Distributed Operating Systems

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(includes slides borrowed from Prof. Petru Eles, lecture slides from Coulouris, Dollimore and Kindberg textbook, MIT course notes, slides and animations from UIUC CS425 Indranil Gupta)

What does an OS do?

- Process/Thread Management
  - Scheduling
  - Communication
  - Synchronization
- Memory Management
- Storage Management
- FileSystems Management
- Protection and Security
- Networking

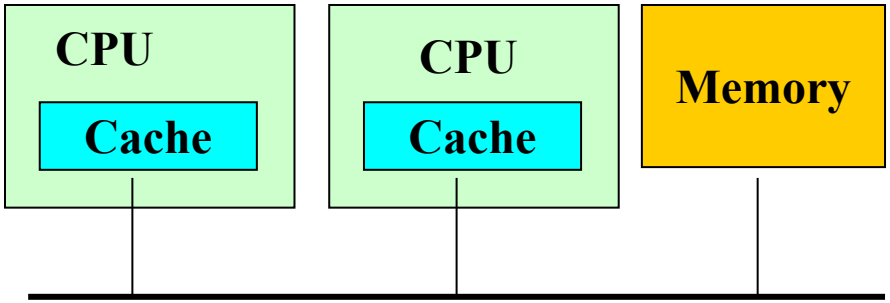
Distributed Operating Systems

Manages a collection of independent computers and makes them appear to the users of the system as if it were a single computer

Multiprocessors

Tightly coupled

Shared memory



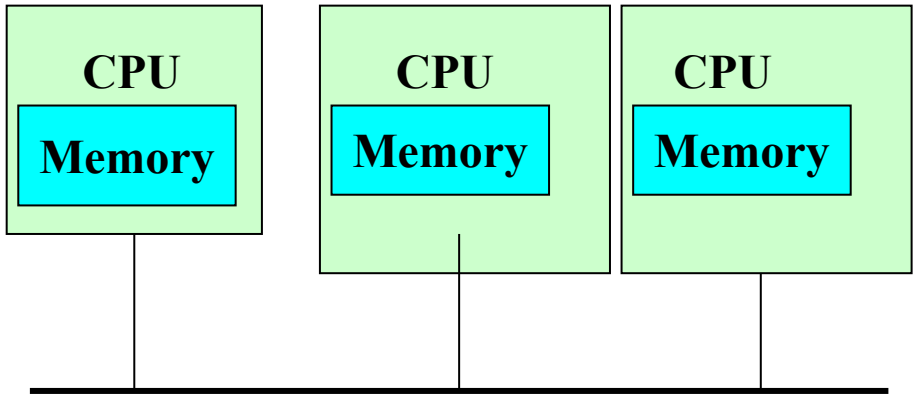
Parallel Architecture

Multicomputers

Loosely coupled

Private memory

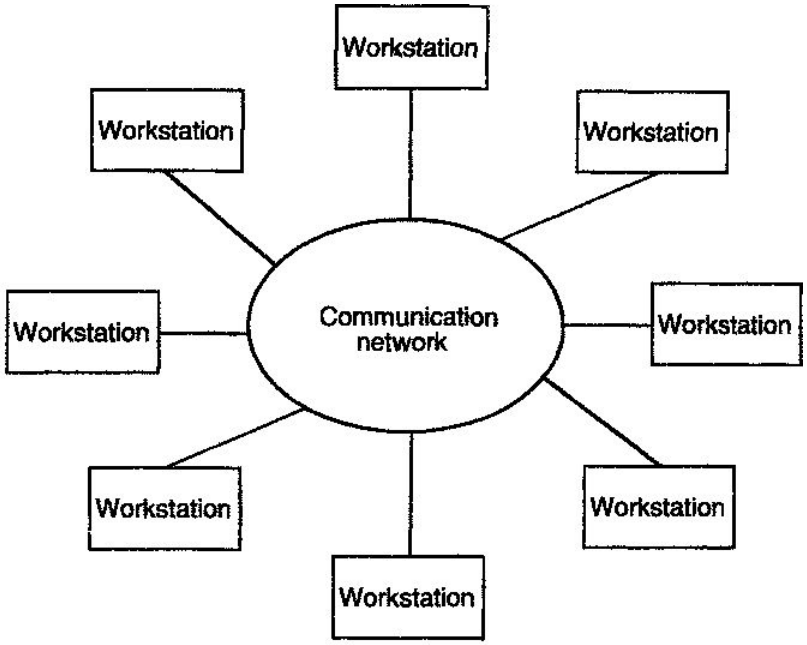
Autonomous



Distributed Architecture

Early Systems - Workstation Model

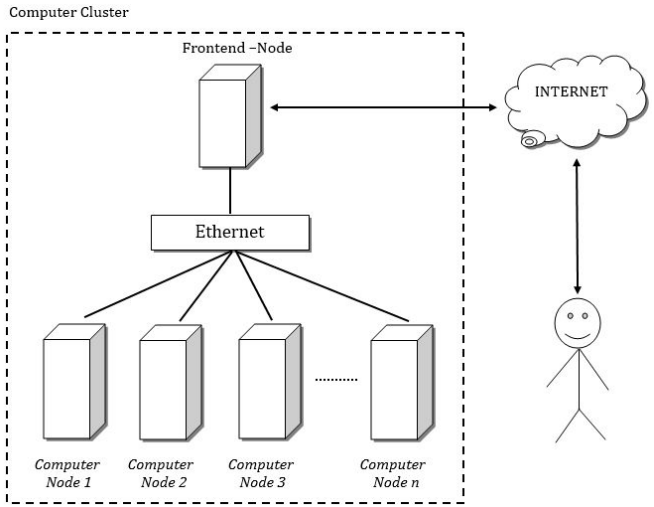
- How to find an idle workstation?
- How is a process transferred from one workstation to another?
- What happens to a remote process if a user logs onto a workstation that was idle, but is no longer idle now?
- Other models - processor pool, workstation server...

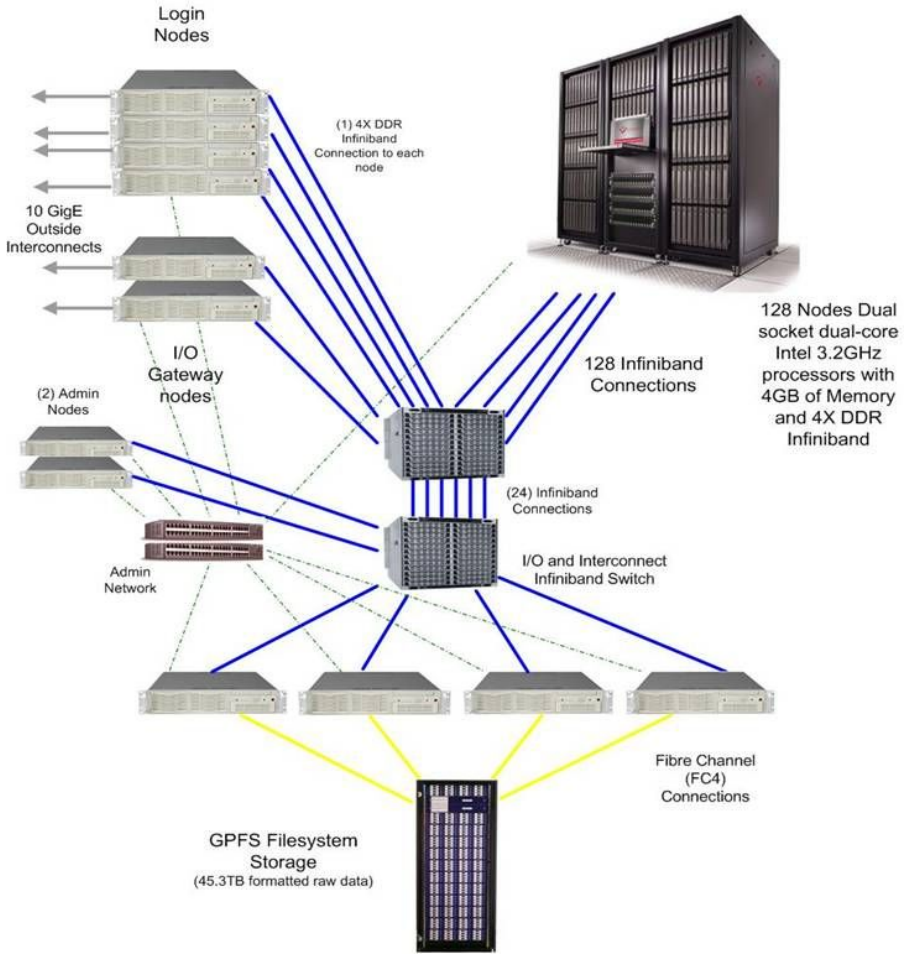


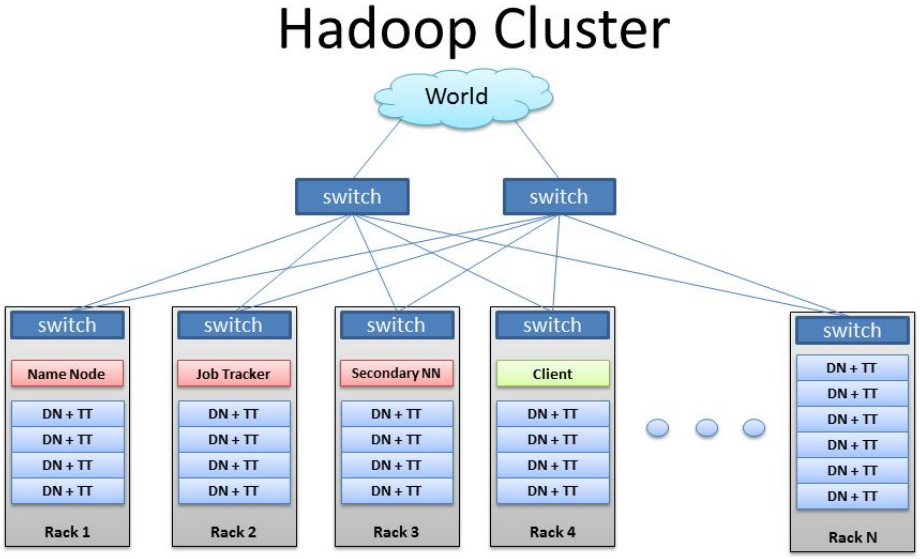
Examples: Berkeley NOW Project, U Wisconsin CONDOR system

Cluster Computing

Loosely connected set of machines that behave as a unit







High Performance Computing (HPC) Cluster

Distributed Operating System (DOS) Types

- Distributed OSs vary based on
  - System Image
  - Autonomy
  - Fault Tolerance Capability
- Multiprocessor OS
  - Looks like a virtual uniprocessor, contains only one copy of the OS, communicates via shared memory, single run queue
- Network OS
  - Does not look like a virtual uniprocessor, contains n copies of the OS, communicates via shared files, n run queues
- Distributed OS
  - Looks like a virtual uniprocessor (more or less), contains n copies of the OS/runtime, communicates via messages, n run queues

Design Issues (cont.)

- ***Transparency***
  - Location transparency
    - processes, cpu's and other devices, files
  - Replication transparency (of files)
  - Concurrency transparency
    - (user unaware of the existence of others)
  - Parallelism
    - User writes serial program, compiler and OS do the rest
- ***Performance***
  - Metrics
    - Throughput, response time
  - Load Balancing (static, dynamic)
  - Communication is slow compared to computation speed
    - fine grain, coarse grain parallelism tradeoff

Also : Scalability, Reliability, Flexibility, Heterogeneity, Security

Design Elements

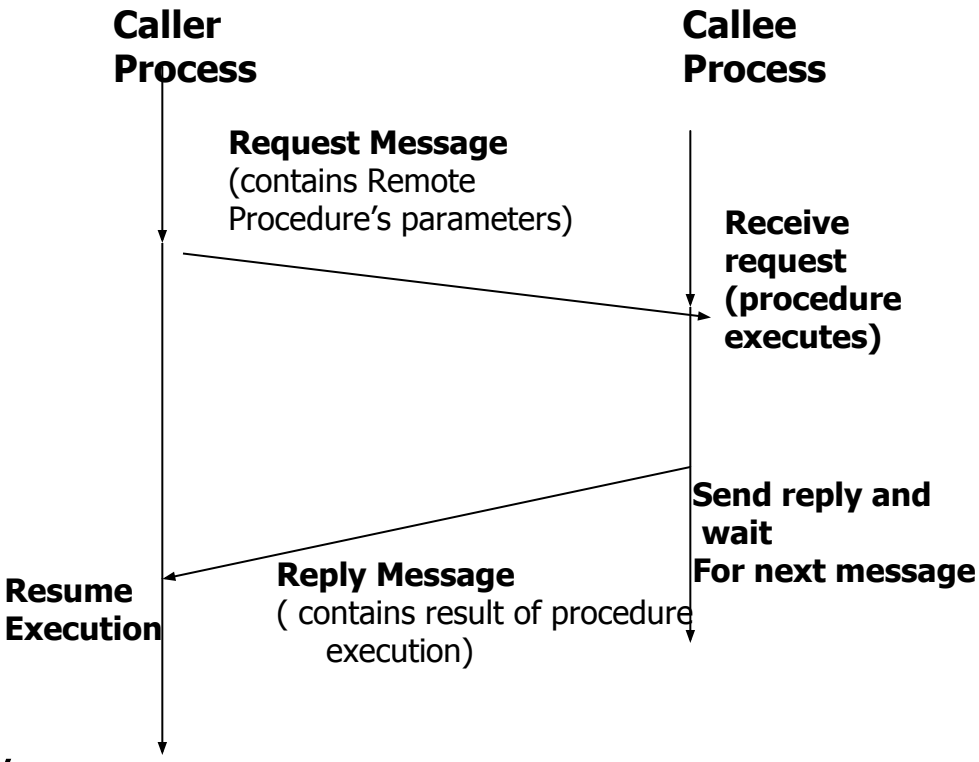
- Process Management
  - Task Partitioning, allocation, synchronization, load balancing, migration
- Communication
  - Two basic IPC paradigms used in distributed systems
    - Message Passing (RPC) and Shared Memory
  - synchronous, asynchronous
- FileSystems
  - Naming of files/directories
  - File sharing semantics
  - Caching/update/replication

Remote Procedure Call

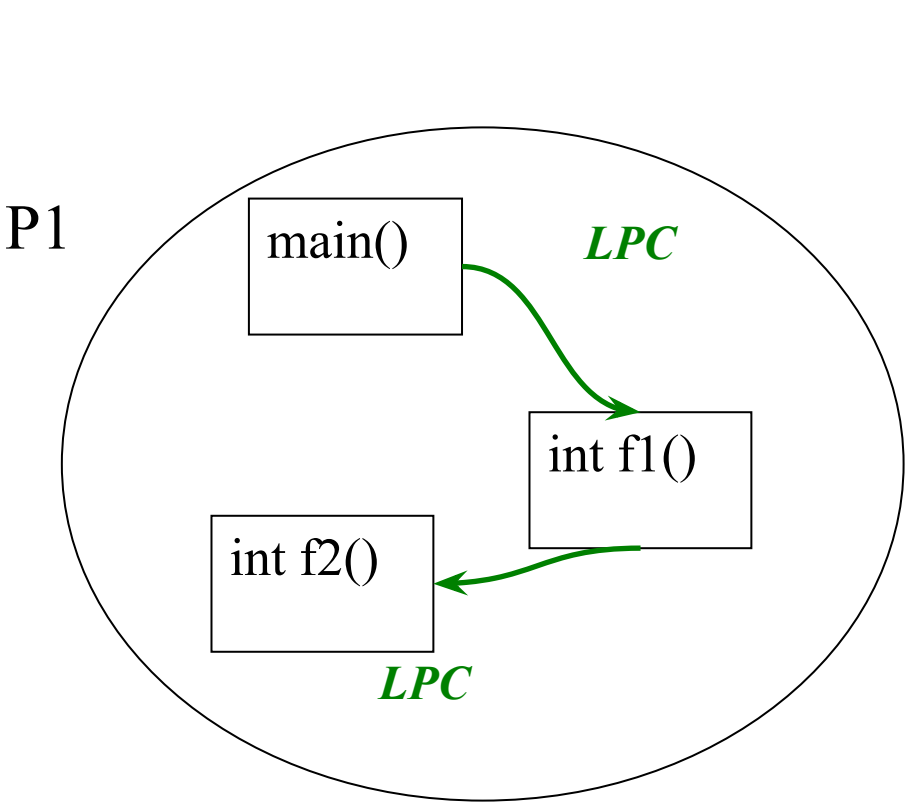
- Basis of early 2 tier client-server systems
- A convenient way to construct a client-server connection without explicitly writing send/ receive type programs (helps maintain transparency).
- Ideas initiated by RFCs in the 70s
- Landmark paper by Birrell and Nelson in 1980’s

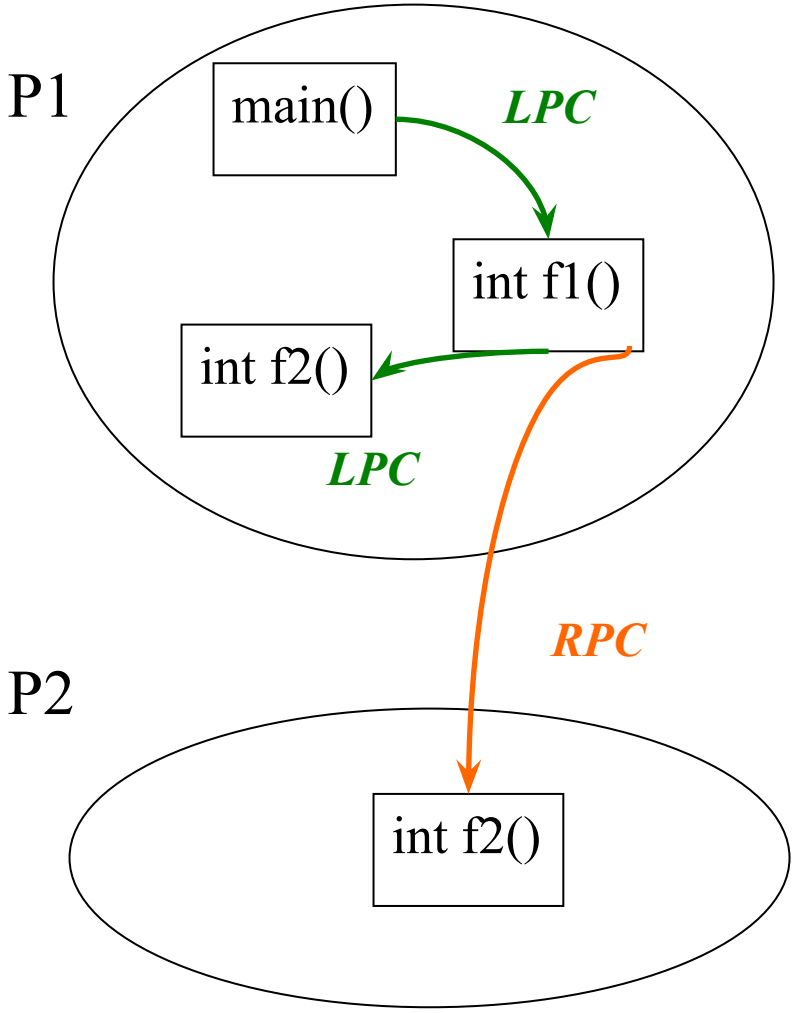
Remote Procedure Calls (RPC)

- General message passing model for execution of remote functionality.
  - Provides programmers with a familiar mechanism for building distributed applications/systems
- Familiar semantics (similar to LPC)
  - Simple syntax, well defined interface, ease of use, generality and IPC between processes on same/different machines.
- It is generally synchronous
- Can be made asynchronous by using multi-threading

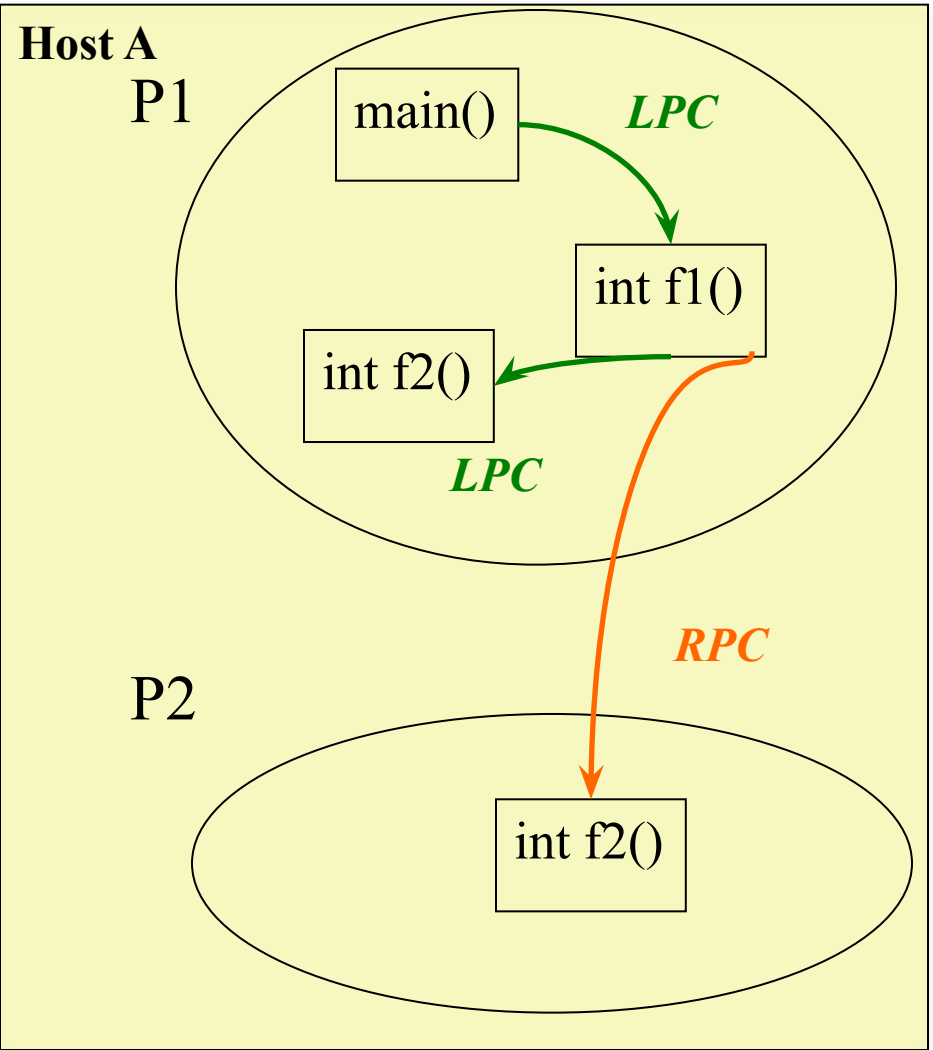


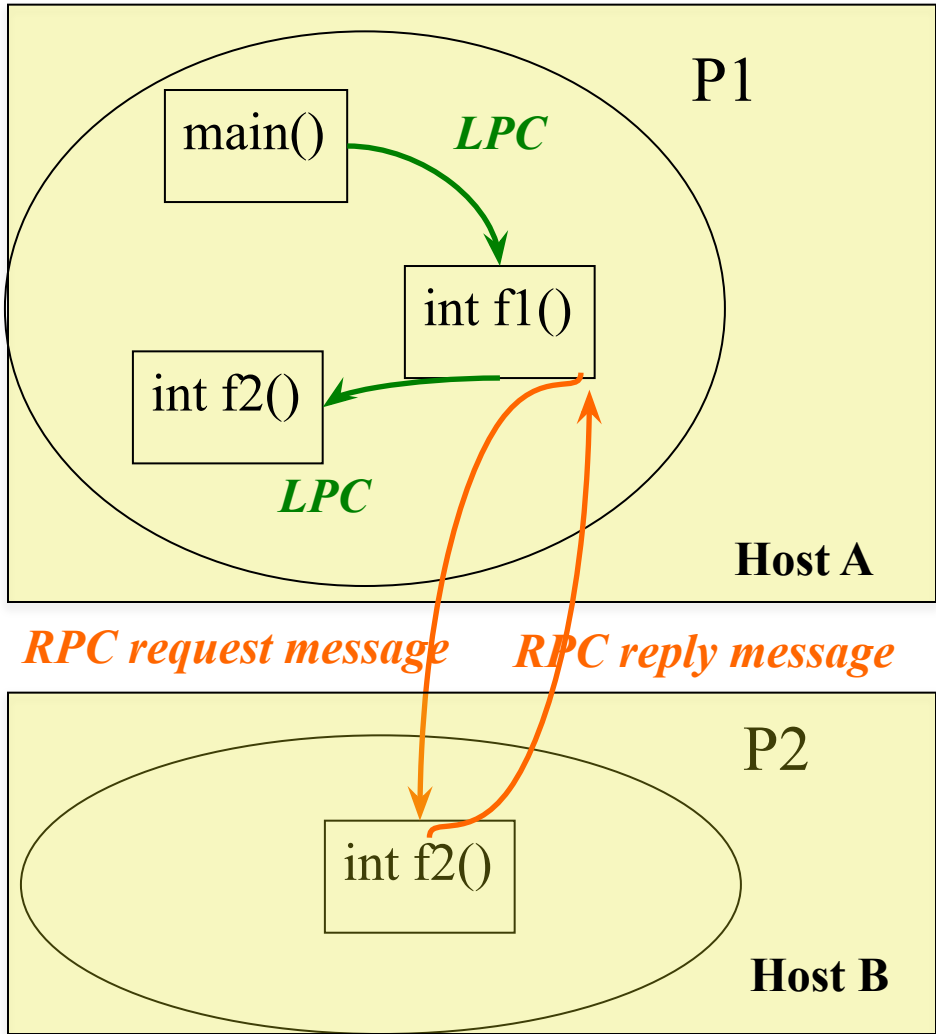
LPC vs. RPC


P1
main()
LPC
int f1()
int f2()
LPC


P1
main()
LPC
int f1()
int f2()
LPC
RPC
P2
int f2()

LPC vs. RPC


Host A
P1
main()
LPC
int f1()
int f2()
LPC
RPC
P2
int f2()


P1
main()
LPC
int f1()
int f2()
LPC
Host A
RPC request message
RPC reply message
P2
int f2()
Host B

RPC Needs :Syntactic and Semantic Transparency

- Resolve differences in data representation (CDR)
- Support multi-threaded programming
- Provide good reliability
- Provide independence from transport protocols
- Ensure high degree of security
- Locate required services across networks
- Support a variety of execution semantics
  - At most once semantics (e.g., Java RMI)
  - At least once semantics (e.g., Sun RPC)
  - Maybe, i.e., best-effort (e.g., CORBA)

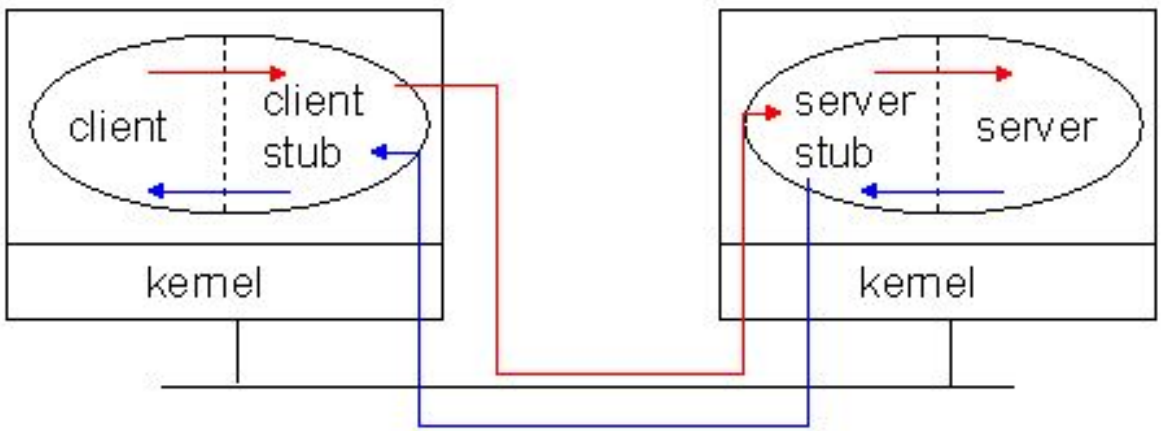
Retransmit request	Filter duplicate requests	Re-execute function or retransmit reply	RPC Semantics
Yes	No	Re-execute	At least once
Yes	Yes	Retransmit	At most once
No	NA	NA	Maybe

RPC Challenges

Achieving exactly the same semantics for LPC and RPC is hard

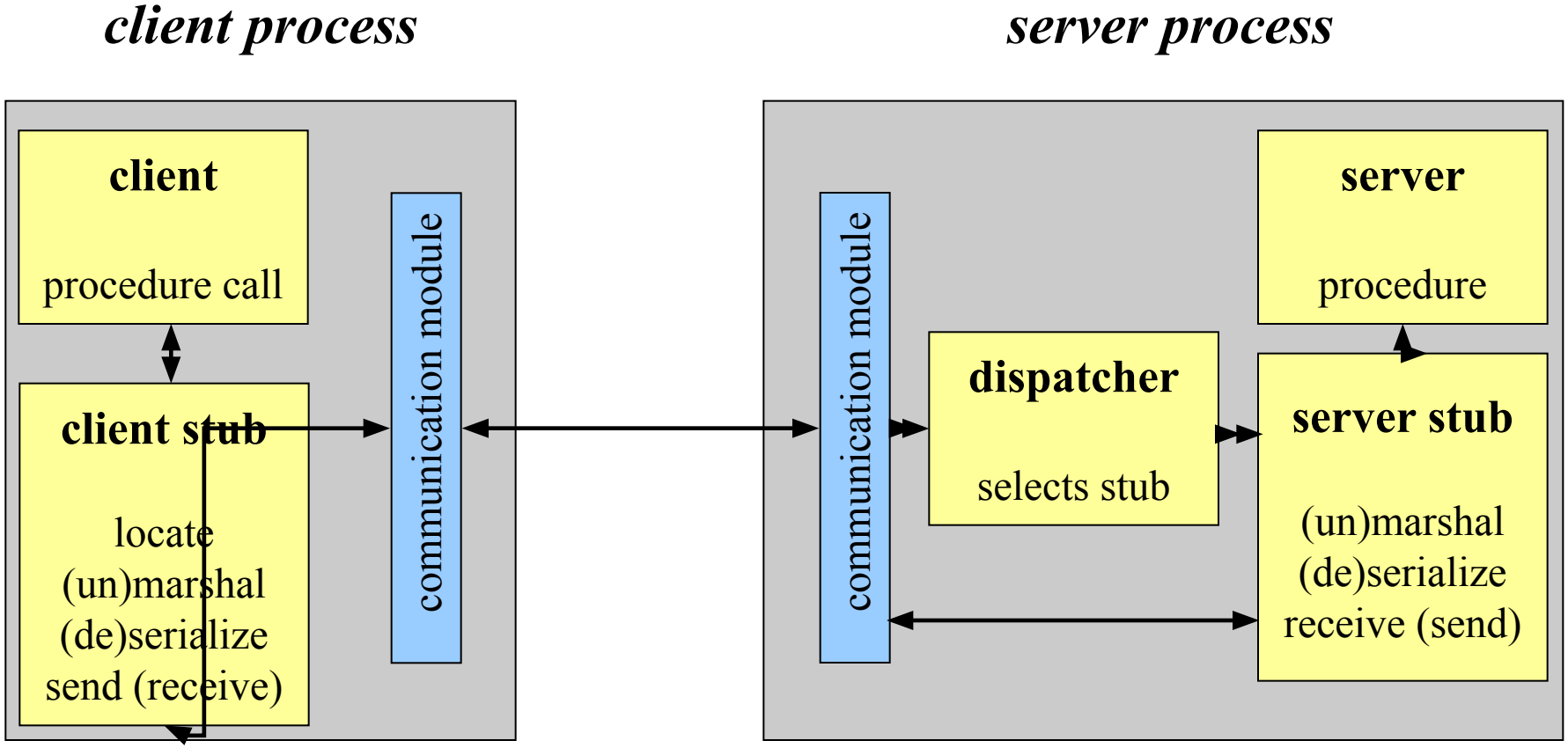
- Disjoint address spaces
- Consumes more time (due to communication delays)
- Failures (hard to guarantee exactly-once semantics)
  - Function may not be executed if
    - Request (call) message is dropped
    - Reply (return) message is dropped
    - Called process fails before executing called function
    - Called process fails after executing called function
    - Hard for caller to distinguish these cases
  - Function may be executed multiple times if request (call) message is duplicated

Implementing RPC - Mechanism



- Uses the concept of stubs; A perfectly normal LPC abstraction by concealing from programs the interface to the underlying RPC
- Involves the following elements
  - The client, The client stub
  - The RPC runtime
  - The server stub, The server

