ZooKeeper: Wait-Free Coordination for Internet-Scale systems

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These slides are slightly modified versions from the original slides by:

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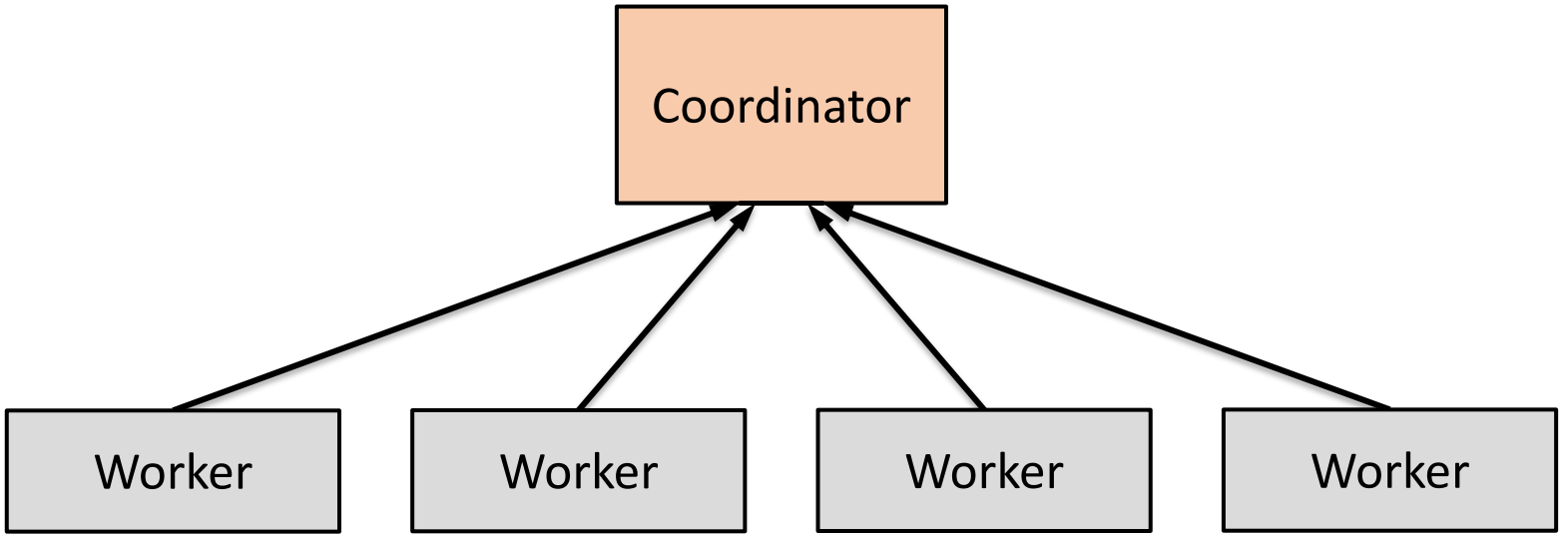
Flavio Junqueira and Benjamin Reed (Yahoo! Research)

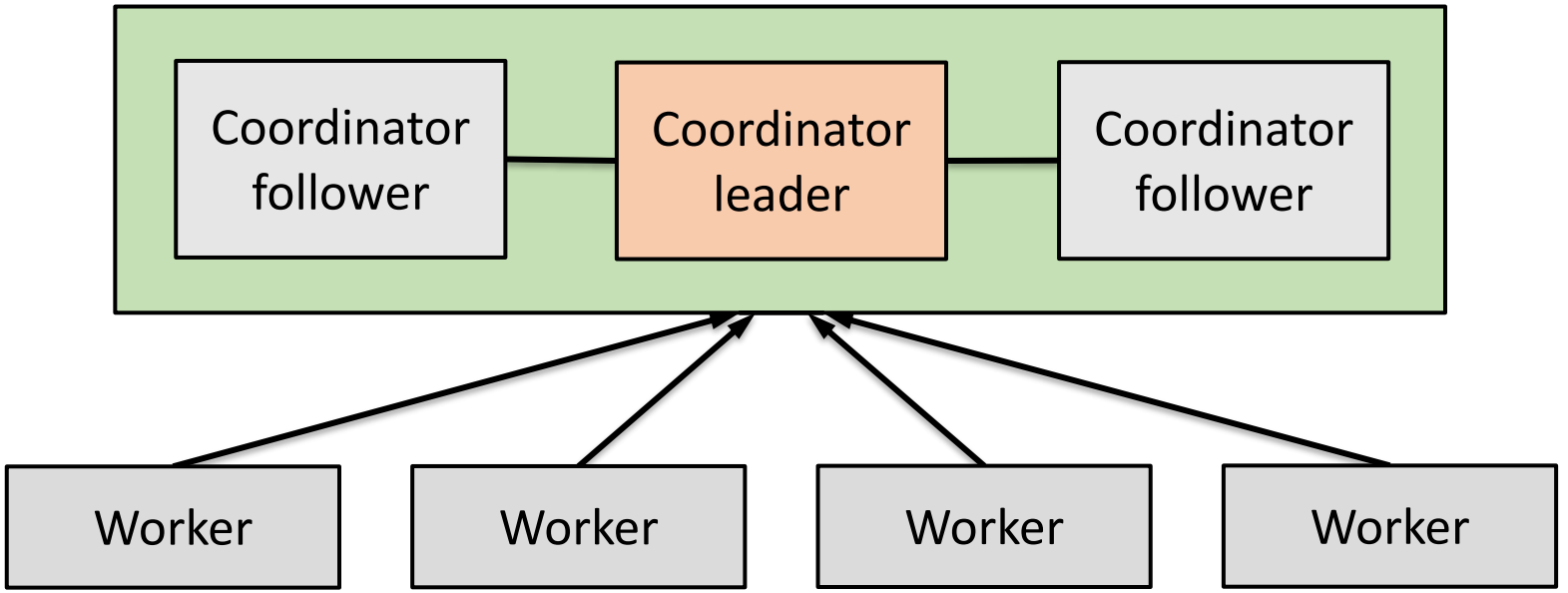
Why Coordination?

- Group membership
- Leader election
- Dynamic configuration
- Status monitoring
- Queuing
- Barriers
- Critical sections

