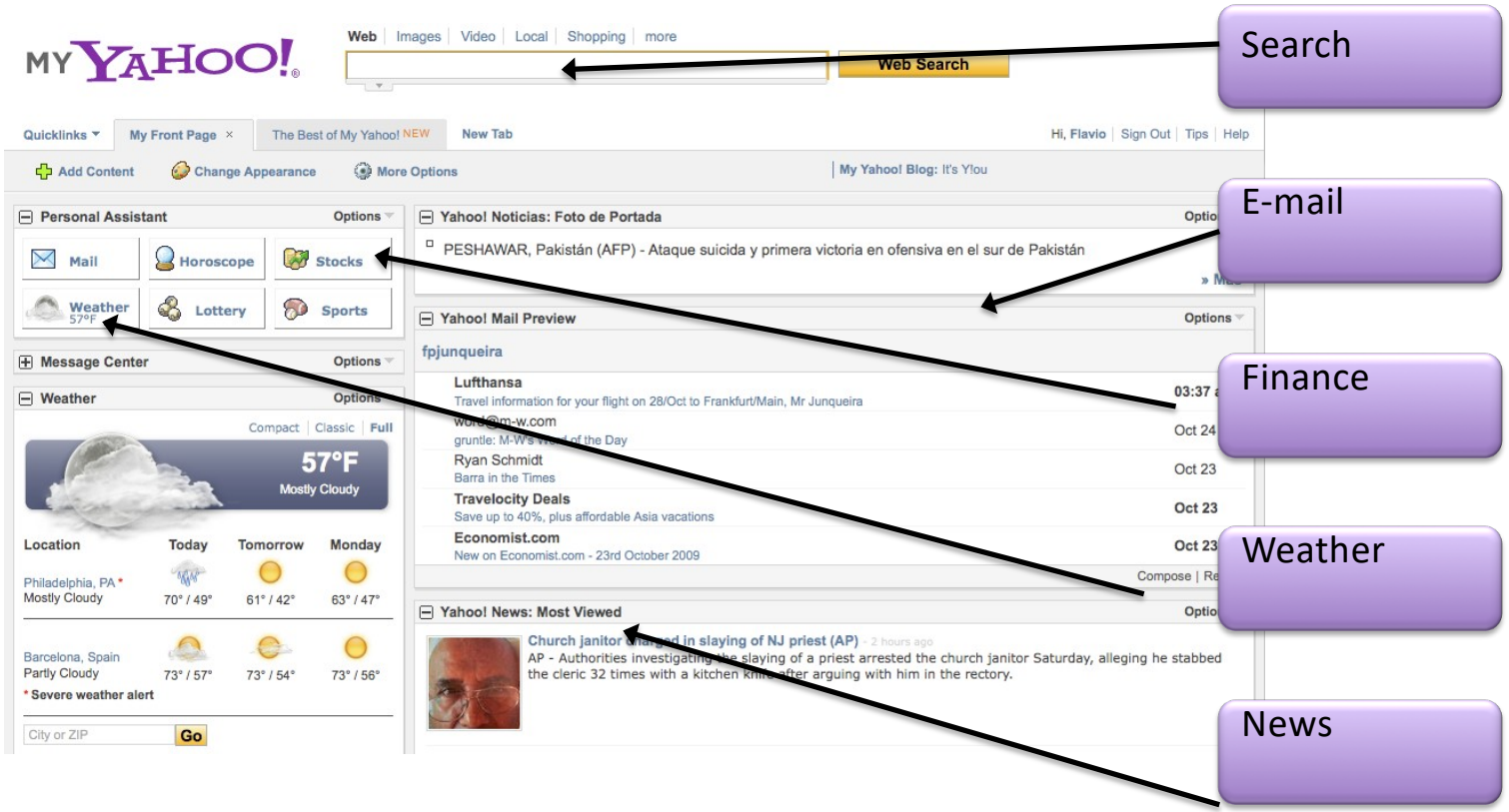
CS 5450

ZooKeeper

"Because coordinating distributed systems is a Zoo"

Slides from Ken Birman and EuroSys 2011 ZooKeeper tutorial

Yahoo! Portal (2011)



Yahoo! Workload (2011)

- Home page
  - 38 million users a day (USA)
  - 2.5 billion users a month (USA)
- Web search
  - 3 billion queries a month
- E-mail
  - 90 million actual users
  - 10 min/visit

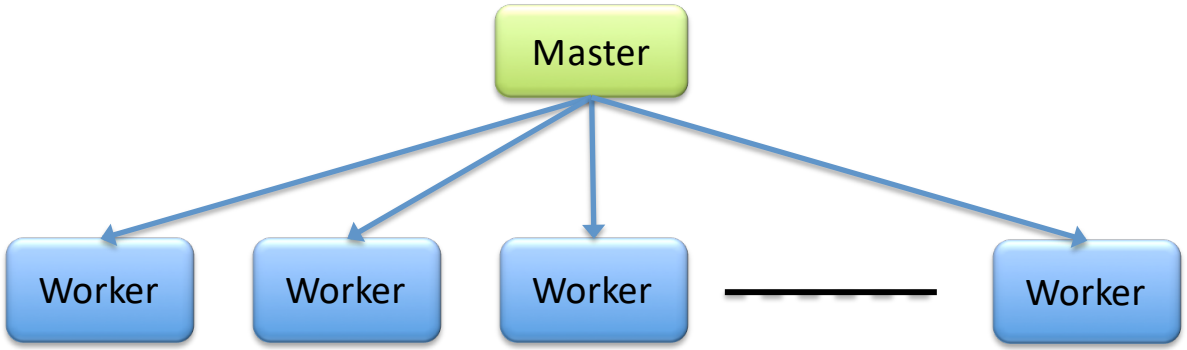
Yahoo! Infrastructure

- Lots of servers
- Lots of processes
- High volumes of data
- Highly complex software systems
- … and developers are mere mortals

Coordination is Important

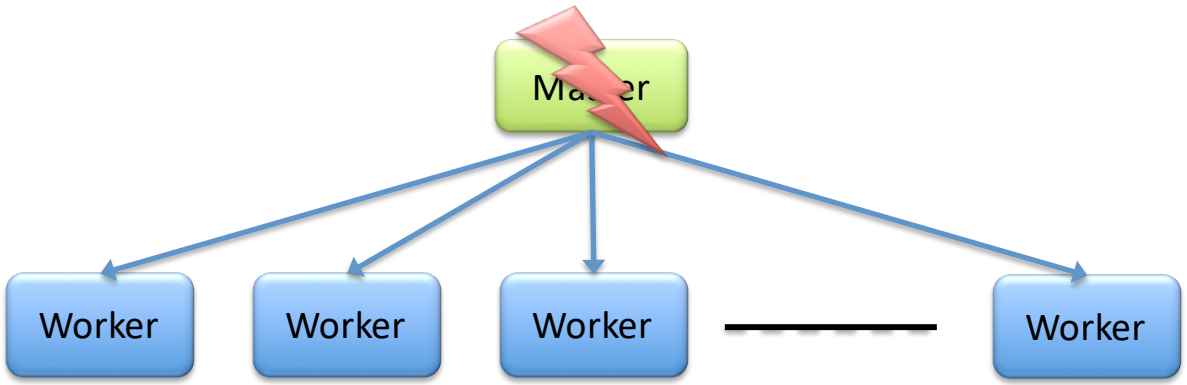
A Simple Master-Worker Model

- Master assigns work
- Workers execute tasks assigned by master



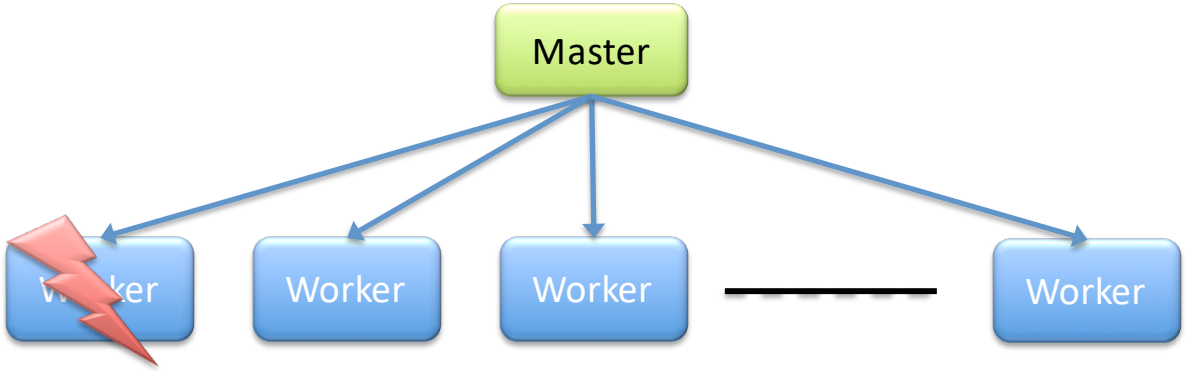
Master Crashes

- Single point of failure
- No work is assigned
- Need to select a new master



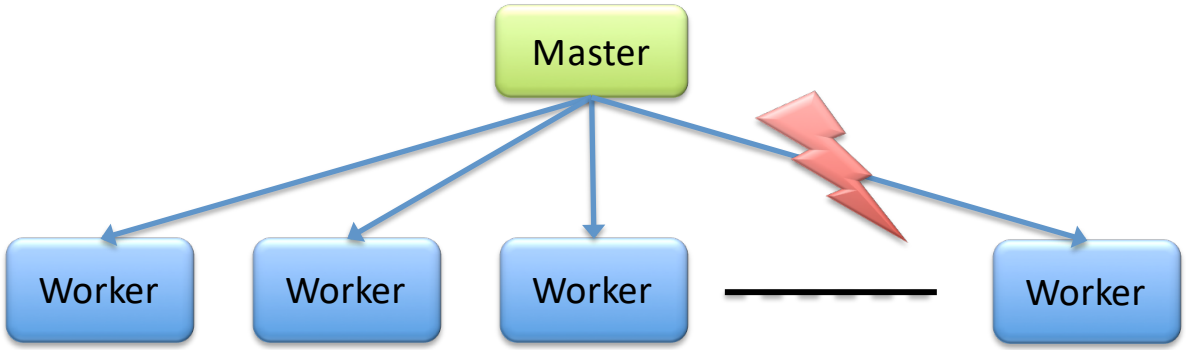
Worker Crashes

- Not as bad… overall system still works
  - … but not if there are dependencies
- Some tasks will never be executed
- Need to detect crashed workers

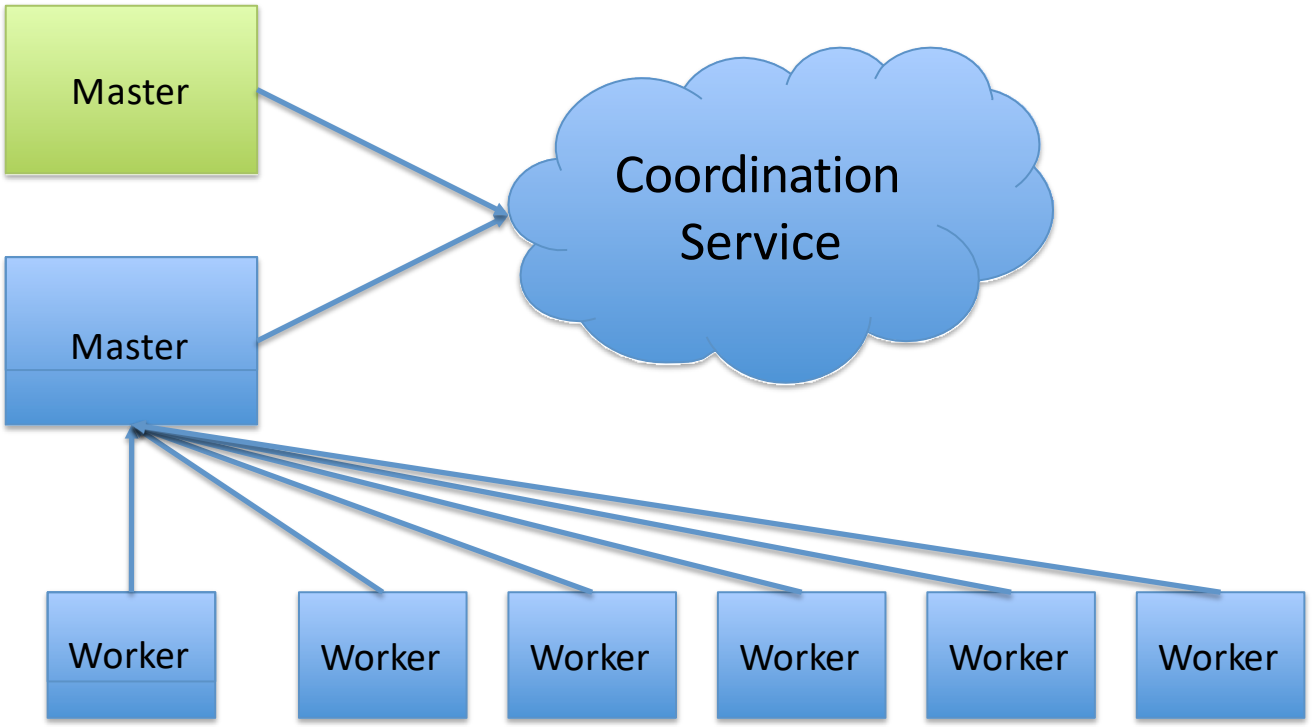


Worker Doesn't Receive Assignment

- Some tasks may not be executed
- Need to guarantee that worker receives assignment



