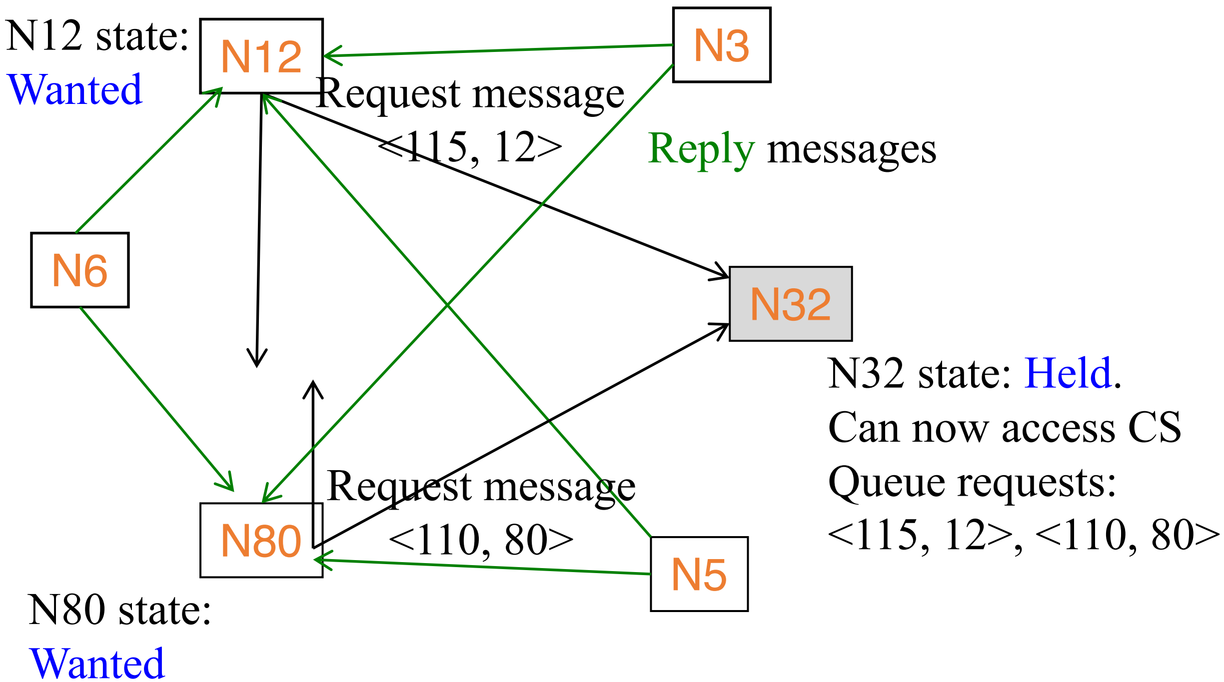

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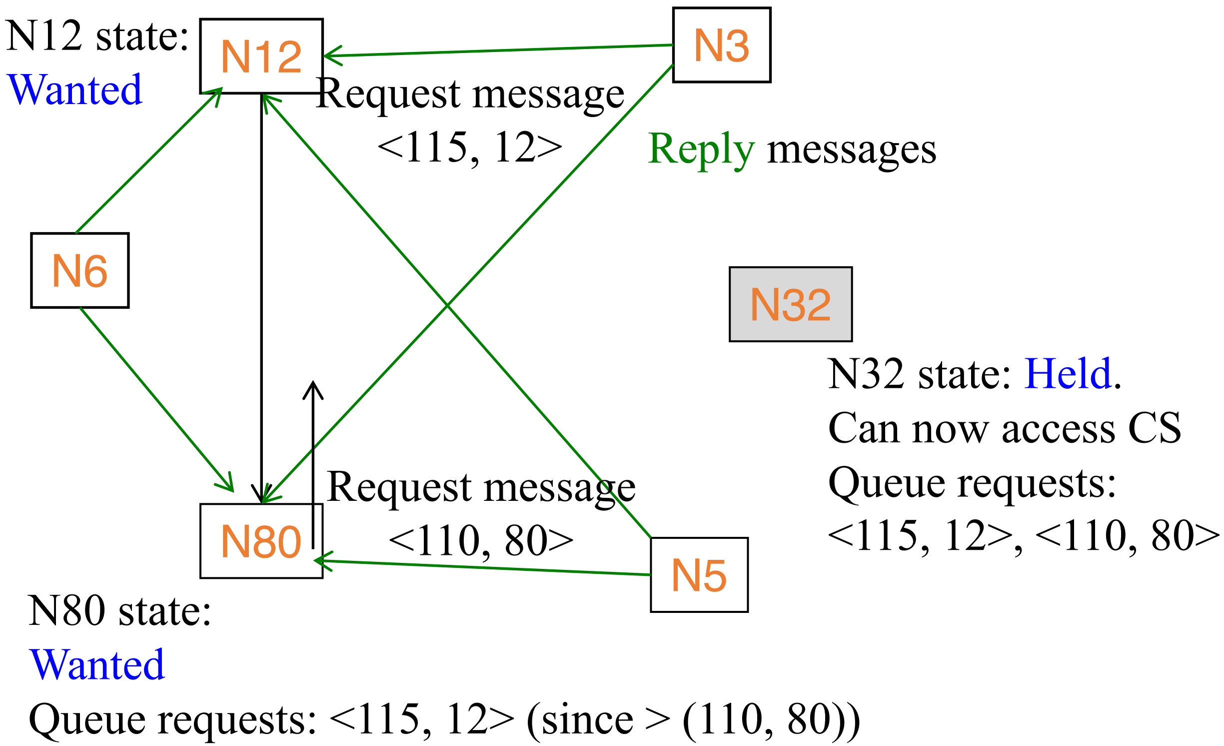

