CS4740
CLOUD COMPUTING

Case study: ZooKeeper

Prof. Chang Lou, UVA CS, Fall 2025

ZooKeeper: wait-free coordination for internet-scale systems

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AGENDA

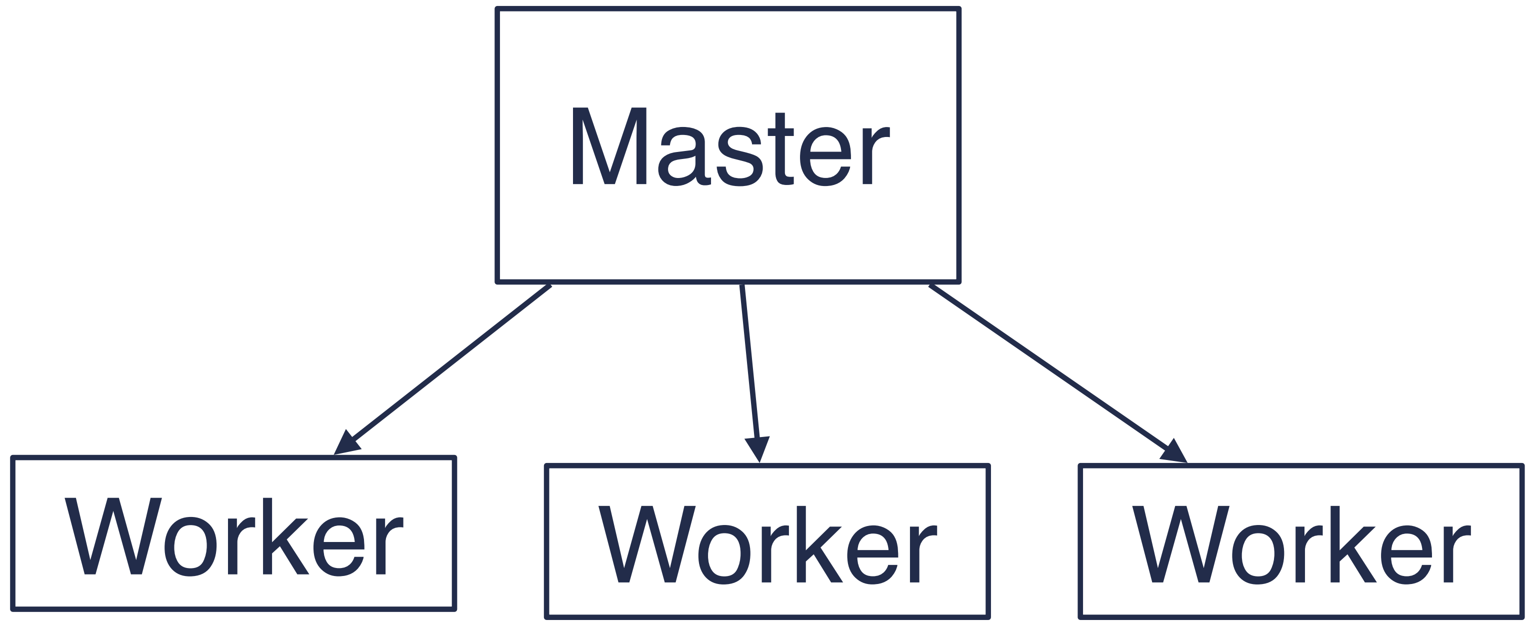
- Motivation: MapReduce Coordinator
- Programming with ZooKeeper
  - Interface
  - Code Example
- Performance

WHY ARE WE READING THIS PAPER?

- A simpler foundation for fault-tolerant applications.
  - the go-to application if you just start learning distributed systems
- High-performance in a real-life service built on Raft-like replication.
- Also because it's very widely used.

