INGI2145: CLOUD COMPUTING (Fall 2015)

Coordination in distributed applications

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Certain lecture slides adapted from Eurecom DSCC by P. Michiardi, M. Vukolic and and from Cornell CS5412 by K. Birman
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Today

- Distributed systems coordination

- Apache Zookeeper
  - Simple, high performance kernel for building distributed coordination primitives
  - Zookeeper is not a specific coordination primitive per se, but a platform/API for building different coordination primitives

Plan for today

- Distributed systems coordination NEXT
  - Consensus, FLP
  - Atomic broadcast, replicated state machine
- Apache Zookeeper
  - Coordination kernel
  - Semantics
  - Programming Zookeeper
  - Internal Architecture

Why do we need coordination?

- Large-scale distributed applications require different forms of coordination. For example:
- Configuration management
  - E.g., list of operational parameters
- Rendezvous
  - E.g., discover final system configuration at run time
- Group membership
  - I.e., which processes are member of the cluster
- Leader election
- Locking
  - I.e., exclusive access to critical resources

Why is coordination difficult?

- Coordination among multiple parties involves agreement among those parties
  - In general, N processes must agree on something, e.g. a bit
- Agreement ←→ Consensus ←→ Consistency

- Consensus in brief
  - All correct processes propose a value
  - All correct processes decide a value (exactly once)
  - A decision must be proposed
  - All decisions must be the same

Connection to consistency

- A system behaves consistently if users can't distinguish it from a non-distributed system that supports the same functionality
  - Many notions of consistency reduce to agreement on the events that occurred and their order
  - Could imagine that our "bit" represents
    - Whether or not a particular event took place
    - Whether event A is the "next" event
- Thus fault-tolerant consensus is deeply related to fault-tolerant consistency

Why is coordination difficult?

- Coordination among multiple parties involves agreement among those parties
  - In general, N processes must agree on something, e.g. a bit
- Agreement ←→ Consensus ←→ Consistency
- FLP impossibility result + CAP theorem
  - Agreement is difficult in a dynamic asynchronous system in which processes may fail or join/leave

Fischer, Lynch and Patterson (FLP)

- A surprising result
  - Impossibility of Asynchronous Distributed Consensus with a Single Faulty Process
- They prove that no asynchronous algorithm for agreeing on a one-bit value can guarantee that it will terminate in the presence of crash faults
  - A node that crashes is indistinguishable from a node that is infinitely slow
  - And this is true even if no crash actually occurs!

In the real world?

- Asynchronous model with crash faults
  - A bit like the real world!
- Fault-tolerant consensus is...
  - Definitely possible (not even all that hard). Just vote!
  - And we can prove protocols of this kind correct
- But we can’t prove that they will terminate
  - Impossibility doesn’t mean the consensus solutions are wrong – only that they live within this limit

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Atomic broadcast

- A.k.a. total order broadcast
- Critical synchronization primitive in many distributed systems
- Fundamental building block to building replicated state machines

Atomic Broadcast (safety)

- Total Order property
  - Let m and m’ be any two messages
  - Let p and q be any two correct processes that deliver m and m’
  - If p delivers m before m’, then q delivers m before m’
- Integrity (a.k.a. No creation)
  - No message is delivered unless it was broadcast
- No duplication
  - No message is delivered more than once
  - (Zookeeper Atomic Broadcast – ZAB deviates from this)

State machine replication

- Think of, e.g., a database (RDBMS)
  - Use atomic broadcast to totally order database operations
- All database replicas apply updates/queries in the same order
  - Since database is deterministic, the state of the database is fully replicated
- To tolerate ≤ f failures, deploy 2f+1 replicas
  - (e.g. with 3 replicas can tolerate 1 failure)

- Extends to any (deterministic) state machine

Consistency of total order

- Very strong consistency
- “Single-replica” semantics

Plan for today

- Distributed systems coordination ✔
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Zookeeper Origins

- Developed initially at Yahoo!
- On Apache since 2008
  - Hadoop subproject
- Top Level project since Jan 2011
  - http://zookeeper.apacher.org

How do we go about coordination?

- One approach
  - For each coordination primitive build a specific service
- Some recent examples
  - Chubby, Google [*Burrows et al, USENIX OSDI, 2006*]
    - Lock service
  - Centrifuge, Microsoft [*Adya et al, USENIX NSDI, 2010*]
    - Lease service

But there is a lot of applications …

- How many distributed services need coordination?
  - Amazon/Google/Yahoo/Microsoft/IBM/…
- And which coordination primitives exactly?
  - Want to change from Leader Election to Group Membership? And from there to Distributed Locks?
  - There are also common requirements in different coordination services
    - Duplicating is bad and duplicating poorly even worse
    - Maintenance?

How do we go about coordination?

- Alternative approach
  - A coordination service
  - Develop a set of lower level primitives (i.e., an API) that can be used to implement higher-level coordination services
  - Use the coordination service API across many applications
- Example: Apache Zookeeper

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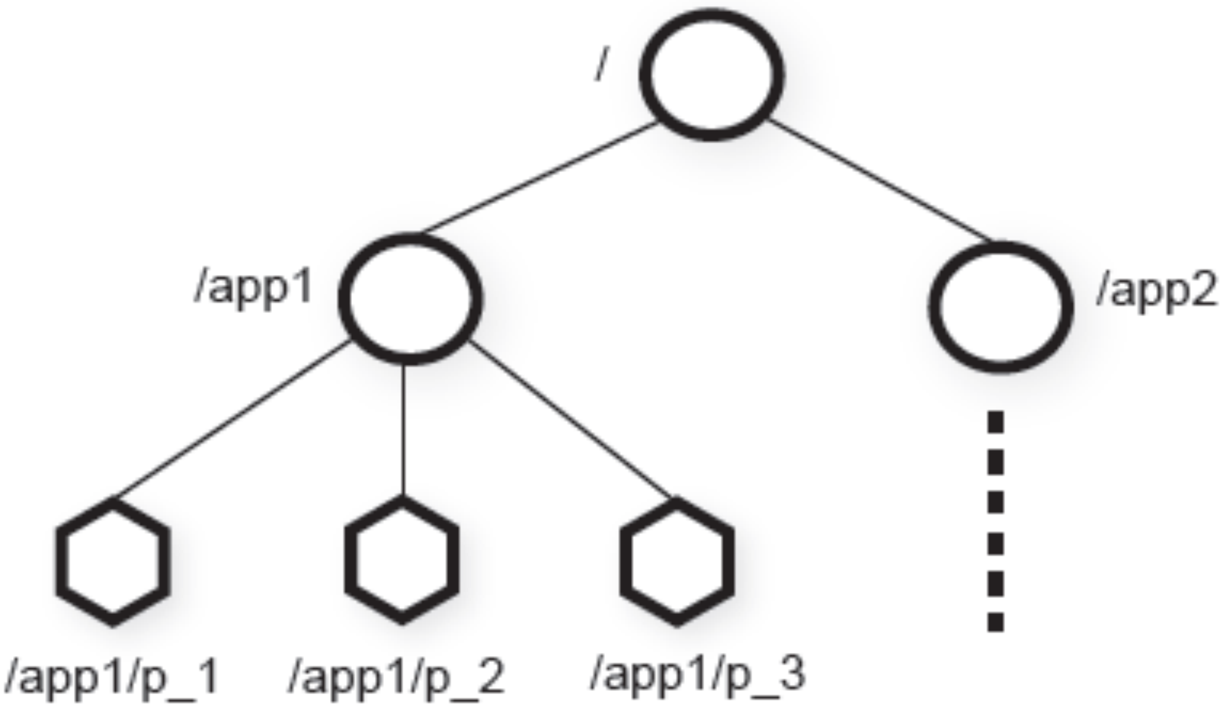
Zookeeper overview