Fault-Tolerant Distributed System



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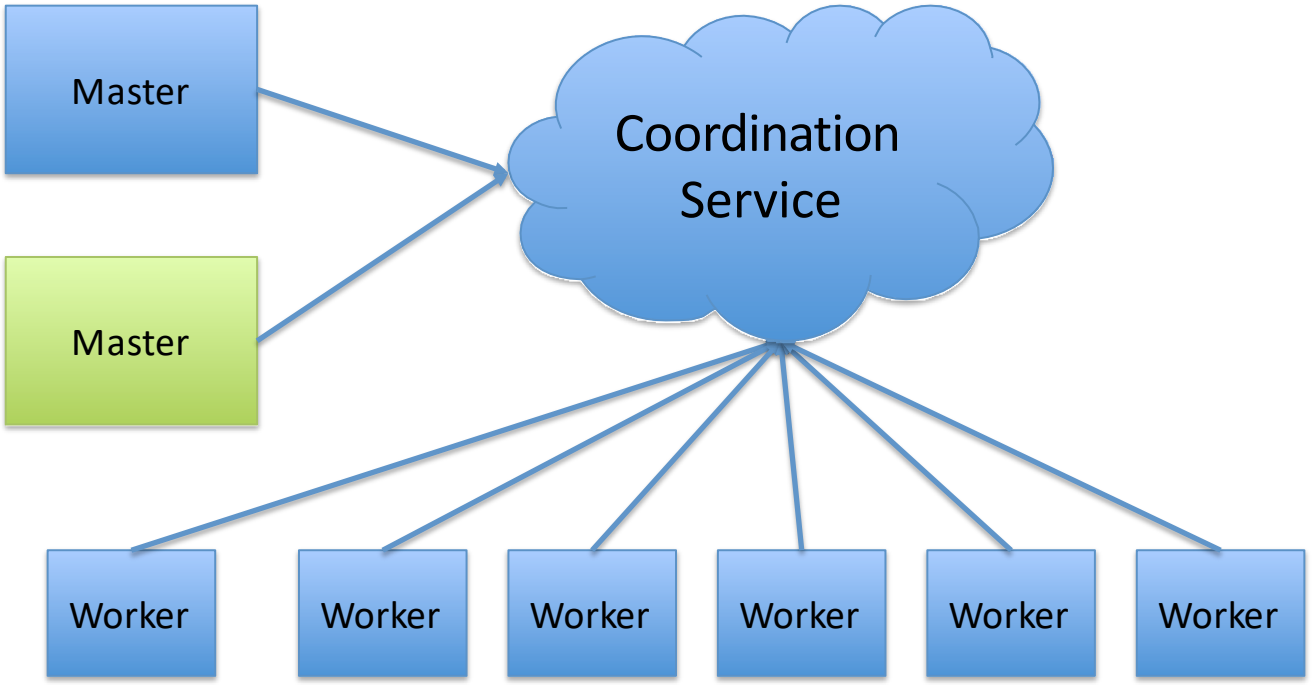
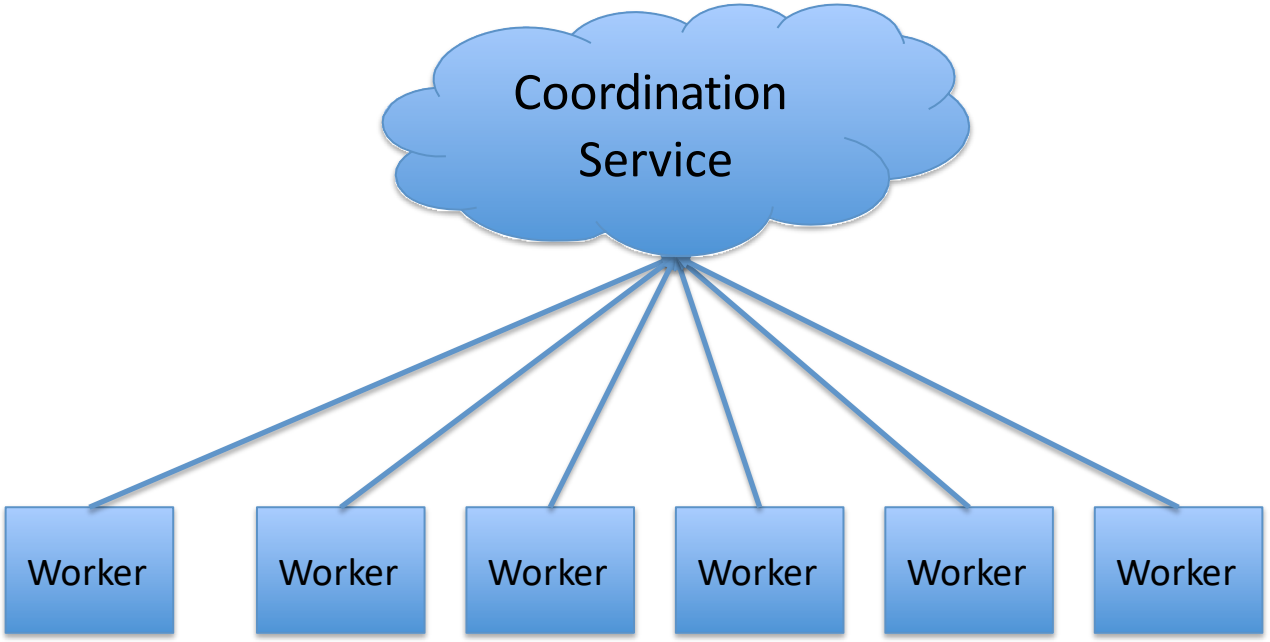


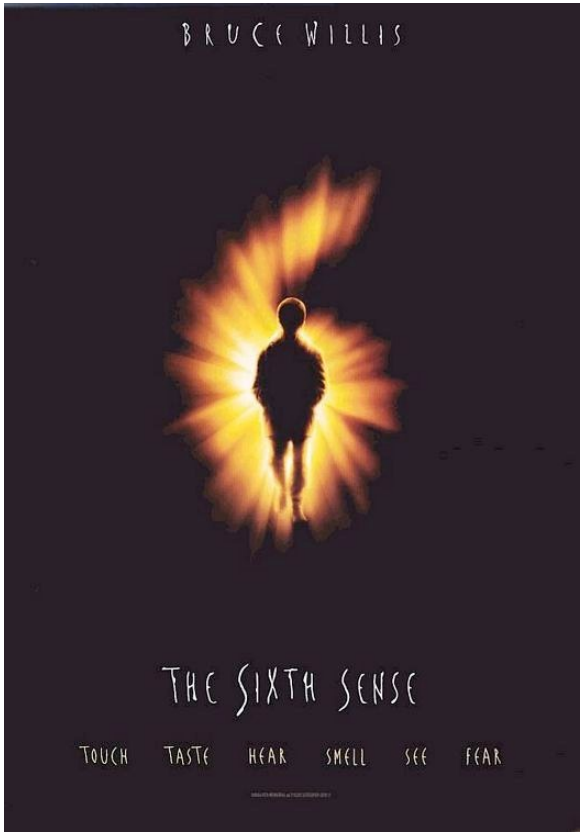
Fully Distributed System



Fallacies of Distributed Computing

1. The network is reliable.
2. Latency is zero.
3. Bandwidth is infinite.
4. The network is secure.
5. Topology doesn't change.
6. There is one administrator.
7. Transport cost is zero.
8. The network is homogeneous.

One More Fallacy



You know who is alive

Why Is This Difficult?

- FLP impossibility result
  - Consensus in asynchronous systems is impossible if a single process can crash
- CAP principle
  - Can’t obtain availability, consistency, and partition tolerance simultaneously

Why Need Coordination Services?

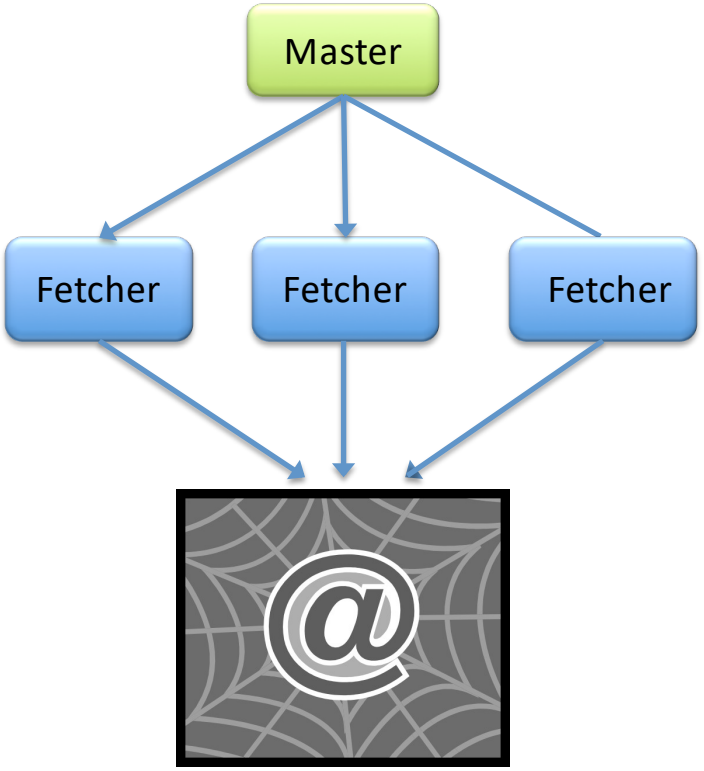
- Many impossibility results
- Many fallacies to stumble upon
- Several common requirements across applications
  - Duplicating is bad
  - Duplicating poorly is even worse
- Coordination service
  - Implement it once and well
  - Share by multiple applications

Bigtable, HBase Requirements

- Master election
  - Tolerate master crashes
- Metadata management
  - ACLs, tablet metadata
- Rendezvous
  - Find tablet server
- Crash detection
  - Live tablet servers

Example: Web Crawling

- Master election
  - Assign work
- Metadata management
  - Politeness constraints
  - Shards
- Crash detection
  - Live workers



More Examples

- GFS – Google File System
  - Master election
  - File system metadata
- KaCa – document indexing system
  - Shard information
  - Index version coordination
- Hedwig – Pub-Sub system
  - Topic metadata
  - Topic assignment

Existing Coordination Systems

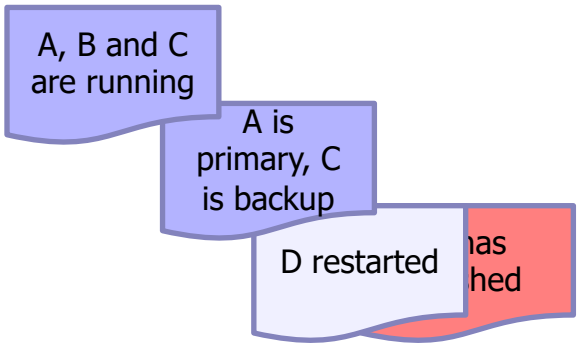
- Chubby (Google)
  - Lock service
- Centrifuge (Microsoft)
  - Lease service
- ZooKeeper (Yahoo!, Apache since 2008)
  - Coordination kernel

Coordination by Logging

- The quality of failure sensing is limited
- If we use timeouts to sense faults, we might make mistakes. Then if we reassign the role but the "faulty" machine is still running and was just transiently inaccessible, we have two controllers!
- This problem is unavoidable in a distributed system, so need agreement on membership, not "apparent timeout" -- the log plays this role
  - Where to log? Global file system?

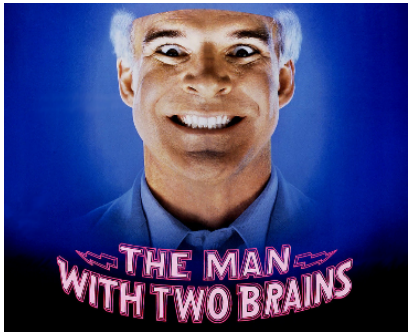
Logging Concurrent Events

- Maintain a global log of computer status events: “crashed”, “recovered”…
- The log is append-only: when you sense something, write to the end of the log
- Issue: if two events occur more or less at the same time, one can overwrite the other, hence one might be lost



Overwrites Cause Inconsistency

- If logging status of machines, some machines may have seen the overwritten update and think that A crashed, but others never saw this msg
  - Worst case: maybe A is really up and the original log report was due to a transient timeout… but now half the system thinks A is up, and half thinks A is down
- The system has a "split brain"