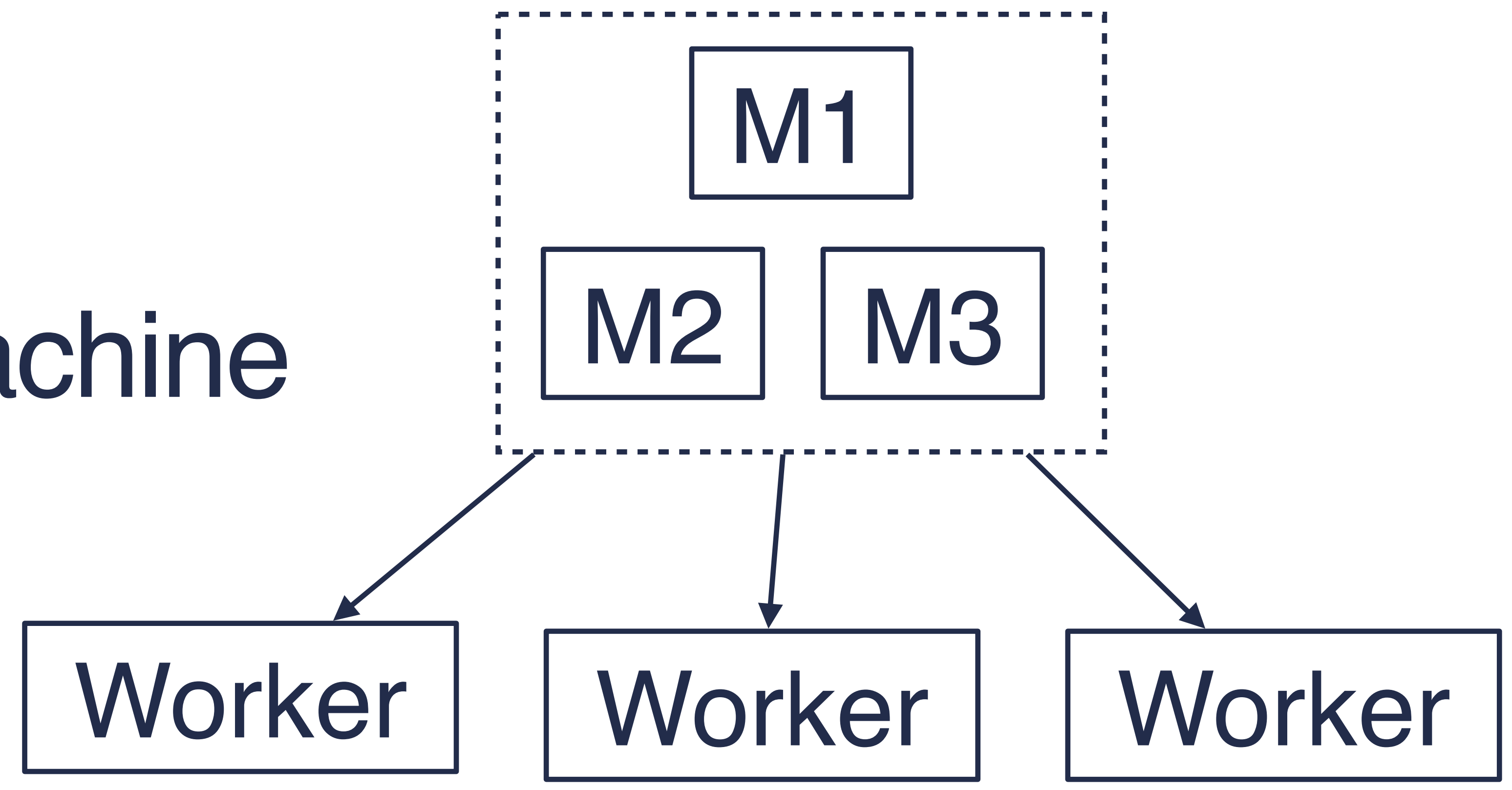
PROBLEM WITH SINGLE COORDINATOR

- if we wanted to make a fault-tolerant service like MR coordinator,
  - we could replicate with Raft, and that would be OK!