RPC – How it works II



RPC - Steps

- Client procedure **calls** the client stub in a normal way
- Client stub **builds** a message and **traps** to the kernel
- Kernel **sends** the message to remote kernel
- Remote kernel **gives** the message to server stub
- Server stub **unpacks** parameters and **calls** the server
- Server **computes** results and **returns** it to server stub
- Server stub **packs** results in a message and **traps** to kernel
- Remote kernel **sends** message to client kernel
- Client kernel **gives** message to client stub
- Client stub **unpacks** results and **returns** to client

RPC - Marshalling and Unmarshalling

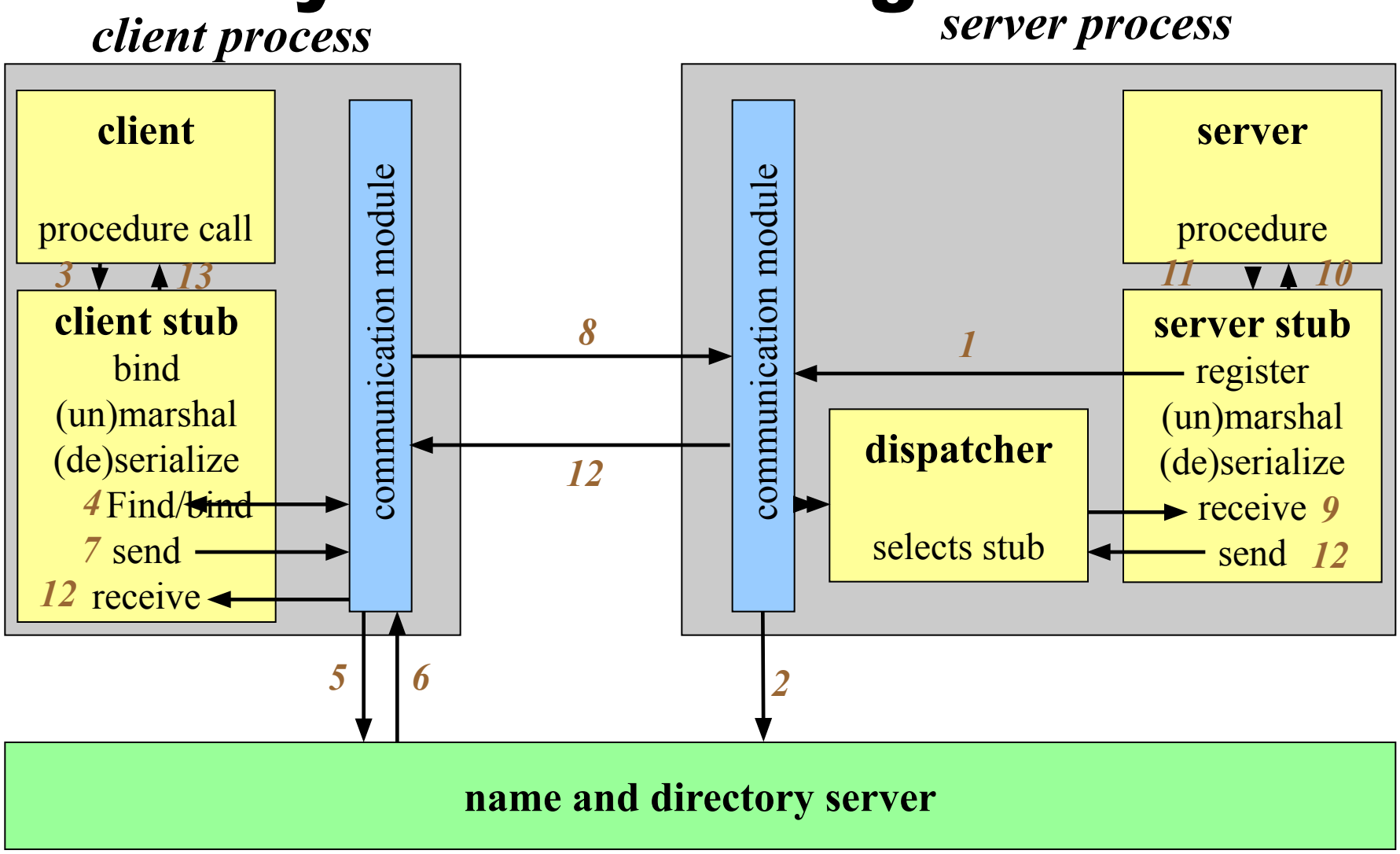
- Different architectures use different ways of representing data
  - **Big endian**: Hex 12-AC-33 stored with 12 in lowest address, then AC in next higher address, then 33 in highest address
    - IBM z, System 360
  - **Little endian**: Hex 12-AC-33 stored with 33 in lowest address, then AC in next higher address, then 12
    - Intel
- Caller (and callee) process uses its own *platform-dependent* way of storing data

- Middleware has a common data representation (CDR)
  - Platform-independent
- Caller process converts arguments into CDR format
  - Called "Marshalling"
- Callee process extracts arguments from message into its own platform-dependent format
  - Called "Unmarshalling"
- Return values are marshalled on callee process and unmarshalled at caller process

RPC - binding

- Static binding
  - hard coded stub
    - Simple, efficient
    - not flexible
  - stub recompilation necessary if the location of the server changes
  - use of redundant servers not possible
- Dynamic binding
  - name and directory server
    - load balancing
  - IDL used for binding
  - flexible
  - redundant servers possible

RPC - dynamic binding



RPC - Extensions

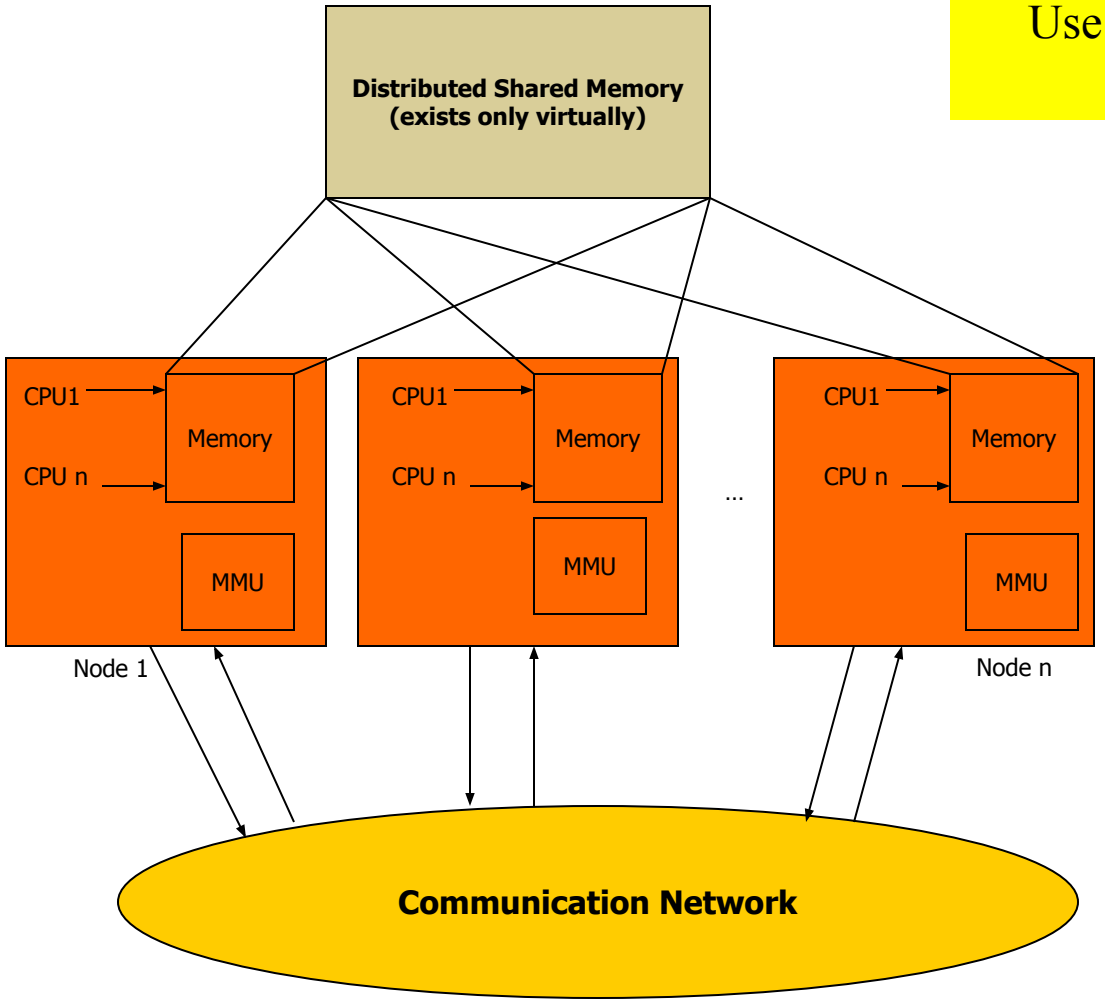
- conventional RPC: sequential execution of routines
- client blocked until response of server
- asynchronous RPC – non blocking
  - client has two entry points(request and response)
  - server stores result in shared memory
  - client picks it up from there

RPC servers and protocols…

- RPC Messages (call and reply messages)
- Server Implementation
  - Stateful servers
  - Stateless servers
- Communication Protocols
  - Request(R)Protocol
  - Request/Reply(RR) Protocol
  - Request/Reply/Ack(RRA) Protocol

- Idempotent operations - can be repeated multiple times, without any side effects
- Examples (x is server-side variable)
  - x=1;
- Non-examples
  - x=x+1;
  - x=x*2

Distributed Shared Memory (DSM)



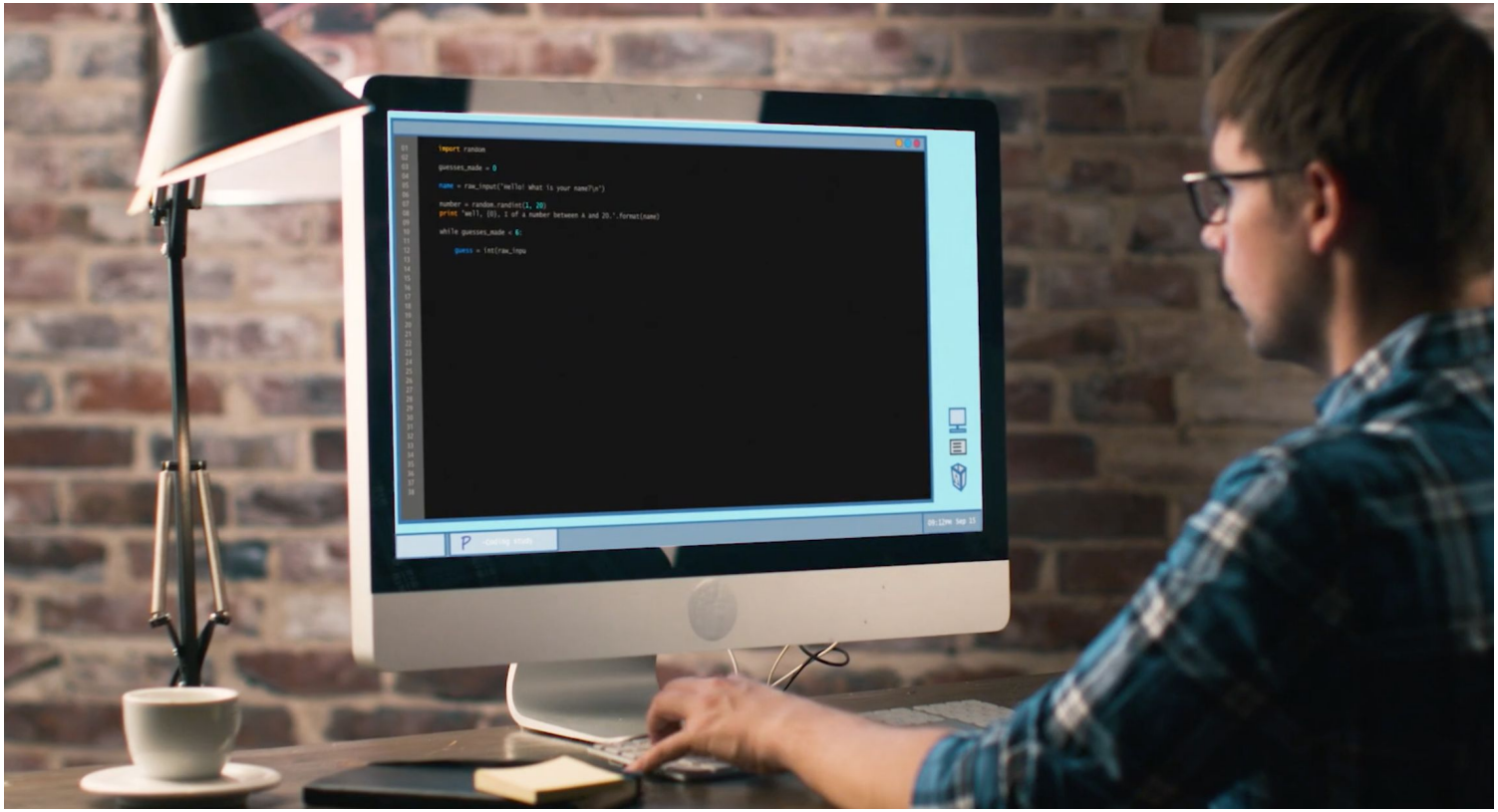
Tightly coupled systems

Use of shared memory for IPC is natural

Loosely coupled distributed-memory processors

Use DSM – distributed shared memory

A middleware solution that provides a shared-memory abstraction.



IRONFLEET: PROVING SAFETY AND LIVENESS OF PRACTICAL DISTRIBUTED SYSTEMS

BY: Chris Hawblitzel, Jon Howell, Manos Kapritsos, Jacob R. Lorch, Bryan Parno, Michael L. Roberts, Srinath Setty, and Brian Zill

JULY 2017

https://vimeo.com/220332220

Issues in designing DSM

- ***Synchronization***
- Granularity of the block size
- Memory Coherence (Consistency models)
- Data Location and Access
- Replacement Strategies
- Thrashing
- Heterogeneity

Synchronization

- Inevitable in Distributed Systems where distinct processes are running concurrently and sharing resources.
- Synchronization related issues
  - Clock synchronization/Event Ordering (recall happened before relation)
  - Mutual exclusion
  - Deadlocks
  - Election Algorithms

Distributed Mutual Exclusion

- Mutual exclusion
  - ensures that concurrent processes have serialized access to shared resources - the critical section problem
  - Shared variables (semaphores) cannot be used in a distributed system
    - Mutual exclusion must be based on message passing, in the context of unpredictable delays and incomplete knowledge
  - In some applications (e.g. transaction processing) the resource is managed by a server which implements its own lock along with mechanisms to synchronize access to the resource.

Distributed Mutual Exclusion

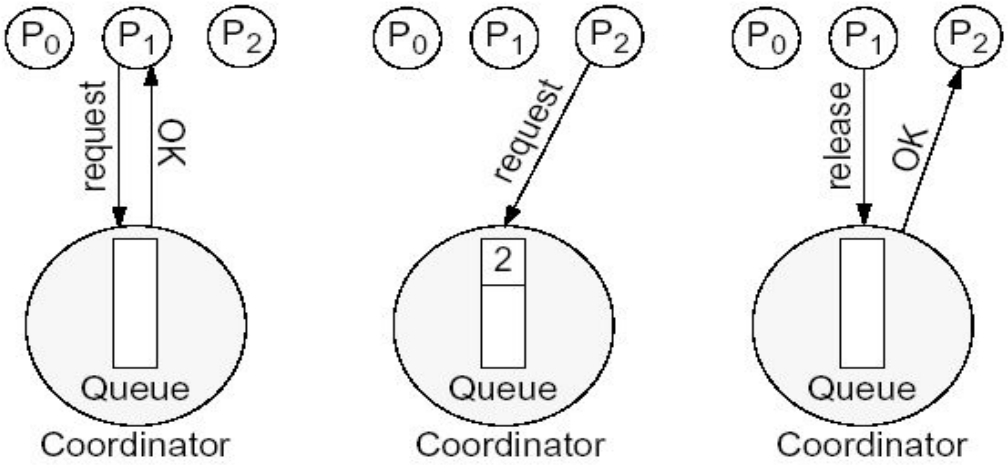
- Basic requirements
  - Safety
    - At most one process may execute in the critical section (CS) at a time
  - Liveness
    - A process requesting entry to the CS is eventually granted it (as long as any process executing in its CS eventually leaves it.
    - Implies freedom from deadlock and starvation

Mutual Exclusion Techniques

- **Non-token Based Approaches**
  - Each process freely and equally competes for the right to use the shared resource; requests are arbitrated by a central control suite or by distributed agreement
    - Central Coordinator Algorithm
    - Ricart-Agrawala Algorithm
- **Token-based approaches**
  - A logical token representing the access right to the shared resource is passed in a regulated fashion among processes; whoever holds the token is allowed to enter the critical section.
    - Token Ring Algorithm
    - Ricart-Agrawala Second Algorithm
- **Quorum-based approaches**
  - Need to coordinate with only some members in a group (quorum).
    - Maekawa's Algorithm -- voting sets

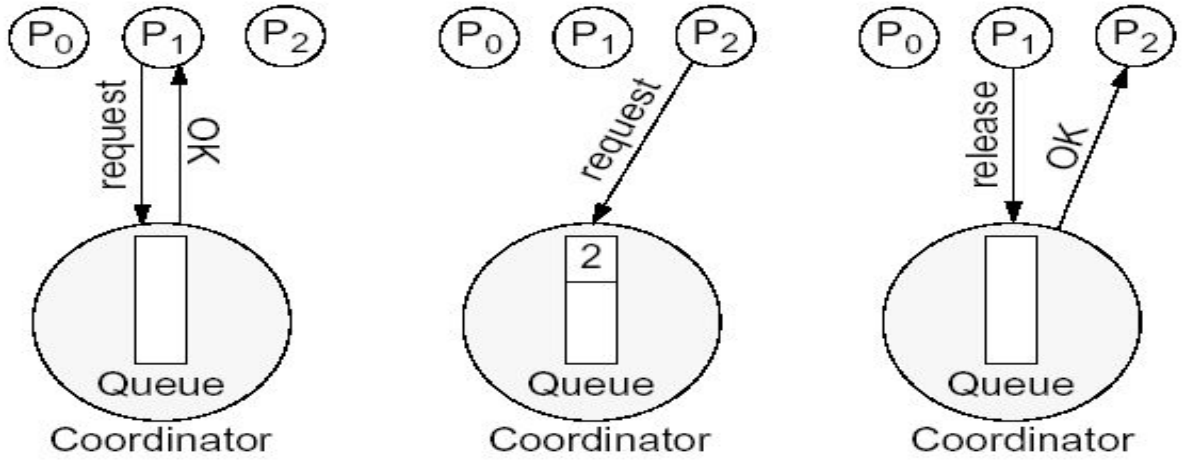
Central Coordinator Algorithm

- A central coordinator grants permission to enter a CS.



- To enter a CS, a process sends a request message to the coordinator and then waits for a reply (during this waiting period the process can continue with other work).
- The reply from the coordinator gives the right to enter the CS.
- After finishing work in the CS the process notifies the coordinator with a release message.

Central Coordinator Algorithm



- A central coordinator grants permission to enter the critical section (CS).
- To enter the CS, a process
  - sends a ***request*** message to the coordinator and
  - waits for a ***reply*** (during this waiting period the process can continue work)
- The reply from the coordinator gives a process the right to enter the CS.
- After completing work in the CS, the process notifies the coordinator with a ***release*** message.

Central Coordinator Algorithm

- Advantages
  - Scheme is easy to implement
  - Requires only 3 messages to get access to a critical section (request, OK, release)

- Issues with centralized coordinator
  - A performance bottleneck
  - Critical point of Failure
    - New coordinator must be elected when existing coordinator fails
    - New coordinator can be one of the processes competing for access to the CS
    - A *leader election* algorithm must select one and only one coordinator.

Ricart-Agrawala Algorithm 1

- In a distributed environment it seems more natural to implement mutual exclusion, based upon distributed agreement - not on a central coordinator.
- It is assumed that all processes keep a (Lamport's) logical clock which is updated according to the clock rules.
  - The algorithm requires a total ordering of requests. Requests are ordered according to their global logical timestamps; if timestamps are equal, process identifiers are compared to order them.
- The process that requires entry to a CS multicasts the request message to all other processes competing for the same resource.
  - Process is allowed to enter the CS when all processes have replied to this message.
  - The request message consists of the requesting process' timestamp (logical clock) and its identifier.
- Each process keeps its state with respect to the CS: released, requested, or held.

Ricart-Agrawala Algorithm 1

- Rule for process initialization

  /* performed by each process P_i at initialization */

[RI1]: $state_{Pi}$:= RELEASED.

- Rule for access request to CS

  /* performed whenever process P_i requests an access to the CS */

[RA1]: $state_{Pi}$:= REQUESTED.
T_{Pi} := the value of the local logical clock corresponding to this request.

[RA2]: P_i sends a request message to all processes; the message is of the form (T_{Pi}, i), where i is an identifier of P_i.

[RA3]: P_i waits until it has received replies from all other n-1 processes.

- Rule for executing the CS

  /* performed by P_i after it received the n-1 replies */

[RE1]: $state_{Pi}$:= HELD.
P_i enters the CS.

- Rule for handling incoming requests

  /* performed by P_i whenever it received a request (T_{Pj}, j) from P_j */

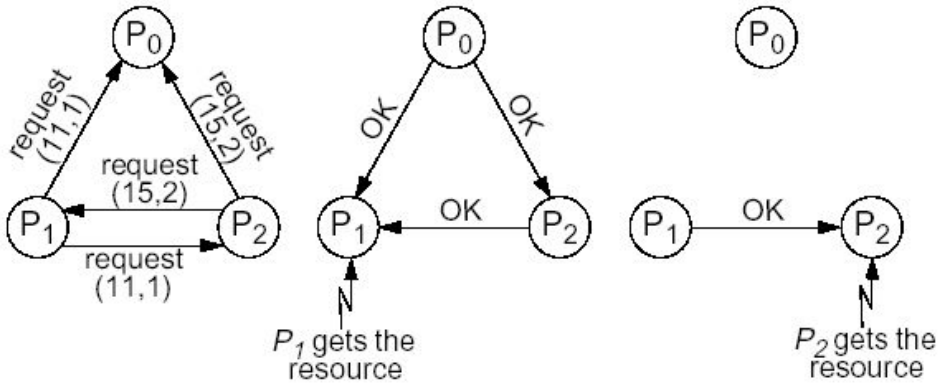
[RH1]: **if** $state_{Pi}$ = HELD **or** (($state_{Pi}$ = REQUESTED) **and** ((T_{Pi}, i) < (T_{Pj}, j))) **then**
Queue the request from P_j without replying.
else
Reply immediately to P_j.
end if.

- Rule for releasing a CS

  /* performed by P_i after it finished work in a CS */

[RR1]: $state_{Pi}$:= RELEASED.
P_i replies to all queued requests.

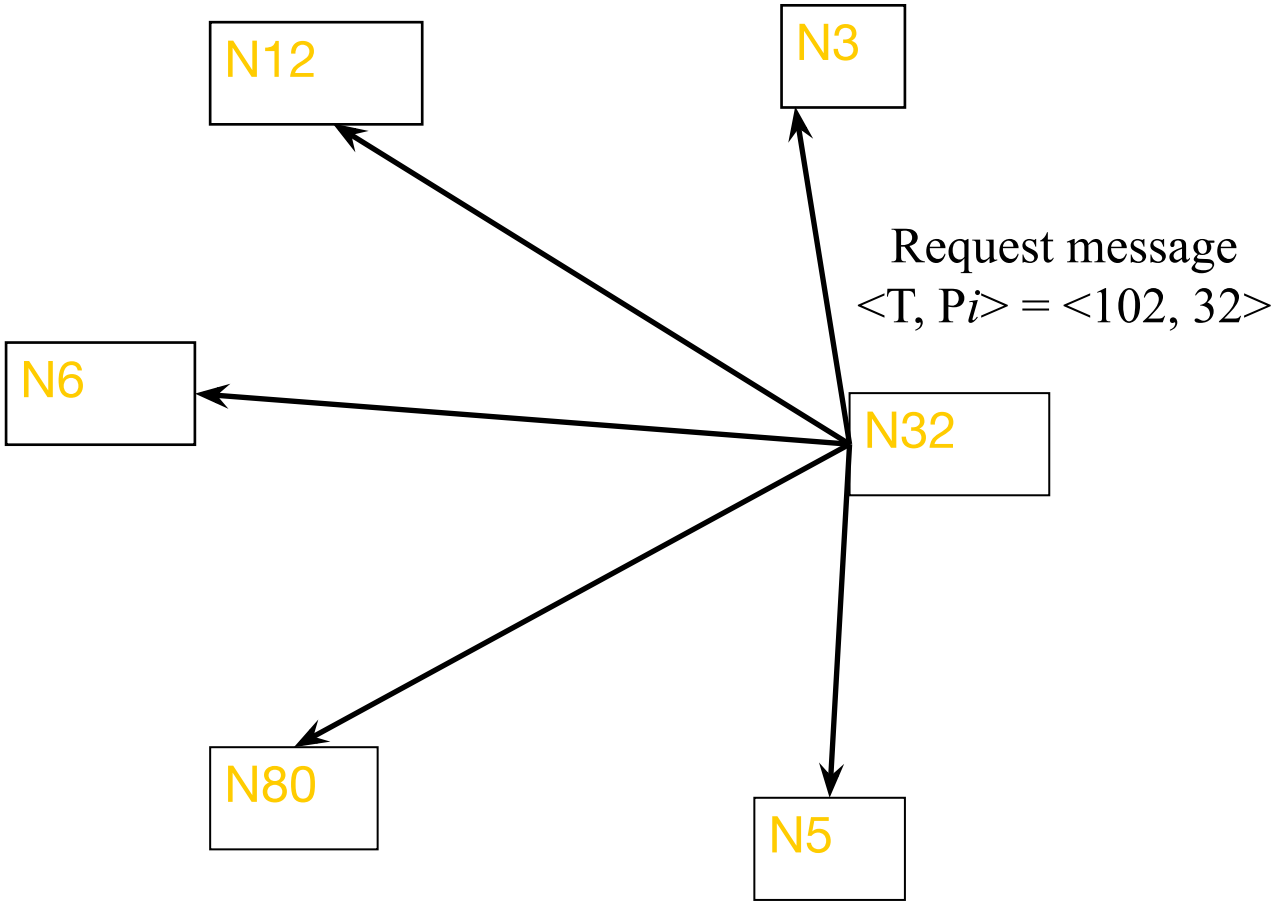
Ricart-Agrawala Algorithm1



- A request issued by a process Pj is blocked by another process Pi only if Pi is holding the resource or if it is requesting the resource with a higher priority (i.e. smaller timestamp) than Pj.

- Issues
  - Expensive in terms of message traffic.
    - requires 2(n-1) messages for entering the CS; (n-1) requests and (n-1) replies.
  - The failure of any process involved makes progress impossible.
    - Special recovery measures must be taken.

Example: Ricart-Agrawala Algorithm1



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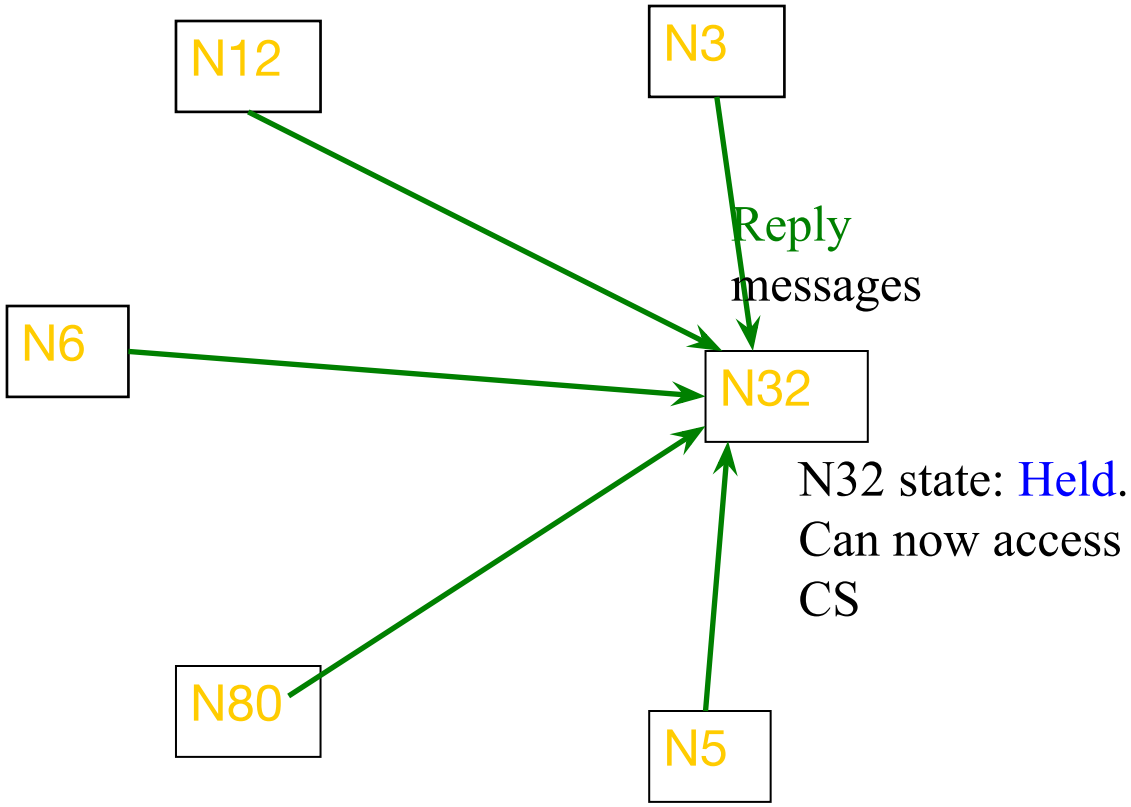

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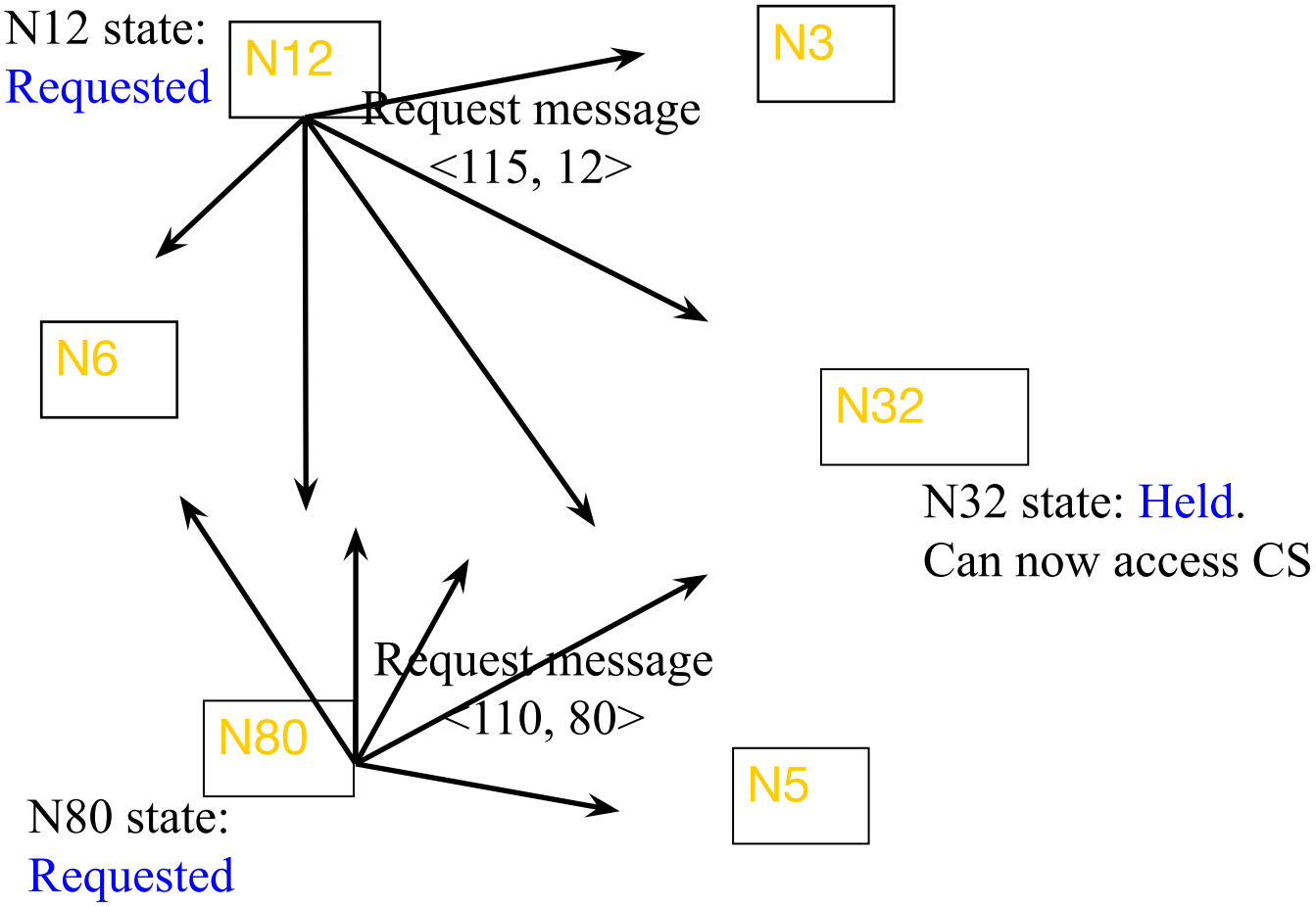

