Distributed databases: Spanner (Google) and Aurora (AWS)

Jinyang Li

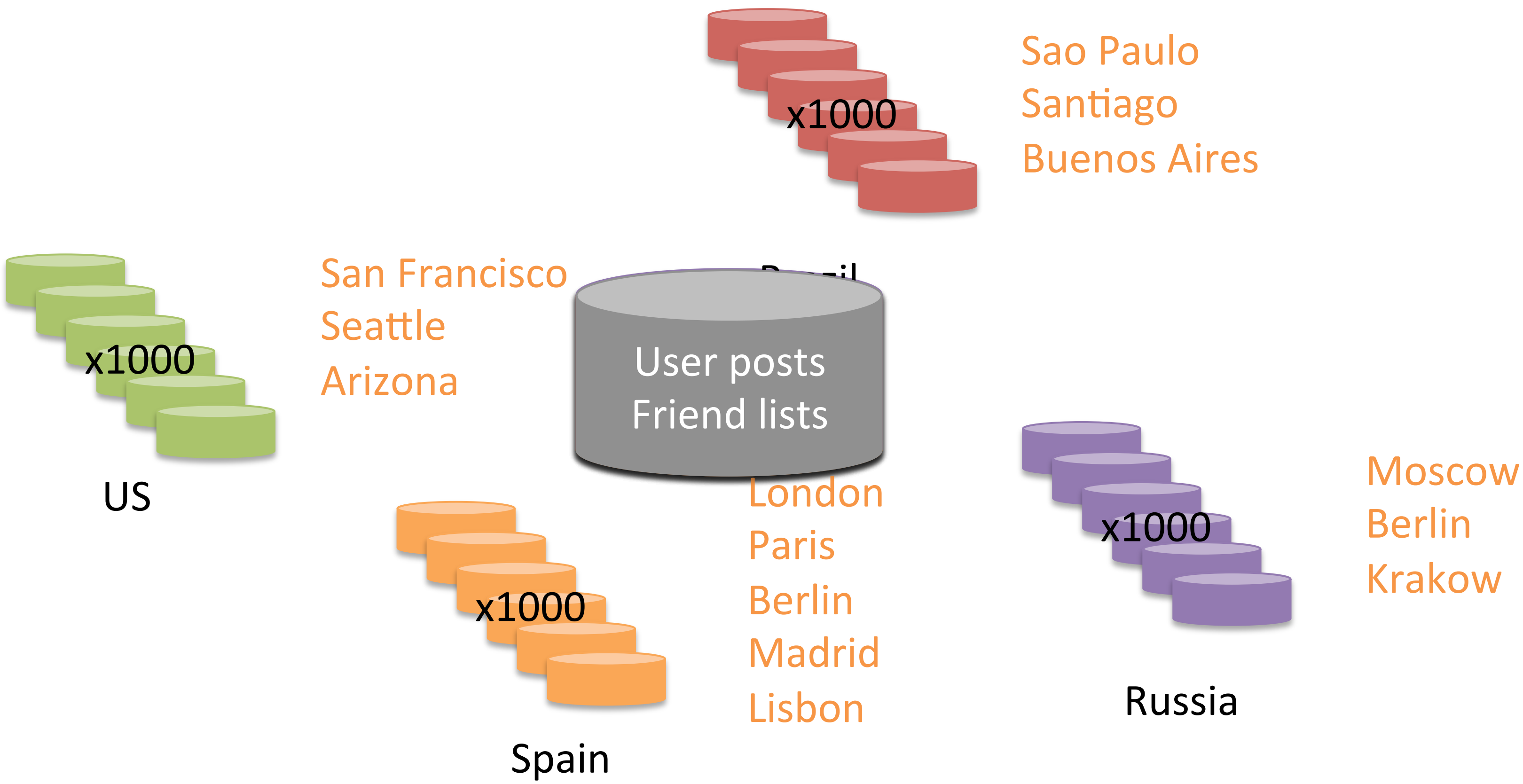
What have we learnt last time

- ACID transactions
  - Atomicity (against crashes)
  - Isolation (semantics in the face of concurrency)
- Techniques for achieving A and I
  - A: WAL logging (REDO logging)
  - I: 2 phase locking for serializablity
- Distributed transaction commit
  - 2-phase commit
  - Not fault tolerant

Spanner's goal

- A global, scalable database
  - General-purpose transactions (ACID)
  - SQL query language
  - Schematized tables
  - Semi-relational data model
- Global: data is replicated in multiple data centers
- Scalable: increase transaction read/write throughput by adding more machines
  - no more sharded mysql

Spanner's setup: example social networking app



How to support distributed transactions? A strawman

- Starting point: A simple impl. of local txs

```
struct DB {
  data sync.Map[string]string
  locks sync.Map[string]LockStatus
}
struct Tx {
  tid int64
  writeset map[string]string
  readset map[string]interface{}
}
```

```
func (s *DB) StartTx() *Tx {
   return &Tx{rand.Int63()}
}

func (s *DB) Read(tx *Tx) {

}

func (s *DB) Write(tx *Tx) {

}

func (s *DB) CommitTx(tx *Tx) {

}
```