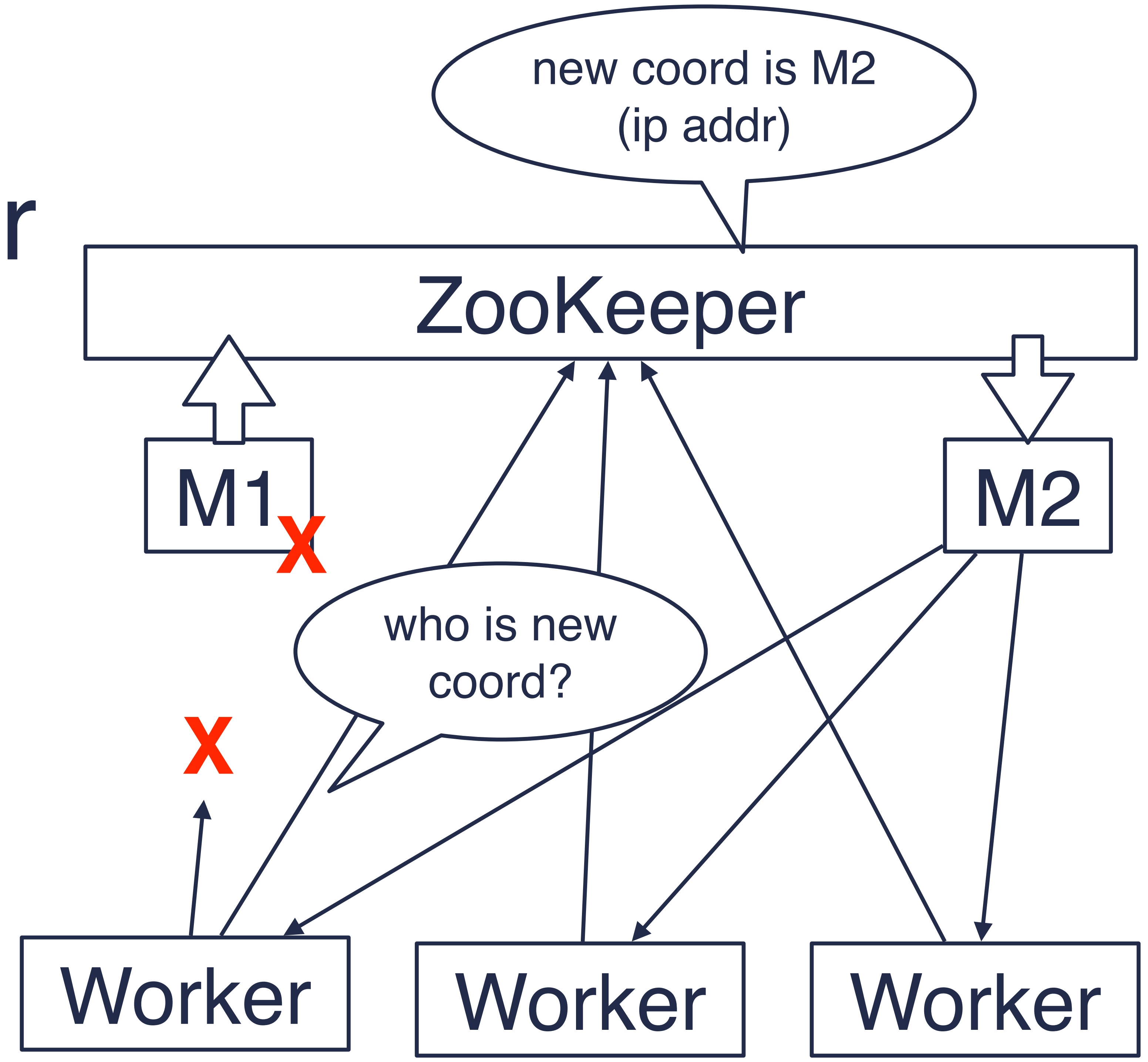
PROBLEM WITH SINGLE COORDINATOR

- but building directly on Raft is complex
  - a replicated state machine is awkward to program
- you can think of state machine replication (Raft) as replicating
  - the computation; the state is replicated as a side-effect.
- can we replicate state **without** replicating computation?
  - yes: use fault-tolerant storage, for example ZooKeeper
  - easier to write the MR coord than with replicated state machine
  - ordinary straight-line code, plus "save" calls



NEW PARADIGM W/ ZOOKEEPER

- now what if MR coord fails?
- we weren't replicating it on a backup coord server
  - but we don't need one!
- just pick any computer, start MR coord s/w on it,
  - have it read state from ZK.
- new coord can pick up where failed one left off.
- makes the most sense in a cloud
  - easy to allocate a replacement server



WHAT MIGHT MR COORD STORE IN ZK?

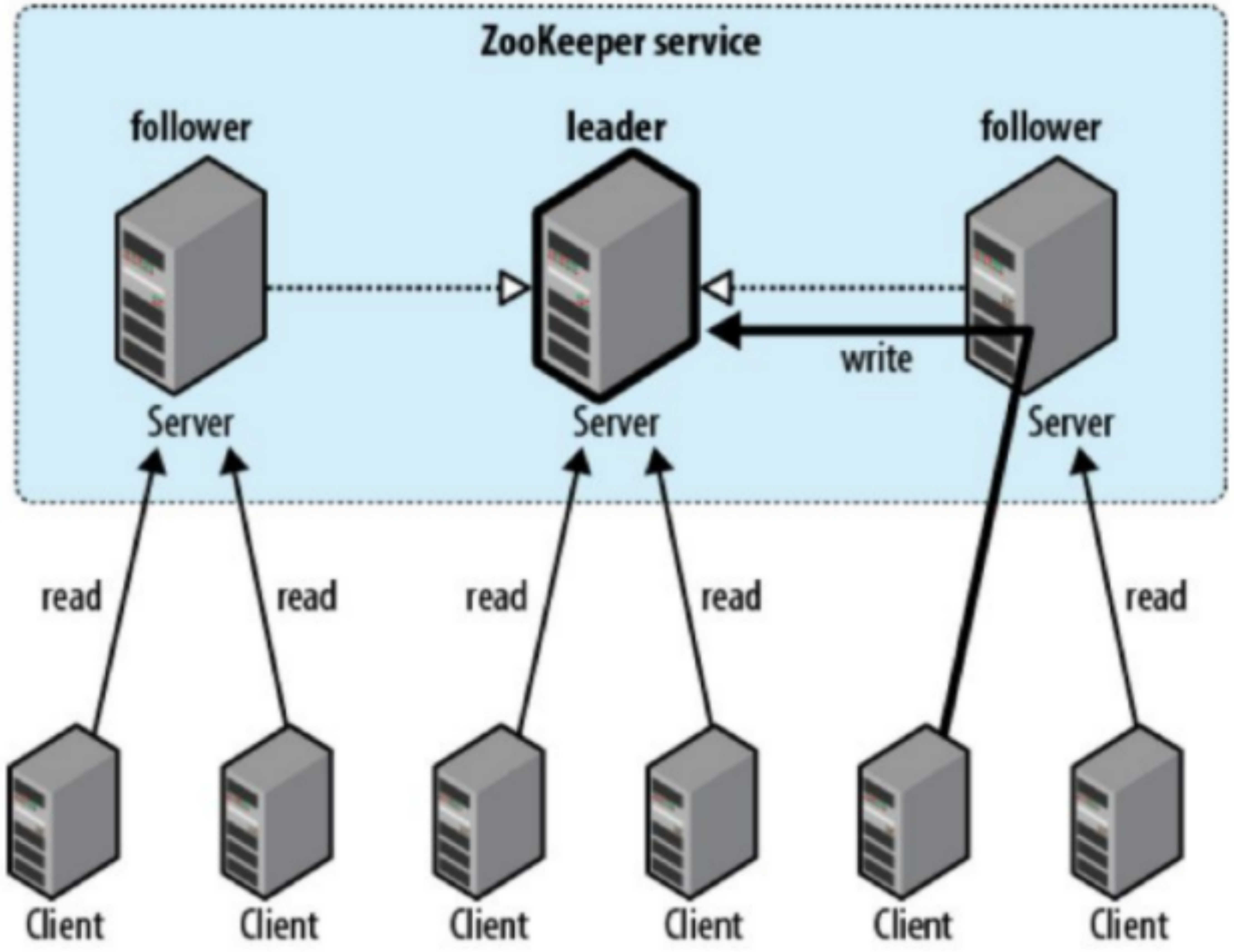
- coord's IP addr, set of jobs, status of tasks, set of workers, assignments
- update data in ZK on each change
- (but big data itself in GFS, not ZK)
- ZK acting as a "configuration service"
  - helps MR coord and worker find each other