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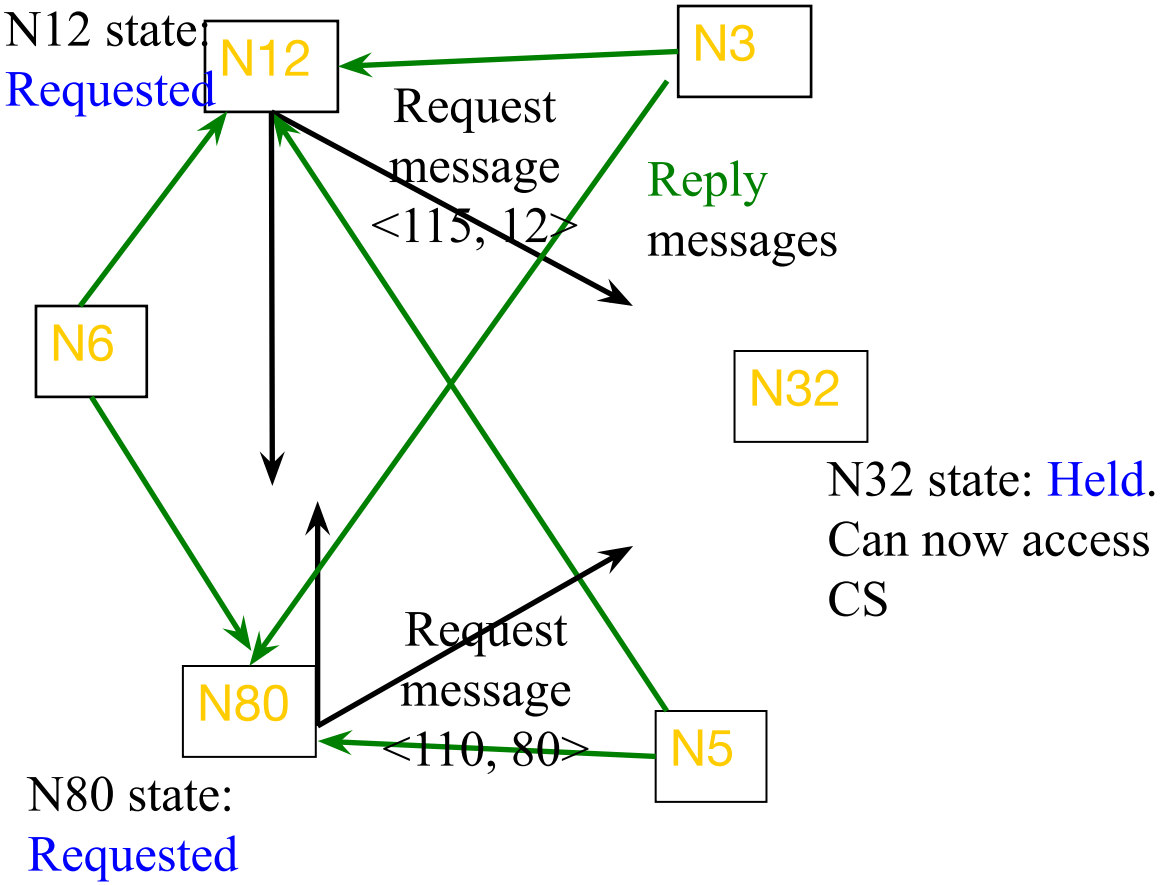

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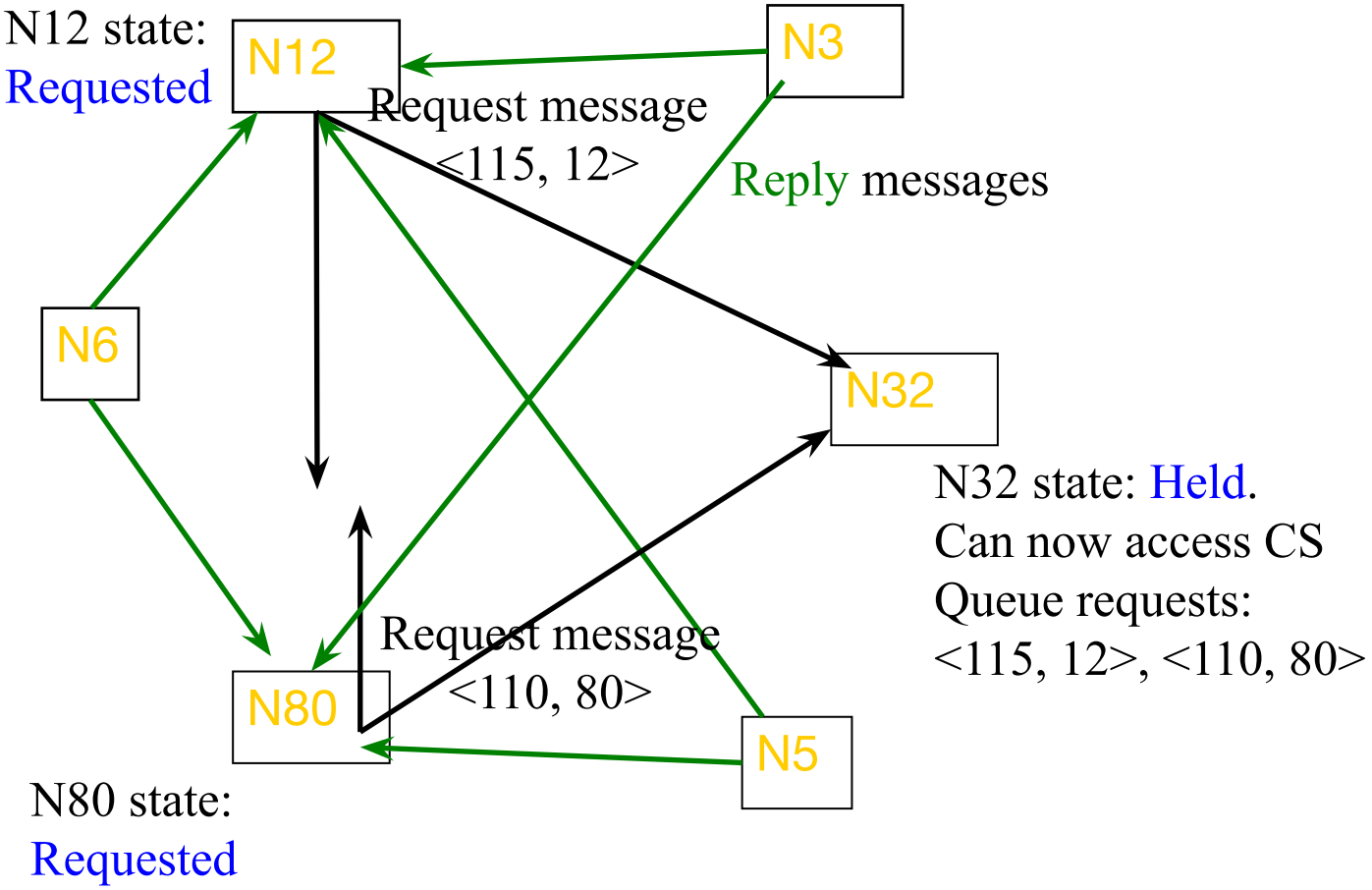

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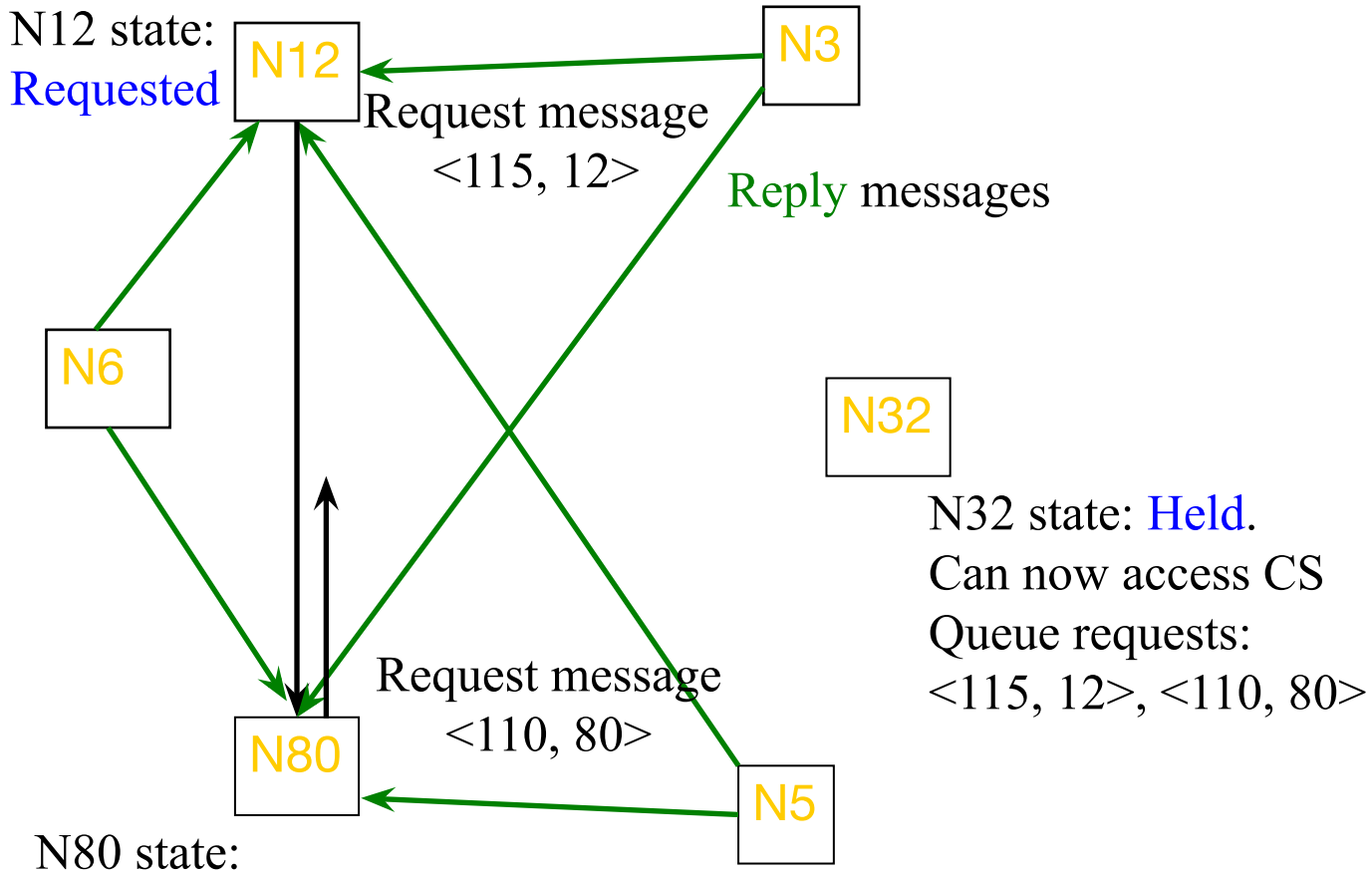

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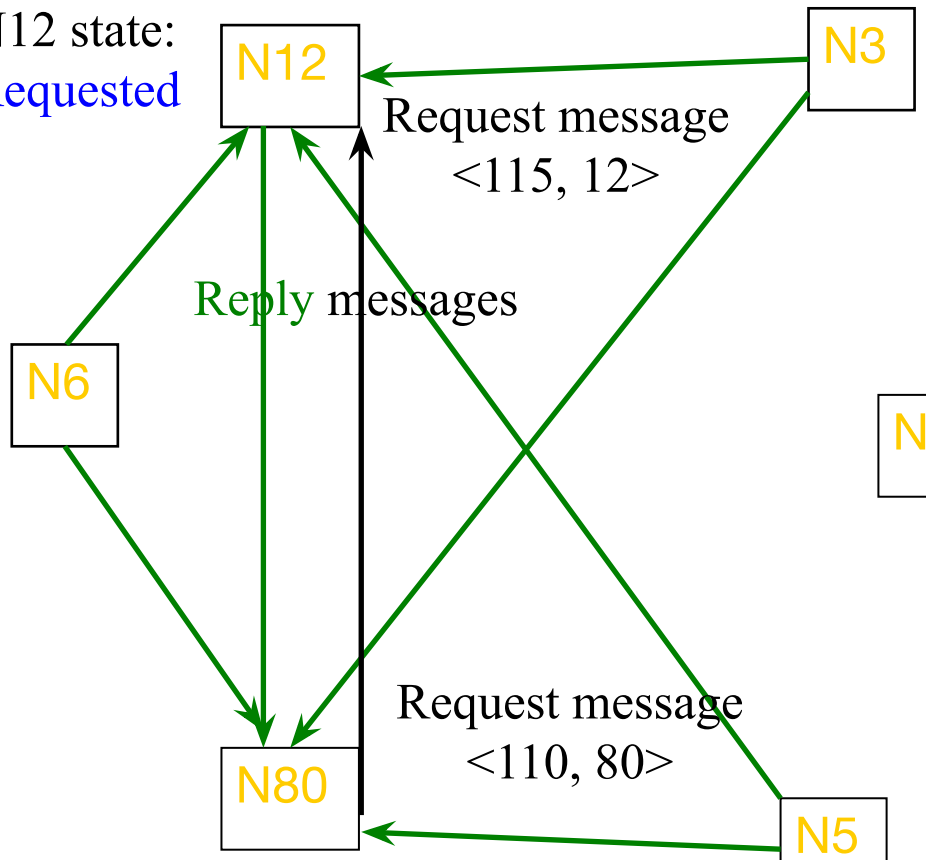
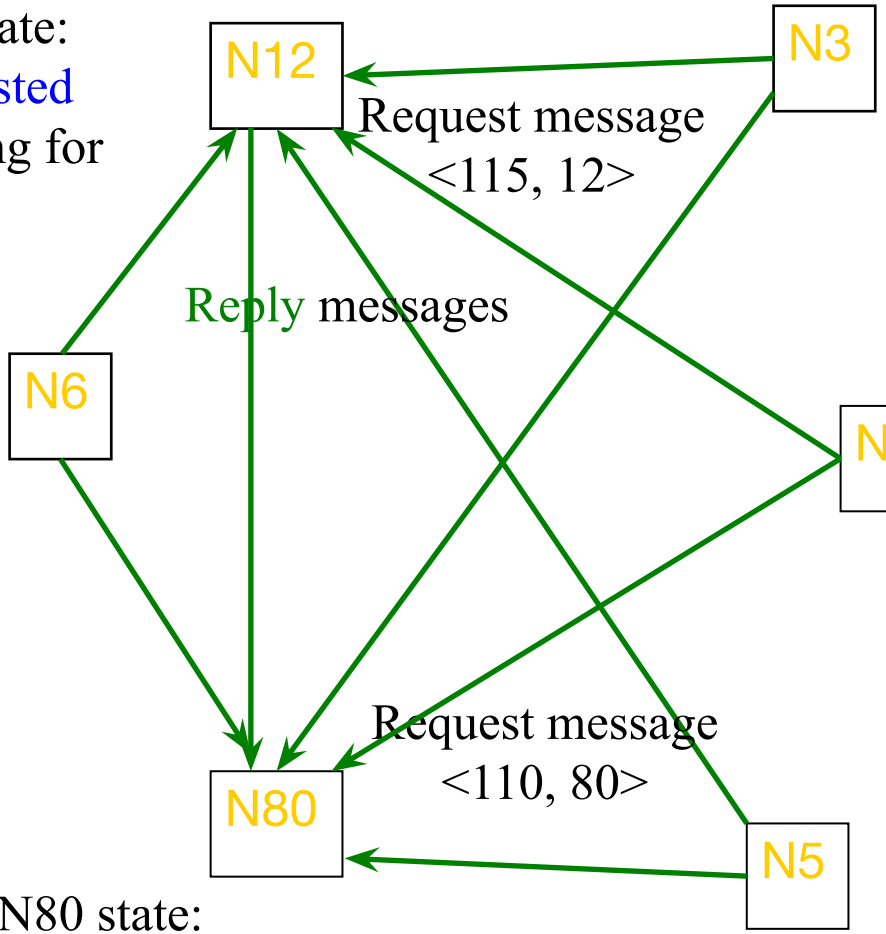


Example: Ricart-Agrawala Algorithm1

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



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

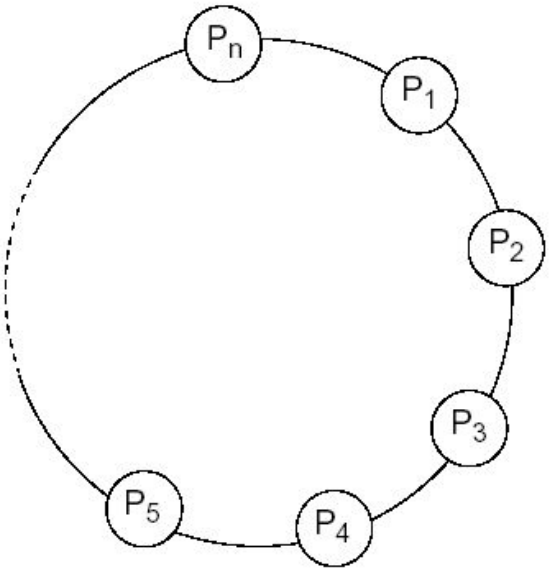
N80 state: Held. Can now access CS. Queue requests: <115, 12>

Token-Based Mutual Exclusion

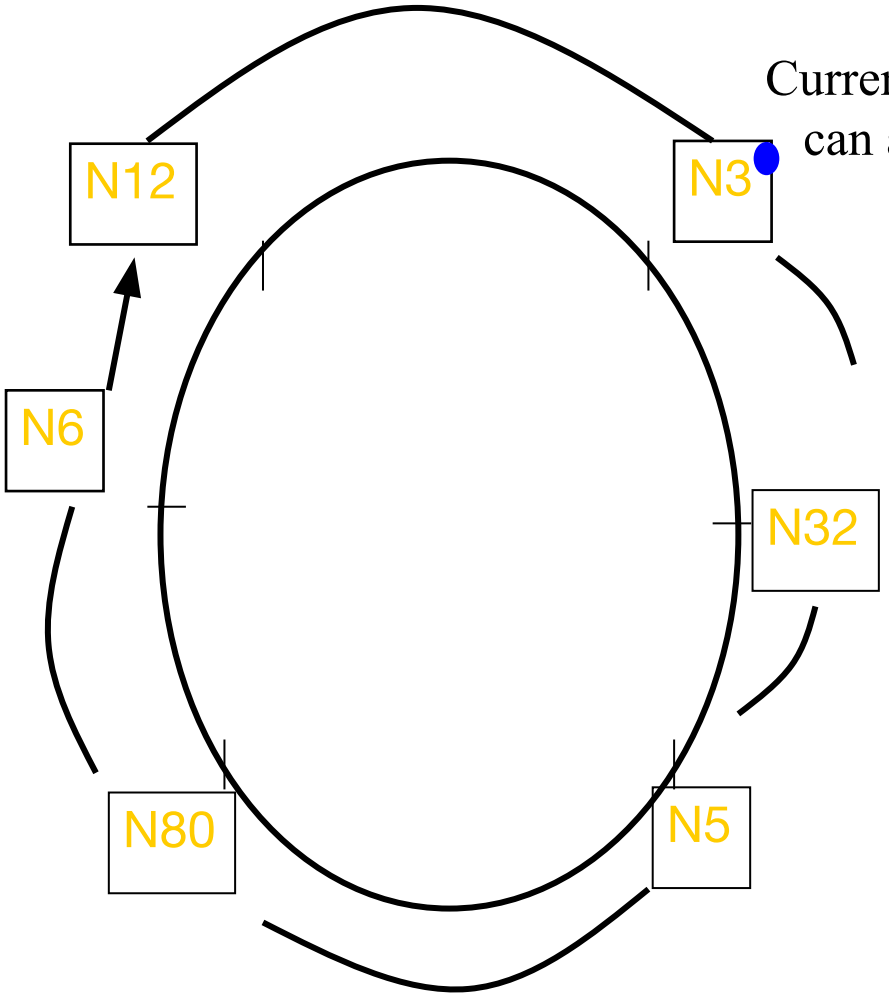
- Token Ring Algorithm
- Ricart-Agrawala Second Algorithm

Token Ring Algorithm

- Simple - arrange the n processes in a logical ring.
- The logical ring topology is created by giving each process the address of one other process which is its neighbor in the clockwise direction.
- Logical ring topology is unrelated to the physical interconnection between computers.

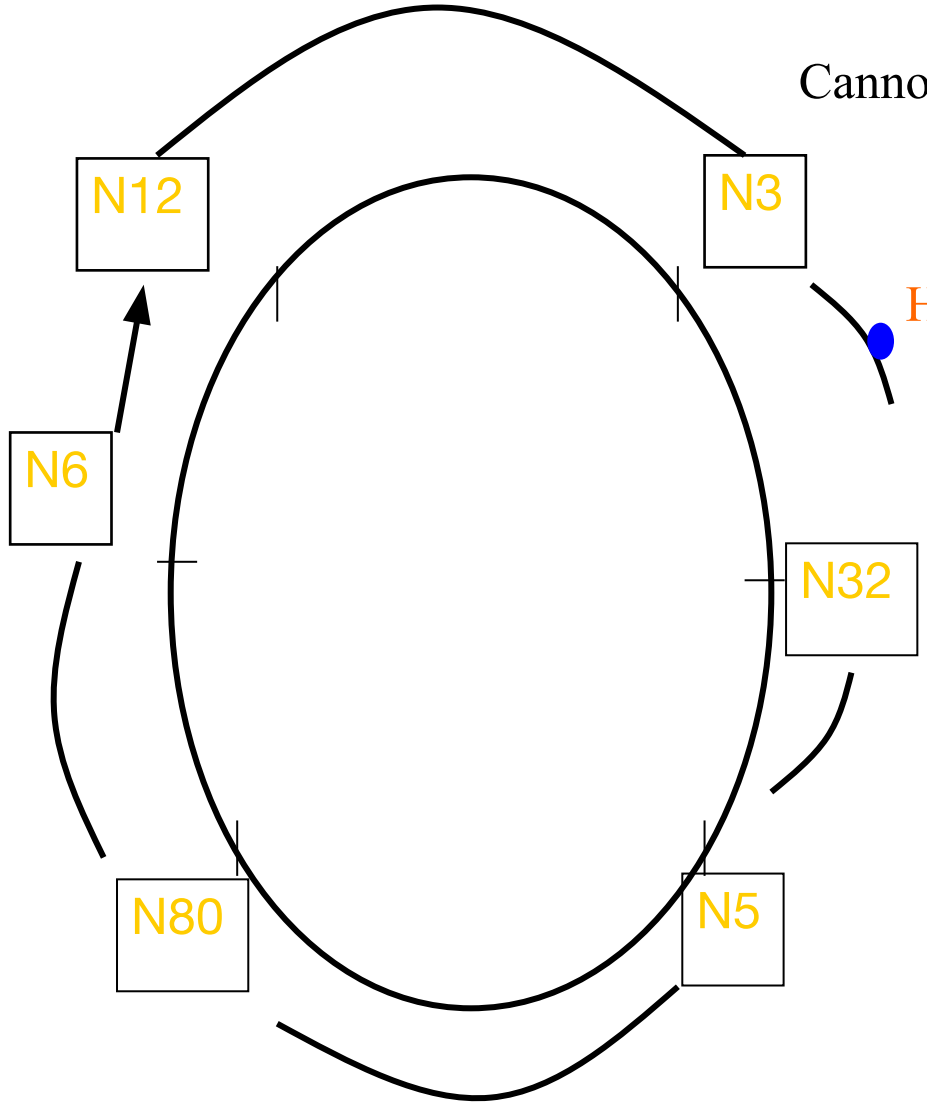


Token Ring-based Mutual Exclusion



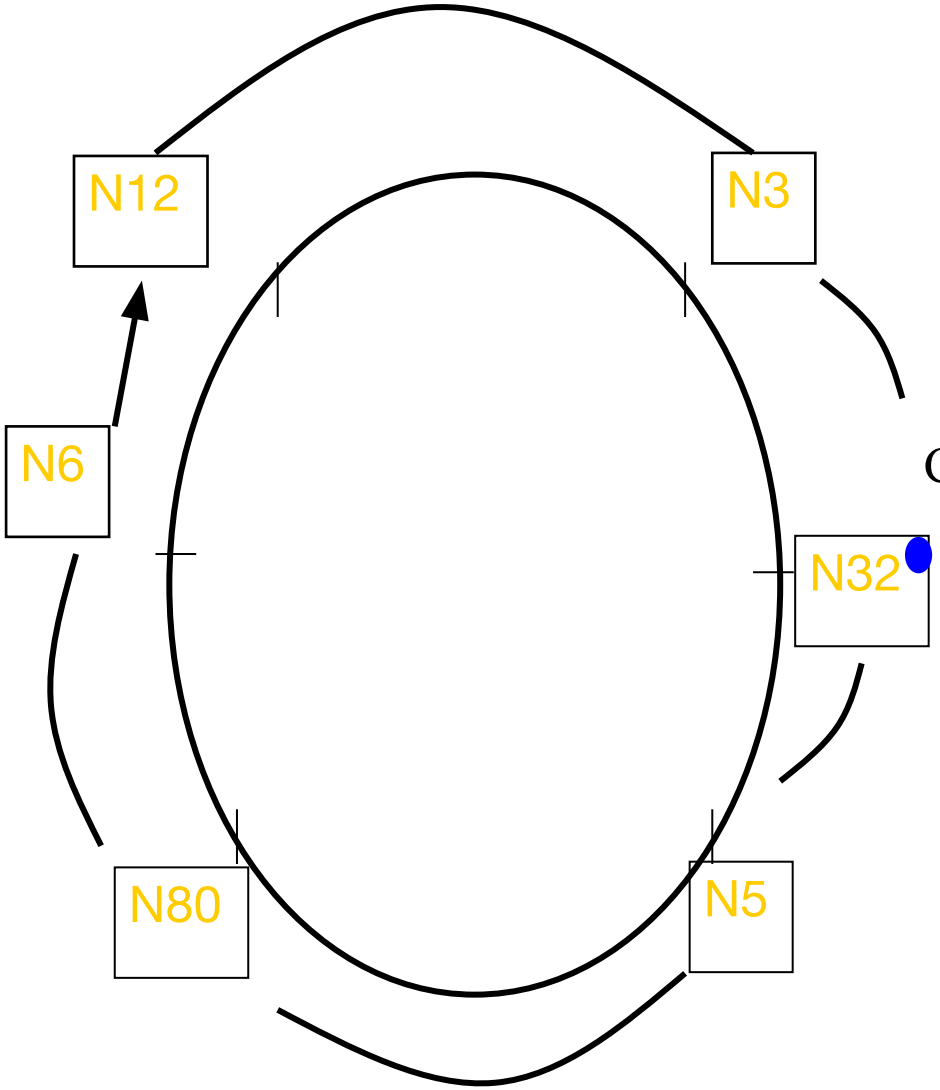
Token:

Token Ring-based Mutual Exclusion



Token:

Token Ring-based Mutual Exclusion



Currently holds token, can access CS

Token:

Token Ring Algorithm

- The token is initially given to one process.
- The token is passed from one process to its neighbor around the ring.
- When a process requires entry to the CS, it waits to receive a token from its neighbor (right) and retains it; enters the CS; when done, it passes the token to its left neighbor (clockwise).
- When a process receives the token, but does not require entry to CS, it passes it along the ring.

Token Ring Algorithm

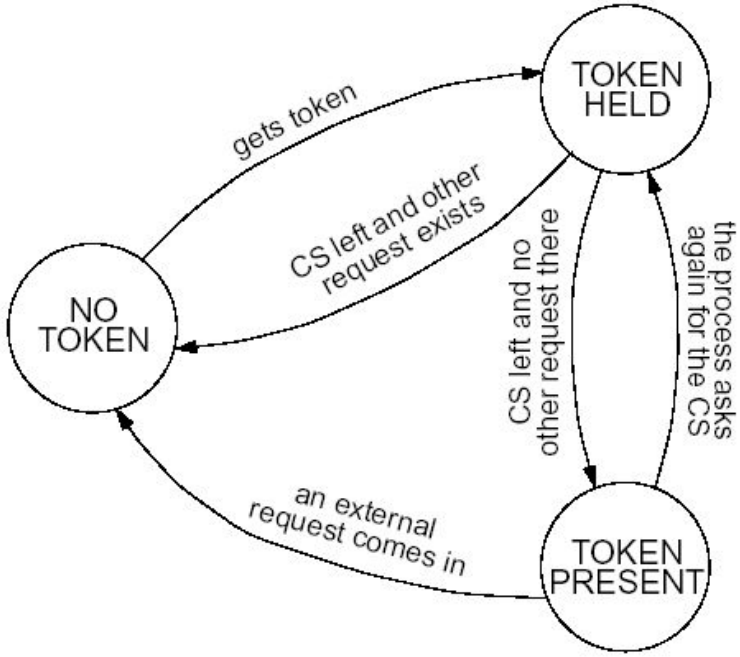
- It can take from 1 to n-1 messages to obtain a token. Messages are sent around the ring even when no process requires the token (additional load on network).
- Works well in heavily loaded situations when there is a high probability that the process which gets the token wants to enter the CS. Works poorly in lightly loaded cases.
- If a process fails → no progress can be made until a reconfiguration is applied to extract the process from the ring.
- If the process holding the token fails → a unique process has to be picked to regenerate token and pass it along the ring (election algorithm).

Ricart-Agrawala Second Algorithm

- A process is allowed to enter the critical section when it gets the token.
  - Initially the token is assigned arbitrarily to one of the processes.
- In order to get the token it sends a request to all other processes competing for the same resource.
  - The request message consists of the requesting process' timestamp (logical clock) and its identifier.
- When a process Pi leaves a critical section
  - it passes the token to one of the processes which are waiting for it; this will be the first process Pj, where j is searched in order [i+1, i+2, ..., n, 1, 2, ..., i-2, i-1] for which there is a pending request.
  - If no process is waiting, Pi retains the token (and is allowed to enter the CS if it needs); it will pass over the token as result of an incoming request.
- How does Pi find out if there is a pending request?
  - Each process Pi records the timestamp corresponding to the last request it got from process Pj, in requestPi[j]. In the token itself, token[j] records the timestamp (logical clock) of Pj's last holding of the token. If requestPi[j] > token[j] then Pj has a pending request.

Ricart-Agrawala Second Algorithm (cont'd)

- Each process keeps its state with respect to the token: NO-TOKEN, TOKEN-PRESENT, TOKEN-HOLD.



Ricart-Agrawala Second Algorithm (cont'd)

The Algorithm

- Rule for process initialization

  /* performed at initialization */

[RI1]: $state_{Pi}$:= NO-TOKEN for all processes P_i, except *one single process* P_x for which $state_{Px}$:= TOKEN-PRESENT.

[RI2]: $token[k]$ initialized 0 for all elements $k = 1 .. n$. $request_{Pi}[k]$ initialized 0 for all processes P_i and all elements $k = 1 .. n$.

- Rule for access request and execution of the CS

  /* performed whenever process P_i requests an access to the CS and when it finally gets it; in particular P_i can already possess the token */

[RA1]: **if** $state_{Pi}$ = NO-TOKEN **then**

P_i sends a request message to all processes; the message is of the form (T_{Pi}, i), where $T_{Pi} = C_{Pi}$ is the value of the local logical clock, and i is an identifier of P_i.

P_i waits until it receives the token.

end if.

$state_{Pi}$:= TOKEN-HELD.

P_i enters the CS.

Ricart-Agrawala Second Algorithm (cont'd)

- Rule for handling incoming requests

/* performed by P_i whenever it received a request (T_{Pj}, j) from P_j */

[RH1]: $request[j] := \max(request[j], T_{Pj})$.

[RH2]: **if** $state_{Pi}$ = TOKEN-PRESENT **then**

P_i releases the resource (see rule RR2).

end if.

- Rule for releasing a CS

/* performed by P_i after it finished work in a CS or when it holds a token without using it and it got a request */

[RR1]: $state_{Pi}$ = TOKEN-PRESENT.

[RR2]: **for** k = [i+1, i+2, ..., n, 1, 2, ..., i-2, i-1] **do**

if request[k] > token[k] **then**

$state_{Pi}$:= NO-TOKEN.

$token[i] := C_{Pi}$, the value of the local logical clock.

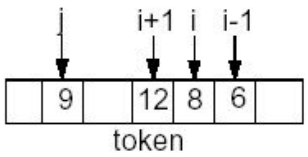
P_i sends the token to P_k.

