Spanner

Tom Anderson (h/t Doug Woos and Dan Ports)

Bigtable in retrospect

- Definitely a useful, scalable system!
- Still in use at Google, motivated lots of NoSQL DBs
- Biggest mistake in design (per Jeff Dean, Google): not supporting distributed transactions!
  - became really important w/ incremental updates
  - users wanted them, implemented themselves, often incorrectly!
  - at least 3 papers later fixed this

Two-phase commit

- keys partitioned over different hosts; one coordinator per transaction
- acquire locks on all data read/written; release after commit
- to commit, coordinator first sends prepare message to all shards; they respond prepare_ok or abort
  - if prepare_ok, they *must* be able to commit transaction
- if all prepare_ok, coordinator sends commit to all; they write commit record and release locks

Is this the end of the story?

- Availability: what do we do if either some shard or the coordinator fails?
  - generally: 2PC is a blocking protocol, can't make progress until it comes back up
- Performance: can we really afford to take locks and hold them for the entire commit process?

Spanner

- Backend for the F1 database, which runs the ad system
- Basic model: 2PC over Paxos
- Uses physical clocks for performance

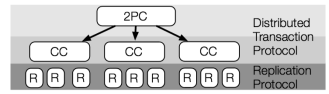
Example: social network

- simple schema: user posts, and friends lists
- but sharded across thousands of machines
- each replicated across multiple continents

Example: social network

- example: generate page of friends' recent posts
- what if I remove friend X, post mean comment?
  - maybe he sees old version of friends list, new version of my posts?
- How can we solve this with locking?
  - acquire read locks on friends list, and on each friend's posts
  - prevents them from being modified concurrently
  - but potentially really slow?

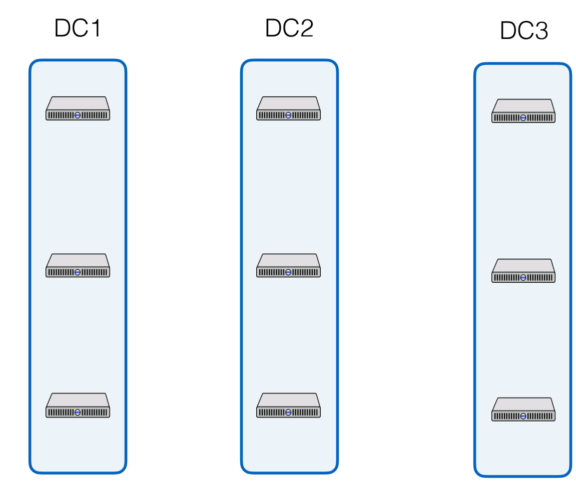
Spanner architecture

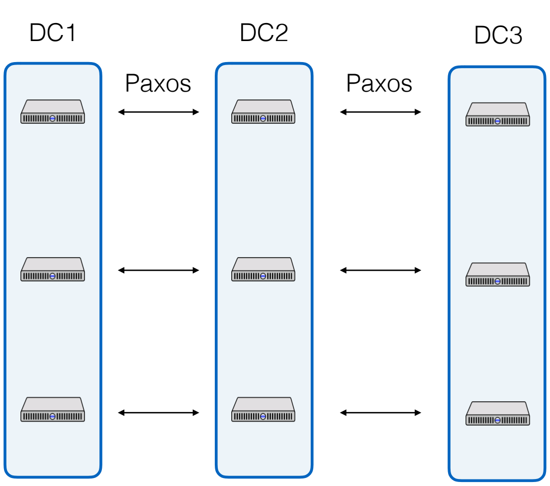


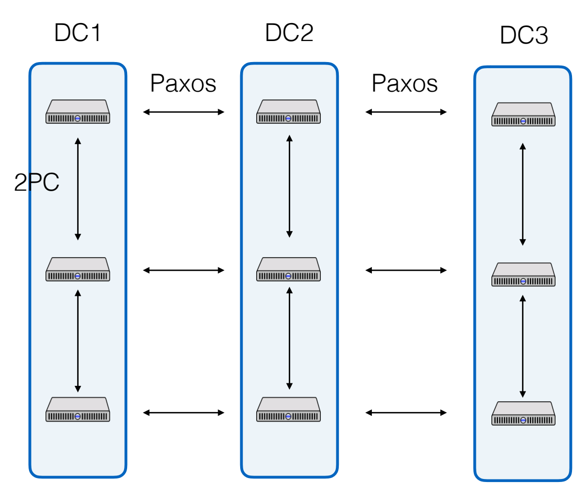
- Each shard is stored in a Paxos group
  - replicated across data centers
  - has a (relatively long-lived) leader
- Transactions span Paxos groups using 2PC
  - use 2PC for transactions
  - leader of each Paxos group tracks locks
  - one group leader becomes the 2PC coordinator, others participants

Basic 2PC/Paxos approach

- during execution, read and write objects
  - contact the appropriate Paxos group leader, acquire locks
- client decides to commit, notifies the coordinator
  - coordinator contacts all shards, sends PREPARE message
  - they Paxos-replicate a prepare log entry (including locks),
  - vote either ok or abort
- if all shards vote OK, coordinator sends commit message
  - each shard Paxos-replicates commit entry
  - leader releases locks







Basic 2PC/Paxos approach

- Note that this is really the same as basic 2PC from before
- Just replaced writes to a log on disk with writes to a Paxos replicated log!
- It is linearizable (= strict serializable = externally consistent)
- So what's left?
  - Lock-free read-only transactions

Lock-free r/o transactions

- Key idea: assign meaningful timestamp to transaction
  - such that timestamps are enough to order transactions meaningfully
- Keep a history of versions around on each node
- Then, reasonable to say:
  r/o transaction X reads at timestamp 10

TrueTime

- Common misconception: the magic here is fancy hardware (atomic clocks, GPS receivers)
  - this is actually relatively standard (see NTP)
- Actual key idea:
  expose the *uncertainty* in the clock value

TrueTime API

- interval = TT.now()
- "correct" time is "guaranteed" to be between interval.latest and interval.earliest
- What does this actually mean?

Implementing TrueTime

- time masters (GPS, atomic clocks) in each data center
- NTP or similar protocol syncs with multiple masters, rejects outliers
- TrueTime returns the local clock value, plus uncertainty
  - uncertainty = time since last sync * 200 usec/sec

Assigning transaction timestamps

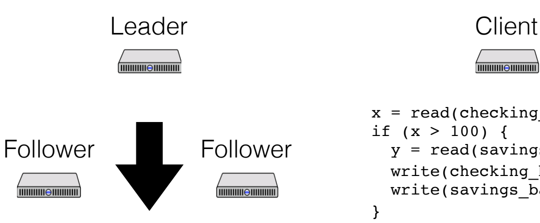
- When in the basic protocol should we assign a transaction its timestamp?
- What timestamp should we give it?
- How do we know that timestamp is consistent with global time?

Assigning transaction timestamps

- When in the basic protocol should we assign a transaction its timestamp?
  - any time between when all locks acquired and first lock released
- What timestamp should we give it?
  - a time TrueTime thinks is in the future, TT.latest
- How do we know that timestamp is consistent with global time?
  - *commit wait*: until TrueTime knows timestamp is in the past
  - thus: we know that when that timestamp was correct, we're holding the locks

Spanner pt 2

1. Distributed transactions, in detail
   - On one Paxos group
   - Between Paxos groups
2. Fast read-only transactions with TrueTime
3. Discussion

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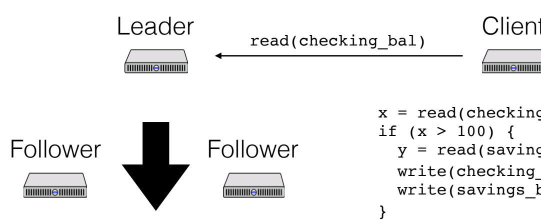


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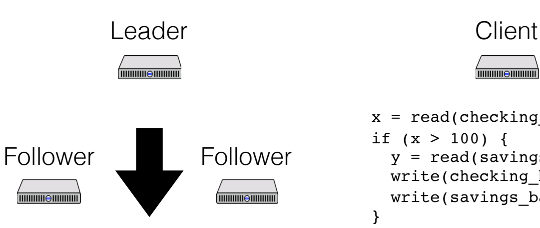


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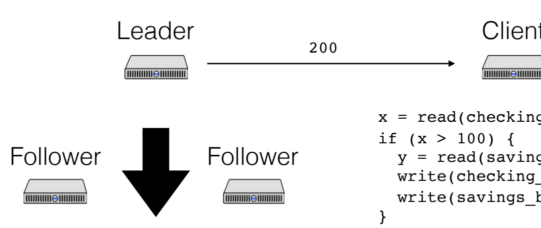


