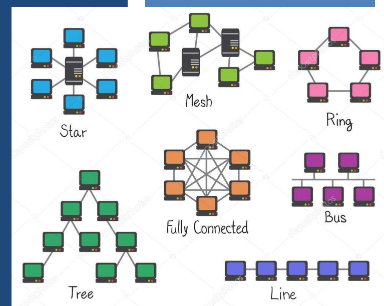
TCSS 558: APPLIED DISTRIBUTED COMPUTING



Chapter 6: Coordination

Consensus Algorithms

Chapter 7: Consistency and Replication

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OBJECTIVES

- Homework 2
- Extra Credit Assignment Posted

- Ch. 6 – Coordination
- 6.2 Logical clocks, Lamport clocks, Vector clocks
- 6.3 Distributed mutual exclusion
- 6.4 Election algorithms

- RAFT Consensus algorithm
- Chapter 7 Consistency and Replication

EXTRA CREDIT – 20 PTS (FINAL)

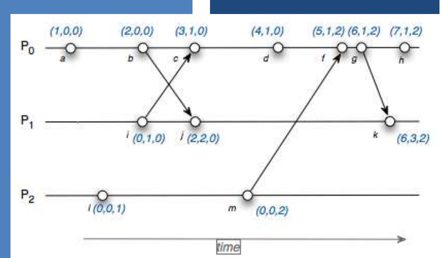
- Write up to be posted - Available until Friday 03/22 @ 11:59pm
- Review TCSS 562 Tutorial #4:
- http://faculty.washington.edu/wlloyd/courses/tcss562/tutorials/TCSS562_f2018_tutorial_4.pdf
- Choose one resource: CPU, memory, disk, or network
- Develop original AWS Lambda service in Java using the FaaS Inspector framework with performance bound by CPU, memory, disk, or network
- Run partestcpu.sh script on laptop, or ec2 instance with <=4 vCPUs
  - `./partestcpu.sh 100 100`
- Capture output using the "parTestCpu.sh script" and paste into a spreadsheet (xlsx)
- Verify that the number of containers is 100 (last row of output)
- Modify your service until it is sufficiently resource bound to achieve 100 containers with single partestcpu.sh 100 100 script run
- Submit spreadsheet, and Java project source code

HOMEWORK 2 UPDATE

- Extension to Thursday 3/14 @ 11:59pm
- Please use extra time to ensure support for multithreading and concurrency
- More time to implement extra credit membership tracking methods
- 5 points extra credit for providing Maven build files (pom.xml)

SHORT-HAND-CODES FOR MEMBERSHIP TRACKING APPROACHES

- Include readme.txt or doc file with instructions in submission
- Must document membership tracking method
- **S-1:** Static file membership tracking only = 0 pts
- **T-1:** TCP membership tracking only = +5 pts (*should be dynamic once servers point to membership server*)
- **U-1:** UDP membership tracking only = +10 pts (*automatically discovers nodes with no configuration*)
- **S+T-2:** Static file + TCP membership tracking = +15 pts (*Static file is not reread to refresh membership during operation*)
- **S+U-2:** Static file + UDP membership tracking = +15 pts (*Static file is not reread to refresh membership during operation*)
- **SD+T-2:** Static file + TCP membership tracking = +20 pts (Static file is periodically reread to refresh membership during operation)
- **SD+U-2:** Static file + UDP membership tracking = +20 pts (*Static file is periodically reread to refresh membership during operation*)
- **T+U-2:** TCP + UDP membership tracking = 20 pts (*both dynamic*)



CH. 6.2: LOGICAL CLOCKS

ORDERING EVENTS IN DISTRIBUTED SYSTEMS

- To order events across nodes (processes), using NTP to synchronize clocks is one approach
- But using monotonically increasing event counters (e.g. logical clocks) may be easier and sufficient to order events
- We would like to understand two conditions:
- **Are events causally related?**
  - Event A causally happens before event B
- **Or are events considered concurrent?**
  - Happening at the same time

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WHAT IS CAUSALITY?

- If an event A causally happens before another event B, then timestamp (A) < timestamp (B)
- When entering a house, must first unlock the door
  - Event (A): Unlocking the door
  - Event (B): Enter the house
  - Unlocking the door ***happens before*** entering the house
- You receive a letter, after it has been sent
  - Event (A): Letter has been sent
  - Event (B): Letter is received
  - Letter being sent ***happens before*** letter being received

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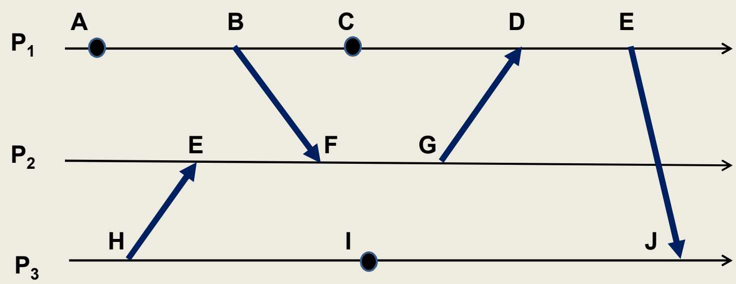
CAUSALITY

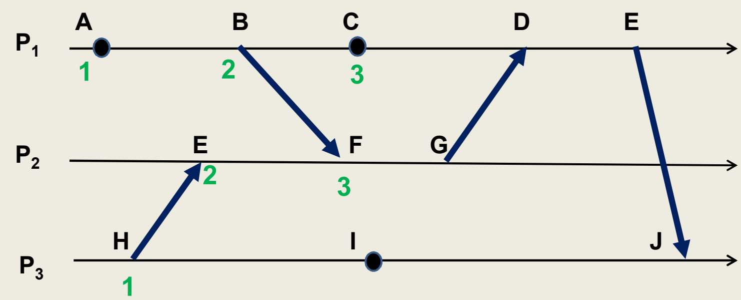


- What are the causal relationships on the graph?
  - A → B
  - B → F
  - A → F
  - H → G
  - F → J
  - H → J
  - C → J
  - I → G ?
  - H → G ?
  - C → G ?
  - B → G ?

WHAT ARE CONCURRENT EVENTS?

- A pair of concurrent events doesn't have a causal path from one event to another
- Lamport timestamps or vector clocks are not guaranteed to be ordered or unequal for concurrent events
- Clock values from different processes can't be compared
- The clock values may suggest that one event "happens before" another, but because they are from different processes they can't be trusted...

CONCURRENT EVENTS



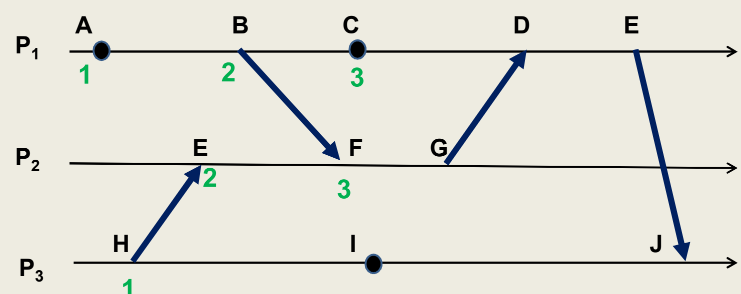
- Are these relationships causal or concurrent?
  - C → F ?
  - 3 == 3
  - H → C
  - 1 < 3

  H & C appear concurrent

  - H → F ?
  - B → F ?