Classic coordination

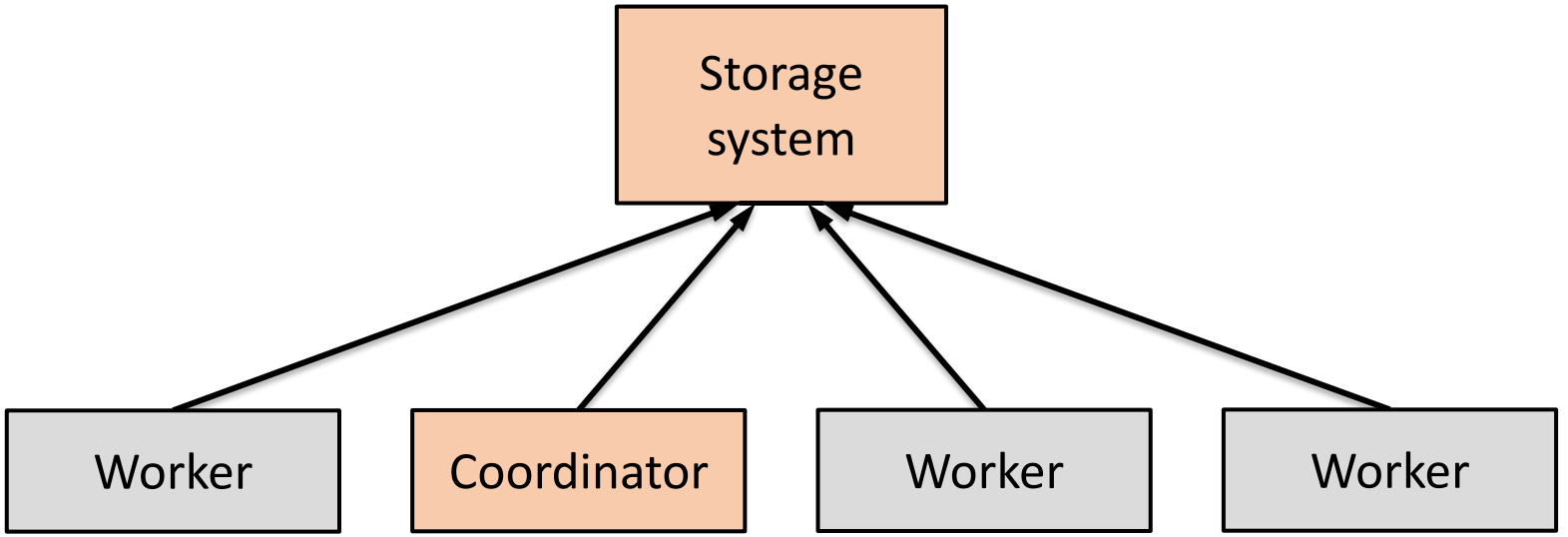


Fault-tolerant coordination



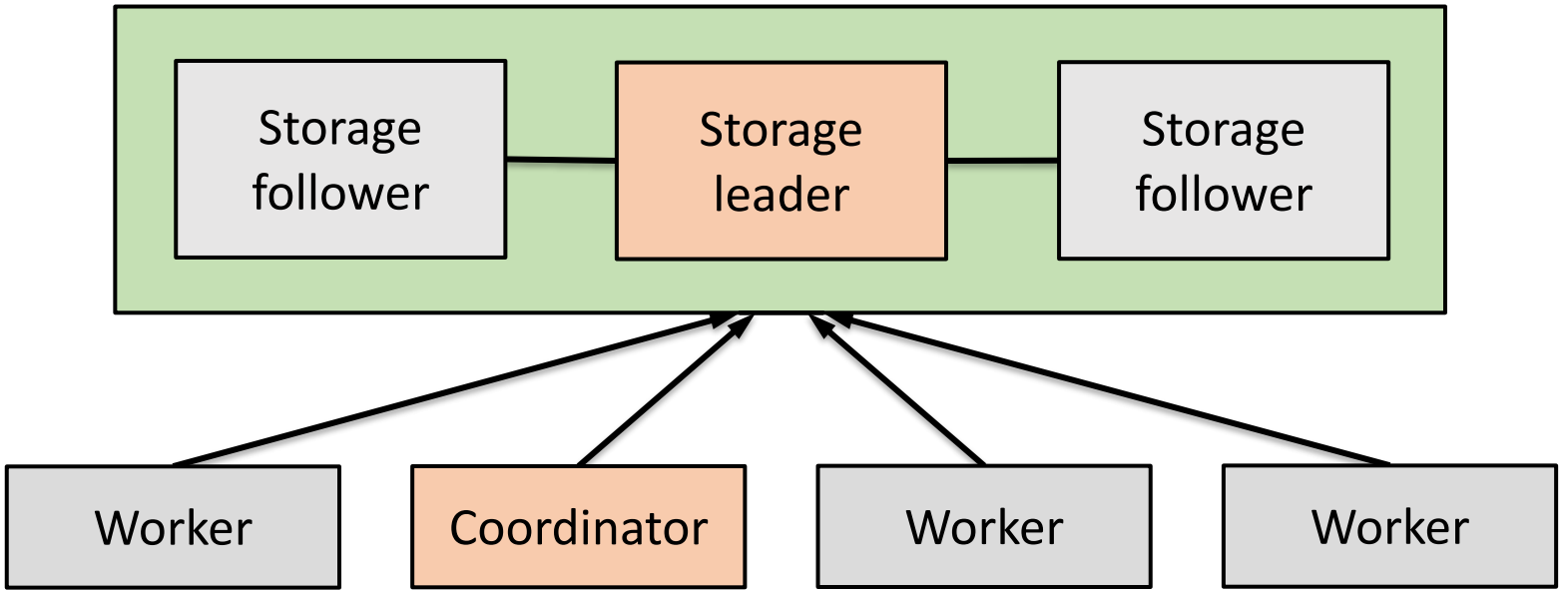
- Use state machine replication for fault tolerance
- Issues
  - Programming coordinator state machine is complicated
  - Coordinator can become bottleneck

Storage-based coordination



- Maintain coordinator state in separate storage system
  - E.g., IP of current coordinator, set of workers, task assignments
- Coordinator, workers coordinate via accesses to storage
  - Any worker can be coordinator

Fault-tolerant storage system



- Replicate storage for fault tolerance
  - Coordinator code is simpler since no state machine needed
- What happens when coordinator fails?
  - Any another worker can take over

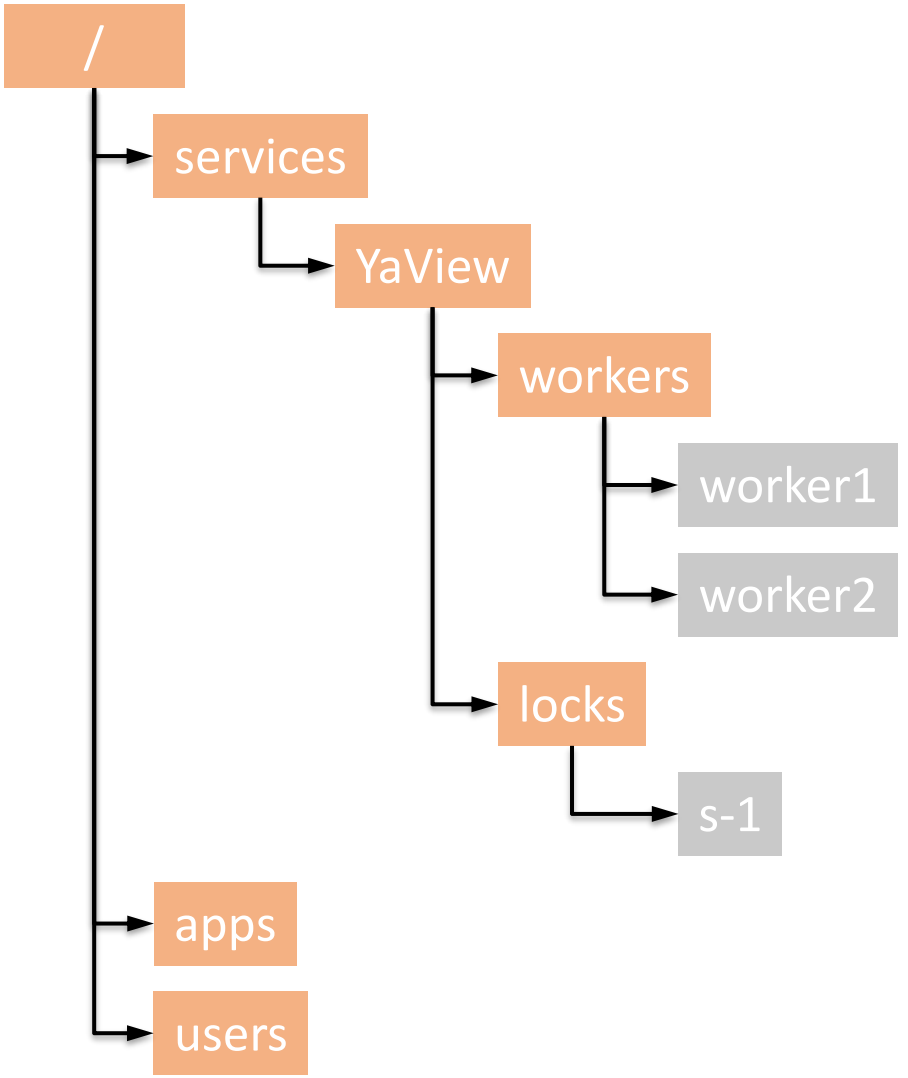
ZooKeeper

- A fault-tolerant storage system that provides general coordination services, i.e., coordination kernel
  - E.g., group membership, locks, leader election, etc.
- Provides high performance
  - Allows multiple outstanding operations by a client
  - Reads are fast (although they may return stale data)
- Reliable and easy to use