NEXT: CHALLENGES

- detect MR coord failure
- elect new MR coord (one at a time! no split brain!)
- new coord needs to be able to recover/repair state read from ZK
  - what if old coord crashed midway through complex update?
- what if old coord doesn't realize it's been replaced
  - can it still read/write state in ZK?
  - can it affect other entities incorrectly? e.g. tell workers to do things?
- performance

ZooKeeper Architecture

ARCHITECTURE



ZooKeeper Interface

ZOOKEEPER DATA MODEL

- the state: a file-system-like tree of znodes
- file names, file content, directories, path names
  - directories help different apps avoid interfering
- each znode has a version number (?)
- types of znodes:
  - regular
  - ephemeral
  - sequential: name + seqno

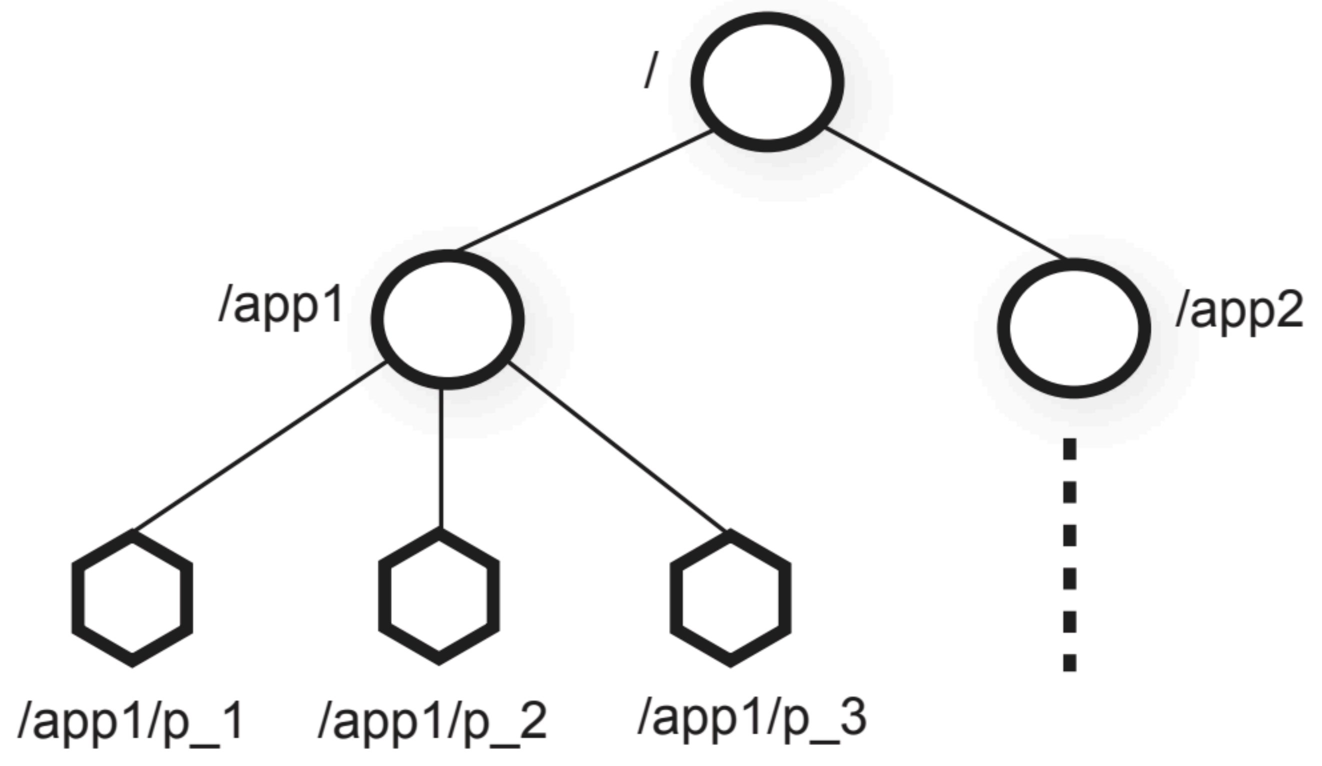


Figure 1: Illustration of ZooKeeper hierarchical name space.

