

Distributed Mutual Exclusion

- In first part of course, saw need to coordinate concurrent processes / threads
 - In particular considered how to ensure **mutual exclusion**: allow only 1 thread in a critical section
- A variety of schemes possible:
 - test-and-set locks; semaphores; event counts and sequencers; monitors; and active objects
- But most of these ultimately rely on hardware support (atomic operations, or disabling interrupts...)
 - not available across an entire distributed system
- Assuming we have some shared distributed resources, how can we provide mutual exclusion in this case?

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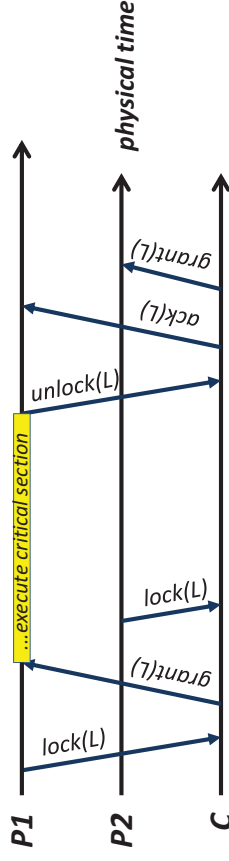
Distributed Systems 8L for Part IB

Handout 3

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Solution #1: Central Lock Server



- Nominate one process C as coordinator
 - If P_i wants to enter critical section, simply sends `lock` message to C, and waits for a reply
 - If resource free, C replies to P_i with a `grant` message; otherwise C adds P_i to a wait queue
 - When finished, P_i sends `unlock` message to C
 - C sends `grant` message to first process in wait queue

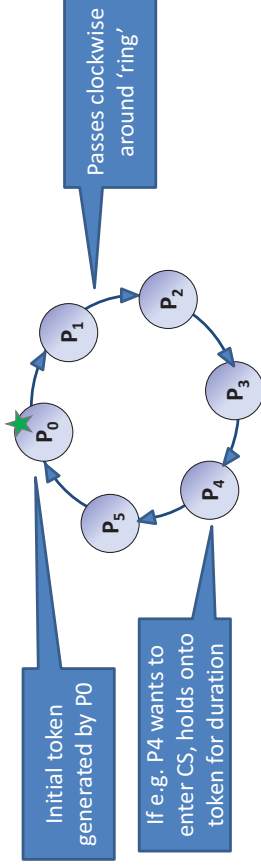
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Central Lock Server: Pros and Cons

- Central lock server has some good properties:
 - **simple** to understand and verify
 - **live** (providing delays are bounded, and no failure)
 - **fair** (if queue is fair, e.g. FIFO), and easily supports priorities if we want them
 - **decent performance**: lock acquire takes one round-trip, and release is 'free' with asynchronous messages
- But C can become a performance bottleneck...
- ... and can't distinguish crash of C from long wait
 - can add additional messages, at some cost

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Solution #2: Token Passing



- Avoid central bottleneck
- Arrange processes in a logical ring
 - Each process knows its predecessor & successor
 - Single token passes continuously around ring
 - Can only enter critical section when possess token; pass token on when finished (or if don't need to enter CS)

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Token Passing: Pros and Cons

- Several advantages :
 - Simple to understand: only 1 process ever has token => mutual exclusion guaranteed by construction
 - No central server bottleneck
 - Liveness guaranteed (in the absence of failure)
 - So-so performance (between 0 and N messages until a waiting process enters, 1 message to leave)
- But:
 - Doesn't guarantee fairness (FIFO order)
 - If a process crashes must repair ring (route around)
 - And worse: may need to regenerate token – tricky!
- And constant network traffic: an advantage???

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Solution #3: Totally-Ordered Multicast

- Scheme due to Ricart & Agrawala (1981)
- Consider N processes, where each process maintains local variable state which is one of { FREE, WANT, HELD }
- To obtain lock, a process P_i sets state: = WANT, and then multicasts lock request to all other processes
- When a process P_j receives a request from P_i:
 - If P_i's local state is FREE, then P_j replies immediately with OK
 - If P_j's local state is HELD, P_j queues the request to reply later
- A requesting process P_i waits for OK from N-1 processes
 - Once received, sets state: = HELD, and enters critical section
 - Once done, sets state: = FREE, & replies to any queued requests
- What about **concurrent requests**?