ZooKeeper API

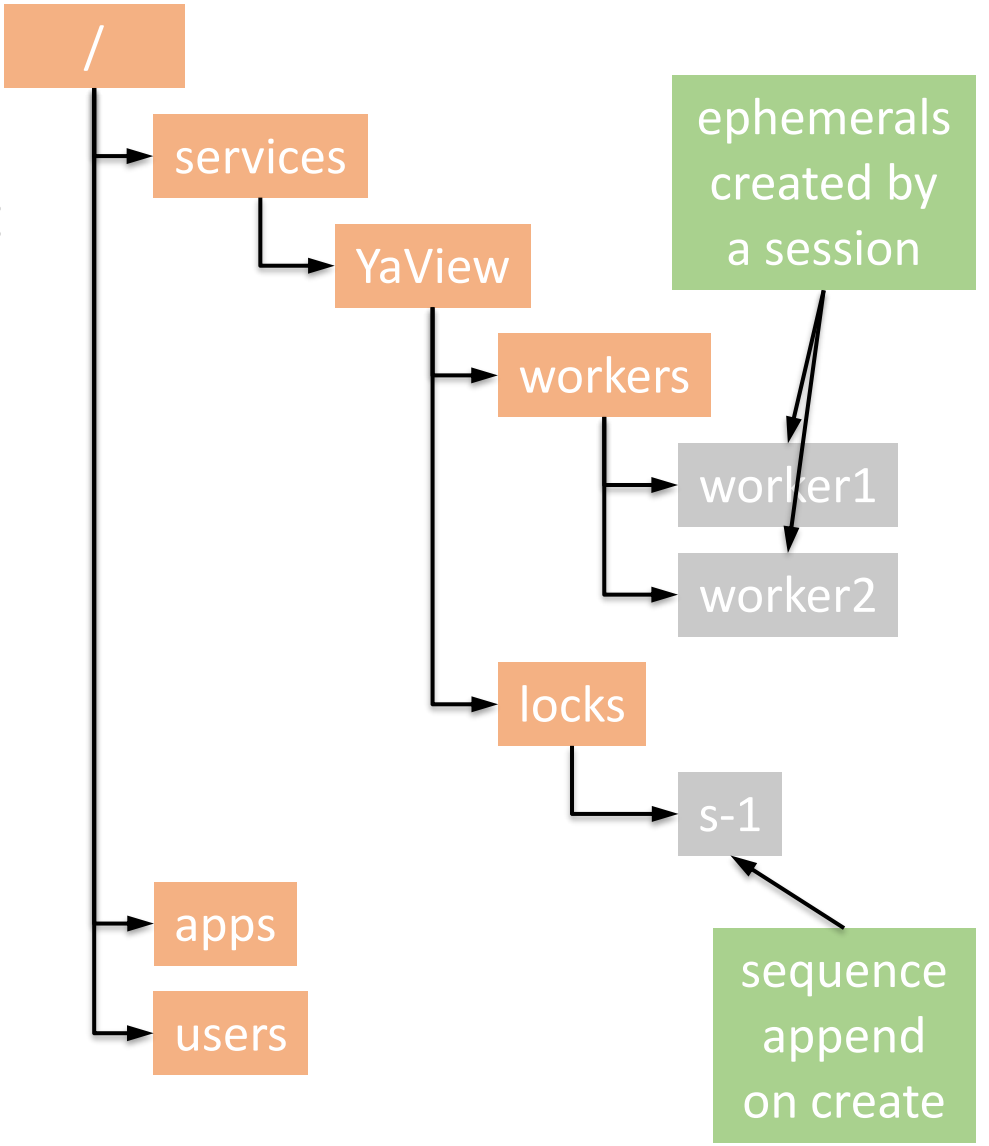
Data model

- Each node is called znode
  - Stores some data, including version
  - Data is read and written in its entirety
- znodes may have children
  - Hierarchal namespace
  - Like a file system, registry
- State maintained in memory



Znode types

- Two special types of znodes:
  - Ephemeral: znode deleted when explicitly deleted, or when client session that created the znode fails
  - Sequence: appends a (unique) monotonically increasing counter



Overview of API

- Operations look like file system operations
  - Take a path name to a znode, e.g., create("/app1/worker1", …)
- Operations are non-blocking (or wait-free)
  - Operations by one client do not block on another client
  - Slow and failed nodes cannot slow down fast ones
  - No deadlocks
- ZooKeeper uses API to provide "coordination recipes"
  - E.g., group membership recipe, locking recipe
- Some recipes necessarily wait on conditions, e.g., locking
  - ZooKeeper supports waiting for conditions efficiently

ZooKeeper API

- Clients open a session with (any) one ZK server, issue operations synchronously or asynchronously

```
s= openSession()
```

```
String create(path, data, acl, flags)
void delete(path, expectedVersion)
Stat setData(path, data, expectedVersion)
```

```
(data, Stat) getData(path, watch)
Stat exists(path, watch)
String[] getChildren(path, watch)
```

```
void sync(s)
```

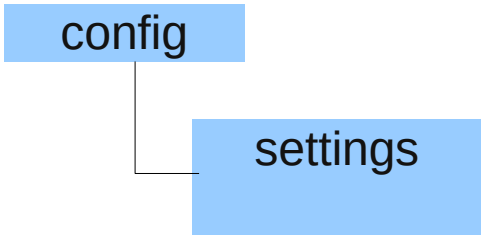
Key API Properties

- Asynchronous operations allow batching operations
- Exclusive file creation (one concurrent create succeeds)
- (d, v) = getData()/setData(x, v) support atomic ops
  - setData fails if data is modified since getData
- Sequence files allow ordering operations across clients
  - E.g., ordering lock operations
- Ephemeral files (i.e., sessions) help with client failure
  - E.g., group membership change, release locks, etc.
- Watches avoid costly repeated polling

Coordination Recipes

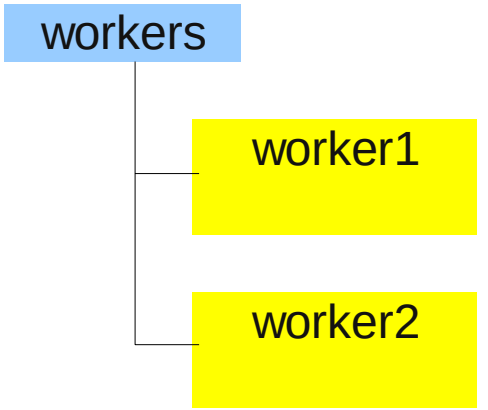
Configuration

- Workers read configuration
  - getData(“.../config/settings”, true)
- Administrators change the configuration
  - setData(“.../config/settings”, newConf, -1)
- Workers are notified of change and then re-read the new configuration
  - getData(“.../config/settings”, true)



Group Membership

- Register worker with host information in group
  - create(“.../workers/worker1”, hostInfo, EPHEMERAL)
- List group members
  - listChildren(“.../workers”, true)