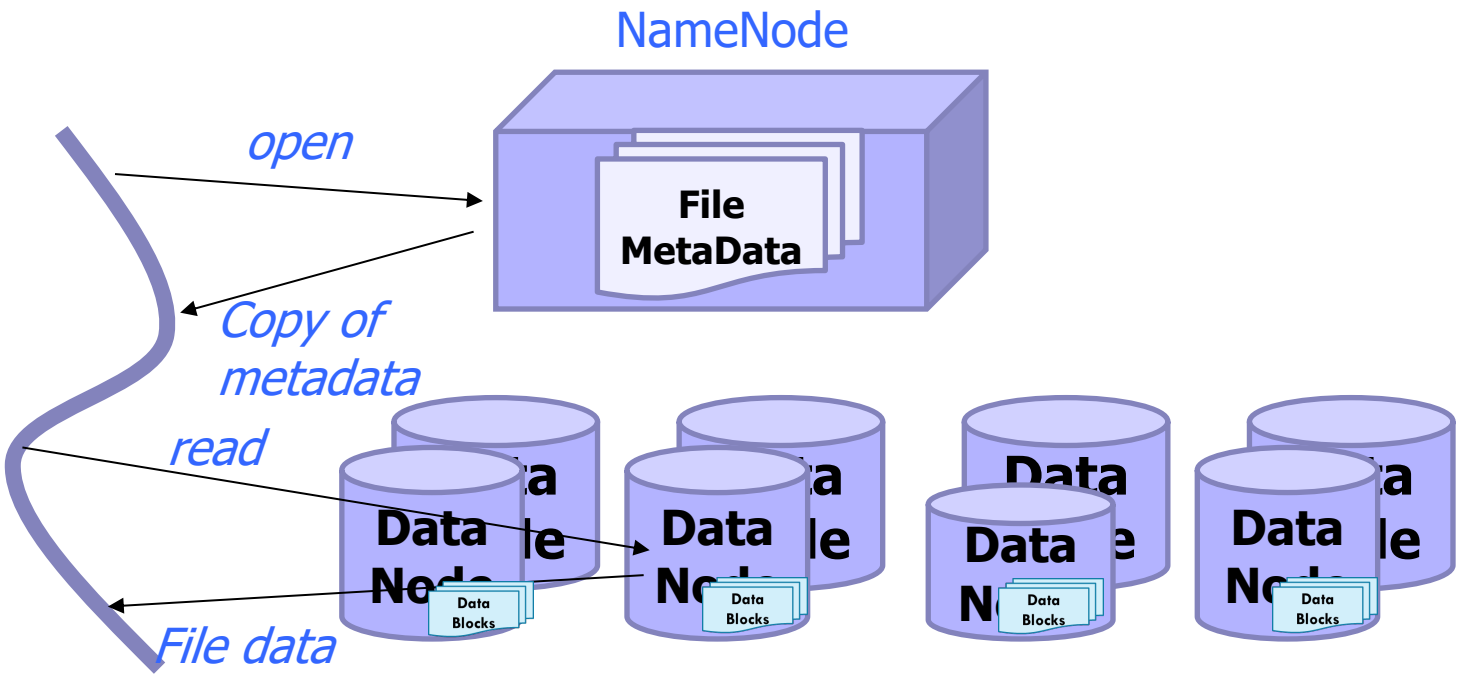
Need to Trust the Log

- If you trust the log, just read log records from top to bottom and get an unambiguous way to track membership
  - Trust in the log depends on the storage where the log is stored
- Even if a logged record is "wrong", e.g. "node 6 has crashed" but it hasn't, everyone is forced to agree to use that record

Need Consistent Storage

- In many systems two or more programs can try to write to the same file at the same time or to create the same file
- The normal Linux file system will work correctly if the programs and the files are all on one machine; writes to the local file system won't interfere
- Distributed, global file systems lack this property!

Global File Systems



Google File System
Amazon S3
Azure storage fabric

Global File Systems: Pros and Cons

Pros	Cons
1. Scales well even for massive objects 2. Works well for large sequential reads/writes, 3. Provides high performance (massive throughput) 4. Simple but robust reliability model	1. NameNode (Master) can become overloaded, especially if individual files become extremely popular 2. … a single point of failure 3. … if slow, can impact the whole data center 4. Concurrent writes to the same file can interfere with one another

With GFS, Can't Trust Log

- These file systems don't guarantee consistency, they are unsafe with concurrent writes
  - The protocol required for safe concurrent writes is slower than their weak consistency model
- Concurrent log appends can…
  - Overwrite each other, so one is lost
  - Be briefly perceived out of order, or some machine might glimpse a written record that will be overwritten a moment later
  - Sometimes two conflicting versions can even linger for extended periods

How Things Goes Wrong

"Append-only log" behavior

1. Machines A, B and C are running

2-a. Machine D is launched

2-b. Concurrently, B thinks A crashed

3. 2-b is overwritten by 2-a

4. A turns out to be fine, after all

In an application using it

- A is selected to be the primary controller for some functionality, C is assigned as backup.
- C notices 2-b and takes over. But A hasn't really crashed – B was wrong!
- **Log entry 2-b is gone.**

  A keeps running.
- Now we have A and C both in the controller role – a split brain!

ZooKeeper

- Many systems need a place to store configuration, parameters, lists of which machines are running, which nodes are "primary" or "backup", etc.
  - Distributed coordination problems
- File-system interface with strong, fault-tolerant semantics
  - Tree model for organizing information into nodes
- Stronger guarantees than GFS, but…
  - Data lives in small files
  - Slow and not very scalable

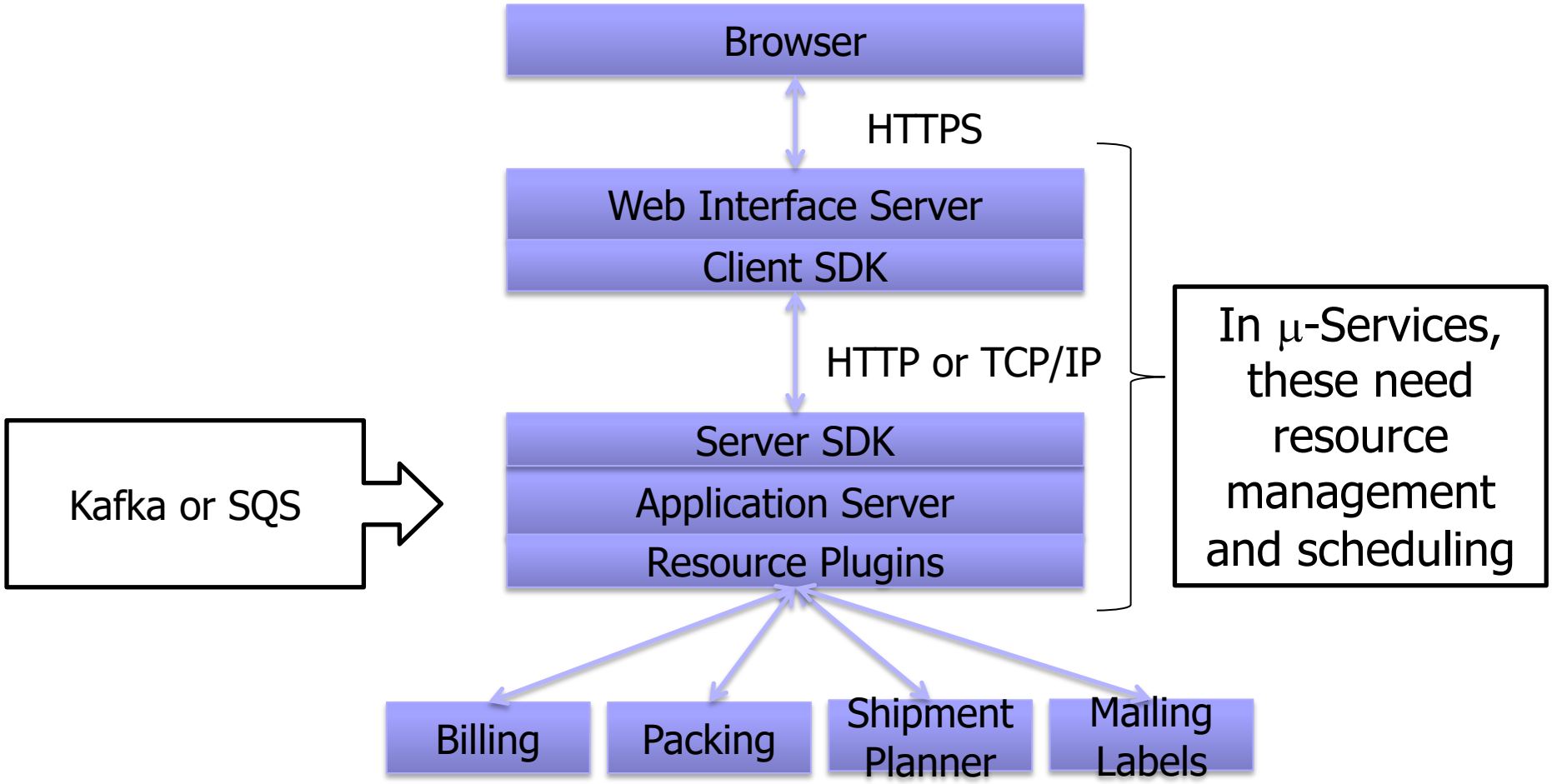
When To Use ZooKeeper

- For small objects used to do distributed coordination, synchronization, or configuration
- Not for persistent data
  - If shut down, loses state
  - Checkpointing every 5s by default, but recent updates will be lost
  - Most applications simply leave ZooKeeper running and if it shuts down, the whole application shuts down and restarts

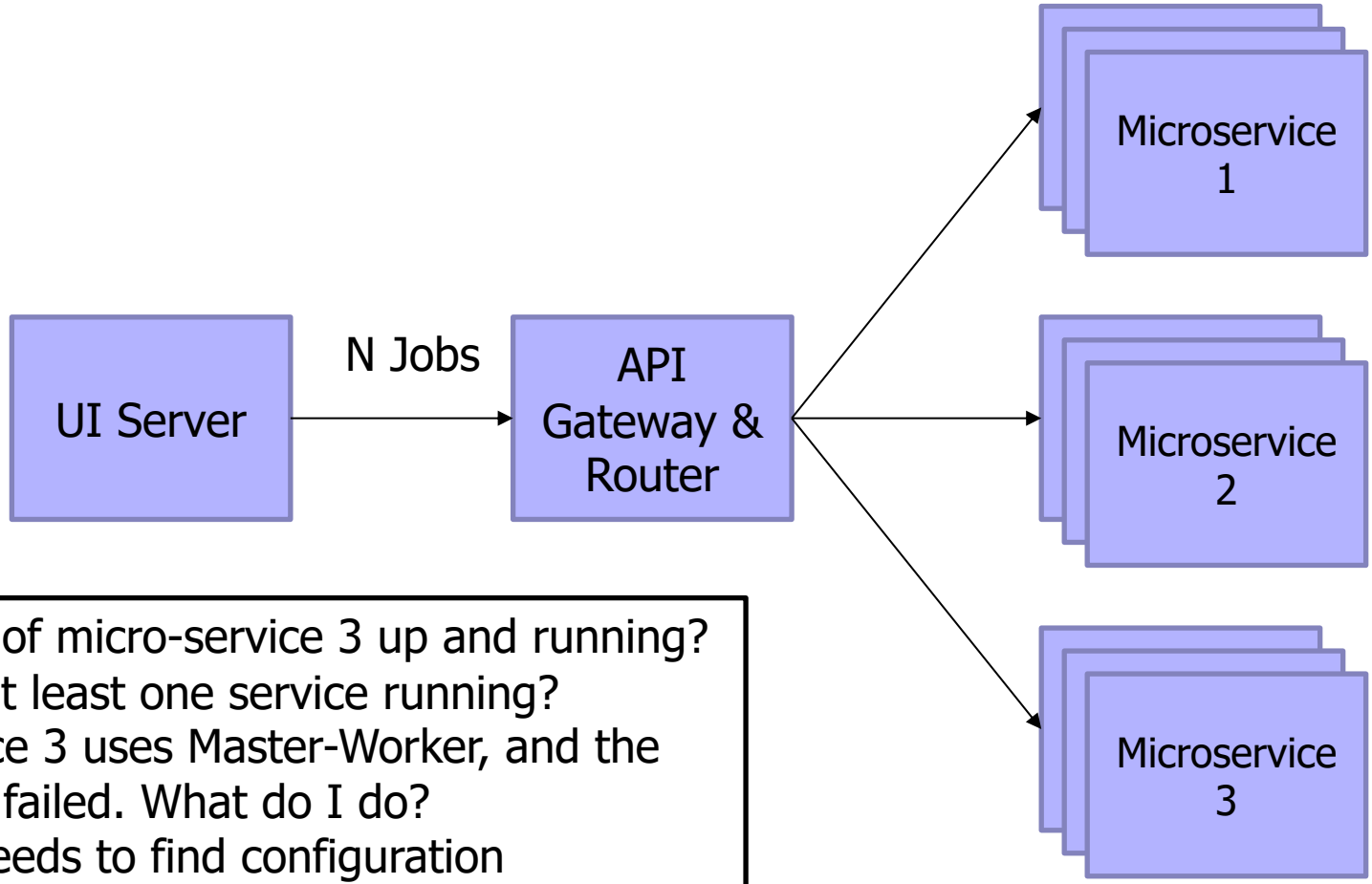
Uses of ZooKeeper

- Naming service
  - Identifying nodes in a cluster by name ("DNS" for nodes)
- Configuration management
  - Up-to-date system config info for a joining node
- Cluster management
  - Joining / leaving of nodes, real-time node status
- Leader election
  - Electing a node as leader for coordination purpose
- Locking and synchronization service
- Highly reliable data registry

Example: Amazon Micro-services

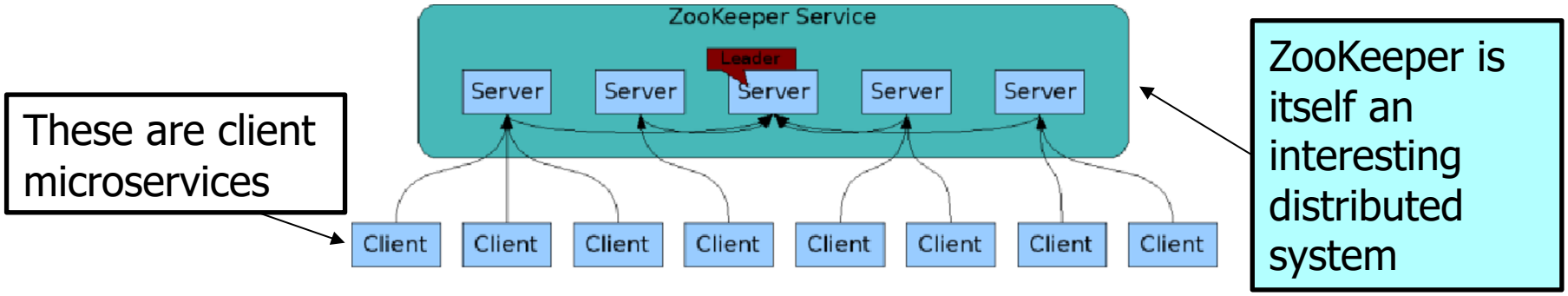


Coordinating A Simple Micro-service



- Is replica 2 of micro-service 3 up and running?
- Do I have at least one service running?
- Micro-service 3 uses Master-Worker, and the Master just failed. What do I do?
- Replica 2 needs to find configuration information. How can it do that?