  Don't know how long delivery of B to P2 takes.

CONCURRENT EVENTS



- Are the...
  - C →...
  - 3 =...

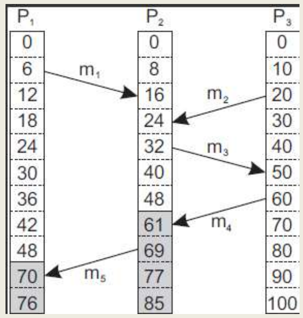
...F ?
...F ?
...ow how
...very of B
...kes.

Simply having a local time stamp less than the time stamp of another process does not guarantee causality

Here for H → C the events are <u>concurrent</u>

CAUSALITY - 2

- Consider the messages:



- P2 receives m1, and subsequently sends m3
- __Causality:__ Sending m3 ***may*** depend on what's contained in m1
- P2 receives m2, receiving m2 is ***not*** related to receiving m1
- ***Is sending m3 causally dependent on receiving m2?*** **YES**

VECTOR CLOCKS

- Lamport clocks (global sense of logical time) does not help to determine causal ordering of messages
- Vector clocks incorporate local time and support capturing causal histories and offer an alternative

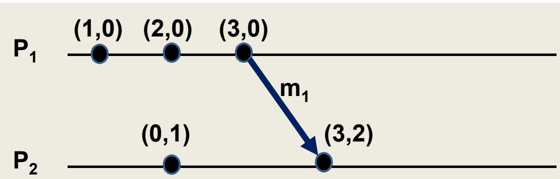
VECTOR CLOCKS - 2

- Vector clocks keep track of **causal history**
- If two local events happened at process P, then the causal history H(p2) of event p2 is {p1,p2}

- P sends messages to Q (*event p3*)
- Q previously performed event q1
- Q records arrival of message as q2
- Causal histories merged at Q H(q2)= {p1,p2,p3,q1,q2}

- Fortunately, can simply store history of last event, as a vector clock → H(q2) = (3,2)
- Each entry corresponds to the last event at the process

VECTOR CLOCKS - 3



- Each process maintains a vector clock which
  - Captures number of events at the local process (e.g. logical clock)
  - Captures number of events at all other processes
- Causality is captured by:
  - For each event at Pi, the vector clock (VC_i) is incremented
  - The msg is timestamped with VC_i; and sending the msg is recorded as a new event at P_i
  - P_j adjusts its VC_j choosing the **max** of: the message timestamp –or– the local vector clock (VC_j)

VECTOR CLOCKS - 4

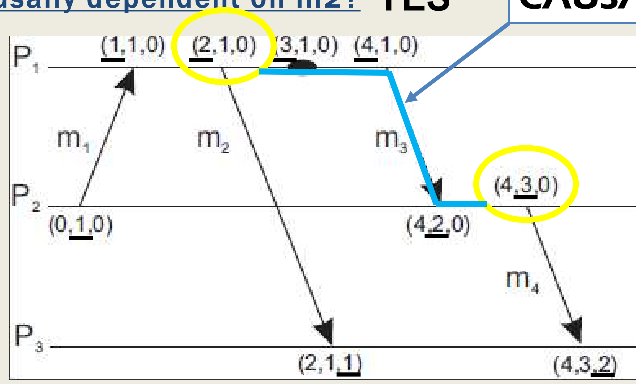
- Pj knows the # of events at Pi based on the timestamps of the received message
- Pj learns how many events have occurred at other processes based on timestamps in the vector
- These events *"may be causally dependent"*
- **In other words:** they may have been necessary for the message(s) to be sent…

VECTOR CLOCKS EXAMPLE

- Is m4 causally dependent on m2? **YES**

CAUSALITY

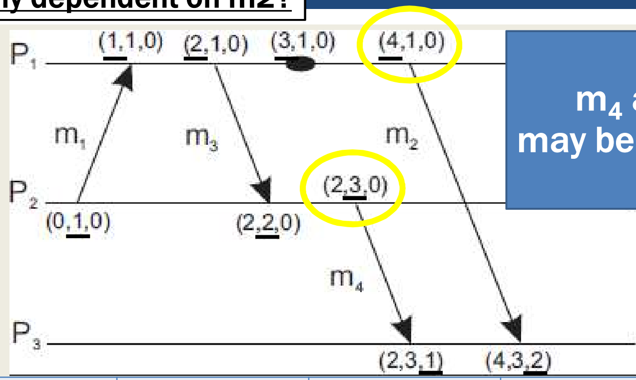
Local clock is Underlined



ts (m_2)	ts(m_4)	ts(m_2)<ts(m_4)	ts(m_2)>ts(m_4)	Conclusion
(2,1,0)	(4,3,0)	Yes	No	m2 may causally precede m4

VECTOR CLOCKS EXAMPLE - 2

Is m4 causally dependent on m2?



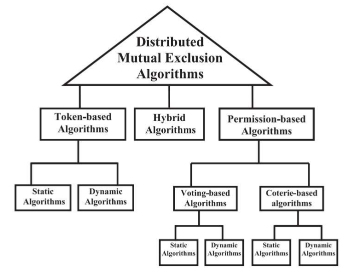
m_4 and m_2 may be concurrent

ts (m_2)	ts(m_4)	ts(m_2)<ts(m_4)	ts(m_2)>ts(m_4)	Conclusion
(4,1,0)	(2,3,0)	No	No	m2 and m4 may conflict

- P3 can't determine if m4 may be causally dependent on m2
- Is m4 causally dependent on m3 ? **YES**

VECTOR CLOCKS - 5

- Disclaimer:
- Without knowing actual information contained in messages, it is not possible to state with certainty that there is a causal relationship or perhaps a conflict
- Vector clocks can help us suggest possible causality
- We never know for sure…



CH. 6.3: DISTRIBUTED MUTUAL EXCLUSION

L16.21

DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS

- Coordinating access among distributed processes to a shared resource requires **Distributed Mutual Exclusion**
- **Algorithms in 6.3**
- Token-ring algorithm
- Centralized algorithm
- Distributed algorithm (Ricart and Agrawala)
- Decentralized voting algorithm (Lin et al.)

