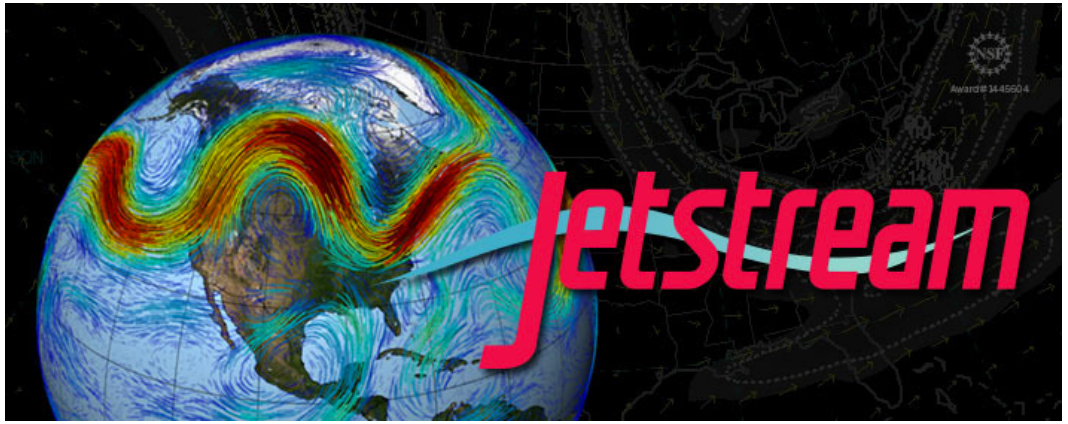
Classes Next Week

- November 1: Guest Lecturers: George Turner and Mike Lowe will present Jetstream and OpenStack
  - We will make more use of Jetstream in the Spring 2017 class.
  - Look under the hood of cloud systems
- November 3: Open Help Session with TA's.
  - Get help with Project Milestone 3.
- Suresh and Marlon will be on travel but online.
  - Please also contact the class TA's for help.



GitHub Issues and Commits

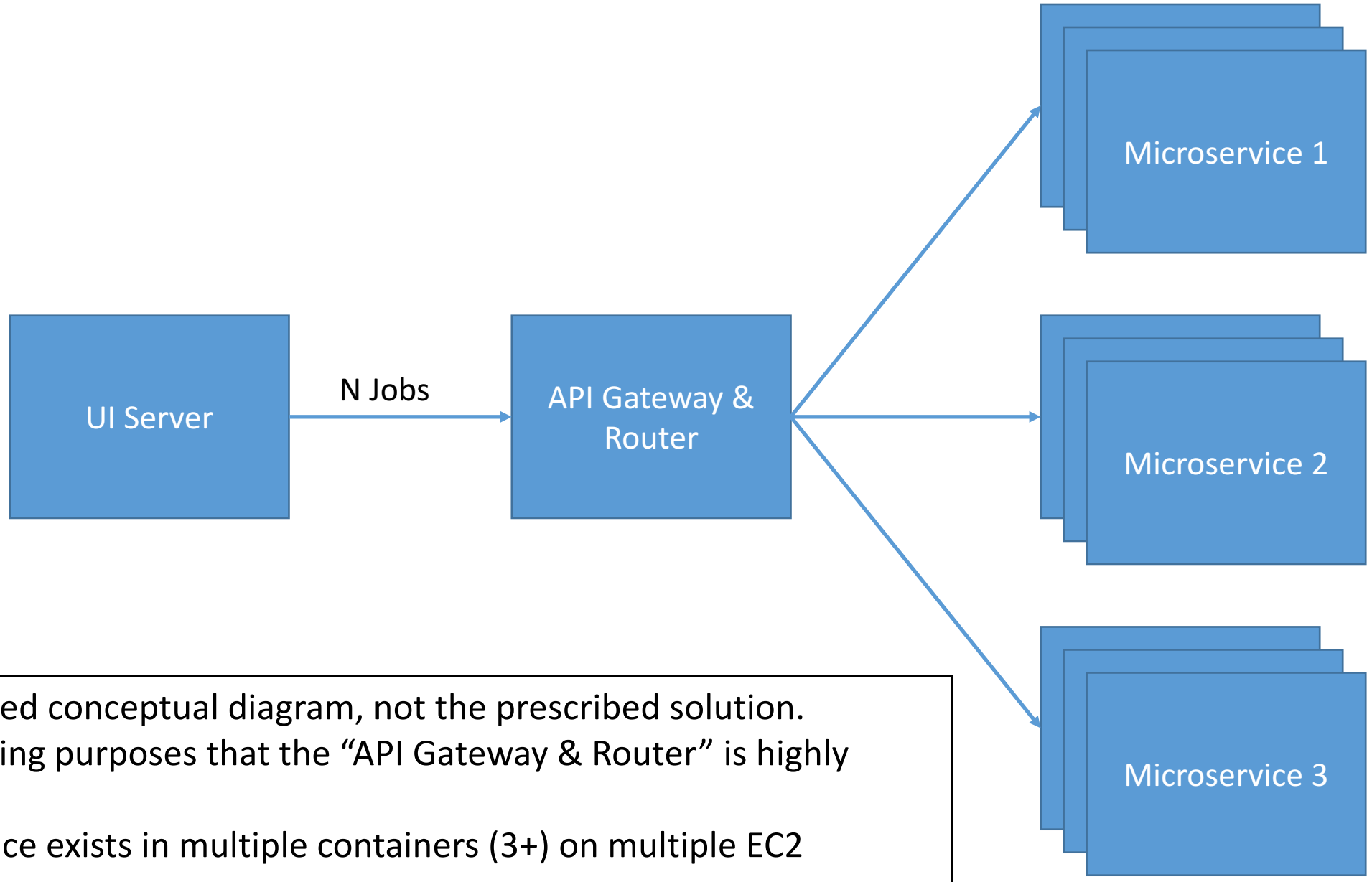
- For PM3 and PM4, all commits must be linked to specific issues (“mention”)
  - You use this to provide an audit trail of your effort on the project.
  - NO COMMITS WITHOUT ISSUES
- Tie wiki entries to git issues also.
- All of your intellectual input into the project should be in GitHub and tied to issues.
- Points will be deducted if you don’t do this correctly.

Project Milestone 3

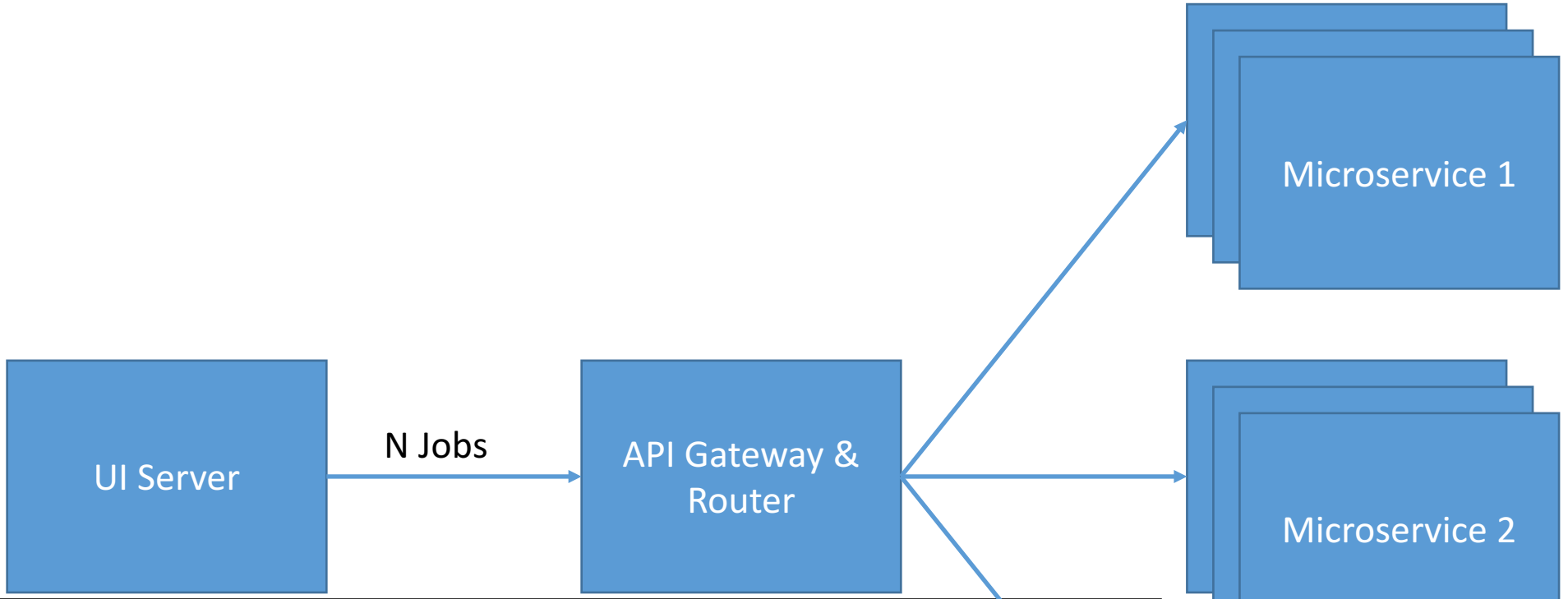
- Project milestone 3 should illustrate the following features.
  - Fault tolerance
  - Load Balancing
  - Continuous upgrades without downtime
- To do this, do the following:
  - Each microservice should run in replicated containers.
  - Your system should decide how to route jobs to a specific replica instance for load balancing and for fault tolerance.
  - Your system should demonstrate that it can withstand losses of replica instances and even entire EC2 instances due to failures.