ZooKeeper Architecture



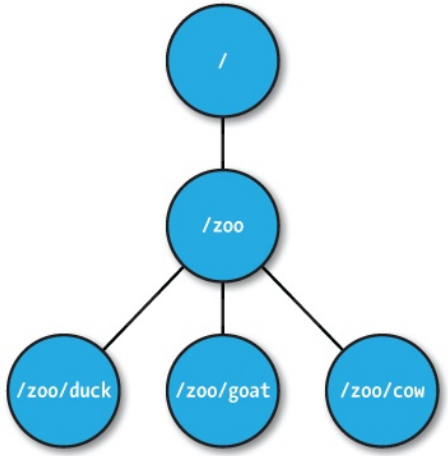
- ZooKeeper Service is replicated over a set of machines
- All machines store a copy of the data **in memory** (!), optional checkpointing to disk
- A leader is elected on service startup
- Client only connects to a single ZooKeeper server & maintains a TCP connection
- Can read from any ZooKeeper server
- Writes go through the leader & need majority consensus

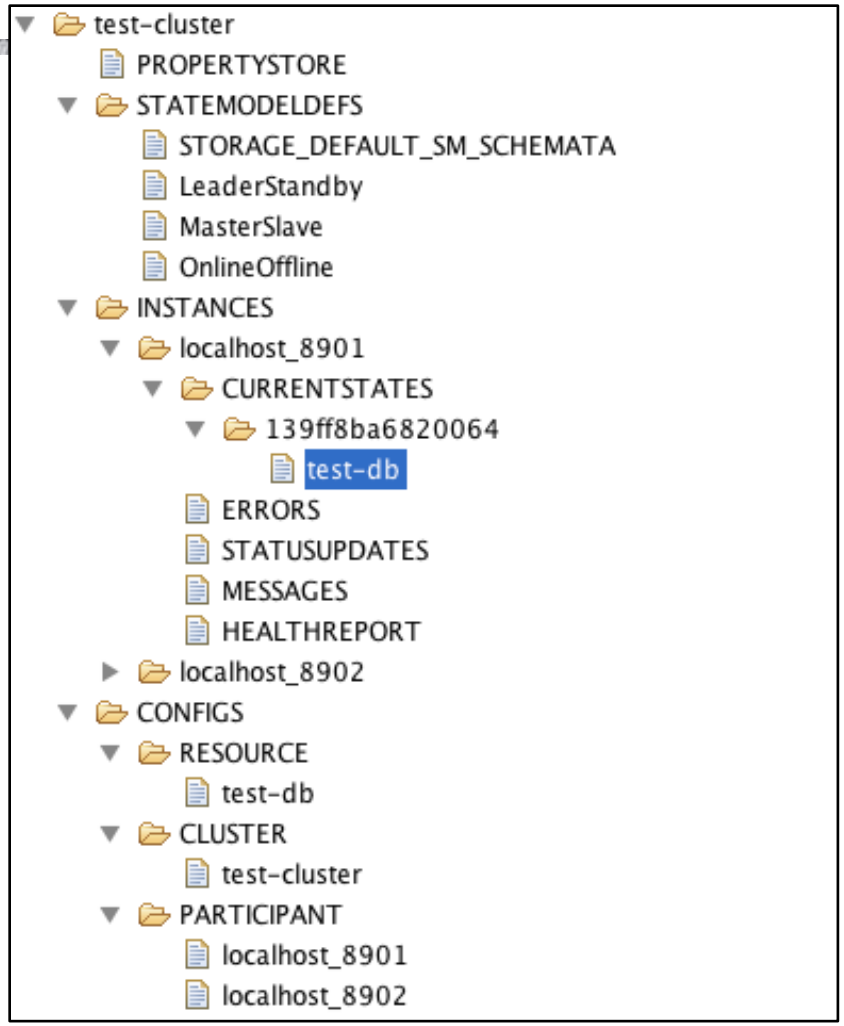
Data Management in ZooKeeper

- Clients (i.e., applications) create and discover nodes on ZooKeeper trees
- Clients put small pieces of data into the nodes and get small pieces out
  - 1 MB max for all data per server by default
  - Each node also has built-in metadata like its version number
- OS analogy: lock files and .pid files on Linux systems

Znodes

- Maintain file meta-data with version numbers for data changes, ACL changes and timestamps.
- Version numbers increases with changes
- Data is read and written in its entirety





Znode Types

Regular

- Clients create and delete explicitly

Ephemeral

- Like regular znodes associated with sessions
- Deleted when session expires

Sequential

- Property of regular and ephemeral znodes
- Has a universal, monotonically increasing counter appended to the name

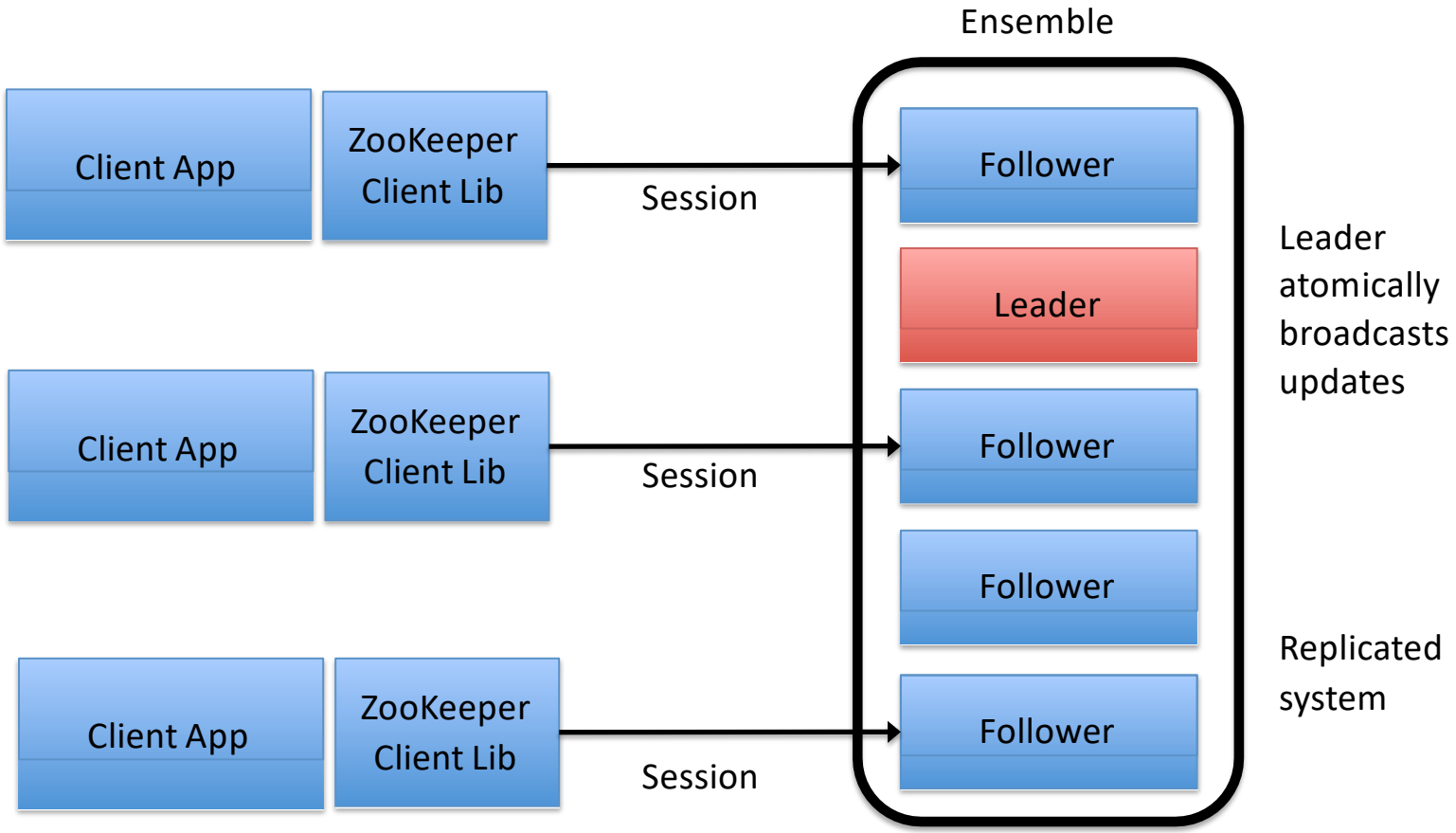
ZooKeeper API (1)

- **create(path, data, flags):** Creates a znode with path name path, stores data in it, and returns the name of the new znode
  - **flags** enables a client to select the type of znode: regular or ephemeral, and set the sequential flag;
- **delete(path, version):** Deletes the znode path if that znode is at the expected version
- **exists(path, watch):** Returns true if the znode with **path** name exists, false otherwise

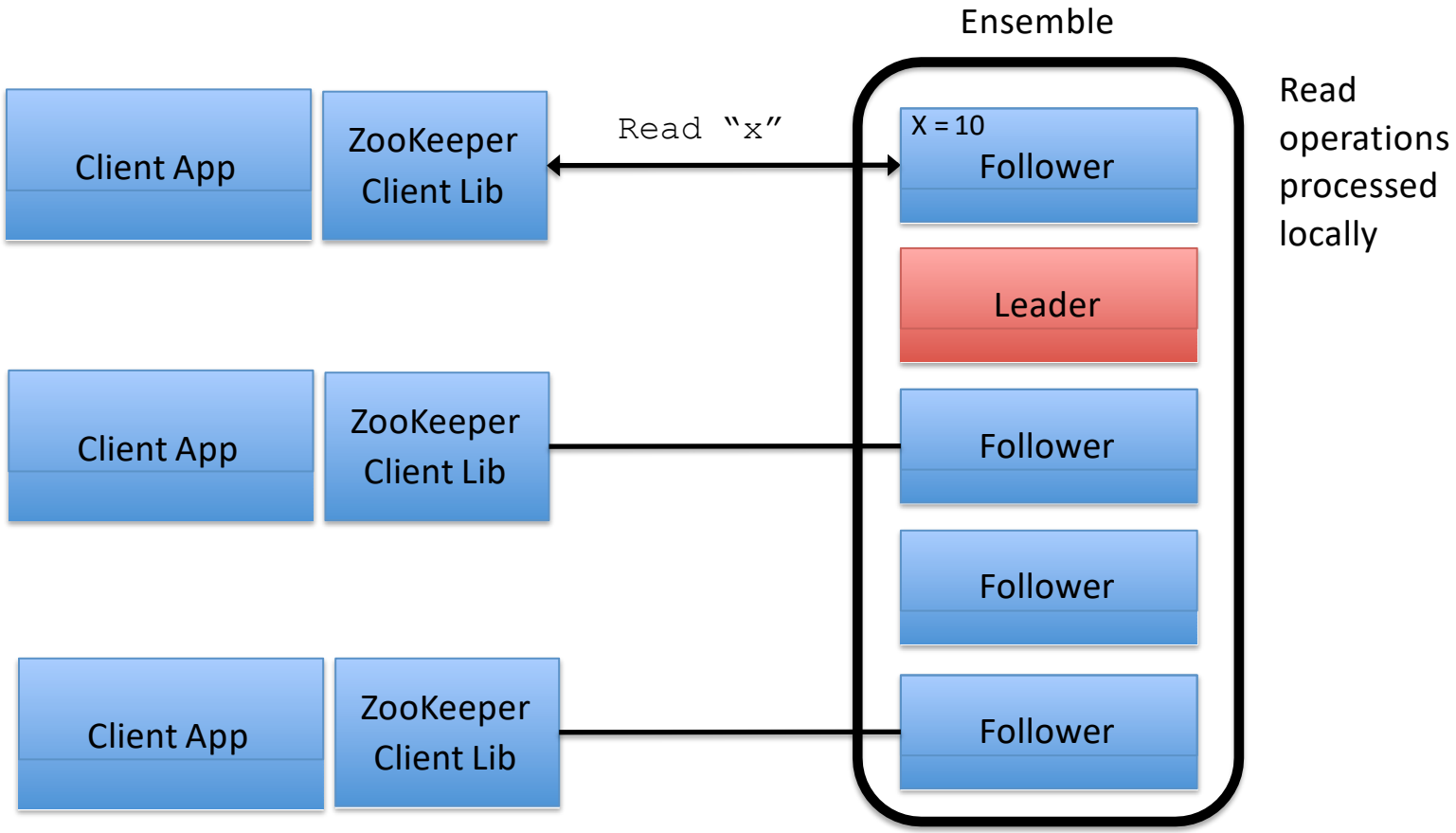
ZooKeeper API (2)

- **getData(path, watch):** Returns the data and metadata (eg, version information) associated with the znode
- **setData(path, data, version):** Writes data to znode **path** if the version number is the current version of the znode
- **getChildren(path, watch):** Returns the set of names of the children of a znode
- **sync(path):** Waits for all updates pending at the start of the operation to propagate to the server that the client is connected to