OPERATIONS (CREATE)

- s = openSession()
- create(s, path, data, flags)
  - exclusive -- fails if path already exists
  - flags specify types: regular, ephemeral, sequential

```
s = openSession()
create(s, "/r")
getChildren(s, "/")
=> /r
create(s, "/r")
=> false, already exists
```

```
s = openSession()
create(s, "/r", ephemeral=true)
getChildren(s, "/")
=> /r
closeSession(s) // or crash
s2 = openSession()
getChildren(s2, "/")
=> null
```

```
s = openSession()
create(s, "/r", sequential=true)
create(s, "/r", sequential=true)
getChildren(s, "/")
=> /r0000000001, /r0000000002
```

OPERATIONS (OTHERS)

- exists(s, path, watch)
  - **watch**=true asks for notification if path is later created/deleted
- getData(s, path, watch) -> data, version
- setData(s, path, data, version)
  - if znode.version = version, then update
- getChildren(s, path, watch)
- delete(s, path, watch)
- these throw an exception if the ZK server says it has terminated the session
  - so that application won't continue

OPERATIONS

– ZooKeeper API well tuned for concurrency and synchronization:
  – + exclusive file creation; exactly one concurrent create returns success
  – + getData()/setData(x, version) supports mini-transactions
  – + sessions help cope with client failure (e.g. release locks)
  – + sequential files create order among multiple clients
  – + watches avoid costly repeated polling

Programming Example

EXAMPLE: SIMPLE LOCK

Lock

```
s = createSession
while true:
    if create(s, "/lock", ephemeral=true)
        // go ahead and do stuff
    else if exists(s, "/lock", watch=true)
        wait for watch event
```

Unlock

```
delete(s, "/lock")
```

Problem: Herd effect
If many clients wait for a lock, they will all vie for the lock when it is released but one client can get the lock.

EXAMPLE: LOCK WITHOUT HERD EFFECT

Lock

```
s = createSession
n = create(s, "/lock/lock-",
ephemeral=true, sequential=true)
while true:
   C= getChildren(s, "/lock", false)
   if n is lowest znode in C, break
   p = znode in C ordered just before n
   if exists(s, p, watch=true)
      wait for watch event
```

Unlock

```
delete(s, n)
```

Why this design works?

EXAMPLE: LOCK WITHOUT HERD EFFECT

- Q: could a lower-numbered file be created after getChildren()?
- Q: can watch fire before it is the client's turn?

```
lock-10 <- current lock holder
lock-11 <- next one
lock-12 <- my request
```

- A: yes
- if client that created lock-11 dies before it gets the lock, the
- watch will fire but it isn't my turn yet.

EXAMPLE: MAPREDUCE COORDINATOR ELECTION

```
s = openSession()
while true:
  if create(s, "/mr/c", ephemeral=true)
    // we are the coordinator!
    setData(s, "/mr/ip", ...)
  else if exists(s, "/mr/c", watch=true)
    // we are not the coordinator
    wait for watch event
```

- exclusive create
  - if multiple clients concurrently attempt, only one will succeed
- ephemeral znode
  - coordinator failure automatically lets new coordinator be elected
- watch
  - potential replacement coordinators can wait w/o polling

REQUIREMENTS FOR SOLUTION

- * want to elect a replacement
- * must cope with crash in the middle of updating state in ZK
- * must cope with possibility that the coordinator *didn't* fail!

REQUIREMENT 1: ELECT NEW COORD

- client failure -> client stops sending keep-alive messages to ZK
- no keep-alives -> ZK leader times out and terminates the session
- session termination -> ZK leader deletes session's ephemeral files
- and ignores further requests from that session
- ephemeral deletions are A-linearizable ZK ops
- now a new MR coordinator can elect itself

REQUIREMENT 2: ATOMICITY

- what if the MR coordinator crashes while updating state in ZK?
- maybe store all data in a single ZK file
  - individual setData() calls are atomic (all or nothing vs failure)
- what if there are multiple znodes containing state data?
  - use paper's "ready" file scheme

REQUIREMENT 3: DEAL WITH OLD COORD

- what if the coordinator is alive and thinks it is still coordinator, but ZK has decided it is dead and deleted its ephemeral /mr/c file?
- a new coordinator will likely be elected.
- will two computers think they are the coordinator?
  - this could happen.
- can the old coordinator modify state in ZK?
  - this cannnot happen!

REQUIREMENT 3: DEAL WITH OLD COORD

- when ZK times out a client's session, two things happen atomically:
  - ZK deletes the clients ephemeral nodes.
  - ZK stops listening to the session -- will reject all operations.
- so old coordinator can no longer modify or read data in ZK!
  - if it tries, its client ZK library will raise an exception
  - forcing the client to realize it is no longer coordinator

REQUIREMENT 3: DEAL WITH OLD COORD

- an important pattern in distributed systems:
- a single entity (e.g. ZK) decides which computers are alive or dead
  - sometimes called a failure detector
- it may not be correct, e.g. if the network drops messages
- but everyone **obeys** its decisions
- agreement is more important than being right, to avoid split brain
- but possibility of being wrong => may need to fence

REQUIREMENT 3: DEAL WITH OLD COORD

- what if coordinator interacts with entities (e.g., workers) other than ZK?