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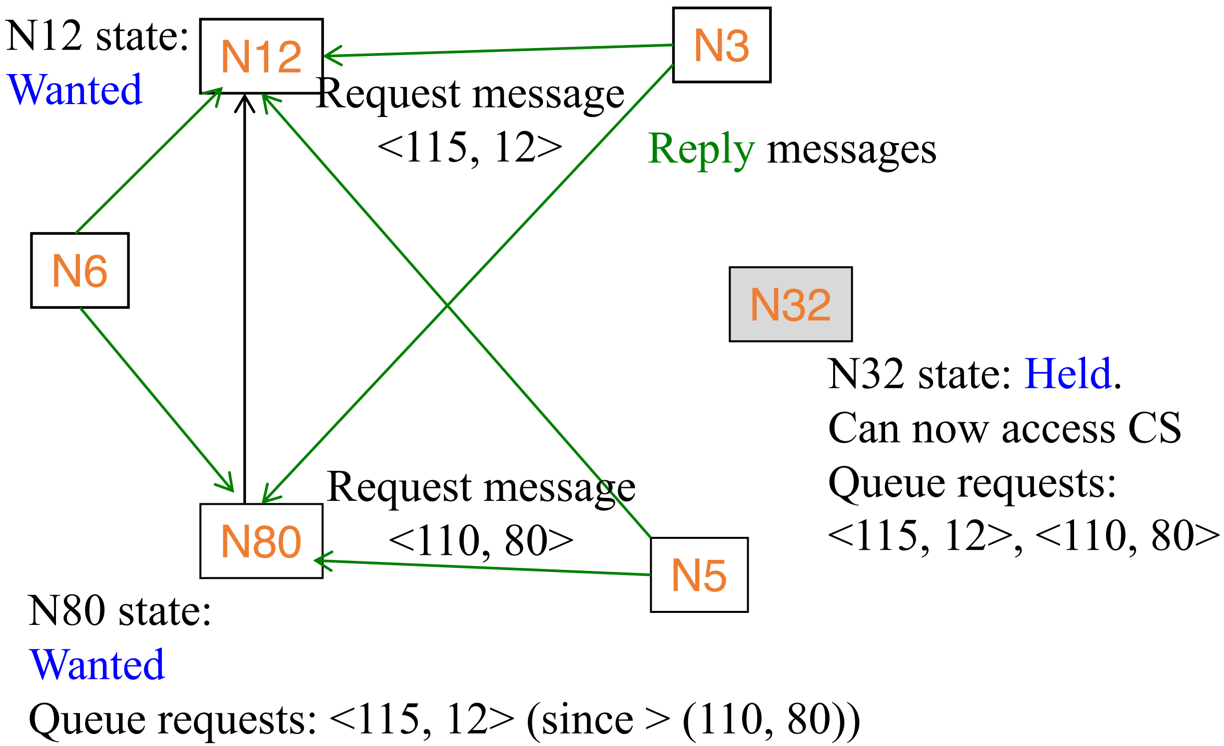