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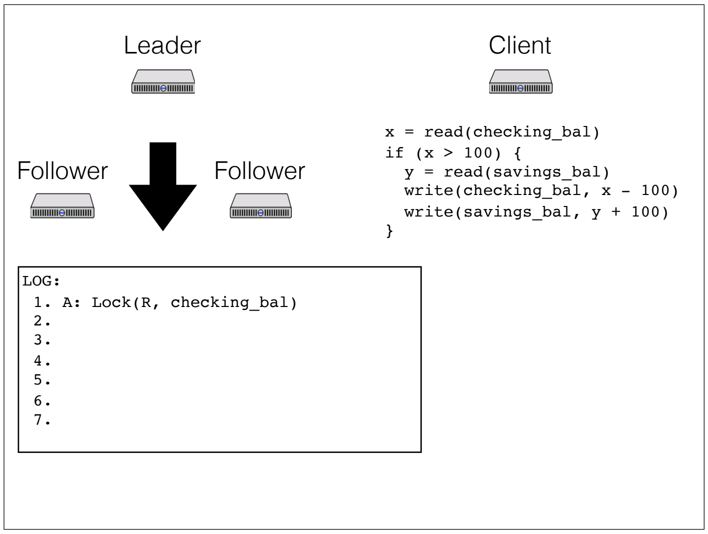
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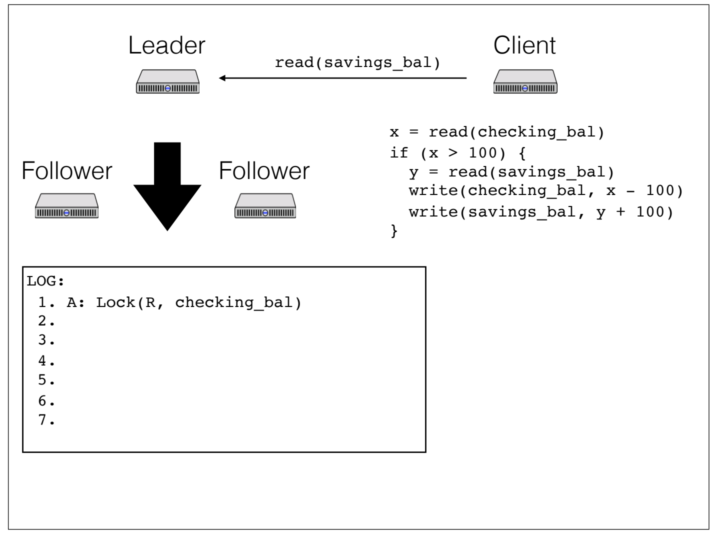
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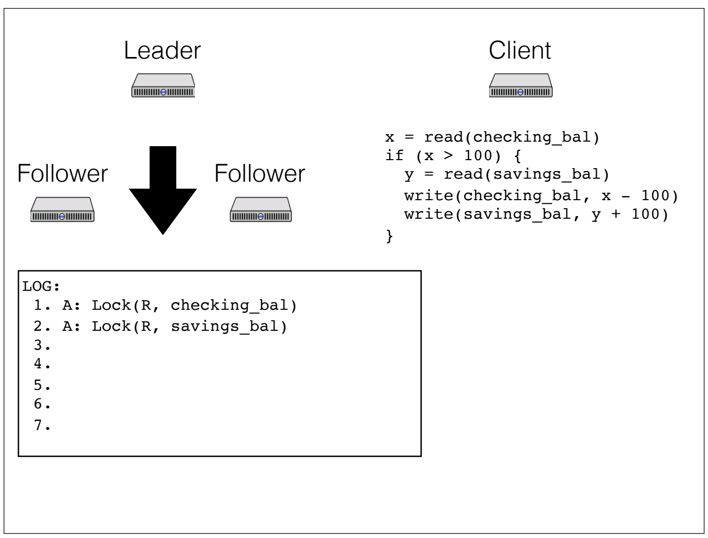
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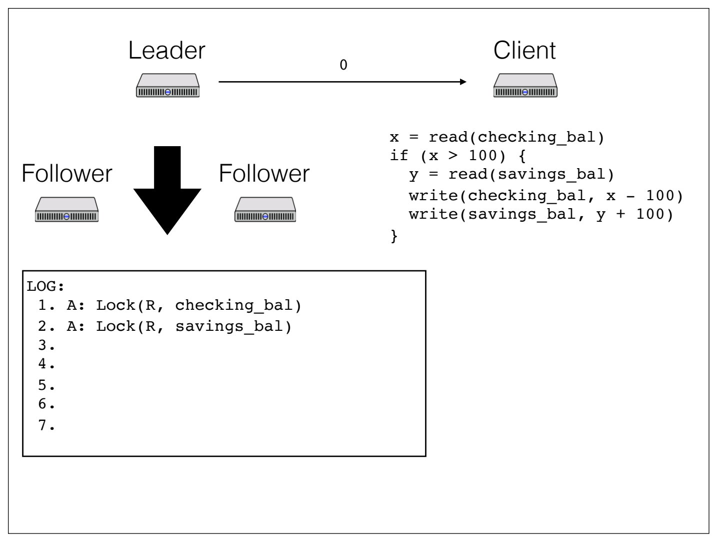
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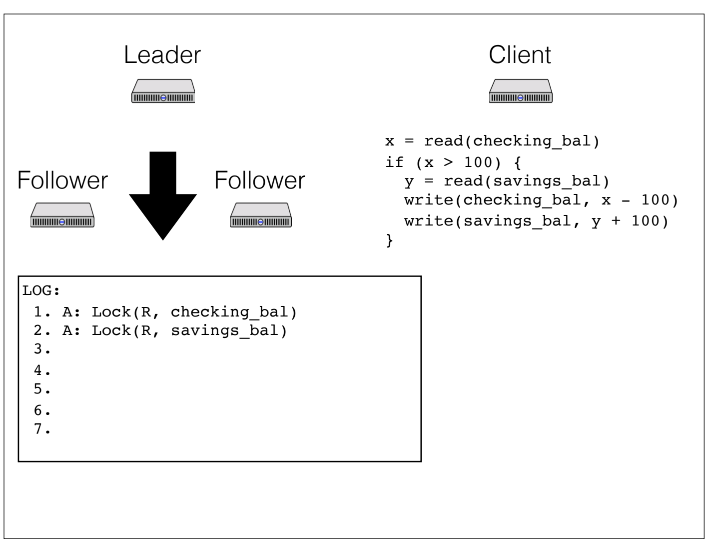
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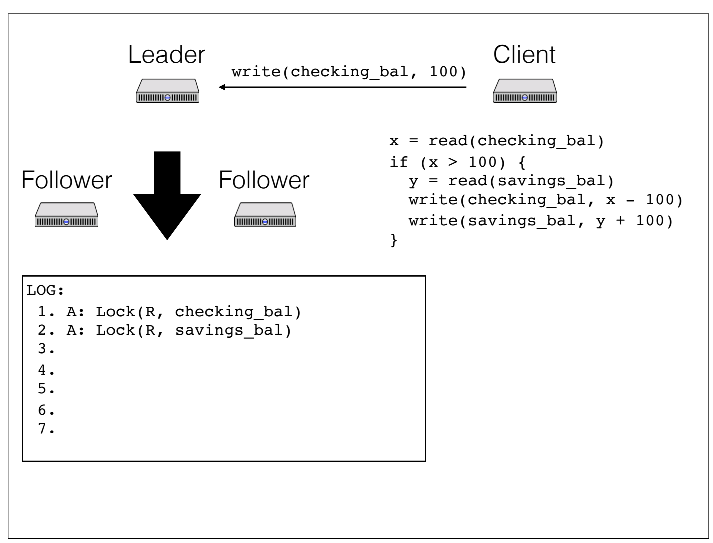
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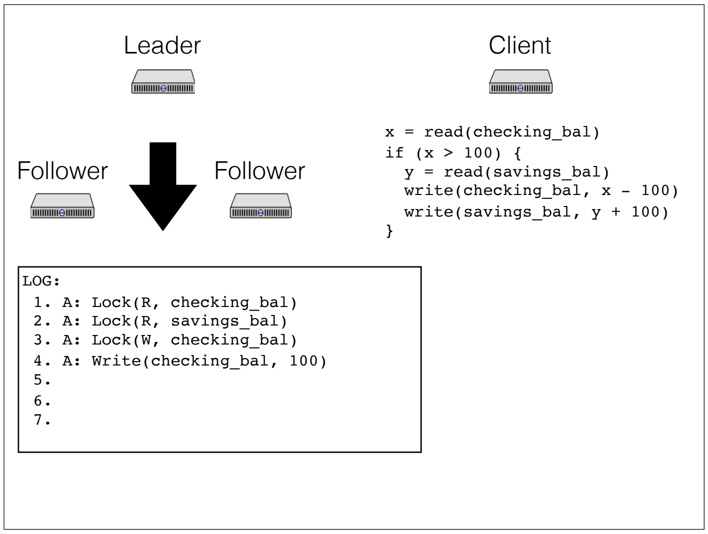
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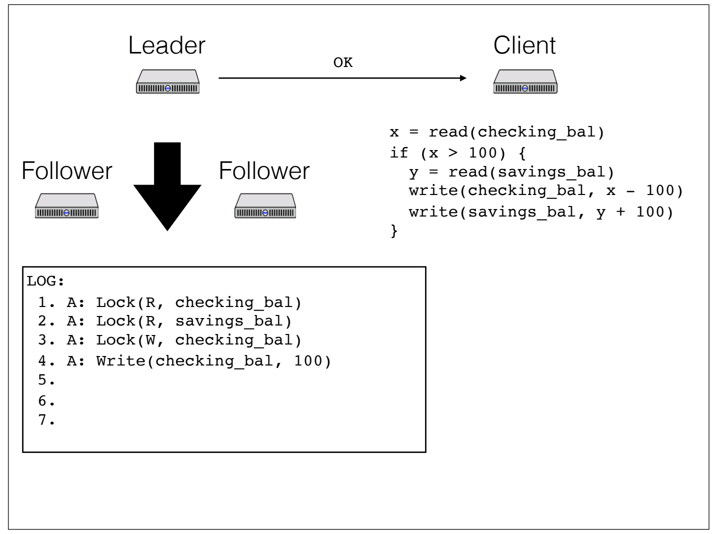
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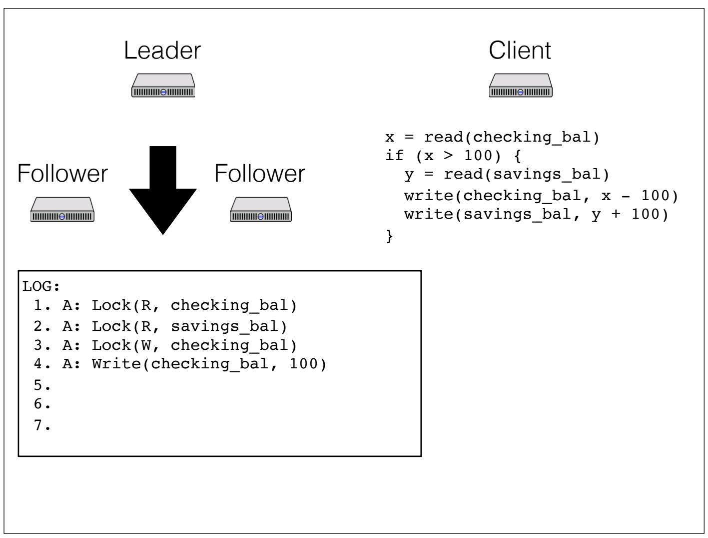
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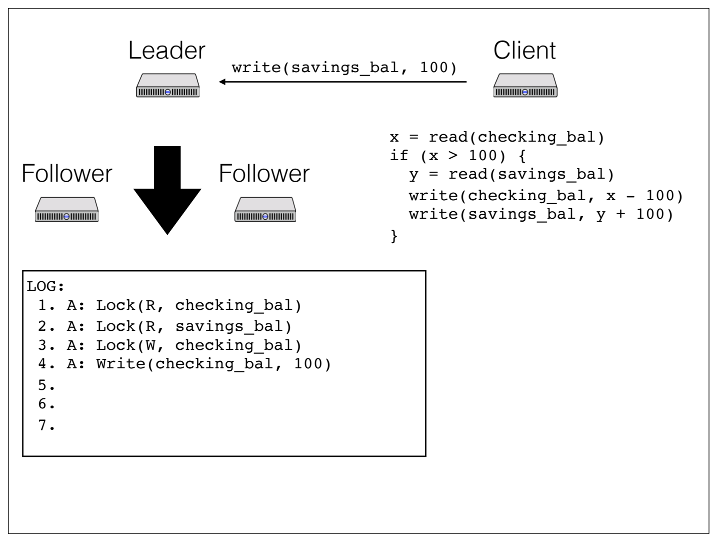
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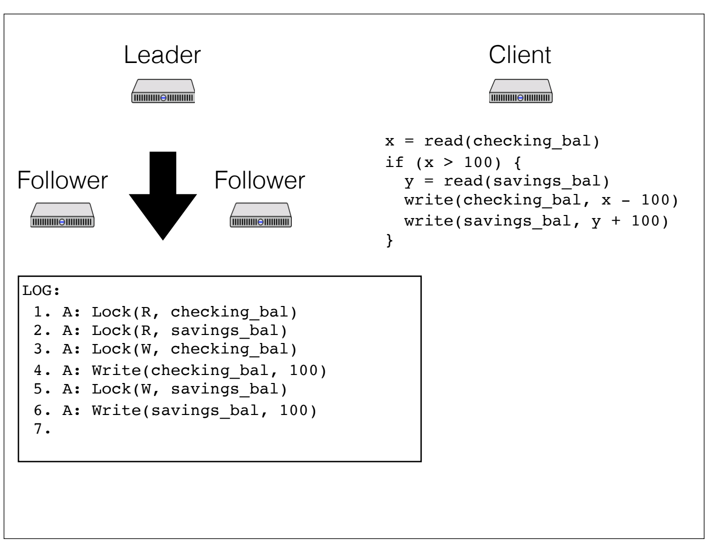
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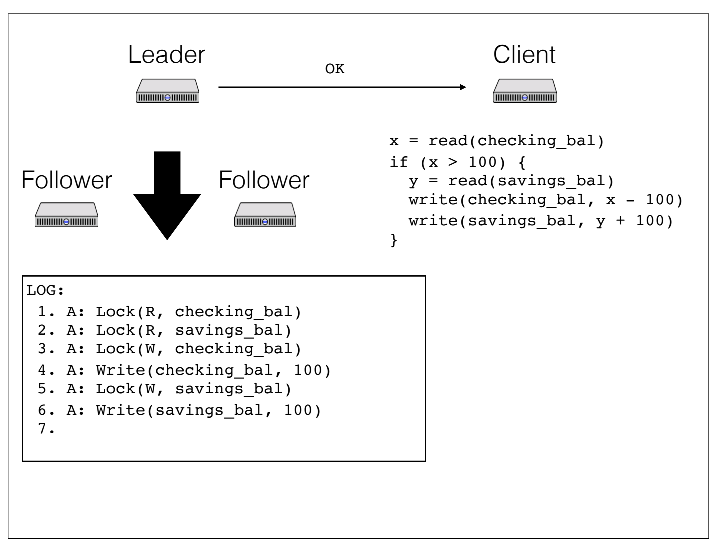
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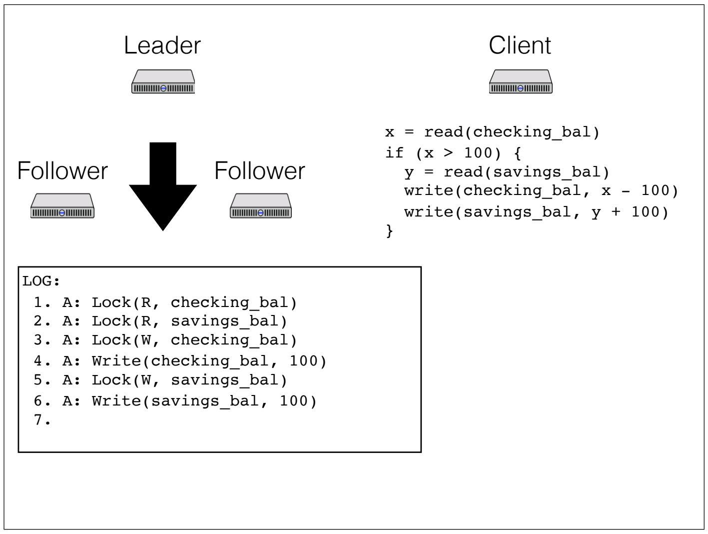