- Client-server architecture
  - Clients access Zookeeper through a client API
  - Client library also manages network connections to Zookeeper servers
- Zookeeper data model
  - Similar to file system
  - Clients see the abstraction of a set of data nodes (***znodes)***
  - Znodes are organized in a hierarchical namespace that resembles customary file systems

Hierarchical znode namespace



Types of Znodes

- Regular znodes
  - Clients manipulate regular znodes by creating and deleting them explicitly
  - (We will see the API in a moment)

- Ephemeral znodes
  - Can manipulate them just as regular znodes
  - However, ephemeral znodes can be removed by the system when the session that creates them terminates
  - Session termination can be deliberate or due to failure

Data model

- In brief, it's a file system with a simplified API
- Only full reads and writes
  - No appends, inserts, partial reads
- Znode hierarchical namespace
  - Think of directories that may also contain some payload data
- Payload not designed for application data storage but for application metadata storage
- Znodes also have associated version counters and some metadata (e.g., flags)

Sessions

- Client connects to Zookeeper and initiates a session
  - Sessions enables clients to move transparently from one server to another
  - Any server can serve client's requests

- Sessions have timeouts
  - Zookeeper considers client faulty if it does not hear from client for more than a timeout
  - This has implications on ephemeral znodes

Client API

- *create(znode, data, flags)*
  - *Flags denote the type of the znode:*
    - *REGULAR, EPHEMERAL, SEQUENTIAL*
    - *SEQUENTIAL flag: a monotonically increasing value is appended to the name of znode*
  - *znode must be addressed by giving a full path in all operations (e.g., '/app1/foo/bar')*
  - *returns znode path*
- *delete(znode, version)*
  - *Deletes the znode if the version is equal to the actual version of the znode*
  - *set version = -1 to omit the conditional check (applies to other operations as well)*

Client API (cont'd)

- *exists(znode, watch)*
  - *Returns true if the znode exists, false otherwise*
  - *watch flag enables a client to set a watch on the znode*
  - *watch is a subscription to receive an information from the Zookeeper when this znode is changed*
  - *NB: a watch may be set even if a znode does not exist*
    - *The client will be then informed when a znode is created*
- *getData(znode, watch)*
  - *Returns data stored at this znode*
  - *watch is not set unless znode exists*

Client API (cont'd)

- *setData(znode, data, version)*
  - *Rewrites znode with data, if version is the current version number of the znode*
  - *version = -1 applies here as well to omit the condition check and to force setData*
- *getChildren(znode, watch)*
  - *Returns the set of children znodes of the znode*
- *sync()*
  - *Waits for all updates pending at the start of the operation to be propagated to the Zookeeper server that the client is connected to*

API operation calls

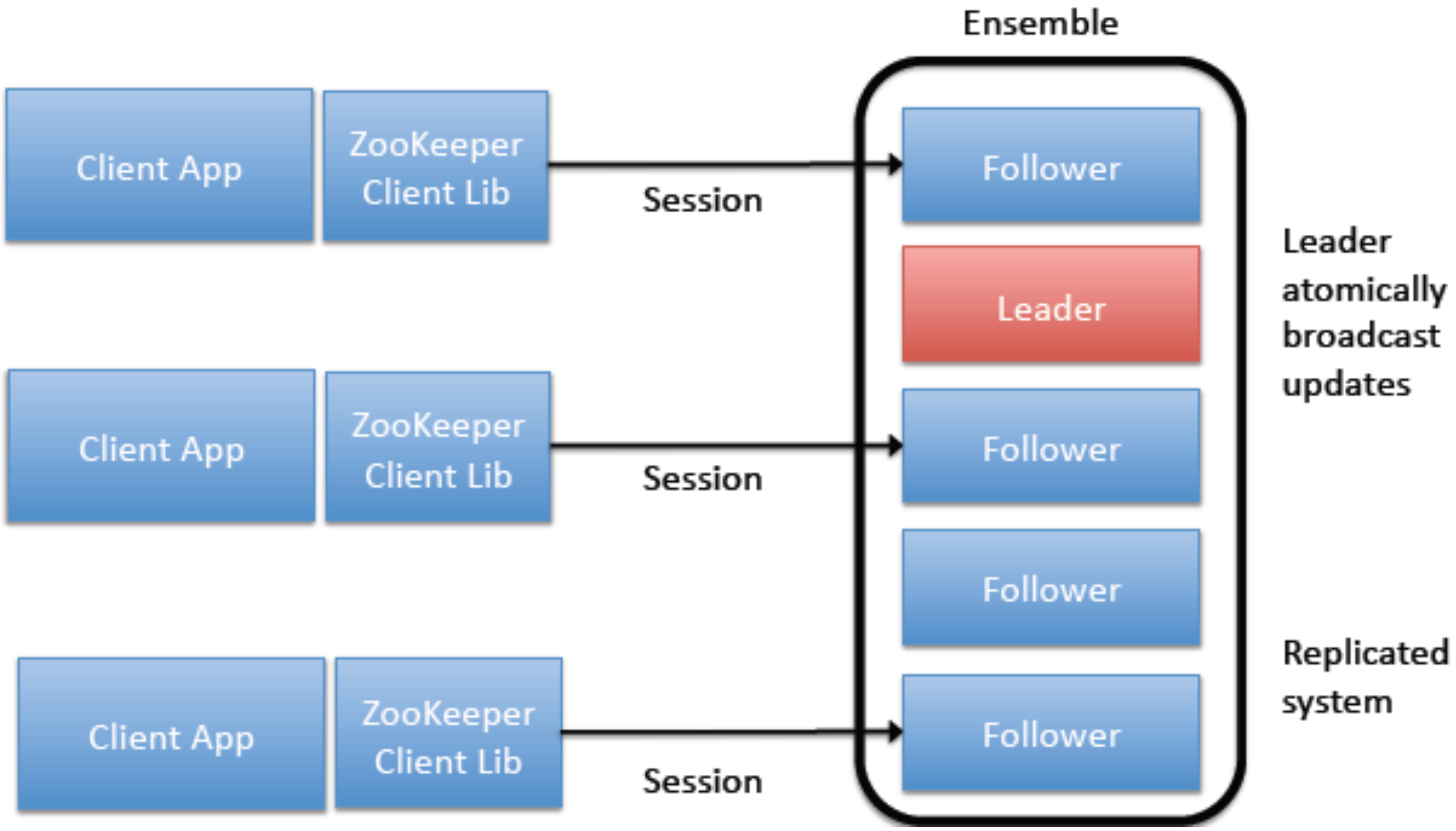
- Can be synchronous or asynchronous
- Synchronous calls
  - A client blocks after invoking an operation and waits for an operation to respond
  - No concurrent calls by a single client
- Asynchronous calls
  - Concurrent calls allowed
  - A client can have multiple outstanding requests