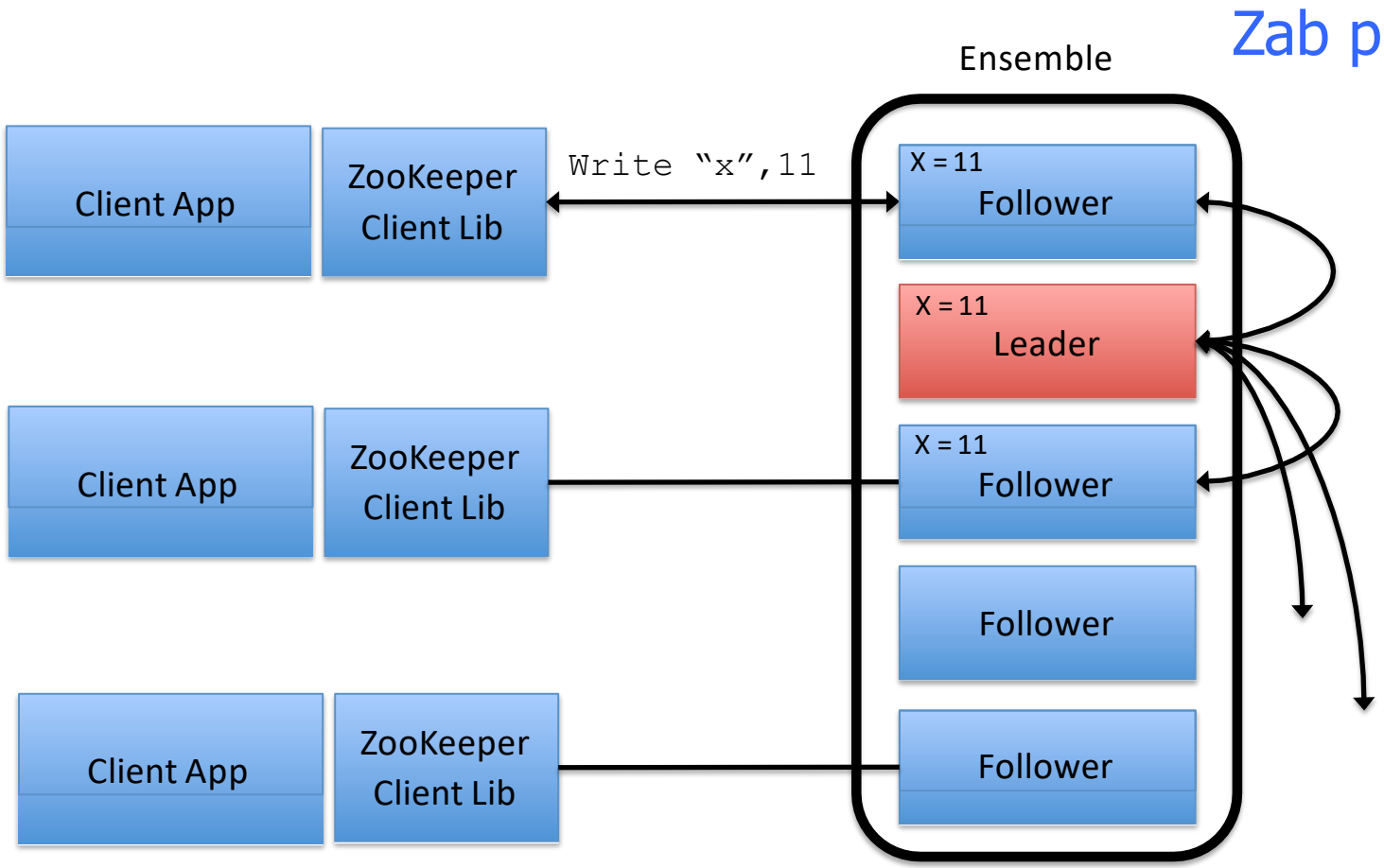
Overview of ZooKeeper API



ZooKeeper Reads



ZooKeeper Writes

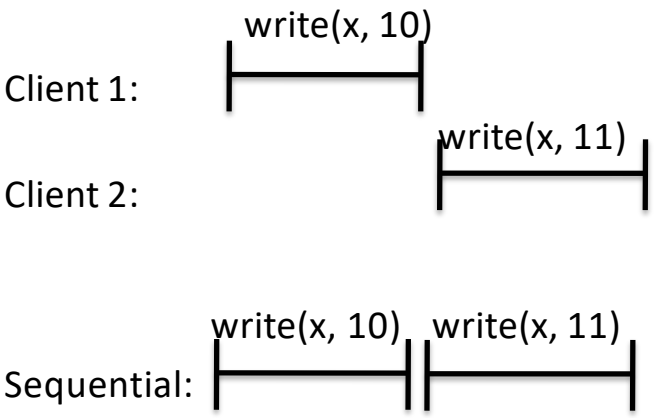


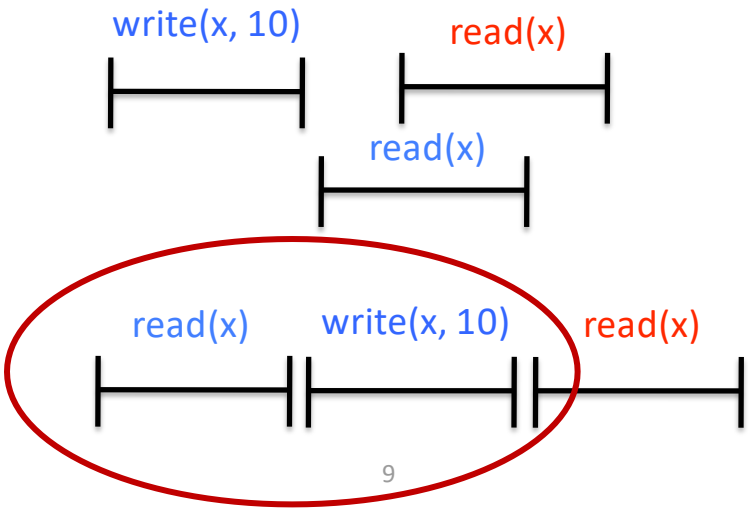
Reads and Writes (Summary)

- Reads are served by any ZooKeeper server
  - Scales linearly, although information can be stale
- Writes require a kind of consensus
  - One ZooKeeper server acts as the leader
  - The leader executes all write requests forwarded by followers
  - The leader then broadcasts the changes
  - The update is successful if a majority of ZooKeeper servers have correct state at the end of the protocol

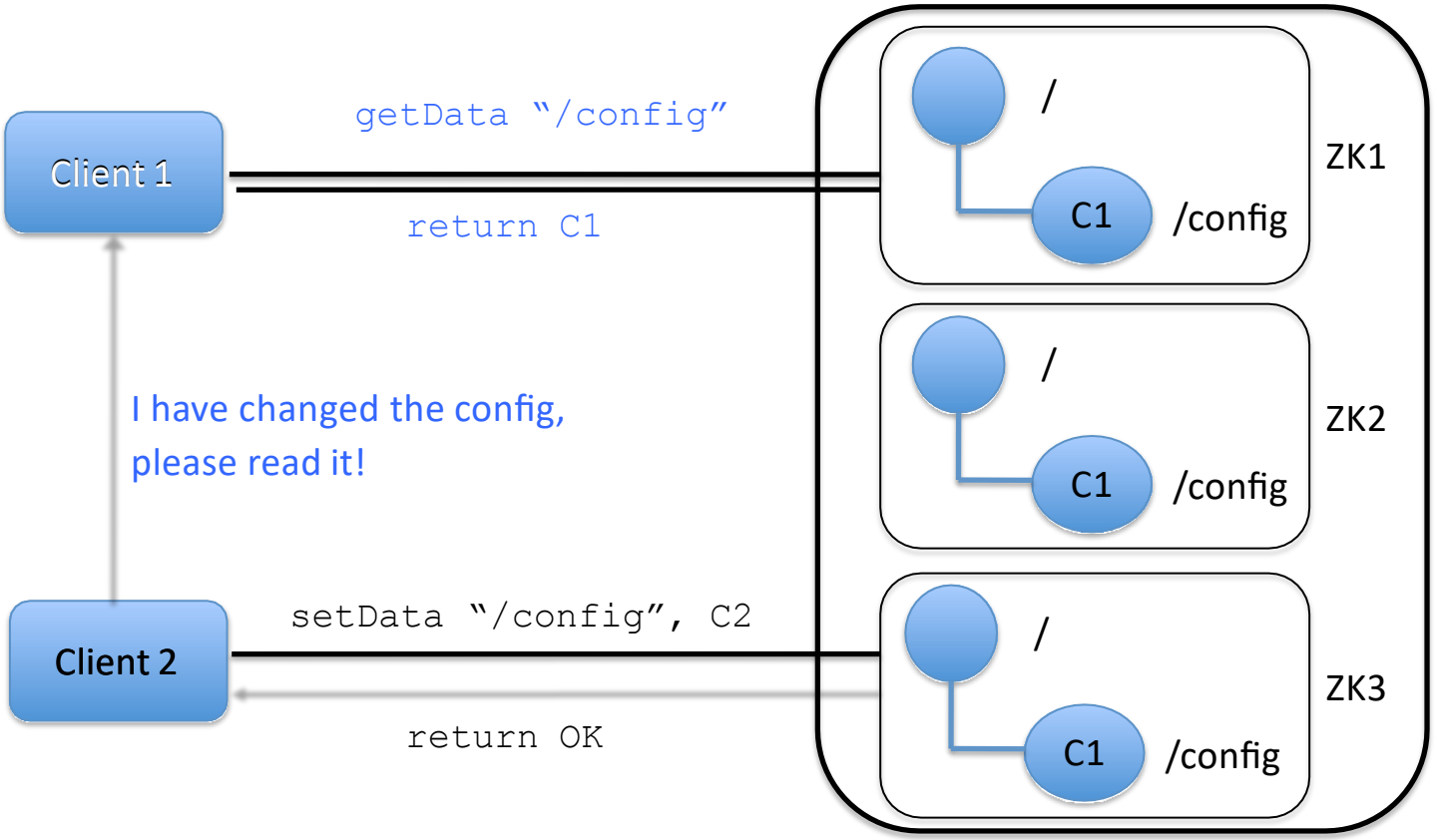
FIFO Order for Client Operations

- Updates: totally ordered, linearizable
- Reads: sequentially ordered



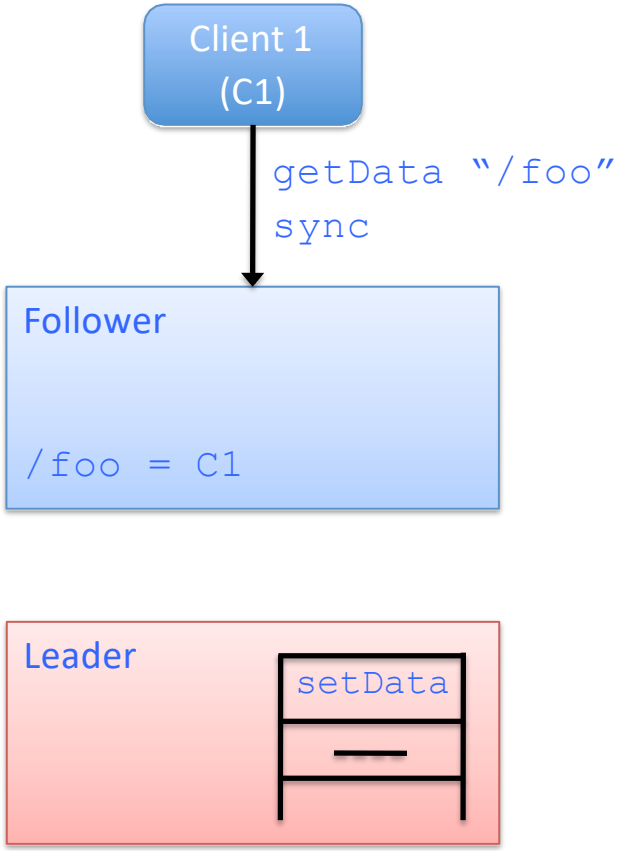


Hidden Channels



sync

- Asynchronous operation executed before read
- Synchronizes the state between follower and leader
- Makes operations linearizable



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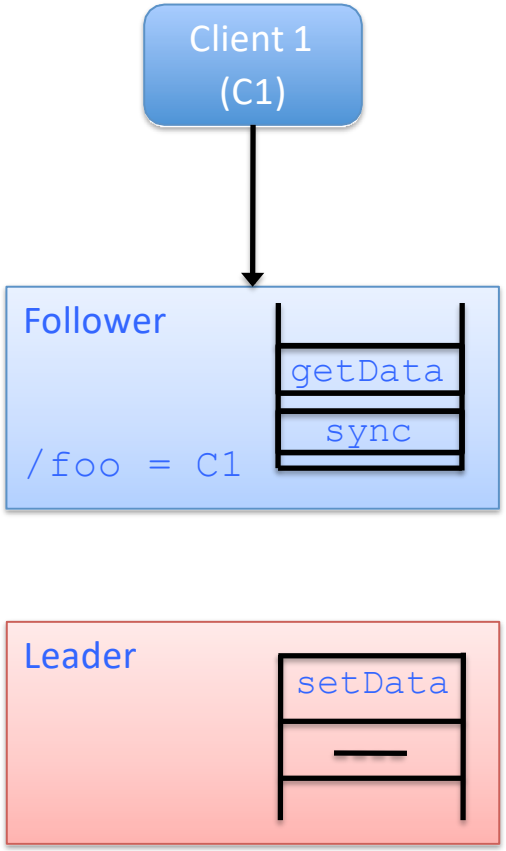

