CS 425 / ECE 428
Distributed Systems
Fall 2023

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Lecture 18: Mutual Exclusion

Why Mutual Exclusion?

- Bank's Servers in the Cloud: Two of your customers make simultaneous deposits of $10,000 into your bank account, each from a separate ATM.
  - Both ATMs read initial amount of $1000 concurrently from the bank's cloud server
  - Both ATMs add $10,000 to this amount (locally at the ATM)
  - Both write the final amount to the server
  - What's wrong?

Why Mutual Exclusion?

- Bank's Servers in the Cloud: Two of your customers make simultaneous deposits of $10,000 into your bank account, each from a separate ATM.
    - Both ATMs read initial amount of $1000 concurrently from the bank's cloud server
    - Both ATMs add $10,000 to this amount (locally at the ATM)
    - Both write the final amount to the server
    - You lost $10,000!
- The ATMs need *mutually exclusive* access to your account entry at the server
    - or, mutually exclusive access to executing the code that modifies the account entry

More Uses of Mutual Exclusion

- Distributed File systems
  - Locking of files and directories
- Accessing objects in a safe and consistent way
  - Ensure at most one server has access to object at any point of time
- Server coordination
  - Work partitioned across servers
  - Servers coordinate using locks
- In industry
  - Chubby is Google's locking service
  - Many cloud stacks use Apache Zookeeper for coordination among servers

Problem Statement for Mutual Exclusion

- ***Critical Section*** Problem: Piece of code (at all processes) for which we need to ensure there is at most one process 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

Our Bank Example

```
ATM1:
    enter(S);
    // AccessResource()
    obtain bank amount;
    add in deposit;
    update bank amount;
    // AccessResource() end
    exit(S); // exit
```

```
ATM2:
    enter(S);
    // AccessResource()
    obtain bank amount;
    add in deposit;
    update bank amount;
    // AccessResource() end
    exit(S); // exit
```

Approaches to Solve Mutual Exclusion

- Single OS:
  - If all processes are running in one OS on a machine (or VM), then
  - Semaphores, mutexes, condition variables, monitors, etc.

Approaches to Solve Mutual Exclusion (2)

- Distributed system:
  - Processes communicating by passing messages

Need to guarantee 3 properties:

- Safety (essential) – At most one process executes in CS (Critical Section) at any time
- Liveness (essential) – Every request for a CS is granted eventually
- Ordering (desirable) – Requests are granted in the order they were made

Processes Sharing an OS: Semaphores

- Semaphore == an integer that can only be accessed via two special functions
- Semaphore S=1; // Max number of allowed accessors

1. **wait(S)** (or **P(S)** or **down(S)**):

enter()

```
while(1) { // each execution of the while loop is atomic
        if (S > 0) {
          S--;
          break;
        }
  }
```

Each while loop execution and S++ are each atomic operations – supported via hardware instructions such as compare-and-swap, test-and-set, etc.

exit()

2. **signal(S)** (or **V(S)** or **up(s)**):

```
S++; // atomic
```

Our Bank Example Using Semaphores

```
Semaphore S=1; // shared
ATM1:
    wait(S);
    // AccessResource()
    obtain bank amount;
    add in deposit;
    update bank amount;
    // AccessResource() end
    signal(S); // exit
```

```
Semaphore S=1; // shared
ATM2:
    wait(S);
    // AccessResource()
    obtain bank amount;
    add in deposit;
    update bank amount;
    // AccessResource() end
    signal(S); // exit
```

Next

- In a distributed system, cannot share variables like semaphores
- So how do we support mutual exclusion in a distributed system?

System Model

- Before solving any problem, specify its System Model:
  - Each pair of processes is connected by reliable channels (such as TCP).
  - Messages are eventually delivered to recipient, and in FIFO (First In First Out) order.
  - Processes do not fail.
    - Fault-tolerant variants exist in literature.

Central Solution

- Elect a central master (or leader)
  - Use one of our election algorithms!
- Leader keeps
  - A **queue** of waiting requests from processes who wish to access the CS
  - A special **token** which allows its holder to access CS
- Actions of any process in group:
  - enter()
    - Send a request to leader
    - Wait for token from leader
  - exit()
    - Send back token to leader

Central Solution

- Leader Actions:
  - On receiving a request from process P*i*

    if (leader has token)

    Send token to P*i*

    else

    Add P*i* to queue
  - On receiving a token from process P*i*

    if (queue is not empty)

    Dequeue head of queue (say P*j*), send that process the token

    else

    Retain token

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
- FIFO Ordering is guaranteed, in order of requests received at leader

Analyzing Performance

Efficient mutual exclusion algorithms use fewer messages, and make processes wait for shorter durations to access resources. Three metrics:

- ***Bandwidth***: the total number of messages sent in each *enter* and *exit* operation.
- ***Client delay***: the delay incurred by a process at each enter and exit operation (when *no* other process is in, or waiting)

  (We will prefer mostly 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)