Project Milestone 3 Outcomes

- You should be able to show that your system has increased capacity over Project Milestone 2.
  - You should be able to explain your observations.
- You should be able to show that your services can withstand failures of both microservices and their host EC2 instances.
  - For example, if your test client can submit 100 jobs to your system, then all 100 jobs should complete correctly.
- You should be able to show that you can upgrade specific microservices without disrupting your whole system (live updates).
  - For example, if you have 3 replicas for one of your services, you should be able to take one down, update it, and bring it back up into service while continuously running jobs through the system.
  - Repeat for the other 2 replicas.
  - To demonstrate this, you will use a client (from Project Milestone 2's capacity testing) that runs 100 jobs. Show that all 100 jobs complete correctly while simultaneously upgrading services.



- This is a simplified conceptual diagram, not the prescribed solution.
- Assume for testing purposes that the “API Gateway & Router” is highly available.
- Each Microservice exists in multiple containers (3+) on multiple EC2 instances (2).



- For capacity testing, plot # of jobs successfully completed per second (or other unit) versus N.
  - Unambiguously define “successfully completed”
  - Find N where jobs fail. Explain other interesting features in your plots.
- For failure testing, set N=1000 (assuming this takes ~5 minutes).
  - Randomly stop and start 1 of the MS instances. Show all 100 jobs still complete.
  - Randomly restart 1 EC2 instance. Show all 1000 jobs still complete.
  - Plot your throughput
- For upgrade testing, show you can deploy a new service without disrupting 1000 jobs. Show that the new services received work. Plot your throughput

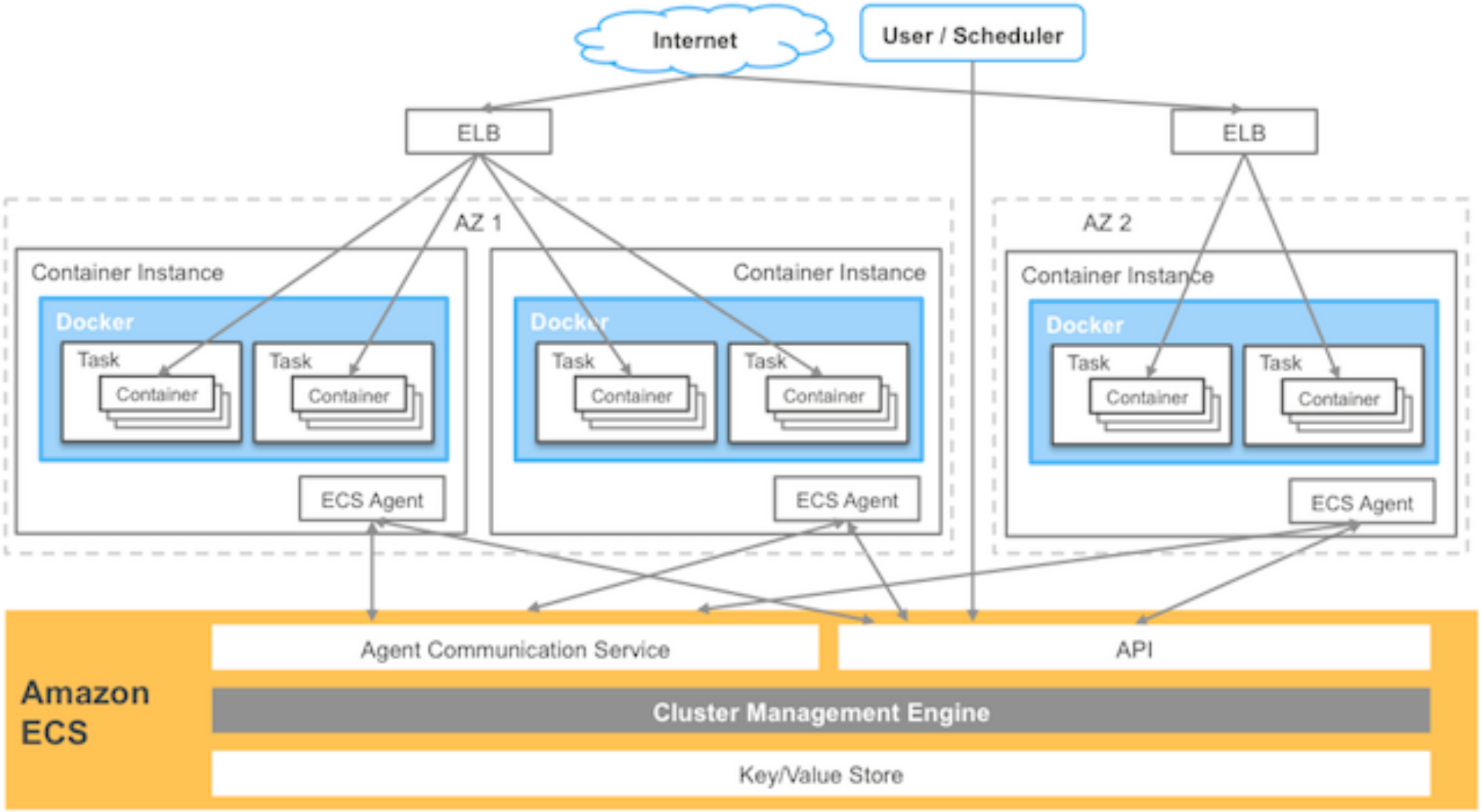
Apache Zookeeper

Hunt, P., Konar, M., Junqueira, F.P. and Reed, B., 2010, June. ZooKeeper: Wait-free Coordination for Internet-scale Systems. In USENIX Annual Technical Conference (Vol. 8, p. 9).

And other papers from http://scholar.google.com. ZK is a great example of successful open source software with strong underlying CS principles documented in scholarly articles.

Amazon and Docker: The Problem Is Scale

- Running a few containers is easy.
- But a microservice architecture assumes lots of different services, each replicated many times.
- Vogels: this is a cluster management problem.
  - Configuration management
  - Service discovery
  - Scheduling
  - Monitoring systems
- And Amazon knows scale



"The ECS agent allows Amazon ECS to communicate with the EC2 instances in the cluster to start, stop, and monitor containers as requested by a user or scheduler. "

"The core of Amazon ECS is the cluster manager, a backend service that handles the tasks of cluster coordination and state management. On top of the cluster manager sits various schedulers."

Apache Mesos?

Web Images More...

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U-Net: A user-level network interface for
T Von Eicken, A Basu, V Buch, W **Vogels** - ACM SIG
Abstract The U-Net communication architecture prov
network interface to enable user-level accessto high-
architecture, implemented on standard workstations
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Astrolabe: A robust and scalable techno
management, and data mining
R Van Renesse, KP Birman, W **Vogels** - ACM transa
Abstract Scalable management and self-organizatior
requirements for a generation of large-scale, highly d
have developed an entirely new distributed informati
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File system usage in Windows NT 4.0
W **Vogels** - ACM SIGOPS Operating Systems Revie
Abstract We have performed a study of the usage of
long-term kernel tracing. Our goal was to provide a n
and 1991 trace-based File System studies, to investi
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Web services are not distributed objects
W **Vogels** - IEEE Internet computing, 2003 - ieeexplore.ieee.org
Abstract Web services are frequently described as the latest incarnation of distributed object technology. This misconception, perpetuated by people from both industry and academia, seriously limits broader acceptance of the true Web services architecture. Although the ...
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The power of epidemics: robust communication for large-scale distributed systems
W **Vogels**, R Van Renesse, K Birman - ACM SIGCOMM Computer ..., 2003 - dl.acm.org
Abstract Building very large computing systems is extremely challenging, given the lack of robust scalable communication technologies. This threatens a new generation of mission-critical but very large computing systems. Fortunately, a new generation of" gossip-based" ...
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www.cs.cornell.edu/vogels/

Gateway Services R...