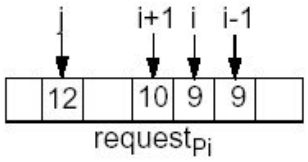
break. /* leave the for loop */

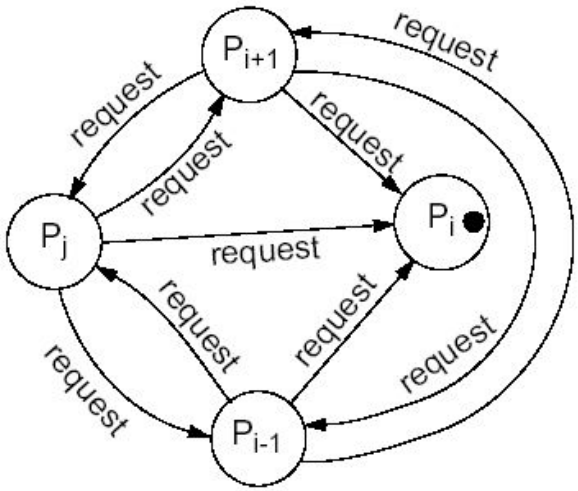
end if.

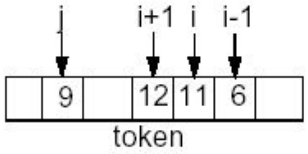
end for.

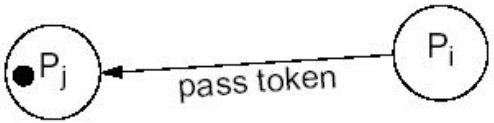
Ricart-Agrawala Second Algorithm (cont'd)

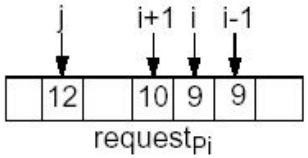


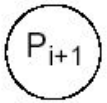


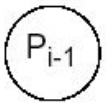












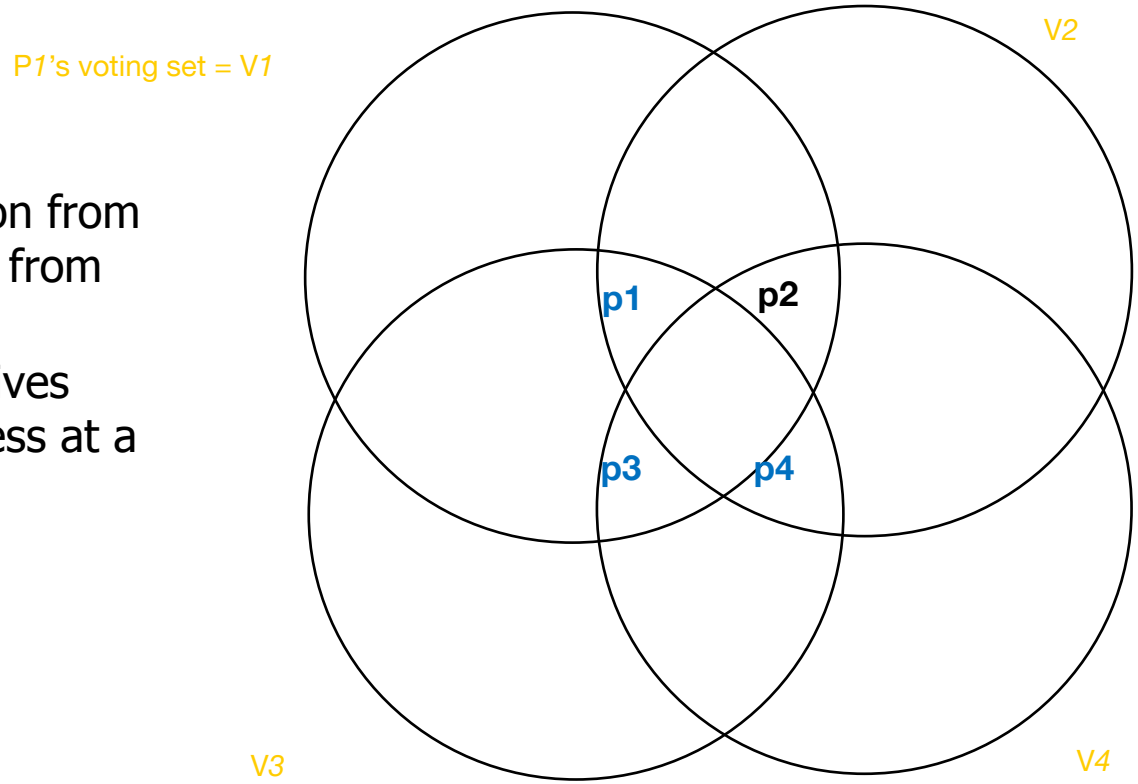
Ricart-Agrawala Second Algorithm (cont'd)

- The complexity is reduced compared to the (first) Ricart-Agrawala algorithm: it requires *n* messages for entering a CS: (*n*-1) requests and one reply.

- The failure of a process, except the one which holds the token, doesn't prevent progress.

Maekawa's Algorithm: Voting Sets

- Ricart-Agrawala1 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 at a time



- 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

Maekawa's Voting Sets

- Each process P*i* is associated with a *voting set* V*i* (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 P*i*, its voting set V*i* = row containing P*i* + column containing P*i*. Size of voting set = $2*\sqrt{N}-1$

Maekawa's Algorithm - 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*

- 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*:

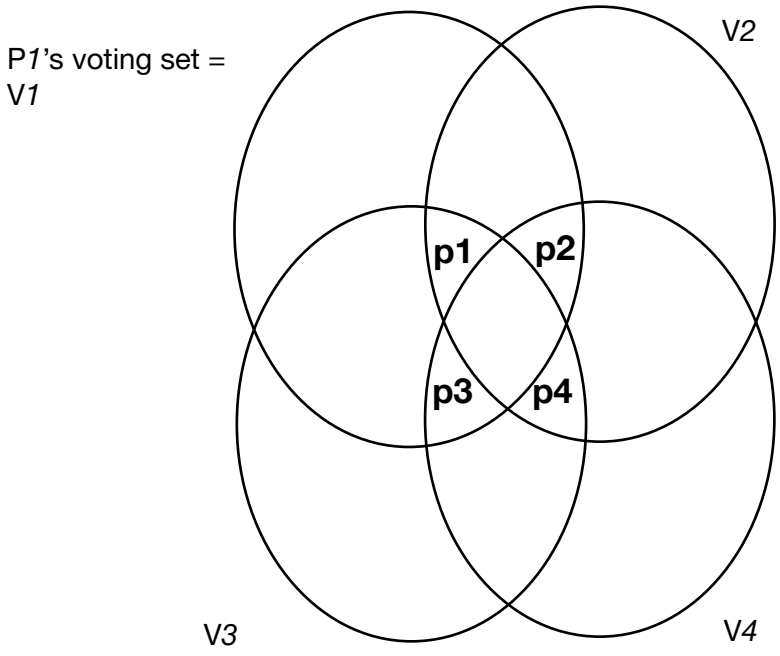
if (queue empty)
    voted = false
else
    dequeue head of queue, say P*k*
    Send Reply *only* to P*k*
    voted = true

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



Election Algorithms

- Many distributed algorithms require one process to act as a coordinator or, in general, perform some special role.
- Examples with mutual exclusion
  - Central coordinator algorithm
    - At initialization or whenever the coordinator crashes, a new coordinator has to be elected.
  - Token ring algorithm
    - When the process holding the token fails, a new process has to be elected which generates the new token.

Election Algorithms

- It doesn't matter which process is elected.
  - What is important is that one and only one process is chosen (we call this process the coordinator)
  - All processes agree on this decision.
  - Let all processes know about this leader

What happens if the leader fails?

- Election is typically started after the failure occurs.
  - The detection of a failure (e.g. the crash of the current coordinator) is normally based on time-out.
    - a process that gets no response for a period of time suspects a failure and initiates an election process.

- An election process is typically performed in two phases:
  - Select a leader with the highest priority.
  - Inform all processes about the winner.

- Assume that each process has a unique number (identifier).
  - In general, election algorithms attempt to locate the process with the highest number, among those which currently are up.

Assumptions - System Model

- *N* processes.
- Each process has a unique id.
- Messages are eventually delivered.
- Failures may occur during the election protocol.

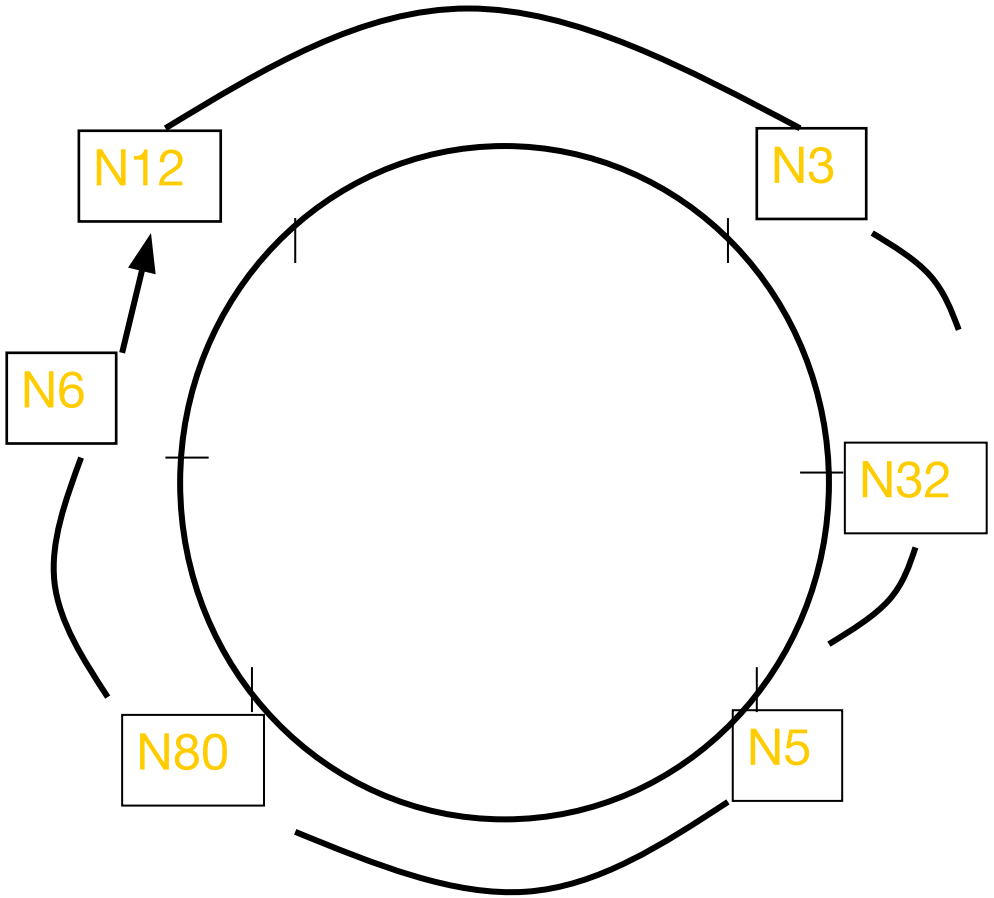
- Any process can call for an election.
- A process can call for at most one election at a time.
- Multiple processes are allowed to call an election simultaneously.
  - All of them together must yield only a single leader
- The result of an election should not depend on which process calls for it.

The Leader Election Problem

- A run of the election algorithm must always guarantee at the end:
  - **Safety**: For all non-faulty processes *p*: (*p*'s 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.

Leader Election: The Ring Algorithm

- *N* processes are organized in a logical ring
  - *i*-th process p_i has a communication channel to $p_{(i+1) \bmod N}$
  - All messages are sent clockwise around the ring.



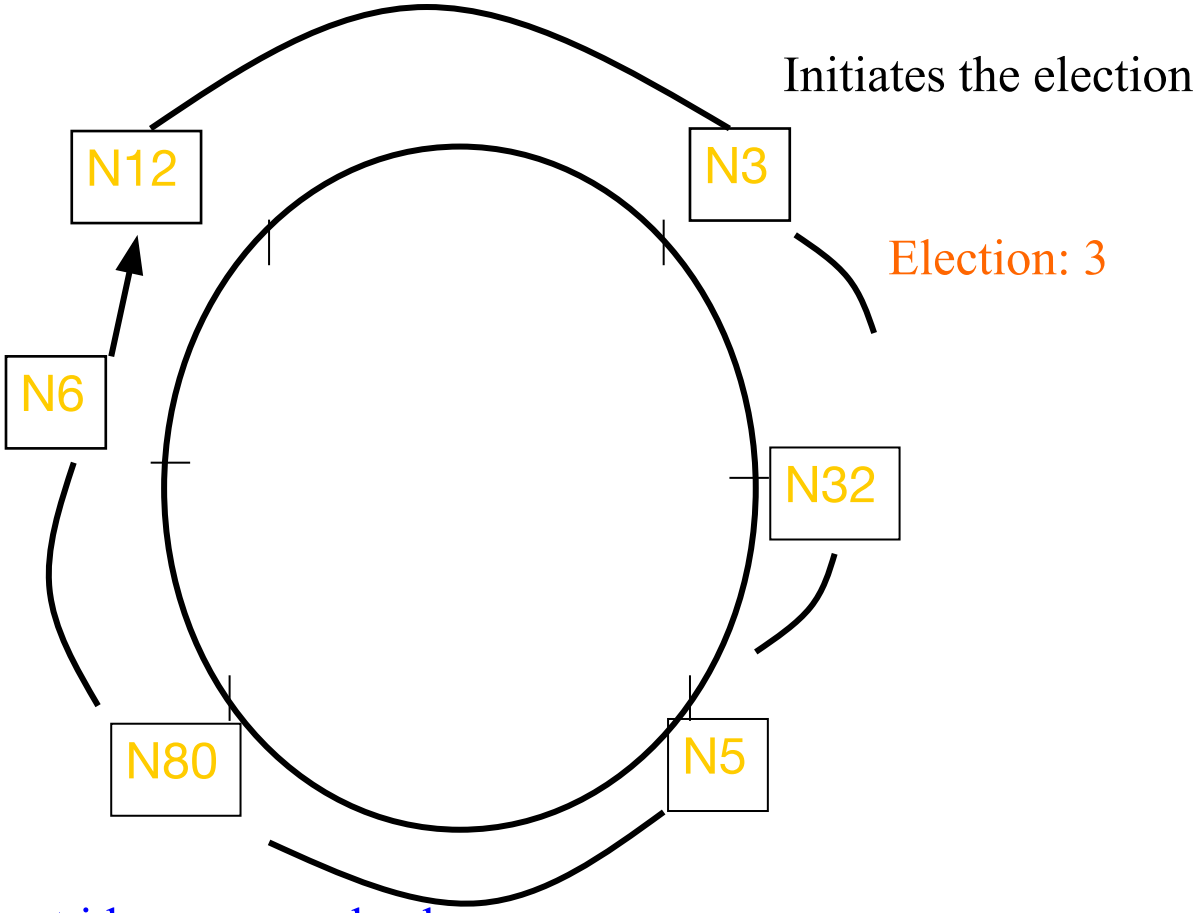
The Ring Election Protocol

- Any process p_i that discovers the old coordinator has failed initiates an "Election" message that contains p_i's own id:attr. This is the *initiator* of the election.
- When a process p_i receives an "Election" message, it compares the attr in the message with its own attr.
  - If the arrived attr is greater, p_i forwards the message.
  - If the arrived attr is smaller and p_i has not forwarded an election message earlier, it overwrites the message with its own id:attr, and forwards it.
  - If the arrived id:attr matches that of p_i, then p_i's attr must be the greatest (why?), and it becomes the new coordinator. This process then sends an "Elected" message to its neighbor with its id, announcing the election result.
- When a process p_i receives an "Elected" message, it
  - sets its variable $elected_i$ ☐ id of the message.
  - forwards the message unless it is the new coordinator.

The Ring-based Algorithm

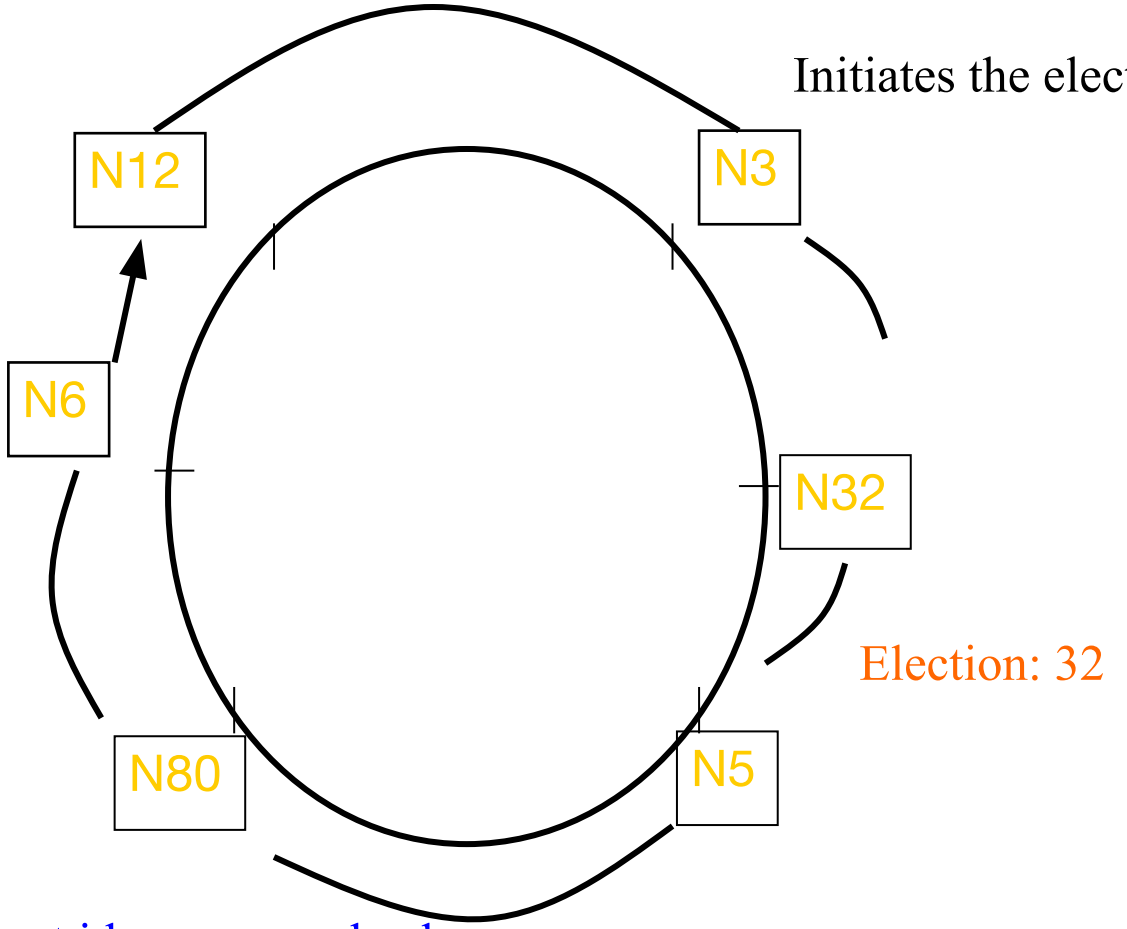
- We assume that the processes are arranged in a logical ring
  - Each process knows the address of one other process, which is its neighbor in the clockwise direction.
- The algorithm elects a single coordinator, which is the process with the highest identifier.
- Election is started by a process which has noticed that the current coordinator has failed.
  - The process places its identifier in an election message that is passed to the following process.
  - When a process receives an election message
    - It compares the identifier in the message with its own.
    - If the arrived identifier is greater, it forwards the received election message to its neighbor
    - If the arrived identifier is smaller it substitutes its own identifier in the election message before forwarding it.
    - If the received identifier is that of the receiver itself, this will be the coordinator.
- The new coordinator sends an elected message through the ring.

Leader Election: Ring Algorithm Example



Goal: Elect highest id process as leader

Leader Election: Ring Algorithm Example



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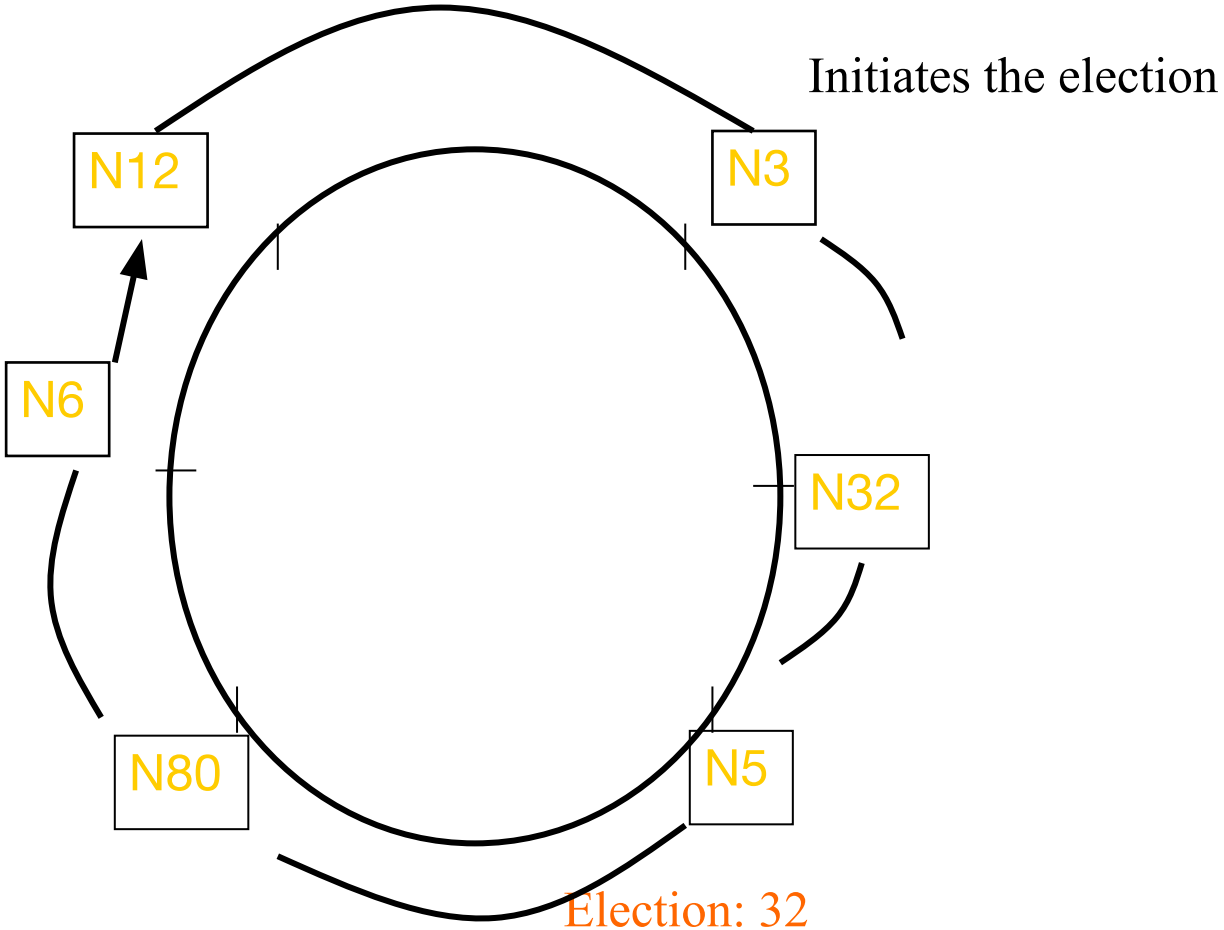
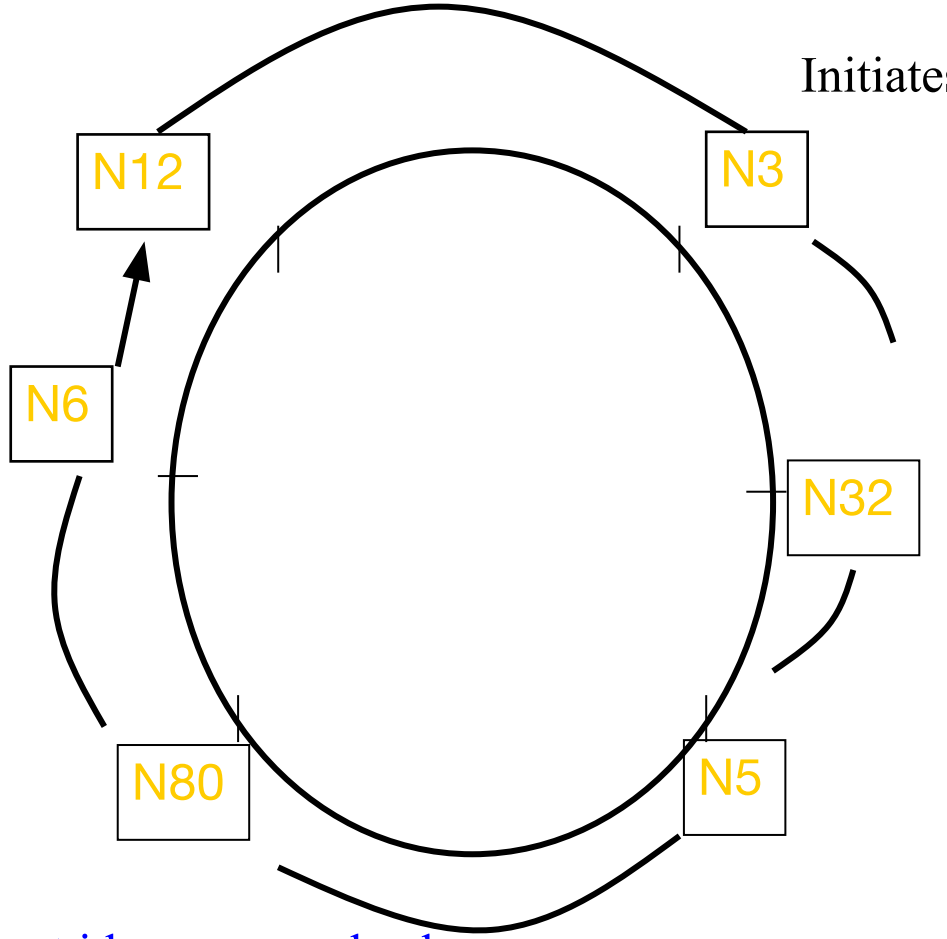
Leader Election: Ring Algorithm Example



Goal: Elect highest id process as leader

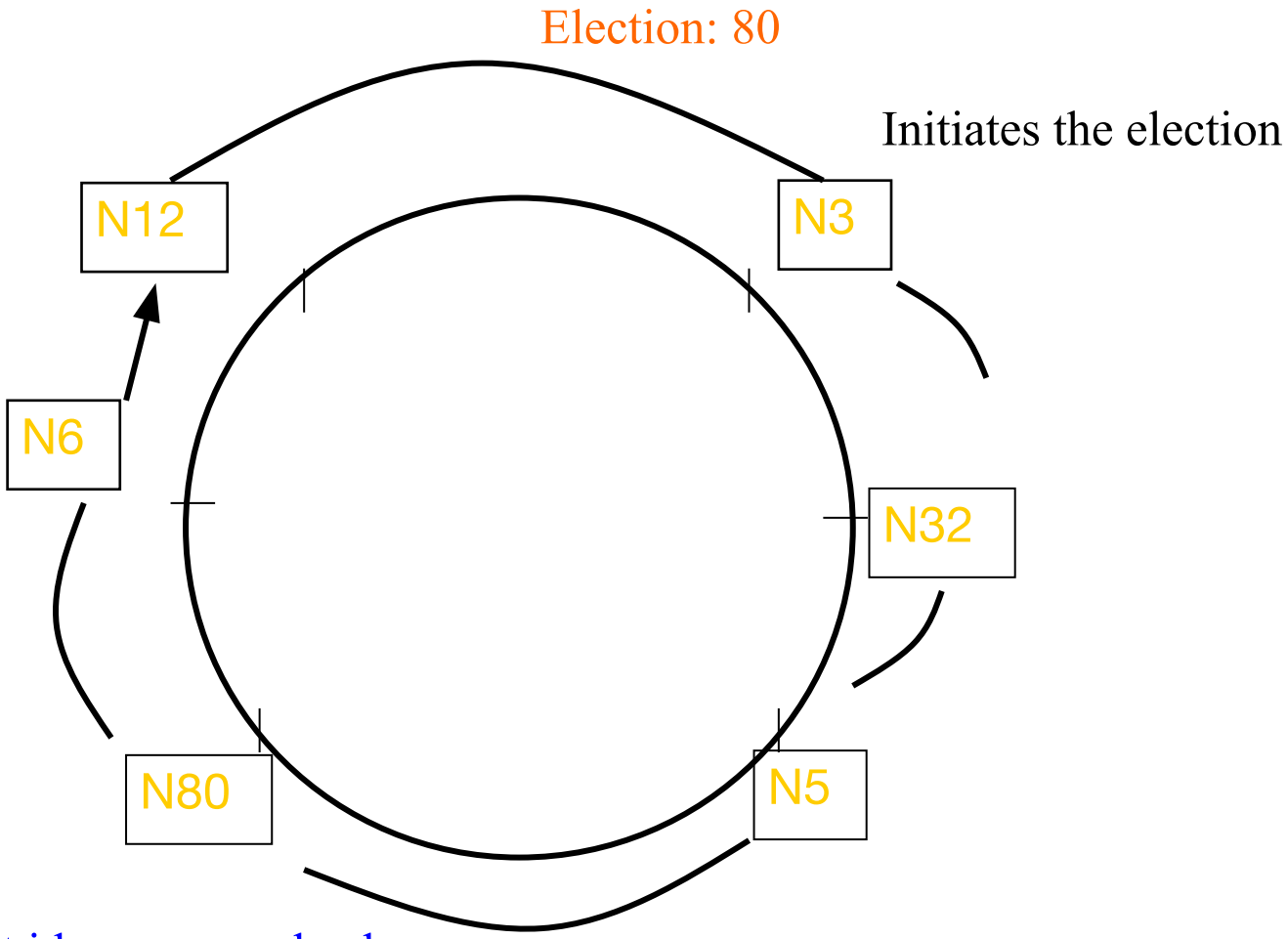
Leader Election: Ring Algorithm Example



Election: 80

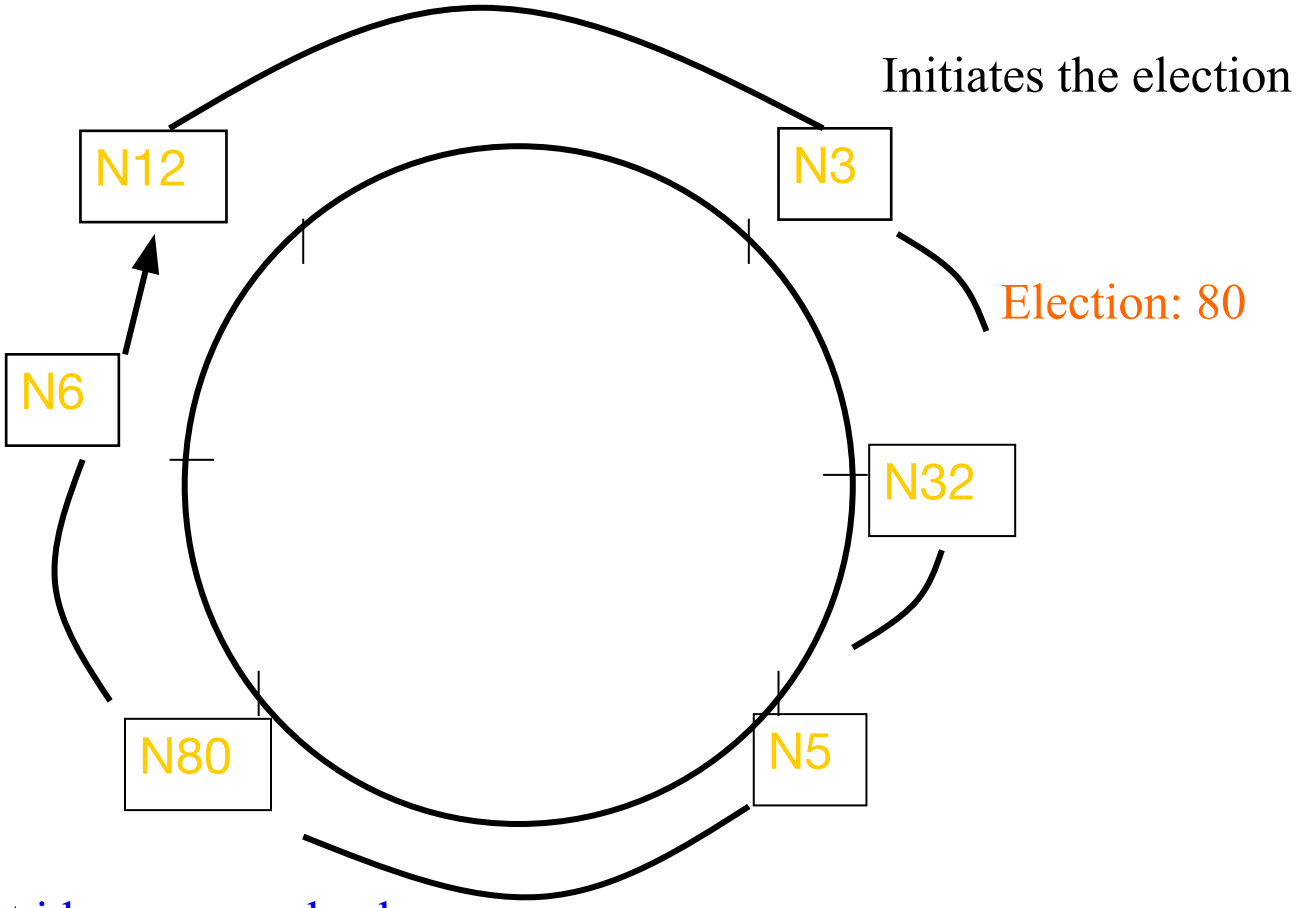
Goal: Elect highest id process as leader

