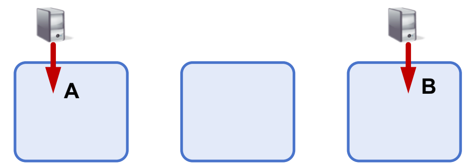
Replication and Consistency

COS 518: *Advanced Computer Systems*
Lecture 3

Michael Freedman

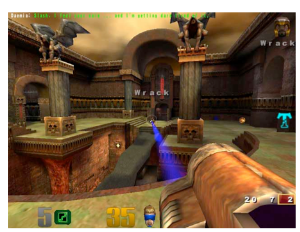
## Correct consistency model?




- Let's say A and B send an op.
- All readers see A → B ?
- All readers see B → A ?
- Some see A → B and others B → A ?

## Time and distributed systems

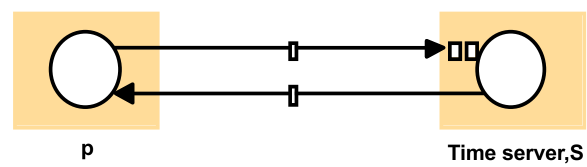
- With multiple events, what happens first?



**A shoots B** | **B shoots A**

**A dies** | **B dies**

## Just use time stamps?




- Clients ask *time server* for time and adjust local clock, based on response
- How to correct for the network latency?

RTT = Time_received – Time_sent

Time_local_new = Time_server + (RTT / 2)

## Is this sufficient?

- Server latency due to load?
  – If can measure: Time_local_new = Time_server + (RTT / 2 + lag)
- But what about asymmetric latency?
  – RTT / 2 not sufficient!
- What do we need to measure RTT?
  – Requires no clock drift!
- What about “almost” concurrent events?
  – Clocks have micro/milli-second precision

## Order by logical events, not by wall clock time

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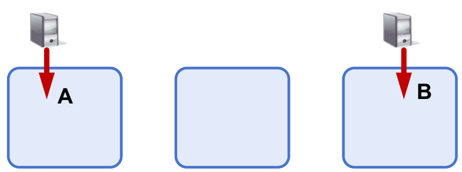
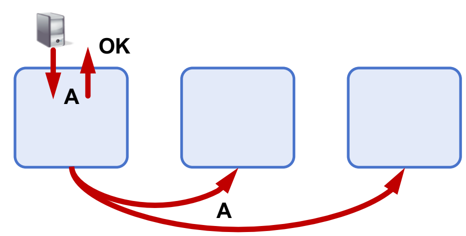
## Correct consistency model?



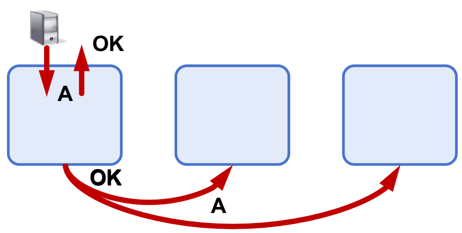

- Let’s say A and B send an op.
- All readers see A → B ?
- All readers see B → A ?
- Some see A → B and others B → A ?

## “Lazy replication”



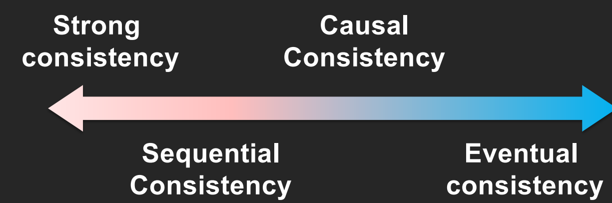

- Acknowledge writes immediately
- Lazily replicate elsewhere (push or pull)
- Eventual consistency: Dynamo, …

## "Eager replication"




- On a write, immediately replicate elsewhere
- Wait until write committed to sufficient # of nodes before acknowledging

## Consistency models



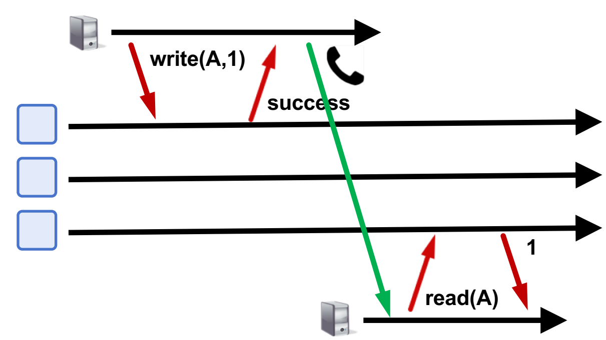



## Strong consistency

- Provide behavior of a single copy of object:
  - Read should return the most recent write
  - Subsequent reads should return same value, until next write
- 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