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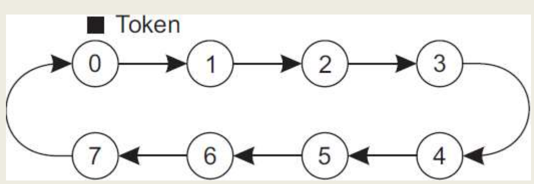
TOKEN-BASED ALGORITHMS

- Mutual exclusion by passing a "token" between nodes
- Nodes often organized in ring
- Only one token, holder has access to shared resource
- Avoids starvation: ***everyone gets a chance to obtain lock***
- Avoids deadlock: easy to avoid

TOKEN-RING ALGORITHM

- Construct overlay network
- Establish logical ring among nodes



- Single token circulated around the nodes of the network
- Node having token can access shared resource
- If no node accesses resource, token is constantly circulated around ring

TOKEN-RING CHALLENGES

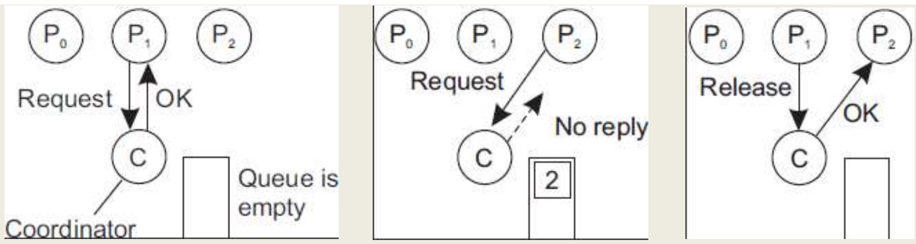
1. If token is lost, token must be regenerated
   - **Problem**: may accidentally circulate multiple tokens
2. Hard to determine if token is lost
   - What is the difference between token being lost and a node holding the token (***lock***) for a long time?
3. When node crashes, circular network route is broken
   - Dead nodes can be detected by adding a receipt message for when the token passes from node-to-node
   - When no receipt is received, node assumed dead
   - Dead process can be "jumped" in the ring

DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS - 3

- **Permission-based algorithms**
- Processes must require permission from other processes before first acquiring access to the resource
  - CONTRAST: Token-ring did not ask nodes for permission
- **Centralized algorithm**
- Elect a single leader node to coordinate access to shared resource(s)
- Manage mutual exclusion on a distributed system similar to how it mutual exclusion is managed for a single system
- Nodes must all interact with leader to obtain ***"the lock"***

CENTRALIZED MUTUAL EXCLUSION

Permission granted from coordinator \/ No response from coordinator



P_1 executes | P_2 blocks | P_1 finishes; P_2 executes

- When resource not available, coordinator can block the requesting process, or respond with a reject message
- P2 must ***poll*** the coordinator if it responds with reject otherwise can wait if simply blocked
- Requests granted permission fairly using FIFO queue
- Just three messages: (request, grant, release)

CENTRALIZED MUTUAL EXCLUSION - 2

- **Issues**
- Coordinator is a single point of failure
- Processes can't distinguish dead coordinator from "permission denied"
  - No difference between CRASH and Block (*for a long time*)
- Large systems, coordinator becomes performance bottleneck
  - Scalability: Performance does not scale

- **Benefits**
- Simplicity:
  Easy to implement compared to distributed alternatives

DISTRIBUTED ALGORITHM

- Ricart and Agrawala [1981], use total ordering of all events
  - Leverages Lamport logical clocks
- Package up resource request message (AKA Lock Request)
- Send to all nodes
- Include:
  - Name of resource
  - Process number
  - Current (logical) time
- Assume messages are sent reliably
  - No messages are lost

DISTRIBUTED ALGORITHM - 2

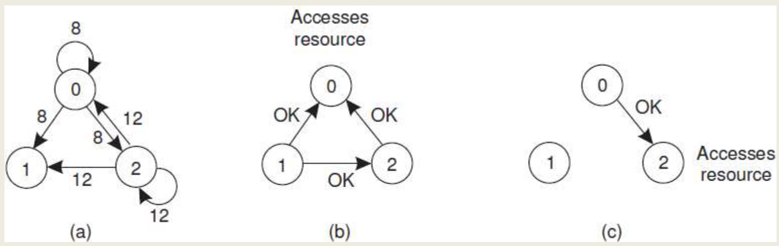
- When each node receives a request message they will:

1. Say OK (*if the node doesn't need the resource*)
2. Make no reply, queue request (*node is using the resource)*
3. Perform a timestamp comparison (*if node is waiting to access the resource*), then:
   1. Send OK if requester has lower logical clock value
   2. Make no reply if requester has higher logical clock value

- Nodes sit back and wait for all nodes to grant permission
- Requirement: every node must know the entire membership list of the distributed system

DISTRIBUTED ALGORITHM - 3

- If Node 0 and Node 2 simultaneously request access
- Node 0's time stamp is lower (8) than Node 2 (12)
- Node 1 and Node 2 grant Node 0 access
- Node 1 is not interested in the resource, it OKs both requests



- In case of conflict, lowest timestamp wins!
  - As seen in step (c)

CHALLENGES WITH DISTRIBUTED ALGORITHM

- Problem: Algorithm has N points of failure !
- Where N = Number of Nodes in the system

- Problem: When node is accessing the resource, it does not respond
  - Lack of response can be confused with failure
  - *Possible Solution:* When node receives request for resource it is accessing, always send a reply either granting or denying permission (ACK)
  - Enables requester to determine when nodes have died

CHALLENGES WITH DISTRIBUTED ALGORITHM - 2

- **Problem**: Multicast communication required –or- each node must maintain full group membership
  - Track nodes entering, leaving, crashing…
- **Problem**: Every process is involved in reaching an agreement to grant access to a shared resource
  - This approach ***may not scale*** on resource-constrained systems
- **Solution**: Can relax total agreement requirement and proceed when a **simple majority** of nodes grant permission
  - *Presumably any one node locking the resource prevents agreement*
- Distributed algorithm for mutual exclusion works best for:
  - Small groups of processes
  - When memberships rarely change

DECENTRALIZED ALGORITHM

- Lin et al. [2004], decentralized voting algorithm
- Resource is replicated N times
- Each replica has its own coordinator
- Accessing resource requires majority vote: Votes from m > N/2 coordinators
- **Assumption #1:** When coordinator does not give permission to access a resource (because it is busy) it will inform the requester

DECENTRALIZED ALGORITHM - 2

- **Assumption #2:** When a coordinator crashes, it recovers quickly, but will have forgotten votes before the crash.
- Approach assumes coordinators reset arbitrarily at any time
- Risk: on crash, coordinator forgets it previously granted permission to the shared resource, and on recovery it errantly grants permission again
- The Hope: if coordinator crashes, *upon recovery*, ***the node granted access to the resource has already finished before the restored coordinator grants access again . . .***

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DECENTRALIZED ALGORITHM - 3

- Even with conservative probability values, the chance of violating correctness **is so low** it can be neglected in comparison to other types of failure
- Leverages fact that a new node must obtain a majority vote to access resource, ***which requires time***

N	m	p	Violation
8	5	3 sec/hour	$< 10^{-15}$
8	6	3 sec/hour	$< 10^{-18}$
16	9	3 sec/hour	$< 10^{-27}$
16	12	3 sec/hour	$< 10^{-36}$
32	17	3 sec/hour	$< 10^{-52}$
32	24	3 sec/hour	$< 10^{-73}$

N	m	p	Violation
8	5	30 sec/hour	$< 10^{-10}$
8	6	30 sec/hour	$< 10^{-11}$
16	9	30 sec/hour	$< 10^{-18}$
16	12	30 sec/hour	$< 10^{-24}$
32	17	30 sec/hour	$< 10^{-35}$
32	24	30 sec/hour	$< 10^{-49}$

N = number of resource replicas, m = required "majority" vote

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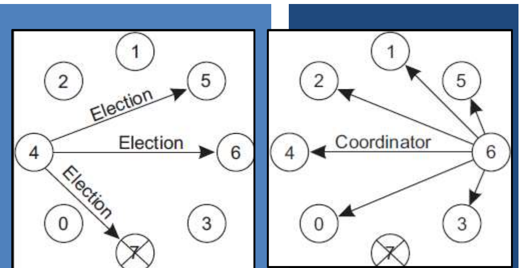
DECENTRALIZED ALGORITHM - 4