Werner Vogels

Building Scalable and Robust Distributed Systems.

ALL GOOD THINGS COME TO AN END...

I have accepted a position in industry and am no longer affiliated the Computer Science Department of Cornell University.

For up-to-date information visit the All Things Distributed weblog.

This one may have helped him land the Amazon job.

Vogels did world class research in distributed systems before becoming CTO of Amazon.

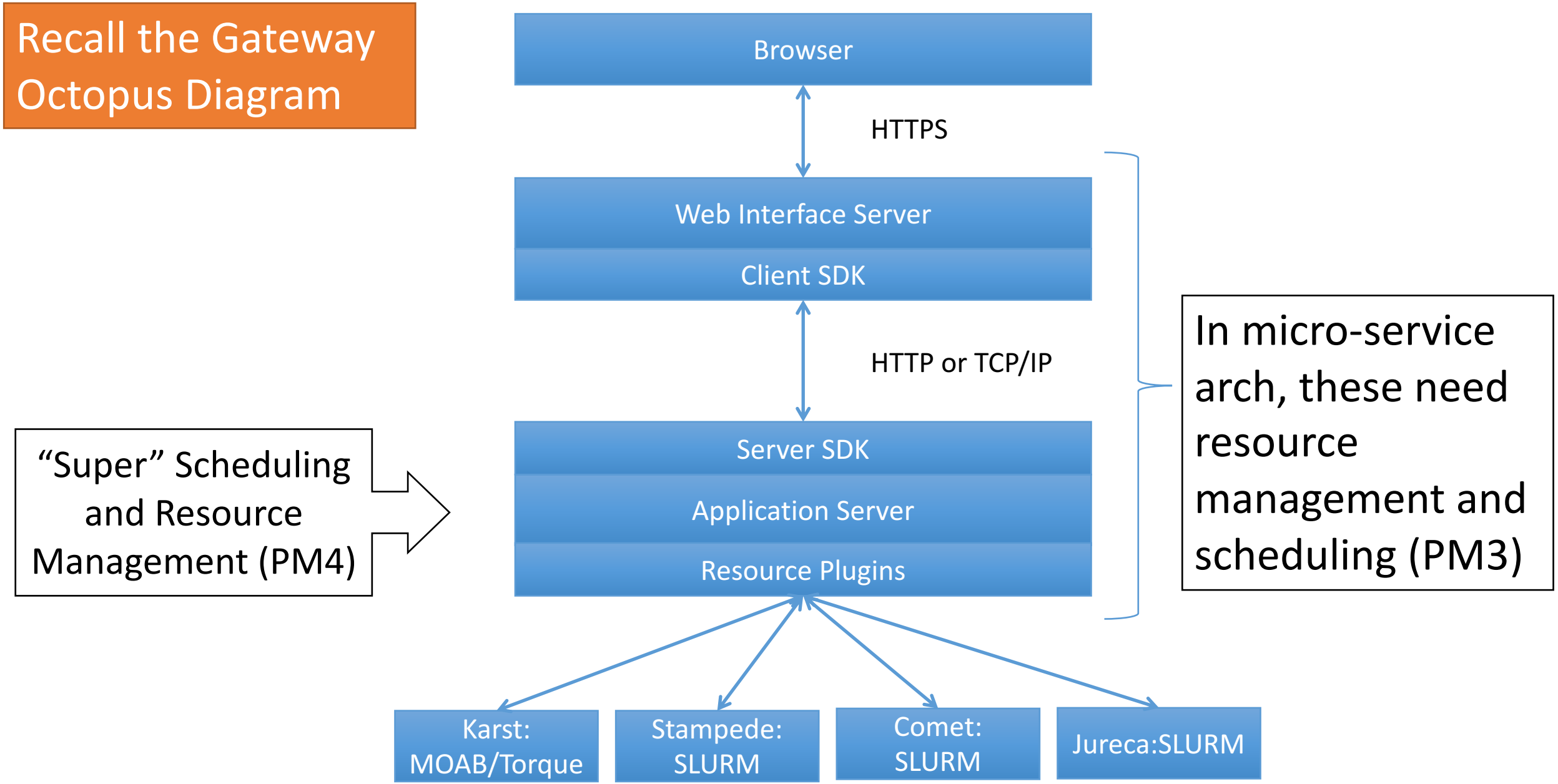
Some General Advice

- Take a class in distributed systems.
- Get a book on distributed systems and read it.
  - Smart people have thought about these problems for a long time.
  - Jim Gray invented two-phase commit c. 1978, for example
  - CS problems often map to non-CS analogies
- There are already many algorithms and design patterns for most problems that you will face.
- The challenge: knowing the right prior solution for the problem at hand
- The anti-pattern: reinventing something in a text book out of ignorance

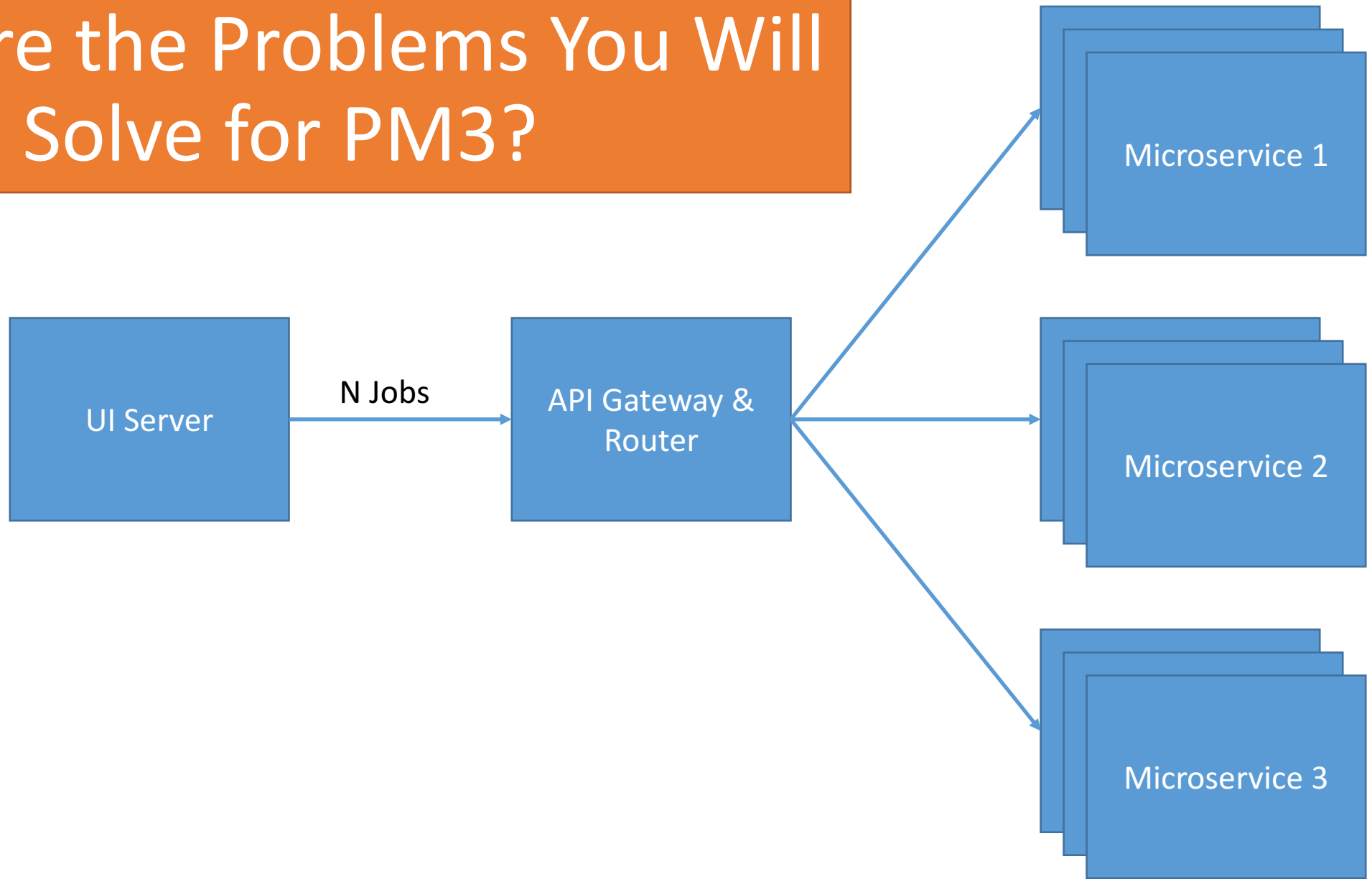
Why Not Just Use ECS?