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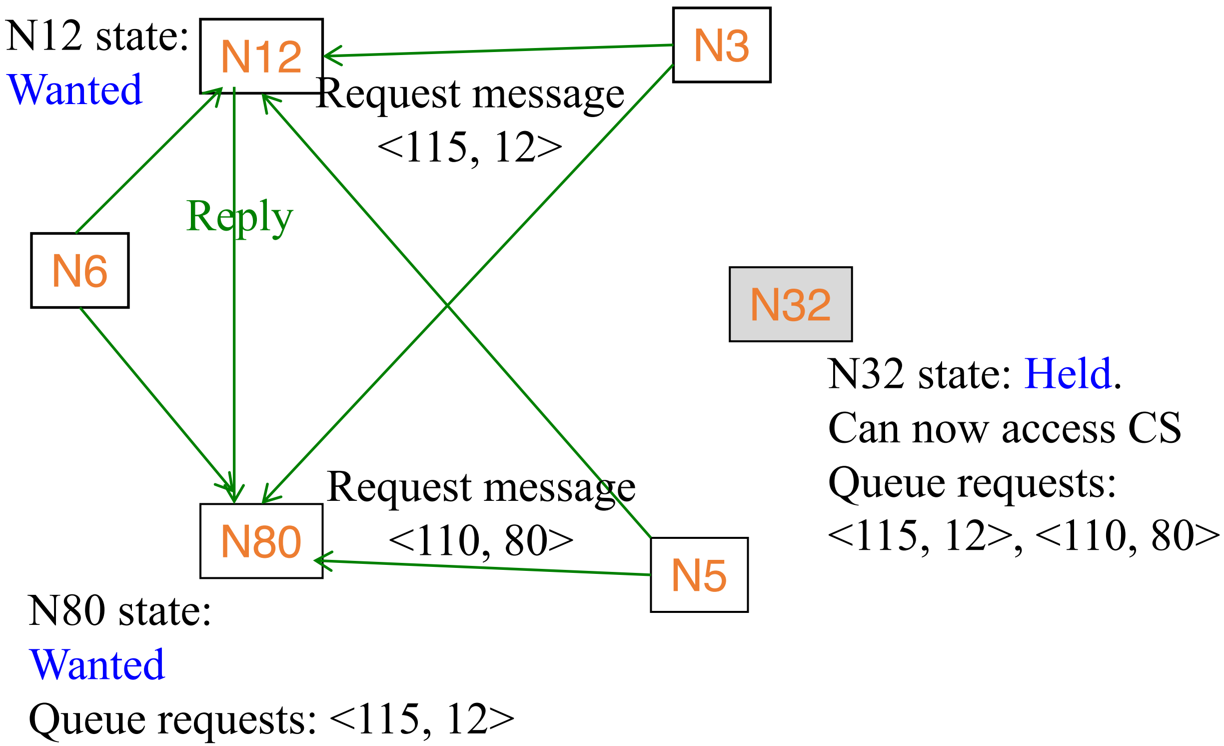