Convention

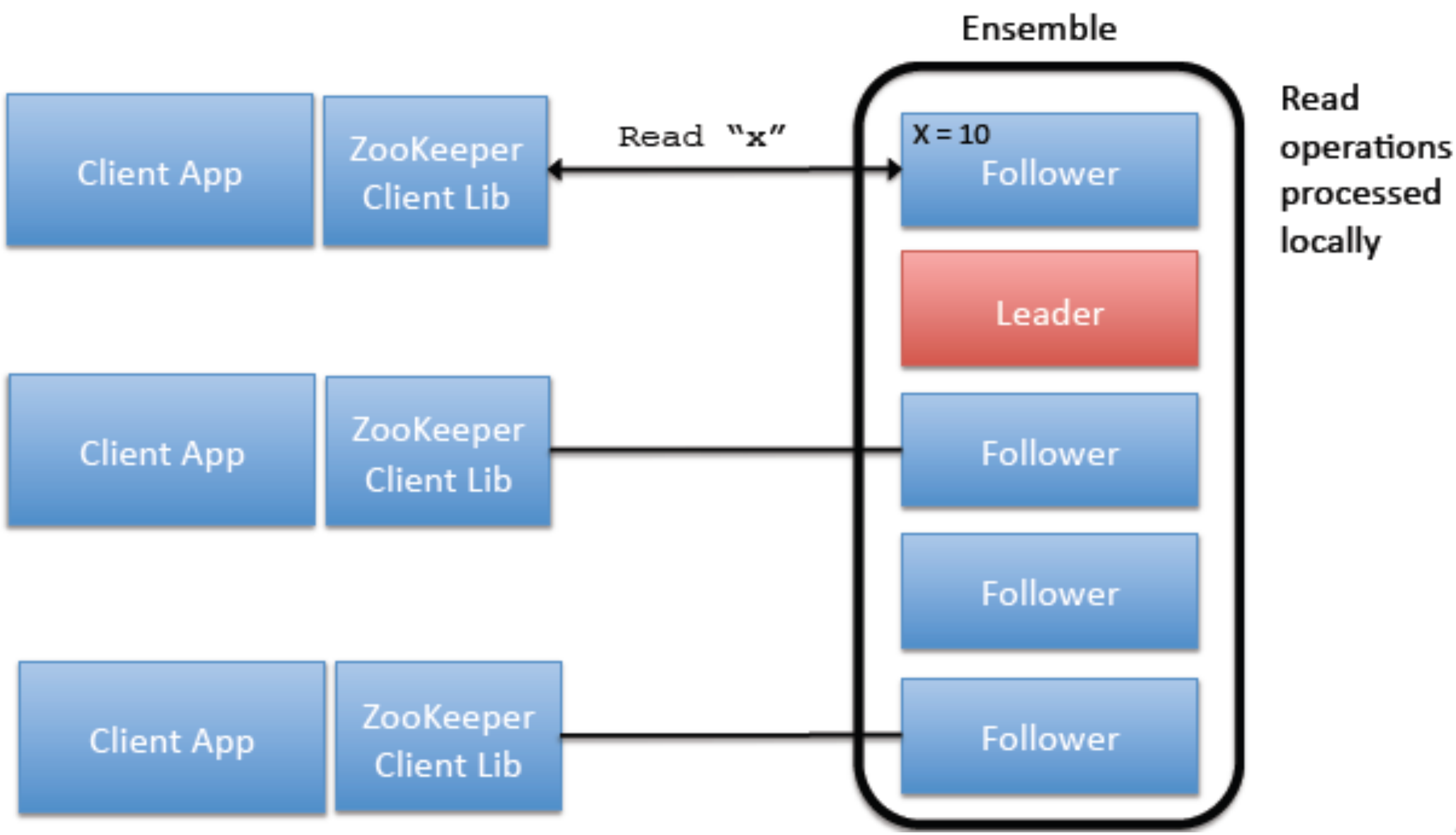
- Update/write operations
  - Create, setData, sync, delete