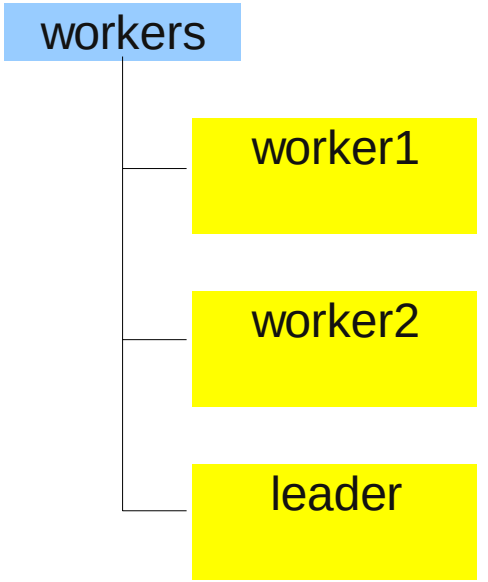


Leader Election

```
while true:
  if exists(“.../workers/leader”, watch=true)
    follow the leader
    return

  if create(“.../workers/leader”, hostname, EPHEMERAL)
    become leader
    return
```

```
If watch is triggered for “.../workers/leader”
  restart leader election process
```



Locks

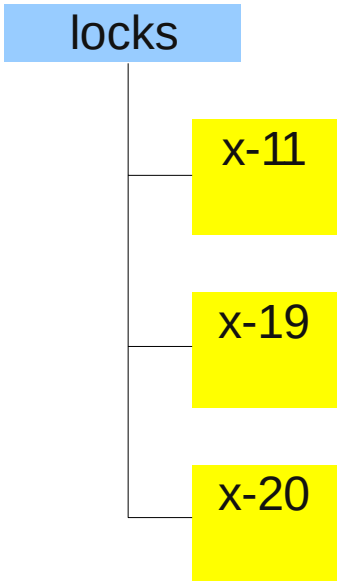
```
lock:
  id = create(“.../locks/x-”, SEQUENCE|EPHEMERAL)

  restart:
  getChildren(“.../locks”, false)
  if id is the 1st child // lock is acquired
    exit

  // wait for previous node
  if exists(name of last child before id, true)
    wait for event // no herd

  goto restart // why?

unlock:
  delete(id)
```

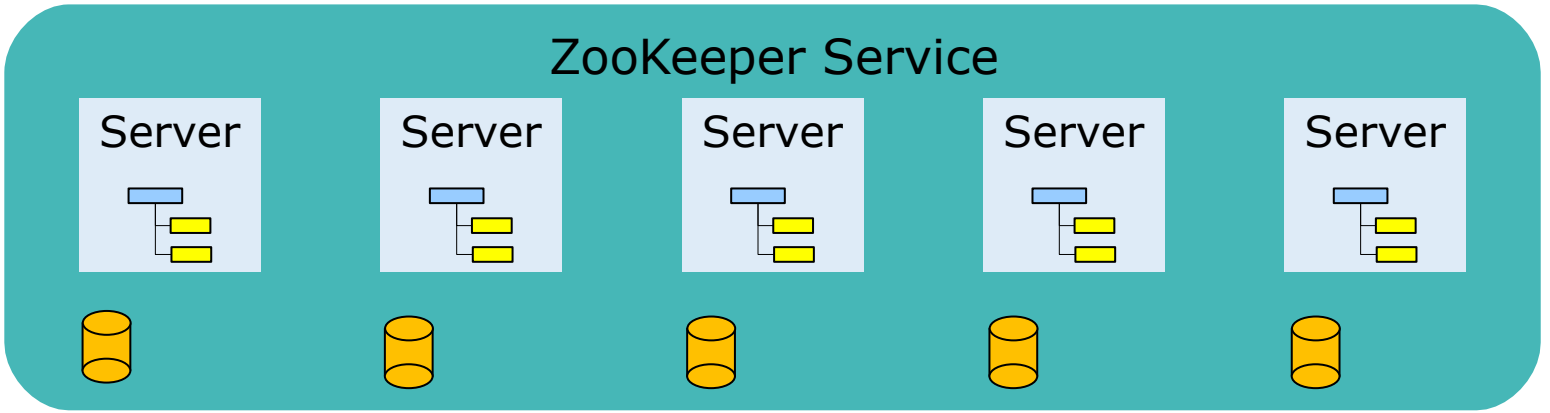


Implementation

ZooKeeper Guarantees

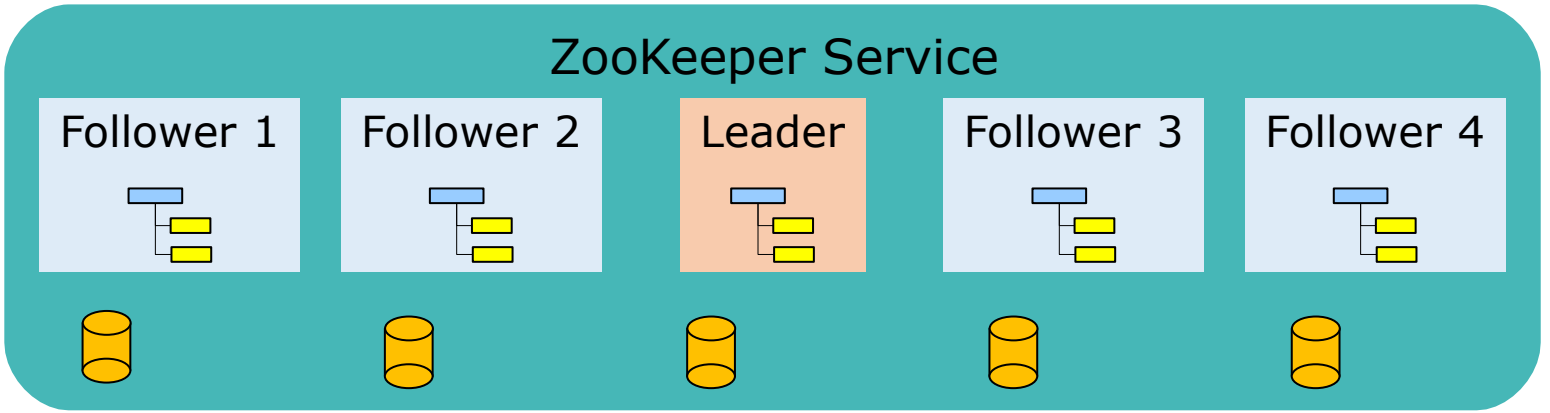
- Linearizable writes
  - Clients see same order of writes
- FIFO client order
  - A client's operations are executed in order
  - Implications:
    - Client A watching for Client B's changes sees them in order
    - A client's read must wait for all its previous writes to be executed
    - Reads may return stale values (see a prefix of writes)
- Hypothesis: wait-free synchronization + linearizable writes + FIFO execution is sufficient for implementing efficient coordination services for read-heavy workloads