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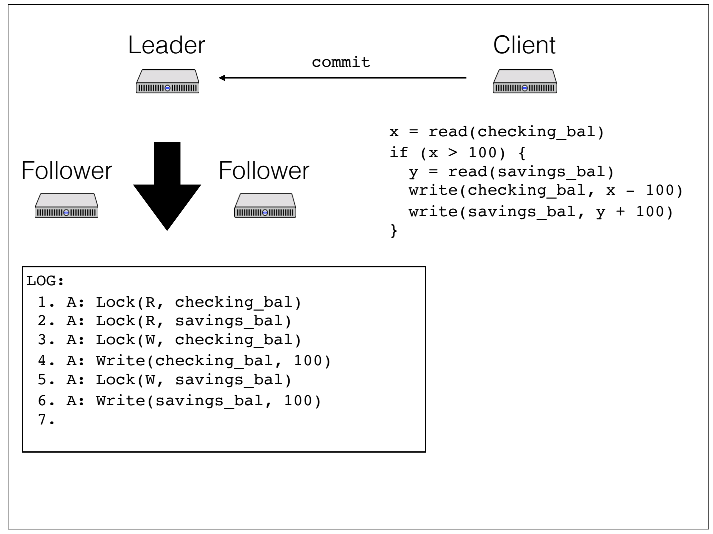
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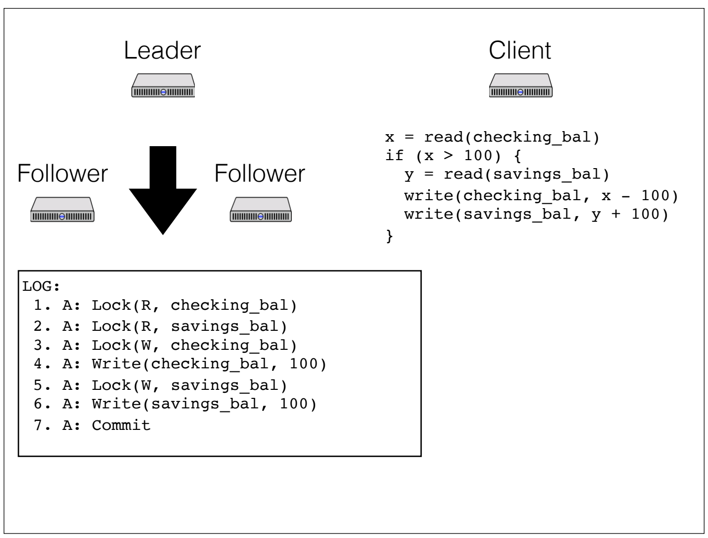
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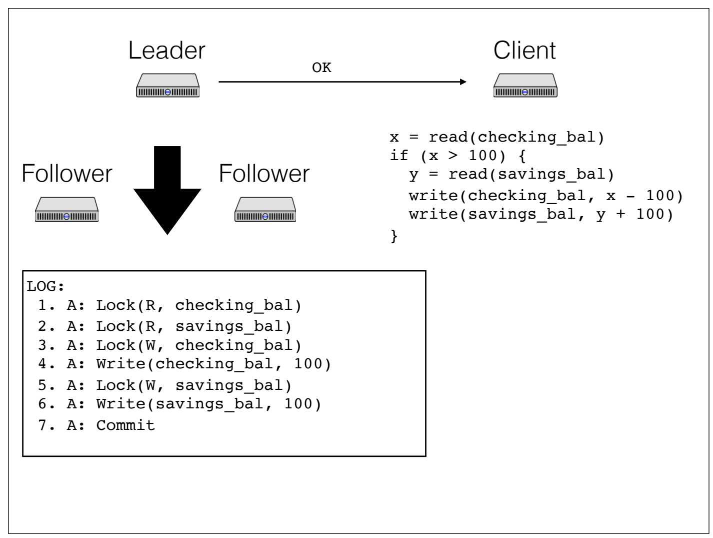
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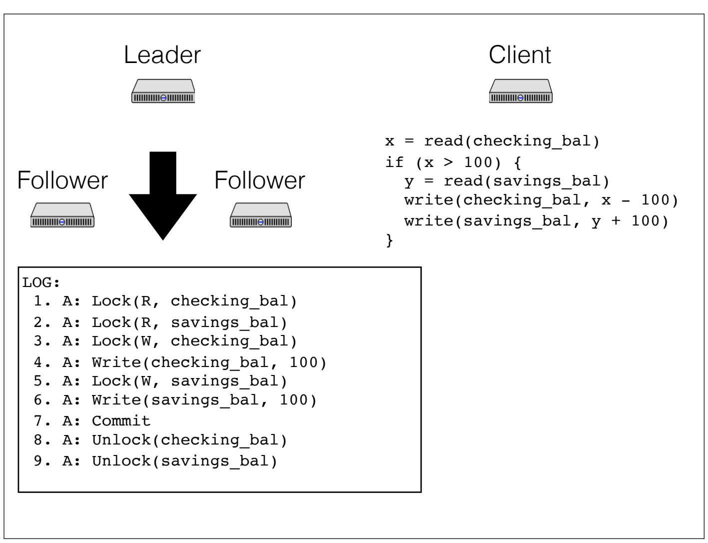
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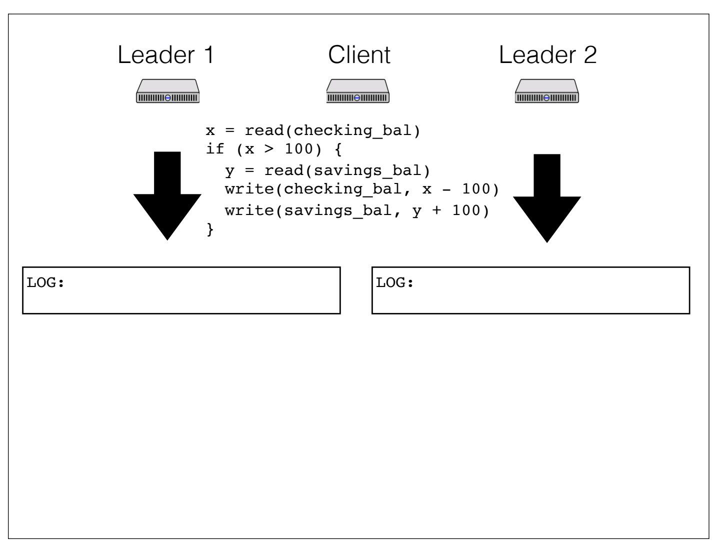
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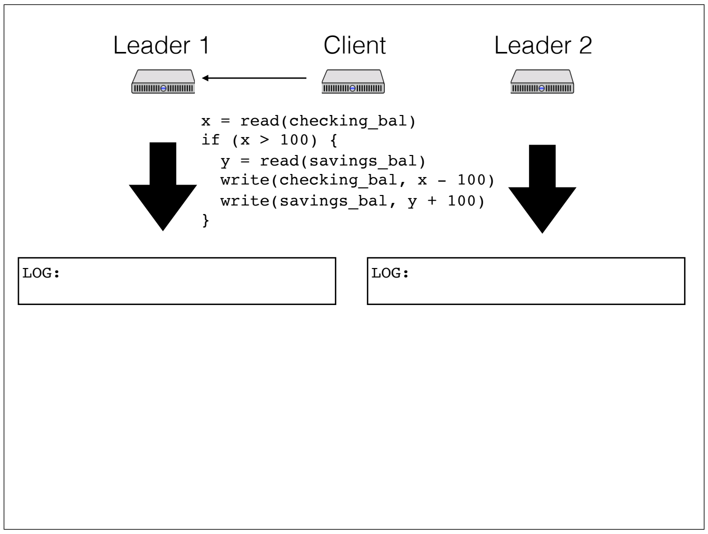
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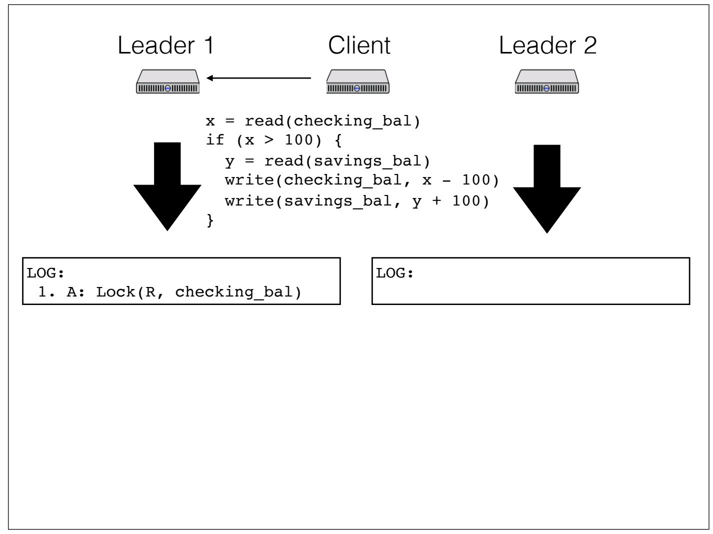
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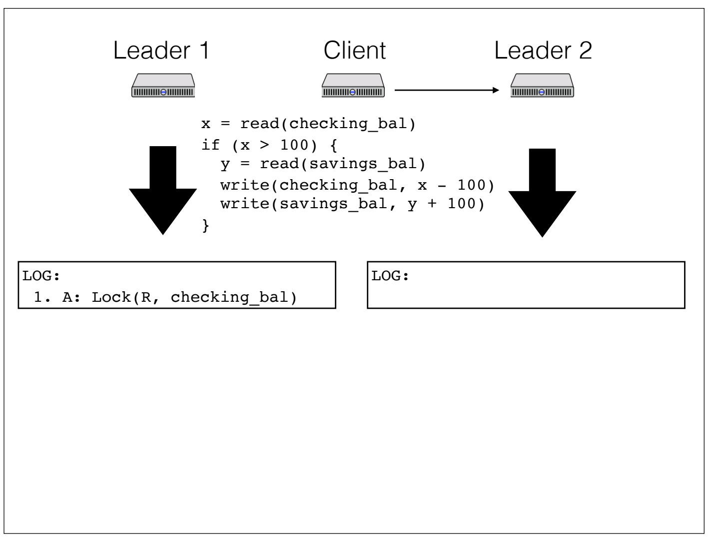
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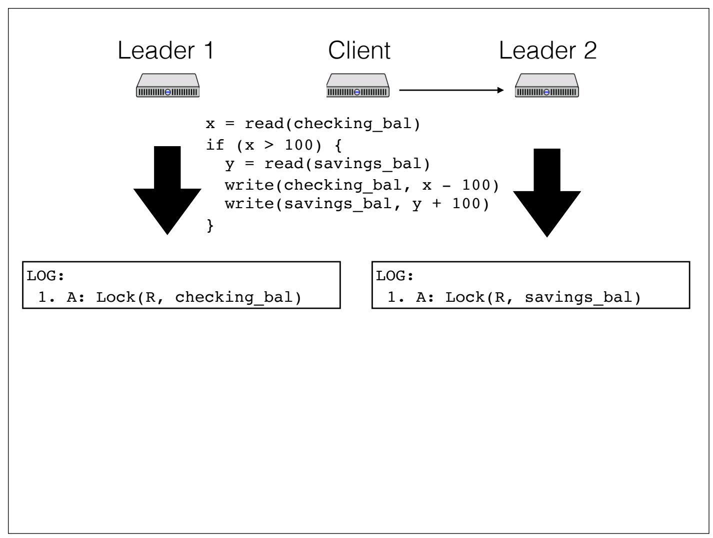
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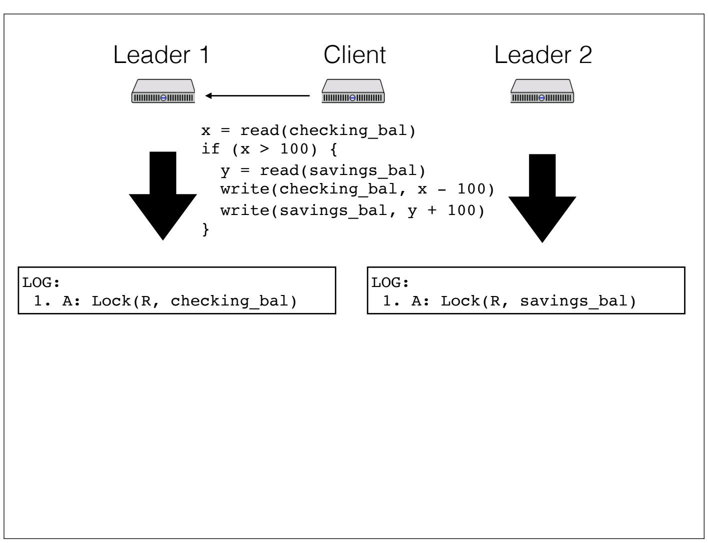
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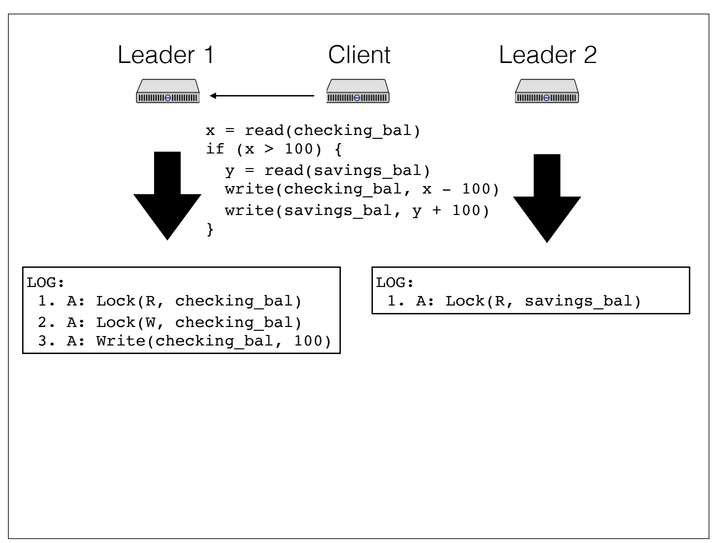
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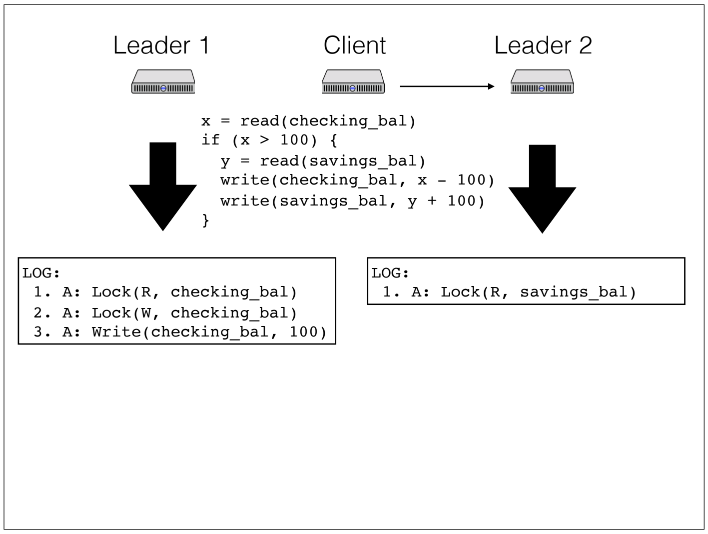
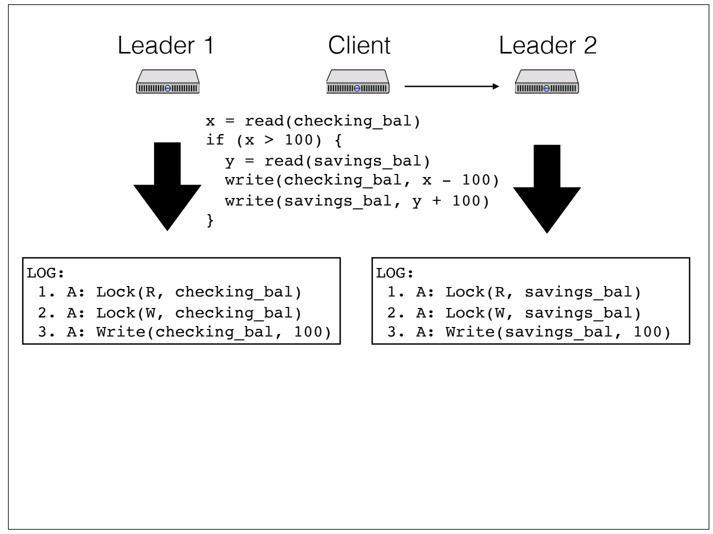
3. A: Write(checking_bal, 100)
LOG:
1. A: Lock(R, savings_bal)