How to support distributed transactions? A strawman

- Starting point: A simple impl. of local txs

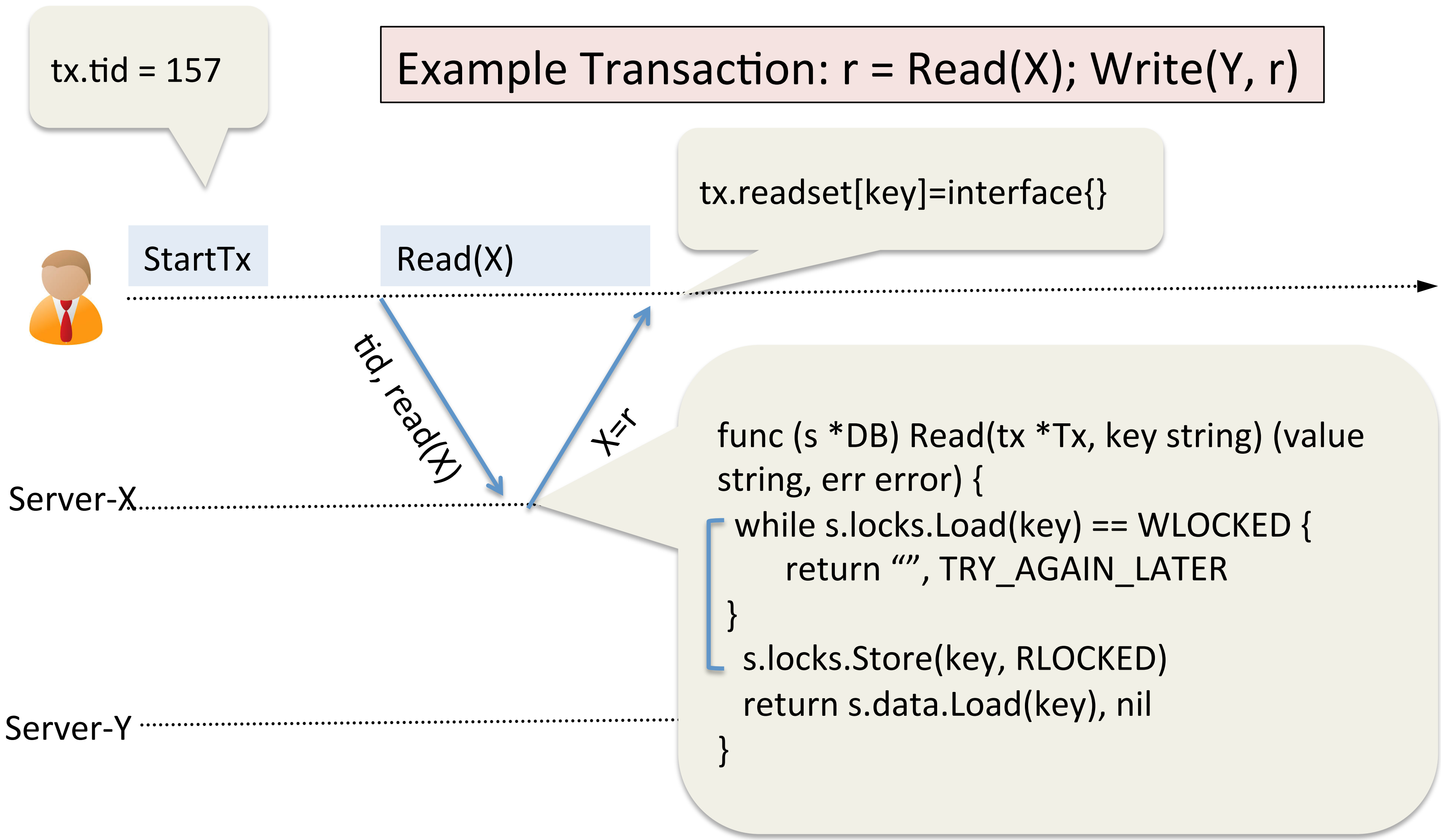
```
func (s *DB) Read(tx *Tx, key string) {
  while s.locks.Load(key) == WLOCKED {
     Wait()  //deadlock detection needed
  }
  s.locks.Store(key, RLOCKED)
  tx.readset[key] = interface{}
  return s.data[key]
}
```

```
func (s *DB) Write(tx *Tx, key, value string)
{
   tx.writeset[key]=value
}
```

```
func (s *DB) CommitTx(tx *Tx) {
  for k, v := range tx.writeset {
    while s.locks.Load(key) != IDLE {
       Wait() //deadlock detection needed
    }
    s.locks.Store(key, WLOCKED)
  }
  s.AppendToLog(tx, "Committed")
  for k, v := range tx.readset {
     s.locks.Store(k, IDLE)
  }
  for k, v := range tx.writeset {
    s.data.Store(k, v)
     s.locks.Store(k, IDLE)
  }
}
```

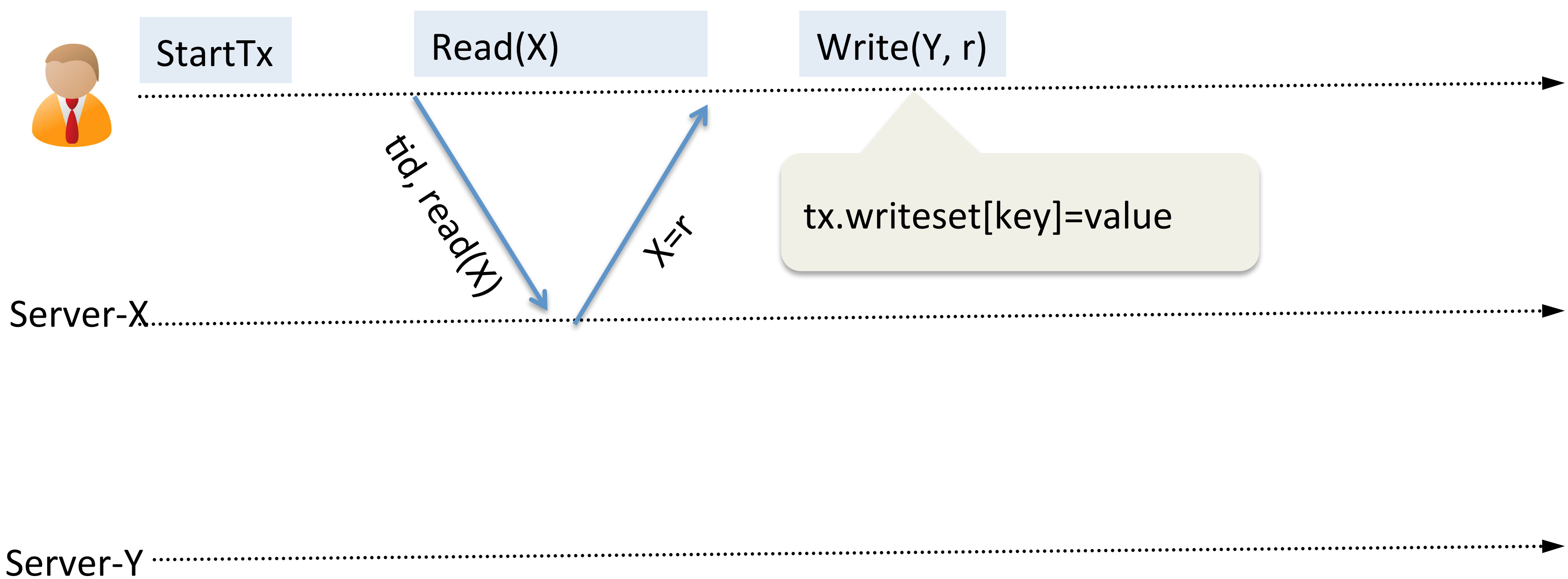
* use mutex to protect the atomicity of code block marked by [