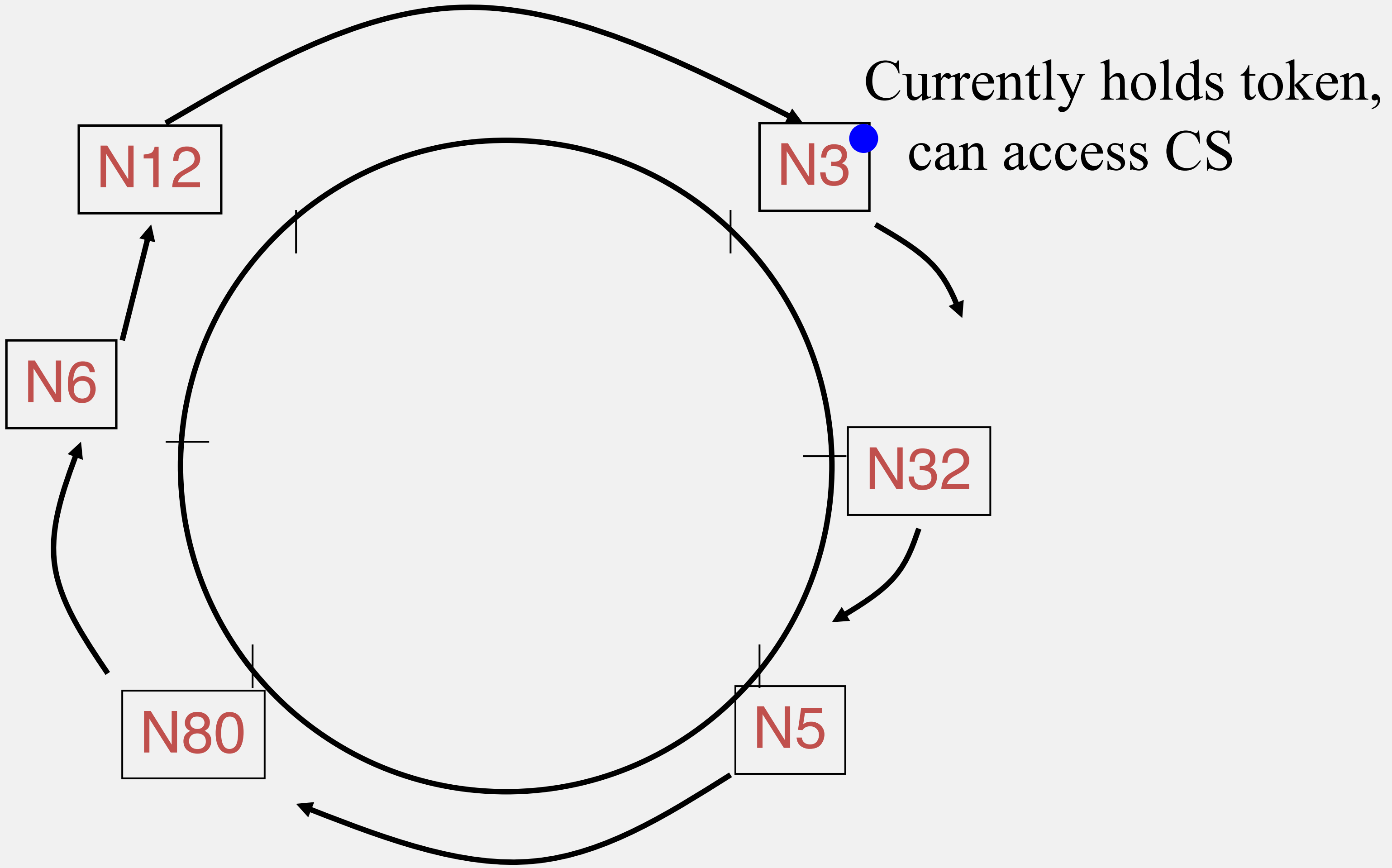
Analysis of Central Algorithm

- ***Bandwidth***: the total number of messages sent in each *enter* and *exit* operation.
    - 2 messages for enter
    - 1 message for exit
- ***Client delay***: the delay incurred by a process at each enter and exit operation (when *no* other process is in, or waiting)
    - 2 message latencies (request + grant)
- ***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)

But…

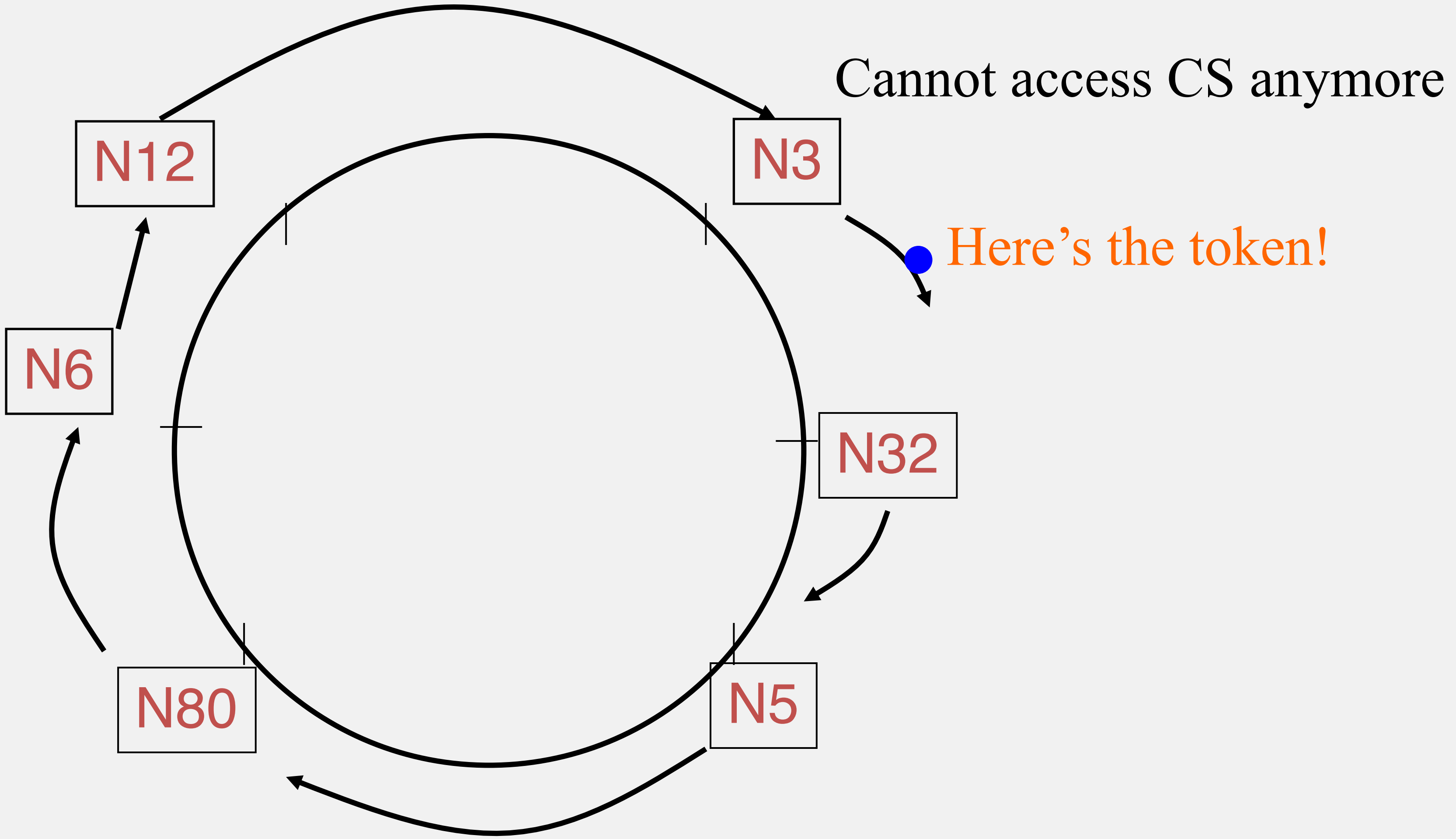
- The leader is the performance bottleneck and SPoF (single point of failure)