- Read operations
  - exists, getData, getChildren

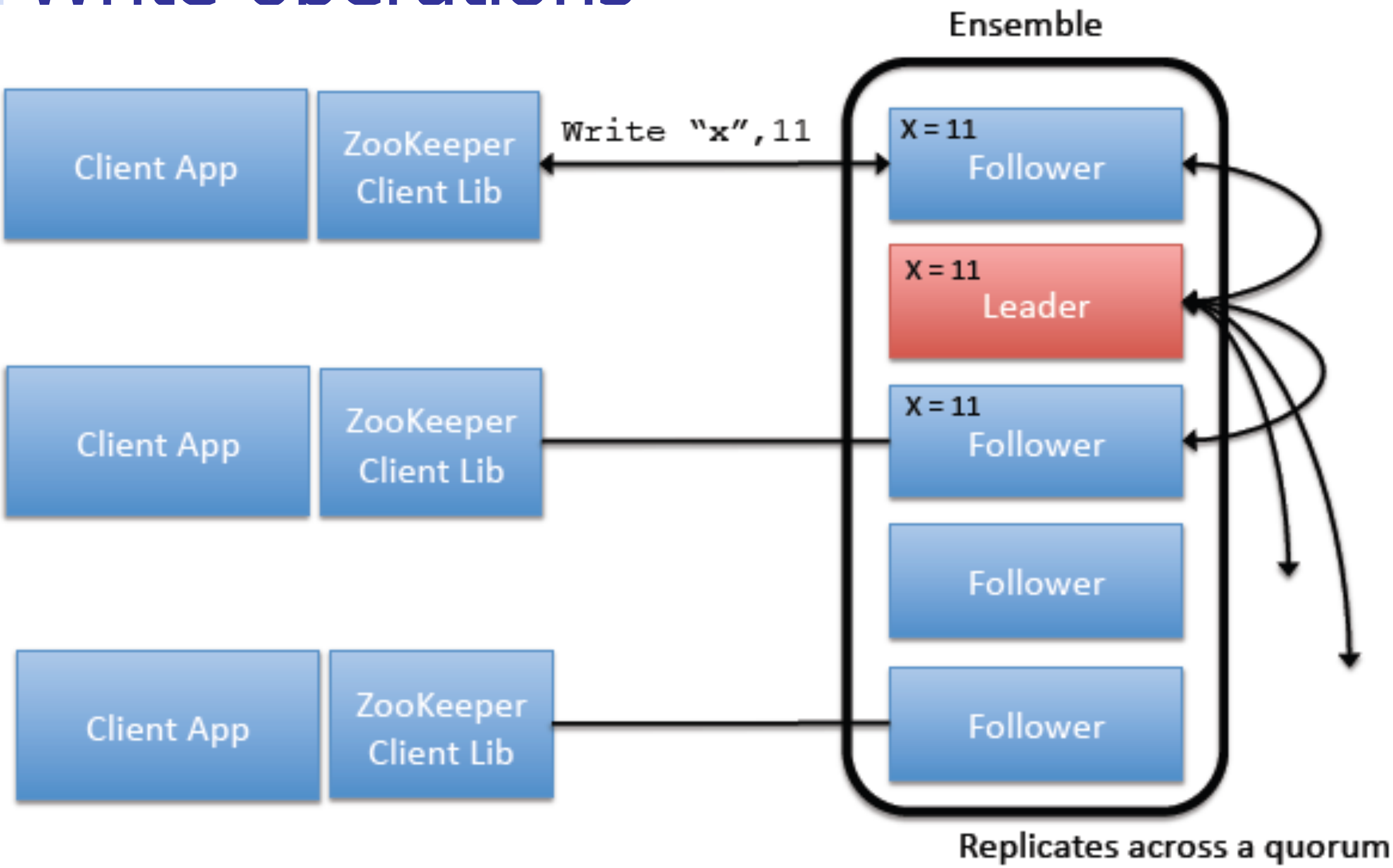
Session overview



Read operations



Write operations



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Zookeeper semantics

- CAP perspective: Zookeeper is in CP
  - It guarantees consistency
  - May sacrifice availability under system partitions (strict quorum based replication for writes)

- Consistency (safety)
  - *Linearizable writes:* all writes are linearizable
  - *FIFO client order:* all requests from a given client are executed in the order they were sent by the client
    - Matters for asynchronous calls

Zookeeper Availability

- Wait-freedom
  - All operations invoked by a correct client eventually complete
  - Under condition that a quorum of servers is available

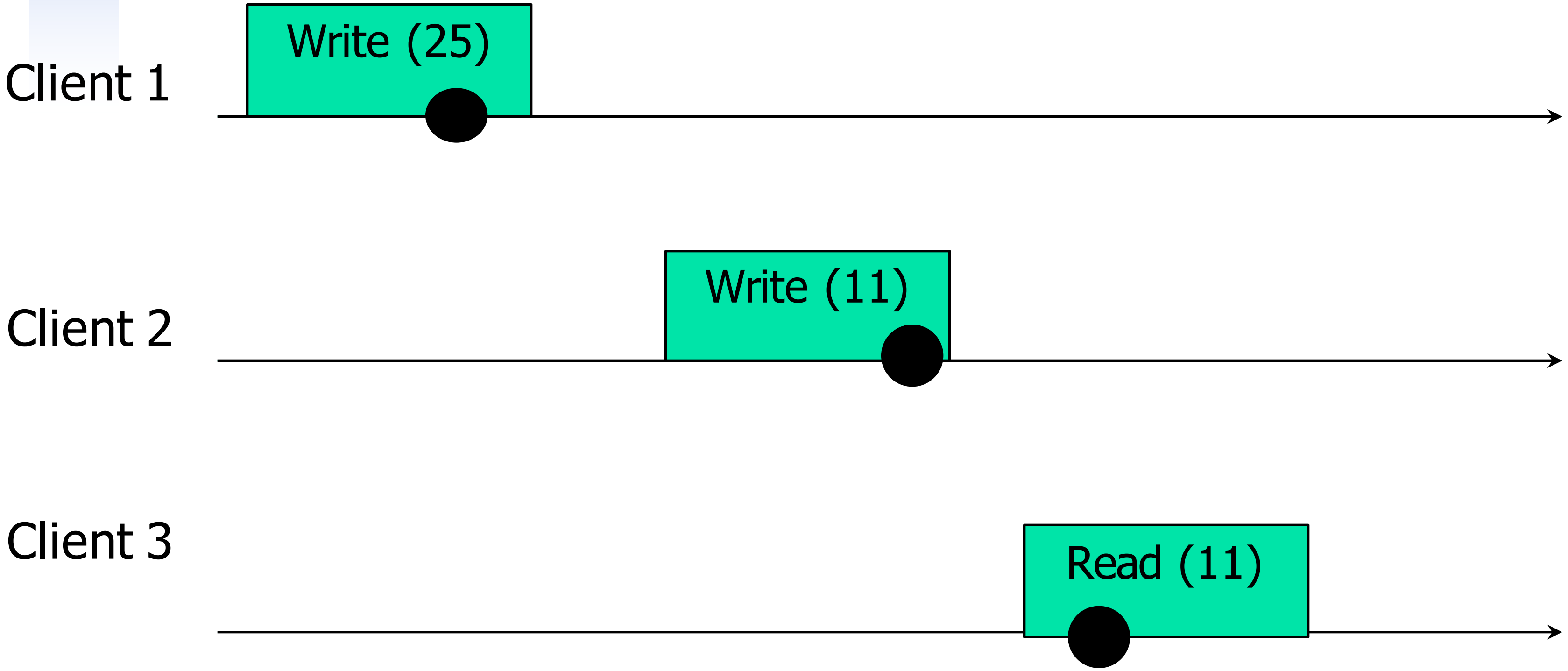
- Zookeeper uses no locks although it can implement locks

