CPSC 422/522 Design & Implementation of Operating Systems

Lecture 23: Replications & Consensus

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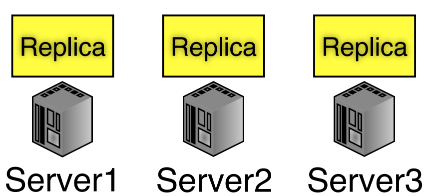
Acknowledgement: some slides are taken from previous lectures by Dr. Ennan Zhai

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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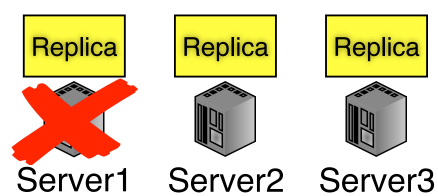
  - Replication provides fault-tolerance if servers fail



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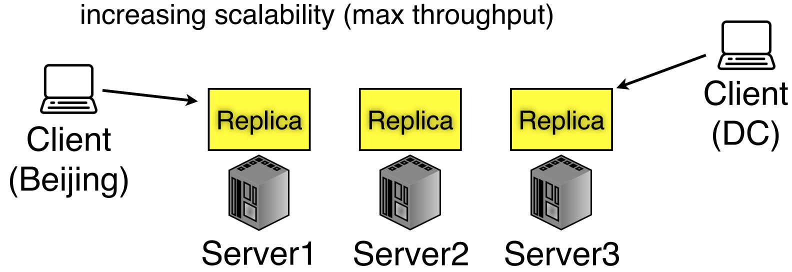
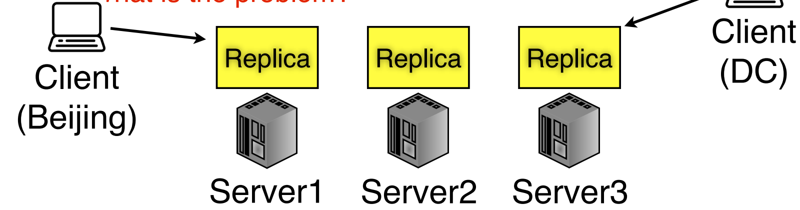
  - Allowing clients to access different servers potentially increasing scalability (max throughput)

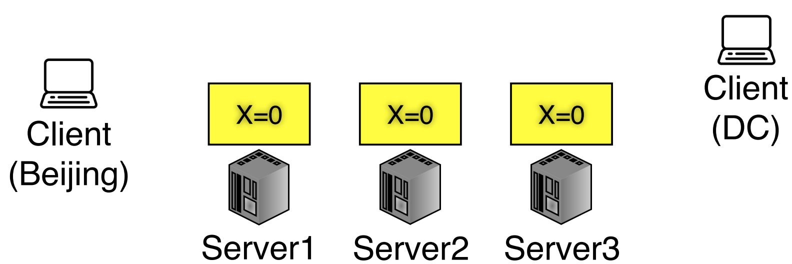


Replication Technique

- 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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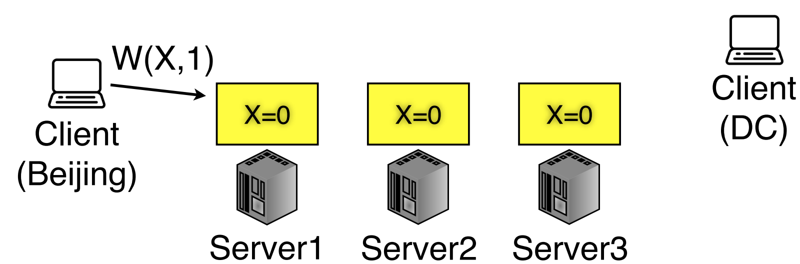

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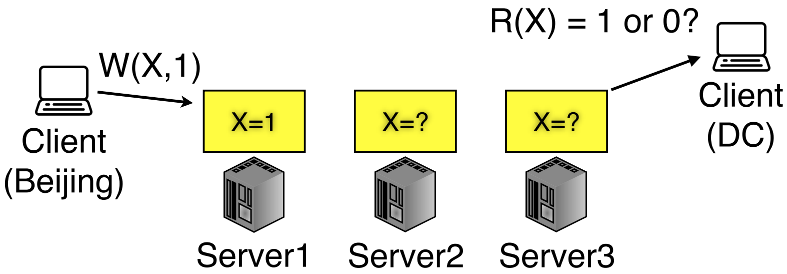

