CPSC 422/522 Design & Implementation of Operating Systems

Lecture 22: Replications & Consensus

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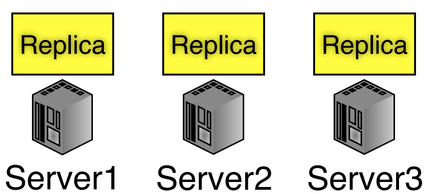
Acknowledgement: some slides are taken from previous lectures by Dr. Ennan Zhai

Lecture Roadmap

- Consistency Issues
- Consistency Models
- Two-Phase Commit
- Consensus
- Case Study: Paxos

Replication Technique

- Distributed systems replicate data across multiple servers



Replication Technique

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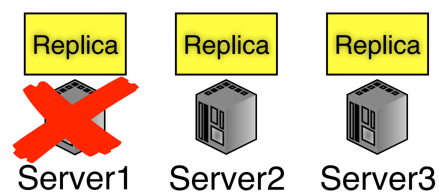

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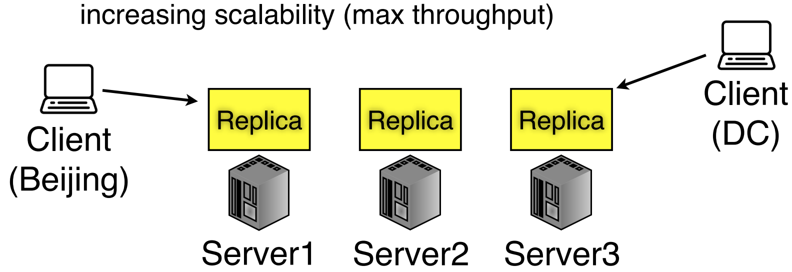
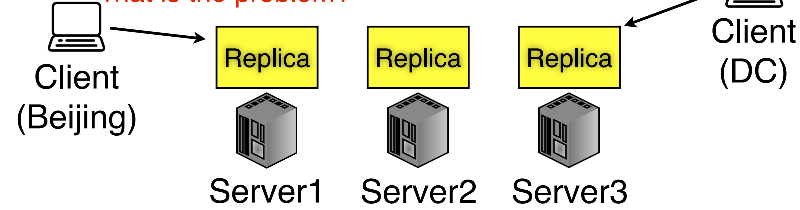
  - Allowing clients to access different servers potentially increasing scalability (max throughput)

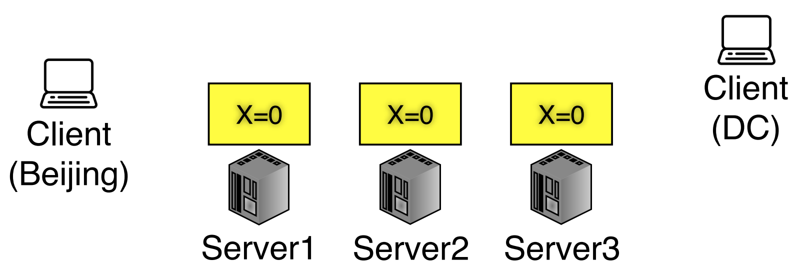


Replication Technique

- Distributed systems replicate data across multiple servers
  - Replication provides fault-tolerance if servers fail
  - Allowing clients to access different servers potentially increasing scalability (max throughput)
  - What is the problem?



Consistency Problem



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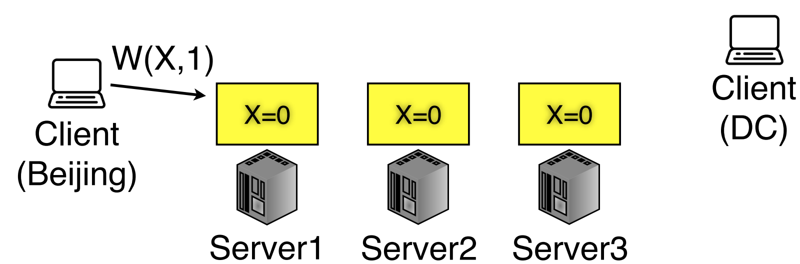

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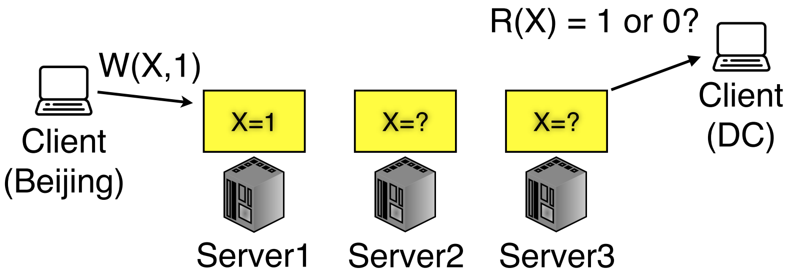

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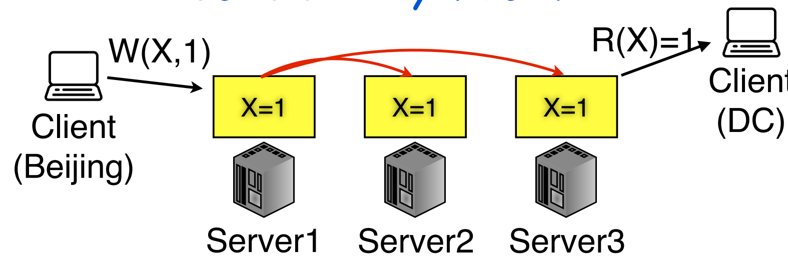

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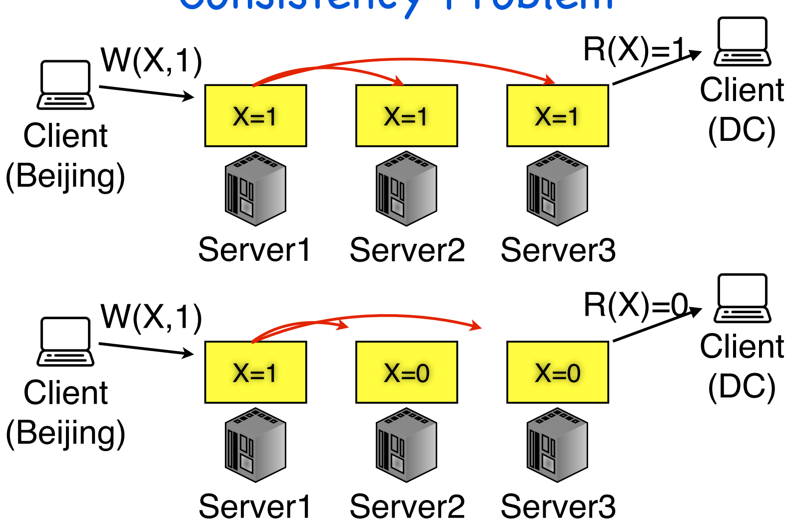

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- Consistency Models
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Consistency Models

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Consistency Models

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- A consistency model basically refers to the degree of consistency that should be maintained for the shared data.
- If a system supports the stronger consistency model, then the weaker consistency model is automatically supported.