- **Back-off Polling Approach for *permission-denied*:**
- If permission to access a resource is denied via majority vote, process can poll to gain access again with a ***random*** delay (***known as back-off***)
- If too many nodes compete to gain access to a resource, majority vote can lead to low resource utilization
  - ***No one can achieve majority vote to obtain access to the shared resource***
- Problem Solution detailed in [Lin et al. 2014]



CH. 6.4: ELECTION ALGORITHMS

ELECTION ALGORITHMS

- Many distributed systems require one process to act as a coordinator, initiator, or provide some special role
- Generally any node (or process) can take on the role
  - In some situations there are special requirements
  - Resource requirements: compute power, network capacity
  - Data: access to certain data/information
- Assumption:
  - Every node has access to a “node directory”
  - Process/node ID, IP address, port, etc.
  - Node directory may not know “current” node availability
- Goal of election: at conclusion all nodes agree on a coordinator

ELECTION ALGORITHMS

- Consider a distributed system with N processes (*or nodes*)
- Every process has an identifier id(P)
- Election algorithms attempt to locate the highest numbered process to designate as coordinator

- **Algorithms:**
- Bully algorithm
- Ring algorithm
- Elections in wireless environments
- Elections in large-scale systems

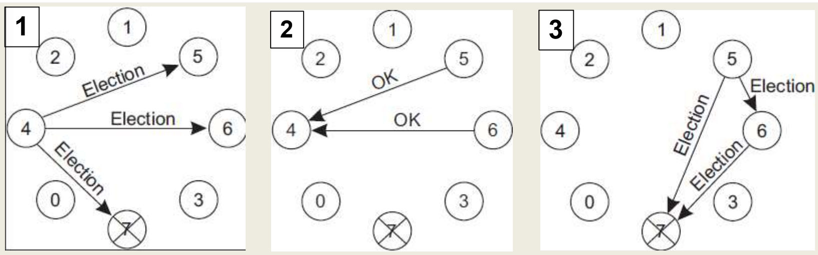
BULLY ALGORITHM

- When ***any*** process notices the coordinator is no longer responding to requests, it initiates an election
- Process P_k initiates an election as follows:
  1. P_k sends an ELECTION message to all processes with higher process IDs (P_{k+1}, P_{k+2}, … P_{N-1})
  2. If no one responds, P_k wins the election and becomes coordinator
  3. If one of the higher-ups answers, it takes over and runs the election.
- When the higher numbered process receives an ELECTION message from a lower-numbered colleague, it responds with "OK", indicating it's alive, and it takes over the election.

BULLY ALGORITHM - 2

- The higher numbered process then holds an election with ***only*** higher numbered processes (nodes).
- Eventually ***all*** processes give up except one, and the remaining process becomes the new coordinator.
- The coordinator announces victory by sending all processes a message stating it is starting as the coordinator.
- If a higher numbered node that was previously down comes back up, it holds an election, and ultimately takes over the coordinator role.
- The process with the "*biggest*" ID in town always wins.
- Hence the name, **bully algorithm**

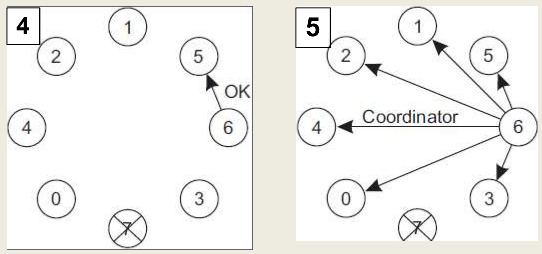
BULLY ALGORITHM - 3



[1] Process 4 holds an election

[2] Process 5 and 6 respond

[3] Process 5 and 6 each hold an election



[4] Process 6 tells Process 5 to stop

[5] Process 6 wins and tells everyone

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BULLY SUMMARY

- Every node knows who is participating in the distributed system
  - Each node has a group membership directory
- First process to notice the leader is offline launches a new election
- GOAL: Find the highest number node that is running
  - Loop over the nodes until the highest numbered node is found
  - May require multiple election rounds
- Highest numbered node is always the ***"BULLY"***

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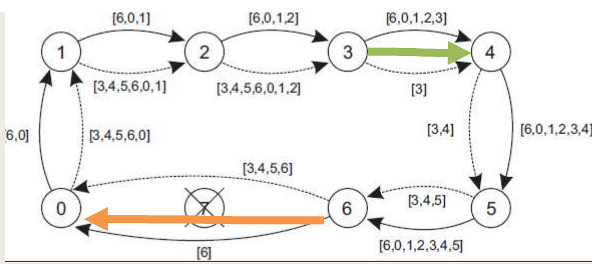
RING ALGORITHM

- Election algorithm based on network of nodes in a logical ring
- *Does not use a token*
- Any process (P_k) starts the election by noticing the coordinator is not functioning

1. P_k builds an **election message**, and sends to its successor
   - If successor is down, successor is skipped
   - Skips continue until a running process is found
2. When the **election message** is passed around, each node adds its ID to a *separate* **active node list**
3. When **election message** returns to P_k, P_k recognizes its own identifier in the **active node list**. Message is changed to COORDINATOR and "**elected(P_k)**" message is circulated.
   - Second message announces P_k is the NEW coordinator

RING: MULTIPLE ELECTION EXAMPLE



- **PROBLEM:** Two nodes start election at the same time: P_3 and P_6
- P_3 sends **ELECT(P_3)** message, P_6 sends **ELECT(P_6)** message
  - P_3 and P_6 both circulate ELECTION messages at the same time
- Also circulated with ELECT message is an **active node list**
- Each node adds itself to the **active node list**
- Each node votes for the highest numbered candidate
- P_6 wins the election because it's the candidate with the **highest ID**

ELECTIONS WITH WIRELESS NETWORKS

- Assumptions made by traditional election algorithms not realistic for wireless environments:
  - Message passing is reliable
  - Topology of the network does not change
- A few protocols have been developed for elections in ad hoc wireless networks
- Vasudevan et al. [2004] solution handles failing nodes and partitioning networks.
  - Best leader can be elected, rather than just a random one

VASUDEVAN ET AL. WIRELESS ELECTION

1. Any node (***source***) (P) starts the **election** by sending an ELECTION message to immediate neighbors (any nodes in range)
2. Receiving node (Q) designates sender (P) as parent
3. (Q) Spreads election message to neighbors, ***but not to parent***
4. Node (R), receives message, designates (Q) as parent, and spreads ELECTION message, ***but not to parent***
5. Neighbors that have already selected a parent immediately respond to R.
   - If ***all*** neighbors already have a parent, R is a leaf-node and will report back to Q quickly.
   - When reporting back to Q, R includes metadata regarding battery life and resource capacity
6. Q eventually acknowledges the ELECTION message sent by P, and also indicates the most eligible node (based on battery & resource capacity)