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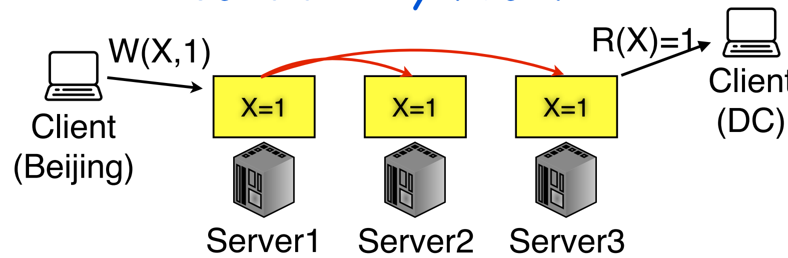

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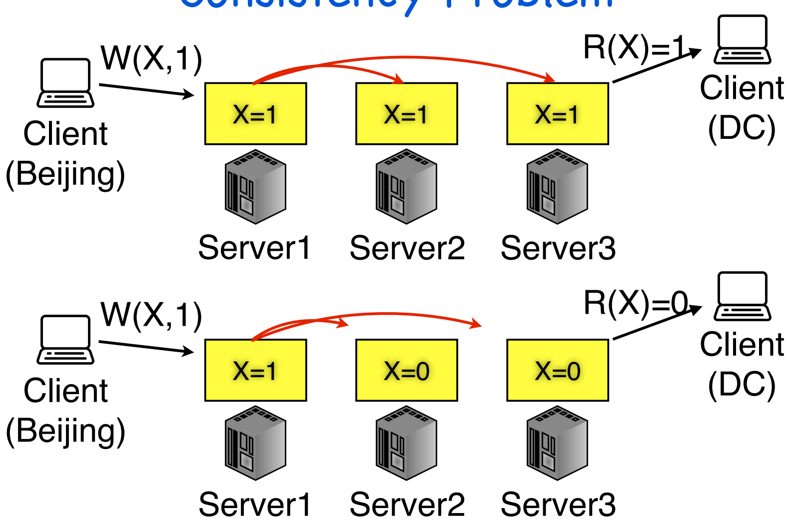

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- Consistency Models
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Consistency Models

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- 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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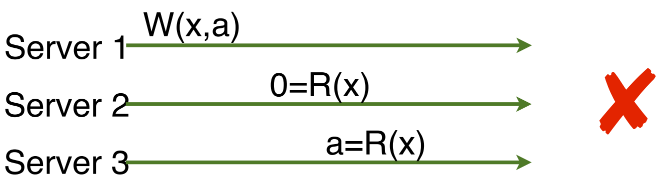

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Strong Consistency

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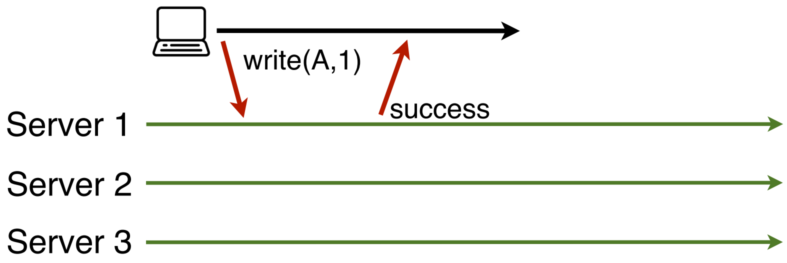
- Telephone intuition:
  - 1. Alice updates Facebook post
  - 2. Alice calls Bob on phone: “Check my Facebook post!”
  - 3. Bob read’s Alice’s wall, sees her post

Strong Consistency ?



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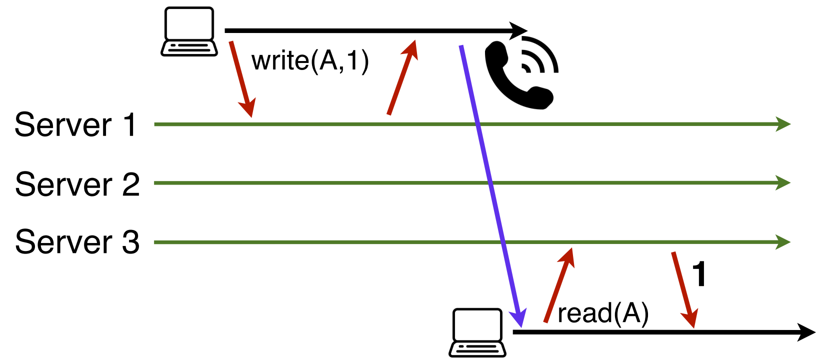

