Primary-Backup and Paxos

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Based in part on material by Ken Birman

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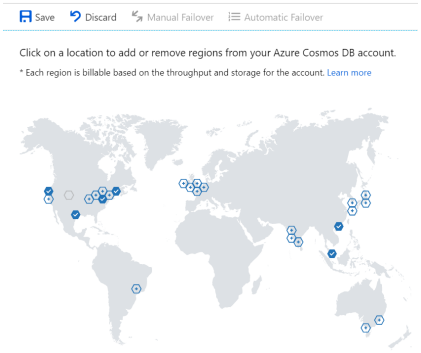
Uses of replication

- High availability
- Share loads for scalability
- Lower latency, improve responsiveness



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Replicated state machine (RSM)

- RSM is a general replication method
- RSM Rules:
  - All replicas start in the same initial state
  - Every replica apply operations in the same order
  - All operations must be deterministic
- All replicas end up in the same state
  - Eventually…

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Issues

- How do we ensure agreement on order of updates?
- Under what conditions should backup take over?
  - "Split brain" problem

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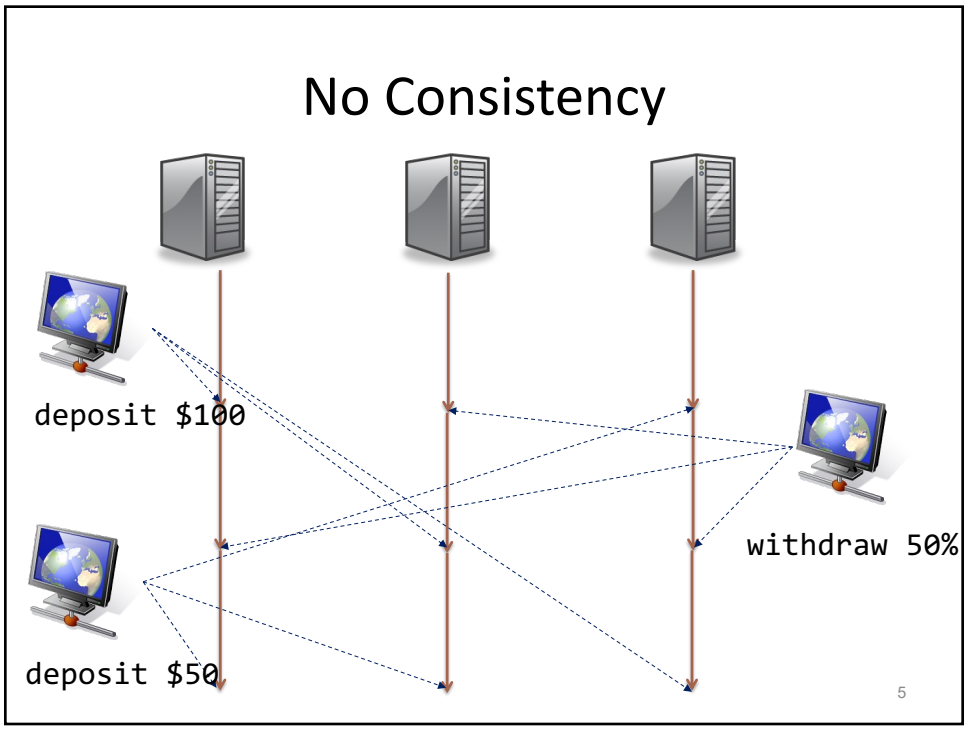
No Consistency
deposit $100
withdraw 50%
deposit $50
5