- But stronger consistency models sacrifice more availability and fault tolerance.

Consistency Models

- Strict consistency
- Strong consistency (Linearizability)
- Sequential consistency
- Causal consistency
- Eventual consistency

Weaker Consistency Models

These models describe when and how different nodes in a distributed system view the order of operations

Consistency Models

- Strict consistency
- Strong consistency

Why we have so many consistency models?

They are used for different application scenarios that balance the trade-off between consistency/availability/fault-tolerance.

operations

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Strict Consistency

- Strongest consistency model we will consider
  - Any read on a data item X returns value corresponding to result of the most recent write on X
- Need an absolute global time
  - “Most recent” needs to be unambiguous
  - Corresponds to when operation was issued
  - Impossible to implement in real-world (network delays)

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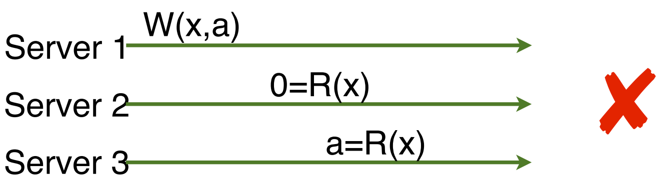

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- Provide behavior of a single copy of object:
  - Read should return the most recent write
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- Provide behavior of a single copy of object:
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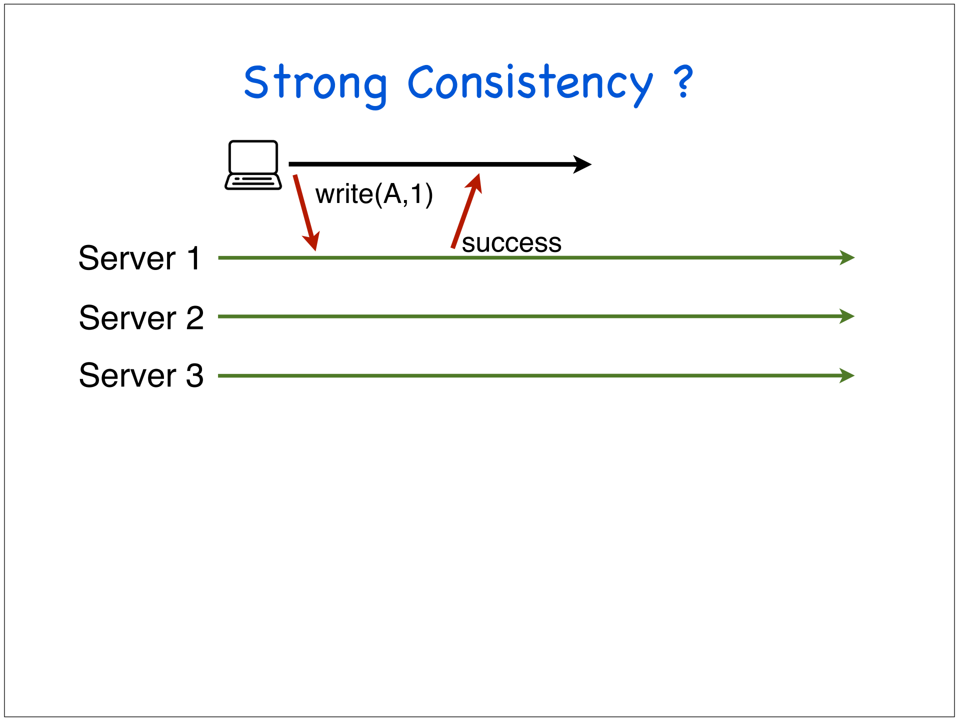
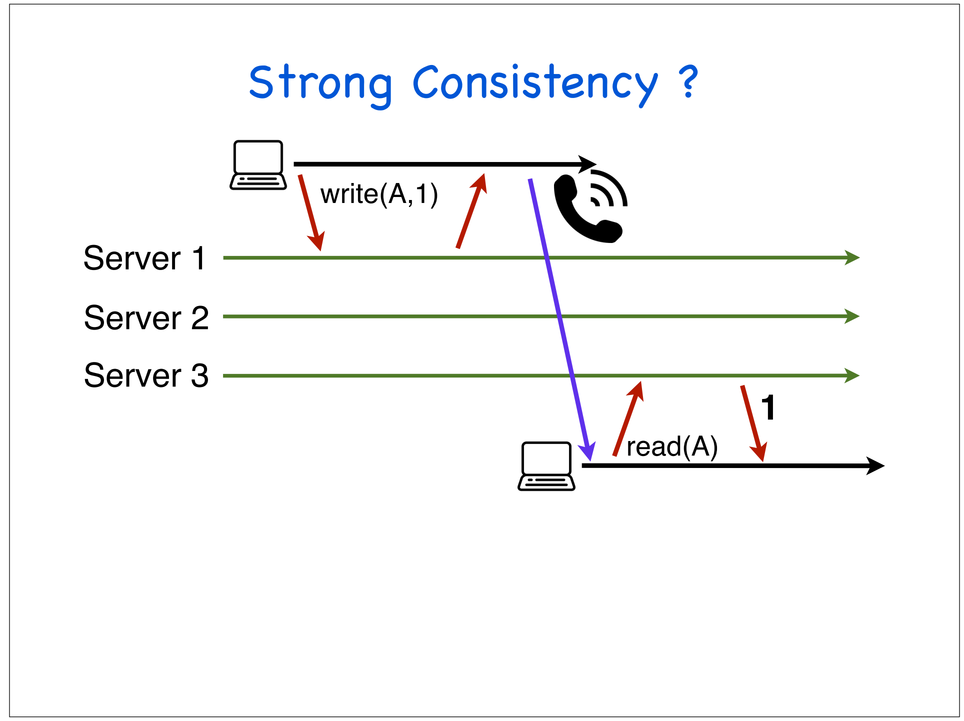
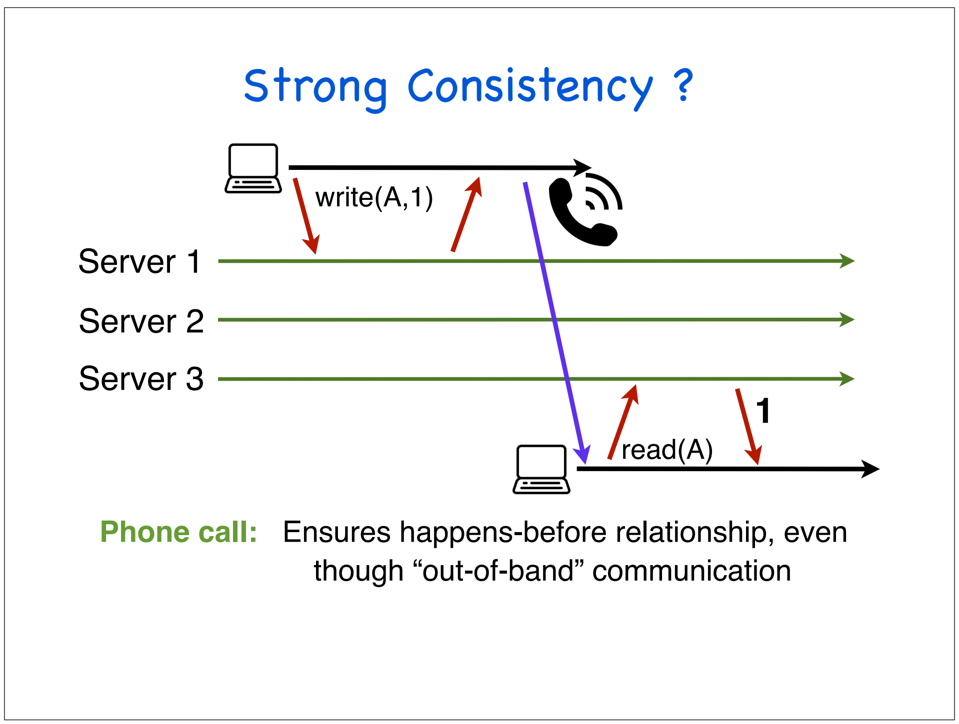
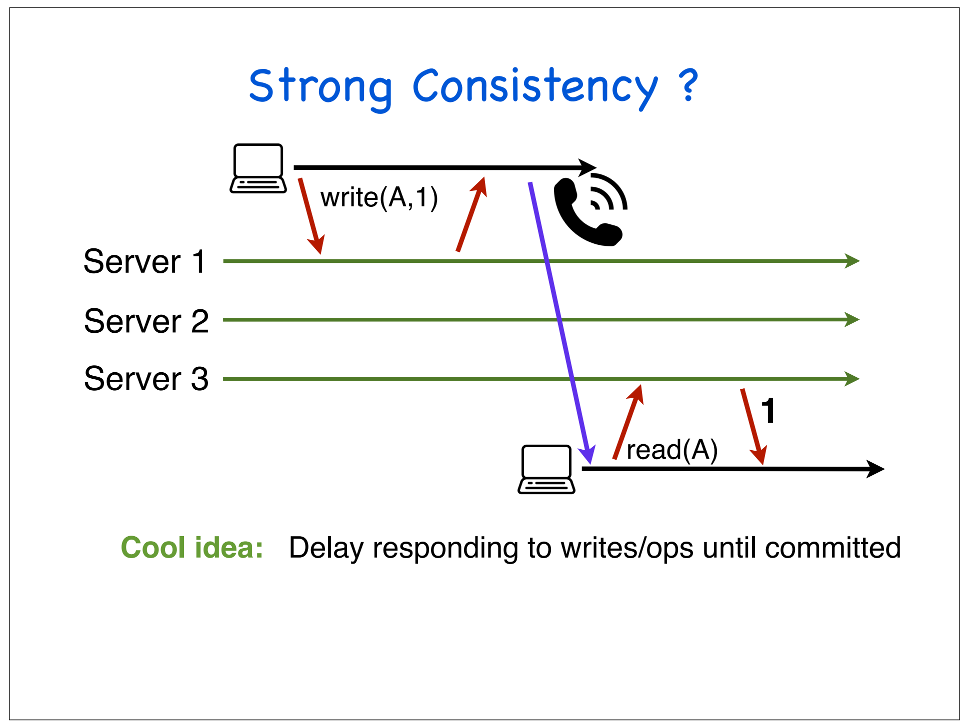
- Telephone intuition:
  - 1. Alice updates Facebook post
  - 2. Alice calls Bob on phone: “Check my Facebook post!”
  - 3. Bob read’s Alice’s wall, sees her post

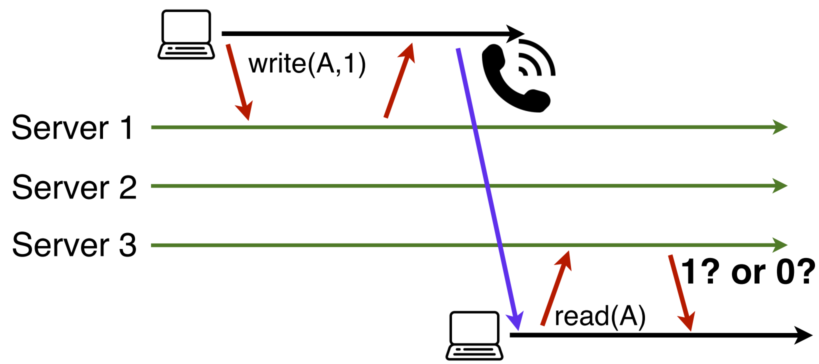

Strong Consistency ?
write(A,1)
success
Server 1
Server 2
Server 3


Strong Consistency ?
write(A,1)
Server 1
Server 2
Server 3
1
read(A)


Strong Consistency ?
write(A,1)
Server 1
Server 2
Server 3
1
read(A)
Phone call: Ensures happens-before relationship, even though “out-of-band” communication


Strong Consistency ?
write(A,1)
Server 1
Server 2
Server 3
1
read(A)
Cool idea: Delay responding to writes/ops until committed

Strong Consistency? This is buggy!