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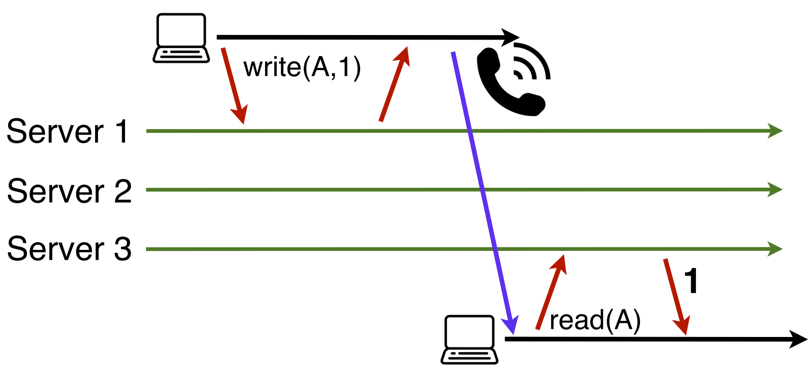
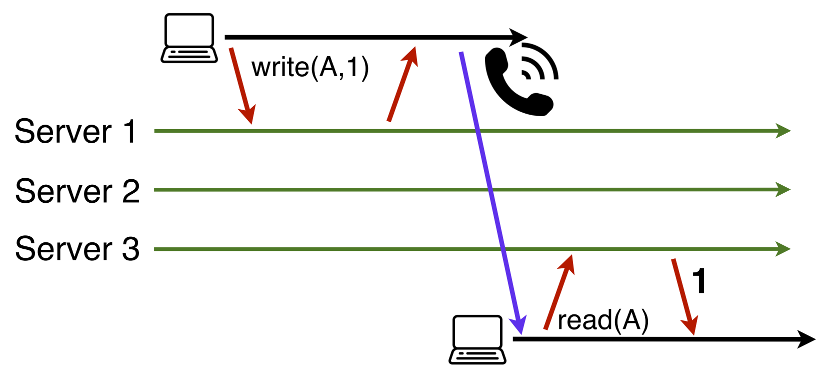


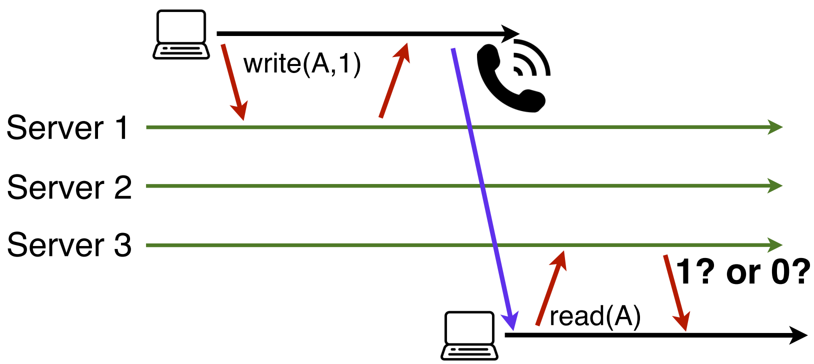
Phone call: Ensures happens-before relationship, even though "out-of-band" communication

Strong Consistency ?



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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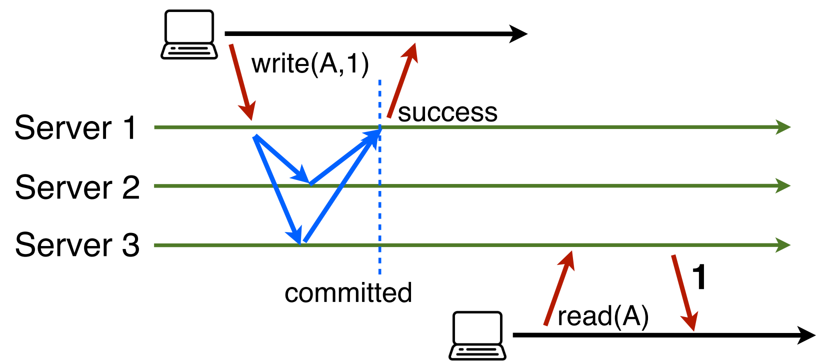

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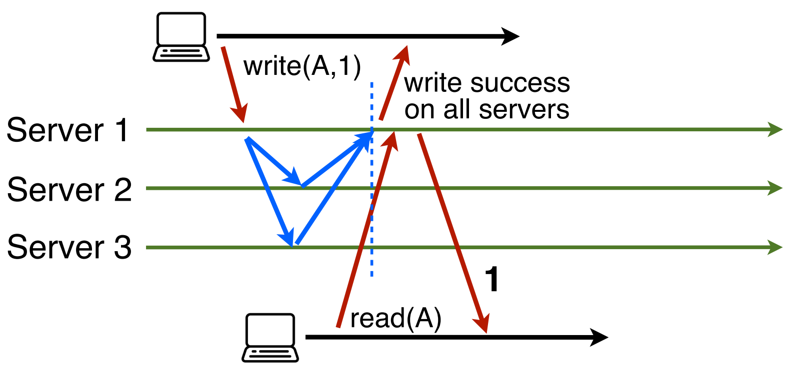
Strong Consistency!!!