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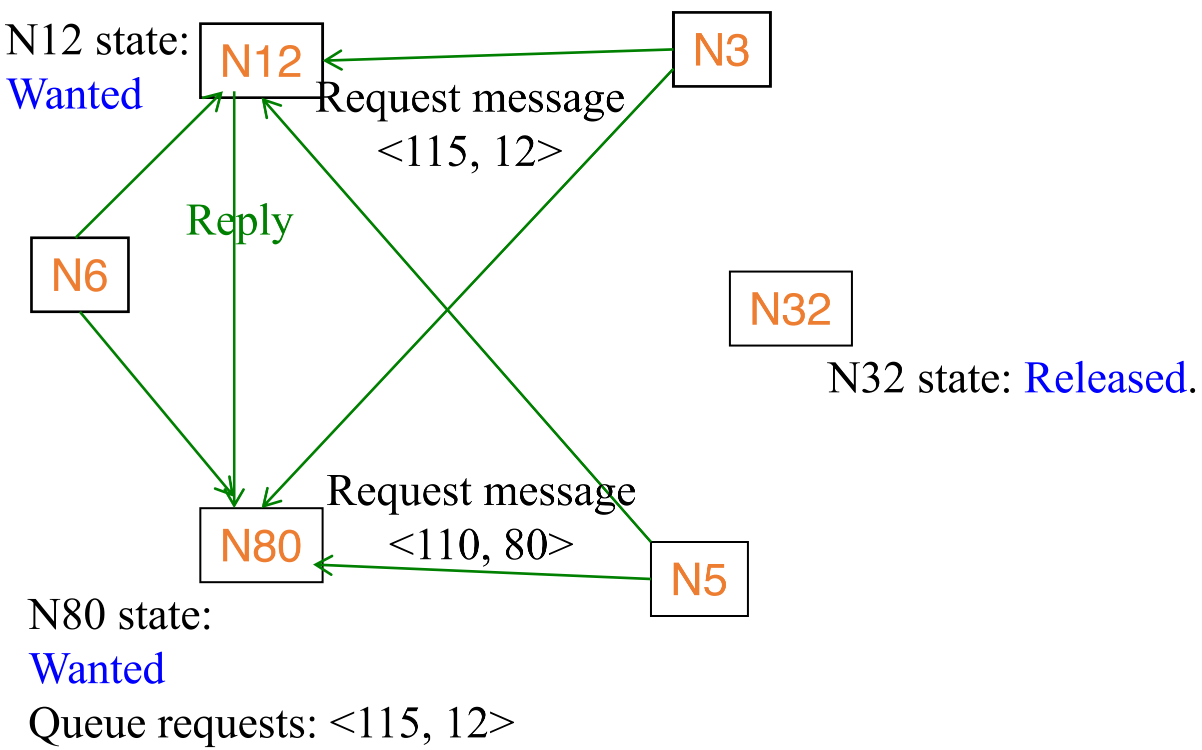