Leader 1
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(W, checking_bal)
3. A: Write(checking_bal, 100)
LOG:
1. A: Lock(R, savings_bal)


Leader 1
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
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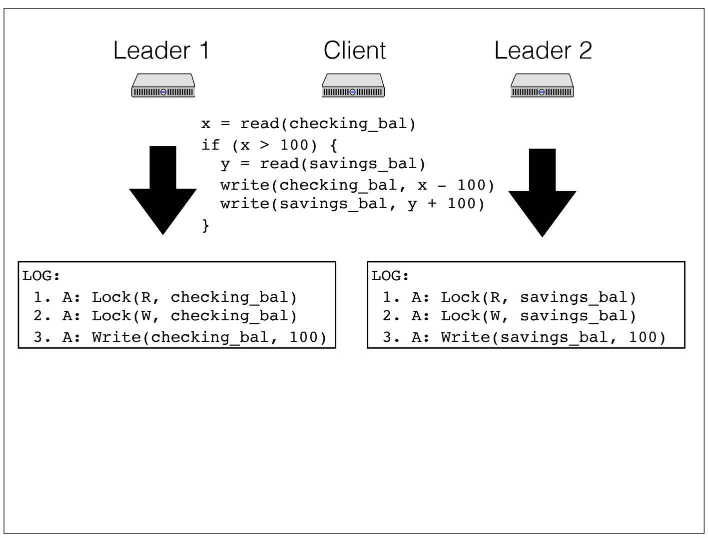
Leader 1
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
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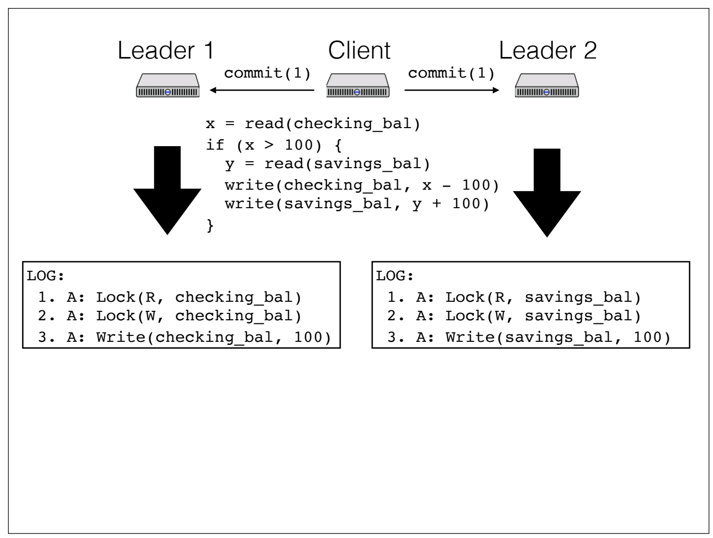
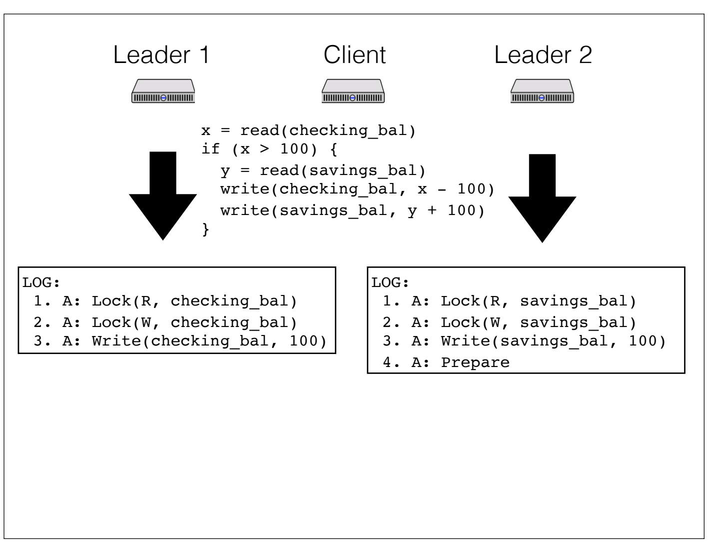
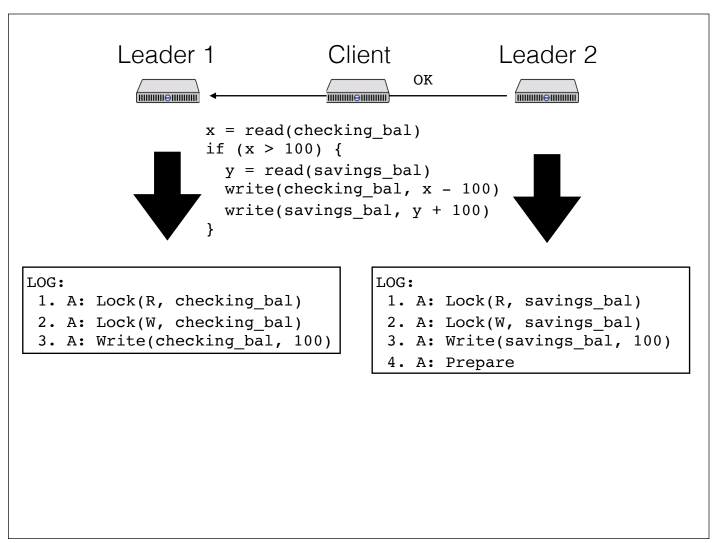
1. A: Lock(R, savings_bal)
2. A: Lock(W, savings_bal)
3. A: Write(savings_bal, 100)