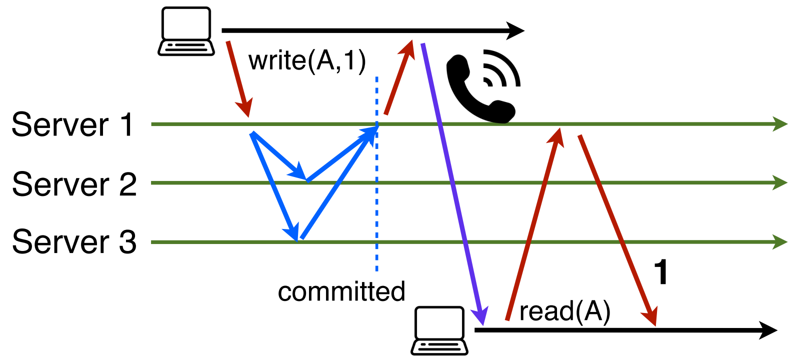


- Order all operations via (1) leader and (2) agreement

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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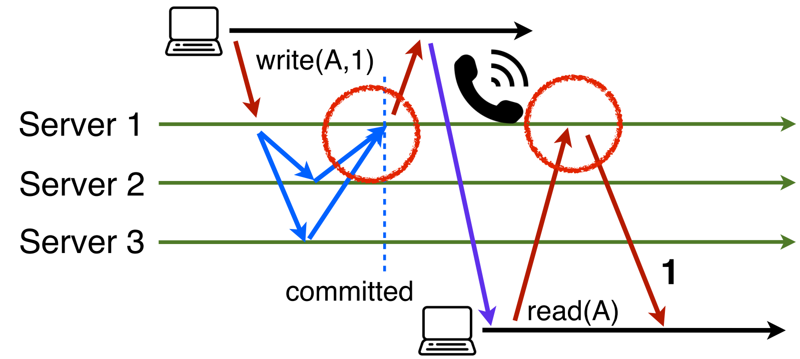

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Weaker Consistency Models

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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~~

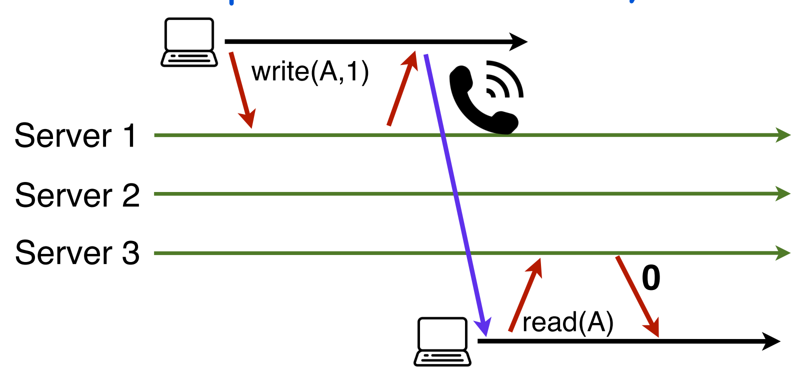
Weaker: Sequential Consistency

- 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

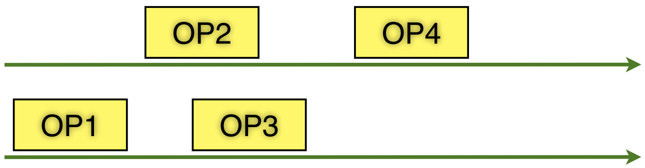
Sequential Consistency



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

Implementing Sequential Consistency

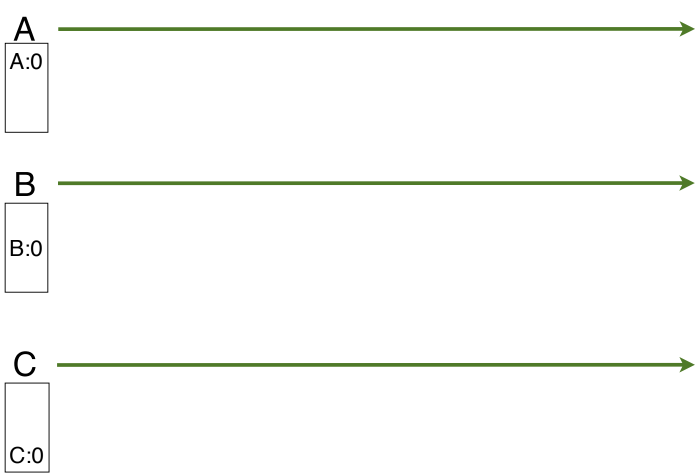
- Nodes use vector clocks to determine if two events had distinct happens-before relationship:
  - If timestamp(a) < timestamp(b) => a ⟶ b
- If ops are concurrent (∃i,j, a[i]<b[i] and a[j]>b[j]):
  - Hosts can order ops a, b arbitrarily but consistently