Ring-based Mutual Exclusion



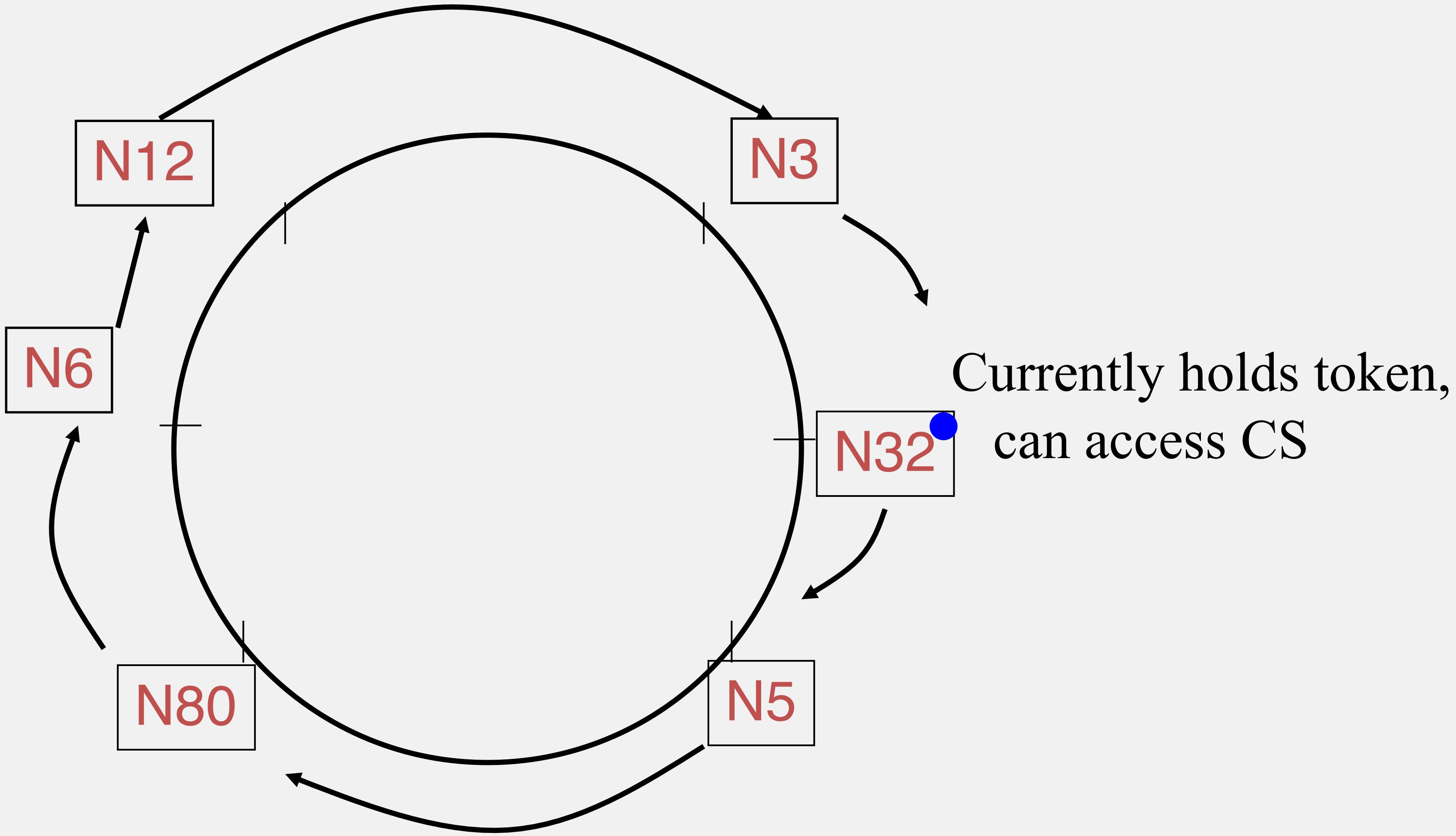
Token: ●

Ring-based Mutual Exclusion



Token: ●

Ring-based Mutual Exclusion



Token: ●

Ring-based Mutual Exclusion

- *N* Processes organized in a virtual ring
- Each process can send message to its 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 Mutual Exclusion

- Safety
  - Exactly one token
- Liveness
  - Token eventually loops around ring and reaches requesting process (no failures)
- Bandwidth
  - Per enter(), 1 message by requesting process but up to *N* messages throughout system
  - 1 message sent per exit()

Analysis of Ring-Based Mutual Exclusion (2)

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

Next

- Client/Synchronization delay to access CS still O(N) in Ring-Based approach.
- Can we make this faster?

System Model

- Before solving any problem, specify its System Model:
  - Each pair of processes is connected by reliable channels (such as TCP).
  - Messages are eventually delivered to recipient, and in FIFO (First In First Out) order.
  - Processes do not fail.

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

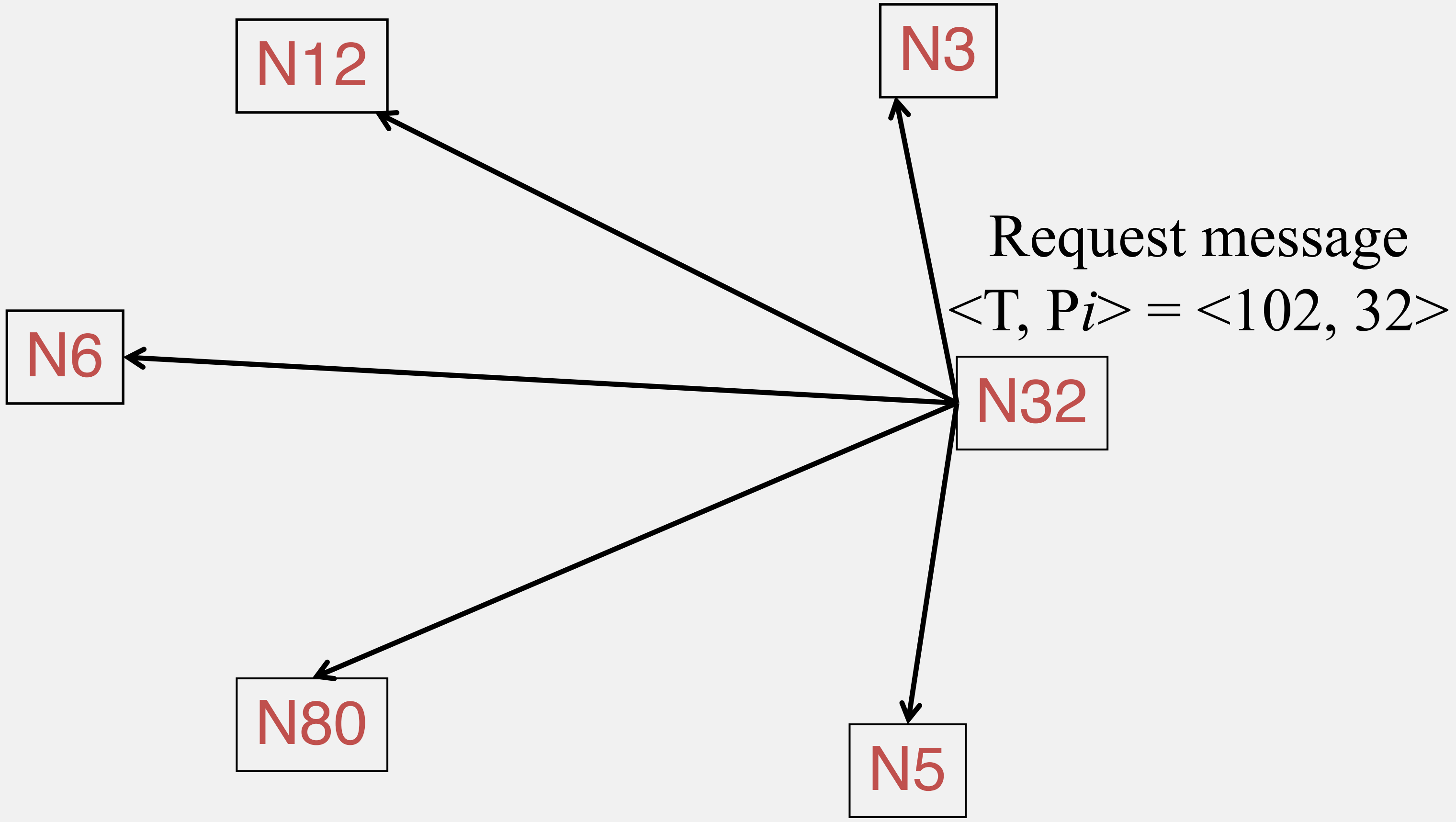
- enter() at process Pi
  - set state to Wanted
  - multicast "Request" <Ti, Pi> to all processes, where Ti = current Lamport timestamp at Pi
  - wait until ***all*** processes send back "Reply"
  - change state to Held and enter the CS
- On receipt of a Request <Tj, Pj> at Pi ($i \neq j$):
  - **if**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

    // lexicographic ordering in (Tj, Pj)