Leader 1
commit(1)
Client
commit(1)
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(W, checking_bal)
3. A: Write(checking_bal, 100)
LOG:
1. A: Lock(R, savings_bal)
2. A: Lock(W, savings_bal)
3. A: Write(savings_bal, 100)


Leader 1
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(W, checking_bal)
3. A: Write(checking_bal, 100)
LOG:
1. A: Lock(R, savings_bal)
2. A: Lock(W, savings_bal)
3. A: Write(savings_bal, 100)
4. A: Prepare


Leader 1
Client
OK
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
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3. A: Write(checking_bal, 100)
LOG:
1. A: Lock(R, savings_bal)
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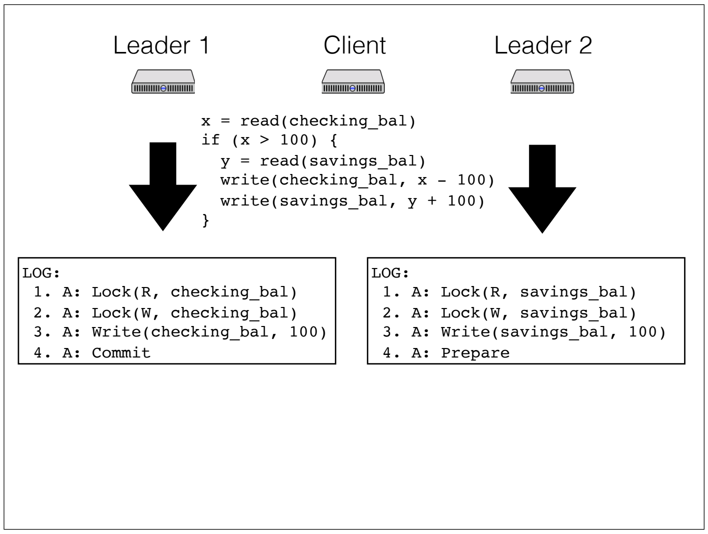
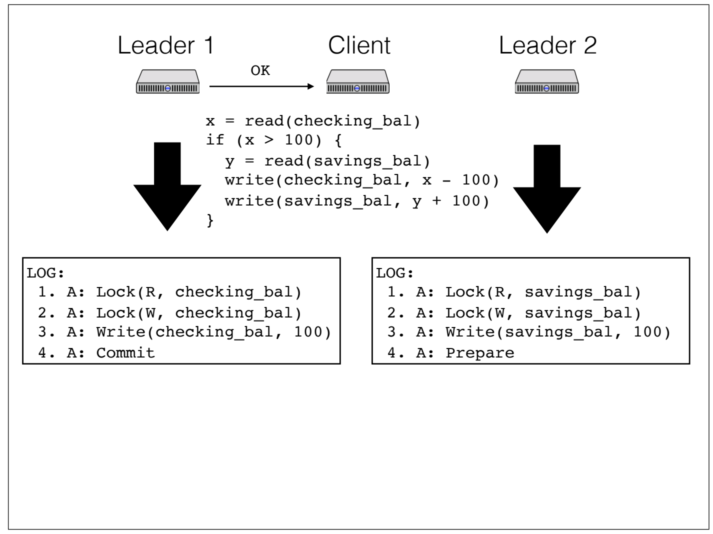
4. A: Prepare