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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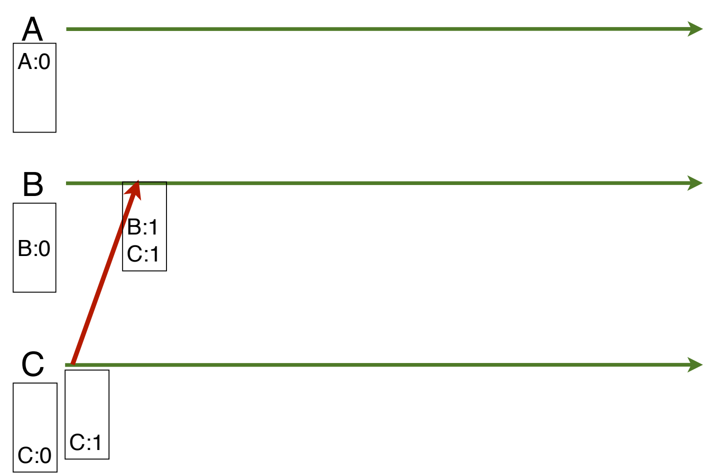

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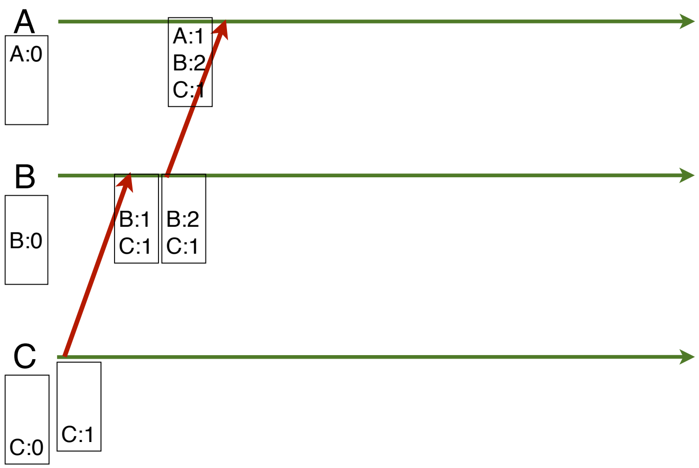

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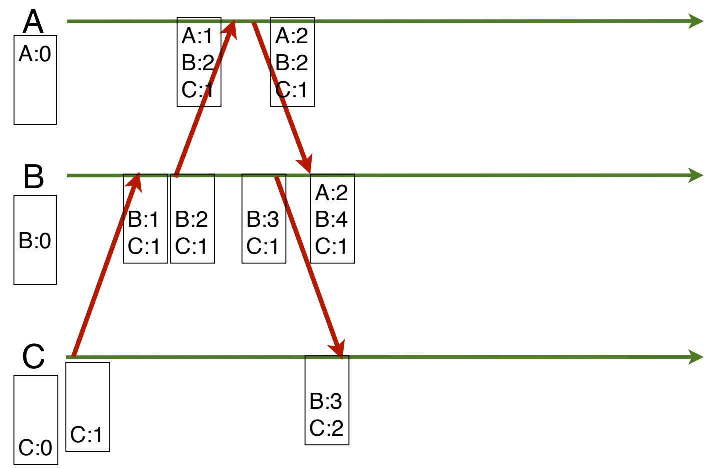

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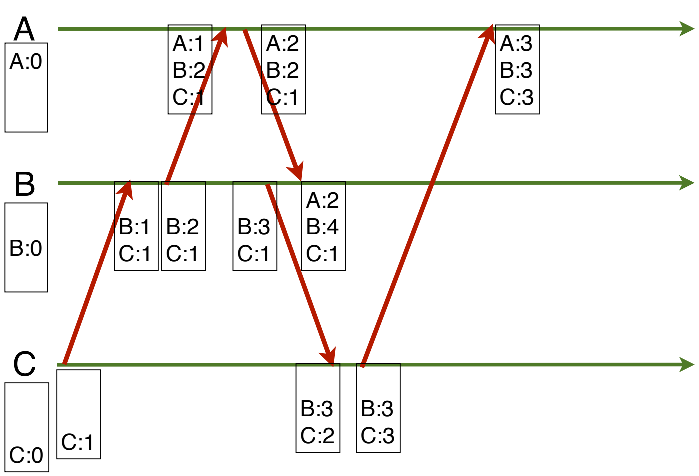