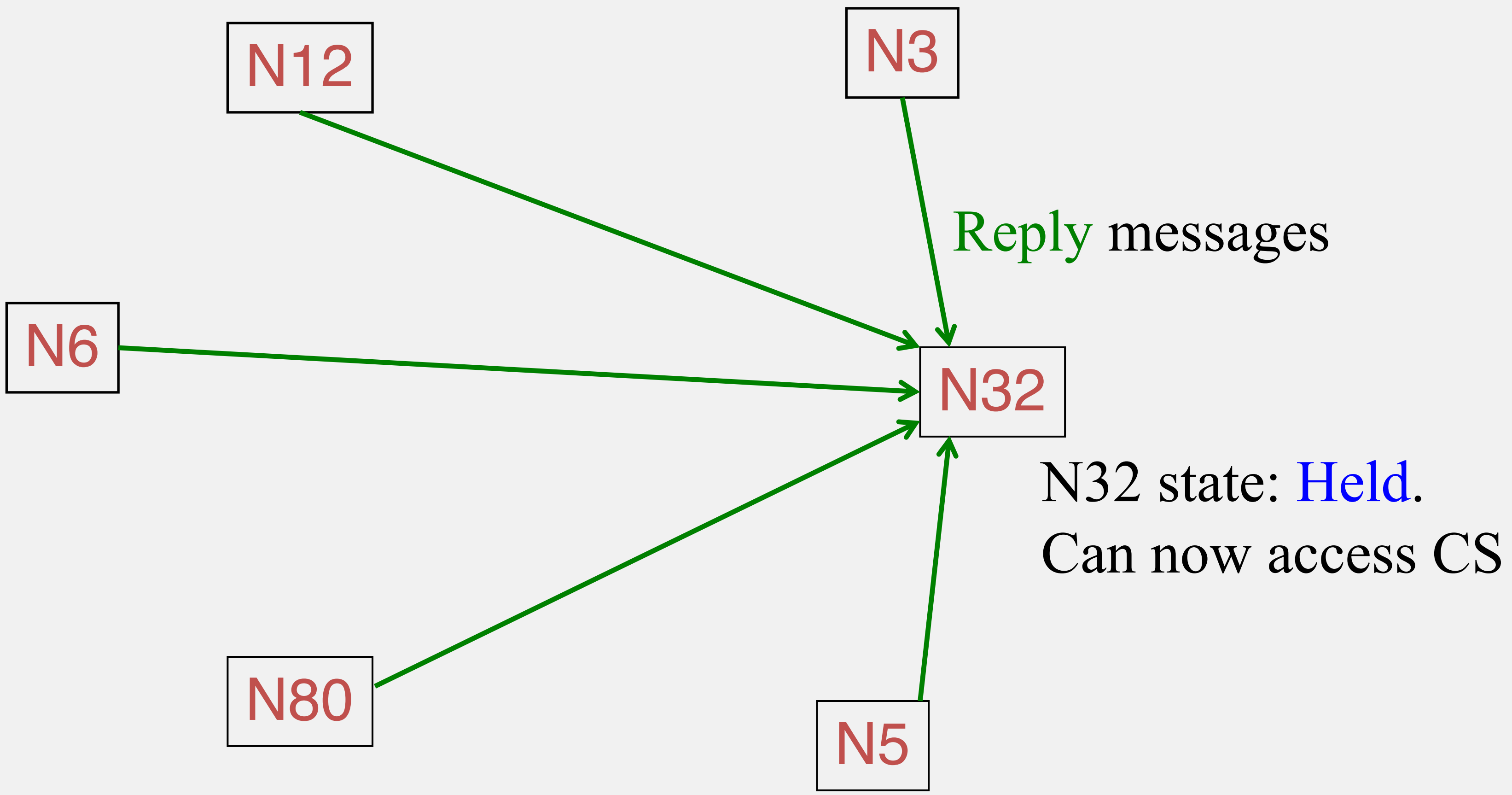
    add request to local queue (of waiting requests)