Leader Election: Ring Algorithm Example



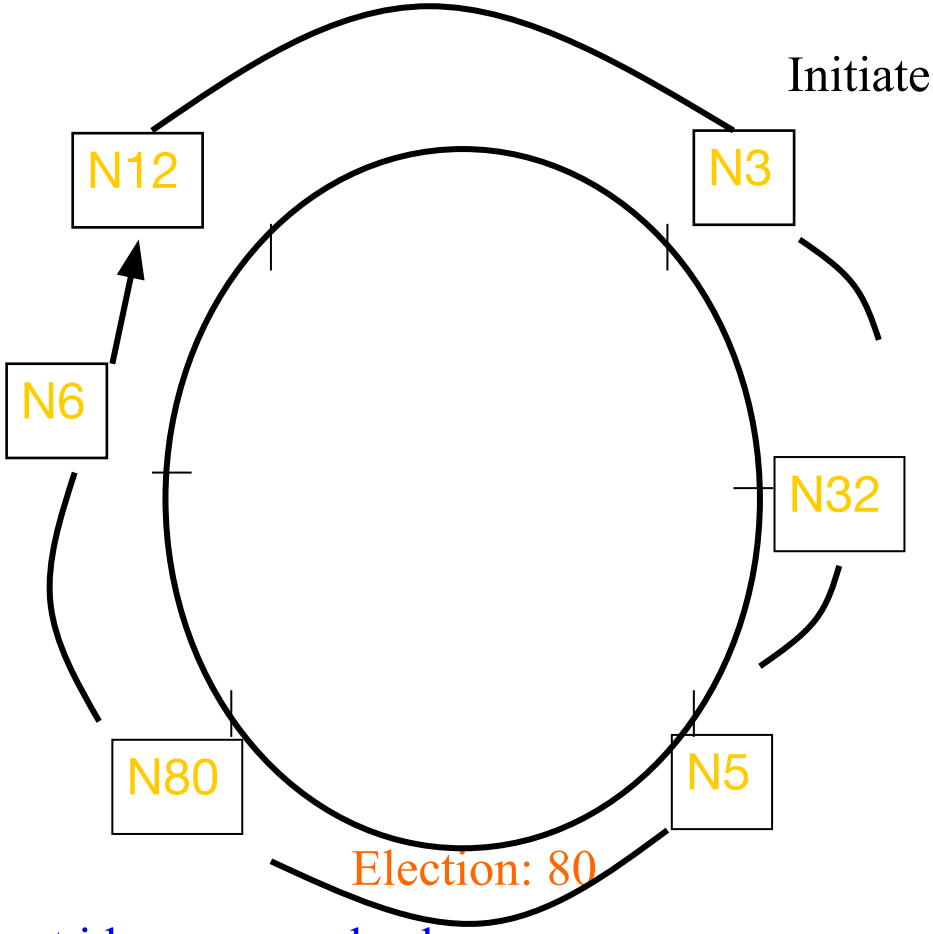
Goal: Elect highest id process as leader

Leader Election: Ring Algorithm Example



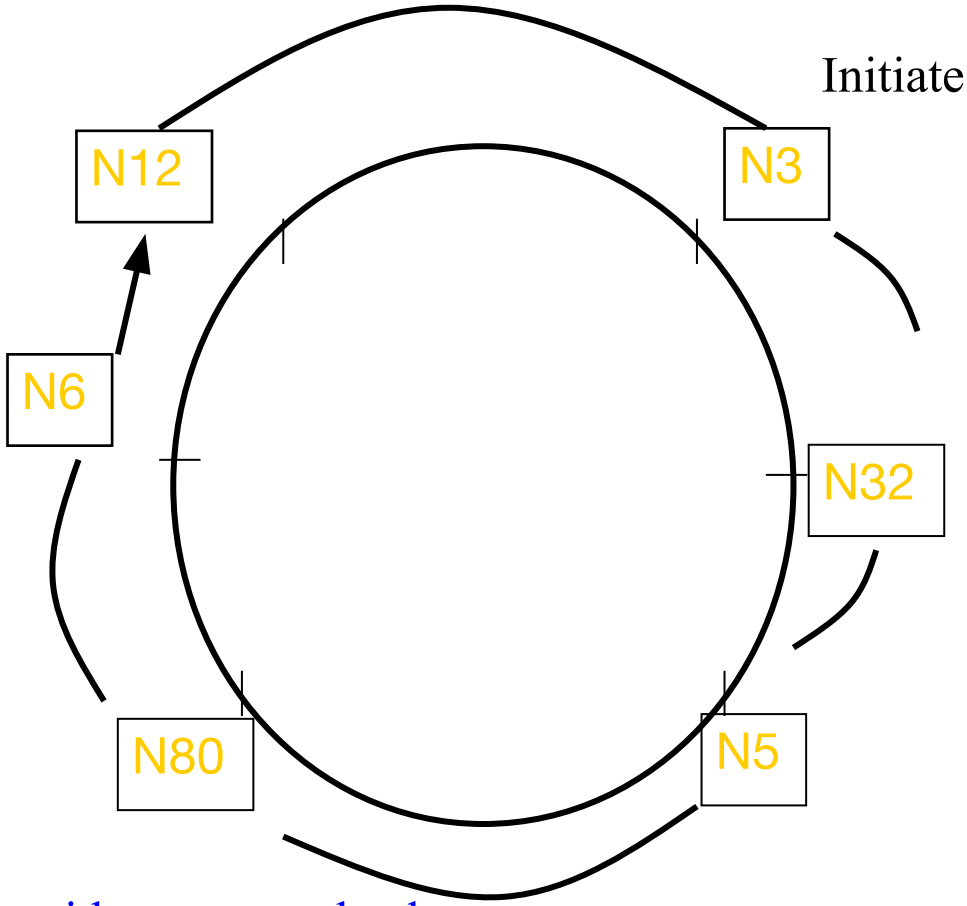
Goal: Elect highest id process as leader

Leader Election: Ring Algorithm Example



Goal: Elect highest id process as leader

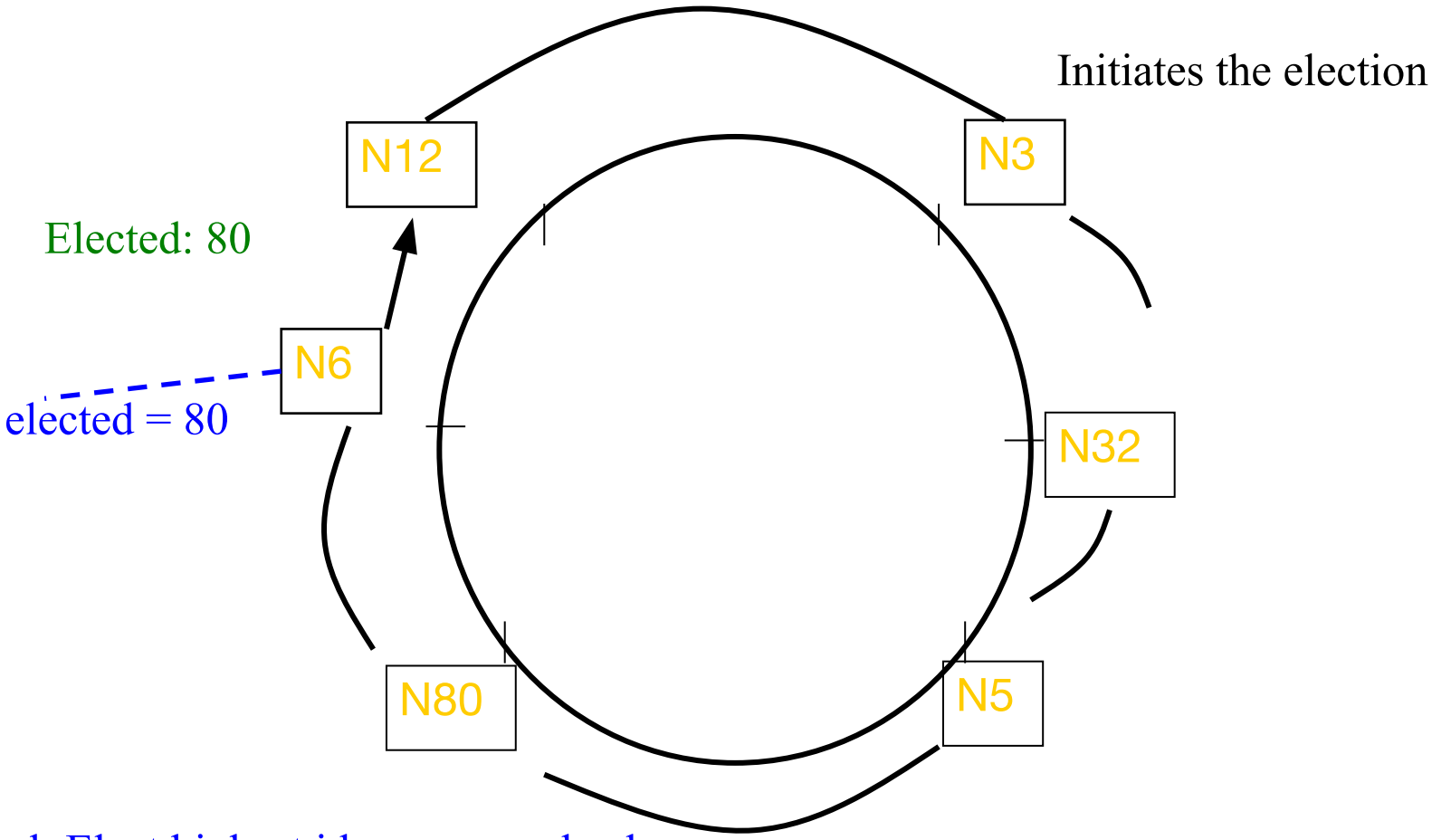
Leader Election: Ring Algorithm Example



Elected: 80

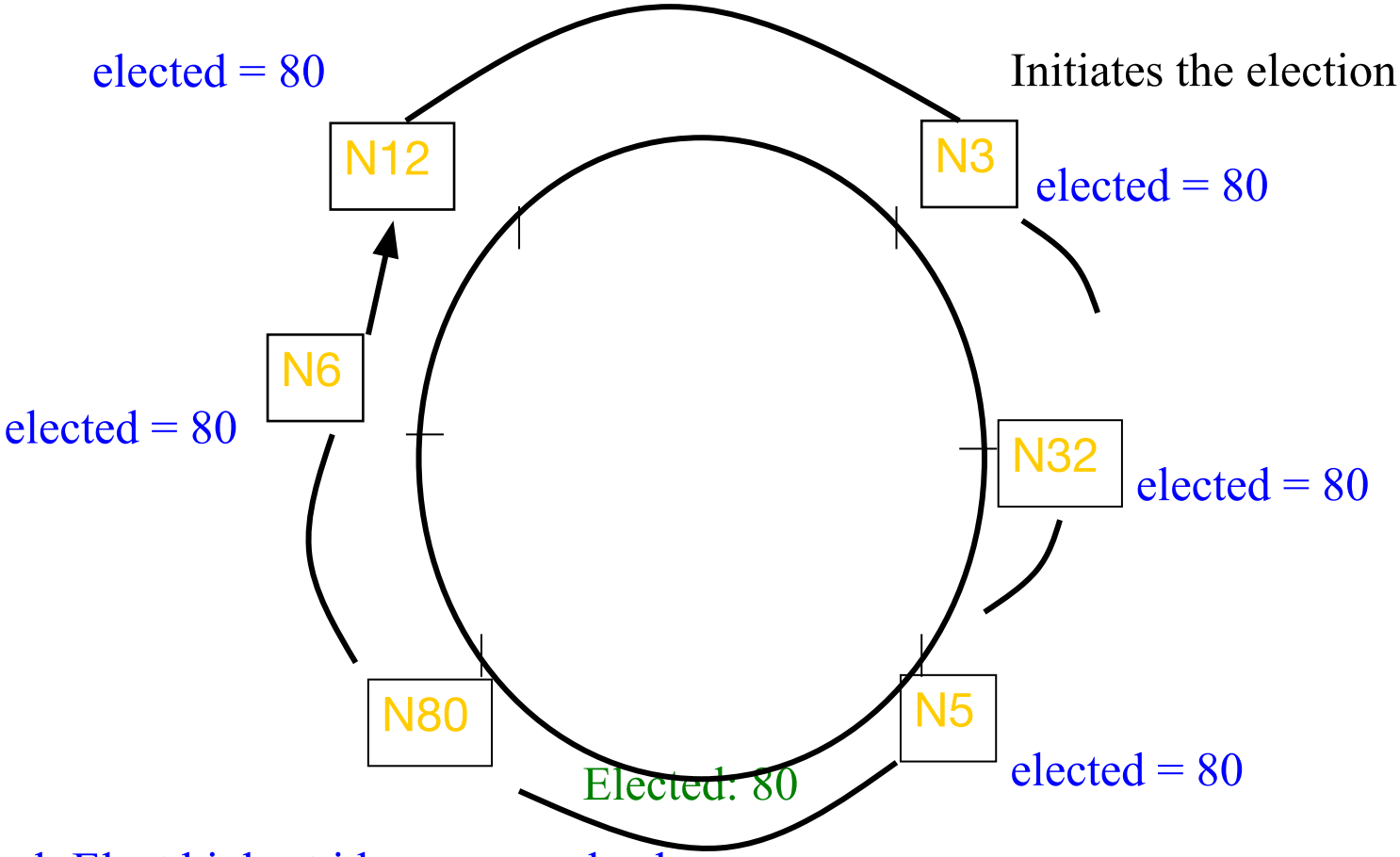
Goal: Elect highest id process as leader

Leader Election: Ring Algorithm Example



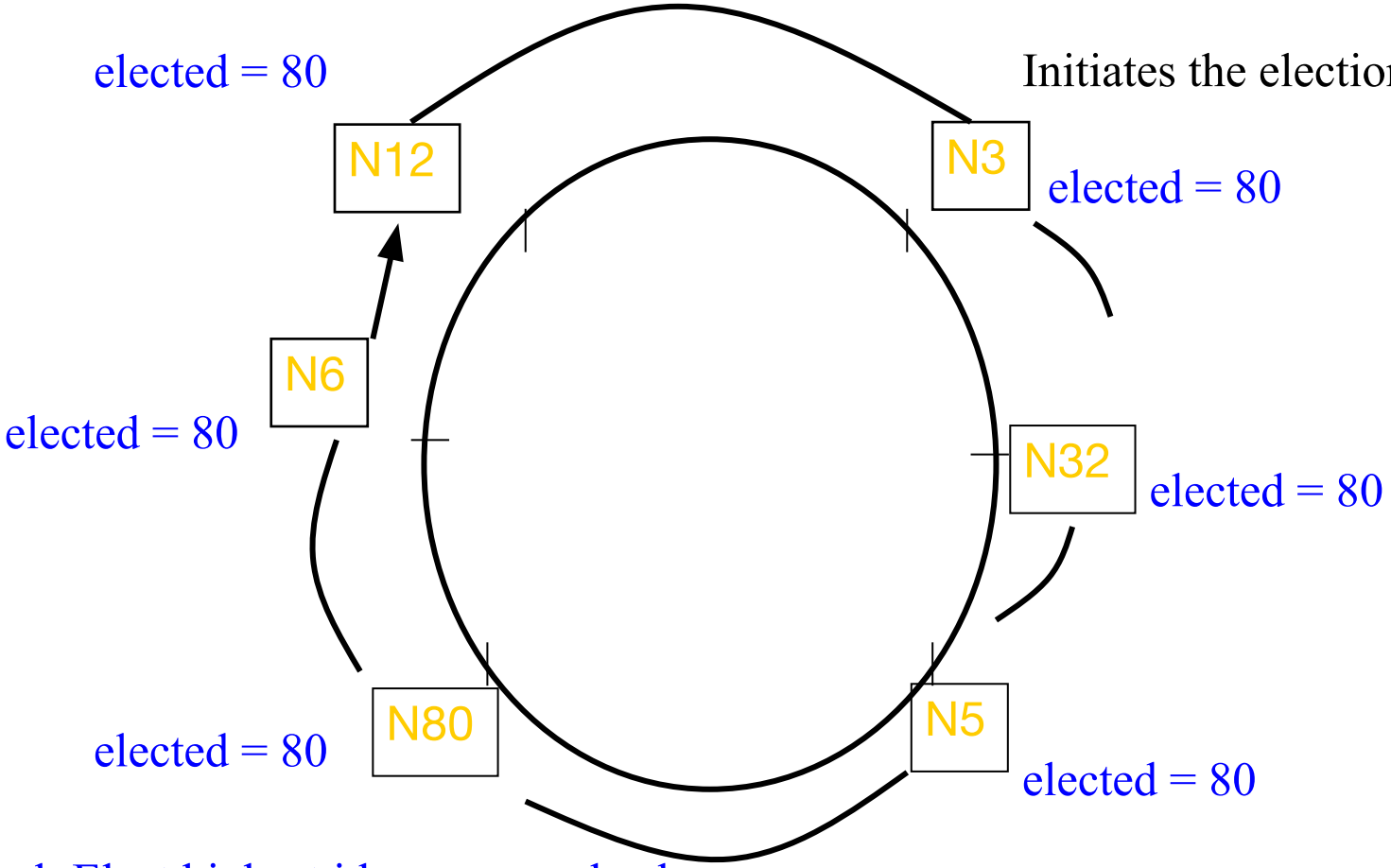
Goal: Elect highest id process as leader

Leader Election: Ring Algorithm Example



Goal: Elect highest id process as leader

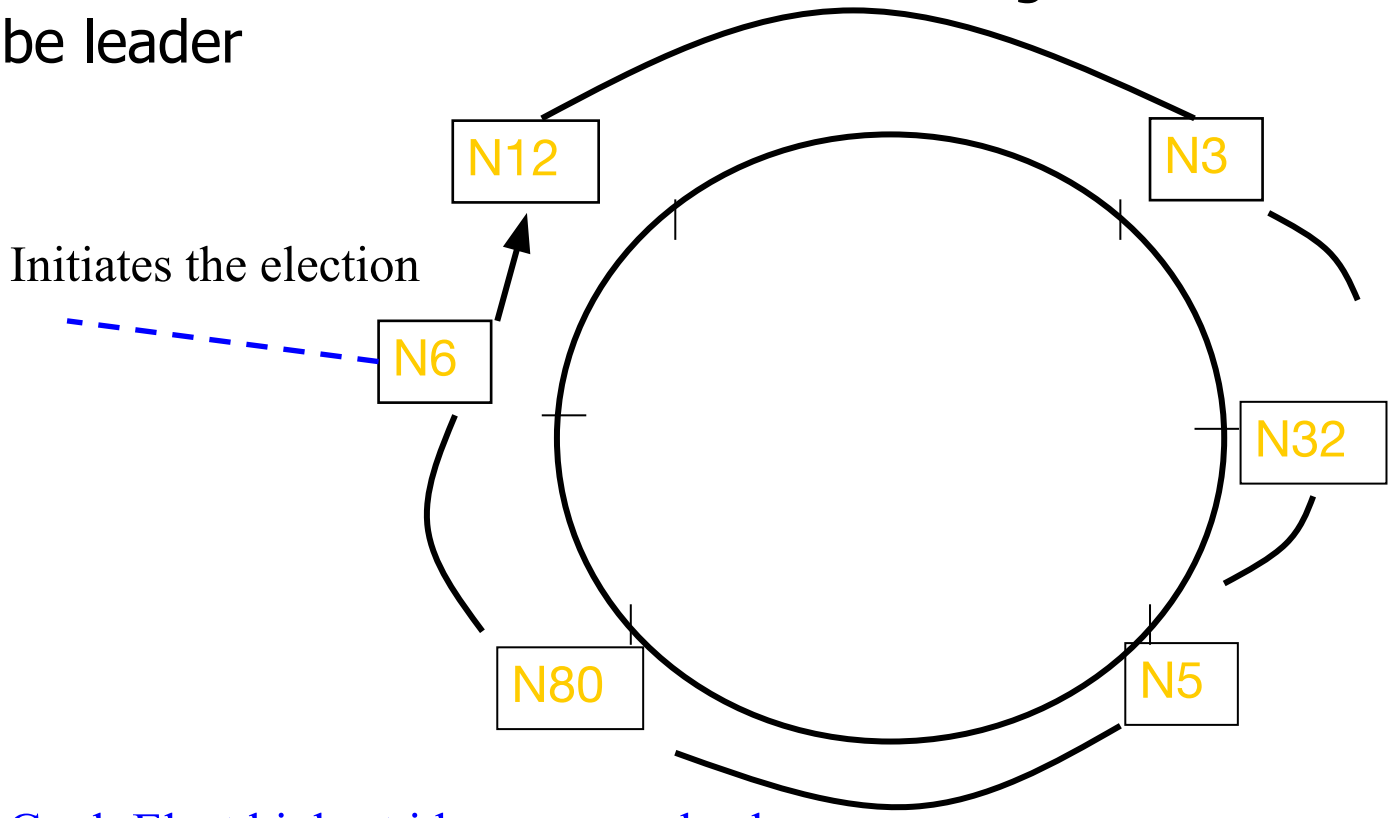
Leader Election: Ring Algorithm Example



Goal: Elect highest id process as leader

Worst-case Analysis

- Let's assume no failures occur during the election protocol itself, and there are *N* processes
- How many messages?
- Worst case occurs when the initiator is the ring successor of the would-be leader



Goal: Elect highest id process as leader

Worst/Best/Avg Case Analysis

Worst-case Analysis

- (*N-1*) messages for Election message to get from Initiator to would-be coordinator
- *N* messages for Election message to circulate around ring without message being changed
- *N* messages for Elected message to circulate around the ring
- Message complexity: (*3N-1*) messages
- Completion time: (*3N-1*) message transmission times
- Thus, if there are no failures, election terminates (liveness) and everyone knows about highest-attribute process as leader (safety)

Best Case Analysis

- Initiator is the would-be leader.
- Message complexity: *2N* messages
- Completion time: *2N* message transmission times

Average Case Analysis

- *(2N + N/2)* messages; *(2N + N/2)* completion time

Leader Election:The Ring Algorithm Multiple Initiators

- Several elections can be active at the same time.
  - Messages generated by later elections should be killed as soon as possible.
- Processes can be in one of two states
  - Participant or Non-participant.
    - Initially, a process is non-participant.

- The process initiating an election marks itself participant.
- Rules
  - Include initiators id with all messages
  - For a participant process, if the identifier in the election message is smaller than the own, does not forward any message (it has already forwarded it, or a larger one, as part of another simultaneously ongoing election).
  - When forwarding an election message, a process marks itself participant.
  - When sending (forwarding) an elected message, a process marks itself non-participant.

Leader Election:The Ring Algorithm Multiple Initiators

- By default, the state of a process is NON-PARTICIPANT

- Rule for election process initiator

  /* performed by a process P_i, which triggers the election procedure */

[RE1]: $state_{Pi}$:= PARTICIPANT.

[RE2]: P_i sends an *election message* with *message.id* := i to its neighbour.

- Rule for handling an incoming *election message*

  /* performed by a process P_j, which receives an *election message* */

[RH1]: **if** *message.id* > j **then**

  P_j forwards the received *election message*.

  $state_{Pj}$:= PARTICIPANT.

elseif *message.id* < j **then**

  if $state_{Pj}$ = NON-PARTICIPANT **then**

    P_j forwards an *election message* with *message.id* := j.

    $state_{Pj}$:= PARTICIPANT

  end if

else

  P_j is the coordinator and sends an *elected message* with *message.id* := j to its neighbour.

  $state_{Pj}$:= NON-PARTICIPANT.

end if.

- Rule for handling an incoming *elected message*

  /* performed by a process P_i, which receives an *elected message* */

[RD1]: **if** *message.id* ≠ i **then**

  P_i forwards the received *elected message*.

  $state_{Pj}$:= NON-PARTICIPANT.

end if.

Failures?

- One option: have predecessor (or successor) of would-be leader N80 detect failure and start a new election run
  - May re-initiate election if
    - Receives an Election message but times out waiting for an Elected message
    - Or after receiving the Elected:80 message
  - But what if predecessor also fails?
  - And its predecessor also fails? (and so on)

Fixing for failures (2)

- Second option: use the failure detector
- Any process, after receiving Election:80 message, can detect failure of N80 via its own local failure detector
  - If so, start a new run of leader election
- But failure detectors may not be both complete and accurate
  - Incompleteness in FD => N80's failure might be missed => Violation of Safety
  - Inaccuracy in FD => N80 mistakenly detected as failed
    - => new election runs initiated forever
    - => Violation of Liveness

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 since consensus is impossible in asynchronous systems, so is election!

Leader Election: The Bully Algorithm

- A process has to know the identifier of all other processes
  - (it doesn't know, however, which one is still up); the process with the highest identifier, among those which are up, is selected.
- Any process could fail during the election procedure.
- When a process Pi detects a failure and a coordinator has to be elected
  - It sends an election message to all the processes with a higher identifier and then waits for an answer message:
  - If no response arrives within a time limit
    - Pi becomes the coordinator (all processes with higher identifier are down)
    - it broadcasts a coordinator message to all processes to let them know.
  - If an answer message arrives,
    - Pi knows that another process has to become the coordinator ☐ it waits in order to receive the coordinator message.
    - If this message fails to arrive within a time limit (which means that a potential coordinator crashed after sending the answer message) Pi resends the election message.
- When receiving an election message from Pi
  - a process Pj replies with an answer message to Pi and
  - then starts an election procedure itself(unless it has already started one) it sends an election message to all processes with higher identifier.
- Finally all processes get an answer message, except the one which becomes the coordinator.

The Bully Algorithm

- By default, the state of a process is ELECTION-OFF

- Rule for election process initiator

/* performed by a process P_i, which triggers the election procedure, or which starts an election after receiving itself an *election message* */

[RE1]: $state_{Pi}$:= ELECTION-ON.

P_i sends an *election message* to all processes with a higher identifier.

P_i waits for *answer message*.

if no *answer message* arrives before time-out **then**

P_i is the coordinator and sends a *coordinator message* to all processes.

else

P_i waits for a *coordinator message* to arrive.

if no *coordinator message* arrives before time-out **then**

restart election procedure according to RE1

end if

end if.

- Rule for handling an incoming *election message*

/* performed by a process P_i at reception of an *election message* coming from P_j */

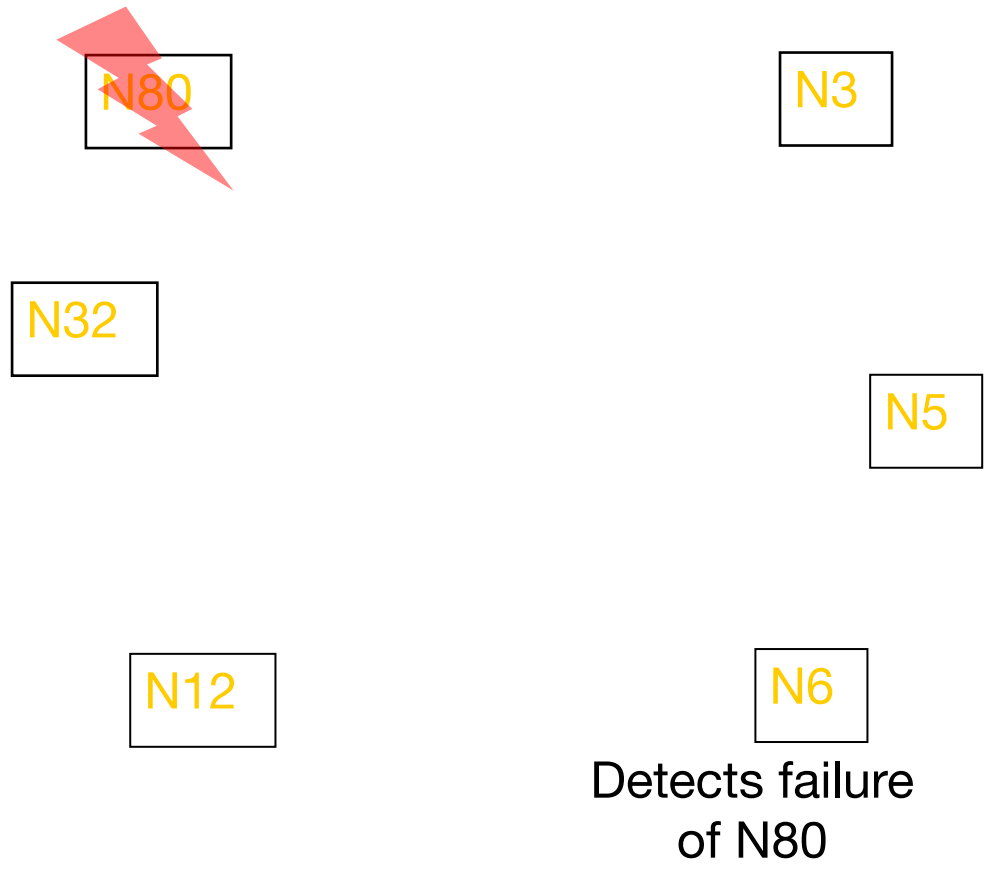
[RH1]: P_i replies with an *answer message* to P_j.