- If this was a business, you would probably choose ECS.
  - Don’t waste time on reinvention.
  - Implementing in-house is more complicated than you would initially guess.
  - Ex: OpenID Connect
- But grad school is your chance to look under the hood and build something “in house”.
  - Learn the tradeoffs between in-house versus off-the-shelf implementations

Recall the Gateway Octopus Diagram



What Are the Problems You Will Need to Solve for PM3?



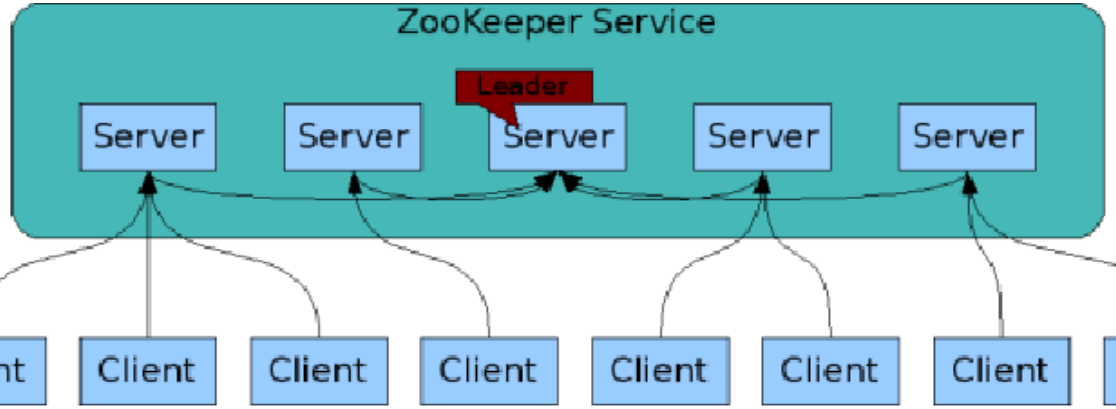
Apache Zookeeper and PM3: Some Answers

- IP addresses, version numbers, and other configuration information of your microservices.
- The health of the microservices.
- The state of a particular calculation.
- Group membership

Apache Zookeeper Is...

- A system for solving **distributed coordination problems** for multiple cooperating clients.
- It looks a lot like a distributed file system...
  - As long as the files are tiny.
  - And you could get notified when the file changes
  - And the full file pathname is meaningful to applications
- `You can use Zookeeper to solve microservice management problems.
- An interesting implementation of a distributed system itself.
  - Look under the hood AND read the papers

The ZooKeeper Service



Zookeeper is itself an interesting distributed system

These are your microservices

- ZooKeeper Service is replicated over a set of machines
- All machines store a copy of the data in memory (!)
- A leader is elected on service startup
- Clients only connect to a single ZooKeeper server & maintains a TCP connection.
- Client can read from any Zookeeper server.
- Writes go through the leader & need majority consensus.

https://cwiki.apache.org/confluence/display/ZOOKEEPER/ProjectDescription

Zookeeper Summary

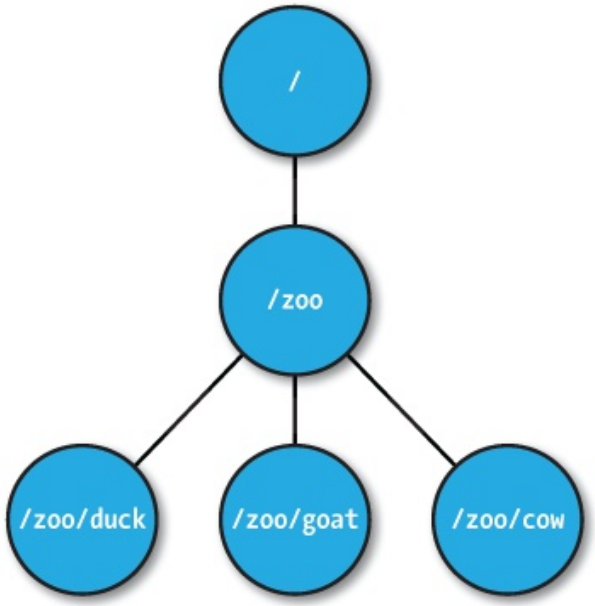
- ZooKeeper provides a simple and high performance kernel for building more complex coordination primitives.
  - Helps distributed components share information
- Clients (your applications) contact Zookeeper services to read and write metadata.
  - Read from cache but writes are more complicated
- Tree model for data.
  - Node names may be all you need
  - Lightly structured metadata stored in the nodes.
- **Wait-free** aspects of shared registers with an **event-driven** mechanism similar to cache invalidations of distributed file systems
- Targets simple metadata systems that read more than they write.
  - Small total storage

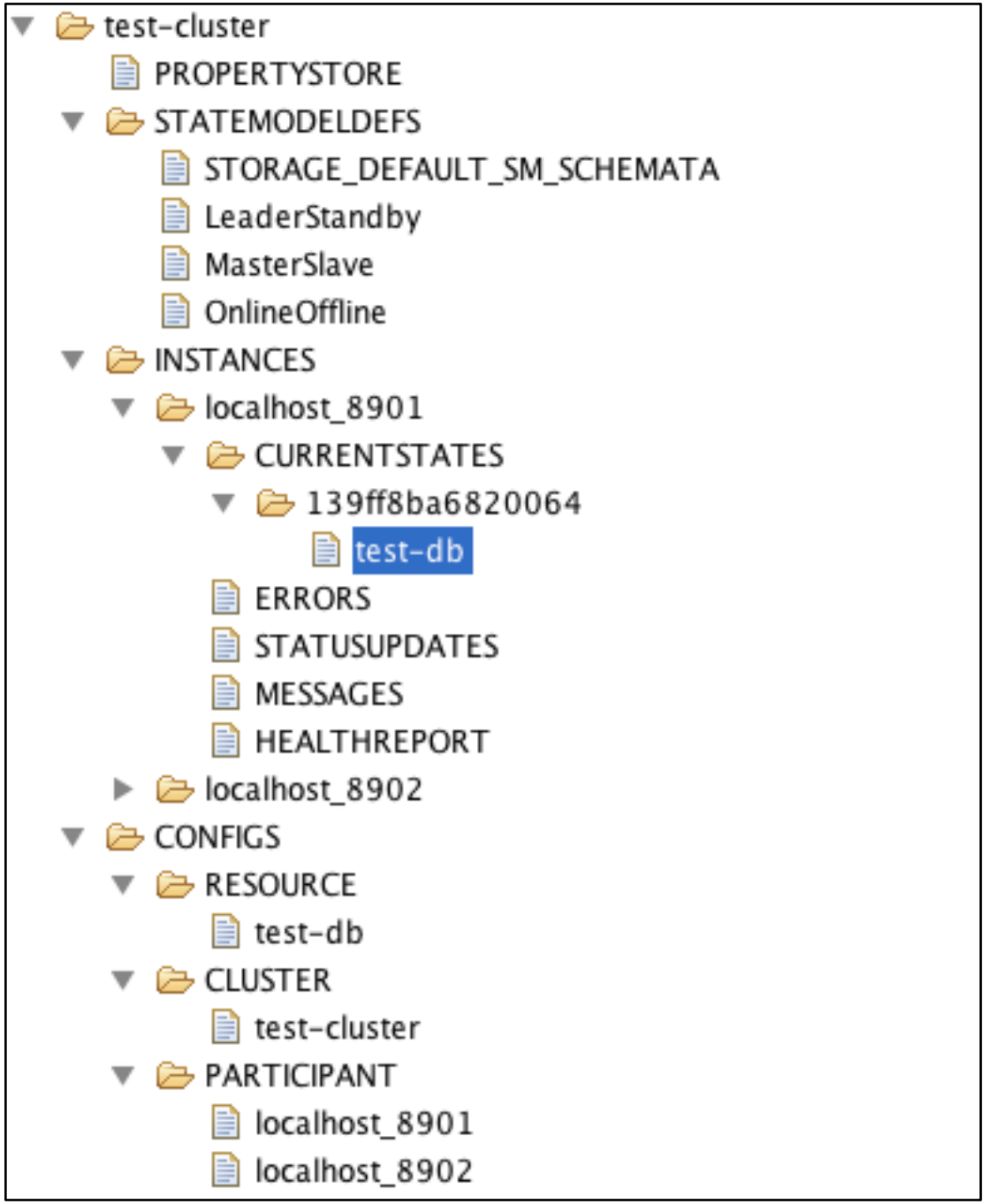
Zookeeper, More Briefly

- Zookeeper Clients (that is, your applications) can create and discover nodes on ZK trees
- Clients can 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.
- You could build a small DNS with Zookeeper.
- Some simple analogies
  - Lock files and .pid files on Linux systems.