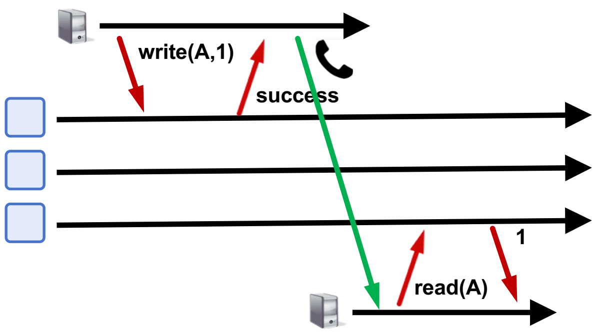


## Strong Consistency?




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

## Strong Consistency?




**One cool trick:** Delay responding to writes/ops until properly committed

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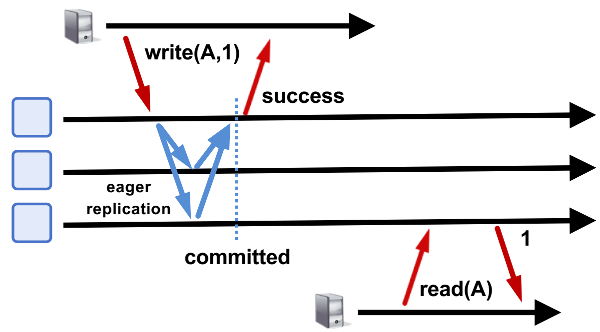
## Strong Consistency? This is buggy!




- Isn't sufficient to return value of third node:
  It doesn't know precisely when op is "globally" committed
- Instead: Need to actually *order* read operation

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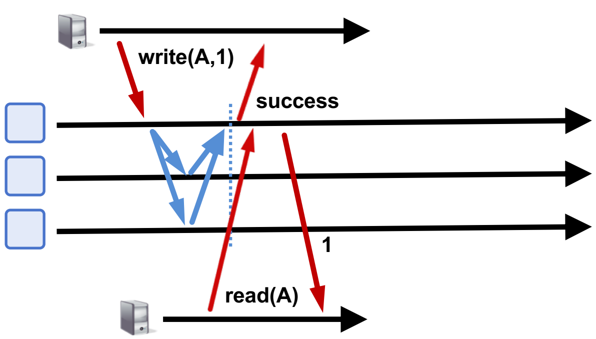
## Strong Consistency!




Order all operations via (1) leader, (2) consensus

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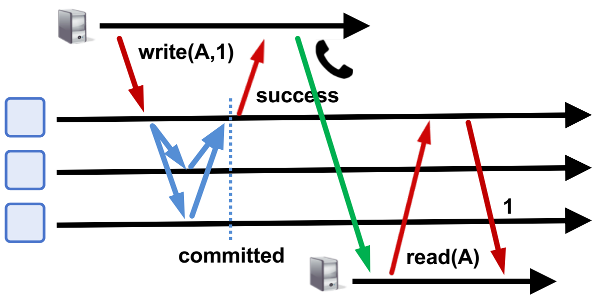
## Strong consistency = linearizability

- Linearizability (Herlihy and Wang 1991)
  1. All servers execute all ops in *some* identical sequential order
  2. Global ordering preserves each client's own local ordering
  3. Global ordering preserves real-time guarantee
     - All ops receive global time-stamp using a sync'd clock
     - If $ts_{op1}(x) < ts_{op2}(y)$, OP1(x) precedes OP2(y) in sequence
- Once write completes, all later reads (by wall-clock start time) 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



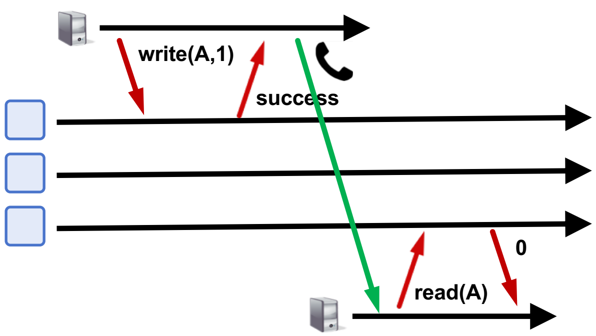

- Once write completes, all later reads (by wall-clock start time) should return value of that write or value of later write.
- Once read returns particular value, all later reads should return that value or value of later write.