- Isn't sufficient to return value of server3:
  It does not know precisely when op is "globally" committed
- Instead: Need to actually order read operation

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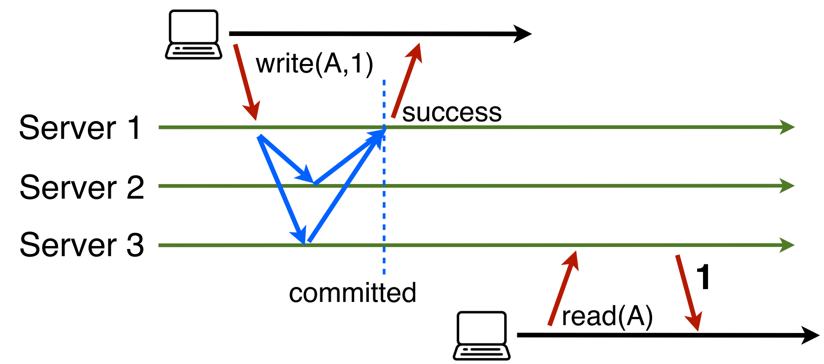

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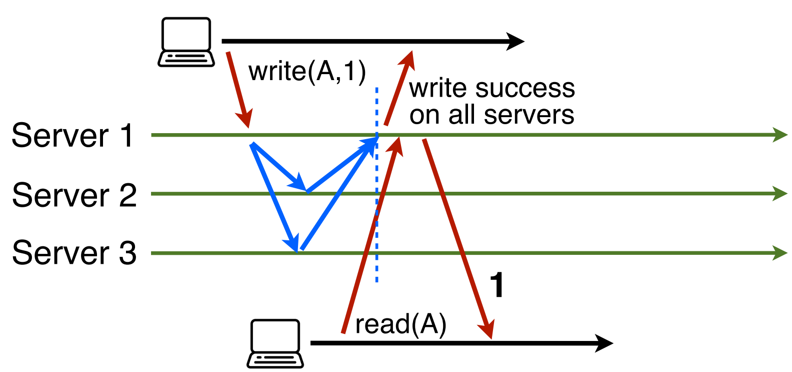
Strong Consistency!!!

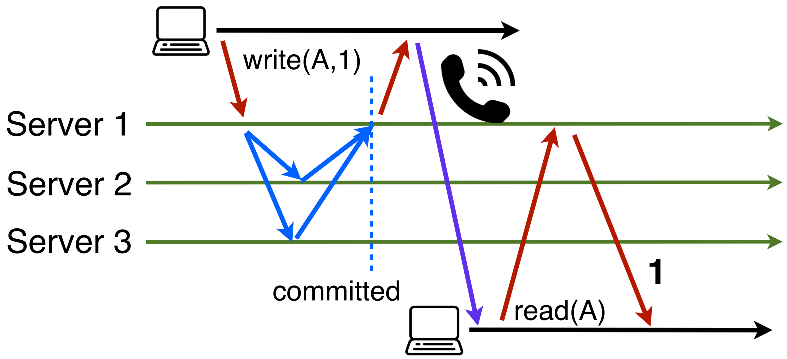


- Order all operations via (1) leader and (2) agreement

Strong Consistency = Linearizability

- Linearizability:
  - All servers execute all ops in some identical sequential order
  - Global ordering preserves each client's own local ordering
  - Global ordering preserves real-time guarantee
    - All operations receive global time-stamp via a sync'd clock
    - If TS(x)<TS(y), then OP(x) precedes OP(y) in the sequence
- Once write completes, all later reads should return value of that write or value of later write
- Once read returns particular value, all later reads should return that value or value of later write

Intuition: Real-time ordering



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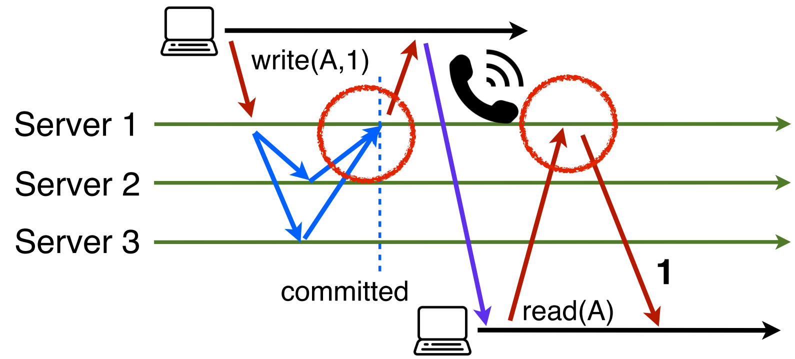

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These models describe when and how different nodes in a distributed system view the order of operations

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- ~~Linearizability~~ Sequential:
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    - ~~All operations receive global time-stamp via a sync'd clock~~
    - ~~If TS(x)<TS(y), then OP(x) precedes OP(y) in the sequence~~

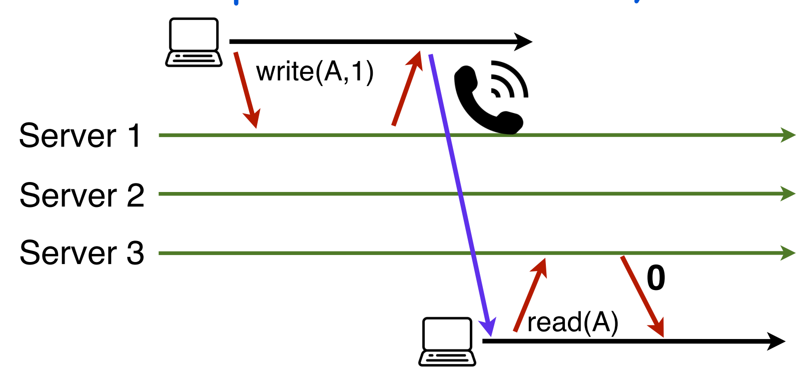
Weaker: Sequential Consistency

- Sequential consistency:

All (read/write) operations on data store were executed in some sequential order, and the operations of each individual process appear in this sequence

- With concurrent ops, "reordering" of ops acceptable, but all servers must see same order:
  - linearizability cares about time but sequential consistency cares about program order

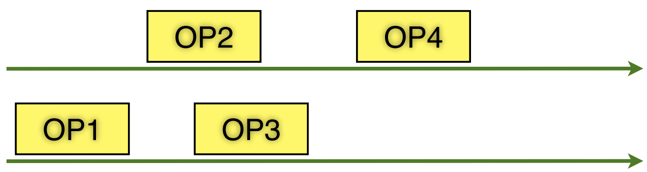
Sequential Consistency



In this example, system orders read(A) before write(A, 1)