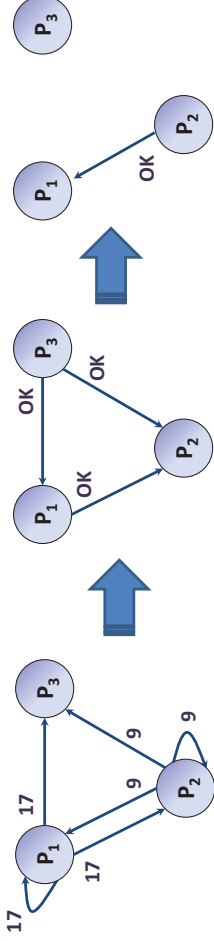
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Handling Concurrent Requests

- Need to decide upon a total order:
 - Each process maintains a Lamport timestamp, T_i
 - Processes put current T_i into request message
 - Insufficient on its own (recall that Lamport timestamps can be identical) => use process id (or similar) to break ties
- Hence if a process P_j receives a request from P_i and P_j has an outstanding request (i.e. P_j's local state is WANT)
 - If (T_j, P_j) < (T_i, P_i) then queue request from P_i
 - Otherwise, reply with OK, and continue waiting
- Note that using the total order ensures **correctness**, but not **fairness** (i.e. no FIFO ordering)
 - Q: can we fix this by using vector clocks?

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Totally-Ordered Multicast: Example



- Imagine P1 and P2 simultaneously try to acquire lock...
 - Both set state to WANT, and both send multicast message
 - Assume that timestamps are 17 (for P1) and 9 (for P2)
- P3 has no interest (state is FREE), so replies Ok to both
- Since $9 < 17$, P1 replies Ok; P2 stays quiet & queues P1's request
- P2 enters the critical section and executes...
- ... and when done, replies to P1 (who can now enter critical section)

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Additional Details

- Completely unstructured decentralized solution ... but:
 - Lots of messages (1 multicast + N-1 unicast)
 - Ok for most recent holder to re-enter CS without any messages
- Variants scheme (due to Lamport):
 - To enter, process P_i multicasts **request**(P_i, T_i) [same as before]
 - On receipt of a message, P_j replies with an **ack**(P_i, T_j)
 - Processes keep all requests and acks in ordered queue
 - If process P_i sees his request is earliest, can enter CS ... and when done, multicasts a **release**(P_i, T_i) message
 - When P_j receives release, removes P_i 's request from queue
 - If P_j 's request is now earliest in queue, can enter CS...
- Note that both Ricart & Agrawala and Lamport's scheme, have N points of failure: doomed if *any* process dies :-)

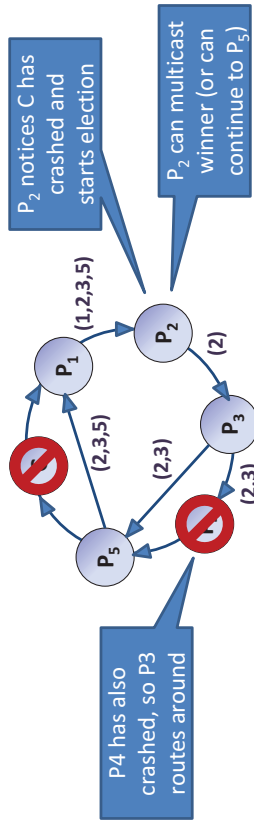
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Leader Election

- Many schemes are built on the notion of having a well-defined 'leader' (master, coordinator)
 - examples seen so far include the Berkeley time synchronization protocol, and the central lock server
- An election algorithm is a dynamic scheme to choose a unique process to play a certain role
 - assume P_i contains state variable **elect** $_i$
 - when a process first joins the group, **elect** $_i$ = UNDEFINED
- By the end of the election, for every P_i ,
 - elect** $_i$ = P_x , where P_x is the winner of the election, or
 - elect** $_i$ = UNDEFINED, or
 - P_i has crashed or otherwise left the system

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Ring-Based Election



- System has coordinator who crashes
- Some process notices, and starts an election
 - Puts its id into a message, and sends to its successor
 - On receipt, a process acks to sender (not shown), and then appends its id and forwards the election message
 - Finished when a process receives message containing its id