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

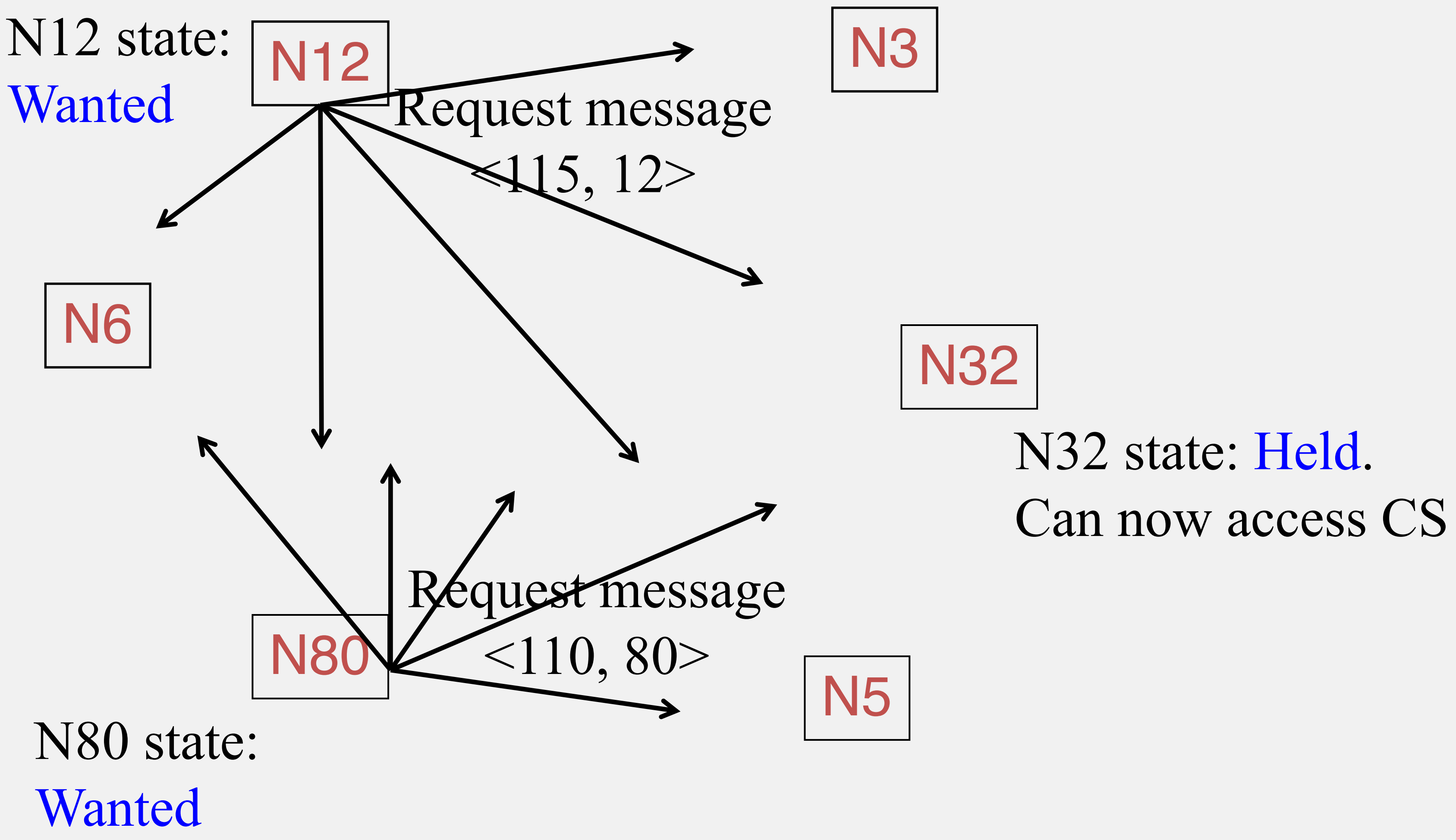
Example: Ricart-Agrawala Algorithm



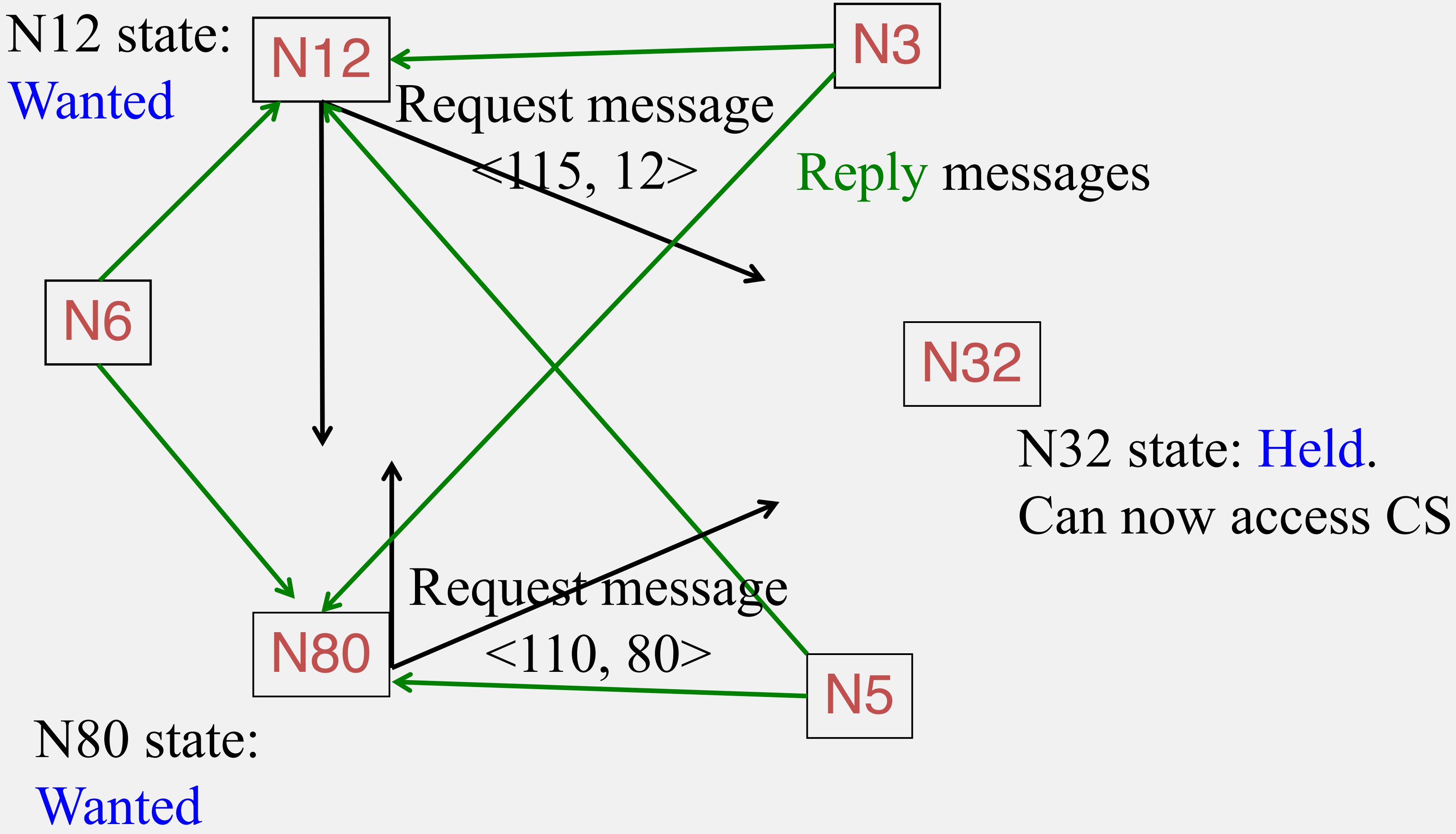
Example: Ricart-Agrawala Algorithm



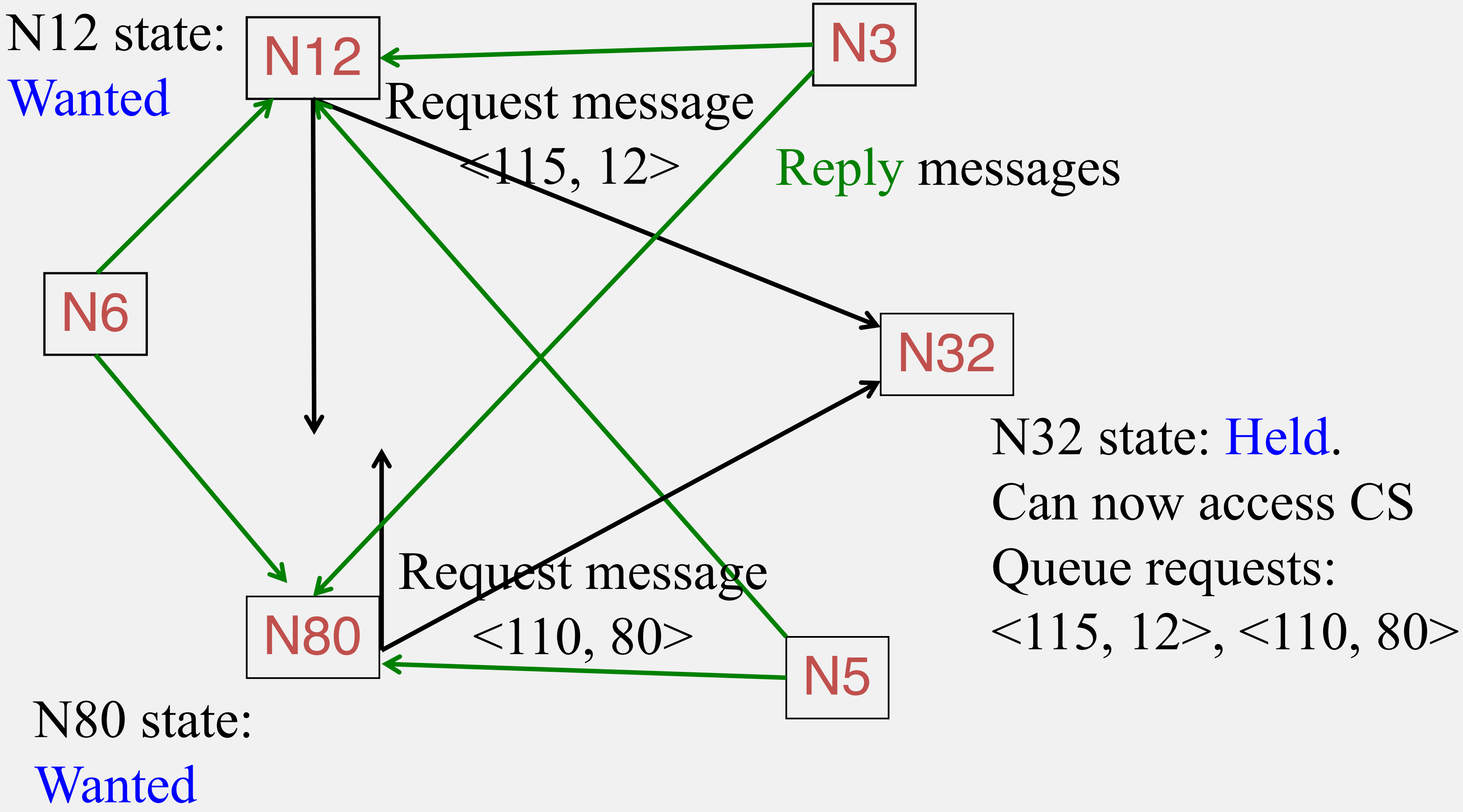
Example: Ricart-Agrawala Algorithm



Example: Ricart-Agrawala Algorithm

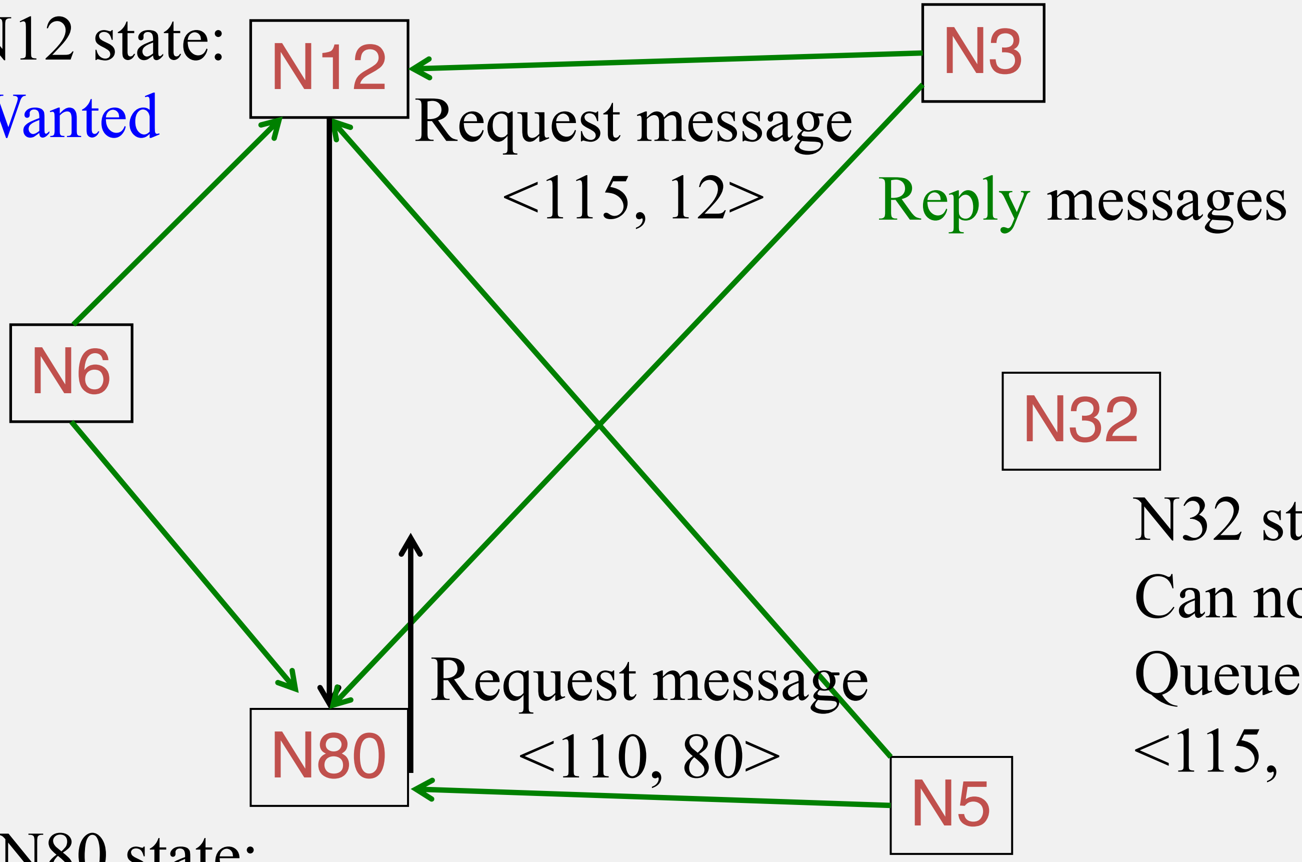


Example: Ricart-Agrawala Algorithm



Example: Ricart-Agrawala Algorithm

N12 state:
Wanted

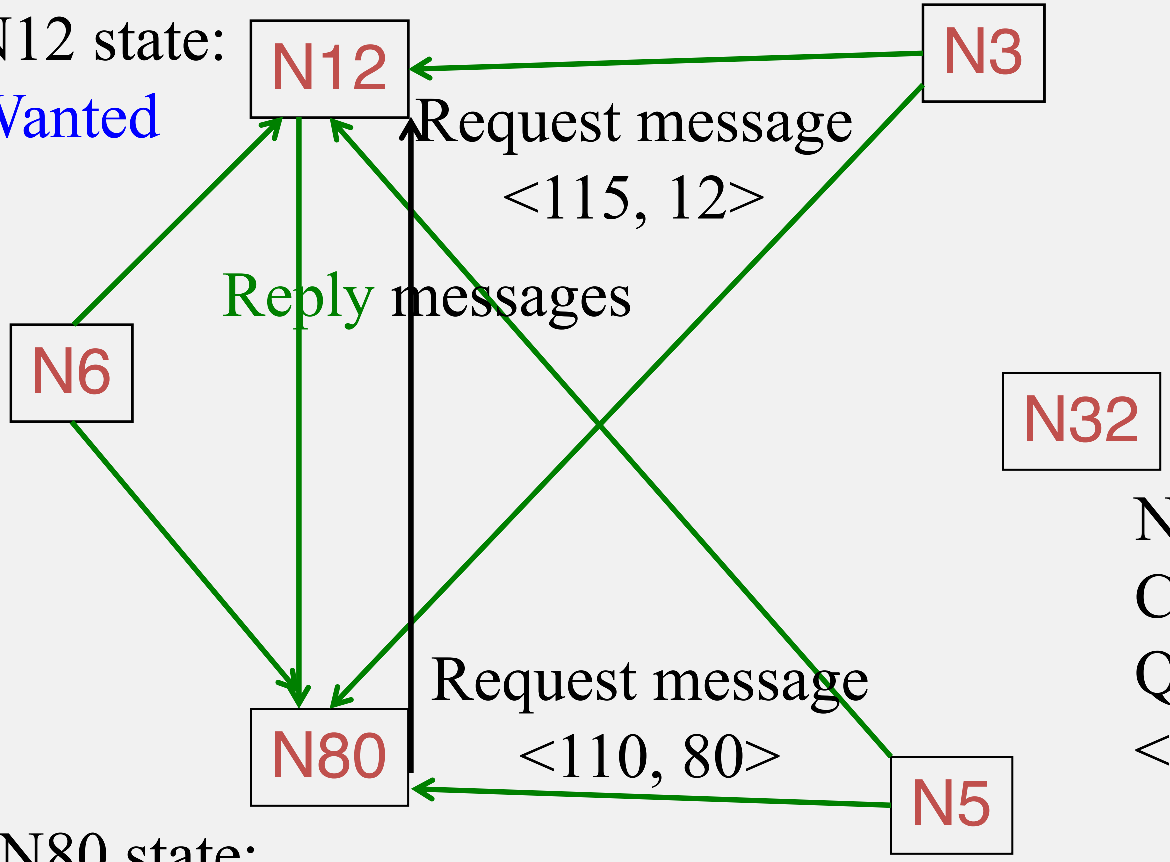


N32 state: Held.
Can now access CS
Queue requests:
<115, 12>, <110, 80>

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

Example: Ricart-Agrawala Algorithm

N12 state:
Wanted

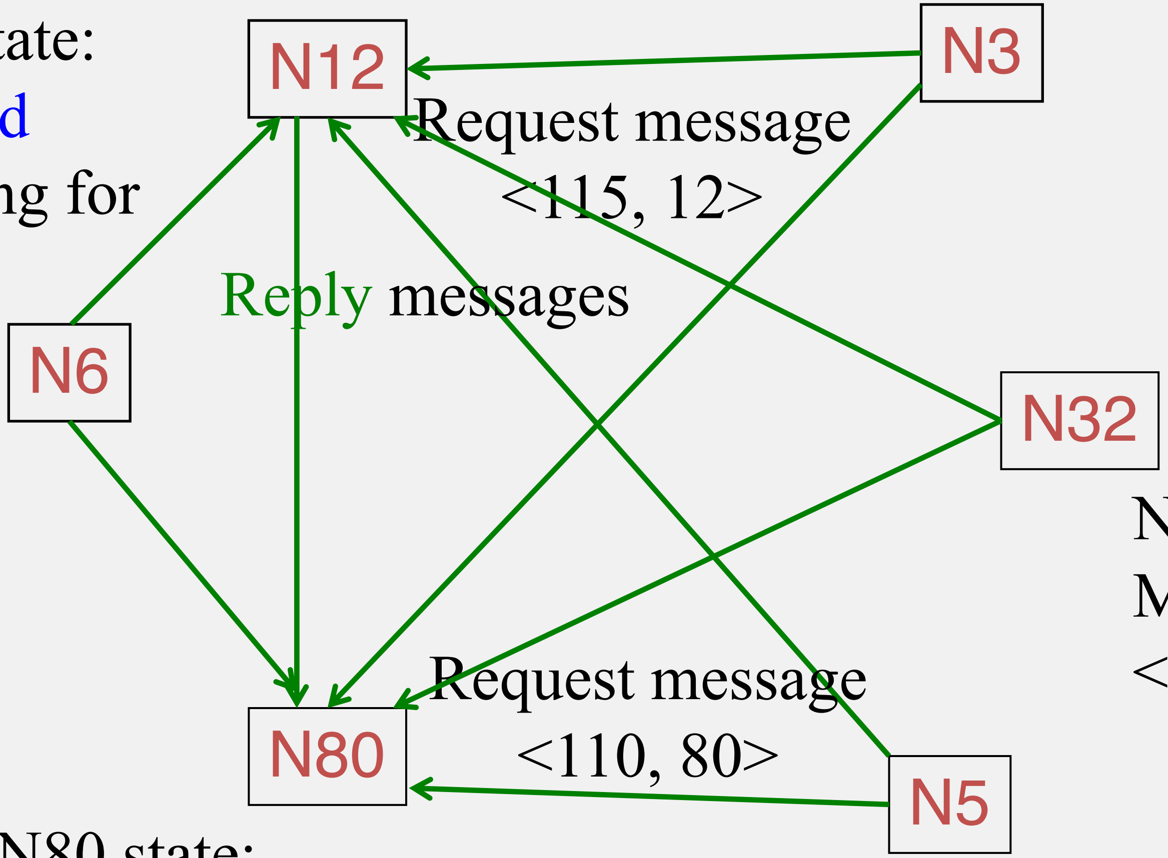


N32 state: Held.
Can now access CS
Queue requests:
<115, 12>, <110, 80>

N80 state:
Wanted
Queue requests: <115, 12>