Implementing Sequential Consistency

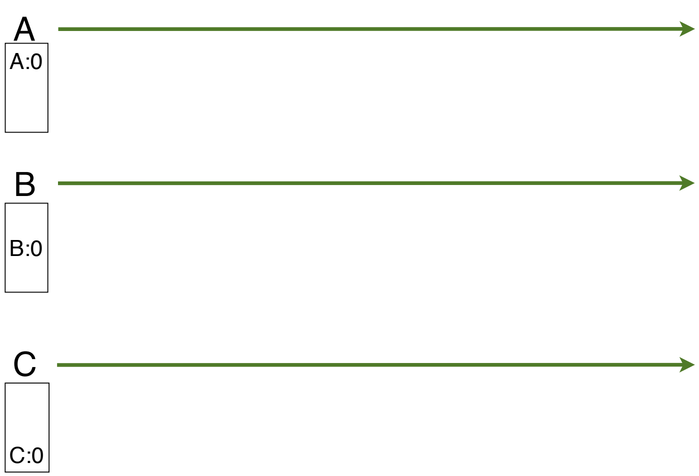
- Nodes use vector clocks to determine if two events had distinct happens-before relationship:
  - If timestamp(a) < timestamp(b) => a $\longrightarrow$ b
- If ops are concurrent (i,j, a[i]<b[i] and a[j]>b[j]):
  - Hosts can order ops a, b arbitrarily but consistently



Building Block: Vector Clock

- Initially all clocks are zero
- Each time a process experiences an internal event, it increments its own logical clock in the vector by one
- Each time for a process to send a message, it increments its own clock and then sends a copy of its own vector
- Each time a process receives a message, it increments its own logical clock by one and updates each element in its vector by max(own, received)

Building Block: Vector Clock



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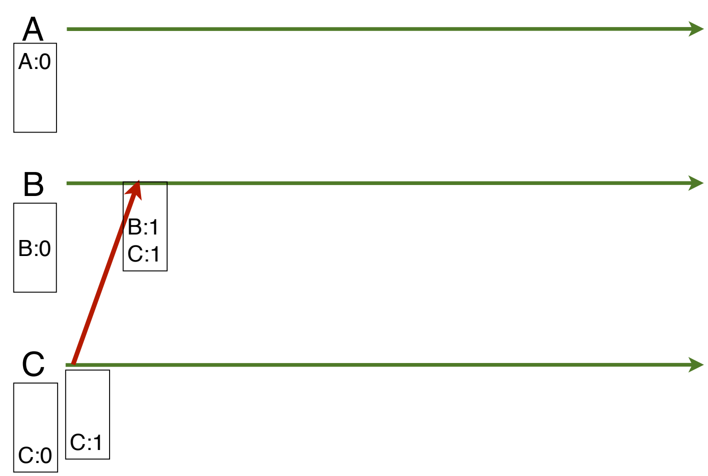

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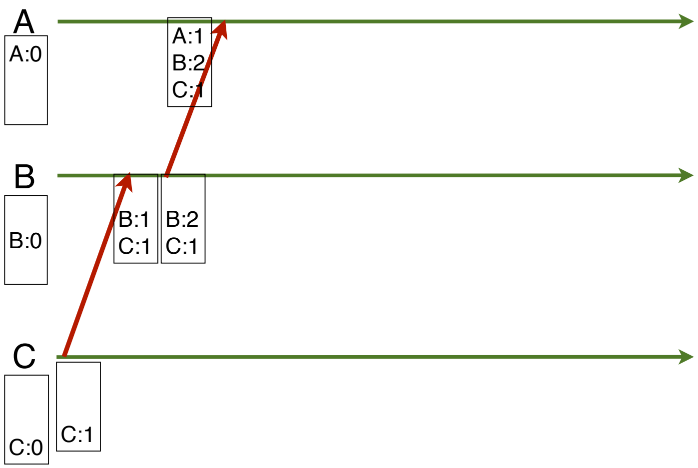

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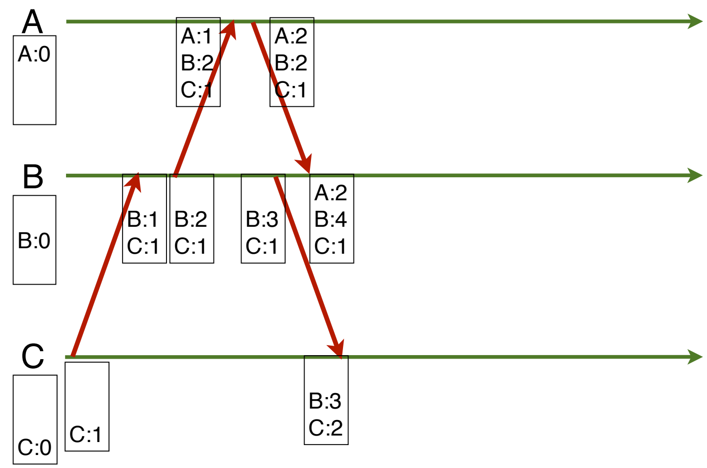

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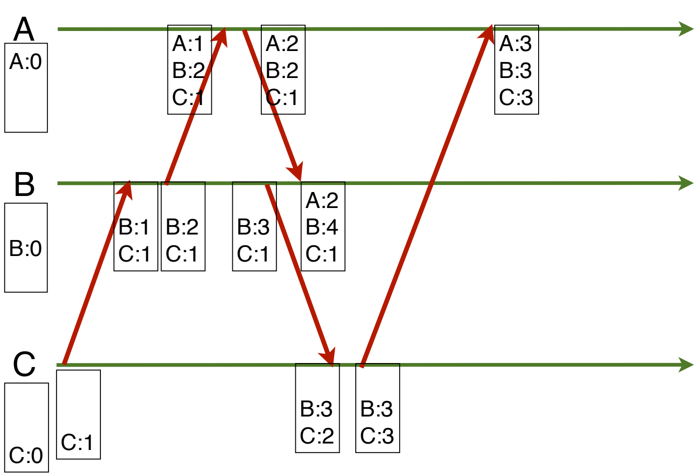