ZNodes

- Maintain a stat structure 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 (1/2)

- **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, 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 path exists, and returns false otherwise.
  - Note the *watch* flag

Zookeeper API (2/2)

- **getData(path, watch)**: Returns the data and meta-data, such as 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.

What Can You Do with this Simple API?

Configuration Management

- All clients get their configuration information from a named znode
  - /root/config-me
- Example: you can build a public key store with Zookeeper
- Clients set watches to see if configurations change
- Zookeeper doesn’t explicitly decide which clients are allowed to update the configuration.
  - That would be an implementation choice
  - Zookeeper uses leader-follower model internally, so you could model your own implementation after this.

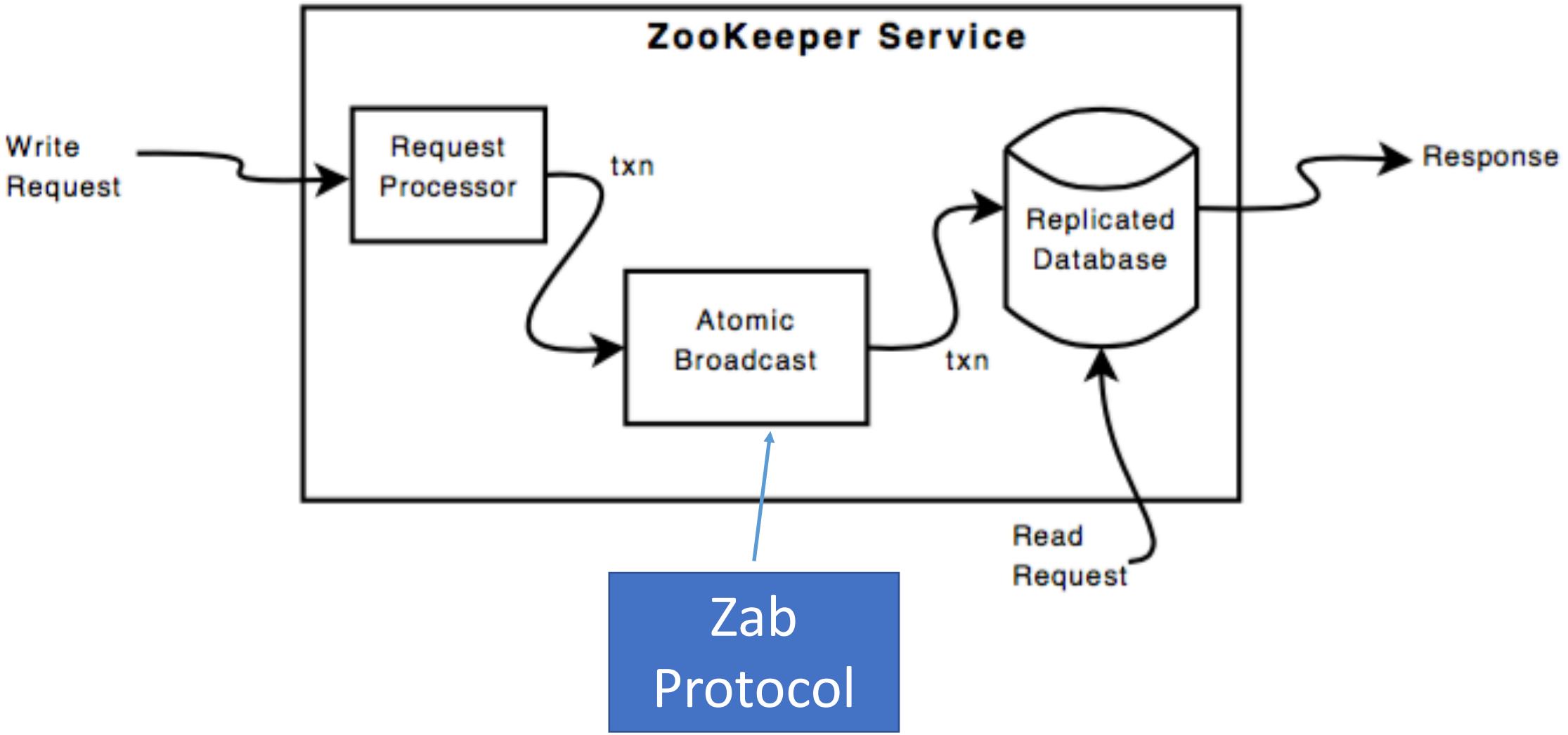
The Rendezvous Problem

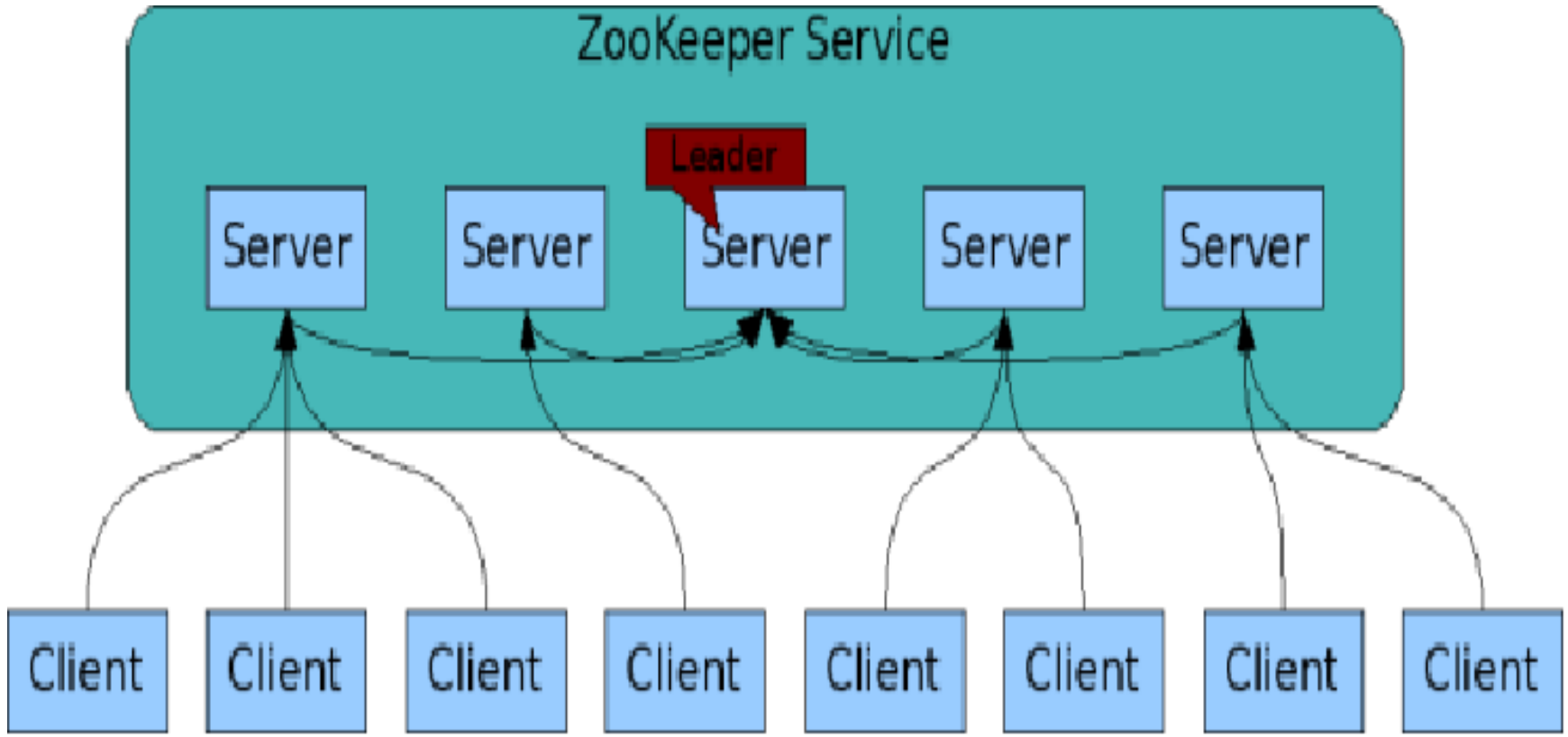
- Classic distributed computing algorithm
- Consider master-worker
  - Specific configurations may not be known until runtime
  - EX: IP addresses, port numbers
  - Workers and master may start in any order
- Zookeeper implementation:
  - Create a rendezvous node: /root/rendezvous
  - Workers read /root/rendezvous 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