Zookeeper consistency vs. Linearizability

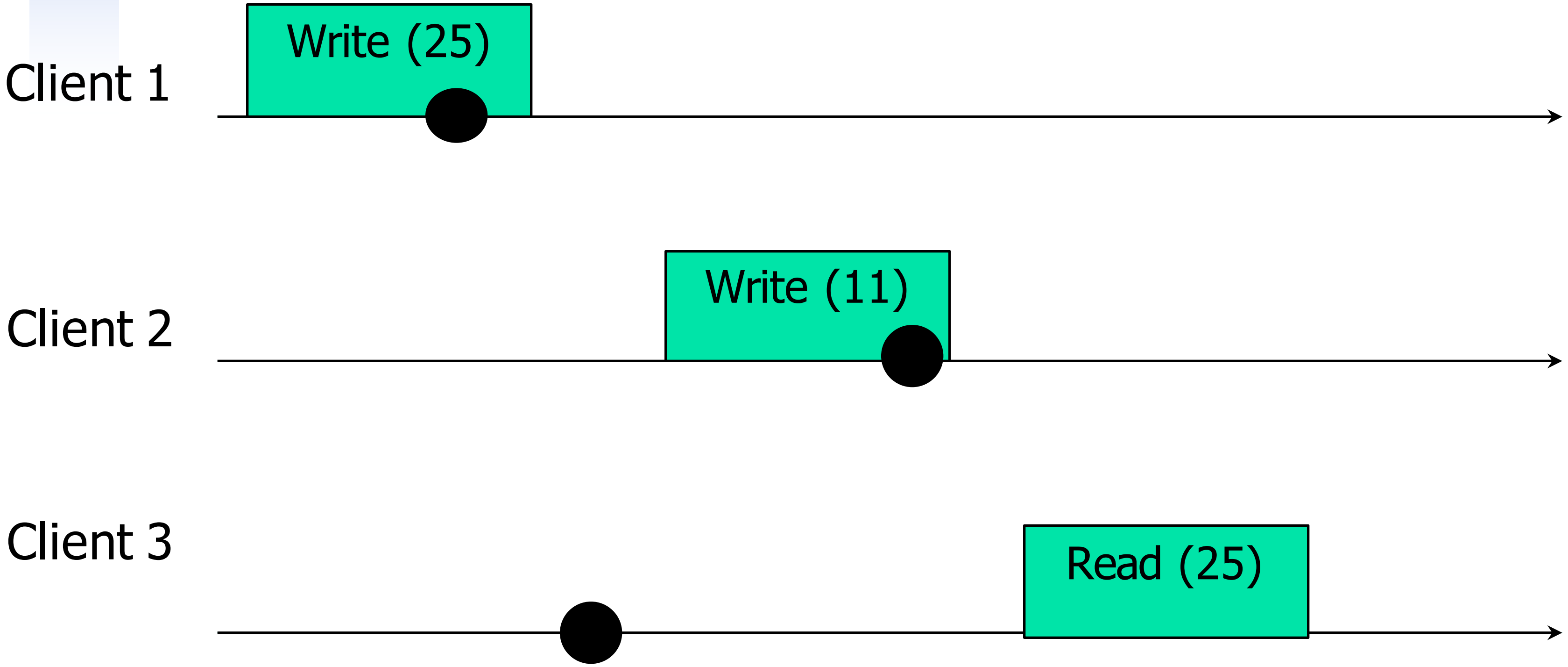
- Linearizability
  - All operations appear to take effect in a single, indivisible time instant between invocation and response

- Zookeeper consistency
  - Writes are linearizable
  - Reads might not be
    - To boost performance, Zookeeper has local reads
    - A server serving a read request might not have been a part of a write quorum of some previous operation
    - ➔ A read might return a stale value

Linearizability



Zookeeper

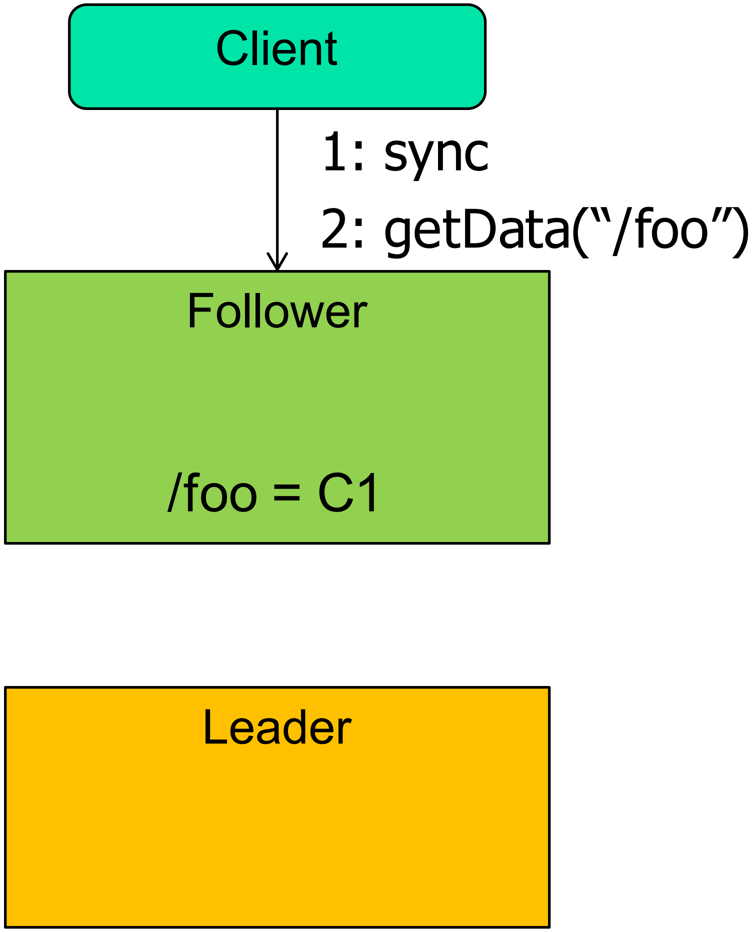


Is this a problem?