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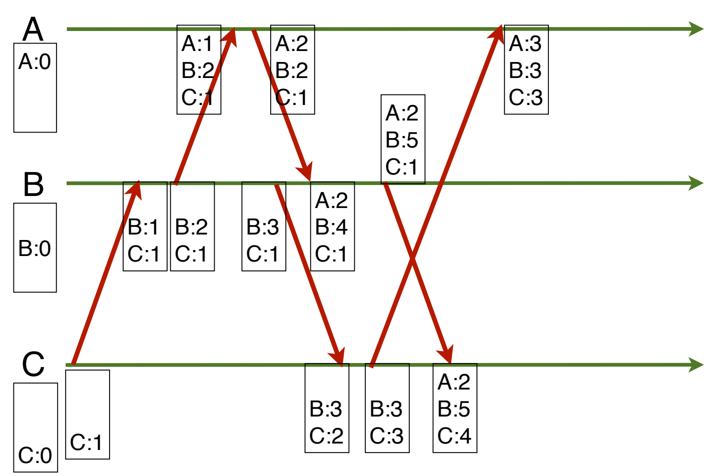

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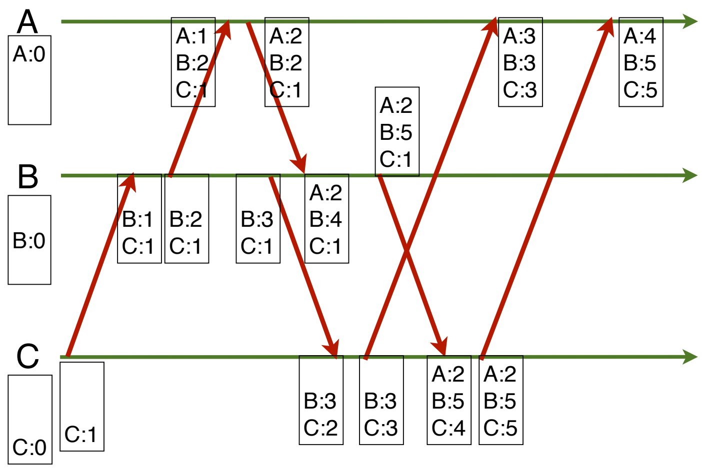

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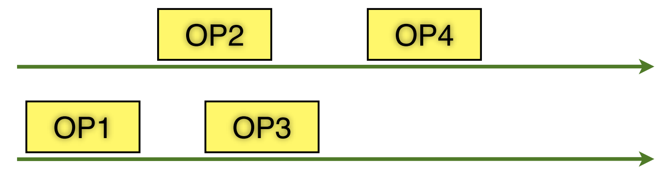
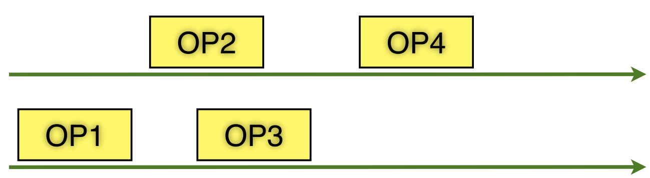


Implementing Sequential Consistency

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

✔



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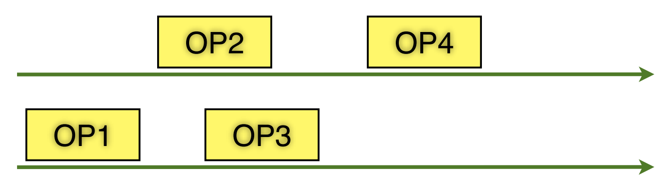

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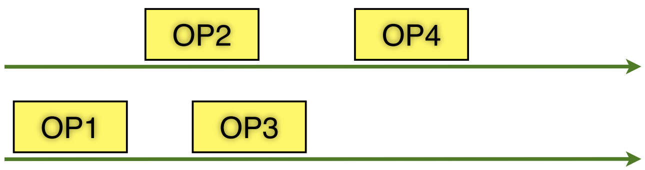

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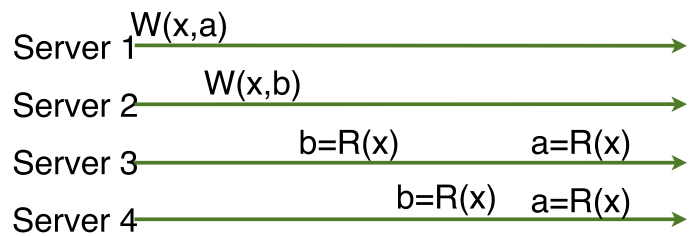
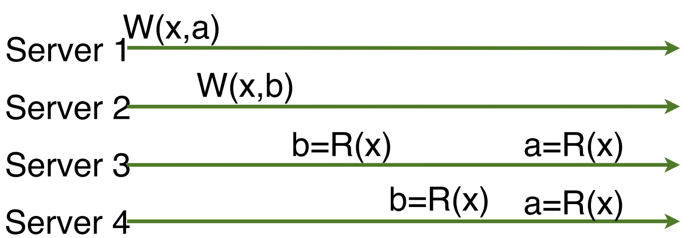


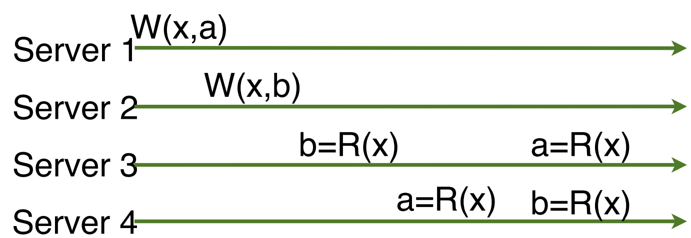
- Is this valid sequential consistency?