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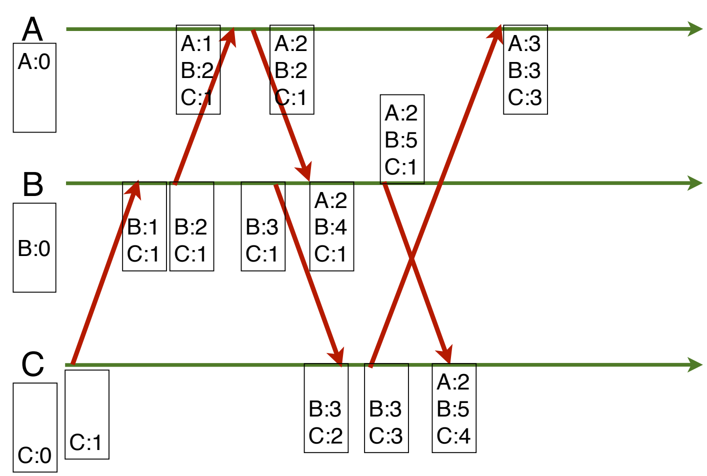

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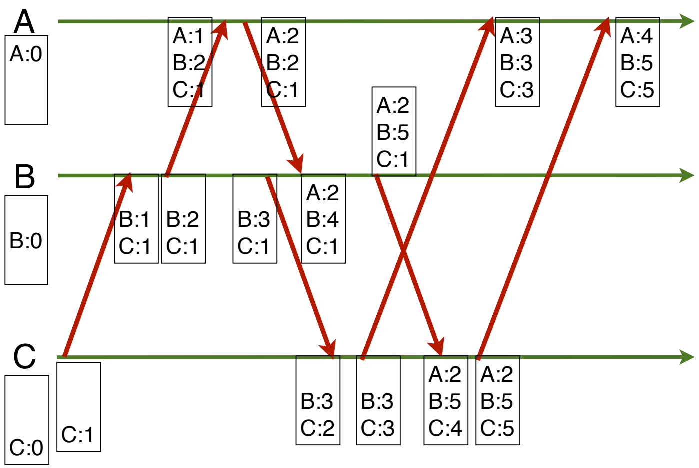

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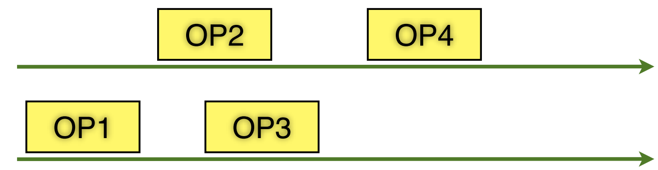
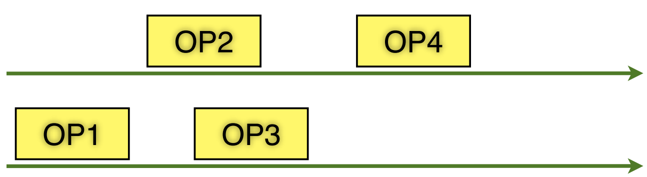


Implementing Sequential Consistency

Host1: OP 1, 2, 3, 4
Host2: OP 1, 2, 3, 4

✔



Implementing Sequential Consistency

Host1: OP 1, 2, 3, 4 Host1: OP 1, 3, 2, 4
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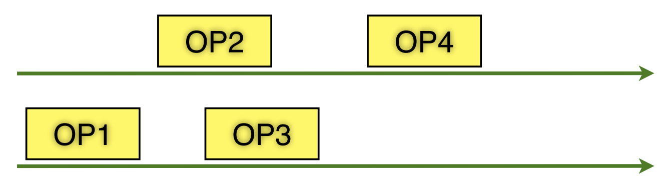

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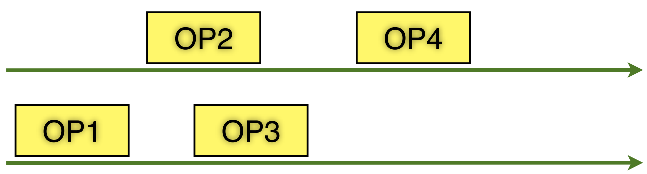
✔	✔	✘



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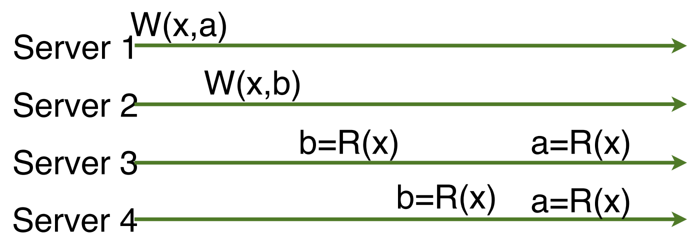
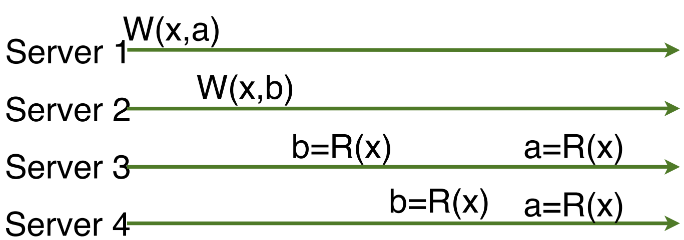


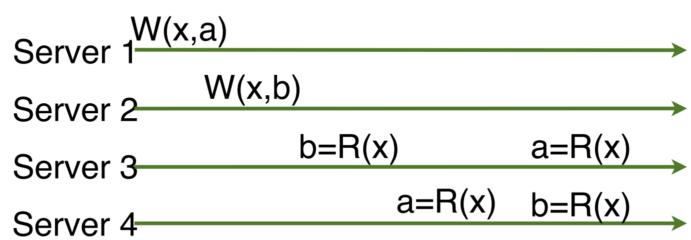
- Is this valid sequential consistency?