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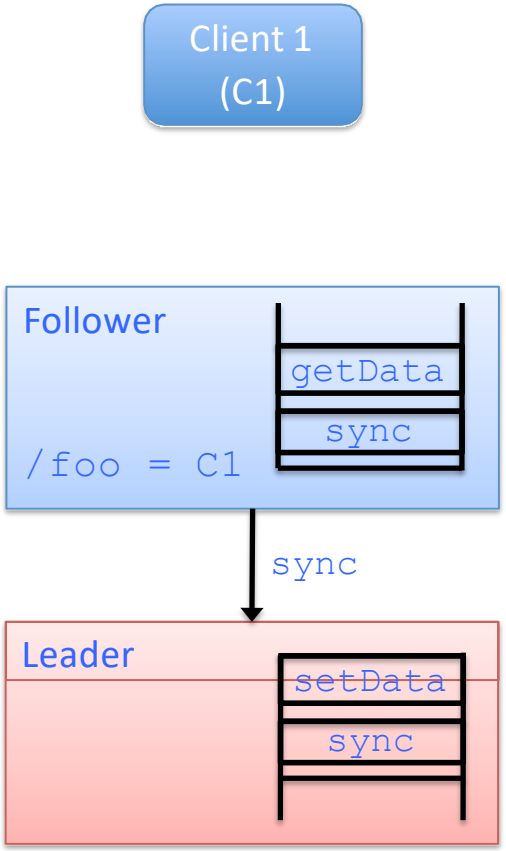

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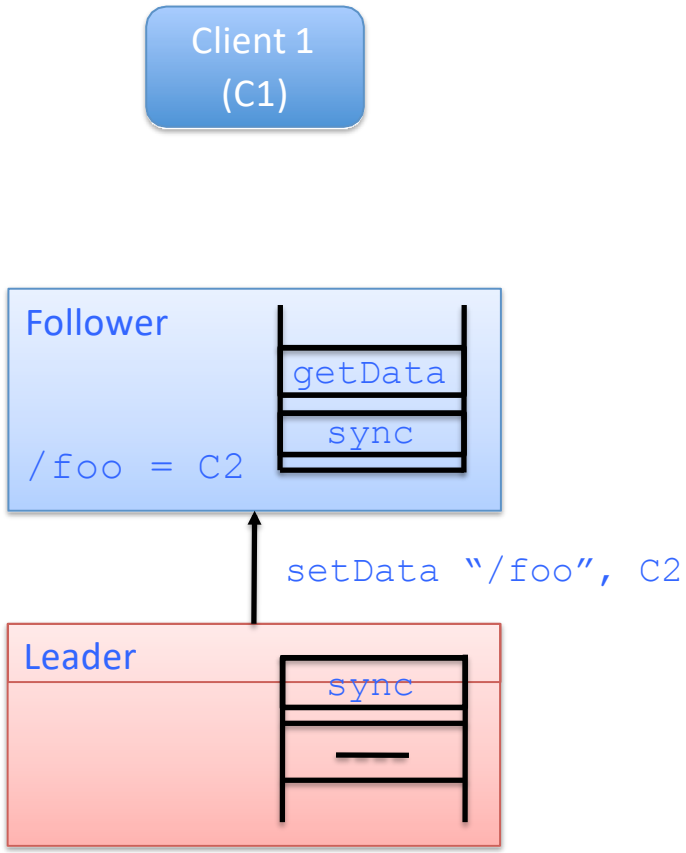

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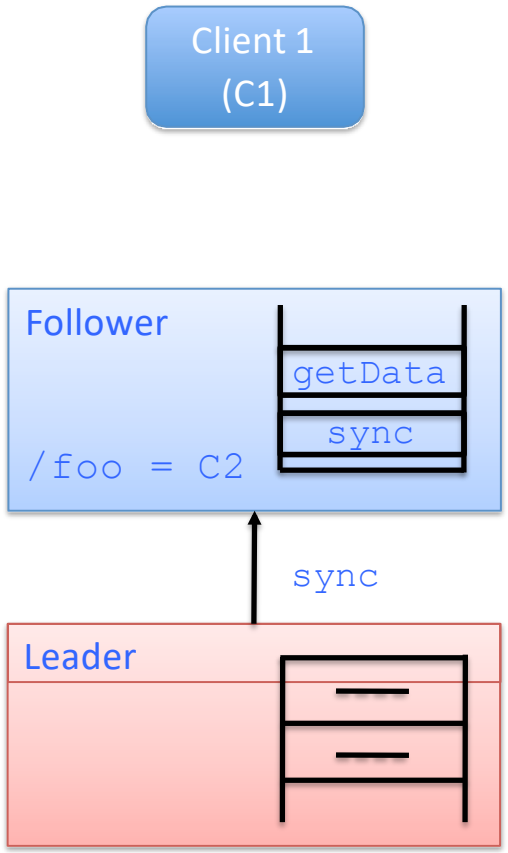

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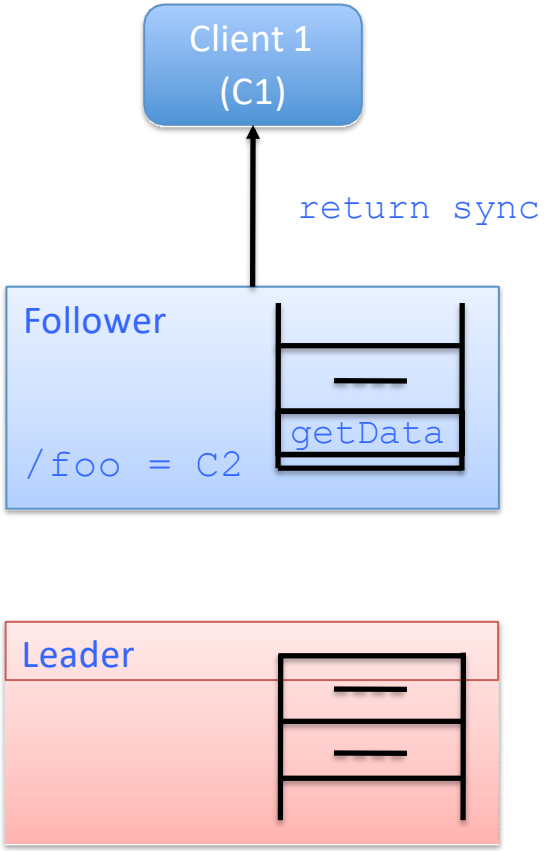

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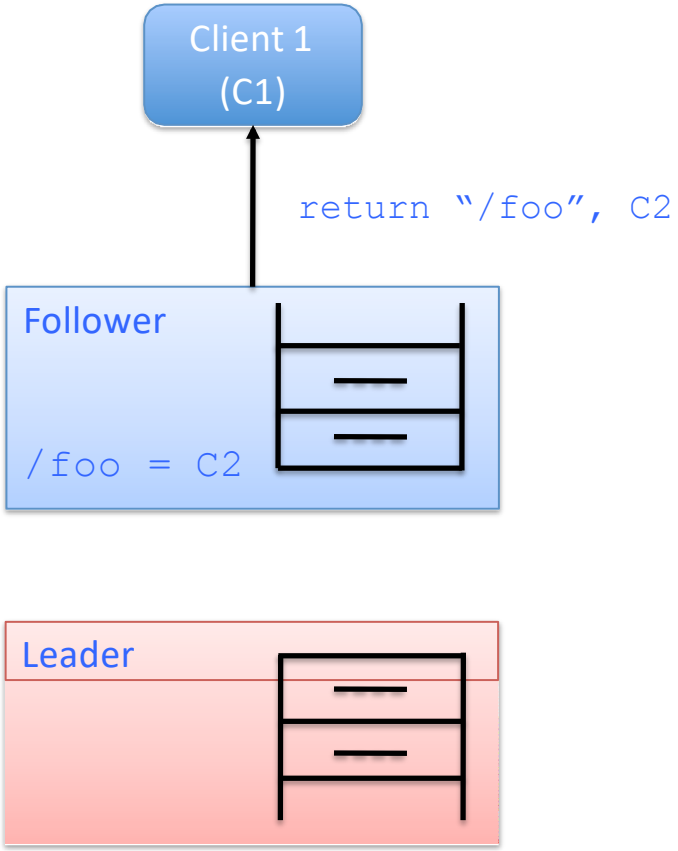
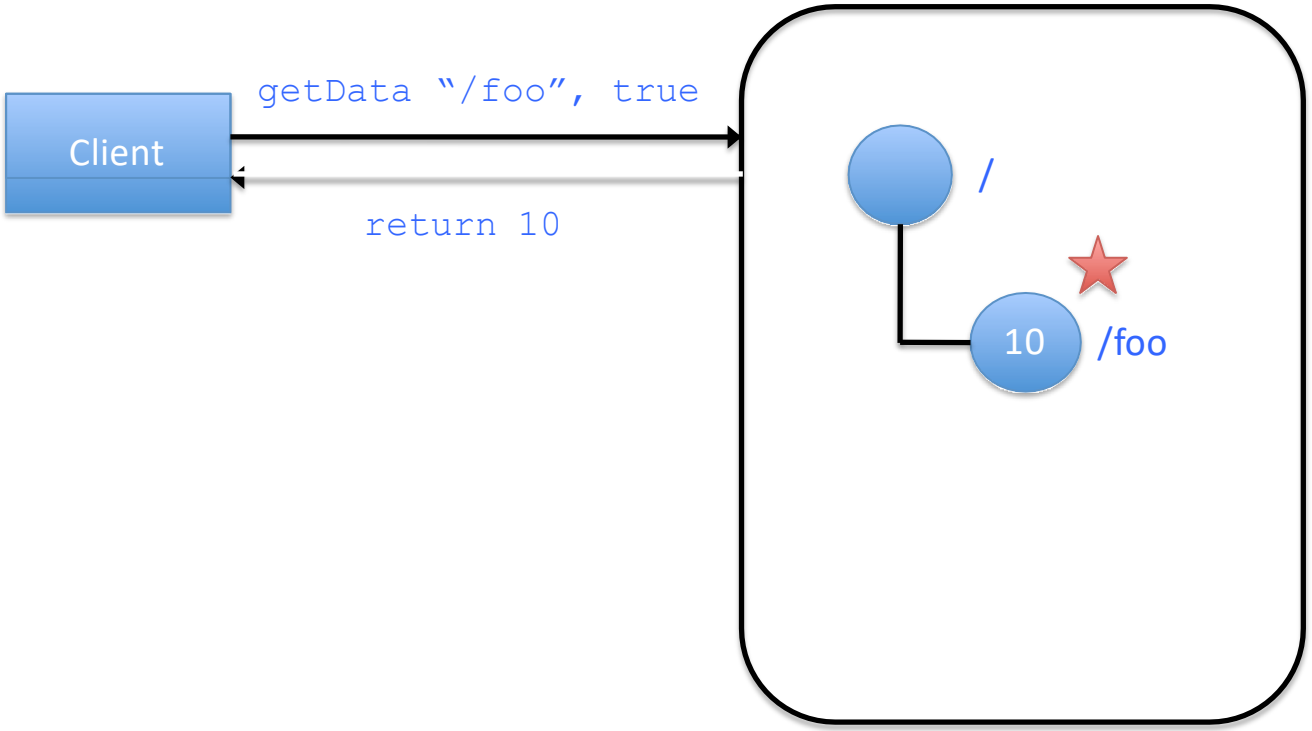


ZooKeeper Watch



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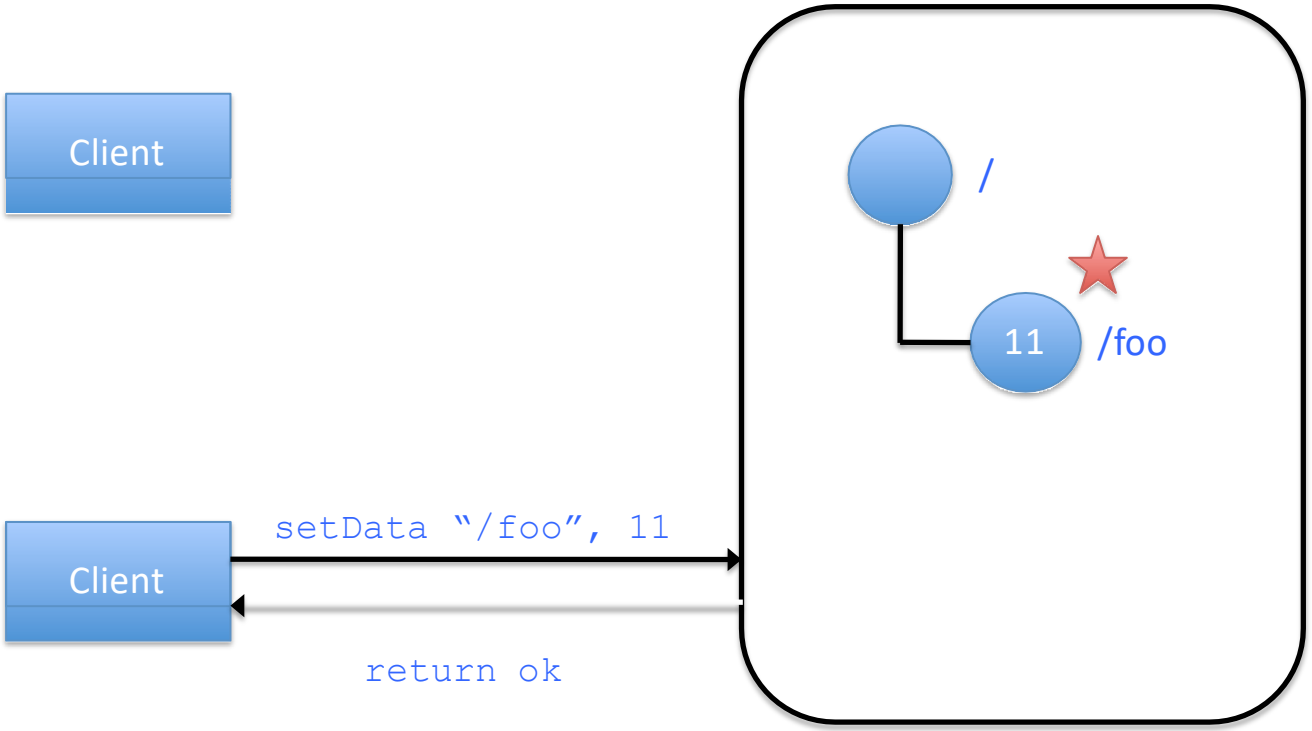