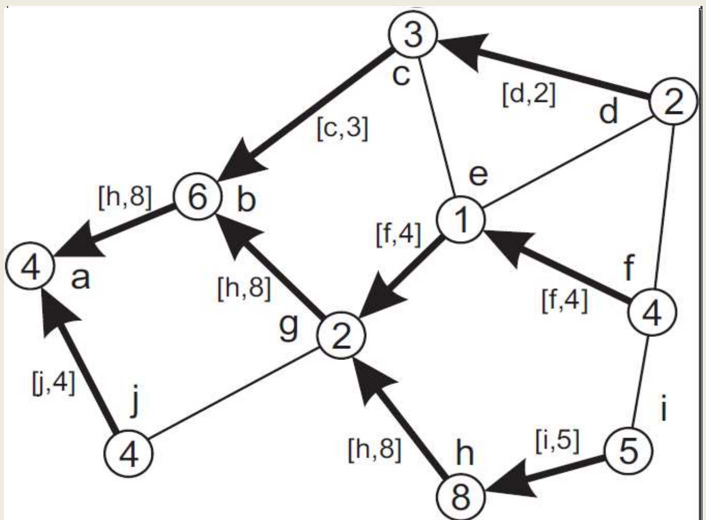
WIRELESS ELECTION - 2
SOURCE NODE: [A]

Node [A] initiates election

Election messages propagated to all nodes

Each node reports to its parent node with best capacity

Node A then facilitates Node H becoming leader



WIRELESS ELECTION - 3

- When multiple elections are initiated, nodes only join one
- Source node tags its ELECTION message with unique identifier, to uniquely identify the election.
- With minor adjustments protocol can operate when the network partitions, and when nodes join and leave

ELECTIONS FOR LARGE-SCALE SYSTEMS

- Large systems often require several nodes to serve as coordinators/leaders
- These nodes are considered ***"super peers"***
- ***Super peers*** must meet operational requirements:

1. Network latency from normal nodes to ***super peers*** must be low
2. ***Super peers*** should be evenly distributed across the overlay network (ensures proper load balancing, availability)
3. Must maintain set ratio of ***super peers*** to normal nodes
4. ***Super peers*** must not serve ***too many normal nodes***

ELECTIONS FOR DHT BASED SYSTEMS

- DHT-based systems use a bit-string to identify nodes
- **Basic Idea**: Reserve fraction of ID space for super peers
- The first $\log_2(N)$ bits of the key identify super-peers
- m=number of bits of the identifier
- k=# of nodes each node is responsible for (Chord system)
- **Example:**
- For a system with m=8 bit identifier, and k=3 keys per node
- Required number of super peers is $2^{(k-m)} \cdot N$, where N is the number of nodes
  - In this case N=32
  - **Only 1 super peer is required for every 32 nodes**

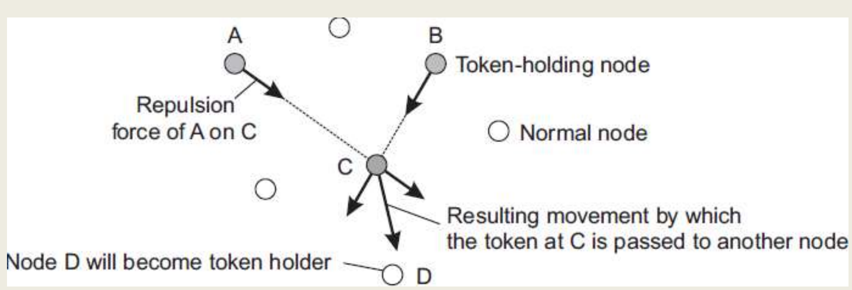
SUPER PEERS IN AN M-DIMENSIONAL SPACE

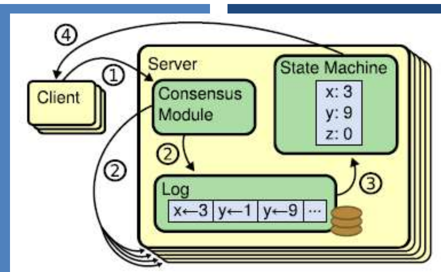
- Given an overlay network, the idea is to position superpeers throughout the network so they are evenly disbursed

- **Use tokens:**
- Give N tokens to N randomly chosen nodes
- No node can hold more than (1) token
- Tokens are "repelling force". Other tokens move away
- All tokens exert the same repelling force
- This automates token distribution across an overlay network

OVERLAY TOKEN DISTRIBUTION

- Gossping protocol is used to disseminate token location and force information across the network
- If forces acting on a node with a token exceed a **threshold**, token is moved away
- Once nodes hold token for awhile they become superpeers





RAFT CONSENSUS

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CONSENSUS IN DISTRIBUTED SYSTEMS

- Paxos Algorithm (originally published in 1989)
- Original algorithm by Leslie Lamport (logical clocks) for consensus
- Single decree Paxos: supports reaching agreement on a single decision
  - To agree on contents of a single log entry
- Multiple decree Paxos: use multiple instances of the protocol to facilitate series of decisions such as a log

- Ensures safety and liveness
- Changes in cluster membership
- Has been proven "correct" (e.g. via proofs)

PAXOS DRAWBACKS

- **As reported by the inventors of RAFT . . .**
  - *Diego Ongaro and John Ousterhout from Stanford University*
- Exceptionally difficult to understand
- Most descriptions focus on single-decree version
- Survey at the 2012 USENIX Symposium (UNIX Users Group, Advanced Computing Systems Association)
  - Few seasoned researchers comfortable with Paxos
  - Understanding typically requires reading multiple papers

PROBLEMS WITH PAXOS

- **Problem 1:** Single Decree Paxos
- Two stages
- Lacks simple intuitive explanation
- Hard to understand why the "single-decree" protocol works
- Used for agreement on just one log entry
- **Problem 2:** Lacks foundation for building practical implementation
- No widely agreed upon algorithm for multi-Paxos
  - Multi decree for agreement on an entire log file
- Lamport's multi-Paxos description has missing detail
  - Mostly focused on single decree

PROBLEMS WITH PAXOS - 2

- Other attempts to flesh out details are divergent from Lamport's own sketches
- Problem 3: Paxos architecture is poor for building practical systems
- Paxos' notion of consensus is for a single log entry
- Consensus approach can be designed around a sequential log
- Problem 4: Paxos approach uses a symmetric peer-to-peer approach vs. a leader-based approach
  - Works when just (1) decision
  - Having a leader simplifies making multiple decisions

RESULTING PROBLEMS

- Implementations of Paxos typically diverge as each develops a different architecture for solving the difficult problem(s) of implementing Paxos
- Paxos formulation is good for proving theorems about correctness, but challenging to use for implementing real systems
  - Though it has been used a fair bit
  - See paper: Consensus in the Cloud: Paxos Systems Demystified
- Observation: significant gaps between the description of the algorithm and the needs of a real-world system, result in final systems based on divergent, unproven protocols

DESIGN GOALS FOR RAFT

- Complete and practical foundation for building systems
  - Reduce design work for developers
- Safe under all conditions
- Efficient for common operations
- UNDERSTANDABLE
  - So Raft can be implemented and extended as needed in real world scenarios

DESIGN GOALS FOR RAFT - 2

- Raft decomposes consensus into sub-problems:
  - Leader election: leader election algorithms adjustable
  - Log replication: leader accepts log entries and coordinates replication across cluster enforcing log consensus
  - Safety: if any state machine applies a log entry, then no other server can apply a different log entry for the same log index
  - Membership changes: must migrate from old-configuration to new-configuration in a coordinated way