ZooKeeper Service



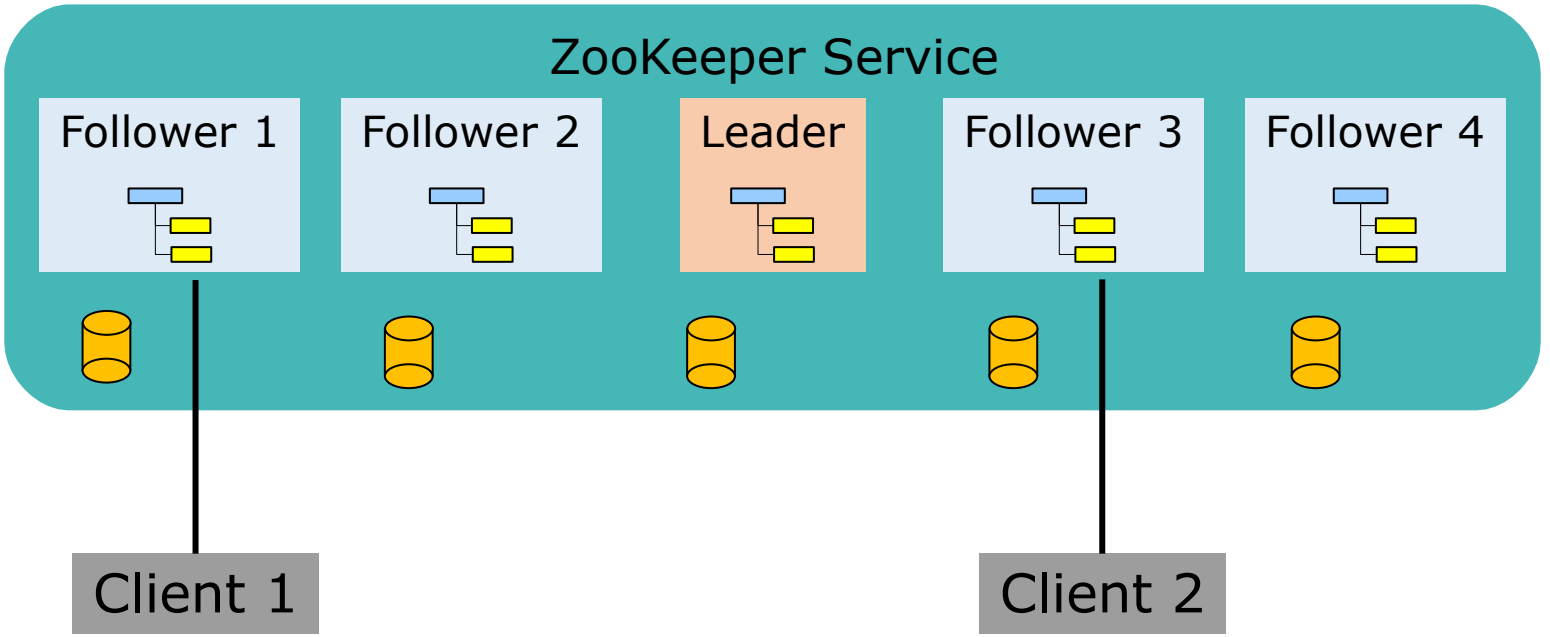
- ZooKeeper maintains a replicated database
- Each server
  - Keeps a copy of the ZooKeeper state in memory
  - Logs writes to ZooKeeper state in a write-ahead log on disk for recovering committed operations
  - Creates and stores snapshots of ZooKeeper state on disk for faster recovery

ZooKeeper Leader



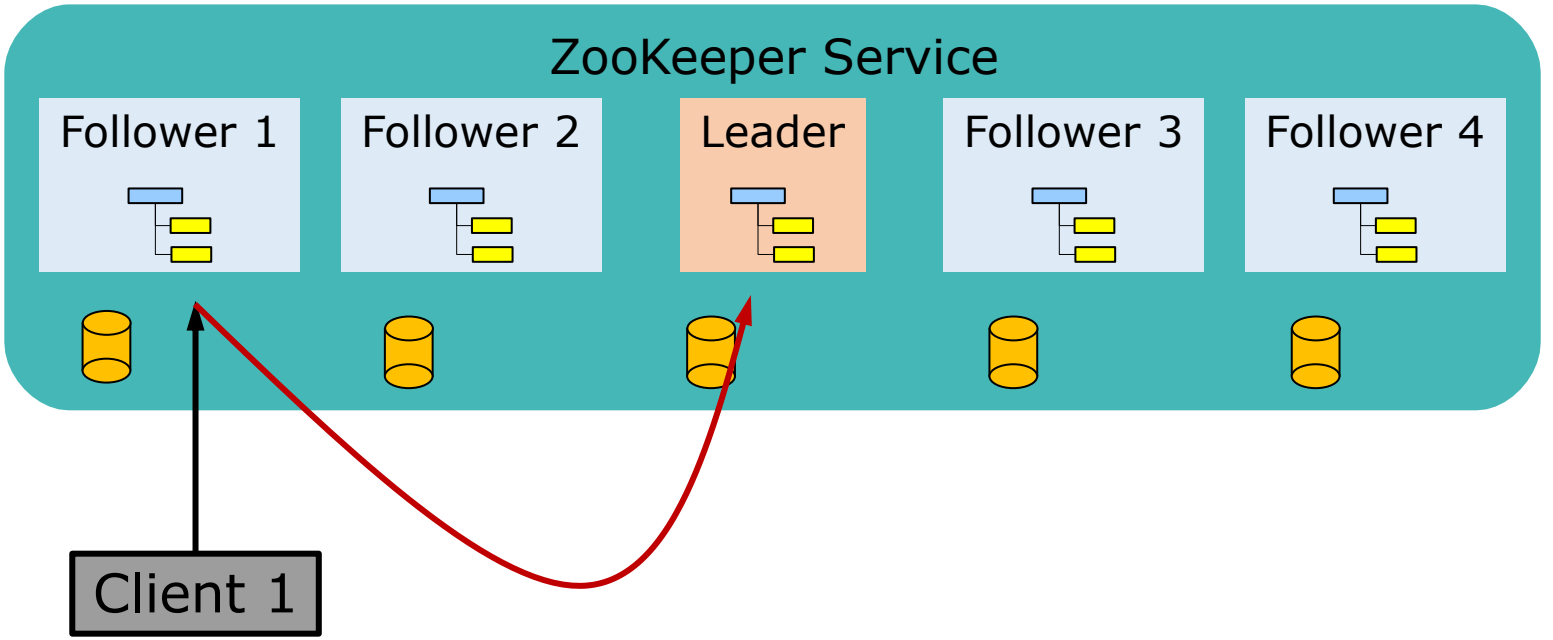
- Servers elect a leader at startup
- If a leader fails, they re-elect another leader using the ZAB leader-based atomic broadcast protocol