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's Algorithm

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

Analysis: Ricart-Agrawala's Algorithm (2)

- Liveness
  - Worst-case: wait for all other (*N*-*1*) processes to send Reply
- Ordering
  - Requests with lower Lamport timestamps are granted earlier

Performance: Ricart-Agrawala's Algorithm

- Bandwidth: 2*(*N-1*) messages per enter() operation
  - *N-1* unicasts for the multicast request + *N-1* replies
  - *N* messages if the underlying network supports multicast (1 multicast + *N-1* unicast replies)
  - *N-1* unicast messages per exit operation
    - 1 multicast if the underlying network supports multicast
- Client delay: one round-trip time
- Synchronization delay: one message transmission time

Ok, but …

- Compared to Ring-Based approach, in Ricart-Agrawala approach
  - Client/synchronization delay has now gone down to O(1)
  - But bandwidth has gone up to O(N)
- Can we get *both* down?

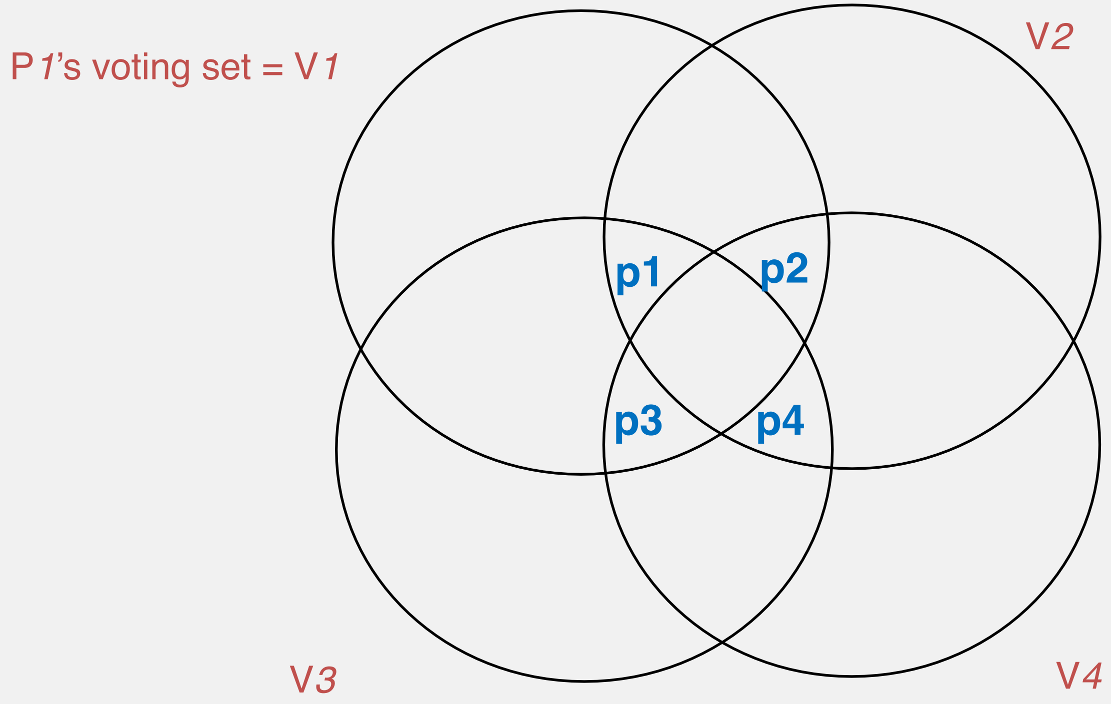
Maekawa’s Algorithm: Key Idea

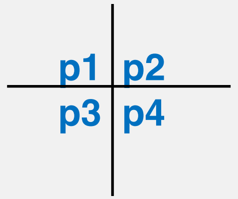
- Ricart-Agrawala requires replies from *all* processes in group
- Instead, get replies from only *some* processes in group
- But ensure that only process one is given access to CS (Critical Section) at a time

Maekawa's Voting Sets

- Each process Pi is associated with a <u>*voting set*</u> Vi (of processes)
- Each process belongs to its own voting set
- *The intersection of any two voting sets must be non-empty*
  - *Same concept as Quorums!*
- Each voting set is of size K
- Each process belongs to M other voting sets
- Maekawa showed that K=M=$\sqrt{N}$ works best
- 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