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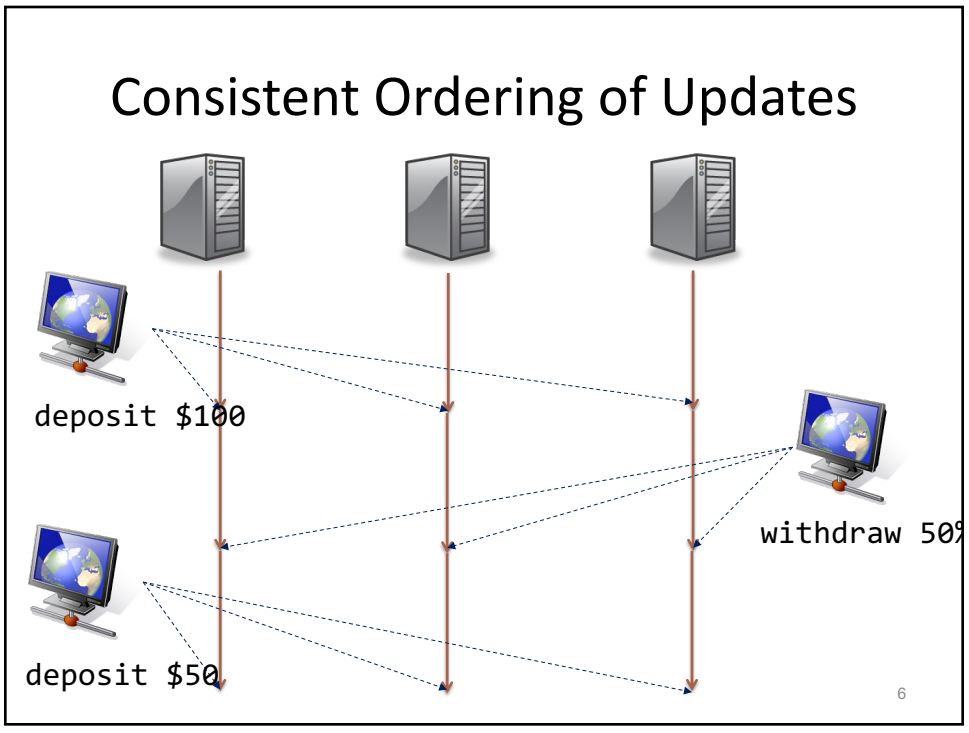
Consistent Ordering of Updates
deposit $100
withdraw 50%
deposit $50
6

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Linearizability

- As soon as one client successfully completes a write, all clients reading from the database must be able to see the value just written (*Recency*)
- Replicated database
- Must not read stale copy of data

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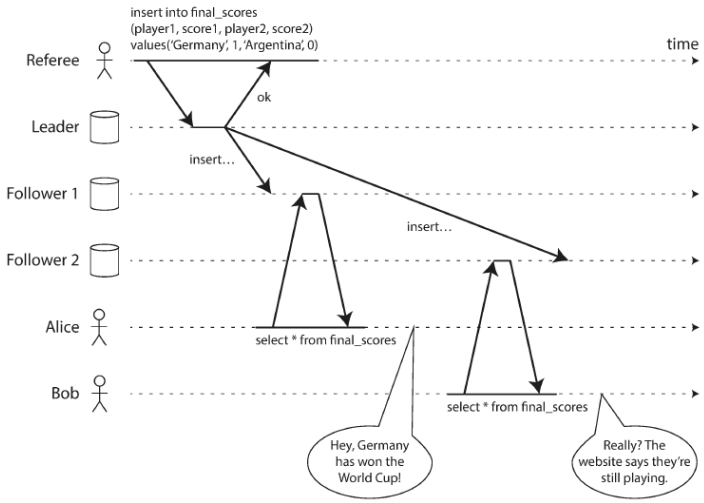
Violation of Linearizability



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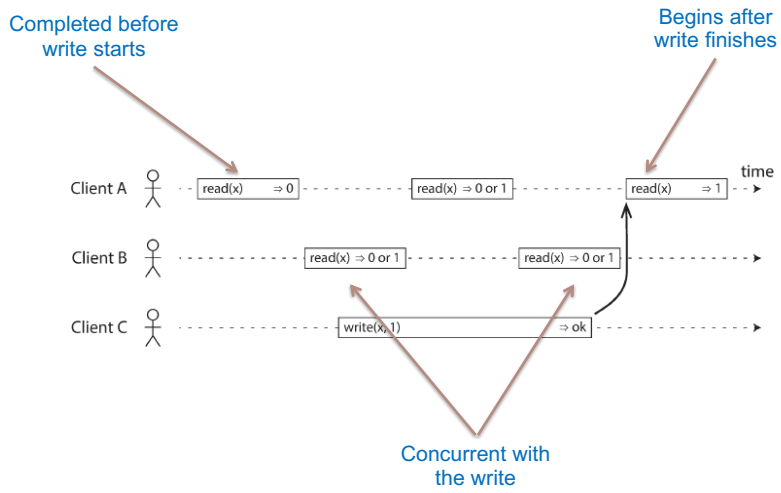
Linearizability



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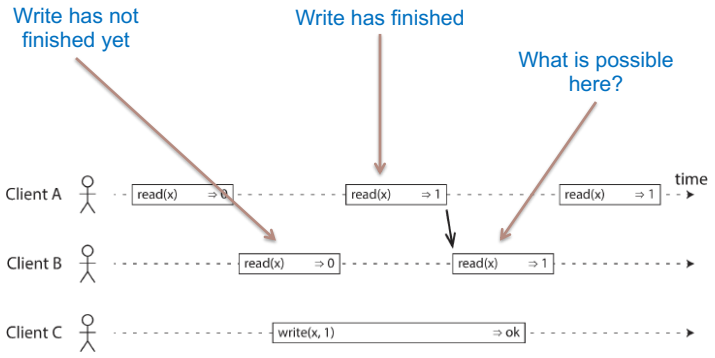
Linearizability