Leader 1
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(W, checking_bal)
3. A: Write(checking_bal, 100)
4. A: Commit
LOG:
1. A: Lock(R, savings_bal)
2. A: Lock(W, savings_bal)
3. A: Write(savings_bal, 100)
4. A: Prepare


Leader 1
OK
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
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4. A: Commit
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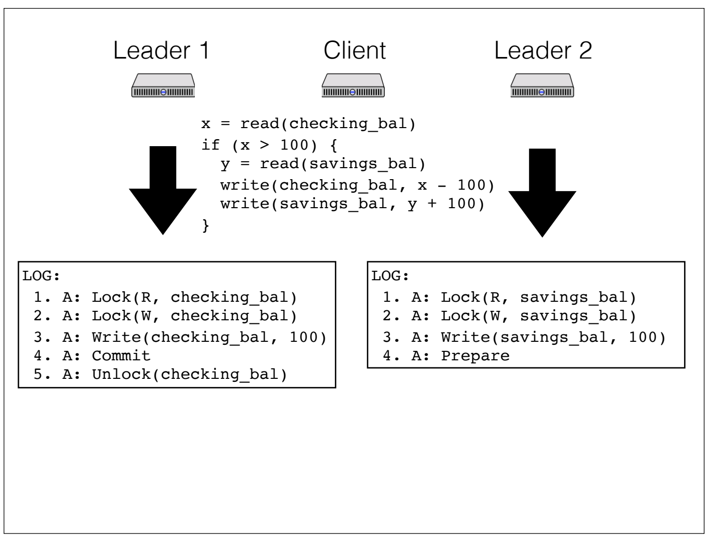
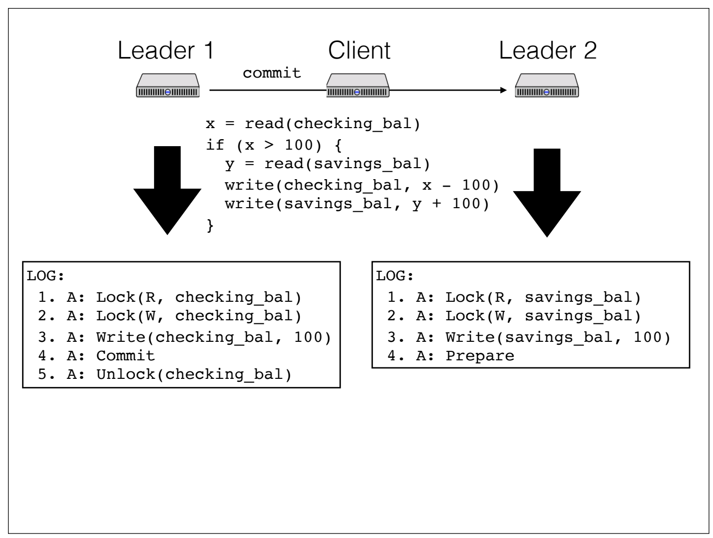
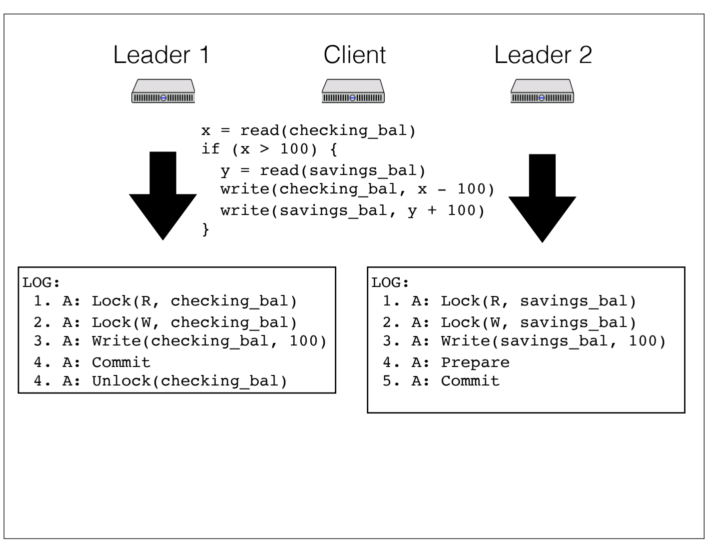
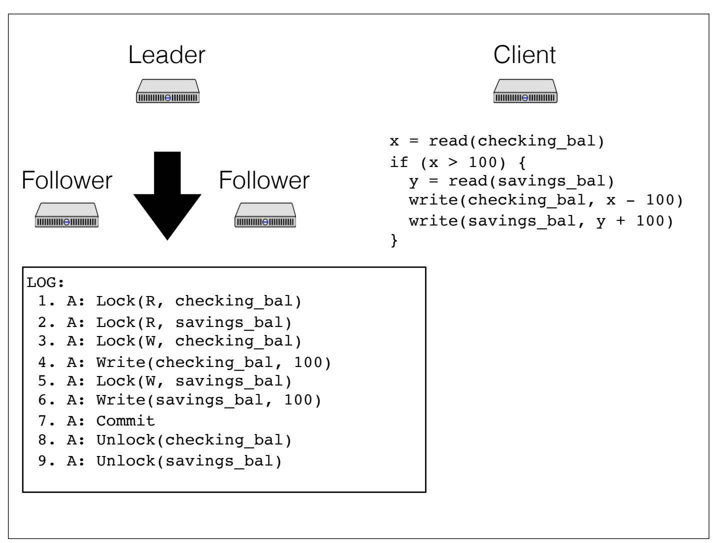
1. A: Lock(R, savings_bal)
2. A: Lock(W, savings_bal)
3. A: Write(savings_bal, 100)
4. A: Prepare


Leader 1
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(W, checking_bal)
3. A: Write(checking_bal, 100)
4. A: Commit
5. A: Unlock(checking_bal)
LOG:
1. A: Lock(R, savings_bal)
2. A: Lock(W, savings_bal)
3. A: Write(savings_bal, 100)
4. A: Prepare


Leader 1
commit
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(W, checking_bal)
3. A: Write(checking_bal, 100)
4. A: Commit
5. A: Unlock(checking_bal)
LOG:
1. A: Lock(R, savings_bal)
2. A: Lock(W, savings_bal)
3. A: Write(savings_bal, 100)
4. A: Prepare


Leader 1
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(W, checking_bal)
3. A: Write(checking_bal, 100)
4. A: Commit
4. A: Unlock(checking_bal)
LOG:
1. A: Lock(R, savings_bal)
2. A: Lock(W, savings_bal)
3. A: Write(savings_bal, 100)
4. A: Prepare
5. A: Commit


Leader
Client
Follower
Follower
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(R, savings_bal)
3. A: Lock(W, checking_bal)
4. A: Write(checking_bal, 100)
5. A: Lock(W, savings_bal)
6. A: Write(savings_bal, 100)
7. A: Commit
8. A: Unlock(checking_bal)
9. A: Unlock(savings_bal)

Leader 1 Client Leader 2

```
x = read(checking_bal)
if (x > 100) {
  y = read(savings_bal)
  write(checking_bal, x - 100)
  write(savings_bal, y + 100)
}
```

```
LOG:
 1. A: Lock(R, checking_bal)
 2. A: Lock(W, checking_bal)
 3. A: Write(checking_bal, 100)
 4. A: Commit
 4. A: Unlock(checking_bal)
```

```
LOG:
 1. A: Lock(R, savings_bal)
 2. A: Lock(W, savings_bal)
 3. A: Write(savings_bal, 100)
 4. A: Prepare
 5. A: Commit
 6. A: Unlock(savings_bal)
```

How can we get fast reads?

R/W transactions are complicated!

- And slow

Can we do fast, lock-free reads?