DESIGN GOALS FOR RAFT - 3

- Simplify the state space
- Reduce the number of states to consider
- Make system more coherent
- Eliminate non-determinisim
- LOGS not allowed to have holes
- Limit ways logs can be inconsistent

RAFT ALGORITHM BASICS

- Begins by electing a leader
- Leader manages log replication
- LEADER ACTIVITIES
  - Accepts log entries from other nodes
  - Replicates them on other servers
  - Tells nodes when safe to apply log entries to their state machines (KV store)
  - Leader can make decisions without consulting others
  - Data flows from leader → to nodes
  - When leader fails, a new leader is elected

RAFT BASICS - 2

- Server states: leader, (*)follower, candidate
  - (*) – initial state of every node is follower
- Nodes redirect all requests to the leader
- Candidate server in a leader election
  - Server with most votes wins election, becomes leader
  - Other nodes become followers
  - Each candidate sponsors its own election, and solicits votes
  - More than one candidate can be conducting an election at the same time

TERMS

- Raft divides time into TERMS of arbitrary length
- Terms are numbered with consecutive integers
- Terms start with an election (term # is incremented)
- If election results in a SPLIT VOTE, term ends, and a *new term* is started with an election
- There is only (1) Leader in any given term
- Terms act as a logical clock
- Each server stores current term number
- Terms are exchanged in communication

TERMS - 2

- If a larger term # is found, then ***all nodes*** update term # and defer to the term's **leader**
  - If **candidate** or **leader** finds its term is out of date, will immediately become a **follower** node
- If server receives request with stale term #, then request is rejected

RAFT METHODS

- Implemented as "RPCs", but can be implemented as TCP stream by marshalling data inputs/outputs
- **RequestVote()**
- Initiated by **candidates** during an election
- **AppendEntriesToLog()**
- Sent by **leaders** to **follower** nodes at regular intervals
- Used as a heartbeat to maintain leadership
- Provides log updates to nodes
- Performs consistency checks
- Commands are retried if no response after timeout
- Commands sent in parallel using multiple threads (performance)

RAFT ELECTIONS

- Every node has a ***randomized*** ElectionTimeout value
- If a node (**follower**) receives no heartbeat from the **leader** after the timeout, node expects the **leader** has gone offline
- **NEW ELECTION:**
- (1) The node ***begins a new election*** as **candidate**, sending RequestVote() to every node in the system
  - **Candidate** immediately votes for itself
  - RequestVote() sent in parallel to all nodes
- (2) Follower votes for **first candidate** a RequestVote() is received from ***only if the candidate's log is at least (or more) up-to-date***
  - *Inspect **candidate** provided last log index and log term values*
- (3) If **candidate** obtains a majority of the votes (*determined by calculating majority total from node directory*) **it wins the election!!!**

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ELECTIONS - 2

- **Election outcomes**
- A – **Candidate** wins
- B – Another server establishes leadership
- C – There is no winner
- Servers vote for only one **candidate**
- Only (1) winner per election
- Only (1) **leader** per term
  - *"Election safety property"*
- New **leader** sends empty heartbeat to nodes to establish leadership

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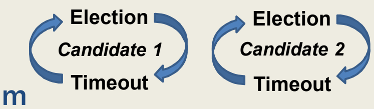
ELECTIONS - 3

- While a **candidate** waits for votes, it may receive an AppendEntries() call from another **leader**
  - If the **leader's** term >= **candidate's** term then the **candidate** concedes the election and returns to **Follower** state
- If multiple elections, then no one **candidate** may receive a majority vote. One election times out ***first*** based on a randomized-election-timeout value
  - Random timeout values help spread out the **candidates** to prevent endless looping
- **KEY IDEA**: by using random timeouts, when no majority vote occurs, a random node times out first and starts a new election before anyone else by incrementing the term #, and sending RequestVote()



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ELECTIONS - 4

- Randomized timeout values should be reset every time
- Paper suggests a min timeout of 150ms, and max of 300ms
- Timeout should be "an order of magnitude" greater (10x) than the node-to-node communication latency
  - *I'm presently using 500 – 1000ms*
- Can experiment with different values

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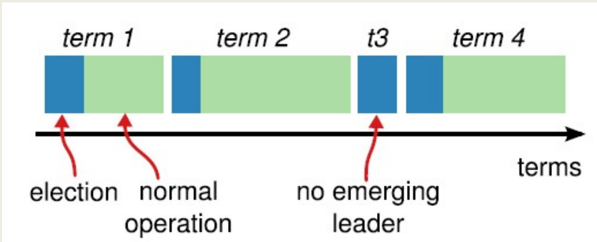
ELECTIONS - 5

- RAFT enforces leader logs to be up-to-date during an election
- Nodes ***ONLY*** vote for a candidate ***if*** :
- **Candidate** local term and log number >= **follower**
- Candidate's log ***must be*** at least as up-to-date as the majority of follower's log

- **MORE up-to-date log is defined as log with:**
- Higher term # in last log entry
- --- OR ---
- When term of last log entries match, log with more entires
- *E.g. longer log*

TYPICAL ELECTION SEQUENCE



- Term 1: normal election
- Term 2: normal election
- Term 3: SPLIT VOTE, no **leader** emerges, election times out
- Term 4: normal election

RAFT SAFETY

Election Safety: at most one leader can be elected in a given term. §5.2

Leader Append-Only: a leader never overwrites or deletes entries in its log; it only appends new entries. §5.3

Log Matching: if two logs contain an entry with the same index and term, then the logs are identical in all entries up through the given index. §5.3

Leader Completeness: if a log entry is committed in a given term, then that entry will be present in the logs of the leaders for all higher-numbered terms. §5.4

State Machine Safety: if a server has applied a log entry at a given index to its state machine, no other server will ever apply a different log entry for the same index. §5.4.3

- Raft guarantees that each of these properties is always true

LOG REPLICATION

- Leader receives commands forwarded from followers
- Ways logs can diverge
- (a) Follower may be missing entries present on leader
- (b) Follower may have extra entries not present on the leader
- (c) Both A and B
- Because raft uses a “coordinator” node to achieve consensus the number of possible ways logs can diverge is limited
- Raft leaders FORCE followers logs to match its own
- Conflicting entries in follower logs are overwritten

LOG REPLICATION - 2

- FOR THE WHOLE SYSTEM THERE IS JUST ONE MONOTONICALLY INCREASING LOG INDEX
  - Akin to Lamport's Clocks

- Possible *follower* states at start of new term
- (a) Missing entries
- (b) Extra uncommitted entries
- (c) Both

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RAFT - LOG REPLICATION ALGORITHM

- Leader:
1. Receives command(s)
2. Appends commands to local log (concurrent hash table)
3. Sends AppendEntries() to followers

- Leader tracks index of its highest committed log entry
- Provides this index to followers in AppendEntries() RPC

- Leader commit to state machine:
- (1) When log entries replicated at a majority of the followers, leader commits to its state machine (KV-store)

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LOG REPLICATION ALGORITHM - 2