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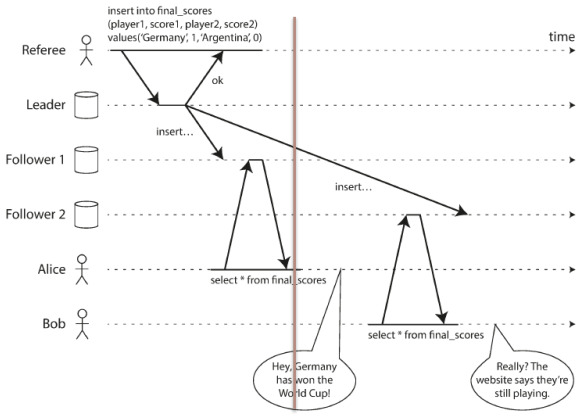
Linearizability



Alice has seen update

Bob sees old value

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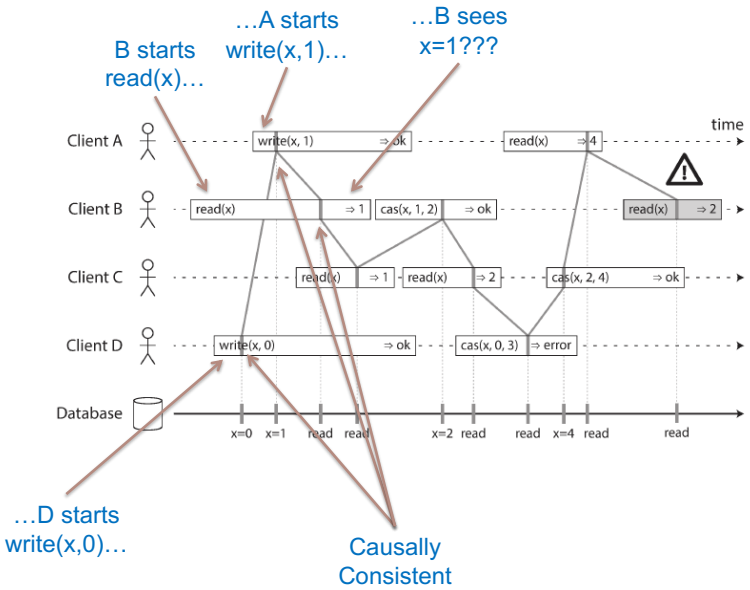
Linearizability & Commit Point



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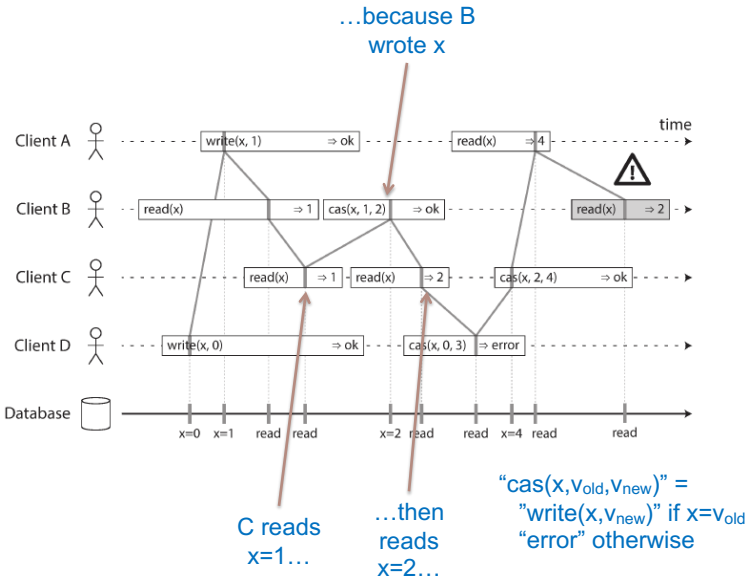
Linearizability & Race Conditions