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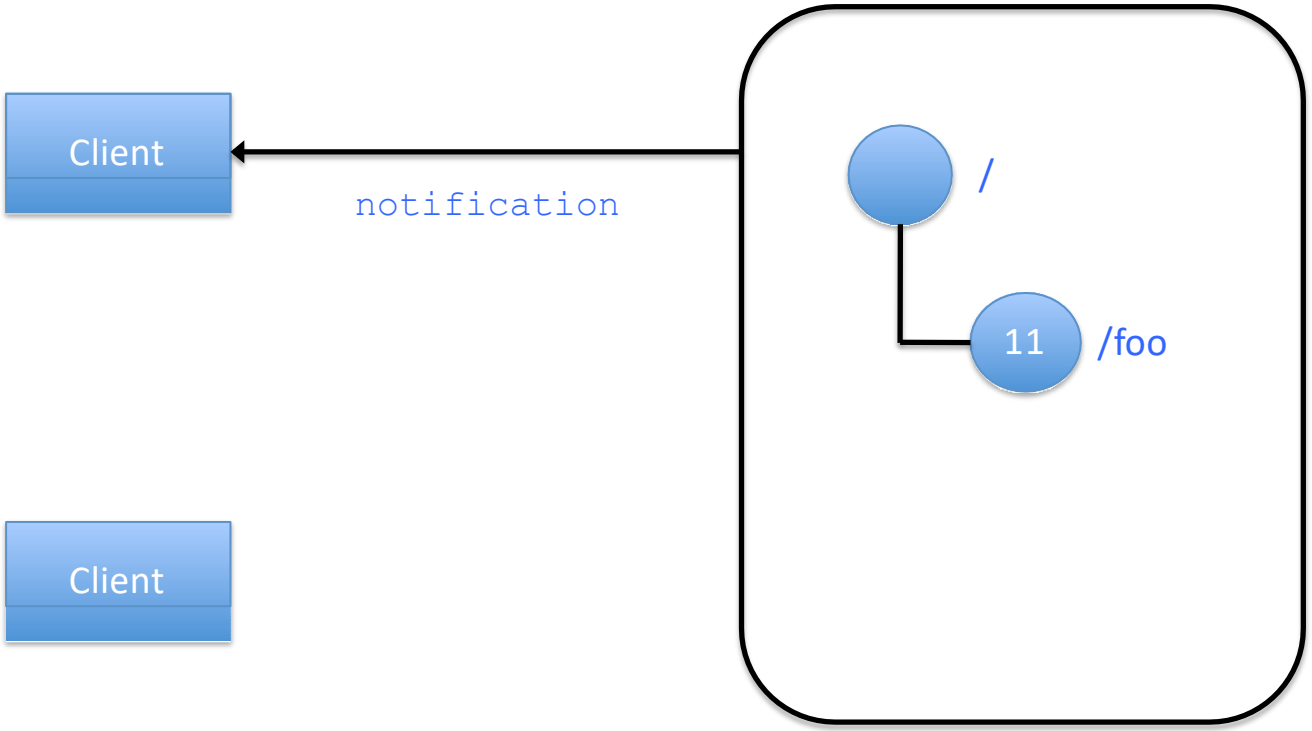


Implementation Details

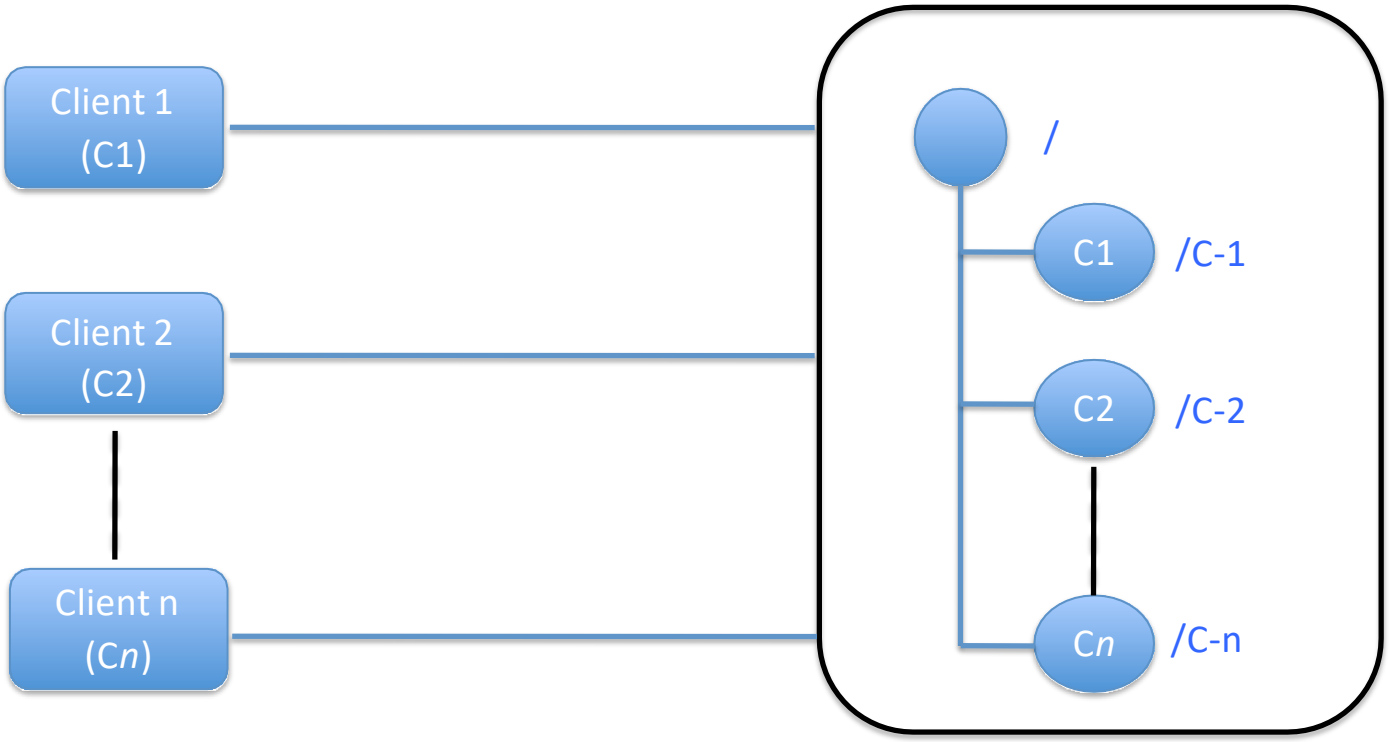
- Uses TCP for its transport layer
  - Message order is maintained by the (reliable?) network
- Assumes reliable file system
  - Logging and DB checkpointing
- Write-ahead logging
  - Requests are first written to the log
  - The ZooKeeper DB is updated from the log
  - ZooKeeper servers can acquire correct state by reading the logs from the file system
    - With checkpoints, need not reread the entire history

Example: Locks

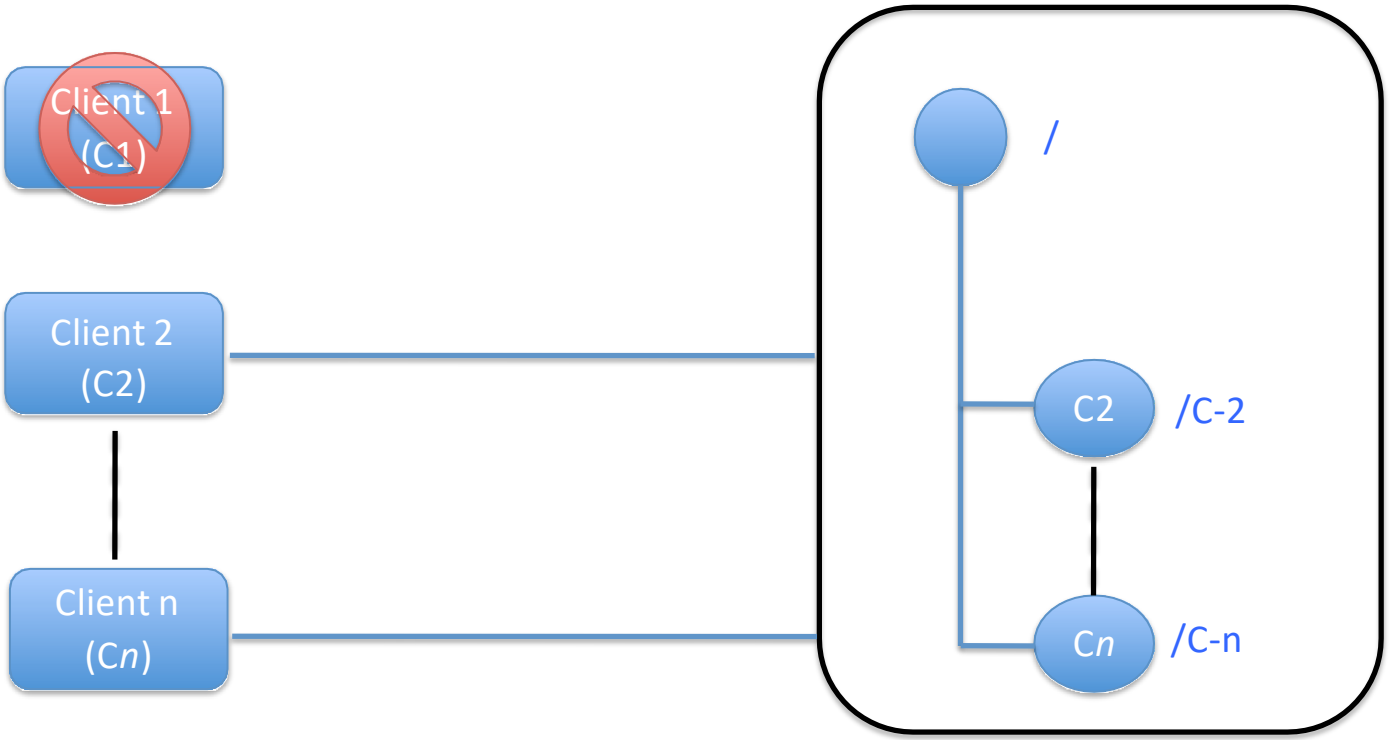
"Who is the leader with primary copy of data?"

- Implementation:
  - Leader creates an ephemeral file: /root/leader/lockfile
  - Other would-be leaders place watches on the lock file
  - If the leader client dies or doesn't renew the lease, clients can attempt to create a replacement lock file
- Use SEQUENTIAL to solve the herd effect problem
  - Create a sequence of ephemeral child nodes
  - Clients only watch the node immediately ahead of them in the sequence