Extending local transactions to distributed setting



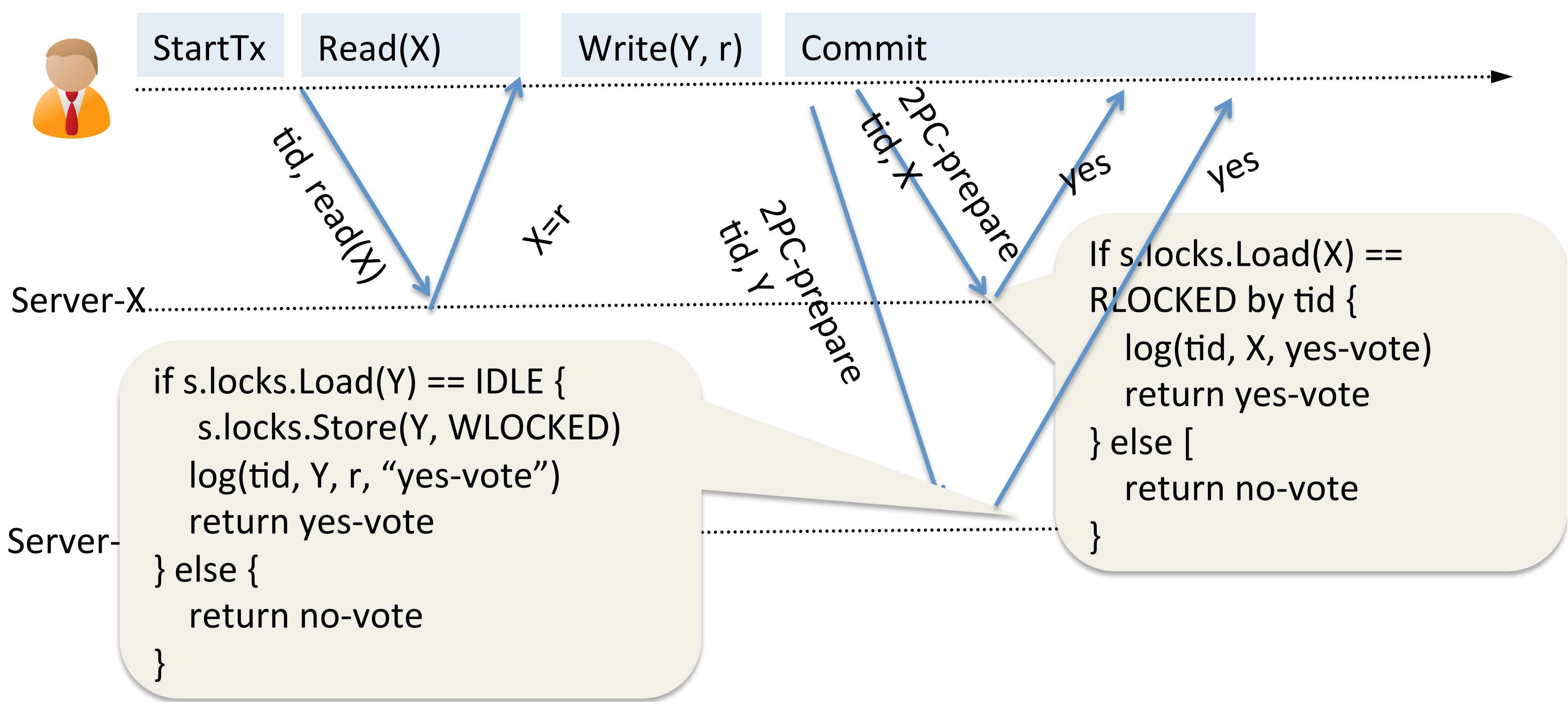
Extending local transactions to distributed setting

Example Transaction: r = Read(X); Write(Y, r)



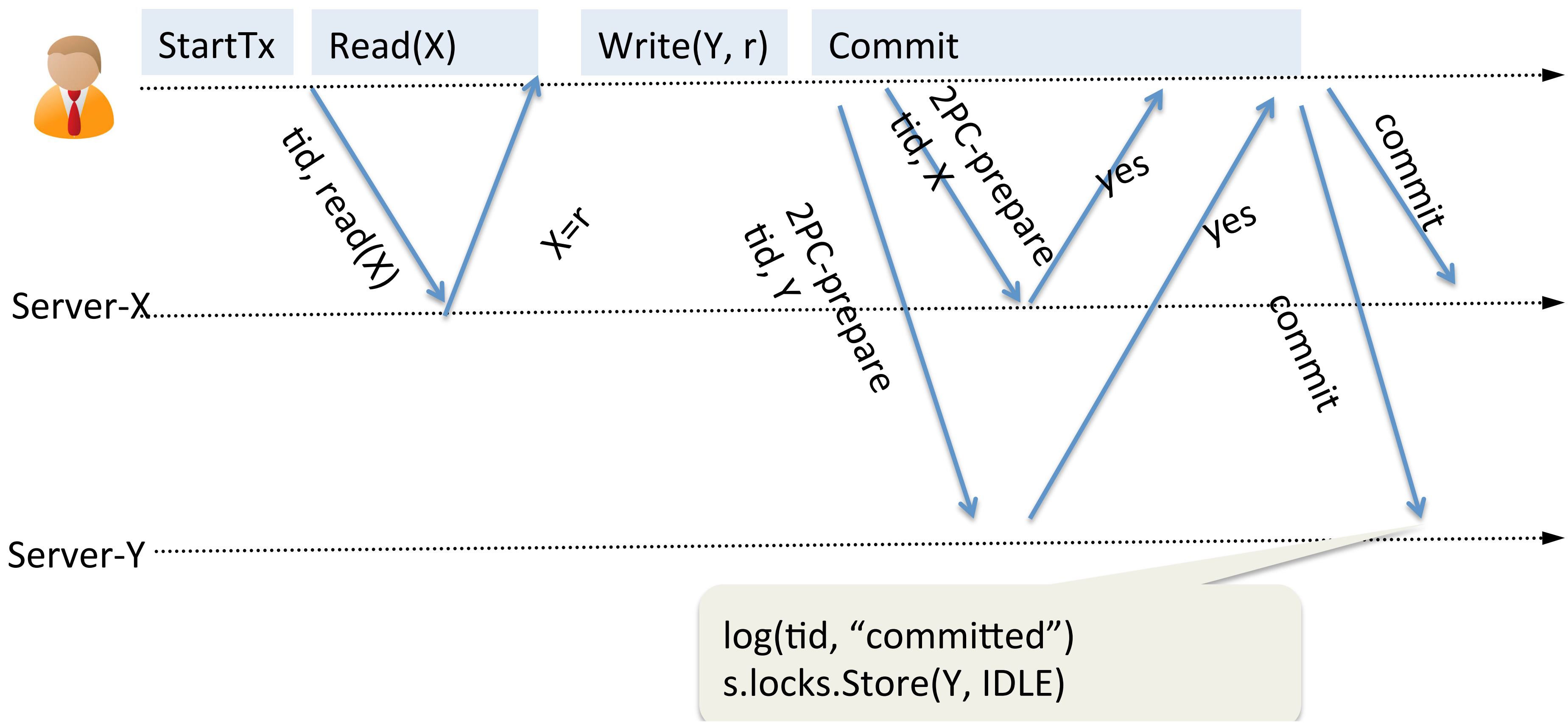
Extending local transactions to distributed setting