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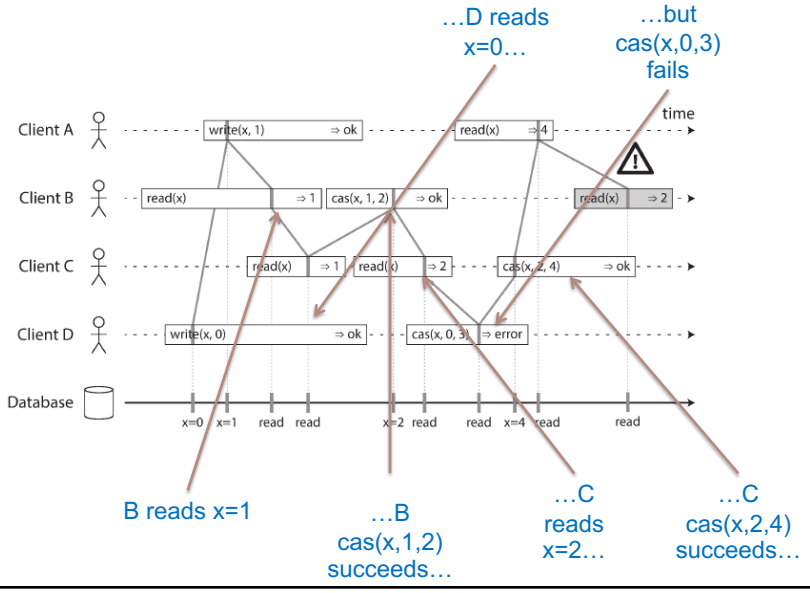
Linearizability & Race Conditions



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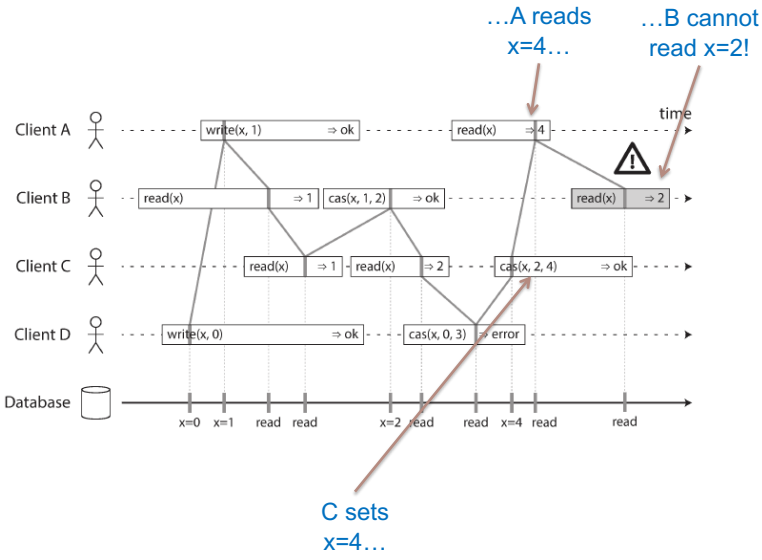
Violation of Linearizability



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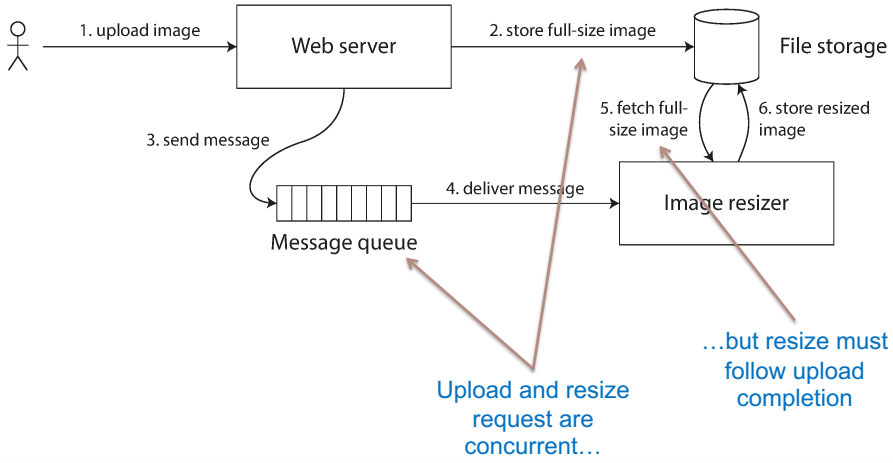
Cross-Channel Timing Dependencies



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Linearizability vs Serializability

- Serializability
  - Isolation property of transactions
  - Actual order of operations may be different from serializable order
- Linearizability
  - Recency guarantee on reads and writes

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Linearizability vs Serializability

- Strong one-copy serializability (strong-1SR)
  - Combine serializability and linearizability (e.g. 2PL, serial execution)
- Serializable Snapshot Isolation (SSI)
  - Not linearizable, reads from consistent snapshot ignore recent writes