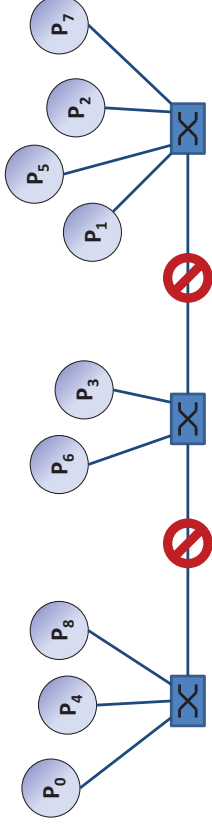
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The Bully Algorithm

- Assume that we know the ids of all processes
- Algorithm proceeds by attempting to elect the process still alive with the highest id
 - Assumes we can reliably detect failures by timeouts
- If process P_i sees current leader has crashed, sends **election** message to all processes with higher ids, and starts a timer
 - Concurrent election initiation by multiple processes is fine
 - Processes receiving an election message reply **OK** to sender, and start an election of their own (if not already in progress)
 - If a process hears nothing back before timeout, it declares itself the winner, and multicasts result
- A dead process that recovers (or new process that joins) also starts an election: can ensure highest ID always elected

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Problems with Elections



- Algorithms rely on being able to use timeouts to reliably detect failure
- However it is possible for networks to fail: a **network partition**
 - Some processes can speak to others, but not all
- Can lead to **split-brain syndrome**:
 - Every partition independently elects a leader => too many bosses!
- To fix, need some secondary (& tertiary?) communication scheme
 - e.g. secondary network, shared disk, serial cables, ...

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“Consensus is impossible”

- Famous result due to Fischer, Lynch & Patterson (1985)
 - Focuses on an asynchronous network (unbounded delays) with at least one process failure
 - Shows that it is possible to get an infinite sequence of states, and hence never terminate
 - Given the Internet is an asynchronous network, then this seems to have major consequences!:
- Not really:
 - Result actually says we can't always guarantee consensus, not that we can never achieve consensus
 - And in practice, we can use tricks to mask failures (such as reboot, or replication), and to ignore asynchrony
 - Have seen solutions already, and will see more later

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Aside: Consensus

- Elections are a specific example of a more general problem: **consensus**
 - Given a set of N processes in a distributed system, how can we get them all to agree on something?
- Classical treatment has every process P_i propose something (a value V_i)
 - Want to arrive at some deterministic function of V_i 's (e.g. 'majority' or 'maximum' will work for election)
- A correct solution to consensus must satisfy:
 - **Agreement**: all nodes arrive at the same answer
 - **Validity**: answer is one that was proposed by someone
 - **Termination**: all nodes eventually decide

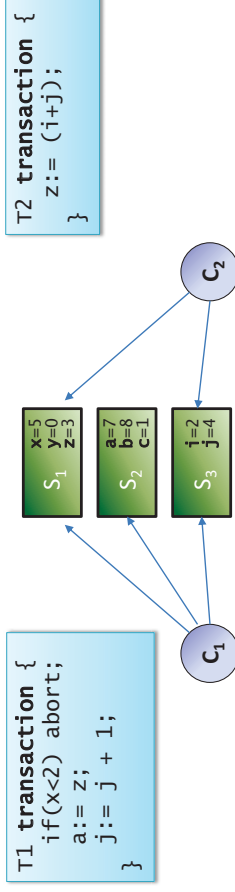
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Transaction Processing Systems

- Last term looked at **transactions**:
 - Support for composite operations (i.e. a collection of reads and updates to a set of objects)
- A transaction is **atomic** (“all-or-nothing”)
 - If it commits, all operations are applied
 - If it aborts, it’s as if nothing ever happened
- A committed transaction moves system from one **consistent** state to another
- Transaction processing systems also provide:
 - **isolation** (between concurrent transactions)
 - **durability** (committed transactions survive a crash)

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A Model of Distributed Transactions



- Multiple servers (S_1, S_2, S_3, \dots), each holding some objects which can be read and written within client transactions
- Multiple concurrent clients (C_1, C_2, \dots) who perform transactions which interact with one or more servers
 - e.g. T1 reads x, z from S_1 , writes a on S_2 , and reads & writes j on S_3
 - e.g. T2 reads i, j from S_3 , then writes z on S_1
- A successful commit implies agreement at all servers