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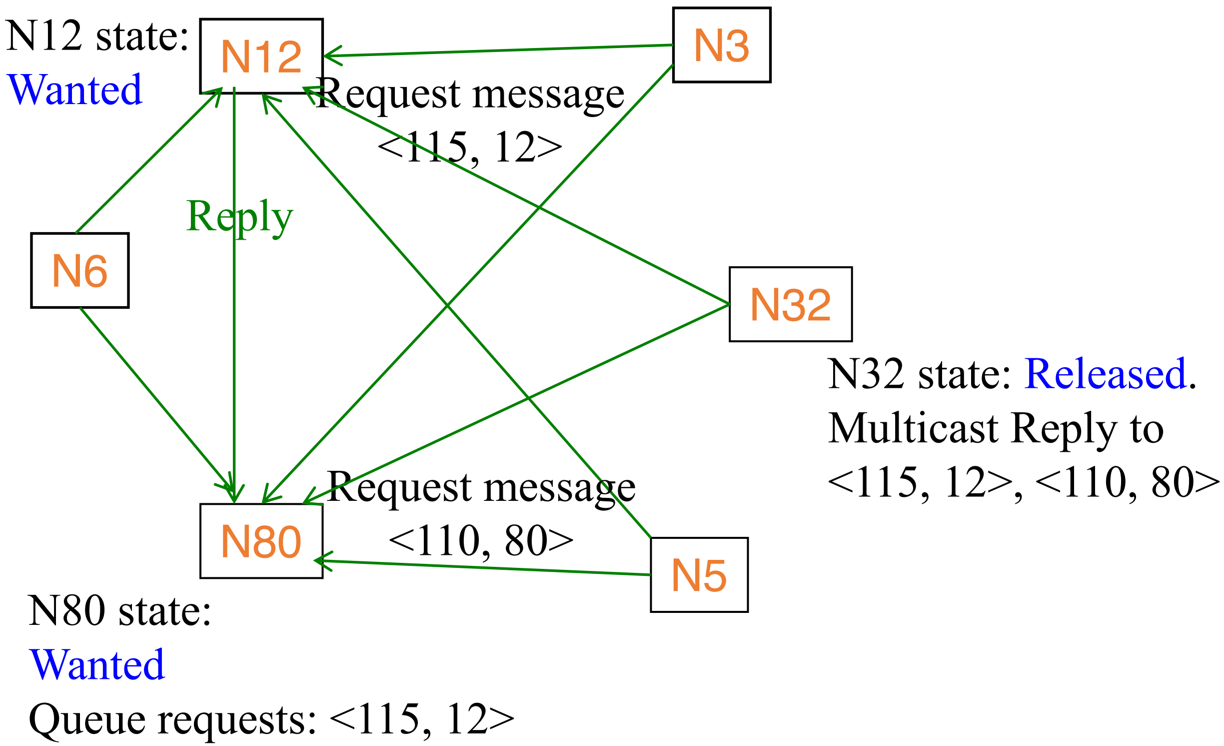

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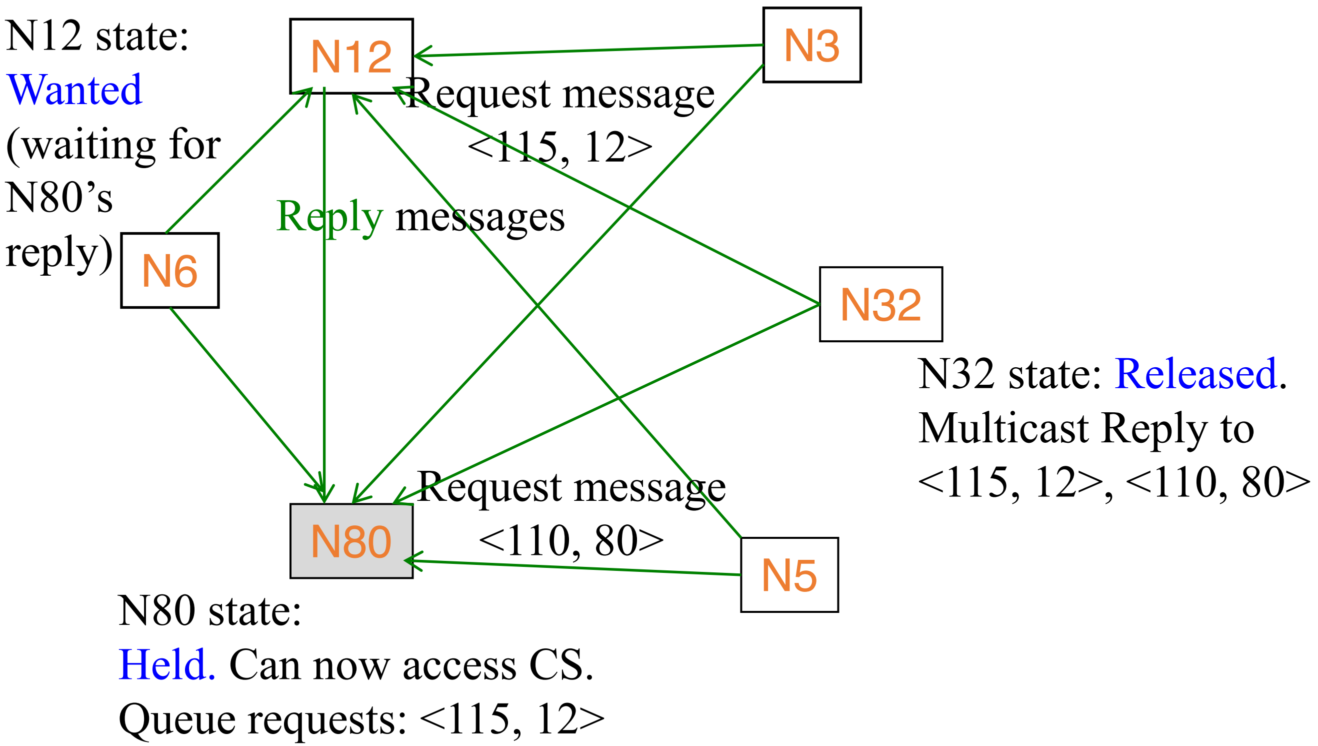