Example Transaction: r = Read(X); Write(Y, r)



Extending local transactions to distributed setting

Example Transaction: r = Read(X); Write(Y, r)



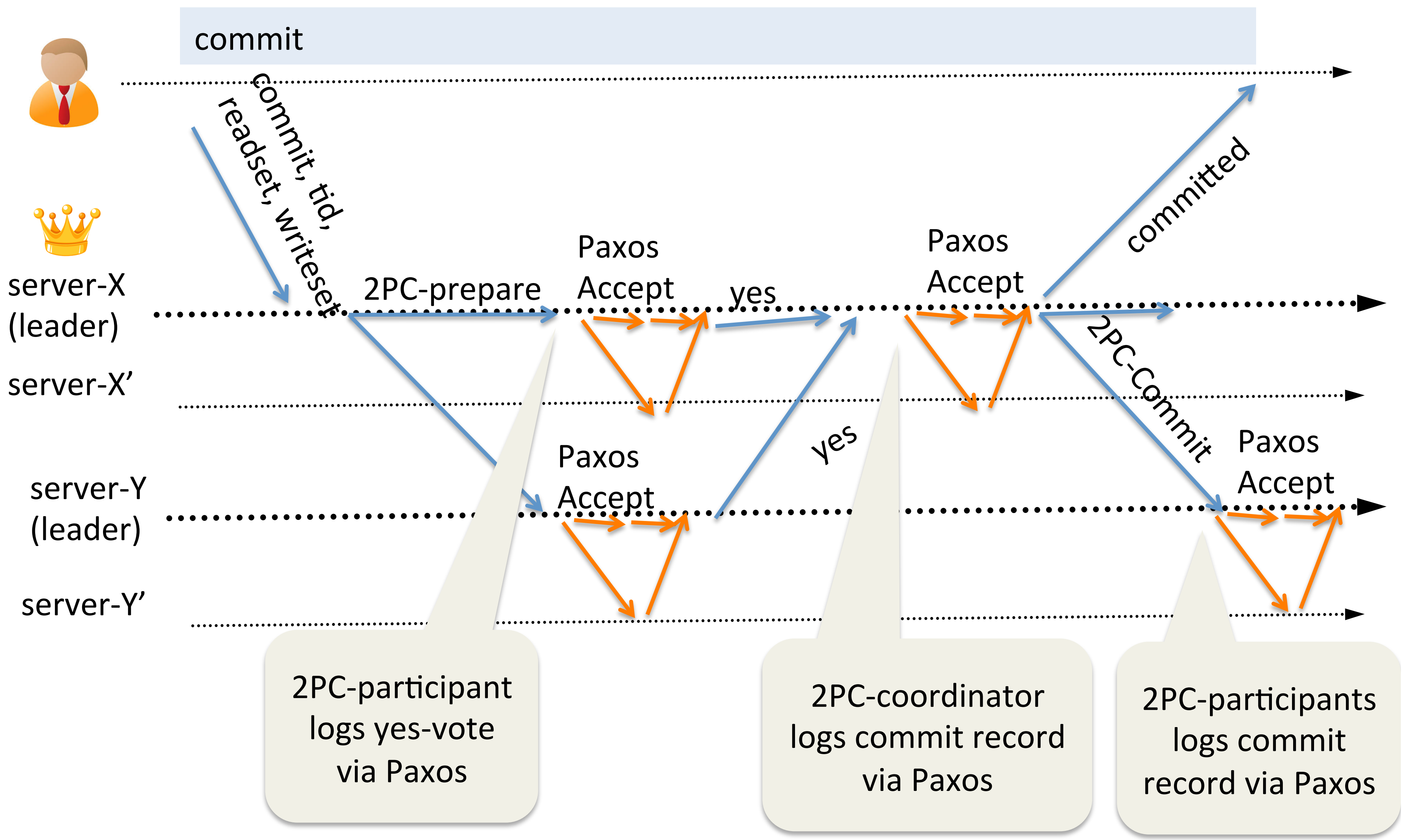
What can go wrong?

- Client fails after acquiring read locks
- Spanner's solution:
  - Client sends keep-alive to servers holding read locks
  - Server times out held read locks
  - 2PC-prepare checks that read locks are still held before voting yes

What can go wrong?

- What if 2PC encounters irrecoverable failure?
- Spanner’s solution:
  - replicate both data and critical 2PC state using Paxos

2PC with Paxos



Other details

- Must the lock table be replicated via Paxos?
- Spanner's solution:
  - No, lock table is only maintained by (Paxos) leader
  - Upon leader change
    - read locks are discarded (safe because 2PC-prepare checks for validity of read locks)
    - write locks are recovered (by scanning Paxos log for 2PC-prepare messages without corresponding 2PC-commit)

Spanner’s biggest innovation

- Strictly serializable read-only transactions
- Why read-only transactions?
  - Many application workloads are read-heavy
  - Facebook’s read vs. write ratio is 30:1 [SIGMETRICS’12]
- Our naive implementation is inefficient
  - read-only txs block read-write transactions
  - esp. bad if read-only txs read lots of objects

How to implement efficient read-only transactions

- Old idea: multi-version concurrency control [Reed Ph.D. thesis, 1978]
- Write-txs do not overwrite data, but write new versions of data
- Read-txs determine which versions of data to read using a timestamp

Example MVCC (local implementation)

```
struct RWTx {
  tid int64
  writeset map[string]string
  readset map[string]interface{}
}
```

```
func (s *DB) StartRWTx() *RWTx {
   //same as before
}
func (s *DB) ReadRWTx(tx *RWTx) {
      // same as before
}
func (s *DB) WriteRWTx(tx *RWTx) {
   // same as before
}
func (s *DB) CommitRWTx(tx *RWTx) {
   //
}
```

```
struct ROTx{
  readTS time.Time
}
```

```
func (s *DB) StartROTx() *ROTx {
}
func (s *DB) ReadROTx(tx *ROTx) {
      // same as before
}
```

Local MVCC (RW transactions)

```
func (s *DB) CommitRWTx(tx *RWTx) {
  for k, v := range tx.writeset {
     while s.locks.Load(key) != IDLE {
        Wait()
     }
     s.locks.Store(key, WLOCKED)
  }
  s.AppendToLog(tx, commitTS, "Committed")
  for k, v := range tx.readset {
     s.locks.Store(k, IDLE)
  }
  for k, v := range tx.writeset {
     s.data[k] = append(
           s.data[k], Record{commitTS, v})
     s.locks[k] = IDLE
  }
}
```