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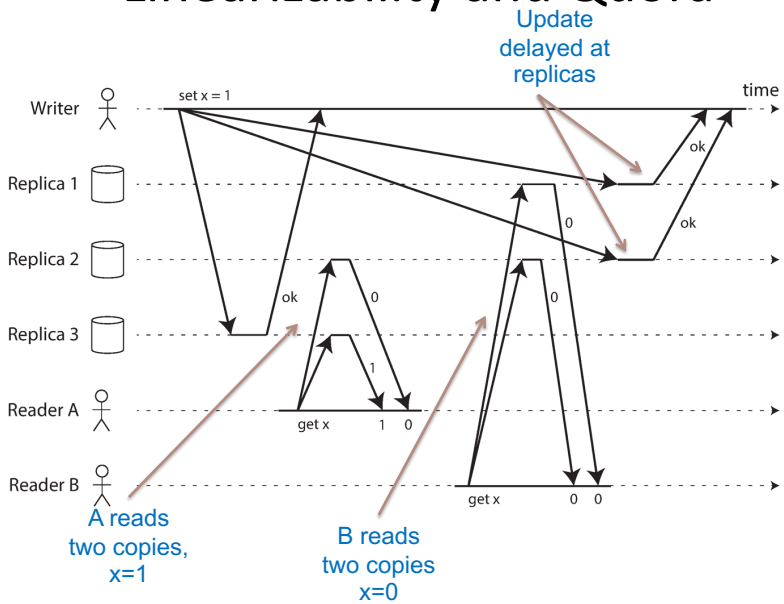
Implementing Linearizability

- Single-Leader replication
  - Potentially linearizable…
  - …snapshot isolation?
- Multi-Leader replication
  - Conflicting writes
  - Not linearizable
- Leaderless replication
  - Quorum consensus?

Assume $Q_w=3$, $Q_r=2$

Linearizability and Quora



Linearizability and Quora

- How to make it linearizable
  - Read: *Synchronously* do read repairs
  - Write: Get read quorum before write
- Issue: latency
- Issue: doesn't extend to e.g. compare-and-set

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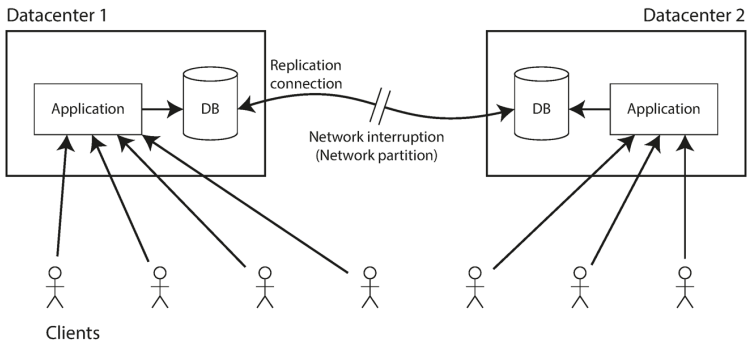
Linearizability vs Availability



Real issue is **Linearizability vs Latency**

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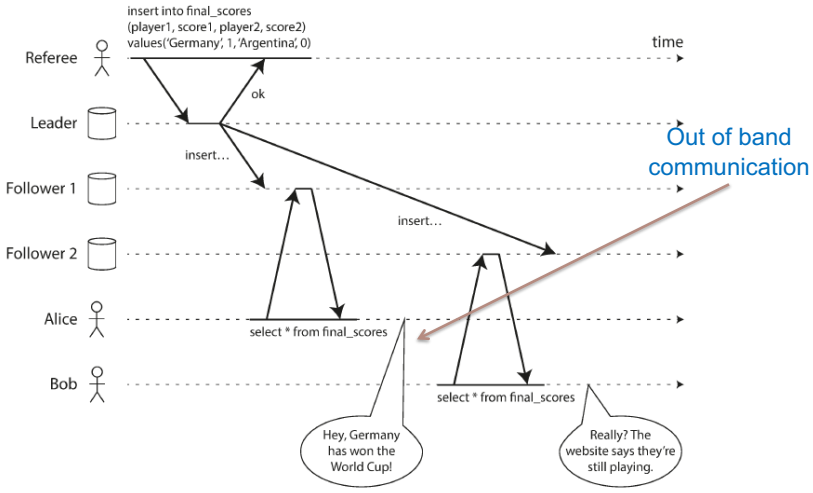
Linearizability and Causality



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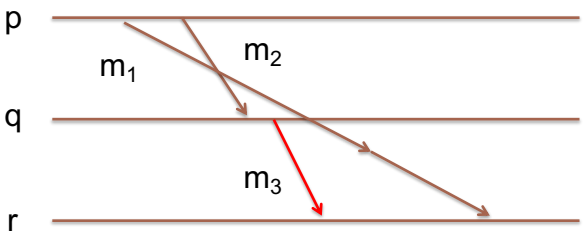
Recall: Causal Message Delivery