Locks

- Familiar analogy: lock files used by Apache HTTPD and MySQL processes
- Zookeeper example: 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

Under the Zookeeper Hood


ZooKeeper Service
Write Request
Request Processor
txn
Atomic Broadcast
txn
Replicated Database
Response
Read Request
Zab Protocol

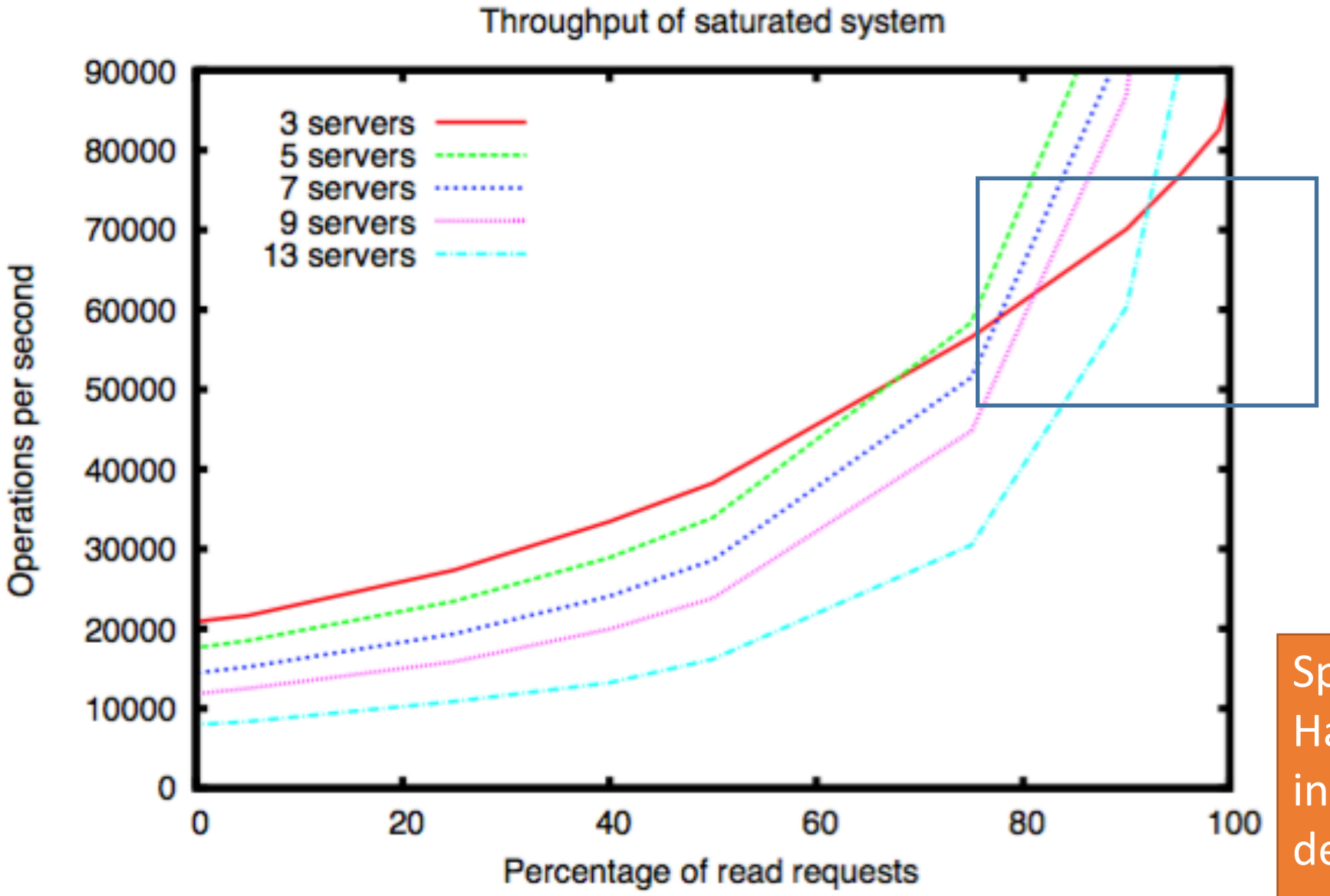

ZooKeeper Service
Leader
Server
Server
Server
Server
Server
Client
Client
Client
Client
Client
Client
Client
Client

Zookeeper Handling of Writes

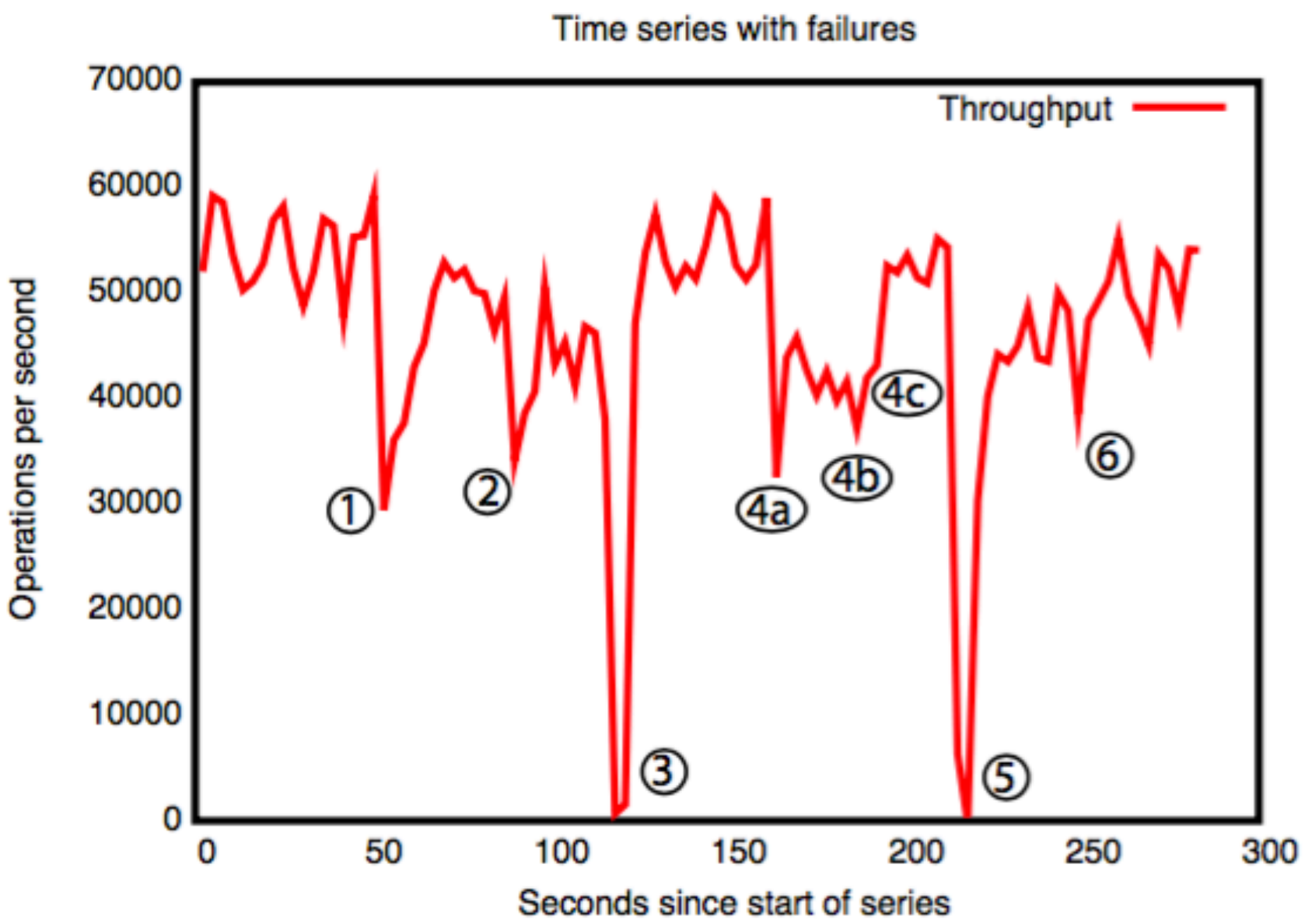
- READ requests are served by any Zookeeper server
  - Scales linearly, although information can be stale
- WRITE requests change state so are handed differently
- One Zookeeper server acts as the leader
- The leader executes all write requests forwarded by followers
- The leader then broadcasts the changes
- The update is successful if a majority of Zookeeper servers have correct state at the end of the process
- Zab protocol

Some Zookeeper Implementation Simplifications

- Uses TCP for its transport layer.
  - Message order is maintained by the network
  - The network is reliable?
- Assumes reliable file system
  - Logging and DB checkpointing
- Does write-ahead logging
  - Requests are first written to the log
  - The ZK DB is updated from the log
- ZK servers can acquire correct state by reading the logs from the file system
  - Checkpoint reading means you don’t have to reread the entire history
- Assumes a single administrator so no deep security



Speed isn't everything. Having many servers increases reliability but decreases throughput as # of writes increases.