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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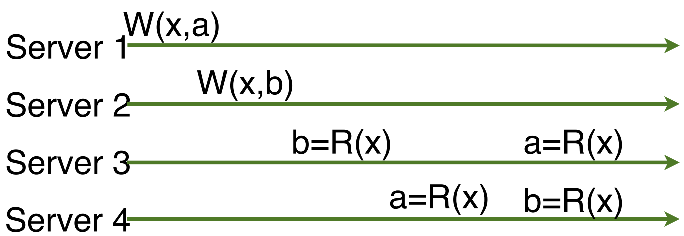
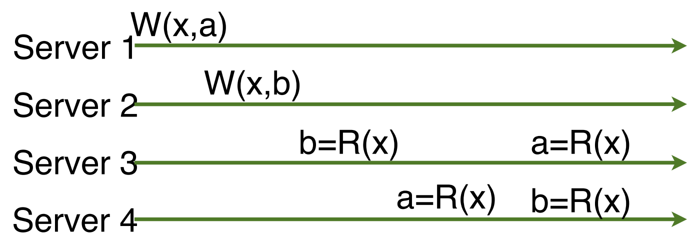


- Is this valid sequential consistency?
  - No, because Server 3 and 4 do not agree on order of ops.
  - In practice, does not matter when events took place on different machine, as long as server agree on order

Sequential Consistency



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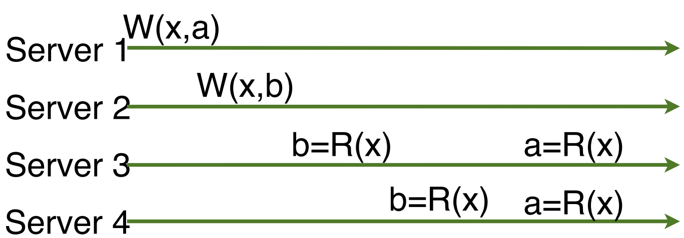
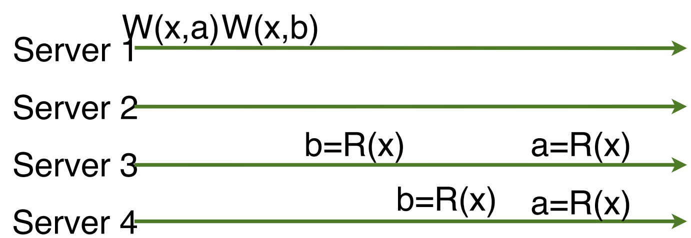
Causal consistency

Sequential Consistency



A valid sequential consistency

Sequential Consistency



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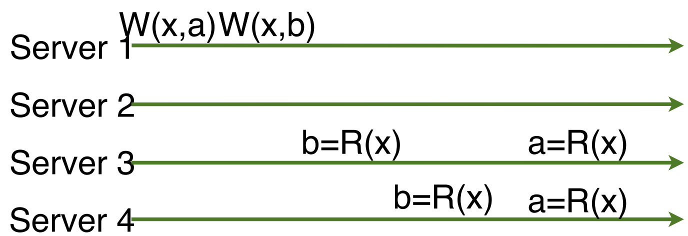
Sequential Consistency



A valid sequential consistency or not?

- No, because it does not preserve local ordering

Consistency Models

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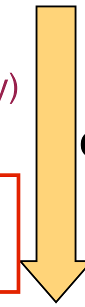
- Strong consistency (Linearizability)
- Sequential consistency
- Causal consistency
- Eventual consistency