- Depends what the application needs
  - May cause inconsistencies in synchronization if not careful
- Despite this, Zookeeper API is a universal object → its consensus number is ∞
    - i.e., Zookeeper can solve consensus (agreement) for arbitrary number of clients
- If an application needs linearizability
  - There is a trick: sync operation
  - Use sync followed by a read operation within an application-level read
    - This yields a "slow read"

sync

- Sync
  - Asynchronous operation
  - Before read operations
  - Flushes the channel between follower and leader
  - Enforces linearizability



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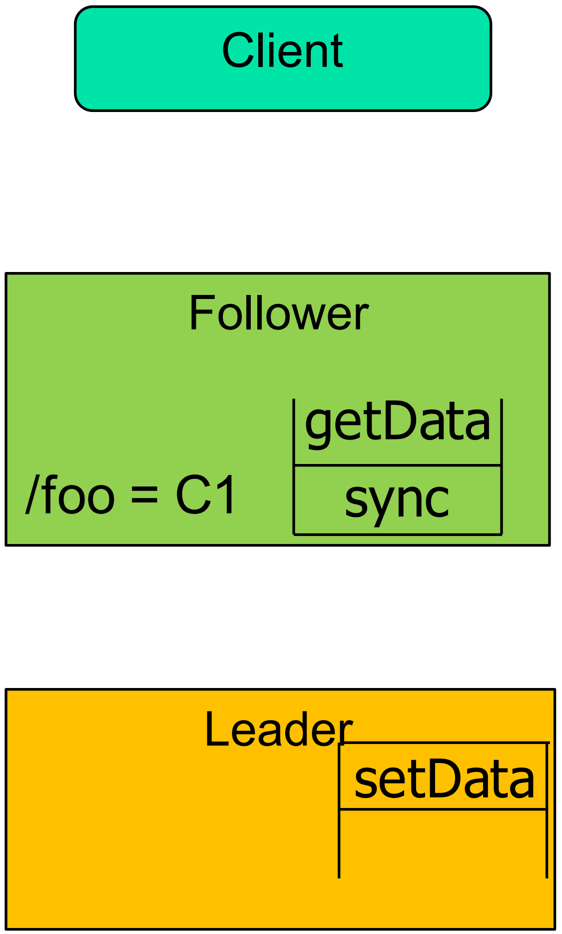

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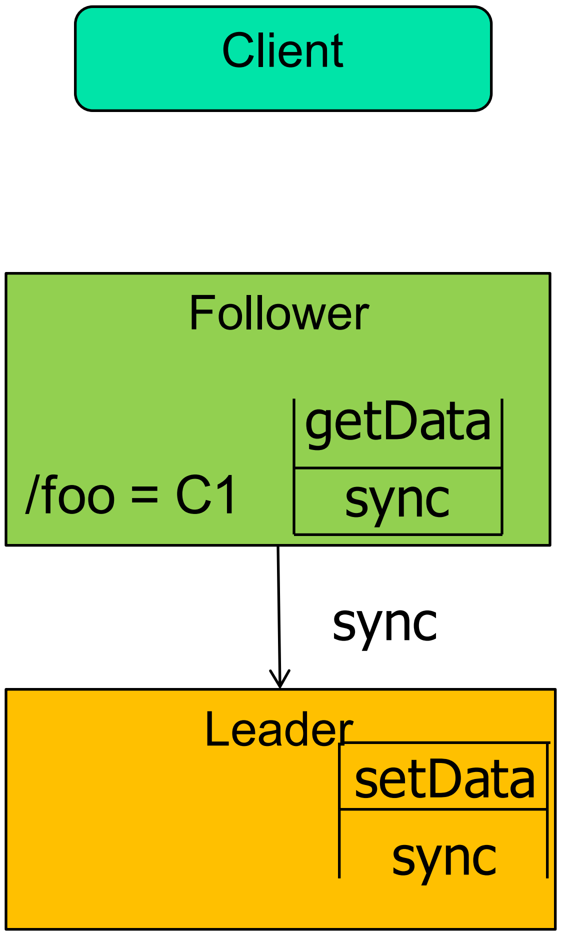

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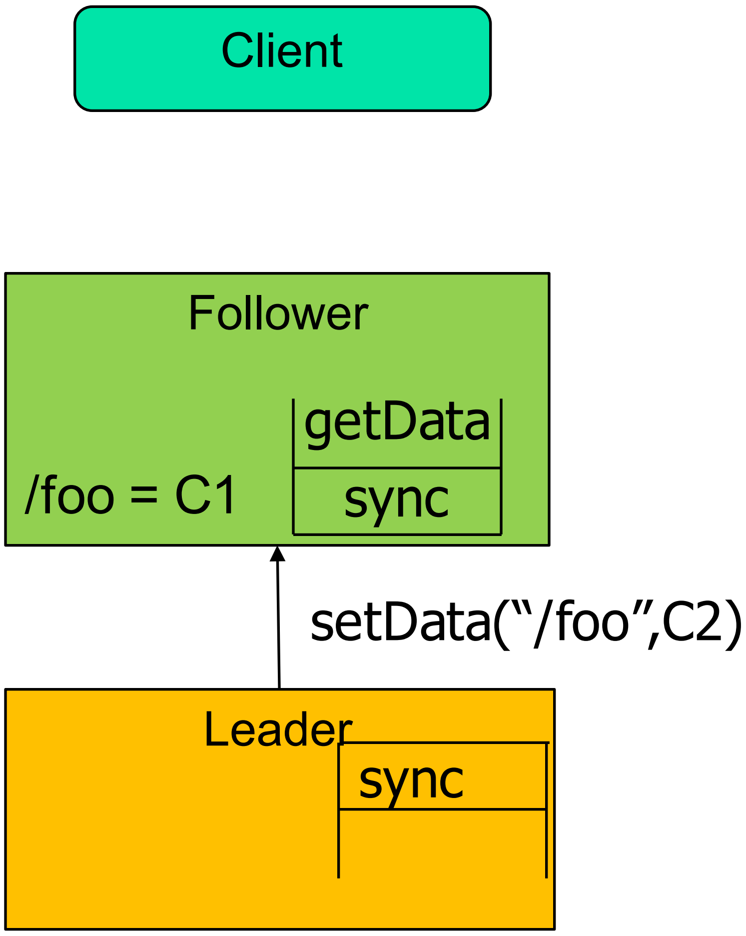