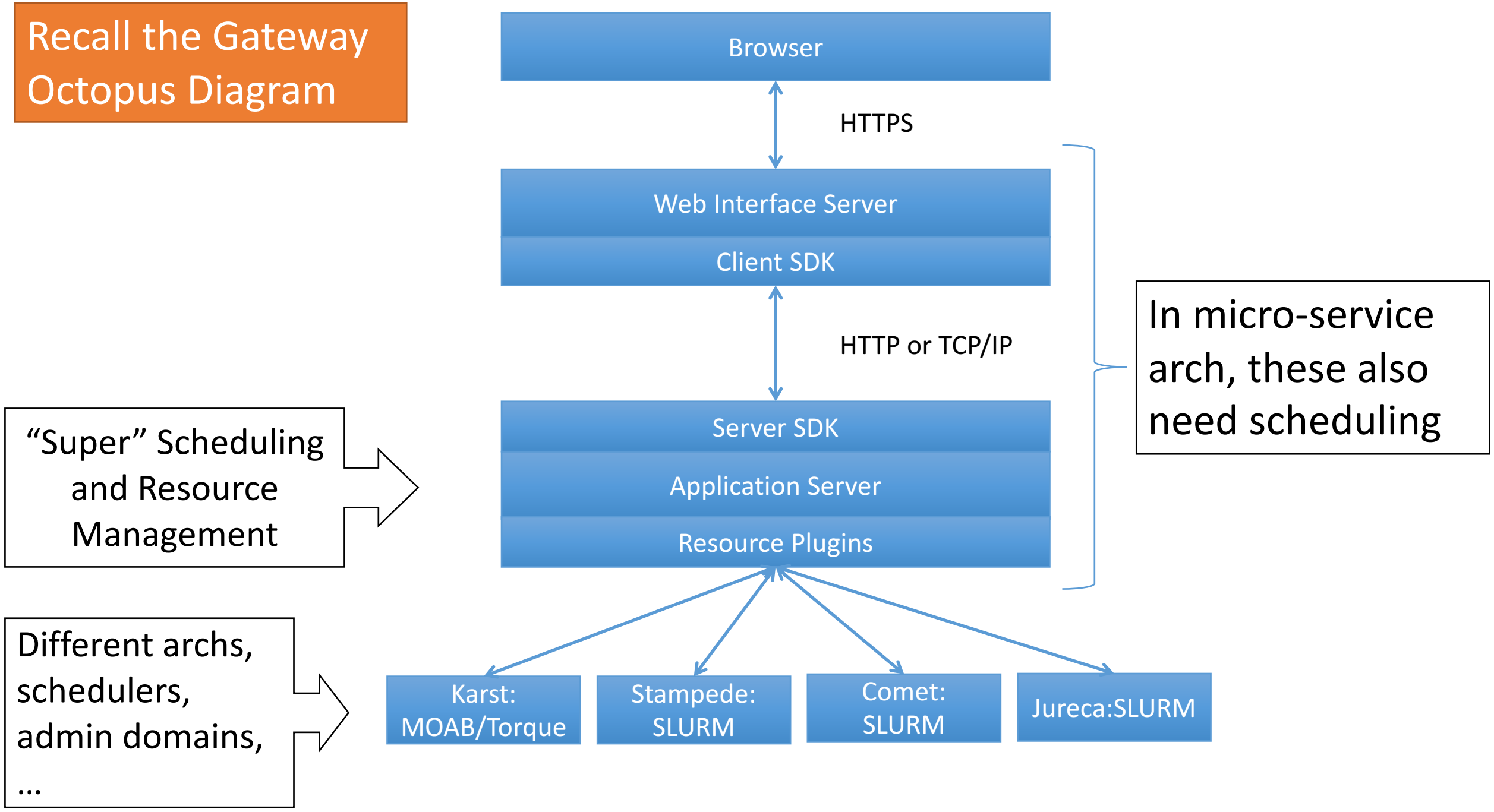


1. Failure and recovery of follower.
2. Failure and recovery of follower.
3. Failure of leader (200 ms to recover).
4. Failure of two followers (4a and 4b), recovery at 4c.
5. Failure of leader
6. Recovery of leader (?)

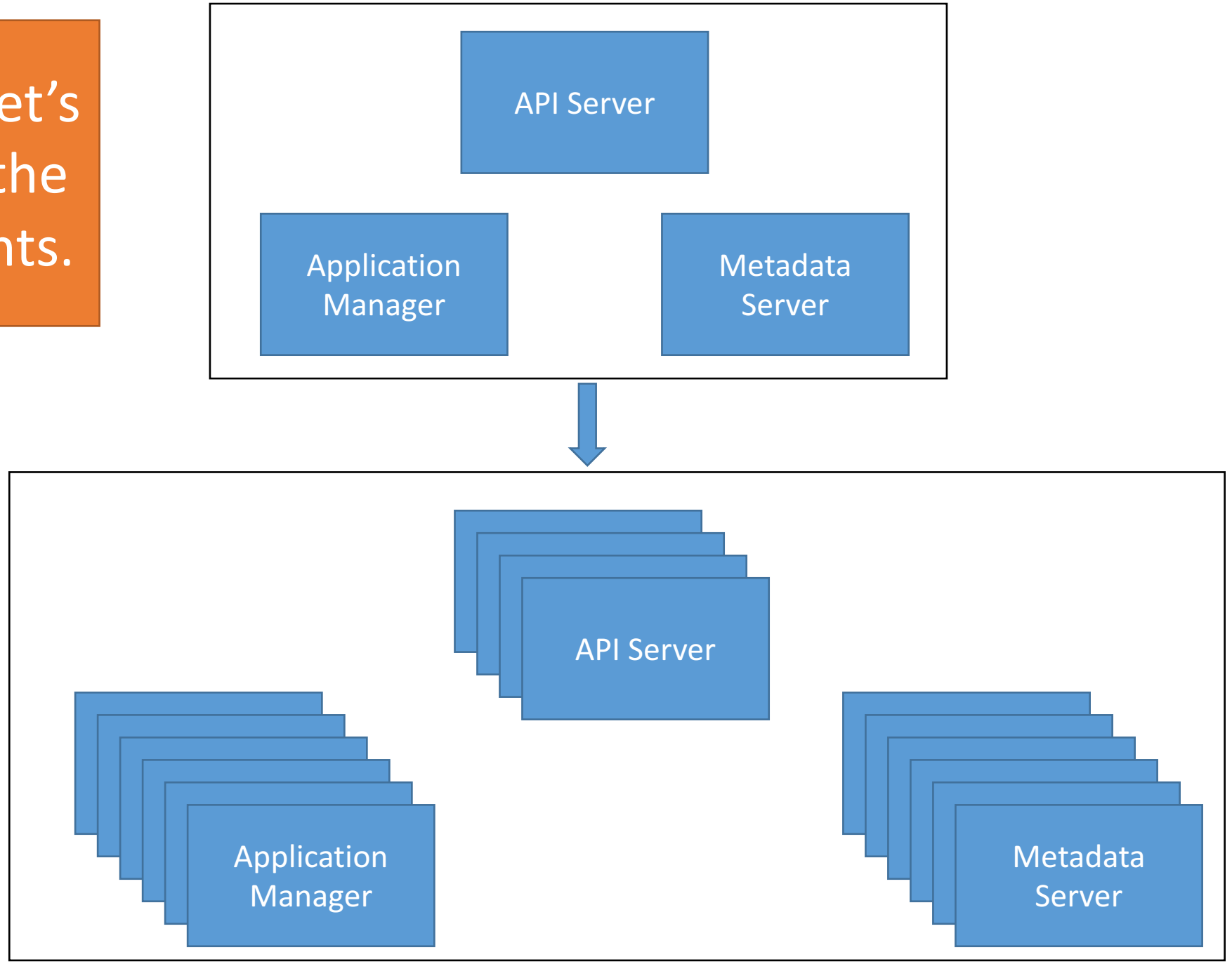
A cluster of 5 zookeeper instances responds to manually injected failures.

Zookeeper and Science Gateways

Recall the Gateway Octopus Diagram



And now let's replicate the components.



Why Do This?

- Fault tolerance
- Increased throughput, load balancing
- Component versions
  - Not all components of the same type need to be on the same version
  - Backward compatibility checking
- Component flavors
  - Application managers can serve different types of resources
  - Useful to separate them into separate processes if libraries conflict.