- Real time to the rescue

TrueTime

API that exposes real time, with uncertainty

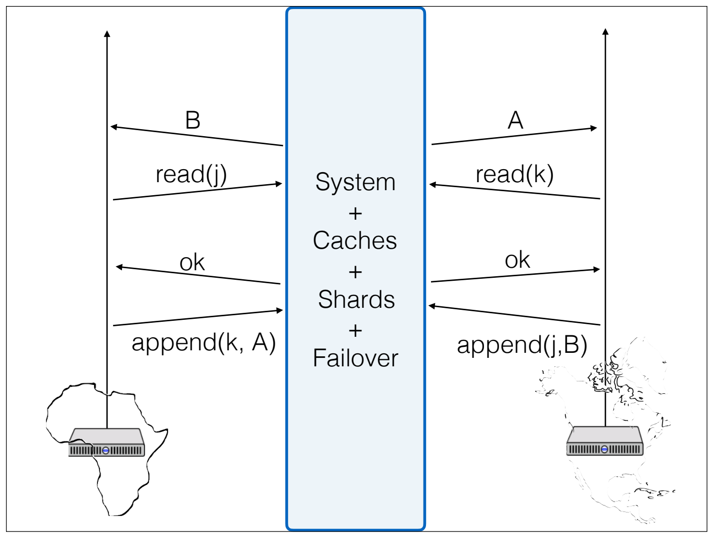
{earliest: *e*, latest: *l*} = TT.now()

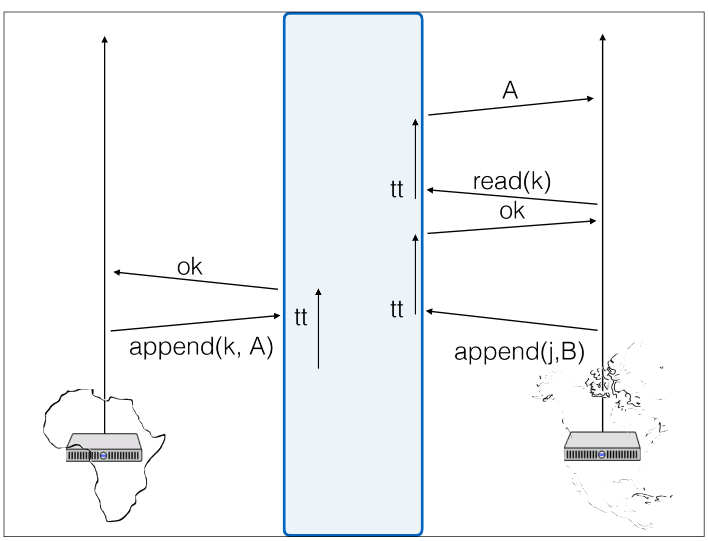
"Real time" is between **earliest** and **latest**

Time is an illusion; lunchtime, doubly so

If I call TT.now() on two nodes simultaneously, intervals *guaranteed* to overlap!

If intervals don't overlap, the later one happened later!





TrueTime usage

Assign a timestamp to each transaction

- At each Paxos group, timestamp increases monotonically

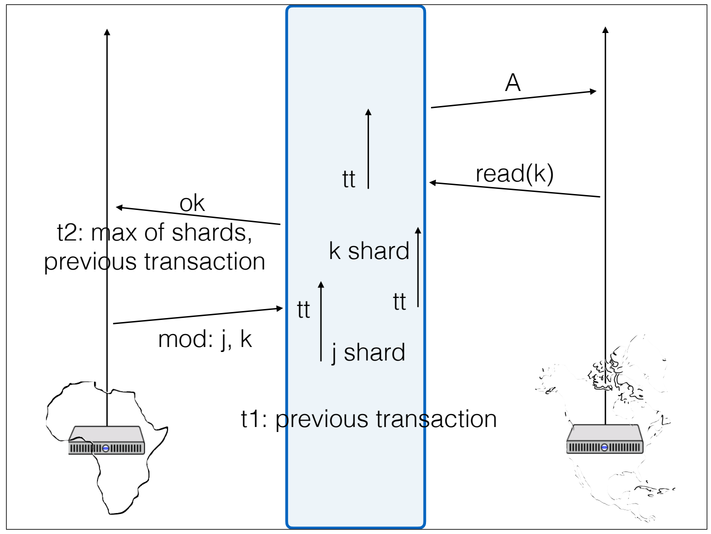
- Globally, if T1 returns before T2 starts, timestamp(T1) < timestamp(T2)

TrueTime usage

Timestamp for an RW transaction chosen by coordinator leader

Timestamps for R/W transactions is max of:

- Local time (when client request reached coord.)
- Prepare timestamps at every participant
- Timestamp of any previous local transaction



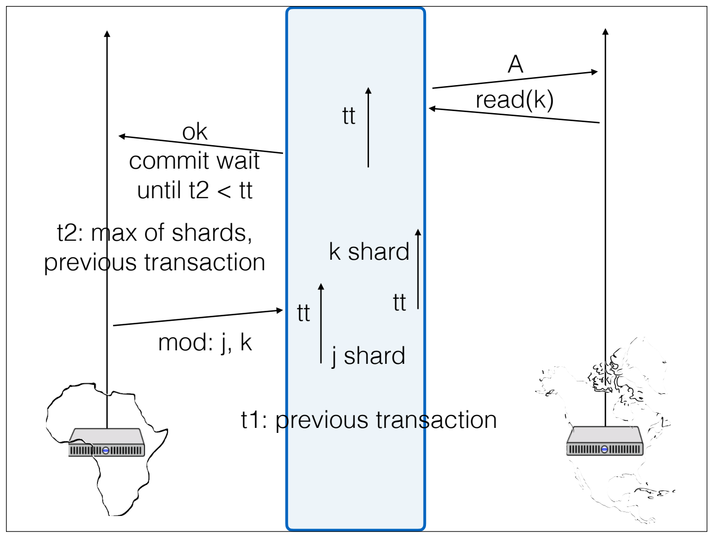
Commit wait

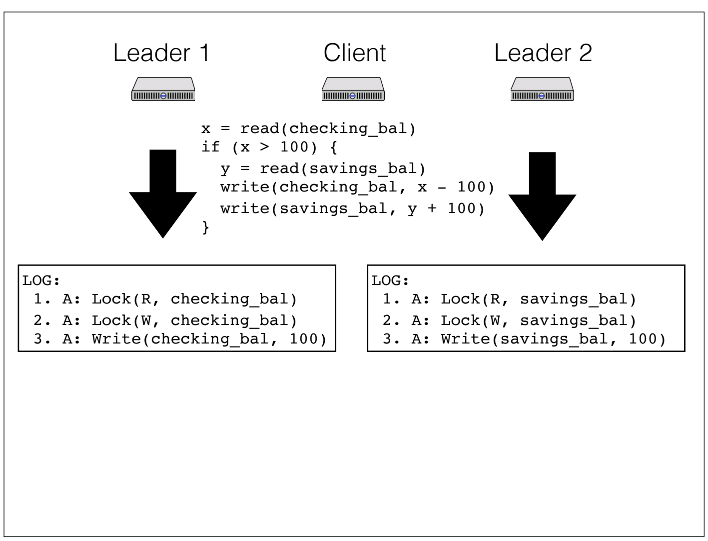
Need to ensure that all future transactions will get a higher timestamp

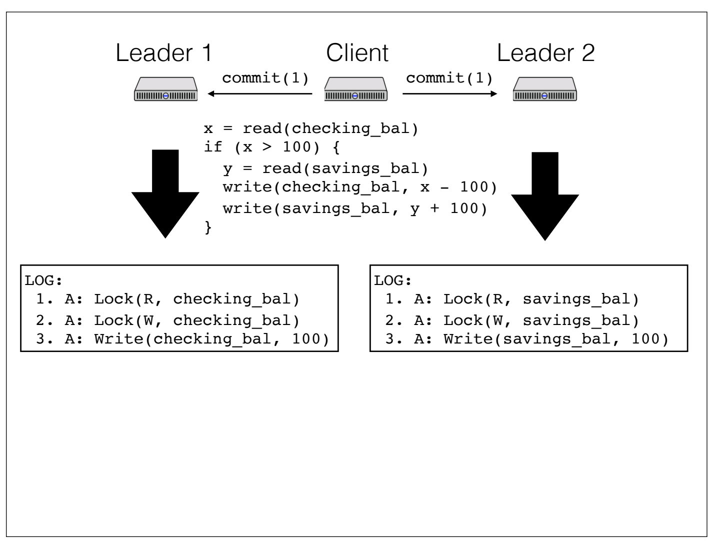
Therefore, need to wait until

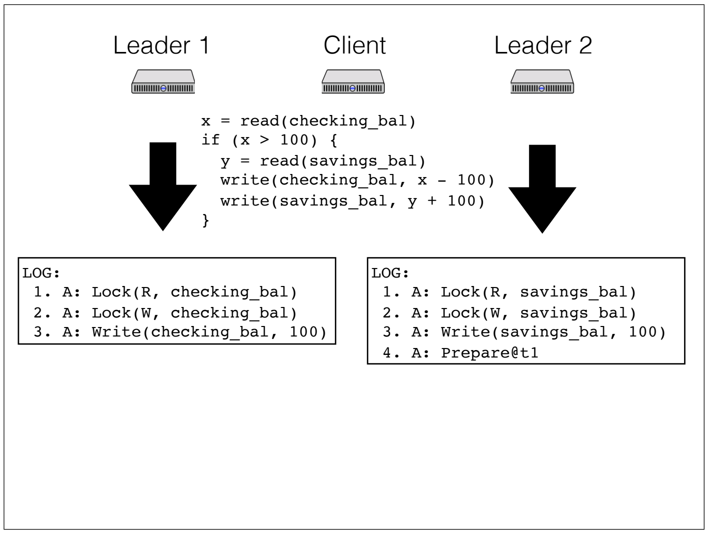
TT.now() > transaction timestamp

And only then release locks








Leader 1
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(W, checking_bal)
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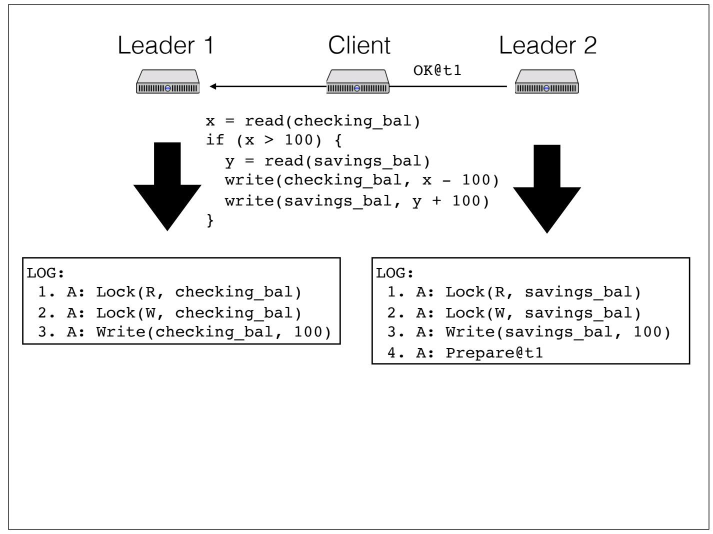
LOG:
1. A: Lock(R, savings_bal)
2. A: Lock(W, savings_bal)
3. A: Write(savings_bal, 100)
4. A: Prepare@t1