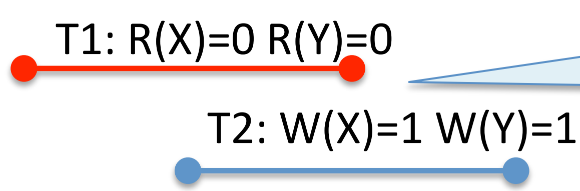
commitTS := time.Now()

commitTS represents the serialization order

Local MVCC (RO transactions)

```
func (s *DB) StartROTx() *ROTx {
    return &ROTx{time.Now()}
}
```

```
func (s *DB) ReadROTx(tx *ROTx, key string) string {
  items := s.data.Load(key) // items is an array of data from old to new
  // read the largest version smaller than tx.readTS
  for i := len(items)-1; i >= 0; i --   {
     if items[i].commitTS < tx.readTS {
         return items[i].data
     }
  }
   return “”
}
```



T1 blocks T2
under 2PL but
not under MVCC

Local MVCC (RO transactions)

```
func (s *DB) StartROTx() *ROTx {
    return &ROTx{time.Now()}
}
```

```
func (s *DB) ReadROTx(tx *ROTx, key string) string {
for  {
   items, lockStatus := atomically retrieve items and lockStatus for the key
   if lockStatus == IDLE { break }
}

for i := len(items)-1; i >= 0; i --   {
      if items[i].commitTS < tx.readTS {
          return items[i].data
      }
  }
   return ""
}
```

lock X, lock Y, commitTS=1, W(X)=1,   unlock X,   W

readTS=2, R(X)=1, R(Y)=0??

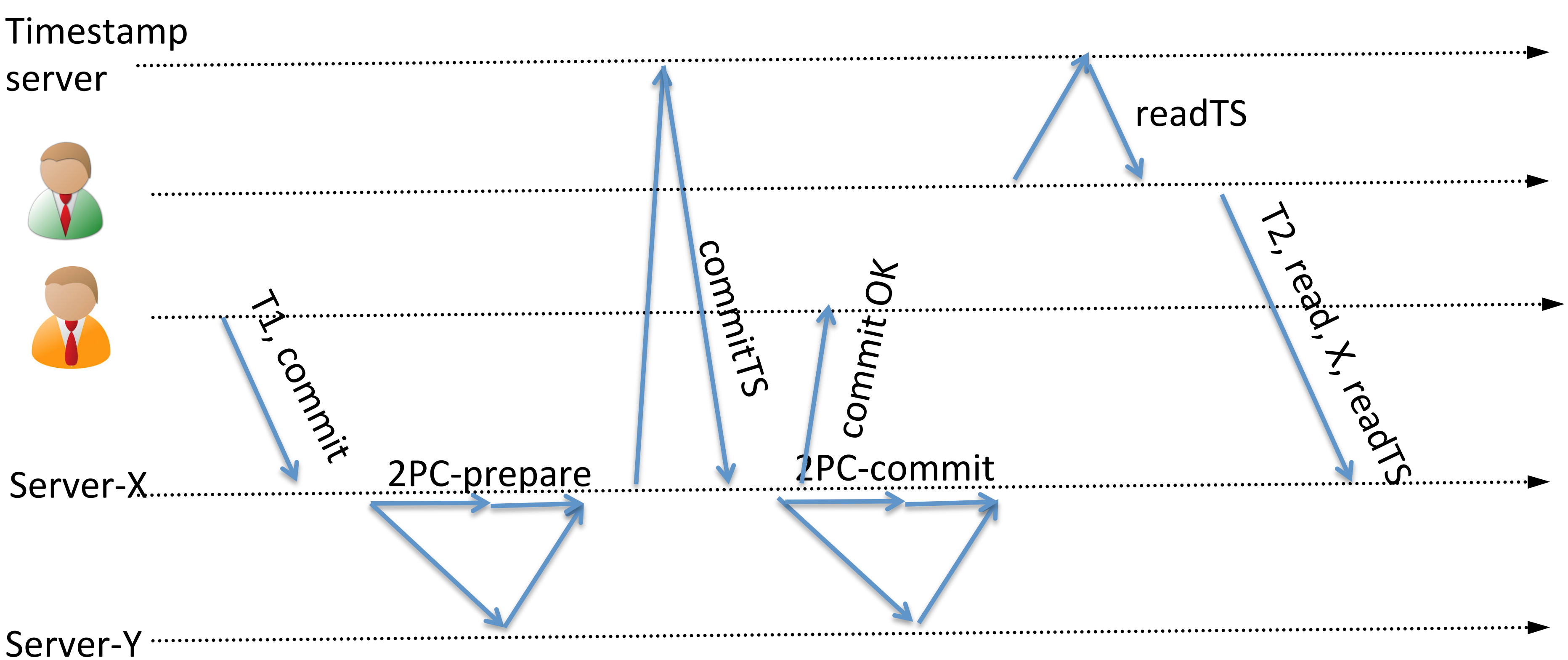
Problem: Not all transactions less than readTS has finished writing

Extending MVCC to distributed setting

- Timestamp requirement for strict serializability:
  - Timestamp for RW transactions obey the serialization order
  - Timestamp of a RO transaction must be larger than any committed RW transactions