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Distributed Transactions

- Scheme described last term was client/server
 - (even though I didn’t say it at the time ;-)
 - Clients communicate with a server (e.g. a database)
- However **distributed transactions** are those which span **multiple** transaction processing servers
- E.g. booking a complicated trip from London to Vail, CO
 - Could fly LHR -> LAX -> EGE + hire a car...
 - ... or fly LHR -> ORD -> DEN + take a public bus
- Want a complete trip (i.e. atomicity)
 - Not get stuck in an airport with no onward transport!
- Must coordinate actions across multiple parties

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Implementing Distributed Transactions

- Can build on top of solution for single server:
 - e.g. use locking or shadowing to provide isolation
 - e.g. use write-ahead log for durability
- Main additional challenge is in coordinating decision to either commit or abort
 - Assume clients create unique transaction id: **TxID**
 - Uses TxID in every read or write request to a server S_i
 - First time S_i sees a given TxID, it starts a tentative transaction associated with that transaction id
 - When client wants to commit, must perform **atomic commit** of all tentative transactions across all servers

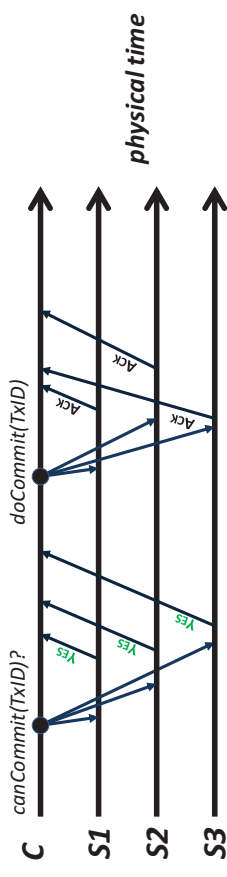
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Atomic Commit Protocols

- A naïve solution would have client simply invoke **commit(TxID)** on each server in turn
 - Will work only if no concurrent conflicting clients, every server commits (or aborts), and no server crashes
- To handle concurrent clients, introduce a **coordinator**:
 - A designated machine (can be one of the servers)
 - Clients ask coordinator to commit on their behalf... and hence coordinator can **serialize** concurrent commits
- To handle inconsistency/crashes, coordinator:
 - Asks all involved servers if they *could* commit TxID
 - Servers S_i reply with a vote $V_i = \{ \text{COMMIT, ABORT} \}$
 - If all $V_i = \text{COMMIT}$, coordinator multicasts **doCommit(TxID)**
 - Otherwise, coordinator multicasts **doAbort(TxID)**

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Two-Phase Commit (2PC)



- This scheme is called **two-phase commit (2PC)**:
 - First phase is **voting**: collect votes from all parties
 - Second phase is **completion**: either abort or commit
- Doesn't require ordered multicast, but needs reliability
 - If server fails to respond by timeout, treat as a vote to abort
- Once all Acks received, inform client of successful commit

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2PC: Additional Details

- Client (or any server) can abort during execution: simply multicasts **doAbort(TxID)** to all servers
- If a server votes to abort, can immediately abort locally
- If a server votes to commit, it must be able to do so if subsequently asked by coordinator:
 - Before voting to commit, server will **prepare** by writing entries into log and flushing to disk
 - (this is why some sources call the first phase “prepare”)
 - Also records all requests from & responses to coordinator
 - Hence even if crashes *after* voting to commit, will be able to recover on reboot

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2PC: Coordinator Crashes

- Coordinator must also persistently log events:
 - Including initial message from client, requesting votes, receiving replies, and final decision made
 - Lets it reply if (rebooted) client or server asks for outcome
 - Also lets coordinator recover from reboot, e.g. re-send any vote requests without responses, or reply to client
- One additional problem occurs if coordinator crashes after phase 1, but before initiating phase 2:
 - servers will be uncertain of outcome...
 - if voted to commit, will have to continue to hold locks, etc
- (other consensus protocols such as 3PC provide better progress guarantees if permanent failure can happen)

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Replication

- Many distributed systems involve replication
 - Multiple copies of some object stored at different servers
 - Multiple servers capable of providing some operation(s)
- Three key advantages:
 - **Load-Balancing**: if have many replicas, then can spread out work from clients between them
 - **Lower Latency**: if replicate an object/server close to a client, will get better performance
 - **Fault-Tolerance**: can tolerate the failure of some replicas and still provide service
- Examples include DNS, web & file caching (& content-distribution networks), replicated databases, ...