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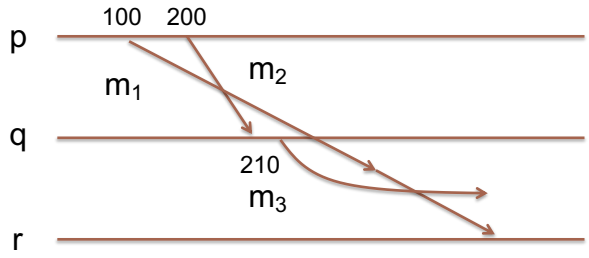
Recall: Causal Message Delivery



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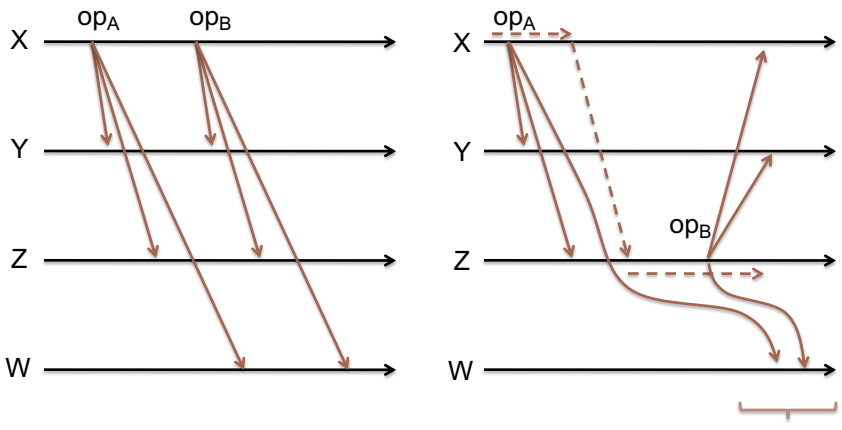
Causal Broadcast Generalizes FIFO



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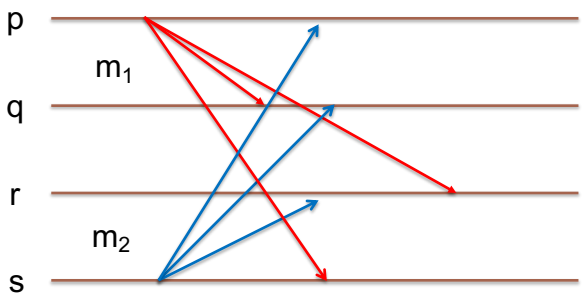
Causal but not Total



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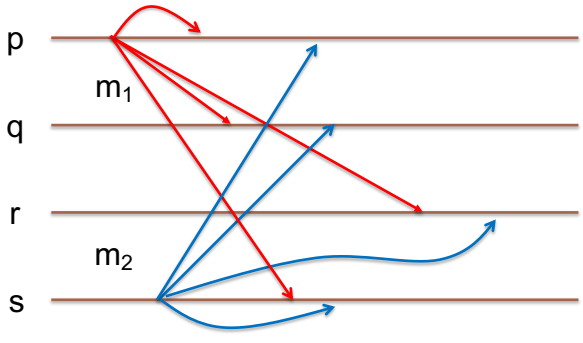
Total Ordered Multicast



Global replicated totally ordered log of messages

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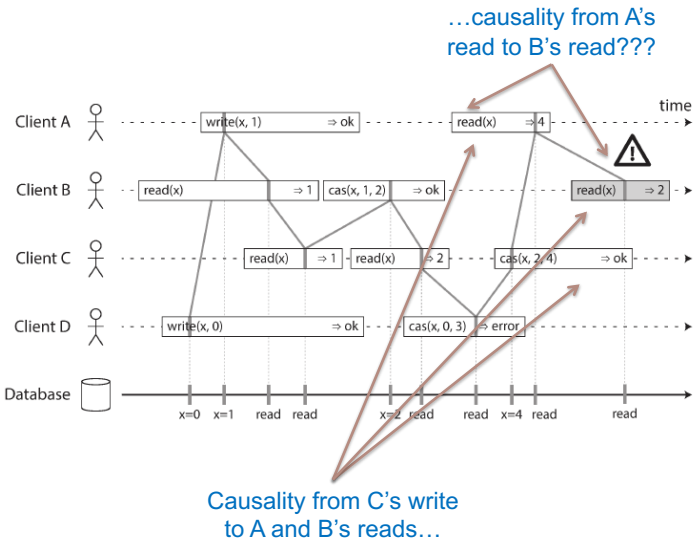
Linearizable vs Causal vs Total



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Linearizable vs Causal vs Total

- Linearizable ⇒ Causal, but not vice versa
- …but causal may be enough!
- …performance similar to eventual consistency

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Linearizable vs Causal vs Total