Analysis: Ricart-Agrawala's Algorithm

- 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'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

- Safety
  - Two processes P*i* and P*j* cannot both have access to CS.
- Liveness
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- Ordering
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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
    - 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.*

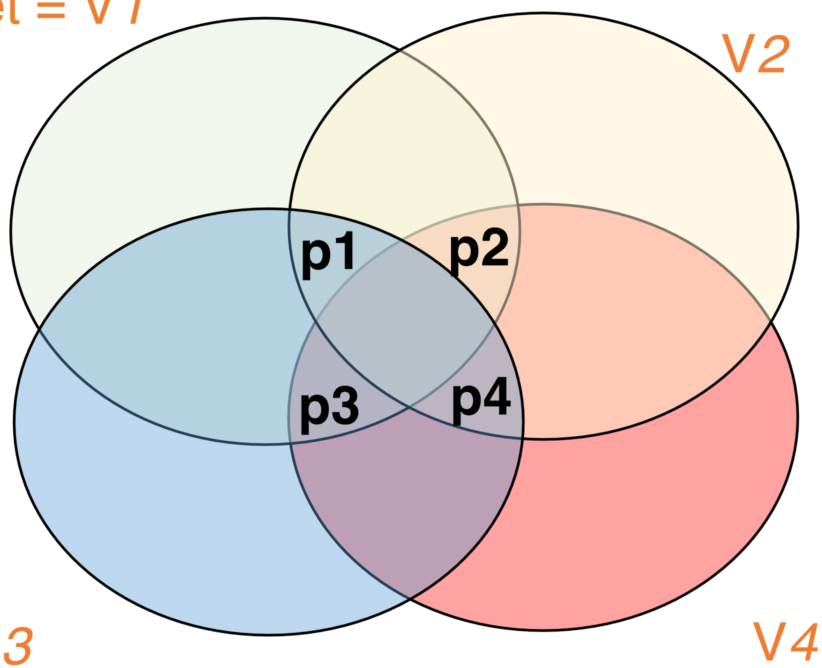
A way to construct voting sets

One way of doing this is to put N processes in a √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
  - $K*N = M*N \Rightarrow K = M$ (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))
    - $K \sim \sqrt{N}$

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. $N \sim 1$ 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.