- Synchronizing follower logs
- (2) If follower rejects AppendEntries() then leader decrements its "follower-nextIndex" by one, and *retries* AppendEntries().
  - "follower-nextIndex" tracks which logs entries are sent to the follower for each AppendEntries() RPC call
- Loop continues until leader ***walks back*** its "follower-nextIndex" until it **matches** what is committed at the follower
  - Follower has a **commitIndex**
  - Tracks 1st phase of a "two-phase" commit
  - Follower has a **lastApplied** index
  - Tracks 2^{nd} phase of "two-phase" commit
- Once leader matches follower-nextIndex, the follower accepts the AppendEntries() RPC, and writes data to its log
  - Conflicting log entries are overwritten

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LOG REPLICATION ALGORITHM - 3

- Leader based consensus algorithms require the leader to "eventually store" all committed log entries
- Raft handles follower node failure by retrying communication indefinitely
  - If crashed server restarts, the log will be resurrected, and the follower's state machine will be restored (kv-store)

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COMMITTING LOG ENTRIES

- Each node keeps a **commitIndex** and **lastApplied** index variable
- **PHASE I**
- Leader: when log message replicated at a majority of follower logs (not state machines) *****- described next slide***
- Leader increments its commitIndex
- Followers set commitIndex to Min (leader-commitIndex , index of last new log entry)

If leaderCommit > commitIndex, set commitIndex = min(leaderCommit, index of last new entry)

- **PHASE II**
- For any node (follower, leader):
- If commitIndex > lastApplied
  - Increment lastApplied by 1
  - commit log[lastApplied] to **state machine** (kv-store)

If commitIndex > lastApplied: increment lastApplied, apply log[lastApplied] to state machine (§5.3)

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UPDATING COMMIT-INDEX OF LEADER

- If there exists an N such that N > commitIndex, a majority of matchIndex[i] ≥ N, and log[N].term == currentTerm: set commitIndex = N (§5.3, §5.4).

- ***How leader determines when to update it's commitIndex***
- Use a ***majority consensus*** of what has been committed at follower logs
- **Leader** maintains follower state arrays:
- **nextIndex[]:** index of next log entry to send to follower
- **matchIndex[]:** index of highest log entry known to be replicated (to log) at follower
- Find N, such that N > $commitIndex_{leader}$
- **and** a majority of matchIndex[i] ≥ N *(from followers)*
- **and** log_entry_{leader}[N].term == $currentTerm_{leader}$
- **then** set $commitIndex_{leader}$ = N

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RAFT CLUSTER MEMBERSHIP – A3

- Cluster discovery performed at startup
- Use any method:
  - Static file, UDP discovery (kv-store), TCP discovery (kv-store)
- One membership is discovered, it can remain static/fixed
- Nodes can go offline, come back online
- One a common configuration is propagated across the system, it can not be changed without restarting
- RAFT specifies a configuration change protocol where the system does a "hand-off" between an old and new configuration (section 6 of the paper)

A3 RAFT SIMPLIFICATIONS

- RequestVote() can be single threaded
  - AppendEntries() probably should have one thread per follower
- TCP client catch exceptions:
  - IOExcpetion – newSocket()
  - IOException – getOutputStream()
  - IOException – getInputStream()
  - Leader should catch exceptions, and retry requests indefinitely
  - Use socket method .setSoTimeout() to set a socket timeout in MS
- Node directory should generate and track nodeIDs
  - E.g. 1, 2, 3, 4, … n
- Node directory should retrieve a node by ID, or IP/PORT

A3 RAFT SIMPLIFICATIONS - 2

- Leader election: if using a single thread for election candidate should retry RequestVote() up to 10 times for a follower then give-up and move to next follower
- Instead of pushing data to followers when put() or del() is received by leader, can wait until next scheduled heartbeat to follower

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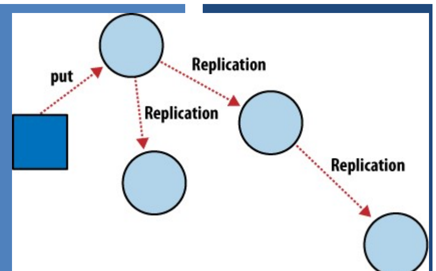

CONSISTENCY AND REPLICATION

L19.86

WHY REPLICATE DATA?

(1) Fault tolerance: continue working after one replica crashes

(2) Provide better protection against corrupted data

(3) Performance

(3a) Scaling up systems (***scalability***)

- Replicate server, load balance workload across replicas

(3b) For providing geographically close replicas

- Replicas at the edge
- **MOVE DATA TO THE COMPUTATION**
- Performance ***perceived*** at the edge increases
- **But what is the cost of localized replication?**

DATA REPLICATION COSTS

- Network bandwidth consumed maintaining replicas
  - Updates must be sent out and coordinated
- Maintaining consistency may be difficult
- All copies must be updated to ensure consistency
- **WHEN** and **HOW** updates need to be performed determines the prices of data replication…
- **Web caching example**
- Web browser caches local content to improve performance
- Doesn't know when content is "stale"
- **Solution:** Place server in charge of replication not browser
- Server invalidates and updates client cached copies
- Track how current copies are
- Degrades server performance → overhead from tracking, etc.

REPLICATION TRADEOFF EXAMPLE

- Process P accesses a local replica N times per second
- Replica is updated M times per second
- Updates involve complete refreshes of the data
- If N << M (very low access rate) many updates M are never accessed by P.
- Network communication overhead for most updates is useless.

- **TRADEOFFS:**
- Either move the replica away from P
  - *So the total number of accesses from multiple processes is higher*
- Or, apply a different strategy for updating the replica
  - *i.e. less frequent updates, possibly need based*

- **BALANCE TRADEOFF BETWEEN REPLICA ACCESS FREQUENCY AND COSTS OF REPLICATION** *(communication overhead)*

REPLICATION: SCALABILITY ISSUES

- **TIGHT CONSISTENCY**
- Reads must return same result
- Replication must occur after an update, before a read
- Provided by synchronous replication
- Update is performed across all copies as a single atomic operation (or transaction)
- **Assignment 2 replication is with tight consistency.**

- Keeping multiple copies consistent is subject to scalability problems
- May need global ordering of operations (e.g. Lamport clocks), or the use of a coordinator to assign order
- Global synchronization across a wide area network is time consuming (network latency)

REPLICATION SCALABILITY - 2

- Only solution is often to ***relax*** the consistency constraints
- Updates do not need to be executed as atomic operations
- Try to avoid instantaneous global synchronizations
- TRADEOFF: consistency
  - Not all copies may always be the same everywhere
- Whether consistency requirements can be relaxed depends on:
  - Access and update patterns
  - Use cases of the data
- Range of consistency models exist
- Implemented with distribution and consistency protocols

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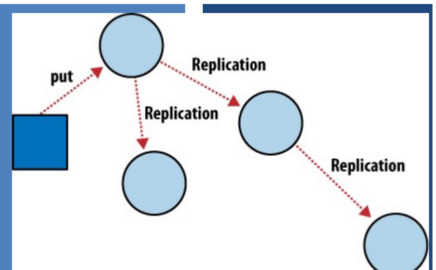
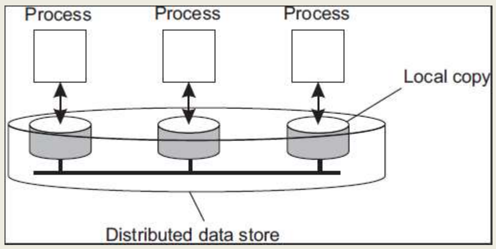