[RH2]: **if** $state_{Pi}$:= ELECTION-OFF **then**

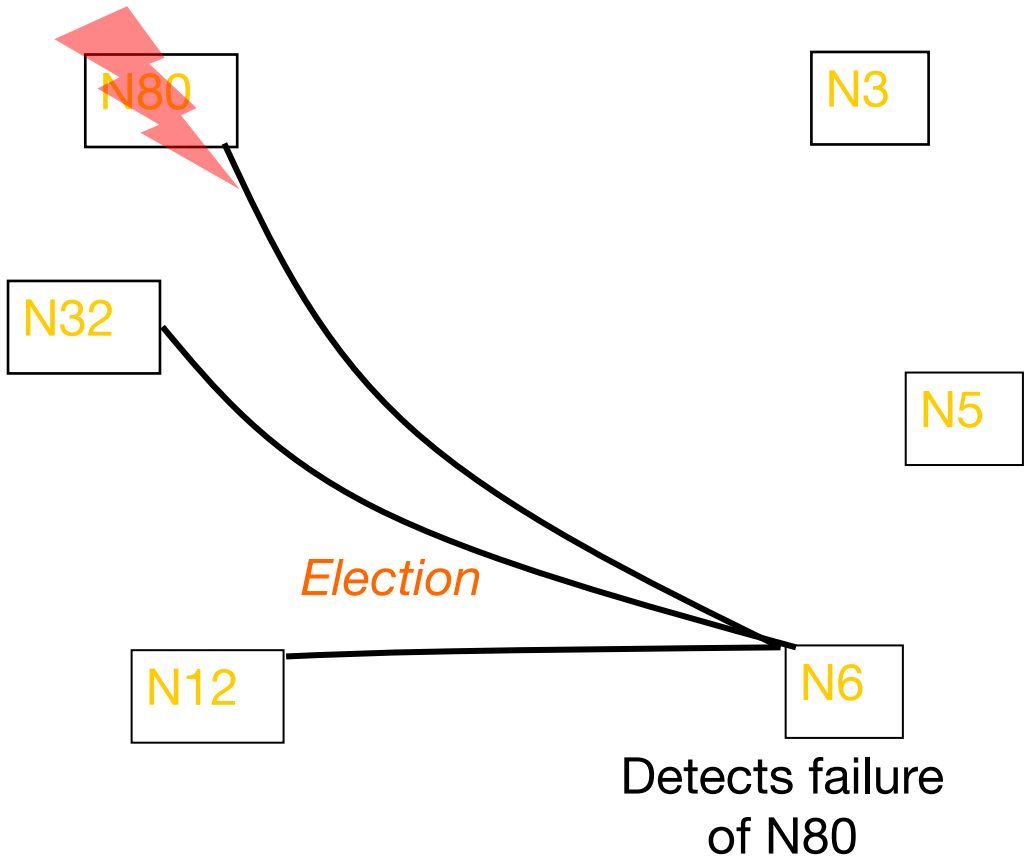
start election procedure according to RE1

end if

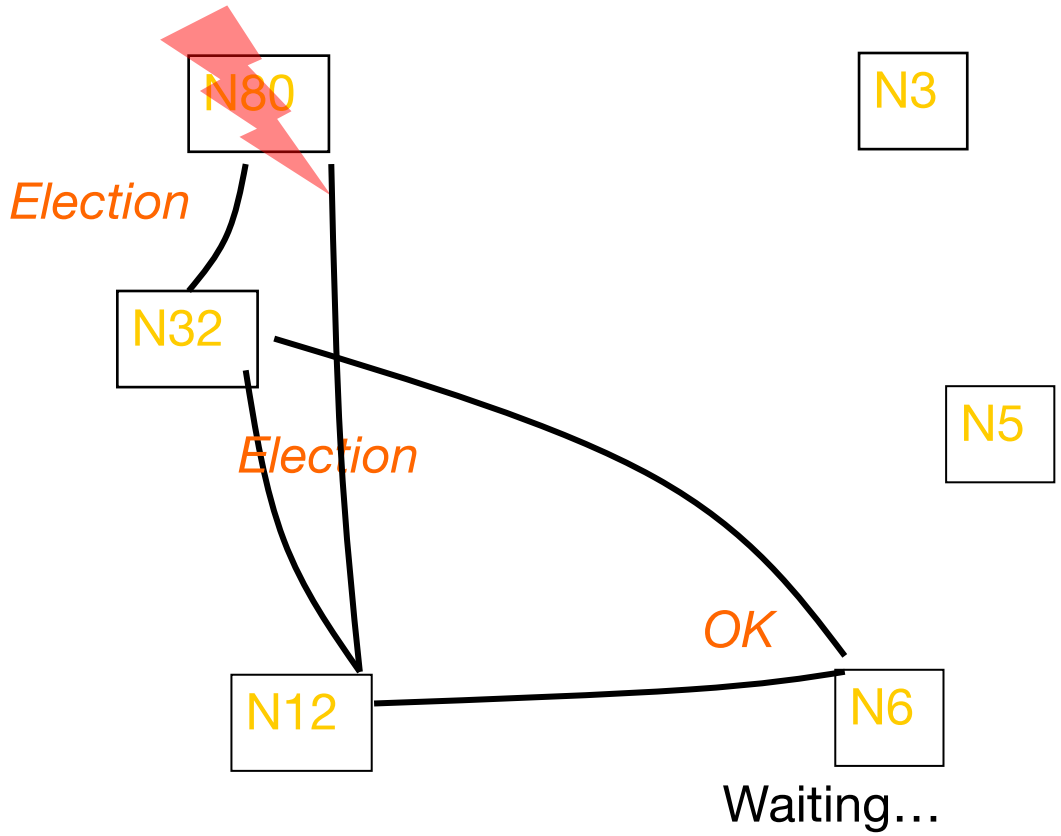
Bully Algorithm: Example



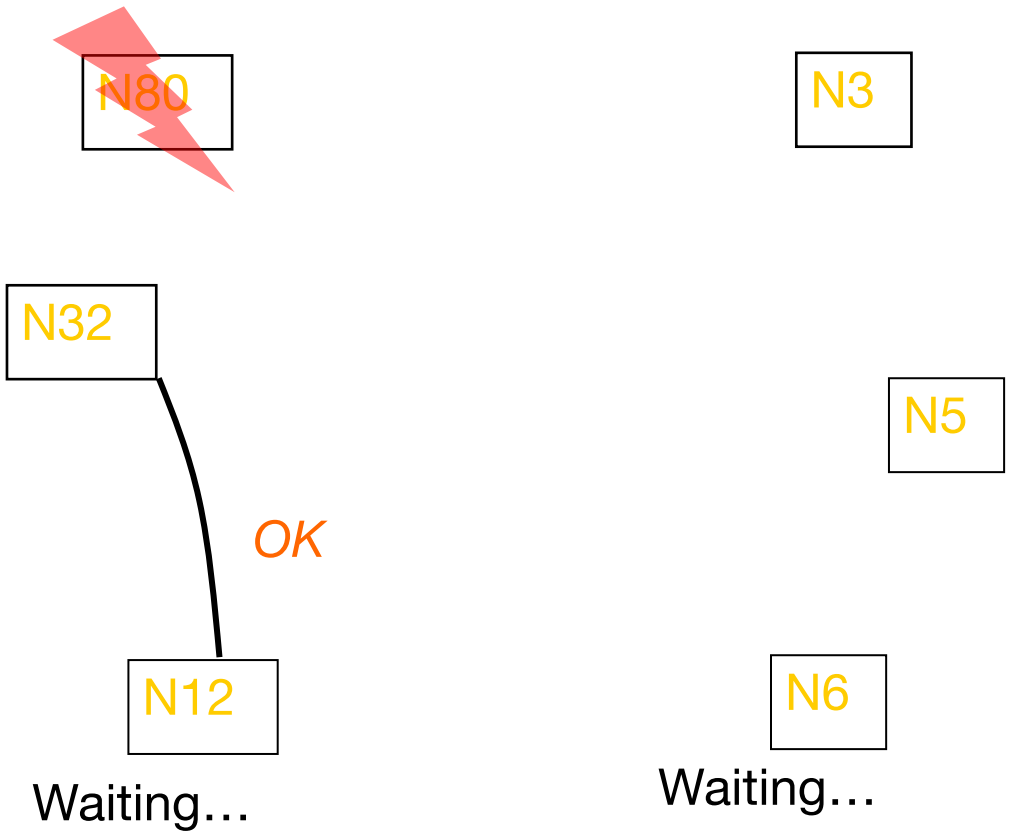
Bully Algorithm: Example



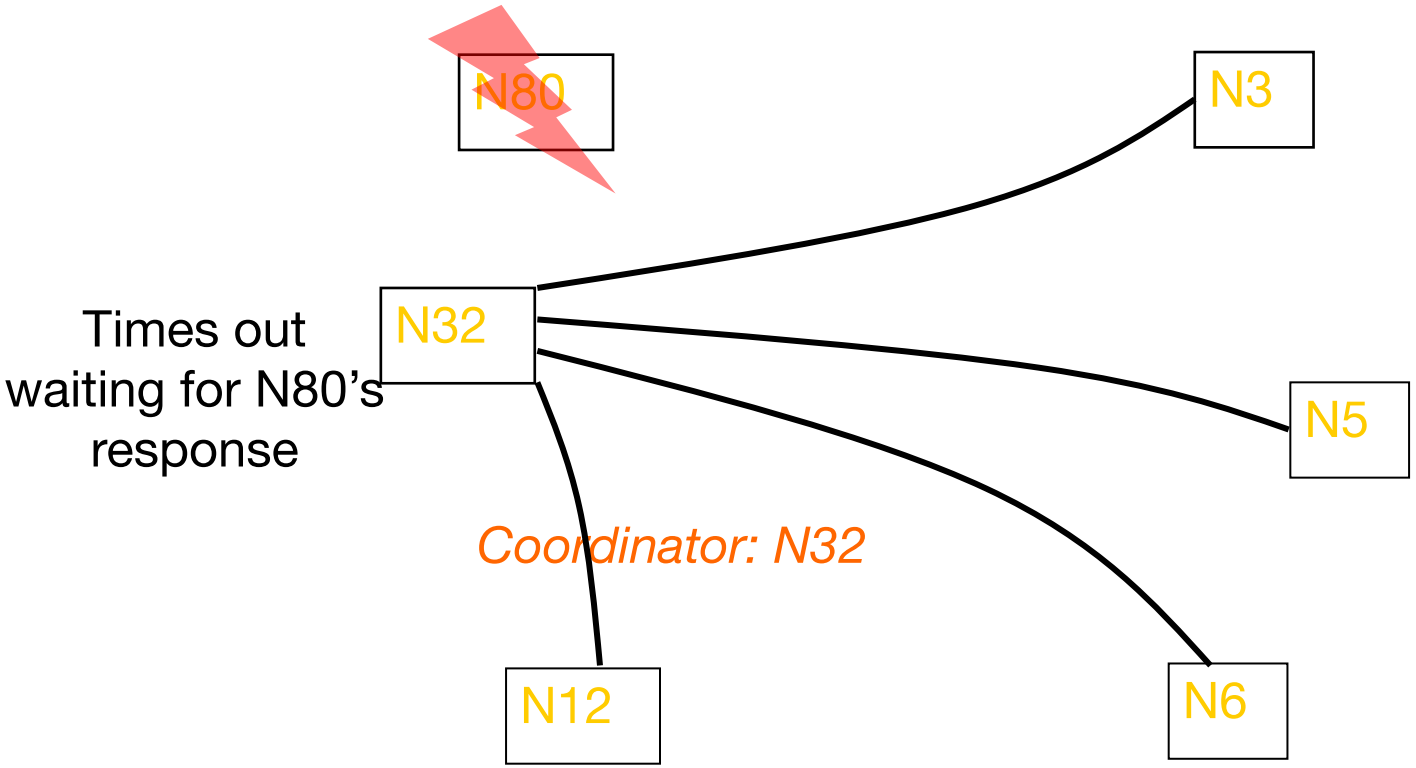
Bully Algorithm: Example



Bully Algorithm: Example

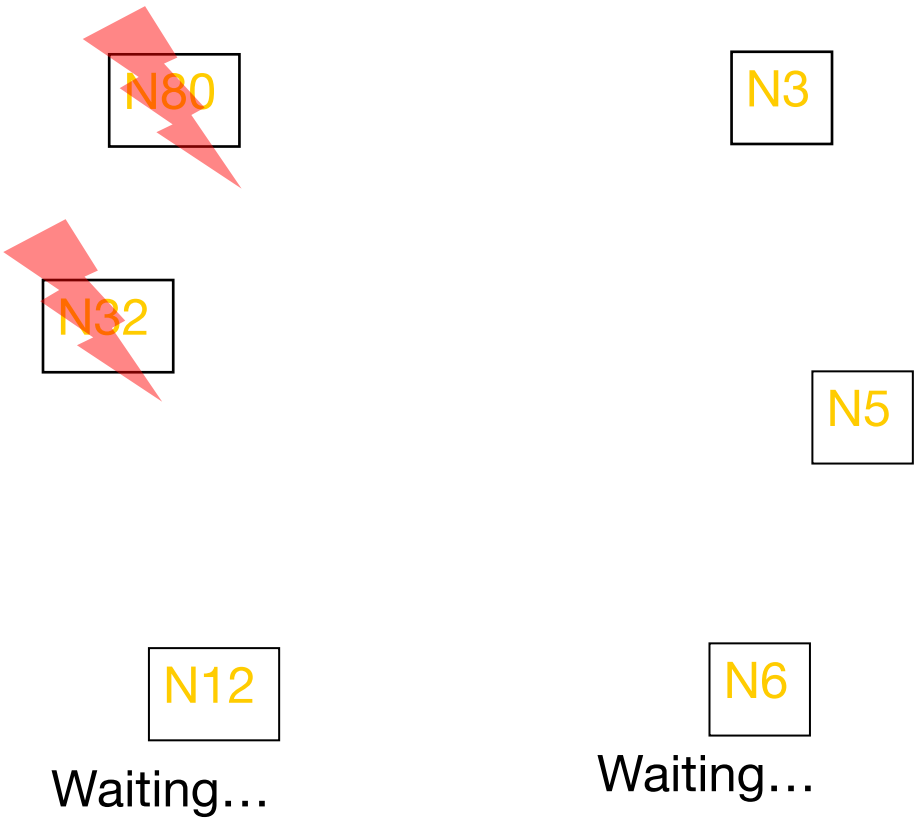


Bully Algorithm: Example

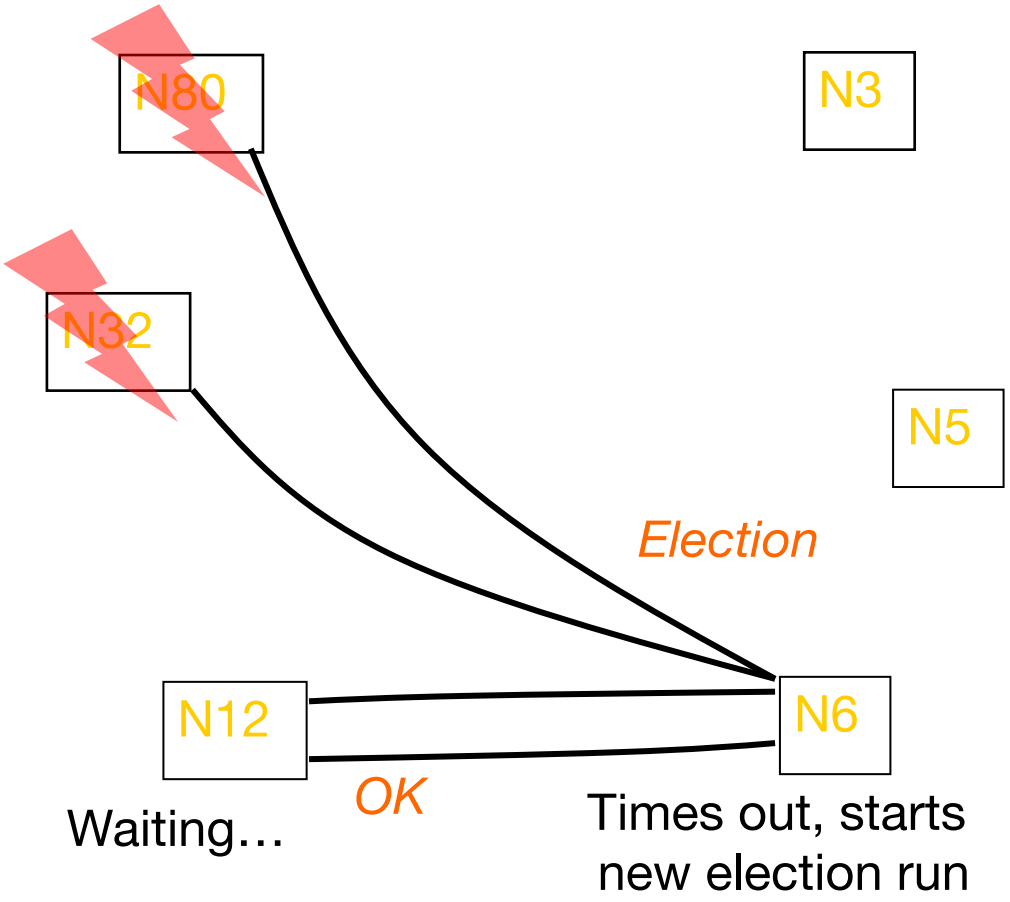


Election is completed

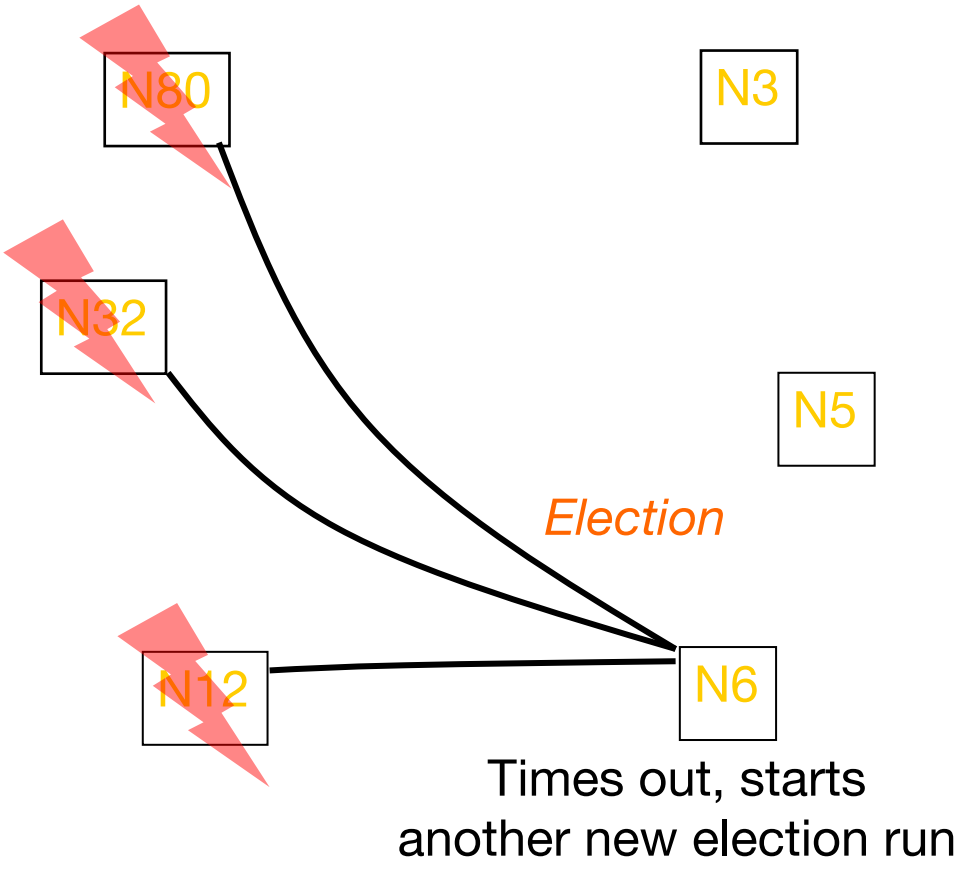
Failures during Election Run



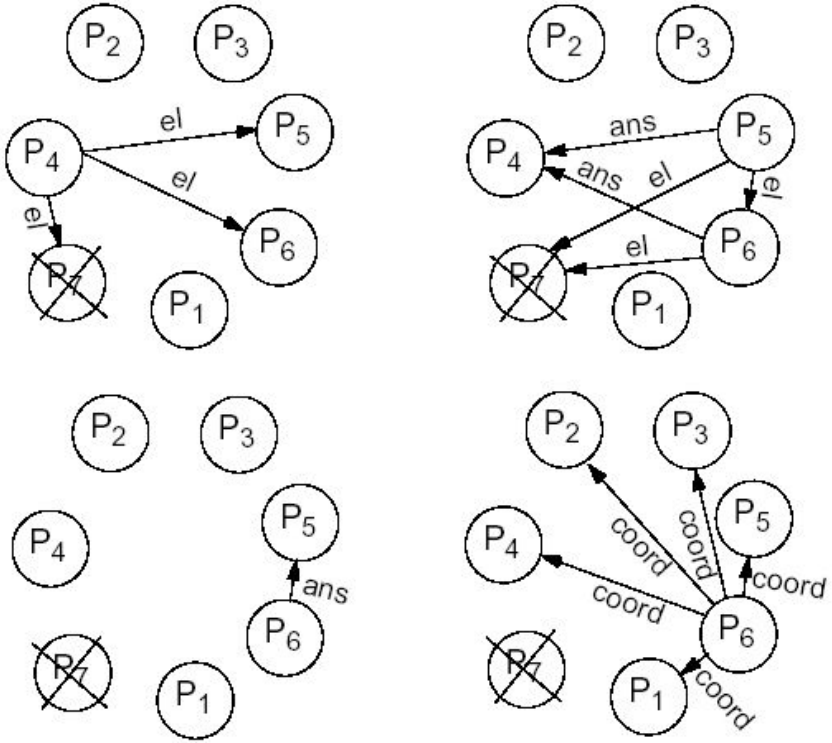
Bully Algorithm: Example



Bully Algorithm: Example



The Bully Algorithm



- If P_6 crashes before sending the coordinator message, P_4 and P_5 restart the election process.

☞ The best case: the process with the second highest identifier notices the coordinator's failure. It can immediately select itself and then send n-2 coordinator messages.

☞ The worst case: the process with the lowest identifier initiates the election; it sends n-1 election messages to processes which themselves initiate each one an election $\Rightarrow O(n^2)$ messages.

The Bully Algorithm: Analysis

- **Worst-case** completion time:
  - When the process with the lowest id in the system detects the 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
    $= N-1 + N-2 + \ldots + 1 = (N-1)*N/2 = O(N^2)$
- **Best-case**
  - Second-highest id detects leader failure
  - Sends (*N-2*) Coordinator messages
  - Completion time: 1 message transmission time

Impossibility?

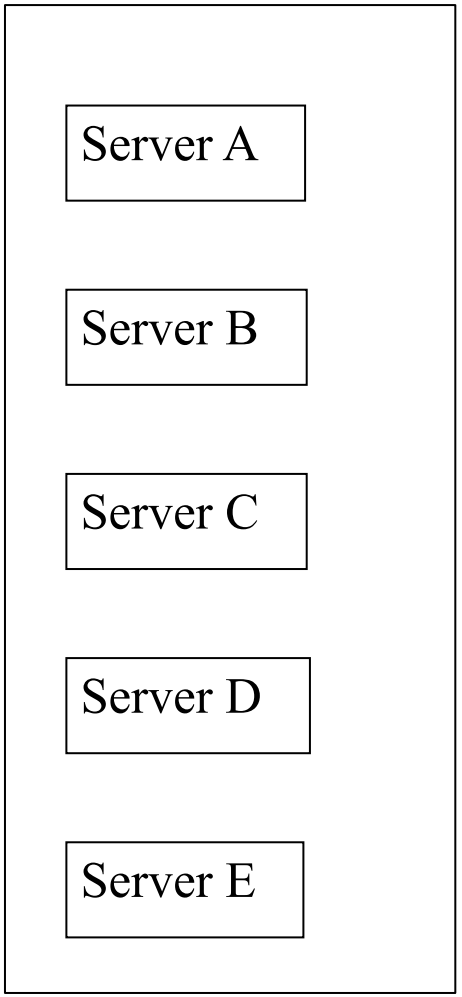
- Since timeouts built into protocol, in asynchronous system model:
  - Protocol may never terminate => Liveness not guaranteed
- But satisfies liveness in synchronous system model where
  - Worst-case one-way latency can be calculated = worst-case processing time + worst-case message latency

Election in Industry

- Several systems in industry use consensus based approaches for election
  - e.g. Paxos is a consensus protocol (safe, but eventually live):
- Google's Chubby system
- Apache Zookeeper

Election in Google Chubby

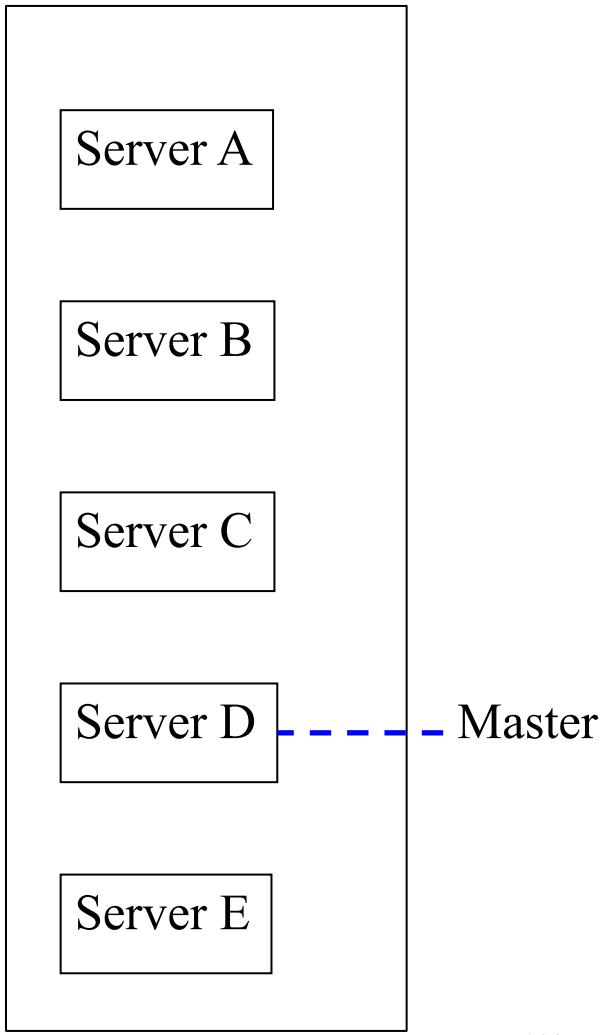
- A system for locking
- Essential part of Google's stack
  - Many of Google's internal systems rely on Chubby
  - BigTable, Megastore, etc.
- Group of replicas
  - Need to have a master server elected at all times



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

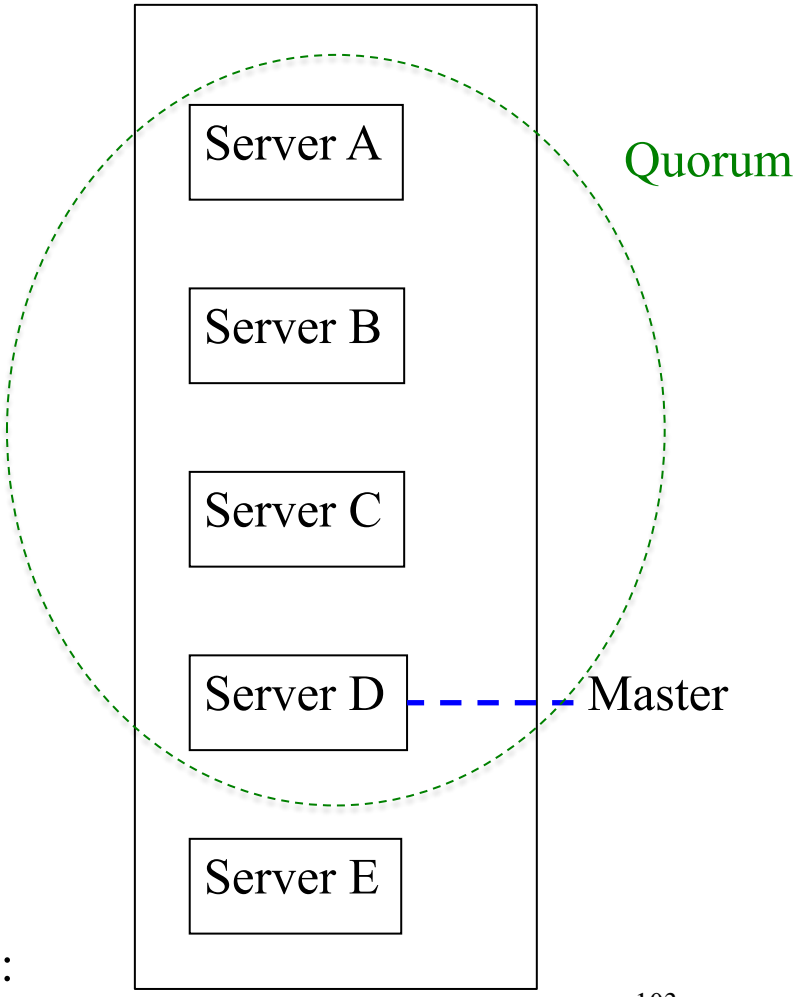
Election in Google Chubby

- Group of replicas
  - Need to have a master (i.e., leader)
- Election protocol
  - Potential leader tries to get votes from other servers
  - Each server votes for at most one leader
  - Server with *majority* of votes becomes new leader, informs everyone



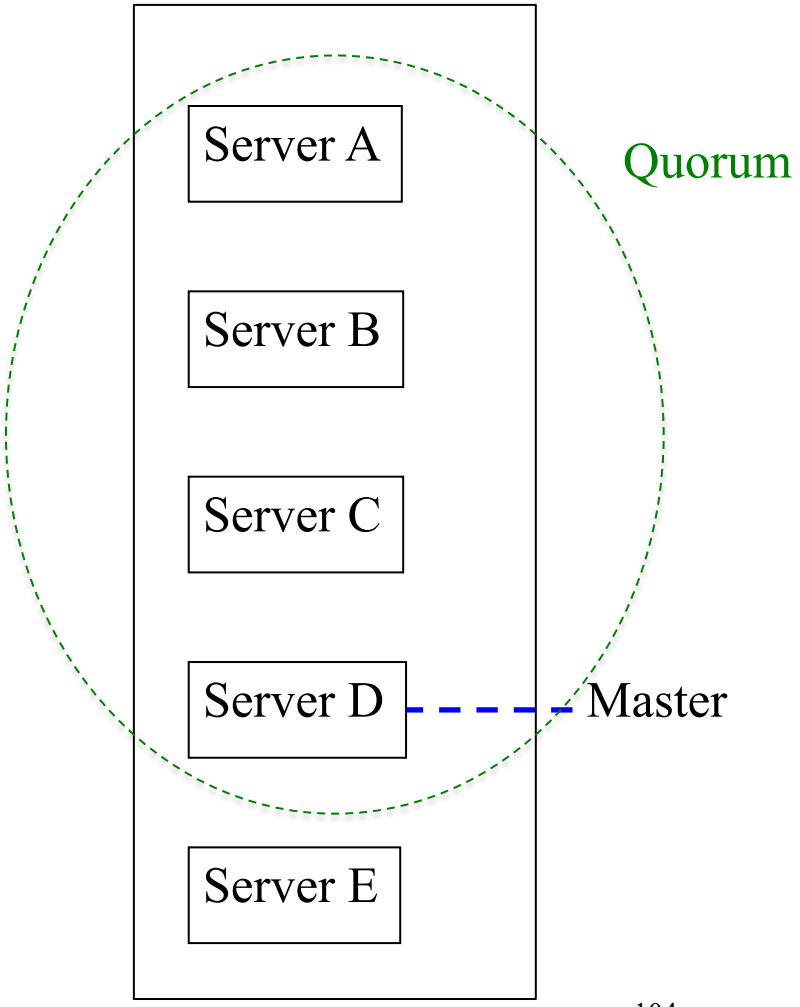
Election in Google Chubby

- Why safe?
  - Essentially, each potential leader tries to reach a *quorum*
  - Since any two quorums intersect, and each server votes at most once, cannot have two leaders elected simultaneously
- Why live?
  - Only eventually live! Failures may keep happening so that no leader is ever elected
  - In practice: elections take a few seconds. Worst-case noticed by Google: 30 s



Election in Google Chubby

- After election finishes, other servers promise not to run election again for "a while"
  - "While" = time duration called "Master lease"
  - Set to a few seconds
- Master lease can be renewed by the master as long as it continues to win a majority each time
- Lease technique ensures automatic re-election on master failure



Summary (Distributed Mutual Exclusion)

- In a distributed environment no shared variables (semaphores) and local kernels can be used to enforce mutual exclusion. Mutual exclusion based] on message passing.
- There are two basic approaches to mutual exclusion: non-token-based and token-based.
- The central coordinator algorithm is based on the availability of a coordinator process which handles all the requests and provides exclusive access to the resource. The coordinator is a performance bottleneck and a critical point of failure. However, the number of messages exchanged per use of a CS is small.
- The Ricart-Agrawala algorithm is based on fully distributed agreement for mutual exclusion. A request is multicast to all processes competing for a resource and access is provided when all processes have replied to the request. The algorithm is expensive in terms of message traffic, and failure of any process prevents progress.
- Ricart-Agrawala's second algorithm is token-based. Requests are sent to all processes competing for a resource but a reply is expected only from the process holding the token. The complexity in terms of message traffic is reduced compared to the first algorithm. Failure of a process (except the one holding the token) does not prevent progress.
- The token-ring algorithm very simply solves mutual exclusion. It is requested that processes are logically arranged in a ring. The token is permanently passed from one process to the other and the process currently holding the token has exclusive right to the resource. The algorithm is efficient in heavily loaded situations.

Summary (Leader Election)

- For many distributed applications it is needed that one process acts as a coordinator. An election algorithm has to choose one and only one process from a group, to become the coordinator. All group members have to agree on the decision.
- The bully algorithm requires the processes to know the identifier of all other processes; the process with the highest identifier, among those which are up, is selected. Processes are allowed to fail during the election procedure.
- The ring-based algorithm requires processes to be arranged in a logical ring. The process with the highest identifier is selected. On average, the ring based algorithm is more efficient then the bully algorithm.
- Industry based approaches - Google Chubby

Distributed Deadlocks

- Deadlocks is a fundamental problem in distributed systems.
- A process may request resources in any order, which may not be known a priori and a process can request resource while holding others.
- If the sequence of the allocations of resources to the processes is not controlled, deadlocks can occur.
- A deadlock is a state where a set of processes request resources that are held by other processes in the set.
- Conditions for a deadlocks
  - Mutual exclusion, hold-and-wait, No-preemption and circular wait.

Modeling Deadlocks

- In addition to the standard assumptions (no shared memory, no global clock, no failures), we make the following assumptions:
- The systems have only reusable resources.
- Processes are allowed to make only exclusive access to resources.
- There is only one copy of each resource.
- A process can be in two states: *running or blocked.*
  - In the running state (also called *active state), a process* has all the needed resources and is either executing or is ready for execution.
  - In the blocked state, a process is waiting to acquire some resource.
- The state of the system can be modeled by directed graph, called a *wait for graph (WFG).*
  - In a WFG , nodes are processes and there is a directed edge from node P1 to mode P2 if P1 is blocked and is waiting for P2 to release some resource.
- A system is deadlocked if and only if there exists a directed cycle or knot in the WFG.