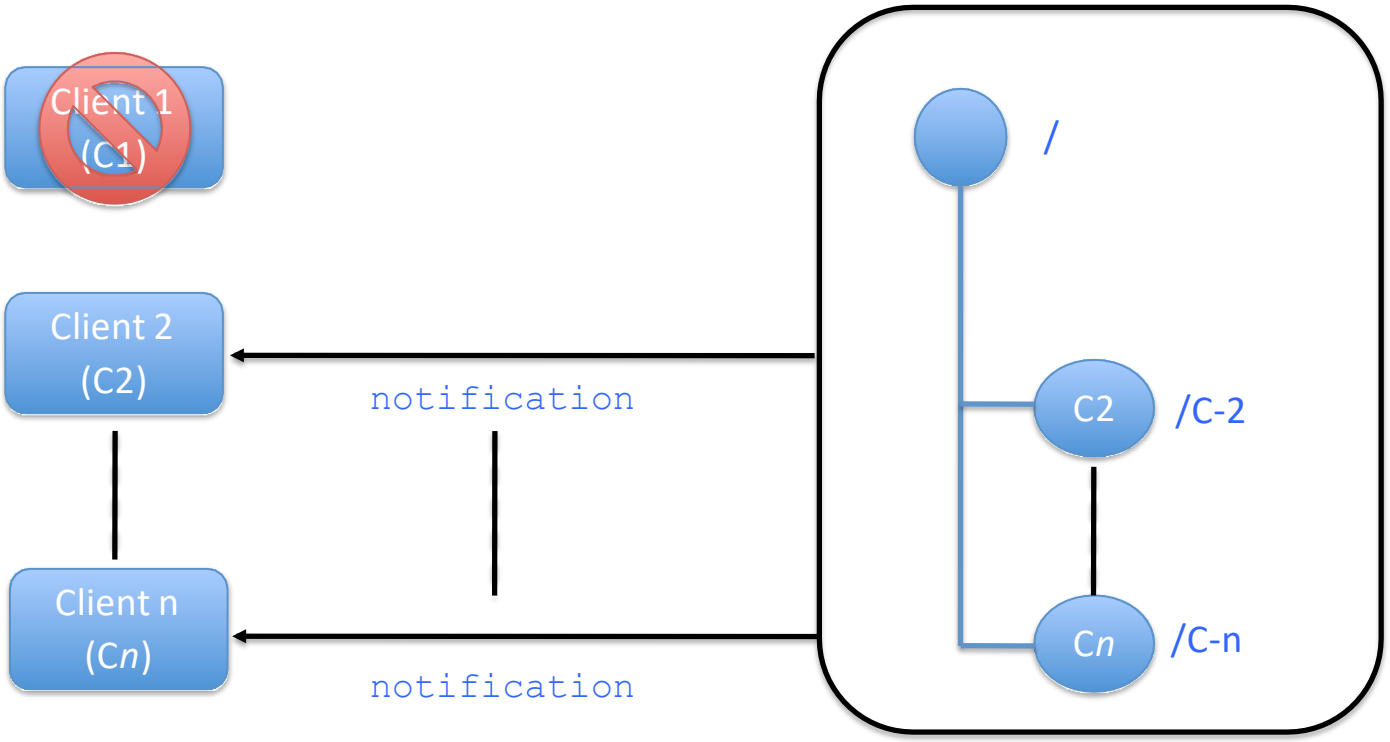
Herd Effect



Herd Effect



Herd Effect

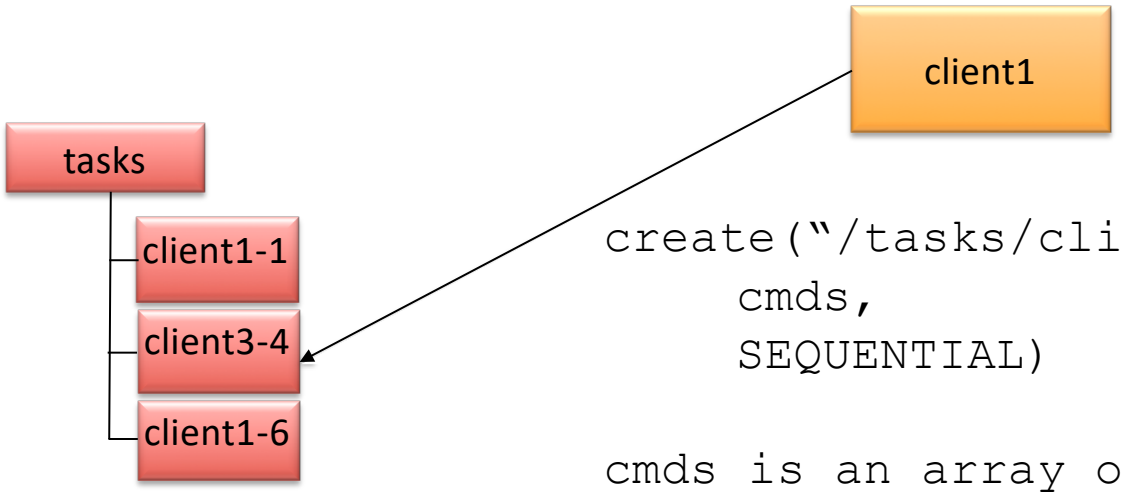


Load spike

Solving the Herd Effect

- Use order of clients
- Each client determines the znode preceding its own znode in the sequential order and watches that znode
- A single notification is generated upon a crash
- Disadvantage for leader election
  - One client is notified of a leader change

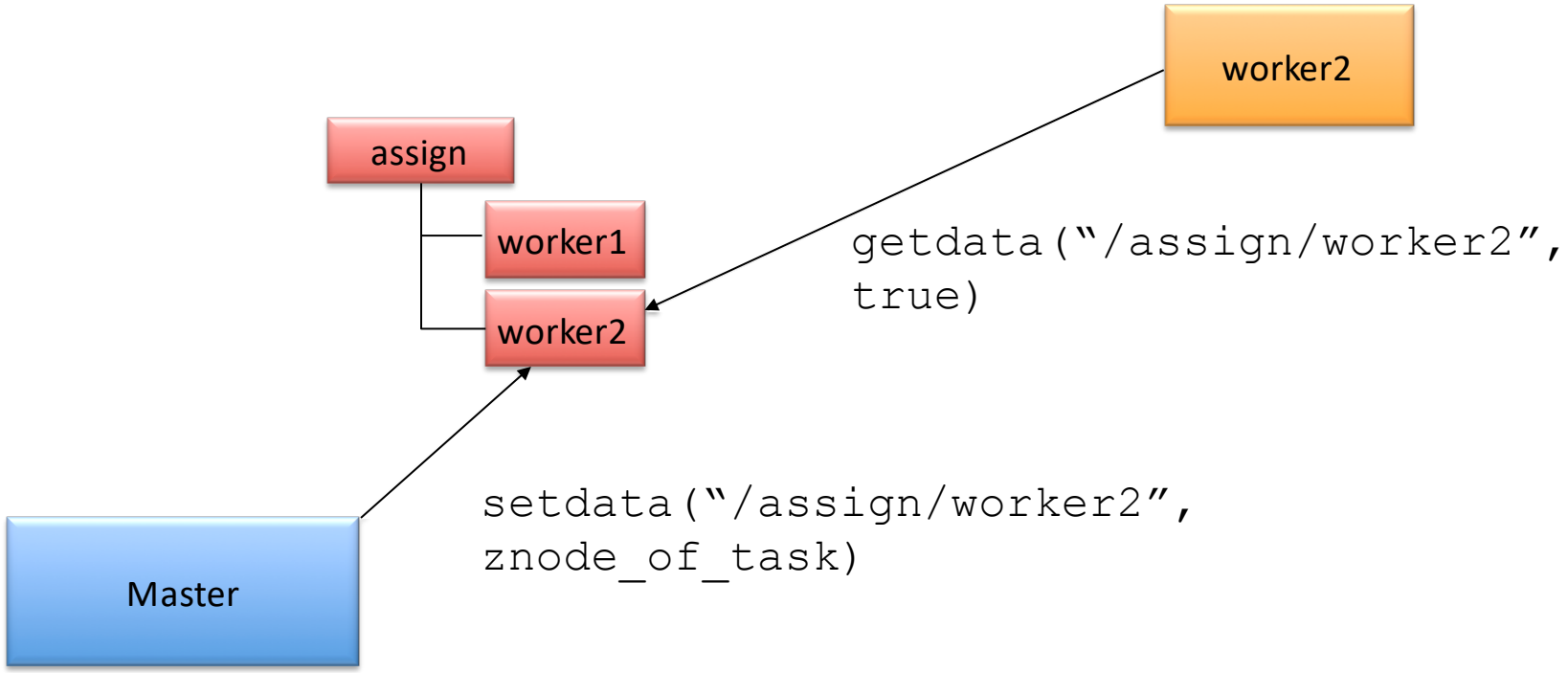
Task Queue




```
create("/tasks/client1-",
       cmds,
       SEQUENTIAL)

cmds is an array of String
```

Configuration Management



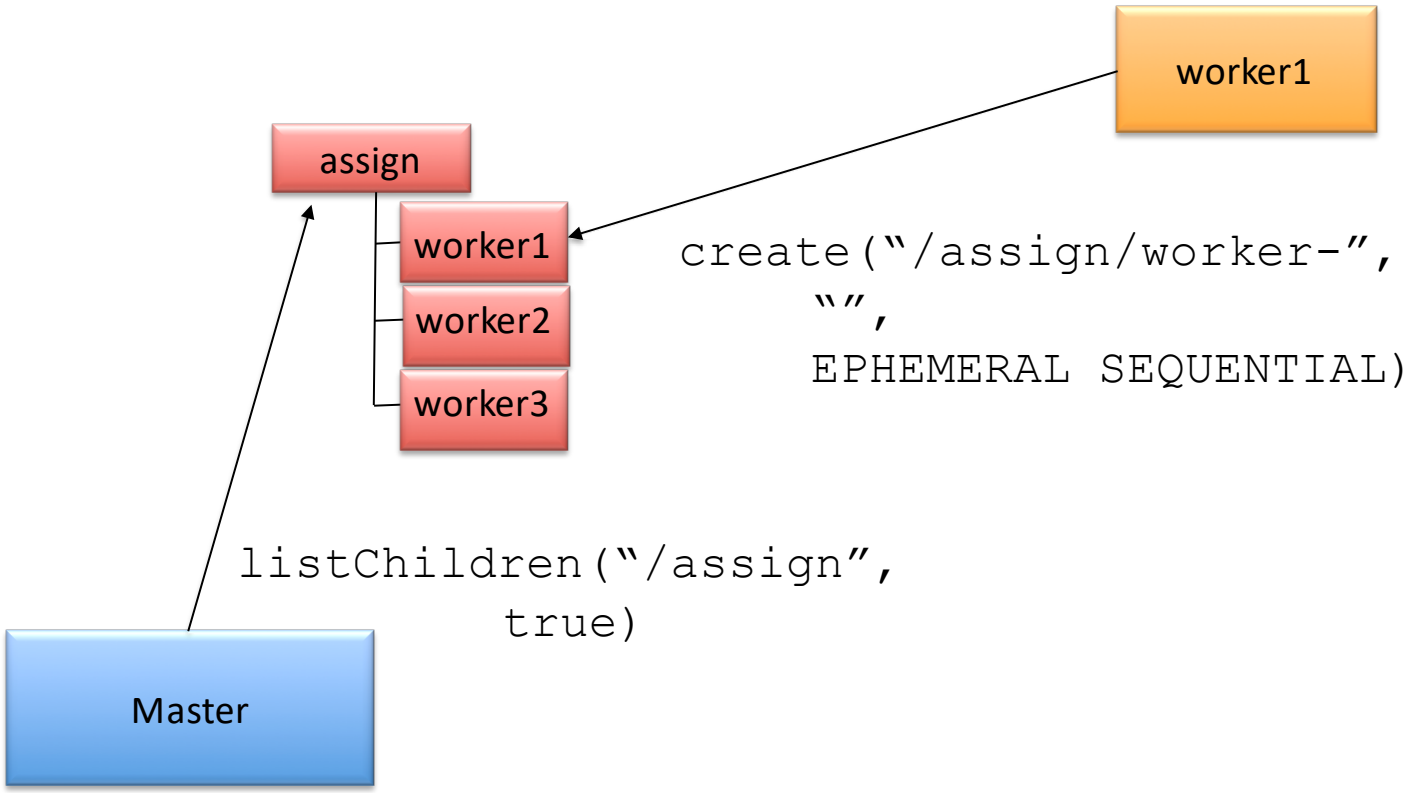
The Rendezvous Problem

- Consider master-worker: specific configurations (IP addresses, port numbers) may not be known until runtime, workers and master may start in any order
- ZooKeeper implementation
  - Create a rendezvous node: /root/rendezvous
  - Workers read /root/rendezvous and set a watch
    - If empty, use watch to detect when master posts its configuration information
  - Master fills in its configuration information (host, port)
  - Workers are notified of content change and get the configuration information

Group Membership

- Problem: a job needs to go to a specific flavor of application manager. How can this be located?
- Solution: have application managers join the appropriate ZooKeeper-managed group when they come up
- Useful to support scheduling

Group Membership



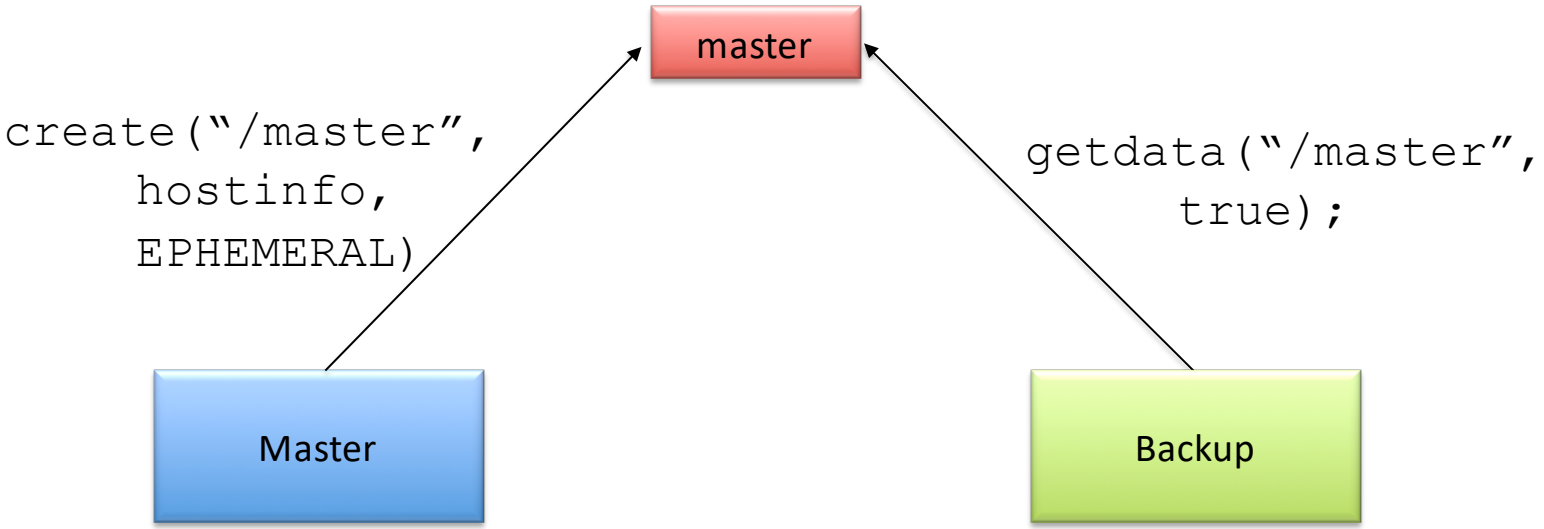
System State

- Which servers are up and running? What versions? Is the server busy or under heavy load?

Leader Election

- Problem: metadata servers are replicated for read access but only the master has write privileges. The master crashes.
- Solution: Use ZooKeeper to elect a new metadata server leader
  - May not be the best way to do this…

Leader Election



Implementing Consensus

- Each process p proposes then decides
- Propose(v)
  - setData “/c/proposal-”, “v”, sequential
- Decide()
  - getChildren “/c”
  - Select znode z with smallest sequence number
  - v’ = getData “/c/z”
  - Decide upon v’

ZooKeeper vs. Paxos

- ZooKeeper is solving the state machine replication problem – similar to Paxos
- ZooKeeper's Zab is similar to the Paxos concept of an "Atomic Multicast" (aka "Vertical Paxos")
- Checkpointing every 5s is not the same as the true durable Paxos. Durable Paxos is like checkpointing on every operation.