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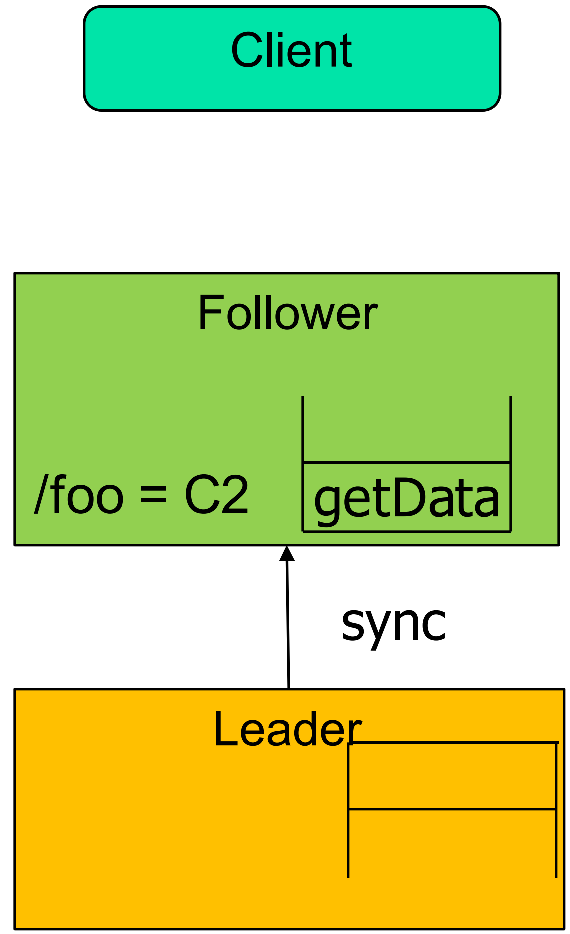

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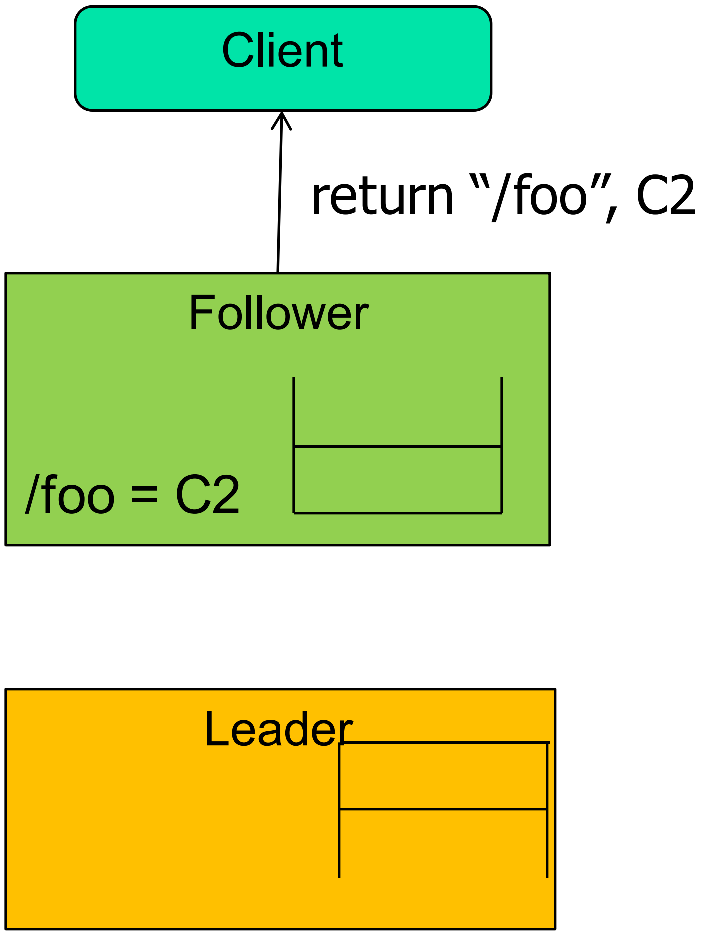

Read performance

- Slow reads (sync + read)
  - Linerizability
  - Slow, leader bottleneck
- “Normal” reads
  - Might be non-linearizable
  - 1 round-trip client/server
- One more option: Caching reads
  - Cache reads at a client, save on a round-trip
  - Set a watch for a notification needed for cache invalidation

Write operations (summary)

- Always go through the slow "path"
- A write request is forwarded by a follower server to the leader
- Leader uses atomic (total-order) broadcast to disseminate messages
  - Using ZAB protocol
- ZAB
  - A variant of Paxos tweaked to support FIFO/causal consistency of asynchronous calls
  - Quorum-based (2f+1 servers, tolerates f failures)

Session consistency

- What if a follower that a client is talking to fails?
  - Or connection is lost for any other reason
  - Some operations might have not been executed

- Upon disconnection
  - Client library tries to contact another server before session expires

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Implementing consensus

- Consensus in brief
  - All correct processes propose a value
  - All correct processes decide a value (exactly once)
  - A decision must be proposed
  - All decisions must be the same
- `Propose(v)`

```
create("/c/proposal-", "v", SEQUENTIAL)
```

- `Decide()`

```
C = getChildren("/c")
Select znode z in C with smallest sequence number
v' = getData(z)
Decide v'
```

Simple configuration management

- Clients initialized with the name of znode
  - E.g., "/config"

```
config = getData("/config", TRUE)
while (true)
      wait for watch notification on "/config"
      config = getData("/config", TRUE)
```

Note: A client may miss some configuration, but it will always "refresh" when it realizes the configuration is stale

Group membership

- Idea: leverage ephemeral znodes
- Fix a znode "/group"
- Assume every process (client) is initialized with its own unique name and ID
  - What to do if there are no unique names?

```
joinGroup()
   create("/group/" + name, [address,port], EPHEMERAL)
getMembers()
   getChildren("/group", false)
```

Set to true to get notified about membership changes

Locks

- Can also use Zookeeper to implement blocking primitives
  - Not to be confused with the fact that Zookeeper is wait-free

- Let's try Locks

A simple lock

Lock(filename)

```
1:      create(filename, “”, EPHEMERAL)
2:      if create is successful
3:              return                  //have lock
4:      else
5:              getData(filename,TRUE)
6:              wait for filename watch
7:              goto 1:
```

Release(filename)

```
        delete(filename)
```

Problems?

- Herd effect
  - If many clients wait for the lock they will all try to get it as soon as it is released

- Only implements exclusive locking

Simple Lock without Herd Effect

```
Lock(filename)
1:      myLock=create(filename + “/lock-”, “”, EPHEMERAL & SEQUENTIAL)
2:      C = getChildren(filename, false)
3:      if myLock is the lowest znode in C then return
4:      else
5:              precLock = znode in C ordered just before myLock
6:              if exists(precLock, true)
7:                      wait for precLock watch
8:                      goto 2:
Release(filename)
        delete(myLock)
```

Read/Write Locks

- The previous lock solves herd effect but makes reads block other reads

- How to do it such that reads always get the lock unless there is a concurrent write?