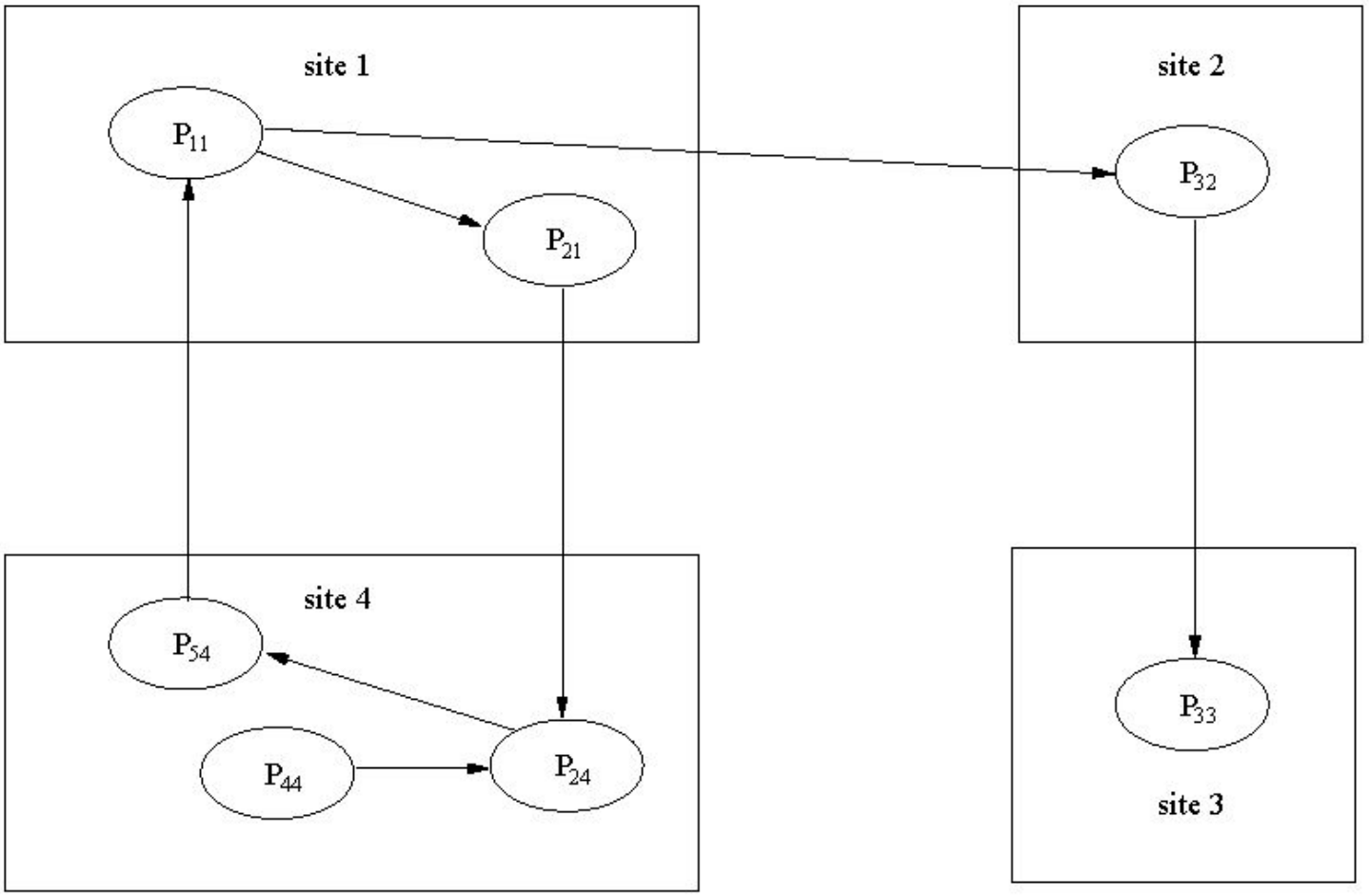


Figure 1: An Example of a WFG

Techniques for Handling Deadlocks

- Note: No site has accurate knowledge of the current state of the system
- Techniques
  - Ignore it…
  - Deadlock Prevention (collective/ordered requests, preemption)
    - Inefficient, impractical
  - Deadlock Avoidance
    - A resource is granted to a process if the resulting global system state is safe
    - Requires advance knowledge of processes and their resource requirements
    - Impractical
  - Deadlock Detection and Recovery
    - Maintenance of local/global WFG and searching of the WFG for the presence of cycles (or knots), local/centralized deadlock detectors
    - Recovery by operator intervention, break wait-for dependencies, termination and rollback

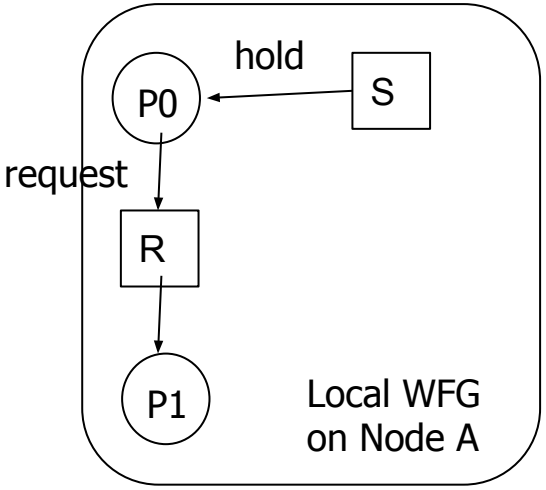
Deadlock Detection: Correctness Criteria

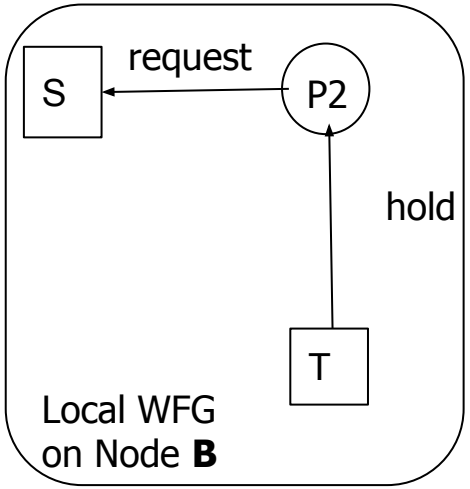
- Safety (No false deadlocks)
  - The algorithm should not report deadlocks which do not exist (called *phantom or false deadlocks).*
- Progress (No undetected deadlocks)
  - The algorithm must detect all existing deadlocks in finite time. In other words, after all wait-for dependencies for a deadlock have formed, the algorithm should not wait for any more events to occur to detect the deadlock.

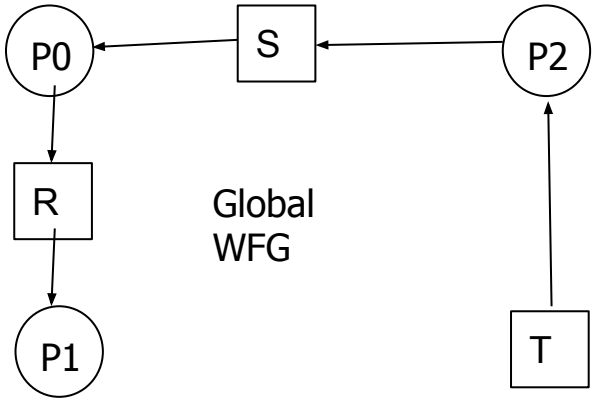
Global Deadlock Detection - Centralized Algorithm

- Choose one site to be the ***coordinator***
- Each site maintains its own WFG
- Every site sends its WFG to *coordinator*
- *Coordinator* constructs a global WFG
  - Messages sent to *coordinator* when edges to (resource request/hold/release) WFG are added/deleted
  - Can List be sent periodically?
- *Coordinator* checks for cycle in global WFG
  - if yes, possibly deadlock
- *Coordinator* may choose victim

Global WFG - Example







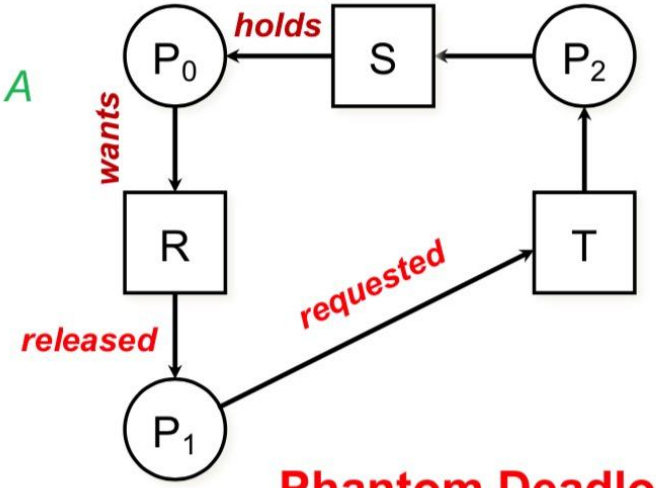
Centralized deadlock detection

Two events occur:

1. Process P_1 releases resource R on system A
2. Process P_1 asks system B for resource T

Two messages are sent to the coordinator:
1 (from A): *release R*
2 (from B): *wait for T*

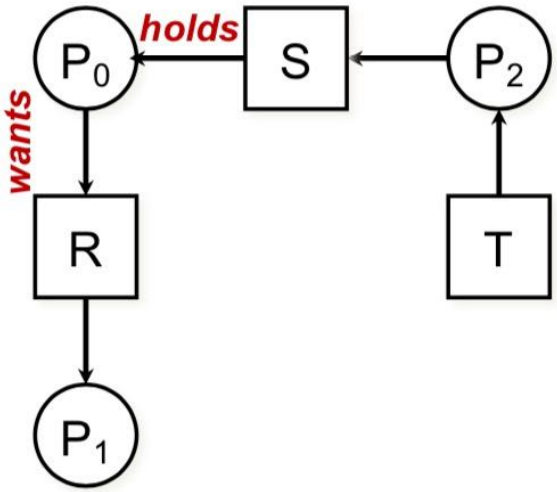
If message 2 arrives first, the coordinator constructs a graph that has a cycle and hence detects a deadlock. This is **phantom deadlock.**



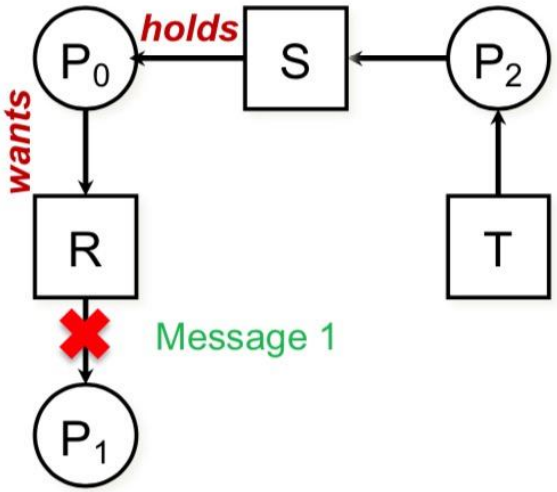
Phantom Deadlock

A *phantom deadlock* is sometimes known as a *false deadlock*

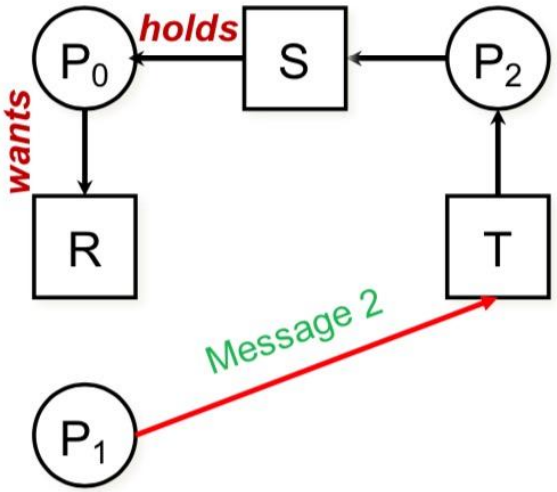
Phantom Deadlock Example



No deadlock



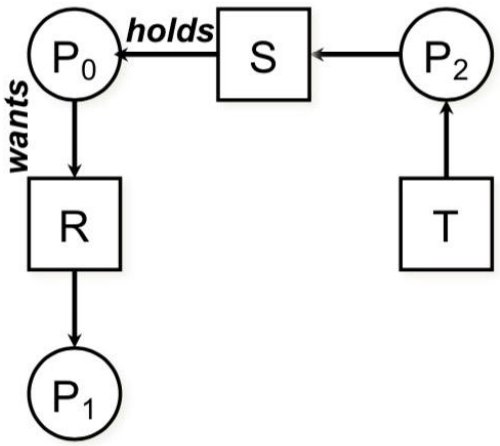
Message 1 from P_1:
release(R)



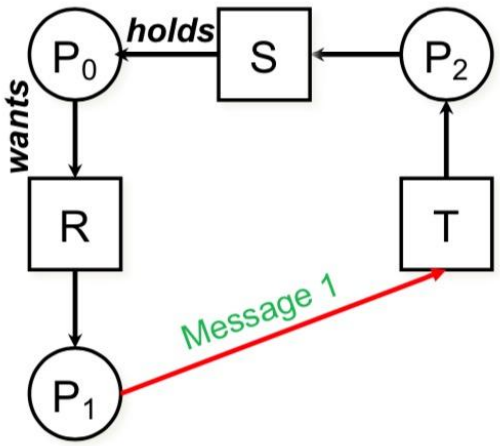
Message 2 from P_1:
wait_for(T)

All good: no deadlock detected!

Phantom Deadlock Example

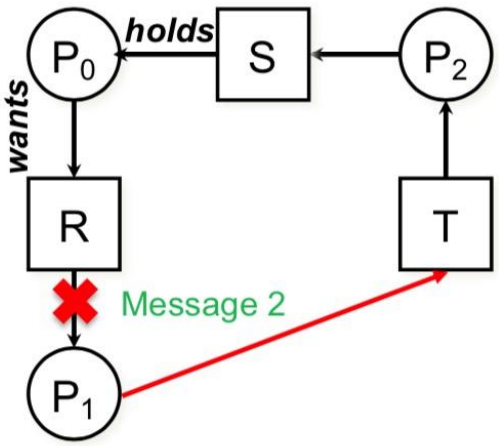


No deadlock



Message 2 from P_1:
wait_for(T)

DEADLOCK detected!
Do Something!



Message 1 from P_1:
release(R)

It really wasn't deadlock since P_1 released R
Too Late!

We detected deadlock because the coordinator received the messages out of order

Avoiding phantom deadlocks

- Impose globally consistent total ordering on all processes
- Coordinator asks each process if there are release messages

Deadlock Detection: Models and Types of Algorithms

- Multiple models
  - Single-resource, AND, OR , AND-OR, P-out-of-Q model
- Classes of Deadlock Detection Algorithms
  - Path-pushing
    - distributed deadlocks are detected by maintaining an explicit global WFG (constructed locally and pushed to neighbors)
  - Edge-chasing
    - the presence of a cycle in a distributed graph structure is verified by propagating special messages called probes, along the edges of the graph. The formation of cycles can be detected by a site if it receives the matching probe sent by it previously.
  - Diffusion computation
    - deadlock detection computation is diffused through the WF
  - Global state detection
    - Take a snapshot of the system and examining it for the condition of a deadlock.

Distributed Deadlock Detection: Chandy-Mishra-Haas Algorithm

Chandy-Misra-Haas algorithm

Edge Chasing

When requesting a resource, generate a probe message

- Send to all process(es) currently holding the needed resource
- Message contains three process IDs: *{blocked_ID, my_ID, holder_ID}*

1. Process that originated the message (*blocked_ID*)
2. Process sending (or forwarding) the message (*my_ID*)
3. Process to whom the message is being sent (*holder_ID*)

Distributed Deadlock Detection: Chandy-Mishra-Haas Algorithm

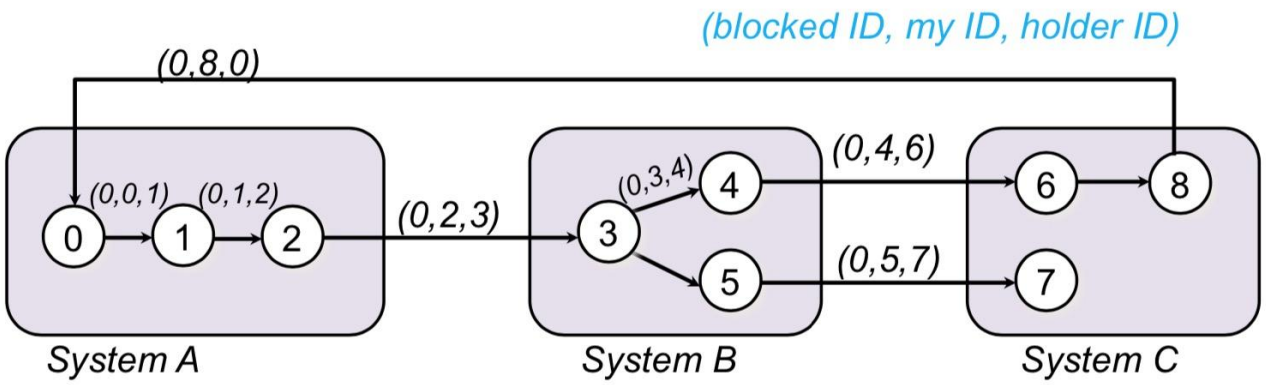
- When *probe* message arrives, recipient checks to see if it is waiting for any processes

- If so, update & forward message: *{blocked_ID, my_ID, holder_ID}*
  - Replace ***my_ID*** field by its own process ID
  - Replace ***holder_ID*** field by the ID of the process it is waiting for
  - Send messages to each process on which it is blocked

- If a message goes all the way around and comes back to the original sender, a cycle exists
  - *We have deadlock*

Distributed Deadlock Detection: Chandy-Mishra-Haas Algorithm

Distributed deadlock detection



- Process 0 needs a resource process 1 is holding
- That means process 0 will block on process 1
  - Initial message from P_0 to P_1: *(0,0,1)*
  - P_1 sends *(0, 1, 2)* to P_2 ; P_2 sends *(0, 2, 3)* to P_3
- Message *(0,8,0)* returns back to sender
  - cycle exists: *deadlock*

Distributed deadlock prevention

- Deny circular wait
- Assign a unique timestamp to each transaction
- Ensure that the *Global Wait-For Graph* can only proceed from young to old or from old to young

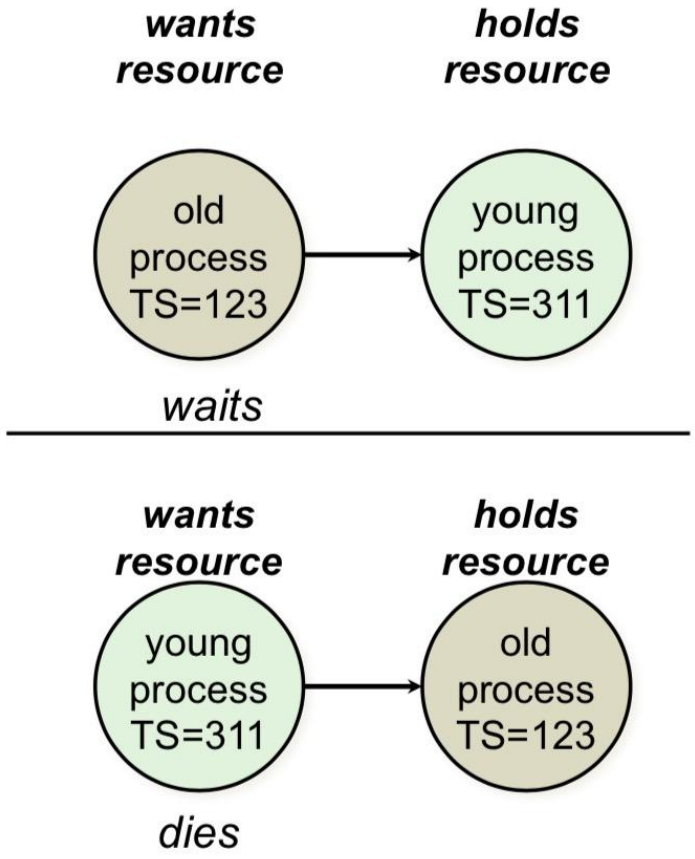
Deadlock prevention

- When a process is about to block waiting for a resource used by another
  - Check to see which has a larger timestamp (which is older)
- Allow the wait only if the waiting process has an older timestamp (is older) then the process waited for
- Following the resource allocation graph, we see that timestamps always have to increase, so cycles are impossible.
- Alternatively: allow processes to wait only if the waiting process has a higher (younger) timestamp than the process waiting for.

Wait-die algorithm

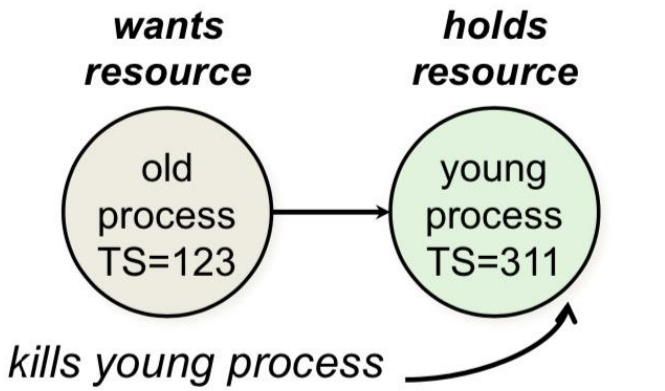
- Old process wants resource held by a younger process
  - old process waits
- Young process wants resource held by older process
  - young process kills itself

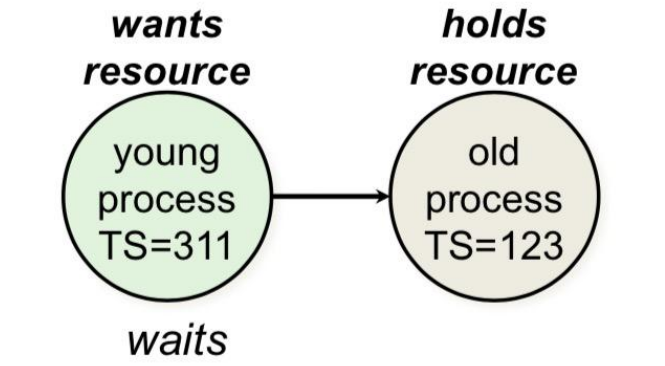
Only permit older processes to wait on resources held by younger processes.



Wound-wait algorithm

- Instead of killing the transaction making the request, kill the resource owner
- Old process wants resource held by a younger process
  - old process kills the younger process
- Young process wants resource held by older process
  - young process waits





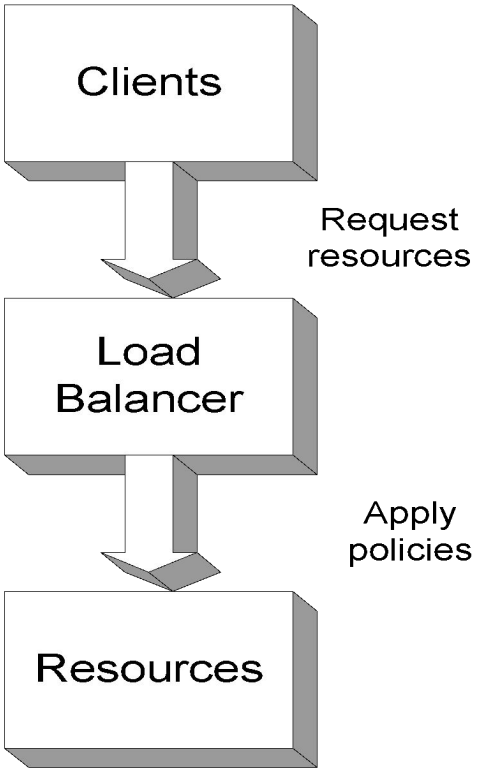
Only permit younger processes to wait on resources held by older processes.

Distributed Process and Resource Management

- Need multiple other policies to determine when and where to execute processes in distributed systems – useful for load balancing, reliability
  - Load Estimation Policy
    - How to estimate the workload of a node
  - Process Transfer Policy
    - Whether to execute a process locally or remotely
  - Location Policy
    - Which node to run the remote process on
  - Priority Assignment Policy
    - Which processes have more priority (local or remote)
  - Migration Limiting policy
    - Number of times a process can migrate

Load Balancing

- Computer overloaded
  - Decrease load maintain scalability, performance, throughput - transparently
  - Load Balancing
    - Can be thought of as "distributed scheduling"
      - Deals with distribution of processes among processors connected by a network
    - Can also be influenced by "distributed placement"
      - Especially in data intensive applications



Load Balancer

- Manages resources
- Policy driven Resource assignment

Load Balancing Issues

- How
  - To search for lightly loaded machines
- When
  - should load balancing decisions be made
  - to migrate processes or forward requests?
- Which
  - processes should be moved off a computer?
  - processor should be chosen to handle a given process or request
- What should be taken into account when making the above decisions? How should old data be handled
- Should
  - load balancing data be stored and utilized centrally, or in a distributed manner
  - What is the performance/overhead tradeoff incurred by load balancing
  - Prevention of overloading a lightly loaded computer

Static vs. dynamic

- Static load balancing - CPU determined at process creation.
- Dynamic load balancing - processes dynamically migrate to other computers to balance the CPU (or memory) load.
  - **Parallel machines** *- dynamic balancing schemes seek to minimize total execution time of a single application running in parallel on a multiple nodes*
  - **Web servers** *- scheduling client requests among multiple nodes in a transparent way to improve response times for interaction*
  - **Multimedia servers -** *resource optimization across streams and servers for QoS; may require admission control*

Process Migration

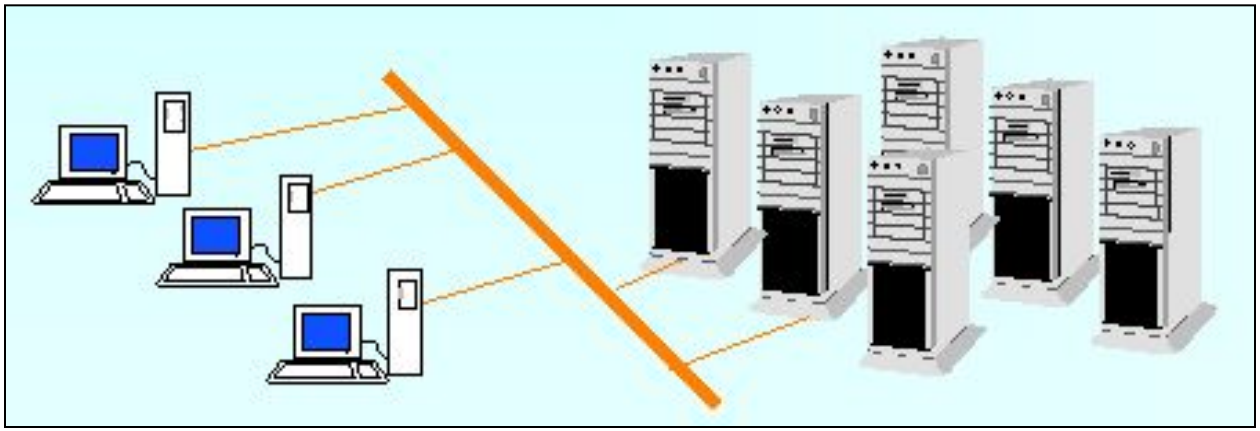
- Process migration mechanism
  - Freeze the process on the source node and restart it at the destination node
  - Transfer of the process address space
  - Forwarding messages meant for the migrant process
  - Handling communication between cooperating processes separated as a result of migration
  - Handling child processes
- Process Migration Policies: Depend on
  - CPU Load
  - Memory Requirements
  - I/O Activity -- Where is the physical device?
  - Communication - which processes communicate with each other?

Process Migration and Heterogeneous Systems

- Converts usage of heterogeneous resources (CPU, memory, IO) into a single, homogeneous cost using a specific cost function.
- Assigns/migrates a job to the machine on which it incurs the lowest cost.
  - Can design online job assignment policies based on multiple factors - economic principles, competitive analysis.
  - Aim to guarantee near-optimal global lower-bound performance.

Mosix: Early Cluster Computing

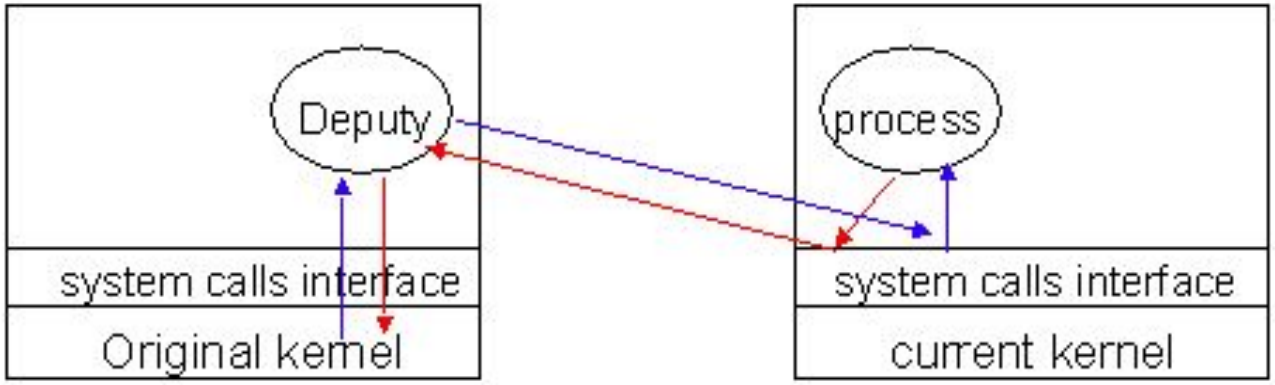
- Mosix (from Hebrew U): Kernel level enhancement to Linux that provides dynamic load balancing in a network of workstations.
- Dozens of PC computers connected by local area network (Fast-Ethernet or Myrinet).
- Any process can migrate anywhere anytime.



Architectures for Migration

Architecture that fits one system image.
Needs location transparent file system.

(Mosix early versions)



Architecture that fits entrance dependant systems.
Easier to implement based on current Unix.

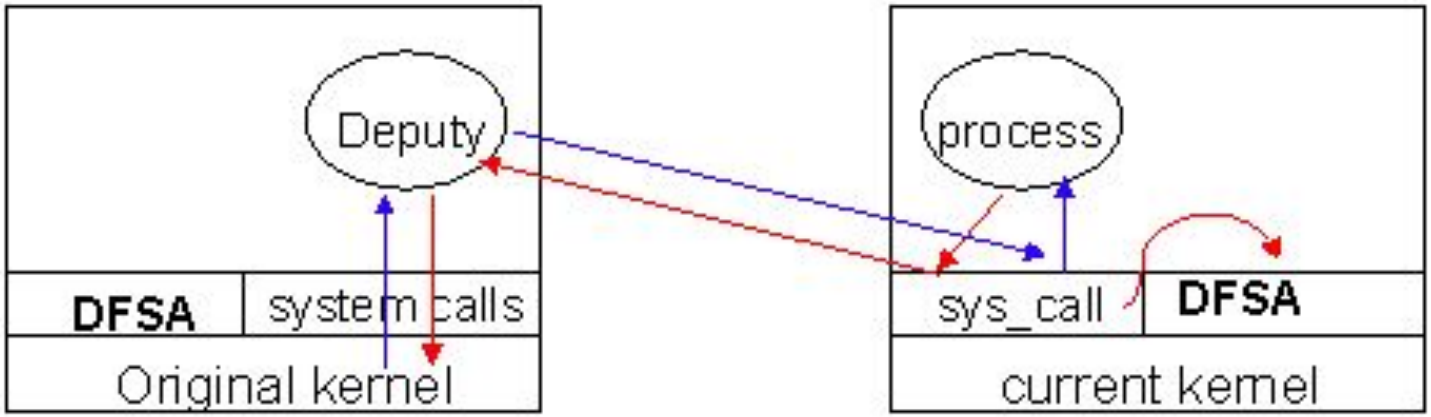
(Mosix later versions)

Mosix: Migration and File Access

Each file access must go back to deputy…

= = Very Slow for I/O apps.

Solution: Allow processes to access a distributed file system through the current kernel.