Configuration Management

- Problem: gateway components in a distributed system need to get the correct configuration file.
- Solution: Components contact Zookeeper to get configuration metadata.
- Comments: this includes both the component's own configuration file as well as configurations for other components
  - Rendezvous problem

Service Discovery

- Problem: Component A needs to find instances of Component B
- Solution: Use Zookeeper to find available group members instances of Component B
  - More: get useful metadata about Component B instances like version, domain name, port #, flavor
- Comments
  - Useful for components that need to directly communicate but not for asynchronous communication (message queues)

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.
- Comments: This is useful to support scheduling

System State for Distributed Systems

- Which servers are up and running? What versions?
- Services that run for long periods could use ZK to indicate if they are busy (or under heavy load) or not.
- Note overlap with our Registry
  - What state does the Registry manage? What state would be more appropriate for ZK?

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.
- Comment: this is not necessarily the best way to do this

Final Thoughts and Cautions

- Zookeeper is powerful but it is only one possible solution.
- A message queue is also very powerful distributed computing concept
  - You could build a queuing system with Zookeeper, but you shouldn't
  - https://cwiki.apache.org/confluence/display/CURATOR/TN
  - There are high quality queuing systems already
- Highly available versus elastic, recoverable components
  - Zookeeper is better in the latter case
- Where is the state of your system? Make one choice. Don't have shadow states.

Introduction to Distributed Systems

Or, What I Have Learned Since 1998

Some Definitions

Distributed Systems	• Multiple software components that work together as a single composite entity.
Distributed Computing	• Distributed components work together to perform large computations by breaking them into smaller parts. • Examples: HTCondor, Apache Hadoop, Apache Spark, MPI, etc
Parallel Computing	• A special case of distributed computing • Typically on a specialized resource (Big Red II, Blue Waters, etc) • Can assume tighter coupling
Science Gateways	• At scale are distributed systems. • Theme for this lecture

Classic Problems in Distributed Systems

- Global Naming
- Identity Management, Authentication, Authorization
- Distributed Transactions
- Distributed State Machines
- Leader Election
- Messaging, publish-subscribe, notification

Classic Distributed Systems Examples

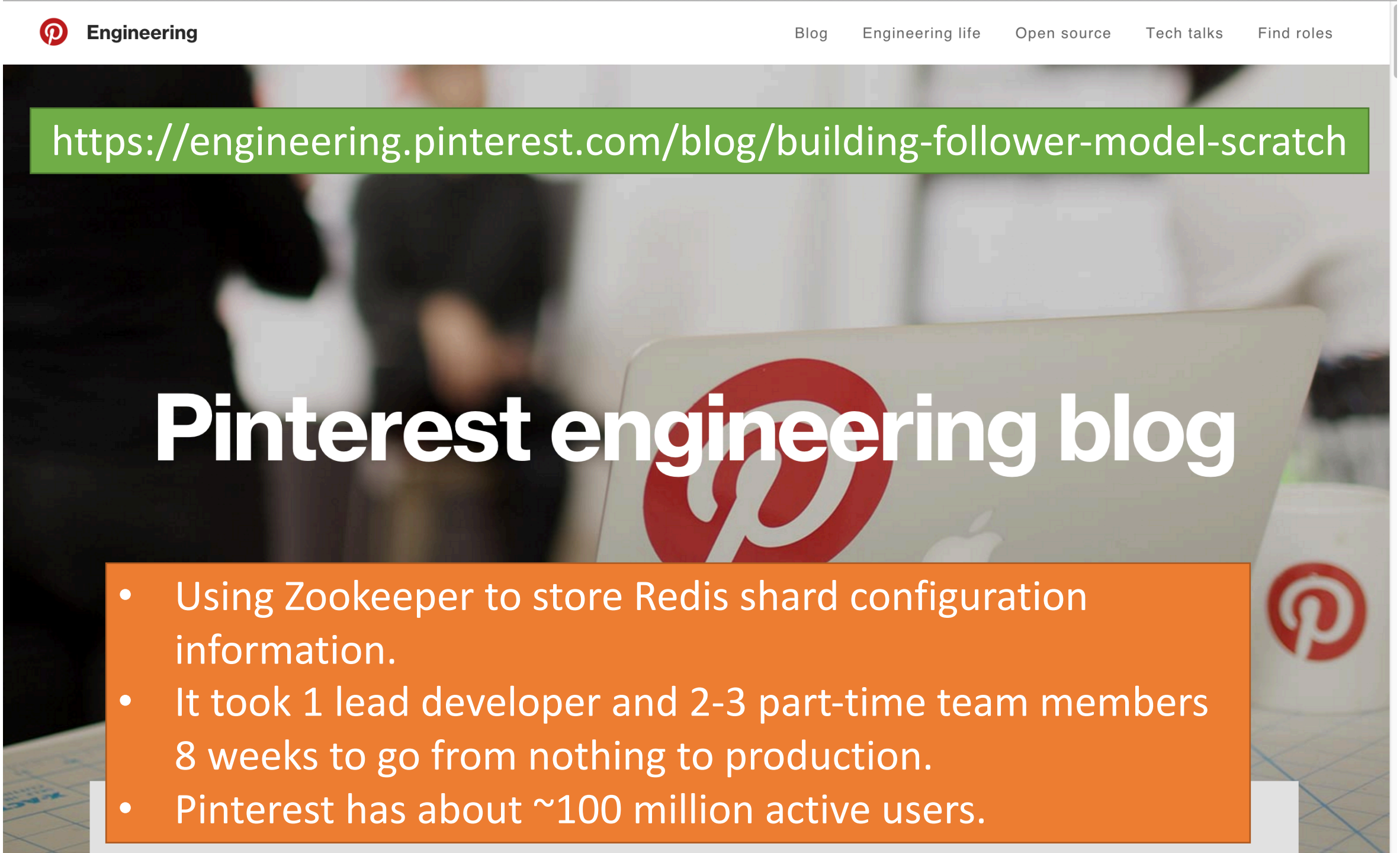
Git	• Versioning
Distributed File Systems	• Write, not just read at scale • Global identities, groups,
Replicated Databases	• Primary copies, leaders, transactions
Resource Managers	• Torque, SLURM, etc • Fault tolerance, process coordination

More Examples

Domain Name Servers	• Naming, caching • Eventual consistency
REST Systems	• Idempotent state • Error messages
Queuing Systems	• Message order, replay, guaranteed delivery
Domain Name Servers	• Scaling power of hierarchies and name spaces

The Fallacies of Distributed Computing

- The network is reliable.
- Latency is zero.
- Bandwidth is infinite.
- The network is secure.
- Topology doesn't change.
- There is one administrator.
- Transport cost is zero.
- The network is homogeneous.


Engineering
Blog
Engineering life
Open source
Tech talks
Find roles
https://engineering.pinterest.com/blog/building-follower-model-scratch
Pinterest engineering blog
• Using Zookeeper to store Redis shard configuration information.
• It took 1 lead developer and 2-3 part-time team members 8 weeks to go from nothing to production.
• Pinterest has about ~100 million active users.

Zookeeper Design Principles

- For read-dominated systems
- Doesn’t prescribe specific coordination primitives.
  - Lower level than that.
- Allow **clients** to create their own coordination applications using the Zookeeper API
  - Configuration Management
  - Locking
  - Rendezvous
  - Group Membership

Zookeeper: Wait-Free Data Objects

Key design choice: wait-free data objects	• Locks are not a Zookeeper primitive • You can use Zookeeper to build lock-based systems
Resembles distributed file systems	• Smaller data
FIFO client ordering of messages	• Asynchronous messaging • Assumes you can order messages globally
Basic idea: idempotent state changes	• Components can figure out the state by looking at the change long • Operations incompatible with state throw exceptions
A good approach when systems can tolerate inconsistent data	• DNS for example • But not E-Commerce, which needs stronger guarantees

Coordination Examples in Distributed Systems

Configuration	•Basic systems just need lists of operational parameters for the system processes: IP addresses of other members •Sophisticated systems have dynamic configuration parameters.
Group Membership, Leader Election	• Processes need to know which other processes are alive • Which processes are definitive sources for data (leaders)? • What happens if the leader is faulty?
Locks	• Implement mutually exclusive access to critical resources.

Zookeeper Caches and Watches

Zookeeper clients cache data	• Reads go to the cache
Watches: notify listening clients when cache has changed	• Watches don’t convey the content of the change. • Only work once; clients decide on the action
Why?	• Networks aren’t uniform or reliable (fallacy) • Centralized, top-down management doesn’t scale
Suitable for read-dominated systems	• If you can tolerate inconsistencies