Sequential Consistency



- Is this valid sequential consistency?
  - It is, because Server 3 and 4 agree on order of ops

Sequential Consistency



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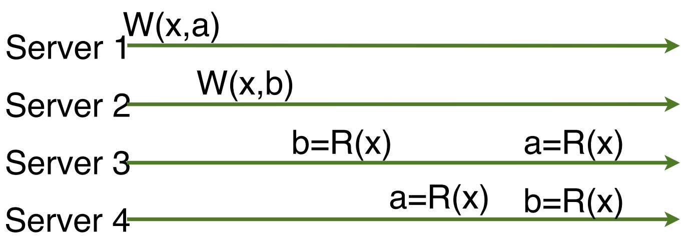
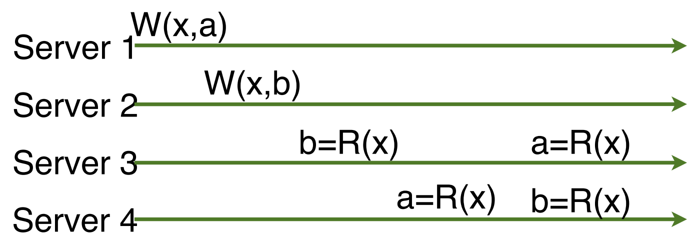


- Is this valid sequential consistency?
  - No, because Server 3 and 4 do not agree on order of ops.
  - In practice, does not matter when events took place on different machine, as long as server agree on order

Sequential Consistency



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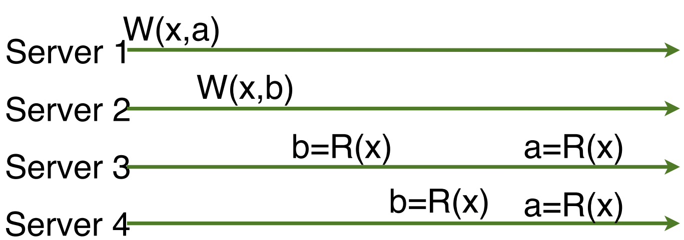
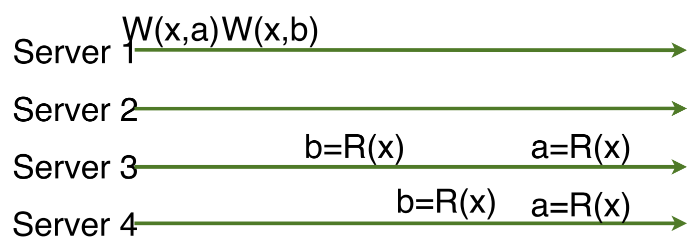
Causal consistency

Sequential Consistency



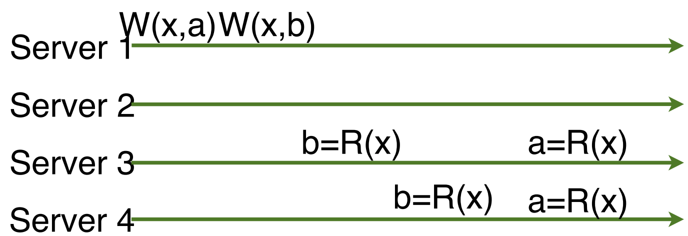
A valid sequential consistency

Sequential Consistency



A valid sequential consistency or not?

Sequential Consistency



A valid sequential consistency or not?

- No, because it does not preserve local ordering

Consistency Models

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- Strong consistency (Linearizability)
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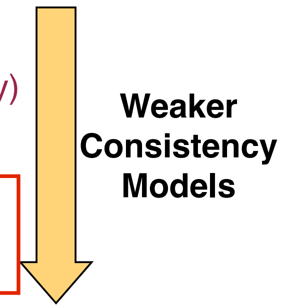
- Eventual consistency



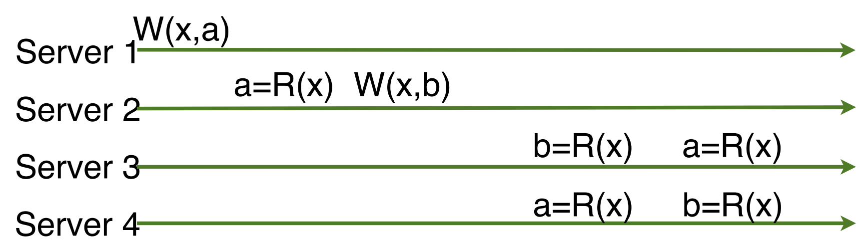
Weak consistency model

These models describe when and how different nodes in a distributed system view the order of operations

Causal Consistency

- Causal consistency:
  - Causal consistency is one of weak consistency models
  - Causally related writes must be seen by all processes in the same order
  - Concurrent writes may be seen in different orders on different machines

Causal Consistency



Not valid

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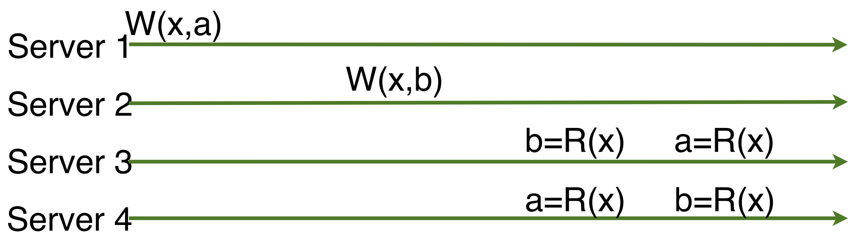
Causal Consistency



Valid

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Weaker Consistency Models

Weak consistency model

These models describe when and how different nodes in a distributed system view the order of operations

Eventual Consistency

- Eventual consistency:
  - Achieve high availability
  - If no new updates are made to a given data item, eventually all accesses to the data will return the last updated value.
- Eventual consistency is commonly used:
  - Git repo, iPhone sync
  - Dropbox and Amazon Dynamo

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Lecture Roadmap

- Consistency Issues
- Consistency Models
- Two-Phase Commit
- Consensus
- Case Study: Paxos

Two-Phase Commit

- Goal: Reliably agree to commit or abort a collection of sub-transactions
- All the operations happens at single master node
  - Concurrent machines
  - Failure and recovery of machines

Achieve strong consistency!