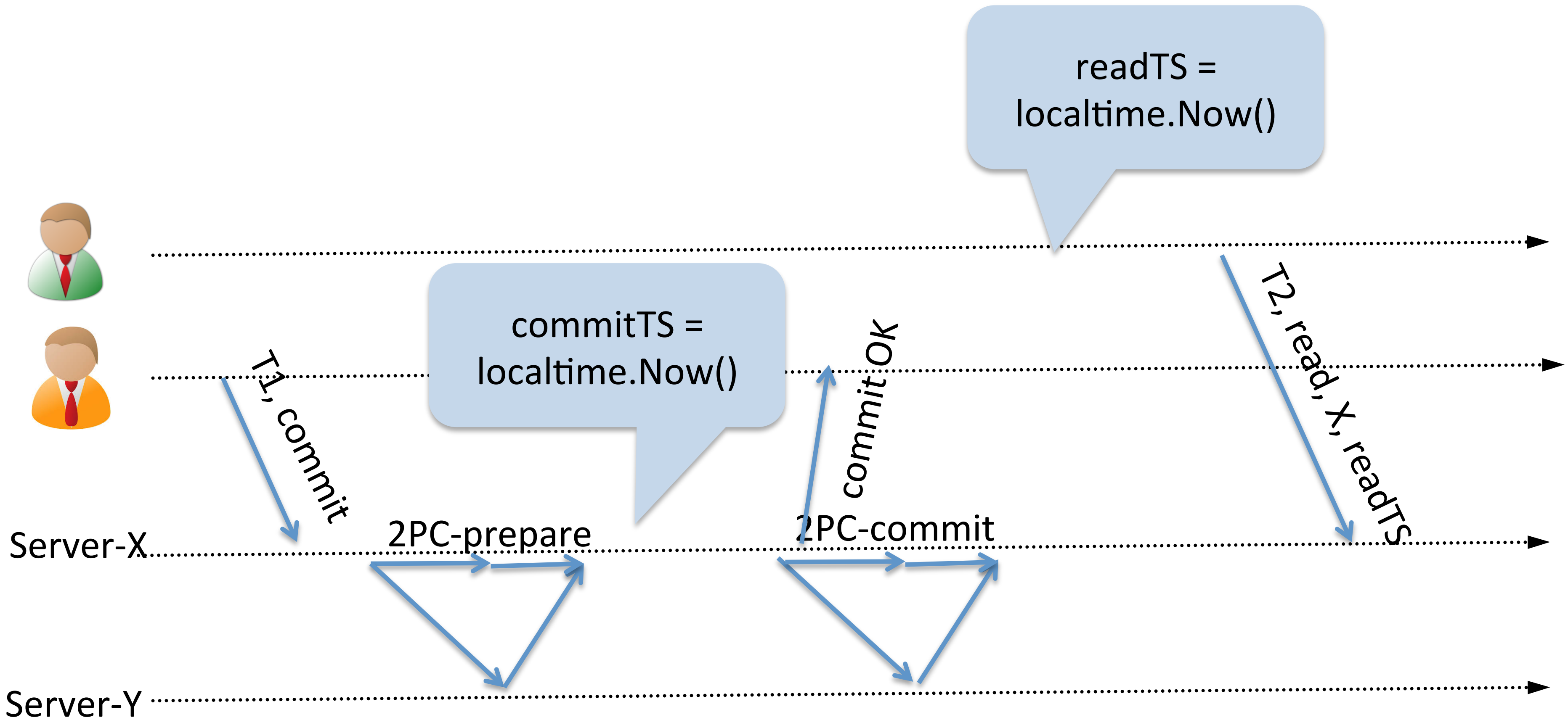
Extending MVCC to distributed setting

- OK if there's a centralized timestamp server



Omitted arrows: Paxos writes to persist "yes-vote"s and commit record of 2PC coordinator (X) and particicpant (Y)

What's wrong if using clocks from different servers?



Problem: T2 starts after T1 finishes, but T2.readTS might be smaller than T1.commitTS due to clock difference

Why doesn't Spanner use a central timestamp server?

- Central performance bottleneck?
- Added Latency
  - A server in european datacenter need to contact the timestamp server in US data center

Spanner's time primitive: TrueTime

- Core API: tt.now()
  - It returns an error bound [earliest, latest], so that earliest < t_abs (true time) < latest
  - Different servers have different error bounds
- Auxilary APIs: tt.After(t)
  - tt.After(t) returns true if t is after true time
- TrueTime is implemented by synchronizing with time masters (GPS clock & atomic clock)

How RW transactions use TrueTime

- Coordinator sends 2PC-prepare:
  - each participant server attaches its tt.Now().latest
- If all vote yes, coordinator chooses commitTS as:
  - max(timestamps of 2PC-prepare replies, tt.Now().latest)
- Spanner-commit-wait→ Coordinator waits till tt.After(commitTS) is true
- Coordinator logs commit status, then sends 2PC-commit

How RO transactions use TrueTime

- A RO transaction's readTS is:
  - readTS = tt.Now().latest
- Why is this correct?
  - Prove: if T2 (ro) starts after T1 (rw) finishes, then T2.readTS > T1.commitTS

T2.readTS > T2's actual start time

because of tt.Now()'s error bound guarantee

T2's actual start time > T1's actual finish

T1's actual finish time > T1.comm

because of coordinator performs commit-wait

Spanner contains other optimizations

- Allow reads by RO transaction to be done at any replica, not just the Paxos leader
- Avoid blocking reads for single-read RO transaction

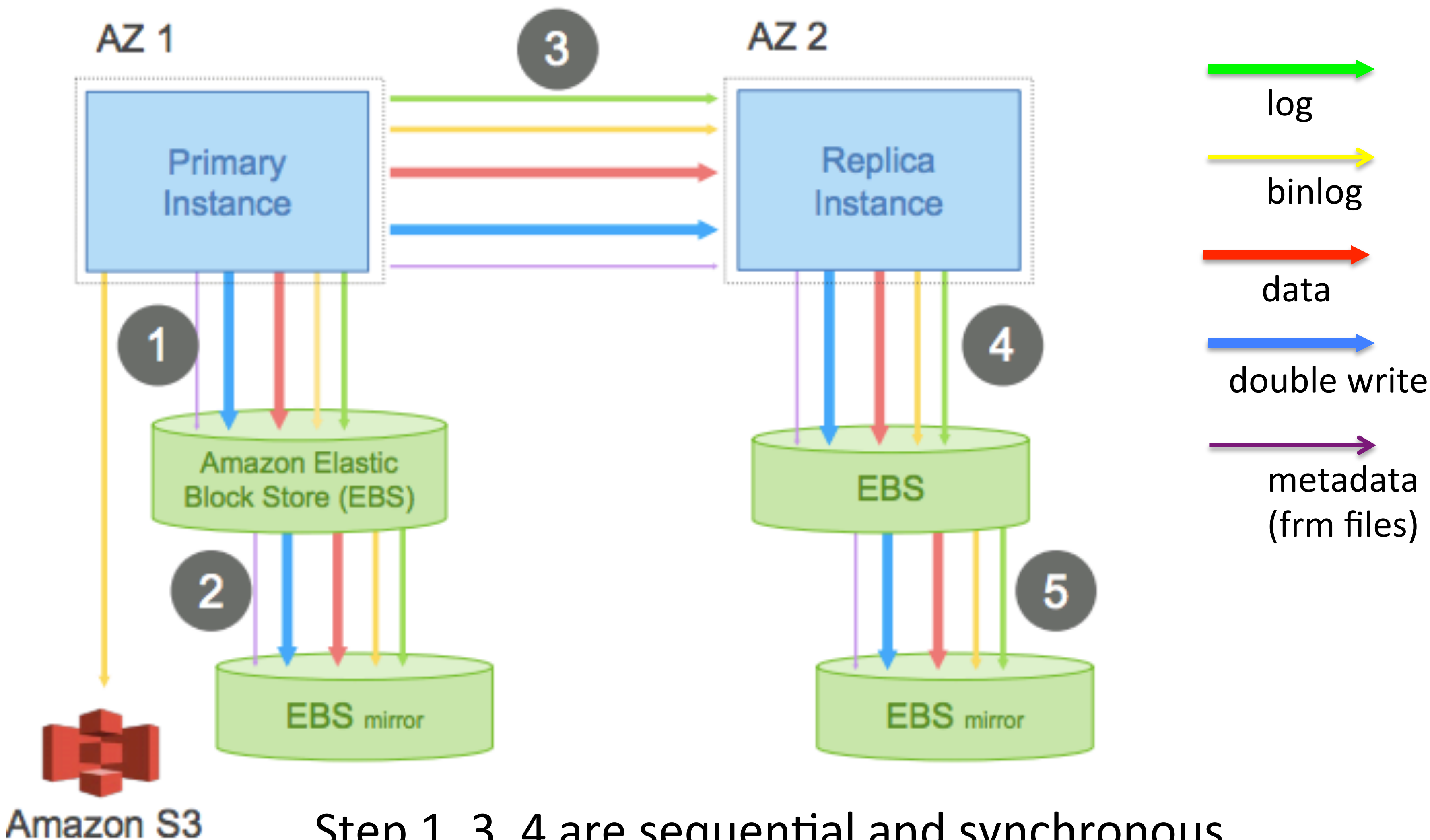
Spanner's performance

- Setup: machines are within 1ms RTTs
- Best-case RW transaction latency (a single 2PC participant)
  - mean: 17ms, 99-th: 75ms
- Commit-wait latency: 5ms, Paxos latency: 9ms