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Replication in a Single System

- One good example is RAID:
 - RAID = Redundant Array of Inexpensive Disks
 - i.e. disks are cheap, so use several instead of just one
 - if replicate data across disks, can tolerate disk crash
- A variety of different configurations (levels)
 - RAID 0: **stripe** data across disks, i.e. block 0 to disk 0, block 1 to disk 1, block 2 to disk 0, and so on
 - RAID 1: **mirror** (replicate) data across disks, i.e. block 0 written on disk 0 and disk 1
 - RAID 5: **parity** – write block 0 to disk 0, block 1 to disk 1, and (block 0 XOR block 1) to disk 2
- Get improved performance since can access disks in parallel
- With RAID 1, 5 also get fault-tolerance

Replication in Distributed Systems

- Have some number of servers (S_1, S_2, S_3, \dots)
 - Each holds a copy of all objects
- Each client C_i can access any replica (any S_j)
 - e.g. clients can choose closest, or least loaded
- If objects are read-only, then trivial:
 - Start with one primary server **P** having all data
 - If client asks S_i for an object, S_i returns a copy
 - (S_i fetches a copy from **P** if it doesn't already have one)
- Can easily extend to allow updates by **P**
 - When updating object O , send invalidate(O) to all S_i
 - (Or add just tag all objects with 'valid-until' field)
- In essence, this is how web caching / CDNs work today

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Replication and Consistency

- Gets more challenging if clients can perform updates
- For example, imagine x has value 3 (in all replicas)
 - C_1 requests **write(x, 5)** from S_4
 - C_2 requests **read(x)** from S_3
 - What should occur?
- With **strong consistency**, the distributed system behaves as if there is no replication present:
 - i.e. in above, C_2 should get the value 5
 - requires coordination between all servers
- With **weak consistency**, C_2 may get 3 or 5 (or ...?)
 - Less satisfactory, but much easier to implement

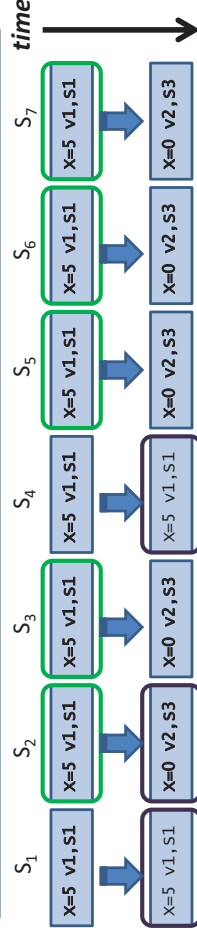
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Achieving Strong Consistency

- Need to ensure any update propagates to all replicas before allow any subsequent reads
- One solution:
 - When S_i receives request to update x , first locks x at all other replicas
 - Once successful, S_i makes update, and propagates to all other replicas, who acknowledge
 - Finally, S_i instructs all replicas to unlock
- Need to handle failure (of replica, or network)
 - Add step to tentatively apply update, and only actually apply (“commit”) update if all replicas agree
- We’ve reinvented distributed transactions & 2PC ;-)

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Example



- Seven replicas ($N=7$), $Q_w = 5$, $Q_r = 3$
- All objects have associated version (T, S)
 - T is logical timestamp, initialized to zero
 - S is a server ID (used to break ties)
- Any write will update at least Q_w replicas
- Performing a read is easy:
 - Choose replicas to read from until get Q_r responses
 - Correct value is the one with highest version

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Quorum Systems

- Transactional consistency works, but:
 - High overhead, and
 - Poor availability during update (worse if crash!)
- An alternative is a **quorum system**:
 - Imagine there are N replicas, a **write quorum** Q_w , and a **read quorum** Q_r , where $Q_w > N/2$ and $(Q_w + Q_r) > N$
- To perform a write, must update Q_w replicas
 - Ensures a majority of replicas have new value
- To perform a read, must read Q_r replicas
 - Ensures that we read *at least one* updated value

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Quorum Systems: Writes

- Performing a write is trickier:
 - Must ensure get entire quorum, or cannot update
 - Hence need a commit protocol (as before)
- In fact, transactional consistency is a quorum protocol with $Q_w = N$ and $Q_r = 1$:
 - But when $Q_w < N$, additional complexity since must bring replicas up-to-date before updating
- Quorum systems are good when expect failures
 - Additional work on update, additional work on reads...
 - ... but increased **availability** during failure

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