- that don't know about the coordinator's ZK session state.
- they may need to fence (i.e. ignore deposed coordinator) -- how?

- idea: worker could "watch" leader znode in ZK to learn of changes.
  - not perfect: window between change and watch notification arrival.

REQUIREMENT 3: DEAL WITH OLD COORD

- idea: each new coordinator gets an increasing "epoch" number.
  - from a file in ZK.
  - coordinator sends epoch in each message to workers.
  - workers remember highest epoch they have seen.
  - workers reject messages with epochs smaller than highest seen.
  - so they'll ignore a superseded coordinator once they
  - see a newer coordinator.

Performance

PERFORMANCE OPTIMIZATION

- Data must fit in memory, so reads are fast (no need to read disk).
  - So you can't store huge quantities of data in ZooKeeper.
- Writes (log entries) must be written to disk, and waited for.
  - So committed updates aren't lost in a crash or power failure.
  - Hurts latency; batching can help throughput.
- Periodically, complete snapshots are written to disk.
  - Fuzzy technique allows snapshotting concurrently with write operations.

PERFORMANCE OPTIMIZATION

- emphasis is on handling many reading/watching clients
- 1) many ZK follower servers; clients are spread over them for parallelism
- client sends all operations to its ZK follower
- ZK follower executes reads locally, from its replica of ZK data
- to avoid loading the ZK leader
- ZK follower forwards writes to ZK leader
- 2) watch, not poll
- the ZK follower (not the ZK leader) does the work

PERFORMANCE OPTIMIZATION

- 3) clients of ZK can launch async operations
- i.e. send request; completion notification delivered to code separately
- unlike RPC
- a client can launch many writes without waiting
- ZK processes them efficiently in a batch; fewer msgs, disk writes
- client library numbers them, ZK executes them in that order
- e.g. to update a bunch of znodes then create "ready" znode

HOW IS THE PERFORMANCE?