Amazon's Aurora

- Takes a very different approach than Spanner
- No-goals:
  - No infinite scalability → No distributed concurrency control
- Yes-goals:
  - High availability in the face of machine crash
  - High performance

Aurora's motivation: Cloud customers running MySQL over EBS



Step 1, 3, 4 are sequential and synchronous
(step 3: block-level software mirroring)

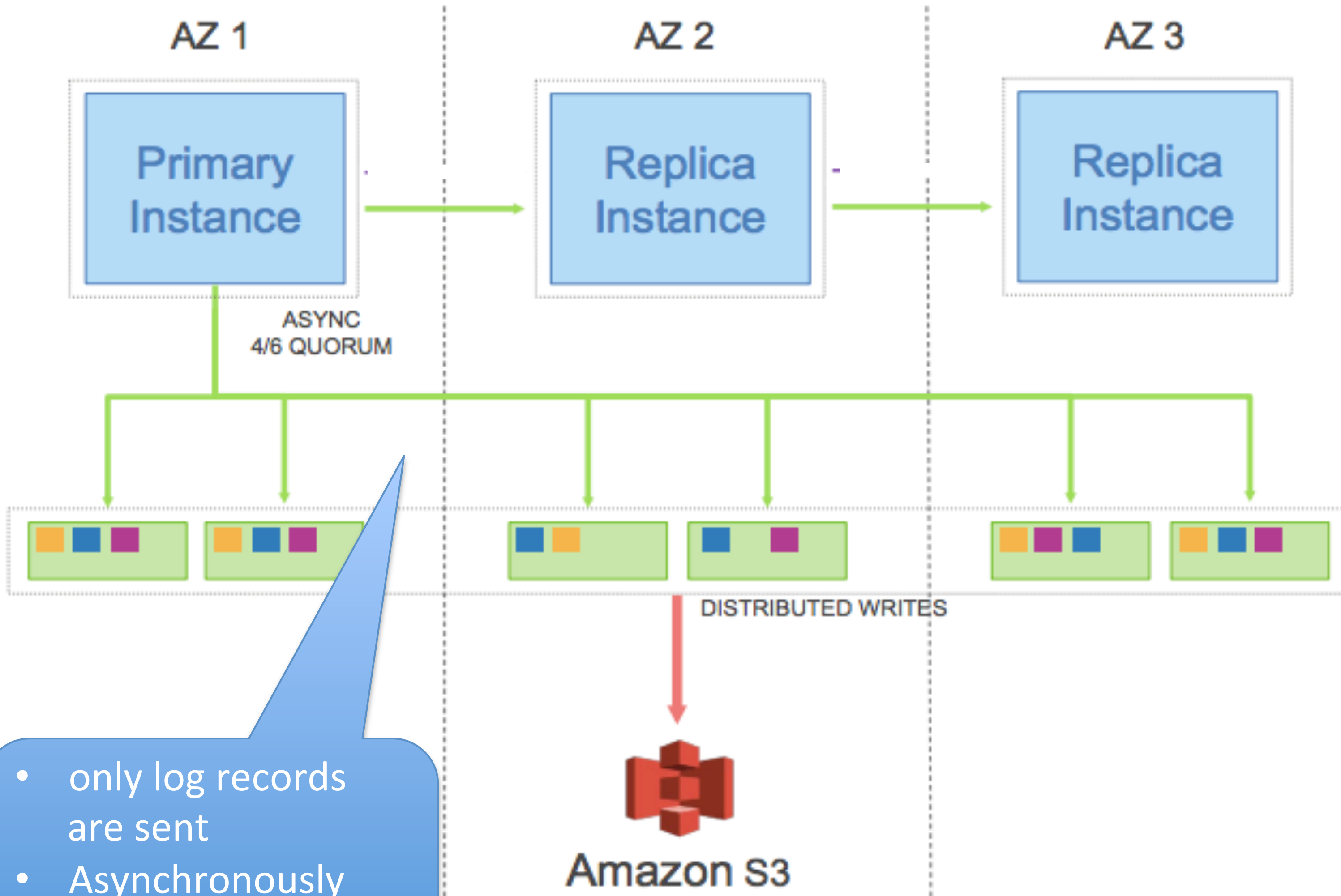
Performance negatives of MySQL over EBS

- Steps (1, 3, 4) are sequential and synchronous:
  - amplifies latency and jitter
- Many writes per user operation: e.g. double writes
  - Write-only workload benchmark
  - 7.4 I/Os per transactions

Aurora's high level design

- Goal:
  - Do fewer IOs, less network traffic
  - minimize synchronization points
- The main insight:
  - REDO log captures db state
  - replicate the REDO log
    - offload REDO processing to storage
- Replicate REDO log using Raft/Paxos?
  - unnecessary: Aurora has a single writer
  - insufficient performance: log should be striped to for better performance