- Can implement Linearizable with Total
- …broadcast update to all replicas
- …more work to prevent stale reads
- …send yourself a message before reading (quorum read)
- …or read from synchronously updated follower

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Linearizable vs Causal vs Total

- Can implement Total with Linearizable
- …linearizable atomic increment-and-set
- …atomically update broadcast counter

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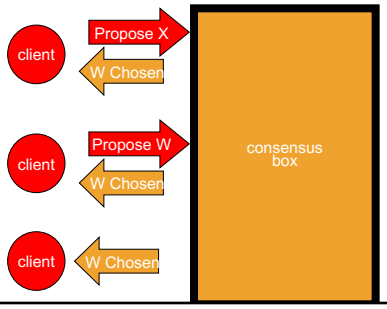
Linearizable vs Total vs Consensus

- Can implement Consensus with Linearizable
- …linearizable atomic increment-and-set

- Can implement Linearizable with Consensus
- …Paxos: Consensus Box

- **Linearizable**
  = Total
  = Consensus!



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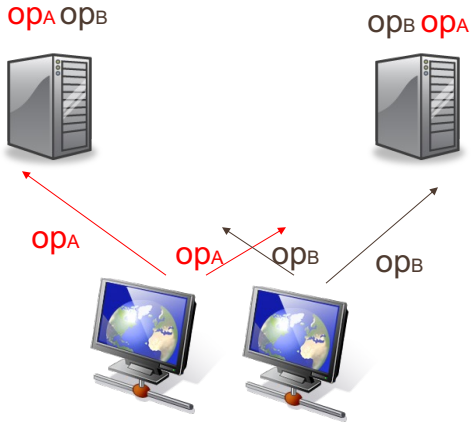
State-Machine Replication



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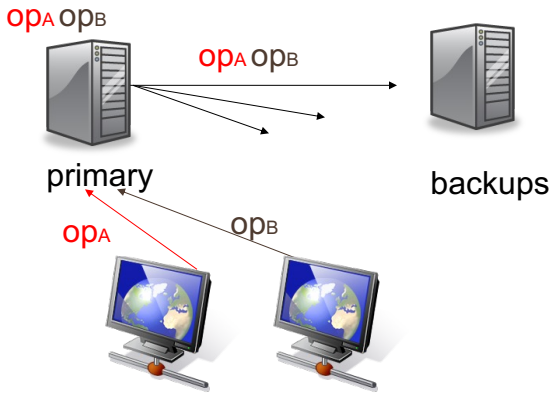
Primary-Backup Replication



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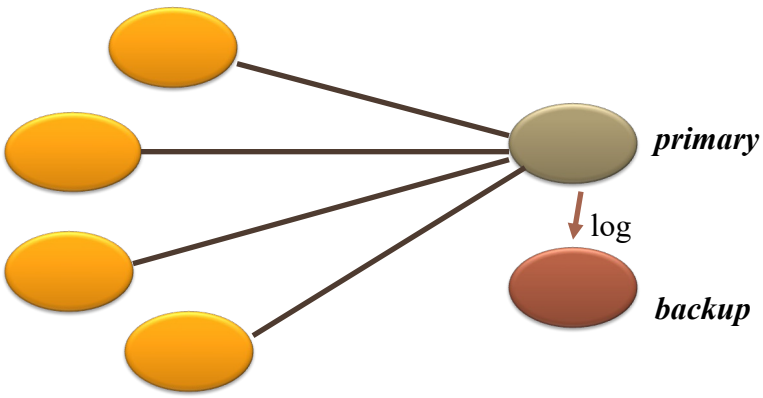
Primary/backup



Clients initially connected to primary, which keeps backup up to date. Backup tracks log

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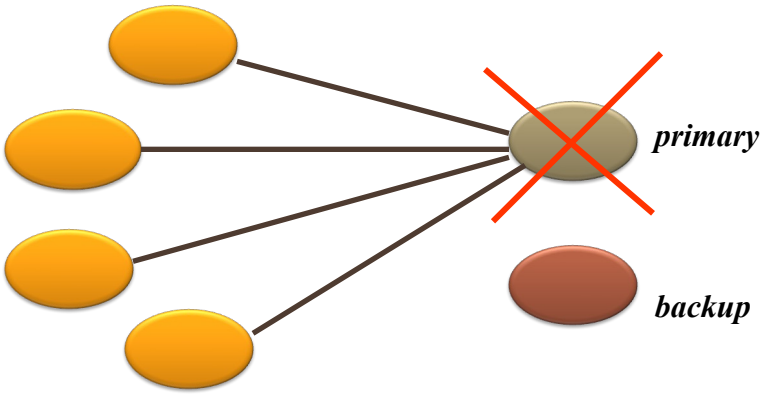
Primary/backup



Primary crashes. Backup sees the channel break.