DATA CENTRIC CONSISTENCY MODELS

L19.92

DATA-CONSISTENCY MODELS

- Data consistency is discussed in the context of
  - Distributed shared memory
  - Distributed shared database
  - Distributed shared file system
- Generically referred to as a ***"data store"***
- Each process has a nearby replica:



DATA-CONSISTENCY MODELS

- **CONSISTENCY MODEL**
- Rules that must be followed to ensure consistency
- Represents a contract between processes and data store
- If processes agree to obey certain rules, store promises to work correctly

- No general rules for loosening consistency
- What can be tolerated is highly application dependent

- Three types of inconsistencies
- Data variation
- Staleness
- Ordering of update operations

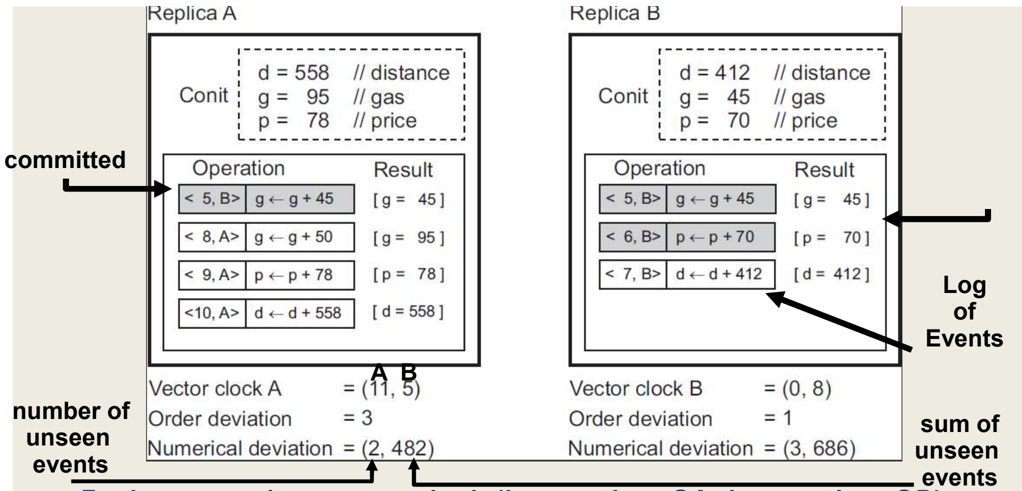
CONTINUOUS CONSISTENCY

- Ranges assigned to "what is allowed" for these deviations:
  - How much data variation?
  - How old/stale can the data be?
  - How much can ordering of update operations vary?
- Idea is to specify bounds for numeric deviation:
- **Relative numeric deviation**: 2% (percent)
- **Absolute numeric deviation**: .2 (implies a particular scale)
- **Numeric deviation**: may also refer to the number of updates applied to a replica
- **Staleness**: specifies bounds relative to time, e.g. how old?
- **Ordering of updates**: updates applied tentatively to local copy; may later be rolled back and applied in different order before becoming permanent

CONSISTENCY UNITS (CONIT)

- Abbreviated as "Conit"
- Specified the unit to measure consistency
- **Example**: Tracking fleet of rental cars
- Variables for a "conit":
- (g) gasoline consumed
- (p) price paid for gasoline
- (d) distance traveled
- Server keep conit consistently replicated

CONSISTENCY UNIT (CONIT)



- Each process has vector clock (known time @A, known time @B)

SEQUENTIAL CONSISTENCY

- Result of any execution is the same as if the operations of all processes were executed in some sequential order, and the operations of each individual process appear ***in this sequence*** in the order specified by its program.

Sequentially Consistent

P1:	W(x)a				
P2:		W(x)b			
P3:			R(x)b		R(x)a
P4:				R(x)b	R(x)a

NOT Sequentially Consistent

P1:	W(x)a				
P2:		W(x)b			
P3:			R(x)b		R(x)a
P4:				R(x)a	R(x)b

- Exact order seen by processes **DOES NOT MATTER**
- As long as they all agree
- Processes here must see: R(x)b, then R(x)a

CAUSAL CONSISTENCY

- Writes that are potentially causally related ***must be seen*** by all processes ***in the same order***.
- ***Concurrent writes*** may be seen ***in a different order*** by different processes.
- Concurrent writes happen with no READS in between
  - Events can be seen as "concurrent events"
- **Which writes are concurrent?**

P1:	W(x)a			W(x)c		
P2:		R(x)a	W(x)b			
P3:		R(x)a			R(x)c	R(x)b
P4:		R(x)a			R(x)b	R(x)c

- **Note** how the reads after the concurrent write for P3 and P4 are ***in a different order.***
- This is ok with causal consistency

CAUSAL CONSISTENCY - 2

- **Which timing graphs uphold causal consistency?**
- (A)

P1:	W(x)a			
P2:		W(x)b		
P3:			R(x)b	R(x)a
P4:			R(x)a	R(x)b

- (B)

P1:	W(x)a				
P2:		R(x)a	W(x)b		
P3:				R(x)b	R(x)a
P4:				R(x)a	R(x)b

- **Which writes are concurrent?**
- For (B), since R(x)a can influence W(x)b, the subsequent reads by P3 and P4 **must be in the same order** . . .

ENTRY CONSISTENCY

- Locks can be used to control access to data members
- Releasing a lock tells the distributed system that a variable needs to be synchronized / updated.
- A simple read without obtaining a lock may result in a stale value

P1:	L(x)	W(x)a	L(y)	W(y)b	U(x)	U(y)		
P2:					L(x)	R(x)a		R(y) NIL
P3:							L(y)	R(y)b

- Here P2 does not obtain L(y) before reading y R(y)
  - P2 receives a stale/old value

CONSISTENCY VS. COHERENCE

- **Consistency models** define what to expect when processes concurrently operate on distributed data
- Data is consistent, if it adheres to the rules of the model

- **Coherence models**: describe what can be expected for only ***a single data item***
- Data item is replicated
- Data item is coherent when copies adhere to consistency model rules
- Coherence often uses **sequential consistency** applied to a single data item
- For concurrent writes, all processes eventually see the same order of updates

EVENTUAL CONSISTENCY

- If no new updates are made to a given data item, eventually all accesses to that item will return the last updated value.
- System must reconcile differences between multiple distributed copies of data
- Servers must exchange data updates
- Servers must reconcile updates to agree on final state
  - Read repair: correction done when read finds inconsistency
  - Write repair: correct done on write operation
  - Asynchronous repair: correction done independently from read and write

EVENTUAL CONSISTENCY - 2

- Most processes mainly read from data store
  - Rarely update data
- How fast should updates be made to read-only processes?
- Example: Content Delivery Networks (video streaming)
  - Updates are propagated slowly
- Conflicts: write-write and read-write (most common)
- Often acceptable to propagate updates in a lazy manner when most processes perform only READ-ONLY access
- All replica gradually (eventually) become consistent

QUESTIONS

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EXTRA SLIDES

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