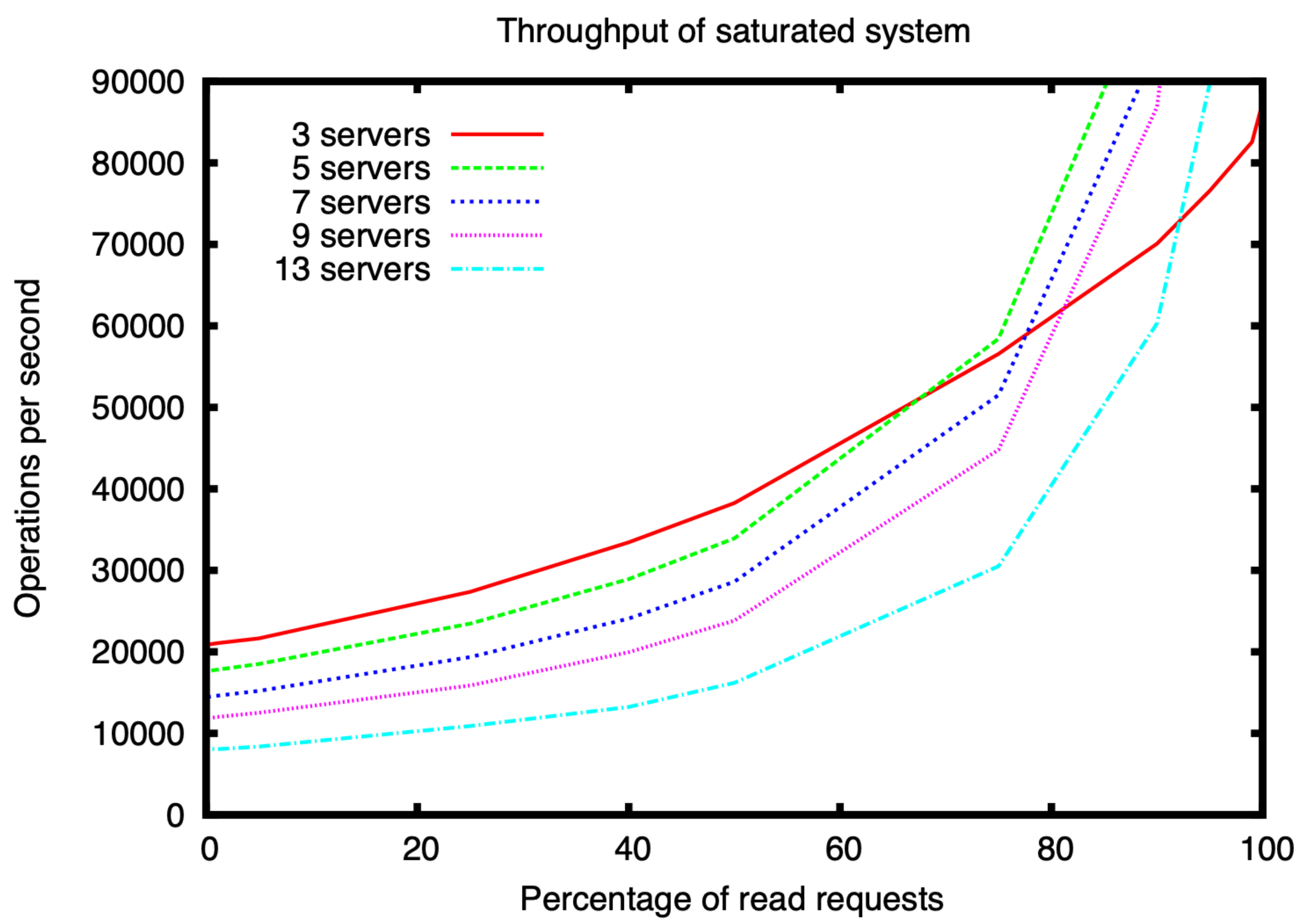


Figure 5: The throughput performance of a saturated system as the ratio of reads to writes vary.

- Overall, can handle 10s of thousands of operations / second.
  - Is this a lot? Enough?
- Why do the lines go up as they move to the right?
- Why does the x=0 performance go down as the number of servers increases?
- Why does the "3 servers" line change to be worst at 100% reads?
- What might limit it to 20,000? Why not 200,000?
  - Each op is a 1000-byte write...

WHAT ABOUT RECOVERY TIME?