## Weaker: Sequential consistency

- Sequential = Linearizability – real-time ordering
  1. All servers execute all ops in *some* identical sequential order
  2. Global ordering preserves each client's own local ordering
- With concurrent ops, "reordering" of ops (w.r.t. real-time ordering) acceptable, but all servers must see same order
  - e.g., linearizability cares about time
    sequential consistency cares about program order

## Sequential Consistency




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



## Valid Sequential Consistency?

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

✓

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

✗

- Why? Because P3 and P4 don't agree on order of ops. Doesn't matter when events took place on diff machine, as long as proc's AGREE on order.
- What if P1 did both W(x)a and W(x)b?
  - Neither valid, as (a) doesn't preserve local ordering

# Even Weaker: Causal consistency

- Potentially ***causally related*** operations?
  - R(*x*) then W(*x*)
  - R(*x*) then W(*y*), $x \neq y$
- Necessary condition: Potentially causally-related writes must be seen by all processes in the same order
  - Concurrent writes may be seen in a different order on different machines

# Causal consistency

| | | | | | | |
|---|---|---|---|---|---|---|
| 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 |

- Allowed with causal consistency, but not with sequential
- W(*x*)*b* and W(*x*)*c* are **concurrent**
  - So all processes don't see them in the same order
- P3 and P4 read the values 'a' and 'b' in order as potentially causally related. No 'causality' for 'c'.

# Causal consistency

| | | | | | | |
|---|---|---|---|---|---|---|
| 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 |

- Why not sequentially consistent?
  - P3 and P4 see W(*x*)*b* and W(*x*)*c* in different order.
- But fine for causal consistency
  - Writes W(*x*)*b* and W(*x*)*c* are **not causally dependent**
    - Write after write has no dependencies

# Causal consistency

| | | | | | |
|---|---|---|---|---|---|
| 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 |

(a) ✗

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

(b) ✓

- A: Violation: W(x)b potentially dependent on W(x)a
- B: Correct. P2 doesn't read value of a before W

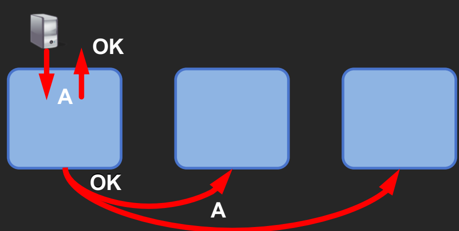
## Causal consistency

- Requires keeping track of which processes have seen which writes
  - Needs a dependency graph of which op is dependent on which other ops
  - …or use vector timestamps!

See COS 418: https://www.cs.princeton.edu/courses/archive/fall17/cos418/docs/L4-time.pptx

## Implementing strong consistency



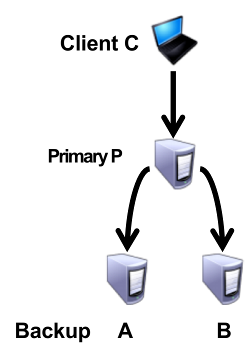



## Recall "eager replication"

- On a write, immediately replicate elsewhere
- Wait until write **committed** to sufficient # of nodes before acknowledging
- What does this mean?



## Two phase commit protocol




1. **C → P:** *"request write X"*
2. **P → A, B:** *"prepare to write X"*
3. **A, B → P:** *"prepared"* or *"error"*
4. **P → C:** *"result write X" or "failed"*
5. **P → A, B:** *"**commit** write X"*

## State machine replication

- **Any server** is essentially a ***state machine***
  - Operations **transition** between states
- Need an op to be executed on all replicas, or none at all
  - *i.e.*, we need **distributed all-or-nothing atomicity**
  - If op is deterministic, replicas will end in same state

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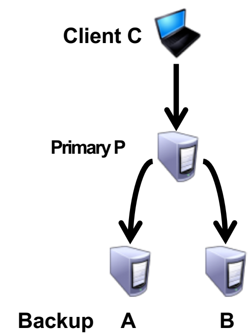
## Two phase commit protocol




1. **C → P:** *"request <op>"*
2. **P → A, B:** *"prepare <op>"*
3. **A, B → P:** *"prepared"* or *"error"*
4. **P → C:** *"result exec<op>" or "failed"*
5. **P → A, B:** *"**commit** <op>"*

What if primary fails?
Backup fails?

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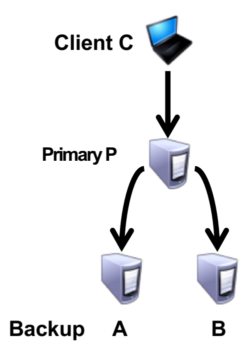
## Two phase commit protocol

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"Okay" (i.e., op is stable) if written to > ½ backups

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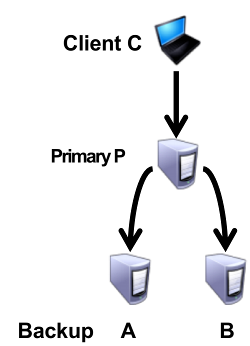
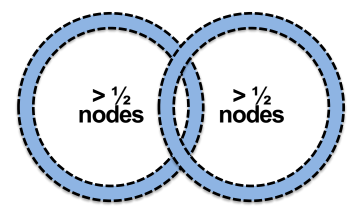
## Two phase commit protocol




- Commit sets always overlap ≥ 1 node
- Any >½ nodes guaranteed to see committed op

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## Wednesday class

Papers: Strong consistency

Lecture: Consensus, view change protocols

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