ZooKeeper Reads



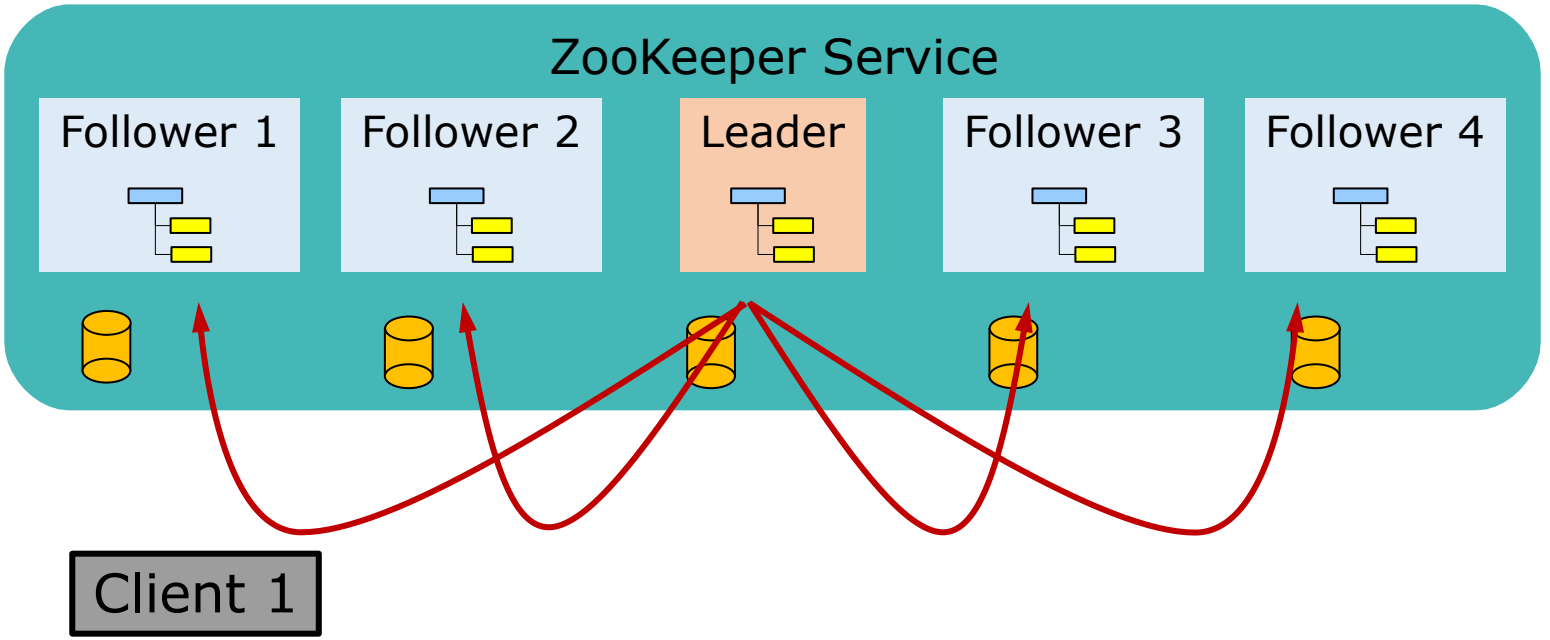
- Clients connect to any one server (follower or leader)
- Client's read (e.g., getData) performed by local server
  - E.g., When Client 2 issues read, Follower 3 reads and returns data from its own copy

ZooKeeper Writes



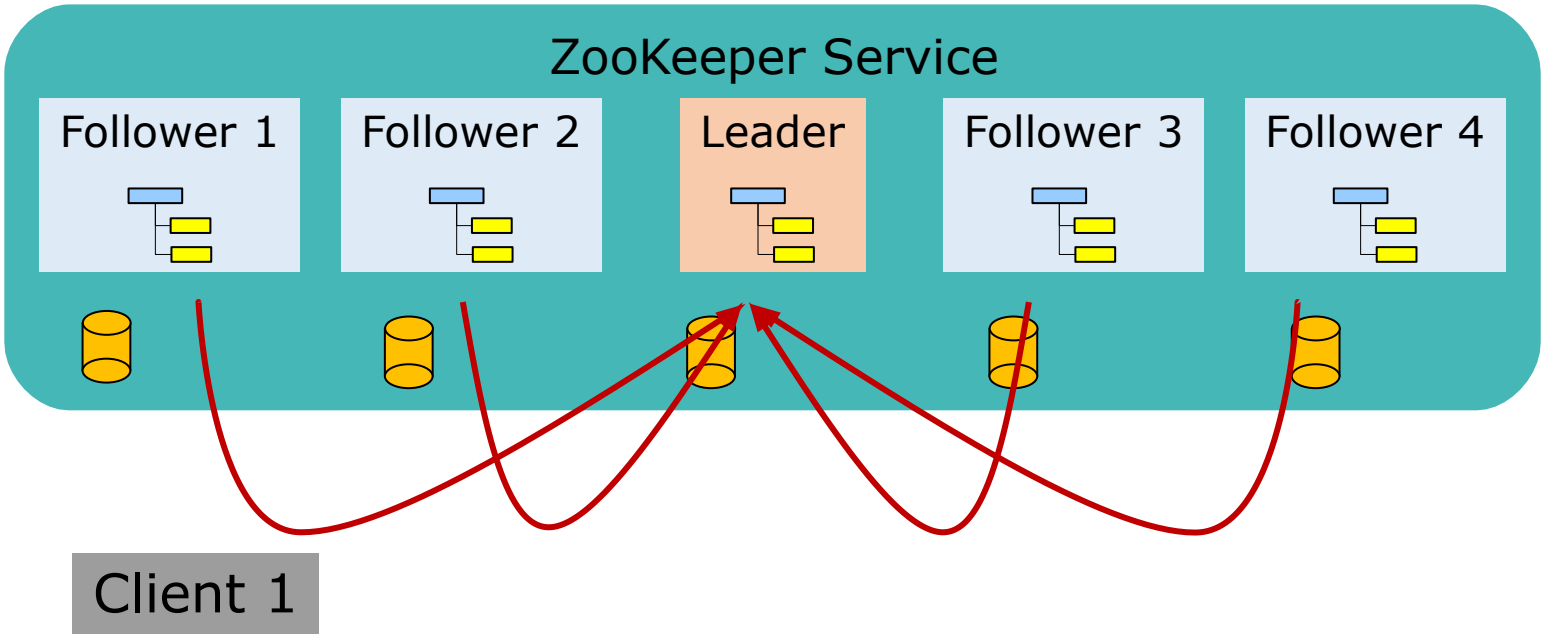
- Client 1's write (e.g., setData) forwarded by local server (Follower 1) to leader

ZooKeeper: Send Write



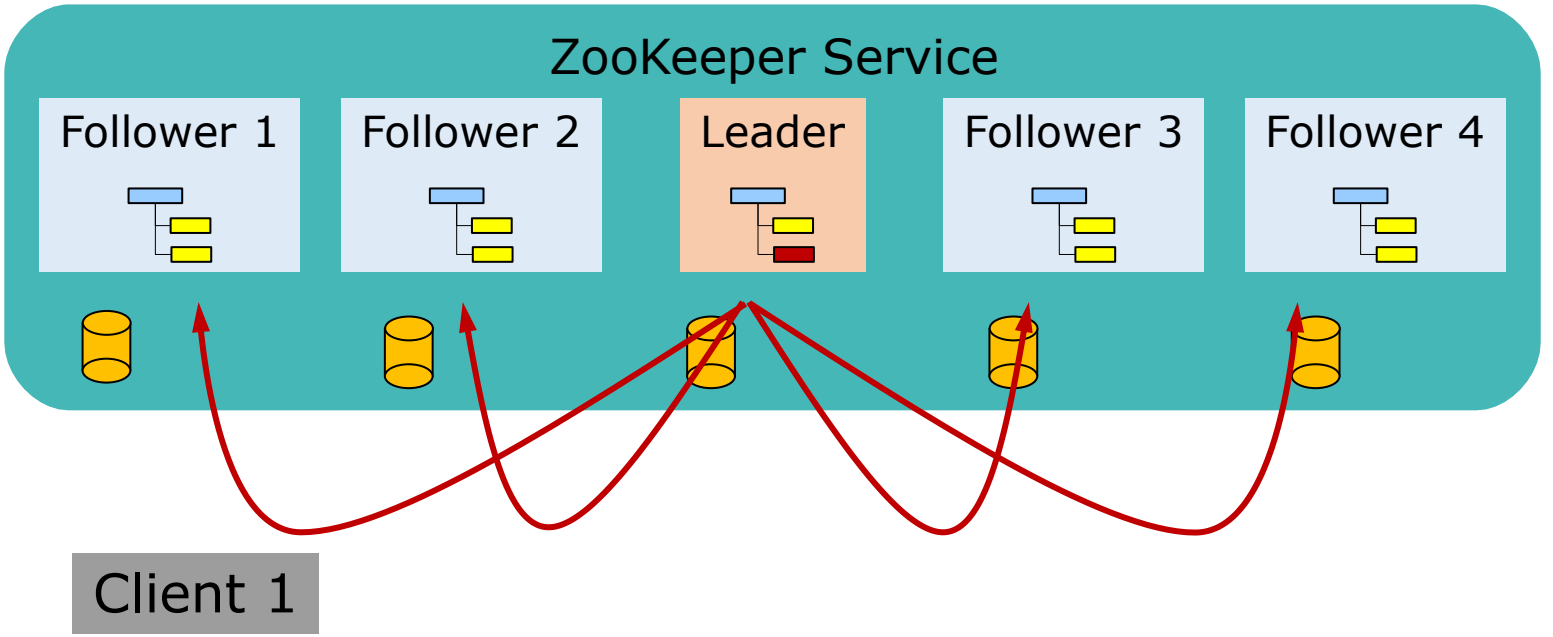
- Leader logs the write to its write-ahead log
- Leader sends write to all followers