Aurora's design



- only log records are sent
- Asynchronously replicated to 4 out of 6 replicas

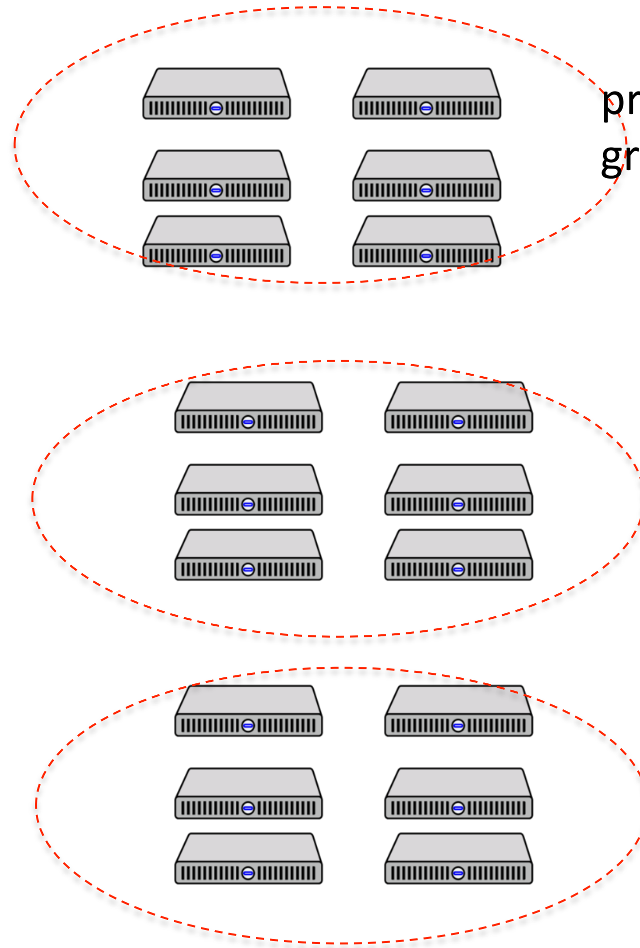
Replicas across Availability Zone

- 6 replicas across 3 availability zones
  - write-quorum = 4, survives either of the two failure scenarios below:
    - an entire AZ is down
    - 2 replicas are down
  - read-quorum = 3, survives either of the two failure scenarios below:
    - an entire AZ + another replica down
    - 3 replicas down

Segmented storage

- Database volume is partitioned into 10GB segments
  - 10TB db → 1000 segments
- Each segment → a potentially different replica set (Protection Group)
- Why segmented stroage?
  - spread storage and processing over more nodes
  - faster recovery time

Segmented storage and REDO log replication



protection group

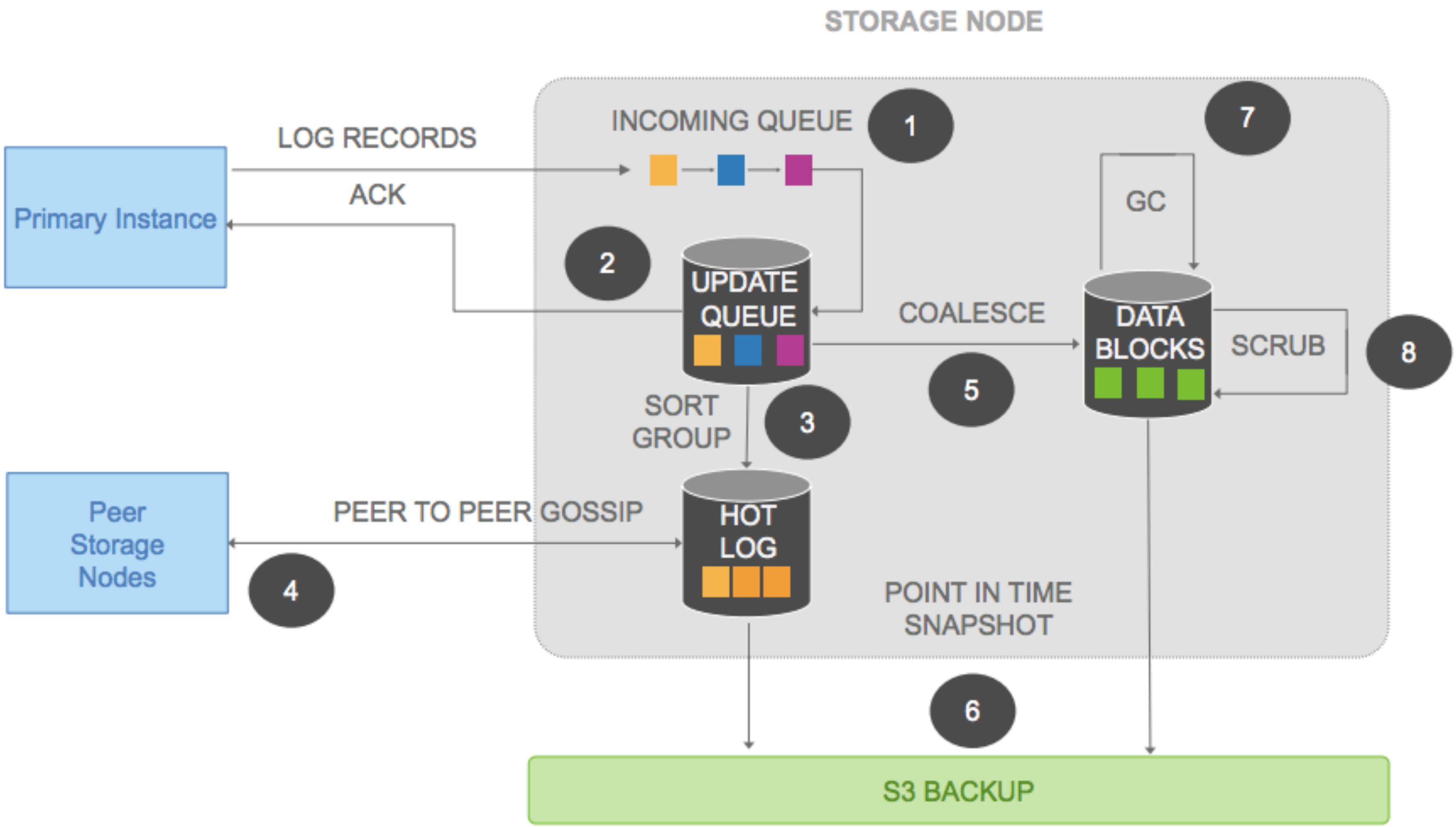
database (aka primary instance)

LSN=1, PageNo=10..., insert record at offset 555

LSN=2, PageNo=33..., insert record at offset 123

LSN=3, PageNo=56..., delete record at offset 10

Storage node processing



Step 2: Persist queue to disk and acknowledge

Step 3: Identify gaps in log
(each record contains LSN of previous record for that PG)

Aurora's failure recovery

- Primary instance crashes, external service promotes another to be the new primary
- New primary needs to establish a consistent state
  - old primary did not complete write-quorum for some records → log may have holes
  - Only the last log record of a (mini)transaction represent consistent state

Aurora failure recovery

- New primary reads from a quorum in every PG to calculate VDL (volume durable LSN)
  - the highest consistent LSN below which all records have been received
- New primary issues a truncation request with range [VDL+1, VDL+Threshold]
  - all storage nodes discard log records in the range
- New primary performs UNDO recovery to unwind partial transactions
- storage nodes replay log on demand when handling read requests

Summary

- Distributed transactions in Spanner
  - 2PL + 2PC with Paxos for fault tolerance
  - use MVCC for efficient read-only transaction
  - Truetime ensures strict serializability without centralized timestamp server
- Distributed transactions are scalable, but not efficient
- Aurora has a single database writer, using striped replicated storage for REDO processig

Midterm statistics