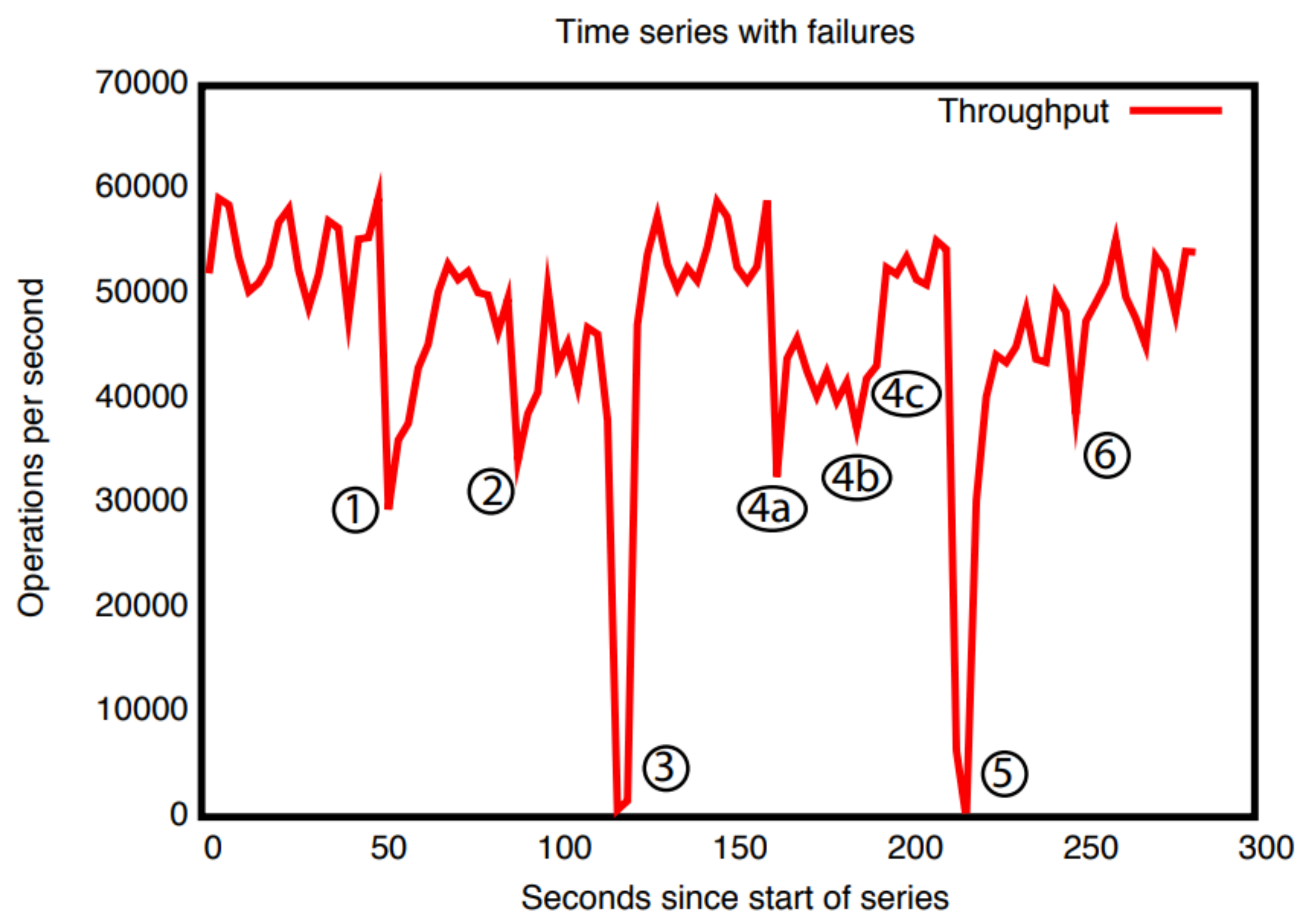


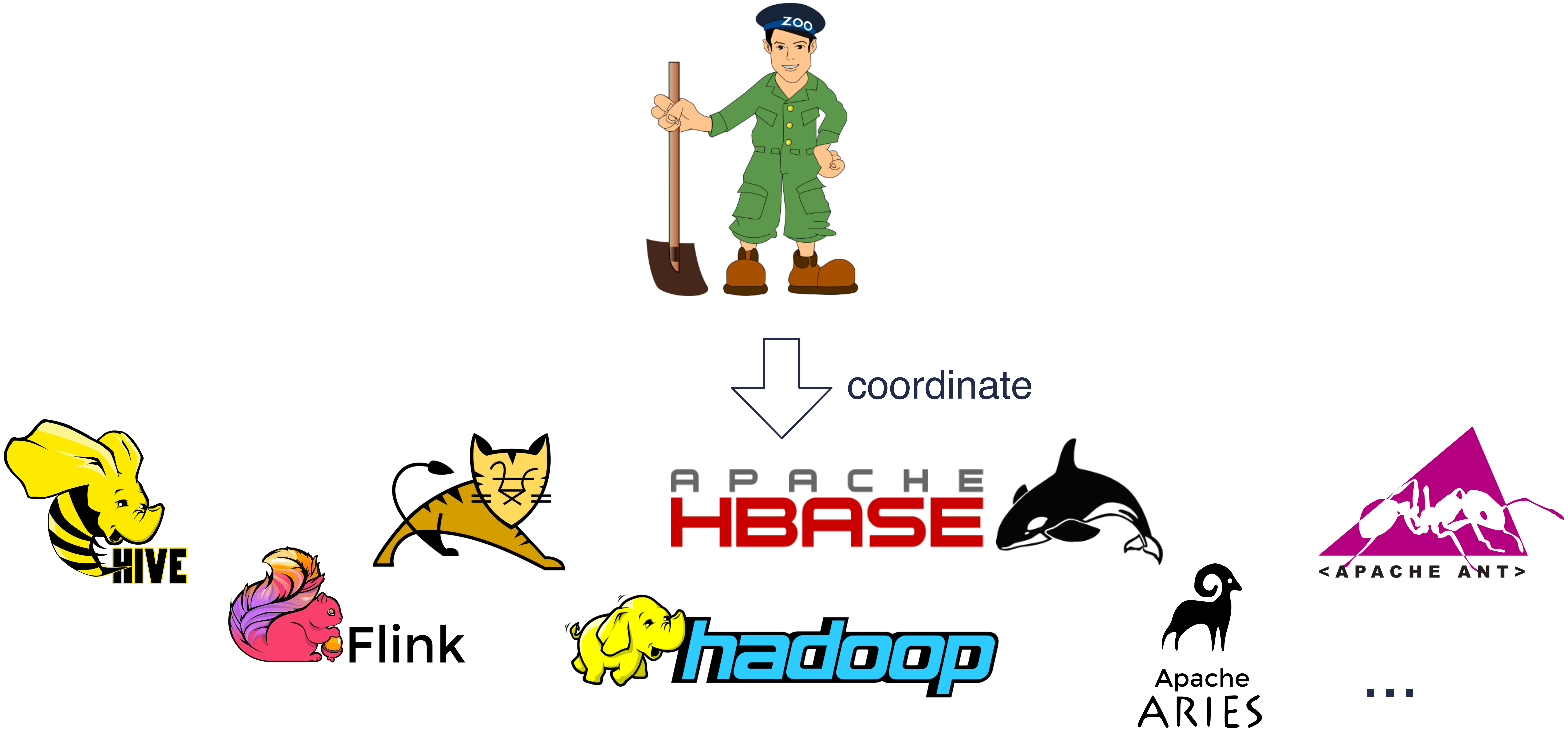
Figure 8: Throughput upon failures.

- Follower failure -> just a decrease in total throughput.
- Leader failure -> a pause for timeout and election.
  - Visually, on the order of a few seconds.

ZOOKEEPER IS VERY WIDELY USED

- see ZooKeeper's Wikipedia page for a list of projects that use it
- often used as a kind of fault-tolerant name service
  - what's the current coordinator's IP address? what workers exist?
- can be used to simplify overall fault-tolerance strategy
  - store all state in ZK e.g. MR queue of jobs, status of tasks
  - then service servers needn't themselves replicate

WHY IT IS CALLED ZOOKEEPER?



NEXT MONDAY: LAB DAY

- We will implement a Leader Election service with ZooKeeper
- Please setup the ZooKeeper on your laptop before class!

Process 1:	Process 2:	Process 3:
I joined the cluster. I became leader!		
	I joined the cluster. I am following node 1!	I joined the cluster. I am following node 1!
I left the cluster.		
	I became leader!	I am following node 2!
I joined the cluster. I am following node 2!		

TAKEAWAYS

–Zookeeper provides simple but convenient interface for coordination.

– Key concepts: session, znode types, watch..

–Efficiency and correctness guarantees depend on how clients use them.

–Next class: [**Lab Day] Implement Leader Election with ZooKeeper**

University of Virginia

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