Read/Write Locks

```
Write Lock(filename)
1:      myLock=create(filename + “/write-”, “”, EPHEMERAL & SEQUENTIAL)
[...]   // same as simple lock w/o herd effect
Read Lock(filename)
1:      myLock=create(filename + “/read-”, “”, EPHEMERAL & SEQUENTIAL)
2:      C = getChildren(filename, false)
3:      if no write znodes lower than myLock in C then return
4:      else
5:              precLock = write znode in C ordered just before myLock
6:              if exists(precLock, true)
7:                      wait for precLock watch
8:                      goto 3:
Release(filename)
        delete(myLock)
```

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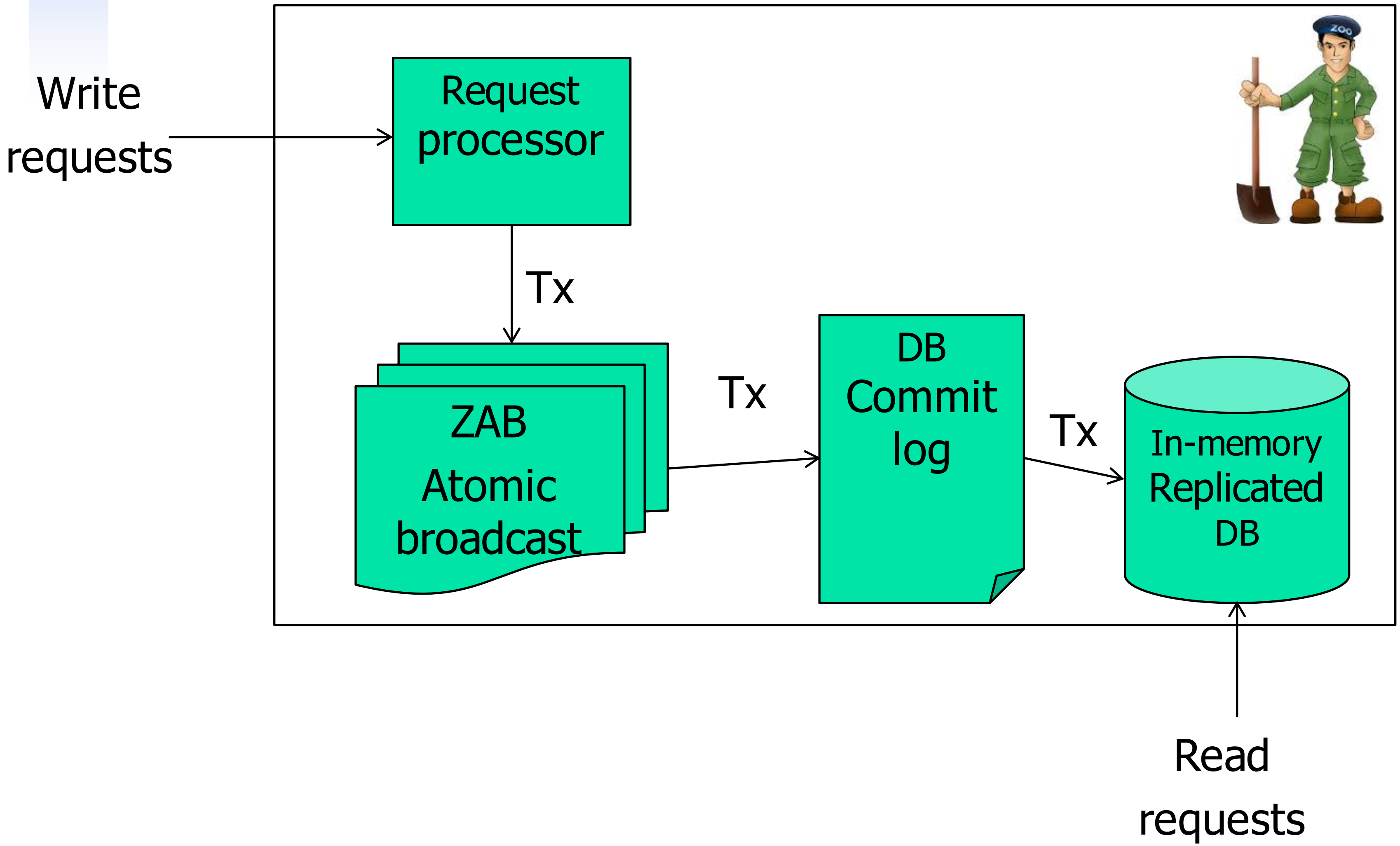
Zookeeper components (high-level)



Zookeeper DB

- Fully replicated
  - To be contrasted with partitioning/placement in storage systems
- Each server has a copy of in-memory DB
  - Store the entire znode tree
  - Default max 1 MB per znode (configurable)
- Crash-recovery model
  - Commit log
  - + periodic snapshots of the database

ZAB: a very brief overview

- Used to totally order write requests
  - Relies on a quorum of servers (f+1 out of 2f+1)
- ZAB internally elects leader replica
  - Not to be confused with Leader Election using Zookeeper API
- Zookeeper adopts this notion of a leader
  - Other servers are followers
- All write requests are sent by followers to the leader
  - Leader sequences the requests and invokes ZAB atomic broadcast

Request processor

- Upon receiving a write request
  - the leader calculates in what state system will be after the write is applied
  - Transforms the operation in the transactional update
- Such transactional updates are then processed by ZAB, DB
  - Guarantees idempotency of updates to the DB originating from the same operation
- Idempotency: Important since ZAB may redeliver a message
  - Upon recovery not during normal operation
  - Also allows more efficient DB snapshots

Further reading

- P. Hunt, M. Kumar, F. P. Junqueira and B. Reed: Zookeeper: Wait-free coordination for Internet-scale systems. In proc. USENIX ATC (2010)

  http://static.usenix.org/event/usenix10/tech/full_papers/Hunt.pdf
- Zookeeper 3.4 Documentation

  http://zookeeper.apache.org/doc/trunk/index.html

  (optional)
- F. P. Junqueira, B. C. Reed, M. Serafini: Zab: High-performance broadcast for primary-backup systems. DSN 2011: 245-256
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- A. Adya, J. Dunagan, A. Wolman: Centrifuge: Integrated Lease Management and Partitioning for Cloud Services. NSDI 2010: 1-16