Example: Voting Sets with N=4





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 (2)

- 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*:

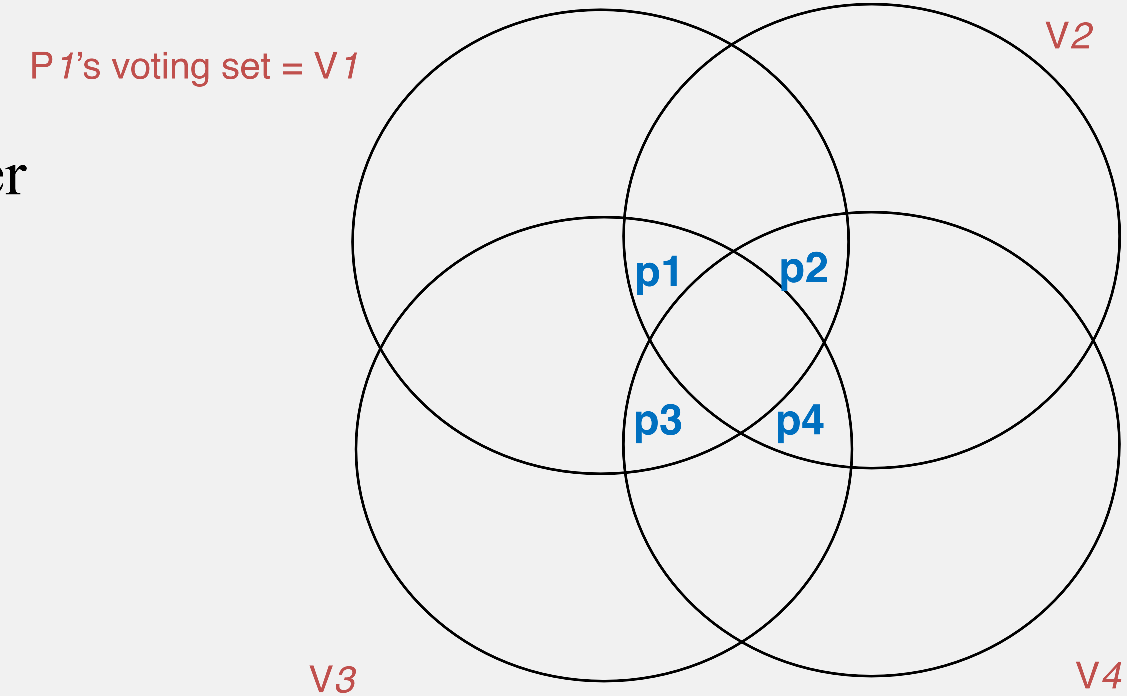
if (queue empty)
    voted = false
else
    dequeue head of queue, say P*k*
    Send Reply *only* to P*k*
    voted = true

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

- A process needs to wait for at most (*N-1*) other processes to finish CS
- But does not guarantee liveness
- Since can have a *deadlock*
- Example: all 4 processes need access
  - P1 is waiting for P3
  - P3 is waiting for P4
  - P4 is waiting for P2
  - P2 is waiting for P1
  - No progress in the system!
- There are deadlock-free versions



Performance

- Bandwidth
  - $2\sqrt{N}$ messages per enter()
  - $\sqrt{N}$ 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

Why $\sqrt{N}$?

- Each voting set is of size K
- 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))
    - $K \sim \sqrt{N}$

Failures?

- There are fault-tolerant versions of the algorithms we've discussed
  - E.g., Maekawa

- One other way to handle failures: Use Paxos-like approaches!

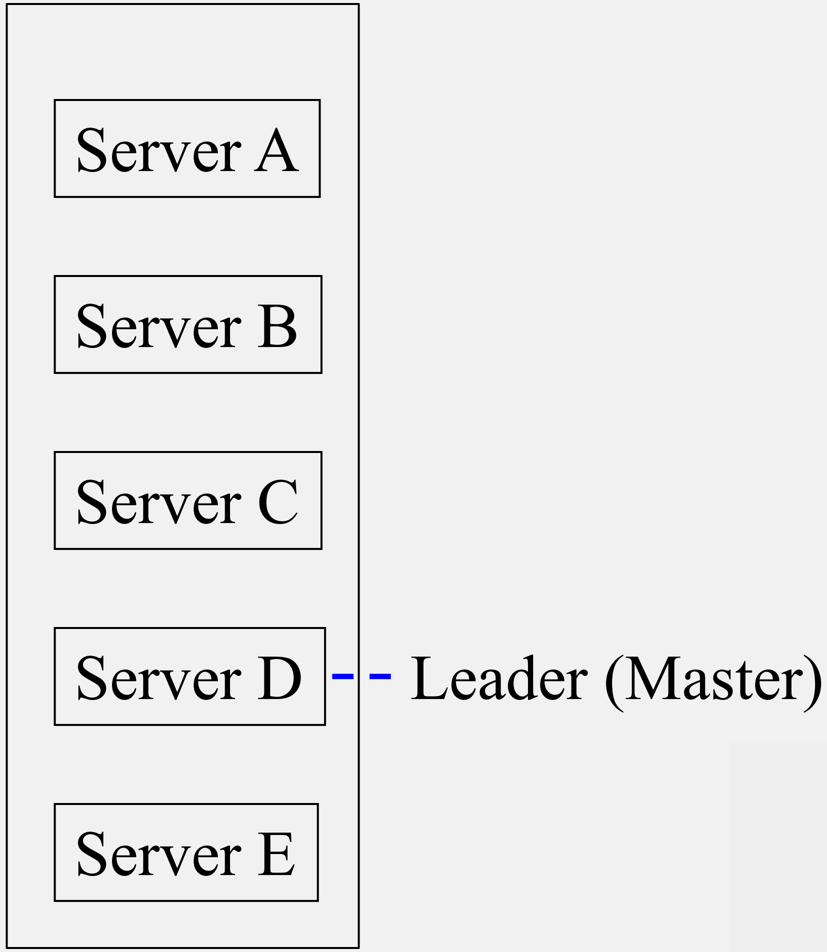
Chubby

- Google’s system for locking
- Used underneath Google’s systems like BigTable, Megastore, etc.
- Not open-sourced but published
- Chubby provides *Advisory* locks only
  - Doesn’t guarantee mutual exclusion unless every client checks lock before accessing resource

Reference: http://research.google.com/archive/chubby.html

Chubby (2)

- Can use not only for locking but also writing small configuration files
- Relies on Paxos-like (consensus) protocol
- Group of servers with one elected as Master (Leader)
  - All servers replicate same information
- Clients send read requests to Leader, which serves it locally
- Clients send write requests to Leader, which sends it to all servers, gets majority (quorum) among servers, and then responds to client
- On leader failure, run election protocol
- On replica failure, just replace it and have it catch up



Summary

- Mutual exclusion important problem in cloud computing systems
- Classical algorithms
  - Central
  - Ring-based
  - Ricart-Agrawala
  - Maekawa
- Industry systems
  - Chubby: a coordination service
  - Similarly, Apache Zookeeper for coordination

Announcements

- Reminder: HW3 due 10/30 (Monday!)
- MP3 due 11/5 (demos 11/6)
- You should have started on both by now.
- If you have uncollected midterms, they are available this week in my office during my OHs (only!)
- Final exam 12/12 7PM-10PM. See details on Piazza and website. Please plan accordingly!