Distributed File Systems (DFS)

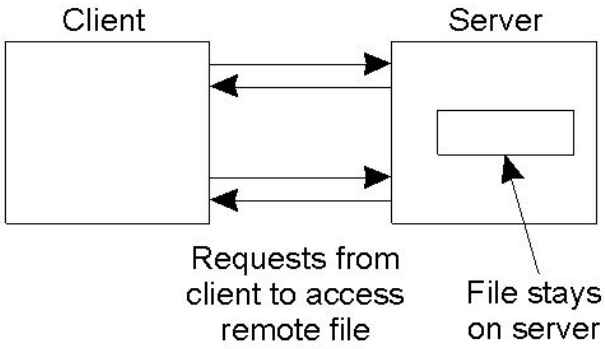
A distributed implementation of the classical file system model

- Requirements
  - Transparency: Access, Location, Mobility, Performance, Scaling
  - Allow concurrent access
  - Allow file replication
  - Tolerate hardware and operating system heterogeneity
  - Security - Access control, User authentication
- Issues
  - File and directory naming – Locating the file
  - Semantics – client/server operations, file sharing
  - Performance
  - Fault tolerance – Deal with remote server failures
  - Implementation considerations - caching, replication, update protocols

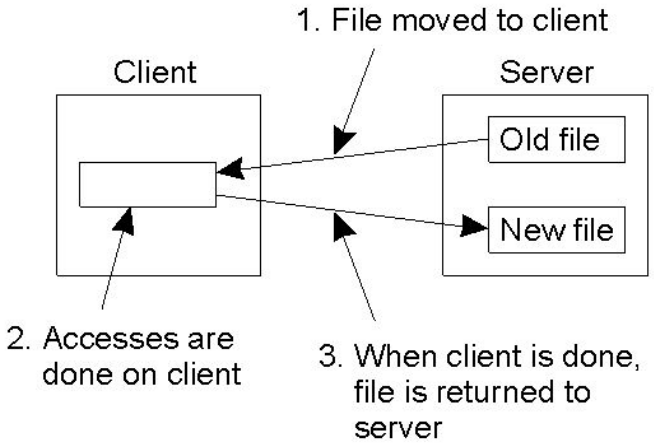
Issues: File and Directory Naming

- Explicit Naming
  - Machine + path /machine/path
    - one namespace but not transparent
- Implicit naming
  - Location transparency
    - file name does not include name of the server where the file is stored
  - Mounting remote filesystems onto the local file hierarchy
    - view of the filesystem may be different at each computer
  - Full naming transparency
    - A single namespace that looks the same on all machines

Distributed File Access Alternatives



Remote access model



Download/upload model

Semantics – File Sharing

One-copy (Sequential) Semantics

- Updates are written to the single copy and are available immediately
- All clients see contents of file identically as if only one copy of file existed
- Issue : Performance
- Soln: Use Caching: after an update operation, no program can observe a discrepancy between data in cache and stored data
  - Extra state; extra traffic

Session semantics

- more relaxed
- Copy file on open, work on local copy and copy back on close
- Changes initially only visible to file that modified it.

Serializable (Transaction semantics)

- Need file locking protocols implemented - share for read, exclusive for write).

Semantics - Operational

- Support fault tolerant operation
  - At-most-once semantics for file operations
  - At-least-once semantics with a server protocol designed in terms of idempotent file operations
  - Replication (stateless, so that servers can be restarted after failure)

DFS Performance

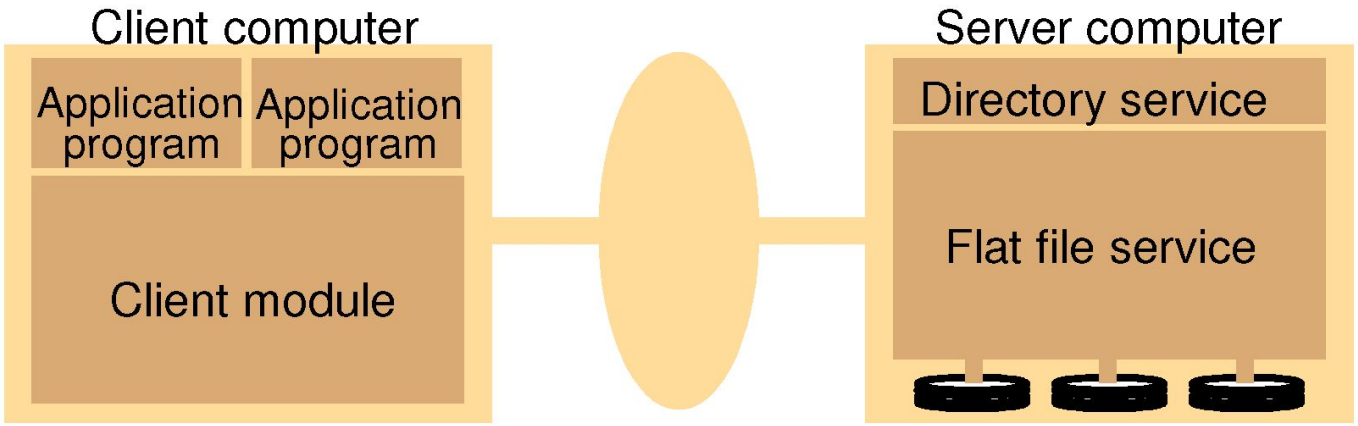
- Efficiency Needs
  - Latency of file accesses
  - Scalability (e.g., with increase of number of concurrent users)
- RPC Related Issues
  - Use RPC to forward every file system request (e.g., open, seek, read, write, close, etc.) to the remote server
    - Remote server executes each operation as a local request
    - Remote server responds back with the result
  - Advantage:
    - Server provides a consistent view of the file system to distributed clients.
  - Disadvantage:
    - Poor performance
    - Solution: Caching

EXTRA Slide

Traditional File system Operations

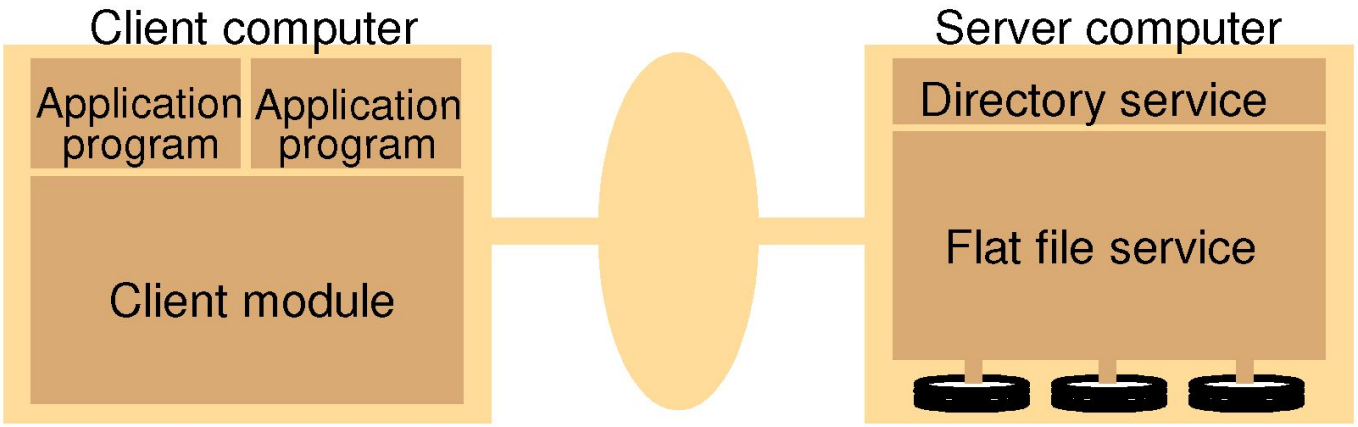
- filedes = *open*(name, mode) Opens an existing file with the given name.
- filedes = *creat*(name, mode) Creates a new file with the given name.
- Both operations deliver a file descriptor referencing the open file. The mode is read, write or both.
- status = *close*(filedes) Closes the open file filedes.
- count = *read*(filedes, buffer, n) Transfers n bytes from the file referenced by filedes to buffer.
- count = *write*(filedes, buffer, n) Transfers n bytes to the file referenced by filedes from buffer.
- Both operations deliver the number of bytes actually transferred and advance the read-write pointer.
- pos = *lseek*(filedes, offset, whence) Moves the read-write pointer to offset (relative or absolute, depending on whence).
- status = *unlink*(name) Removes the file name from the directory structure. If the file has no other names, it is deleted.
- status = *link*(name1, name2) Adds a new name (name2) for a file (name1).
- status = *stat*(name, buffer) Gets the file attributes for file name into buffer.

Architecture



- Flat File Service
  - Performs file operations
  - Uses "unique file identifiers" (UFIDs) to refer to files
  - Flat file service interface
    - → RPC-based interface for performing file operations
    - → Not normally used by application level programs

Architecture (2)

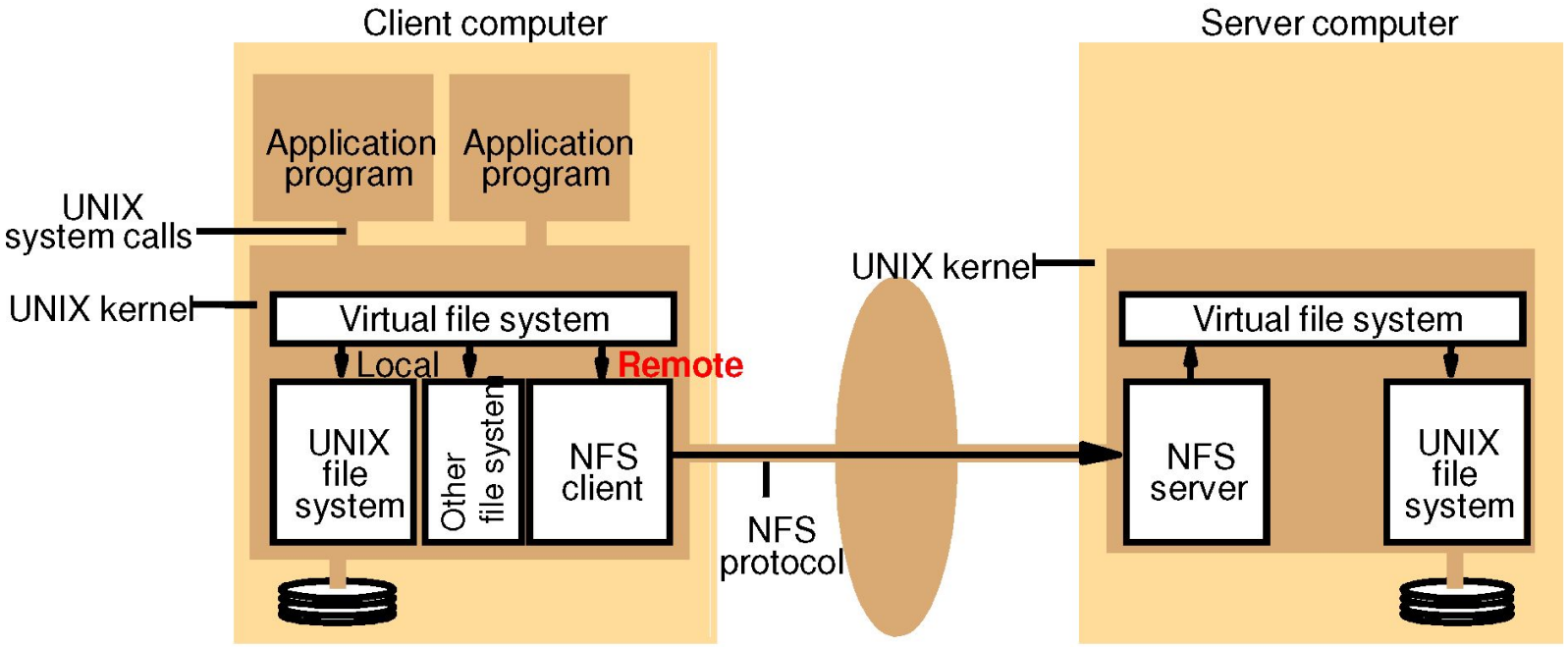


- Directory Service
  - Mapping of UFIDs to "text" file names, and vice versa
- Client Module
  - Provides API for file operations available to application program

Network File Systems : Sun-NFS

- **Supports heterogeneous systems**
  - Architecture
    - Server exports one or more directory trees for access by remote clients
    - Clients access exported directory trees by mounting them to the client local tree
    - Diskless clients mount exported directory to the root directory
  - Protocols
    - Mounting protocol
    - Directory and file access protocol - stateless, no open-close messages, full access path on read/write
  - Semantics - no way to lock files

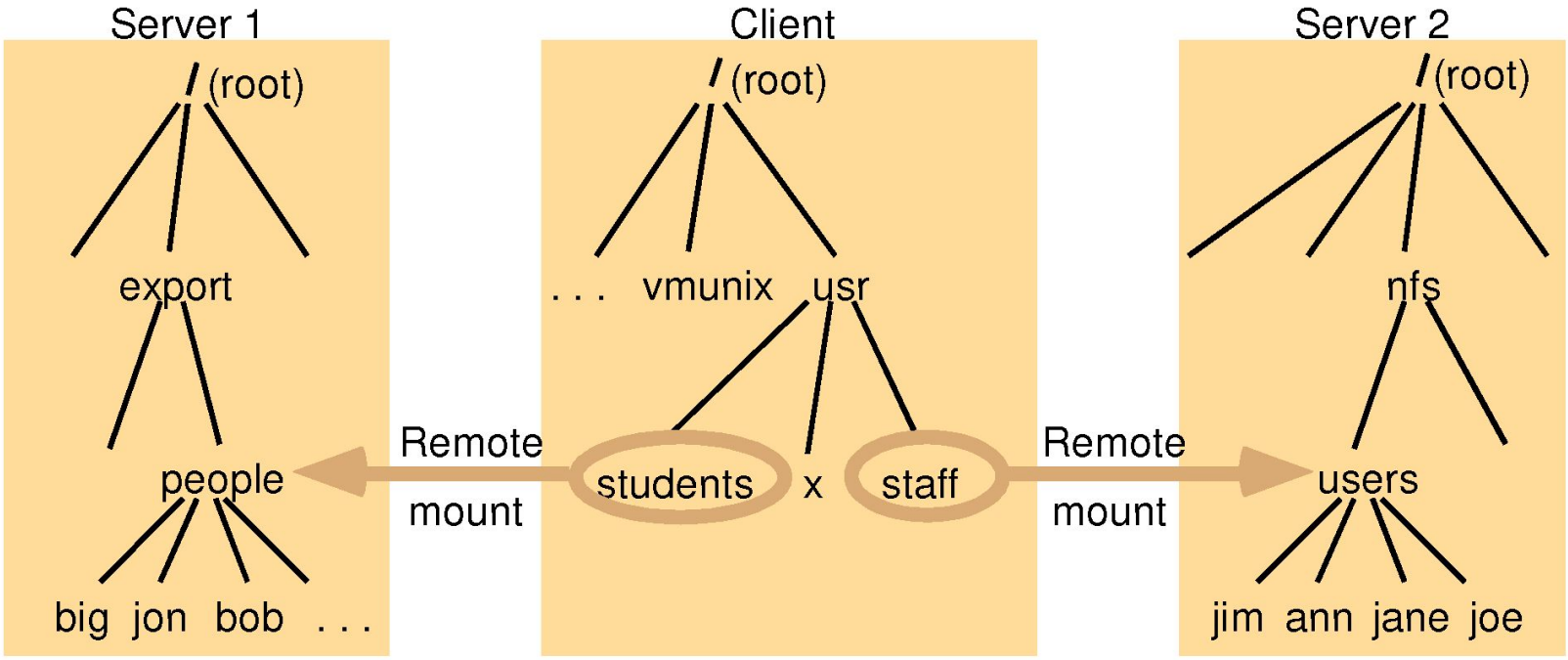
Sun Network File System



Mounting of File Systems

- Making remote file systems available to a local client, specifying remote host name and pathname
- Mount protocol (RPC-based)
  - Returns file handle for directory name given in request
  - Location (IP address and port number) and file handle are passed to Virtual File System and NFS client
- Hard-mounted (mostly used in practice)
  - User-level process suspended until operation completed
  - Application may not terminate gracefully in failure situations
- Soft-mounted
  - Error message returned by NFS client module to user-level process after small number of retries

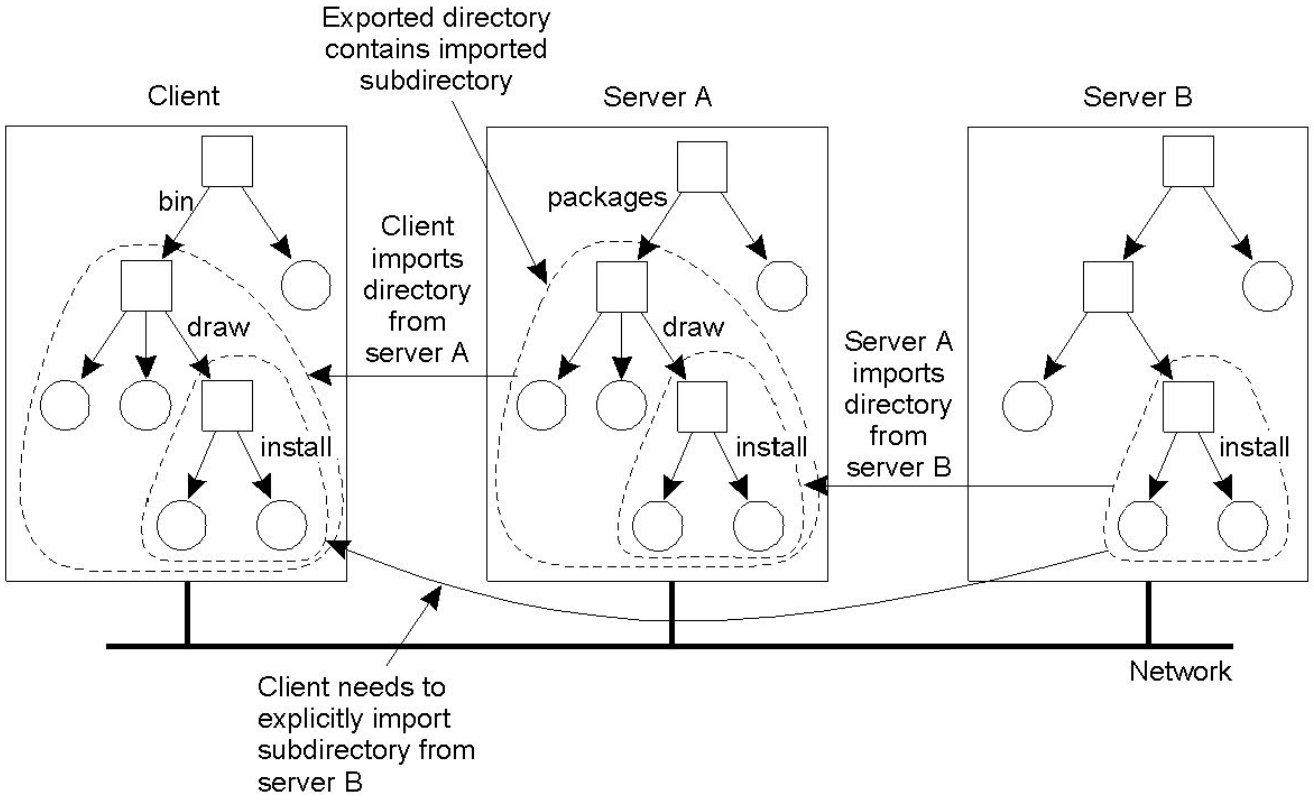
Mounting Example



The file system mounted at */usr/students* in the client is actually the sub-tree located at */export/people* in Server 1; the file system mounted at */usr/staff* in the client is actually the sub-tree located at */nfs/users* in Server 2.

Naming (2)

- Mounting nested directories from multiple servers in NFS.



Example 2 : Andrew File System

- Supports information sharing on a large scale
  - 10,000+ clients
- Most files are small
  - reads more common than writes; typically one user at a time; access locality expected.
- Uses a session semantics
  - Entire file is copied to the local machine (Venus) from the server (Vice) when open. If file is changed, it is copied to server when closed.
    - Works because in practice, most files are changed by one person
- AFS File Validation (older versions)
  - On open: Venus accesses Vice to see if its copy of the file is still valid. Causes a substantial delay even if the copy is valid.
  - Vice is stateless

Example 3: The Coda Filesystem

- CoDA -- Constant Data Availability
- Descendant of AFS that is substantially more resilient to server and network failures.
- General Design Principles
  - know the clients have cycles to burn, cache whenever possible, exploit usage properties, minimize system wide change, trust the fewest possible entries and batch if possible
- Directories are replicated in several servers (Vice)
- Support for mobile users
  - When the Venus is disconnected, it uses local versions of files. When Venus reconnects, it reintegrates using optimistic update scheme.

Other DFS Challenges

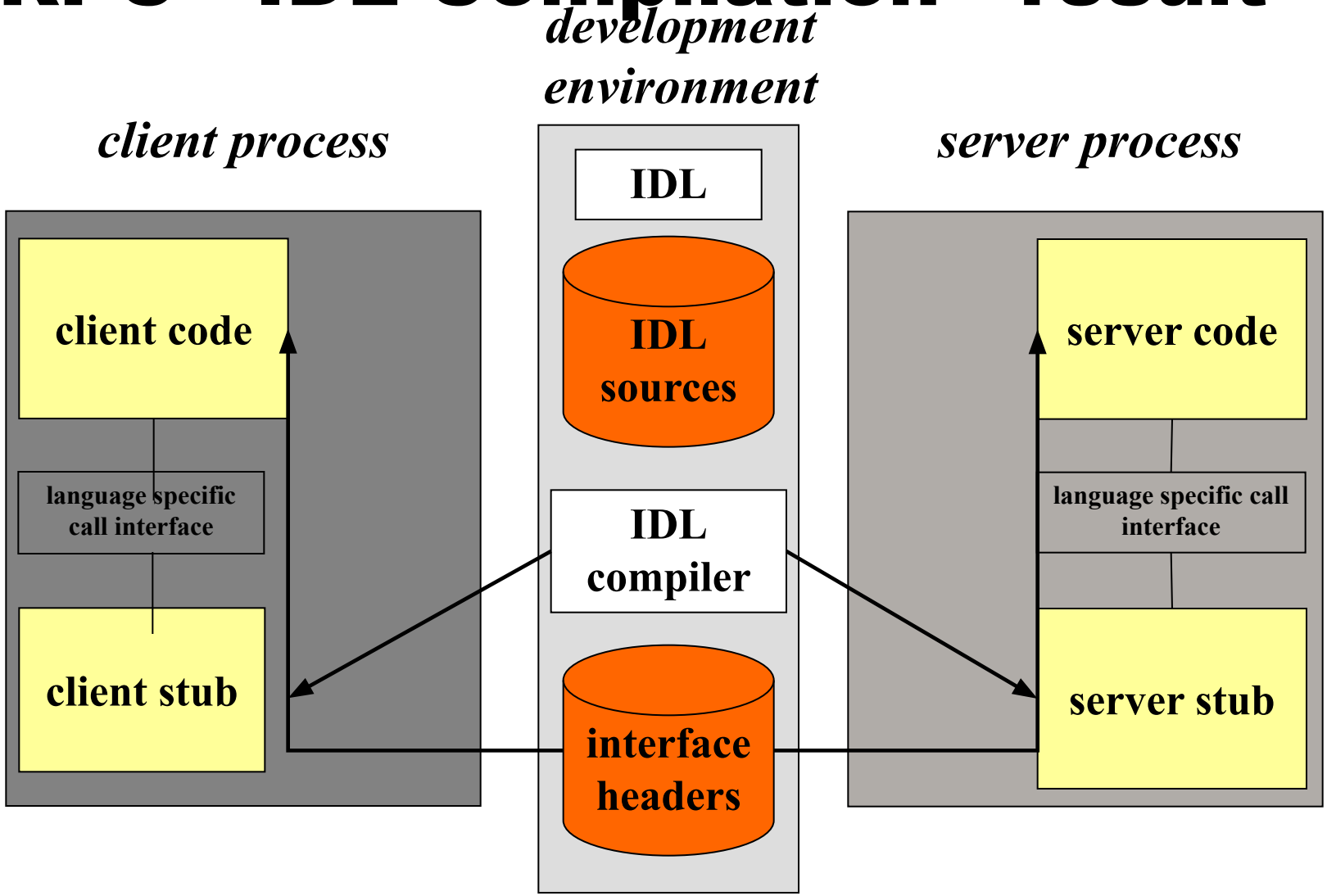
- Naming
  - Important for achieving location transparency
  - Facilitates Object Sharing
  - Mapping is performed using directories. Therefore name service is also known as *Directory Service*
- Security
  - Client-Server model makes security difficult
  - Cryptography based solutions

EXTRA SLIDES (REMOVE)

How Stubs are Generated

- Through a compiler
  - e.g. DCE/CORBA IDL – a purely declarative language
  - Defines only types and procedure headers with familiar syntax (usually C)
- It supports
  - Interface definition files (.idl)
  - Attribute configuration files (.acf)
- Uses Familiar programming language data typing
- Extensions for distributed programming are added

RPC - IDL Compilation - result



RPC NG: DCOM & CORBA

- Object models allow services and functionality to be called from distinct processes
- DCOM/COM+(Win2000) and CORBA IIOP extend this to allow calling services and objects on different machines
- More OS features (authentication,resource management,process creation,…) are being moved to distributed objects.

Sample RPC Middleware Products

- JaRPC (NC Laboratories)
  - libraries and development system provides the tools to develop ONC/RPC and extended .rpc Client and Servers in Java
- powerRPC (Netbula)
  - RPC compiler plus a number of library functions. It allows a C/C++ programmer to create powerful ONC RPC compatible client/server and other distributed applications without writing any networking code.
- Oscar Workbench (Premier Software Technologies)
  - An integration tool. OSCAR, the Open Services Catalog and Application Registry is an interface catalog. OSCAR combines tools to blend IT strategies for legacy wrappering with those to exploit new technologies (object oriented, internet).
- NobleNet (Rogue Wave)
  - simplifies the development of business-critical client/server applications, and gives developers all the tools needed to distribute these applications across the enterprise. NobleNet RPC automatically generates client/server network code for all program data structures and application programming interfaces (APIs)— reducing development costs and time to market.
- NXTWare TX (eCube Systems)
  - Allows DCE/RPC-based applications to participate in a service-oriented architecture. Now companies can use J2EE, CORBA (IIOP) and SOAP to securely access data and execute transactions from legacy applications. With this product, organizations can leverage their current investment in existing DCE and RPC applications

Some recent views on RPC

RPC vs. REST

http://steve.vinoski.net/pdf/IEEE-Convenience_Over_Correctness.pdf

New messaging formats

-- Google ProtoBuf

-- Apache Thrift (Facebook)

Protocol Buffer

lóhika

- Designed ~2001 because everything else wasn't that good those days
- Production, proprietary in Google from 2001-2008, open-sourced since 2008
- Battle tested, very stable, well trusted
- Every time you hit a Google page, you're hitting several services and several PB code
- PB is the glue to all Google services
- Official support for four languages: C++, Java, Python, and JavaScript
- Does have a lot of third-party support for other languages (of highly variable quality)
- Current Version - protobuf-2.4.1
- BSD License

protobuf

Protocol Buffers - Google's data interchange format

Apache Thrift

lóhika

- Designed by an X-Googler in 2007
- Developed internally at Facebook, used extensively there
- An open Apache project, hosted in Apache's Inkubator.
- Aims to be the next-generation PB (e.g. more comprehensive features, more languages)
- IDL syntax is slightly cleaner than PB. If you know one, then you know the other
- Supports: C++, Java, Python, PHP, Ruby, Erlang, Perl, Haskell, C#, Cocoa, JavaScript, Node.js, Smalltalk, OCaml and Delphi and other languages
- Offers a stack for RPC calls
- Current Version - thrift-0.8.0
- Apache License 2.0

Thrift

EXTRA Slide

Selected NFS operations (2)

symlink(newdirfh, newname, string) -> status	Creates an entry *newname* in the directory *newdirfh* of type symbolic link with the value *string*. The server does not interpret the *string* but makes a symbolic link file to hold it.
readlink(fh) -> string	Returns the string that is associated with the symbolic link file identified by *fh*.
mkdir(dirfh, name, attr) -> newfh, attr	Creates a new directory *name* with attributes *attr* and returns the new file handle and attributes.
rmdir(dirfh, name) -> status	Removes the empty directory *name* from the parent directory *dirfh*. Fails if the directory is not empty.
readdir(dirfh, cookie, count) -> entries	Returns up to *count* bytes of directory entries from the directory *dirfh*. Each entry contains a file name, a file handle, and an opaque pointer to the next directory entry, called a *cookie*. The *cookie* is used in subsequent *readdir* calls to start reading from the following entry. If the value of *cookie* is 0, reads from the first entry in the directory.
statfs(fh) -> fsstats	Returns file system information (such as block size, number of free blocks and so on) for the file system containing a file *fh*.

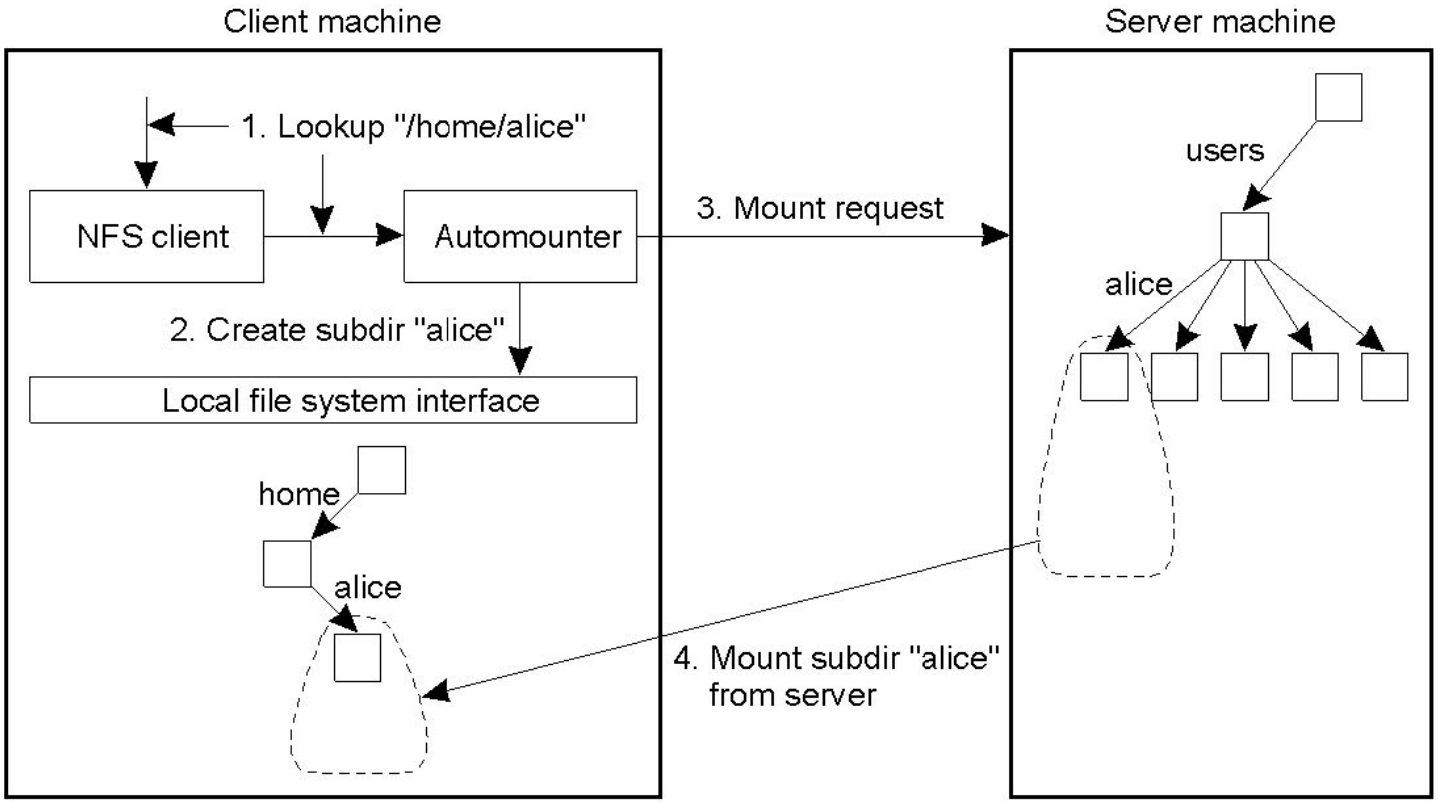
EXTRA Slide

Selected NFS Operations

lookup(dirfh, name) -> fh, attr	Returns file handle and attributes for the file *name* in the directory *dirfh*.
create(dirfh, name, attr) -> newfh, attr	Creates a new file name in directory *dirfh* with attributes *attr* and returns the new file handle and attributes.
remove(dirfh, name) status	Removes file name from directory *dirfh*.
getattr(fh) -> attr	Returns file attributes of file *fh*. (Similar to the UNIX *stat* system call.)
setattr(fh, attr) -> attr	Sets the attributes (mode, user id, group id, size, access time and modify time of a file). Setting the size to 0 truncates the file.
read(fh, offset, count) -> attr, data	Returns up to *count* bytes of data from a file starting at *offset*. Also returns the latest attributes of the file.
write(fh, offset, count, data) -> attr	Writes *count* bytes of data to a file starting at *offset*. Returns the attributes of the file after the write has taken place.
rename(dirfh, name, todirfh, toname) -> status	Changes the name of file *name* in directory *dirfh* to *toname* in directory to *todirfh*
link(newdirfh, newname, dirfh, name) -> status	Creates an entry *newname* in the directory *newdirfh* which refers to file *name* in the directory *dirfh*.

EXTRA Slide

Automounting (1)



A simple automounter for NFS.