Weaker Consistency Models

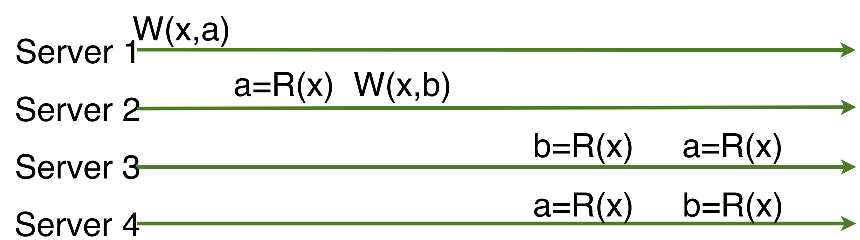
Weak consistency model

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

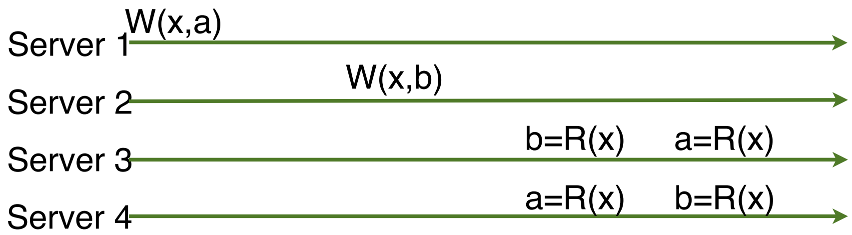
Causal Consistency



Not valid

Causally related writes must be seen by all processes in the same order

Causal Consistency



Valid

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- 👉 Eventual consistency

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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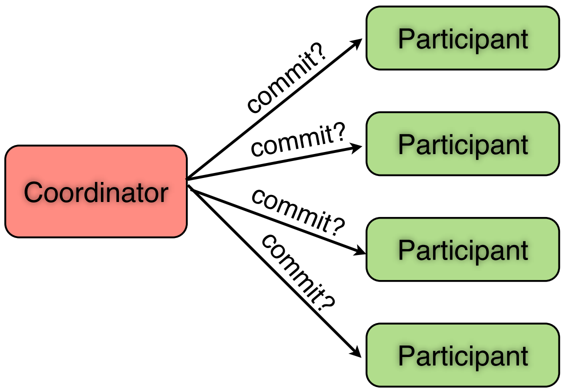
This is exactly how two-phase commit works

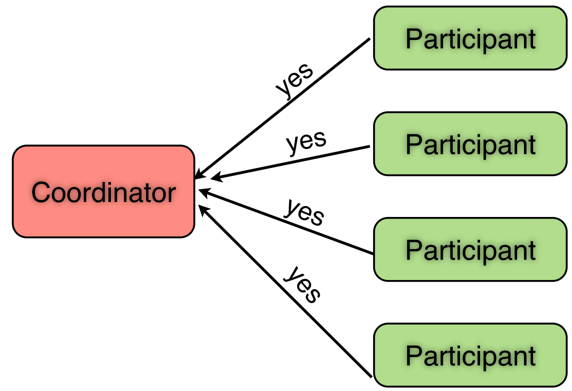
Two-Phase Commit Protocol

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



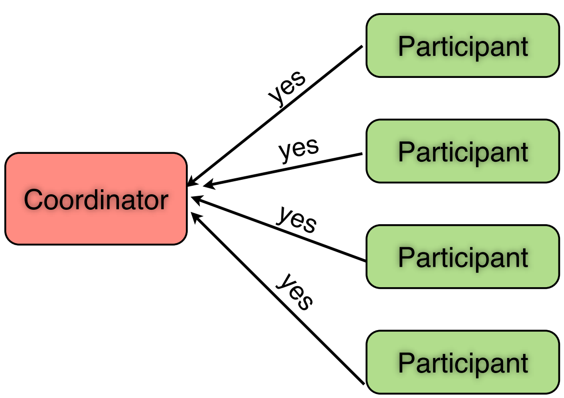
Two-Phase Commit Protocol

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



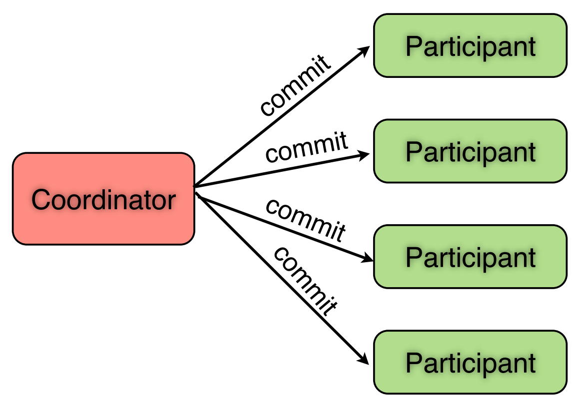
Two-Phase Commit Protocol

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



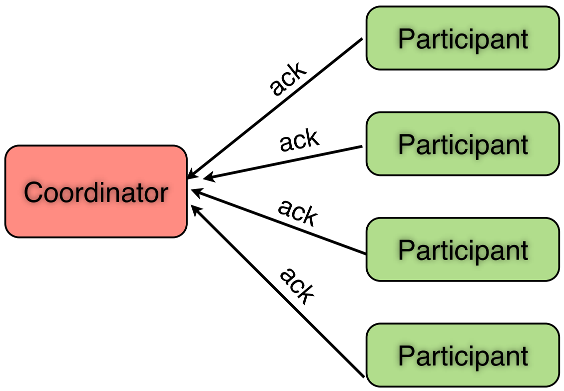
Two-Phase Commit Protocol

- 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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- Consensus
- Case Study: Paxos

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

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- 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