ZooKeeper: Receive Acks



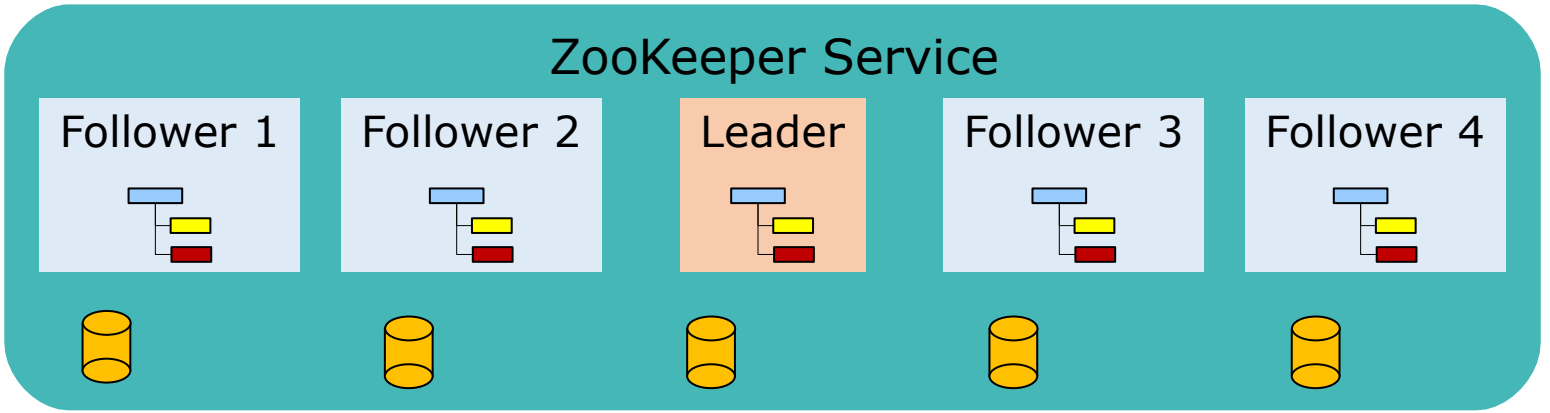
- Followers log the write to their write-ahead log
- Respond to the leader

ZooKeeper: Commit Write



- When leader receives acks from a majority of servers, it commits the write (need 2f+1 servers to handle f failures)
- Leader applies write to ZooKeeper state in memory
- Leader informs followers that write is committed