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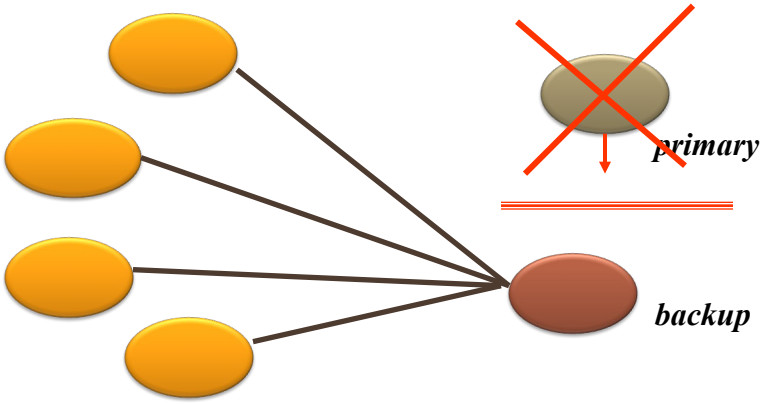
Primary/backup



Clients detect the failure and reconnect to backup.

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Issues

- How do we ensure agreement on order of updates?
- Under what conditions should backup take over?
  - "Split brain" problem

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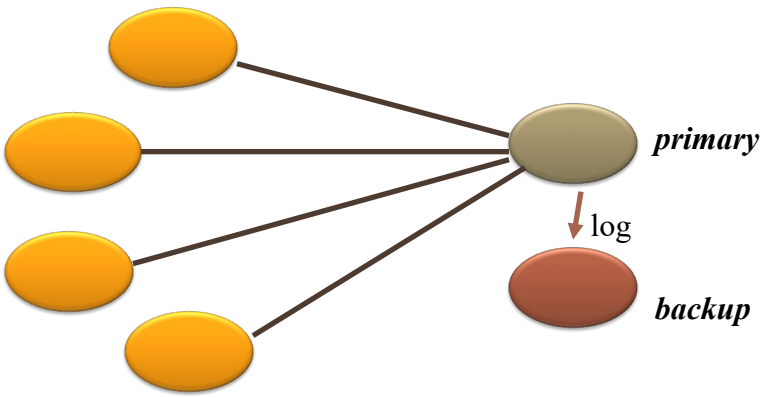
Split brain



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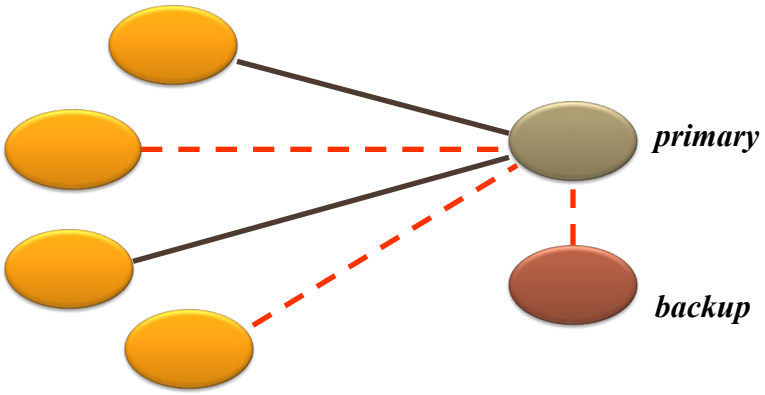
Split brain



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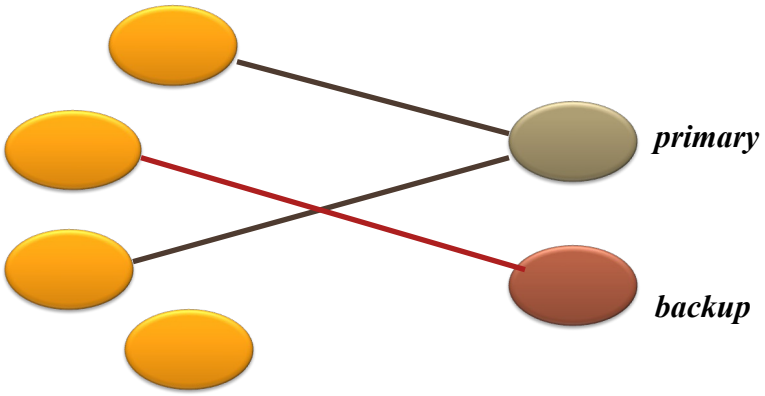
Split brain



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Solutions

- Single server with restart
- Allow backup to “kill” the primary
  - Process groups membership service
- “Majority vote”
  - Quorum consensus

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