Intuitive Example

- You want to organize outing with 3 friends at 6pm Tue
  - Go out only if all friends can make it
- What do you do?
  - Call each of them and ask if can do 6pm Tue (voting phase)
  - If all can do Tue, call each friend back to ACK (commit)
  - If one cannot do Tue, call others to cancel (abort)

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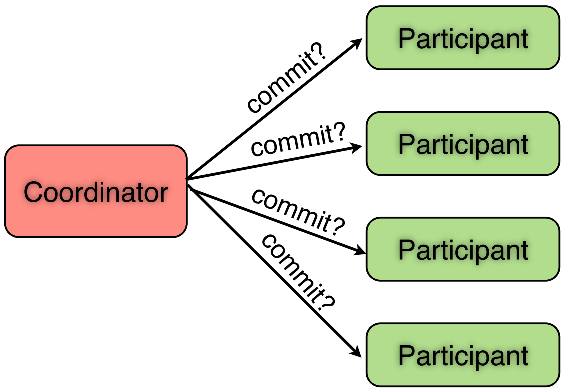
This is exactly how two-phase commit works

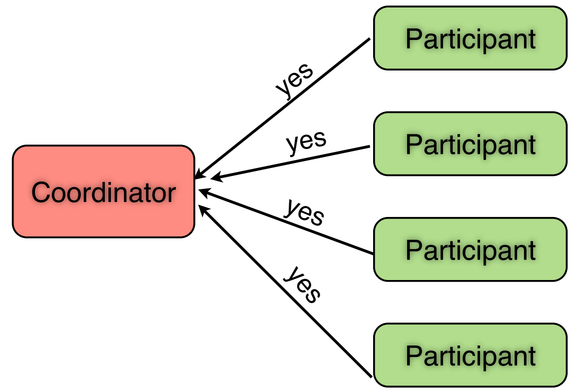
Two-Phase Commit Protocol

- Phase 1: Voting phase
  - Get commit agreement from every participant



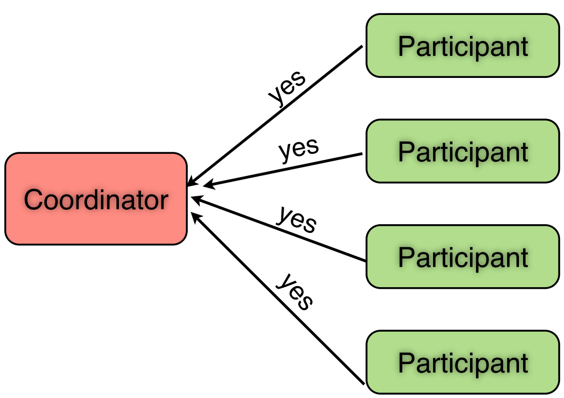
Two-Phase Commit Protocol

- Phase 1: Voting phase
  - Get commit agreement from every participant



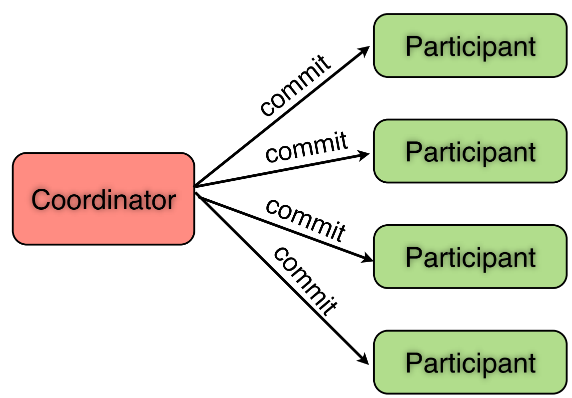
Two-Phase Commit Protocol

- Phase 1: Voting phase
  - Get commit agreement from every participant
  - A single “no” response means that we will have to abort



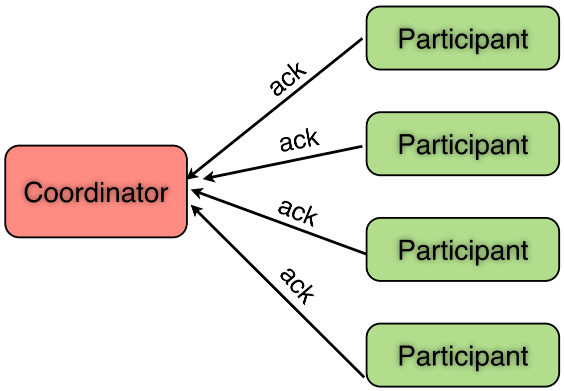
Two-Phase Commit Protocol

- Phase 2: Commit phase
  - Send the results of the vote to every participant
  - Send abort if any participant voted “no” in Phase 1



Two-Phase Commit Protocol

- Phase 2: Commit phase
  - Get “committed” acknowledgements from every participant



Two-Phase Commit Protocol

- Two-phase commit assumes a fail-recover model
  - Any failed system will eventually recover
- A recovered system cannot change its mind
  - If a node agreed to commit and then crashed, it must be willing and able to commit upon recovery
- If the leader fails?
  - Lose availability: system not longer “live”

Lecture Roadmap

- Consistency Issues
- Consistency Models
- Two-Phase Commit
- Consensus
- Case Study: Paxos

Consensus / Agreement Problem

- Definition:
  - A general agreement about something
  - An idea or opinion that is shared by all the people in a group
- Given a set of processors, each with an initial value:
  - **Termination:** All non-faulty processes eventually decide on a value
  - **Agreement:** All processes that decide do so on the same value
  - **Validity:** The value that has been decided must have proposed by some process

Consensus / Agreement Problem

- Goal: N processes want to agree on a value
- Correctness (safety):
  - All N nodes agree on the same value
  - The agreed value has been proposed by some node

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- Fault-tolerance:
  - If <= F faults in a window, consensus reached eventually
  - Liveness not guaranteed: If > F faults, no consensus
  - Given goal of F, what is N? Depends on fault model ("Crash fault" need 2F+1; Byzantine fault needs 3F+1)

Lecture Roadmap

- Consistency Issues
- Consistency Models
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Paxos

- Safety:
  - Only a single value is chosen
  - Only a proposed value can be chosen
  - Only chosen values are learned by processes
- Liveness:
  - Some proposed value eventually chosen if fewer than half of processes fail
  - If value is chosen, a process eventually learns it

Paxos

- Three conceptual roles:
  - **Proposers:** propose values
  - **Acceptors:** accept values, where chosen if majority accept
  - **Learners:** learn the outcome (the chosen value)
- In reality, a process can play any/all roles

Paxos

- Three conceptual roles:
  - **Proposers:** propose values
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- In reality, a process can play any/all roles
- Ordering: proposal is tuple [proposal #, value] = [n,v]
  - Proposal # strictly increasing, globally unique
  - Globally unique? Trick: set low-order bits to proposer's ID

Paxos + Two-Phase Commit

- Use Paxos for view-change
  - If anybody notices current master unavailable, or one or more replicas unavailable
  - Propose view change Paxos to establish new group: Value agreed upon = <2PC Master, {2PC Replicas} >.
- Use two-phase commit for actual data
  - Writes go to master for two-phase commit
  - Reads go to acceptors and/or master