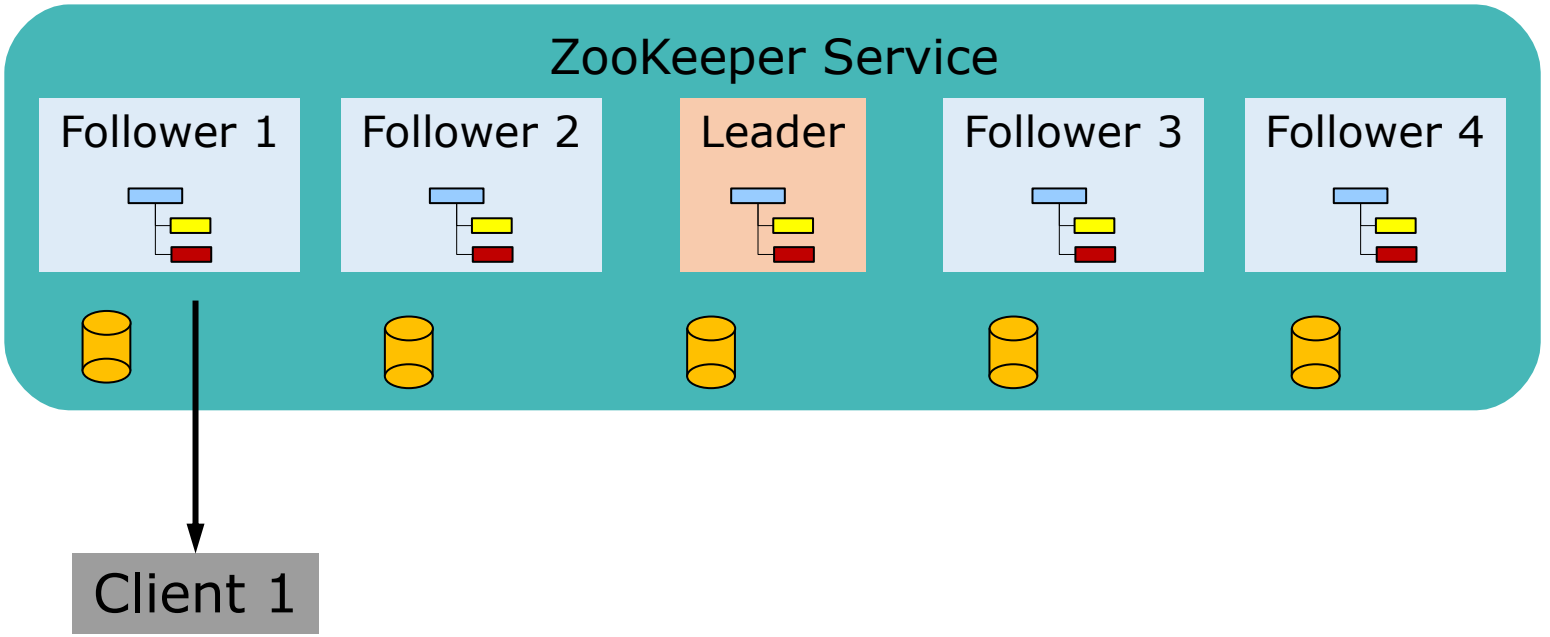
ZooKeeper: Apply Write



Client 1

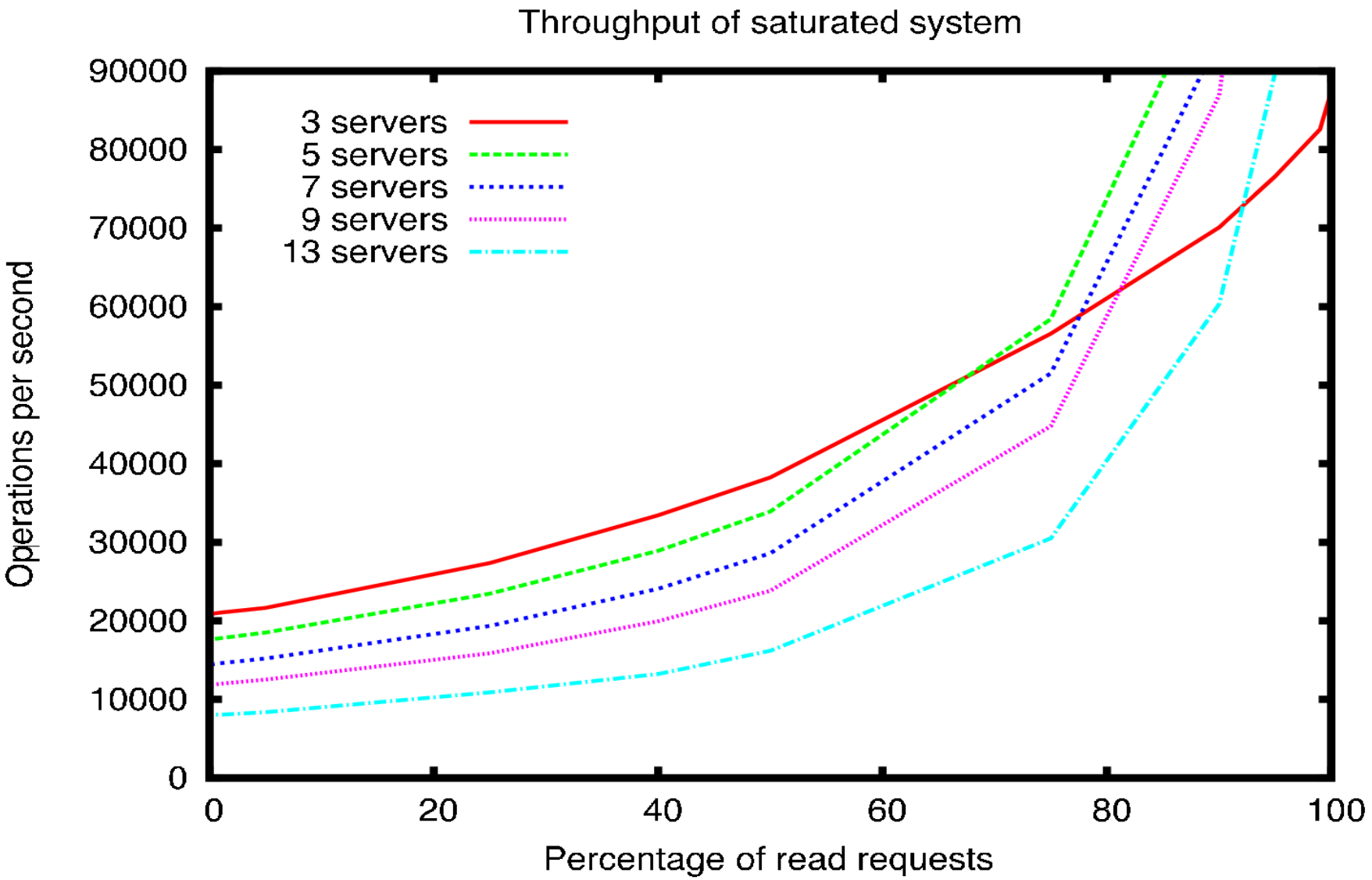
- Each follower:
  - Commits the write
  - Applies write to ZooKeeper state in memory
  - Issues watch notifications to clients connected to follower

ZooKeeper: Write Response

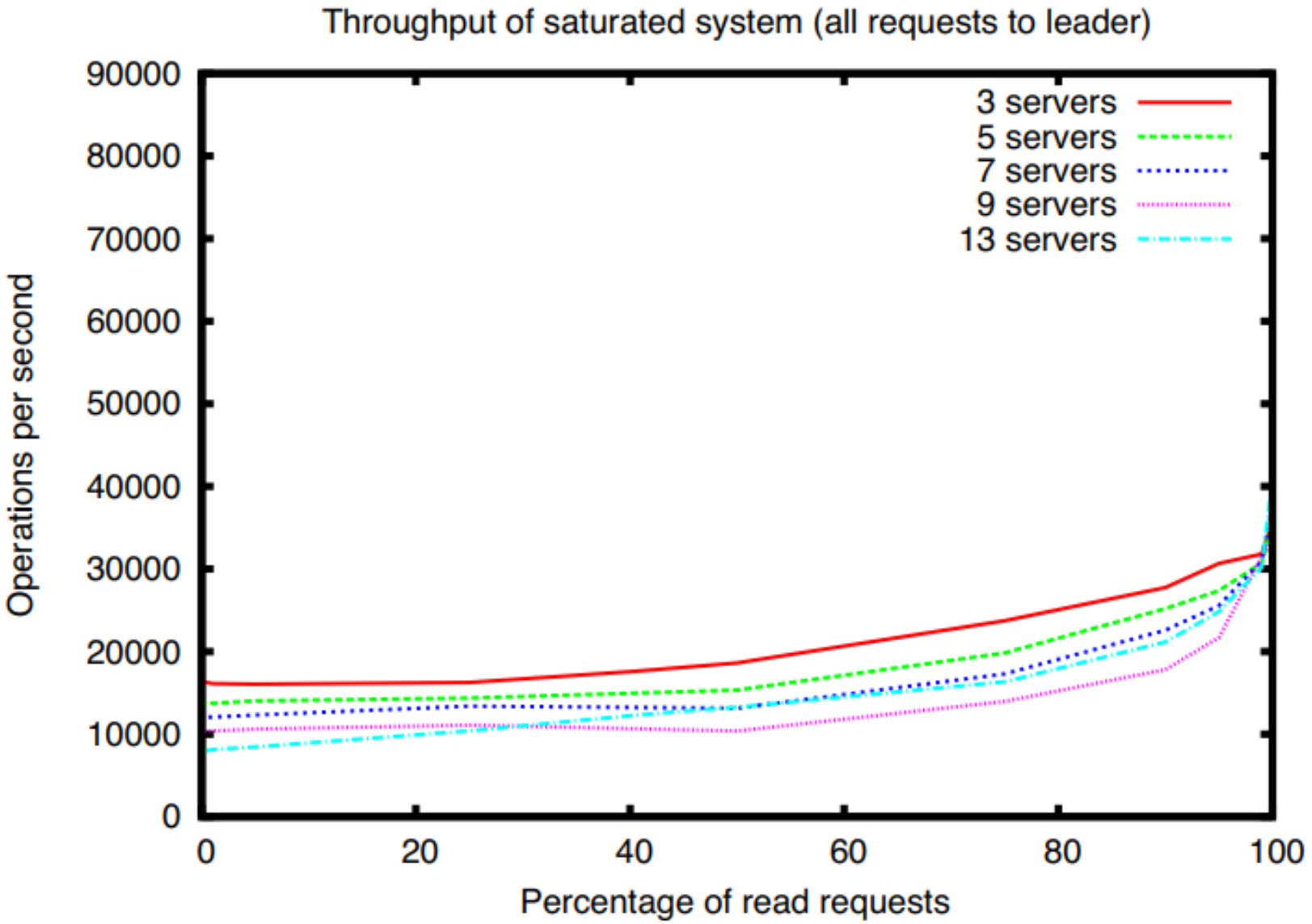


- Follower 1 delivers write response to Client 1

ZooKeeper Performance



Performance With Strong Consistency



Summary

- Easy to use
- High read performance
- General
- Reliable
- Released as an Apache open-source project
  - Relatively easy to use
  - Today, used extensively for coordination functions

Discussion

Q1

- What are wait-free operations? Why does the paper base the ZooKeeper design on wait-free operations?

Q2

- Compare ZooKeeper with RAFT in terms of
  - Functionality/purpose of the system
  - Replication method
  - Consistency guarantees and performance
  - Use of timeouts

Q3

- Why does ZooKeeper provide FIFO execution guarantees for each client's operations?

Coordinator

```
delete("…/ready", …);
setData("…/config1", …);
setData("…/config2", …);
create("…/ready", …);
```

Worker

```
if (exists("…/ready", watch=true))
  getData("…/config1")
  getData("…/config2")
```

Q4

- The ZK locking implementation has no timeout. What would happen if the lock holder dies?

Q5

- ZooKeeper converts write operations into idempotent transactions when applying them to all servers. What does idempotent mean? Why do these transactions need to be idempotent?