Leader 1
Client
Leader 2
OK@t1
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(W, checking_bal)
3. A: Write(checking_bal, 100)
LOG:
1. A: Lock(R, savings_bal)
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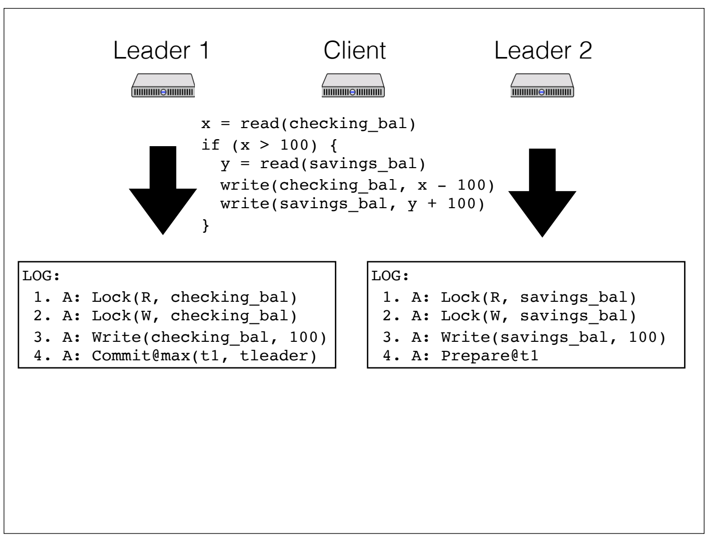
3. A: Write(savings_bal, 100)
4. A: Prepare@t1


Leader 1
Client
Leader 2
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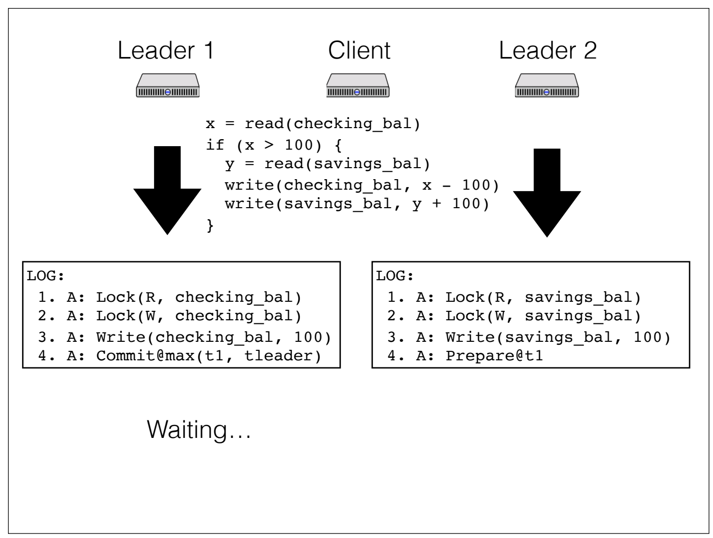
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(W, checking_bal)
3. A: Write(checking_bal, 100)
4. A: Commit@max(t1, tleader)
LOG:
1. A: Lock(R, savings_bal)
2. A: Lock(W, savings_bal)
3. A: Write(savings_bal, 100)
4. A: Prepare@t1


Leader 1
Client
Leader 2
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if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
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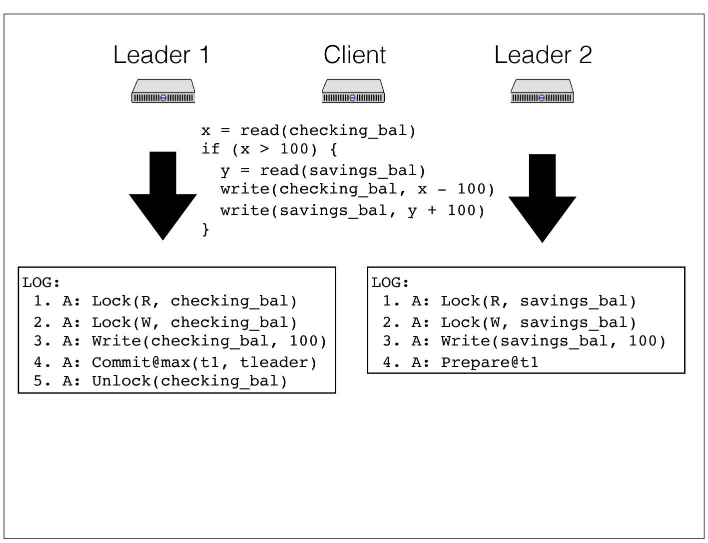
}
LOG:
1. A: Lock(R, checking_bal)
2. A: Lock(W, checking_bal)
3. A: Write(checking_bal, 100)
4. A: Commit@max(t1, tleader)
LOG:
1. A: Lock(R, savings_bal)
2. A: Lock(W, savings_bal)
3. A: Write(savings_bal, 100)
4. A: Prepare@t1
Waiting…


Leader 1
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
y = read(savings_bal)
write(checking_bal, x - 100)
write(savings_bal, y + 100)
}
LOG:
1. A: Lock(R, checking_bal)
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3. A: Write(checking_bal, 100)
4. A: Commit@max(t1, tleader)
5. A: Unlock(checking_bal)
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1. A: Lock(R, savings_bal)
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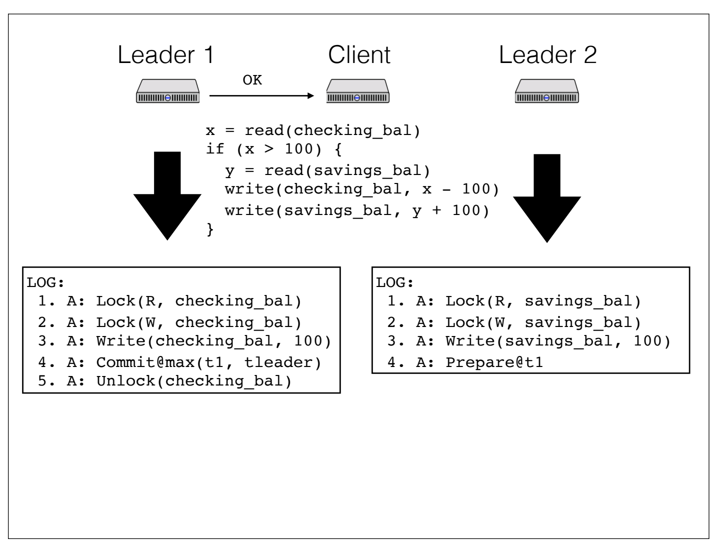
3. A: Write(savings_bal, 100)
4. A: Prepare@t1


Leader 1
OK
Client
Leader 2
x = read(checking_bal)
if (x > 100) {
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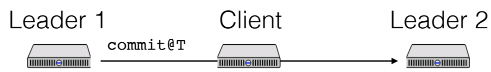


```
x = read(checking_bal)
if (x > 100) {
  y = read(savings_bal)
  write(checking_bal, x - 100)
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```

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```

```
LOG:
 1. A: Lock(R, savings_bal)
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```


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x = read(checking_bal)
if (x > 100) {
  y = read(savings_bal)
  write(checking_bal, x - 100)
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}
```

```
LOG:
 1. A: Lock(R, checking_bal)
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```
LOG:
 1. A: Lock(R, savings_bal)
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 3. A: Write(savings_bal, 100)
 4. A: Prepare@t1
 5. A: Commit@max(t1, tleader)
 6. A: Unlock(savings_bal)
```

TrueTime usage

Timestamps for RO transactions

- Client can choose a timestamp
- For external consistency, always safe to choose

`TT.now().latest`

A response from a replica is a promise: will never have a new transaction that commits before timestamp

Can read from any replica that has seen a Paxos write after timestamp

TrueTime implementation

GPS, atomic clocks

Armageddon masters and timeslave daemons

All local clocks synced with masters, and expose uncertainty to local apps

Assumptions made about local clock drift

Commit wait

- What does this mean for performance?
- Larger TrueTime uncertainty bound
  => longer commit wait
- Longer commit wait => locks held longer
  => can't process conflicting transactions
  => lower throughput
- i.e., if time is less certain, Spanner is slower!

What does this buy us?

- Can now do a read-only transaction at a particular timestamp, have it be meaningful
- Example: pick a timestamp T in the past,
  read version w/ timestamp T from all shards
  - since T is in the past, they will never accept a transaction with timestamp < T
  - don't need locks while we do this!
- What if we want the current time?

What if TrueTime fails?

- Google argument: picked using engineering considerations, less likely than a total CPU failure
- But what if it went wrong anyway?
  - can cause very long commit wait periods
  - can break ordering guarantees, no longer externally consistent
  - but system will always be serializable: gathering many timestamps and taking the max is a Lamport clock

Conclusions

What's cool about Spanner?

- Distributed transactions with decent performance
- What makes that possible?
- Read-only transactions with great performance
- What makes that possible?

Clocks are a form of communication!

Discussion

CPU errors and bad clocks

- When does Google discover errors?

Disaster preparedness

Is Spanner's complexity scary?

What happens if there is high clock skew?

- If we know about it
- If we don't?

Timestamp details

- Coordinator actually collects several TrueTime timestamps:
  - timestamps from when each shard executed prepare
  - timestamp that coordinator received commit request from client
  - highest timestamp of any previous transaction
- Actually picks a timestamp greater than max of these, waits for it to be in the past