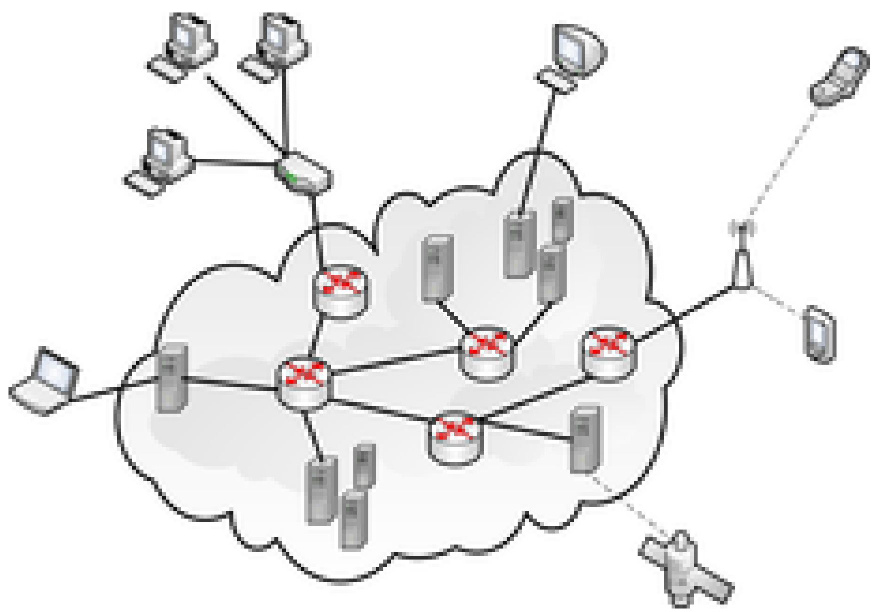
ECE419 - Distributed Systems: Introduction, Motivation & Overview

http://ece419.msrg.utoronto.ca

Slides available in Quercus

(**before** or after lecture)



ECE 419 in a Nutshell

- Introduction to distributed systems
  - Principles, foundations
  - Algorithms, protocols
  - Case studies, applications, architectures

- Learn to build and run distributed systems

- My **office hour:** Monday, 6-7 PM (by appointment)

ECE 419 in a Nutshell

Lectures

Occasional Tutorial Lecture

Our Project:
Four Milestones

Four Assignments

Exams (midterm & final)

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Agenda This Week

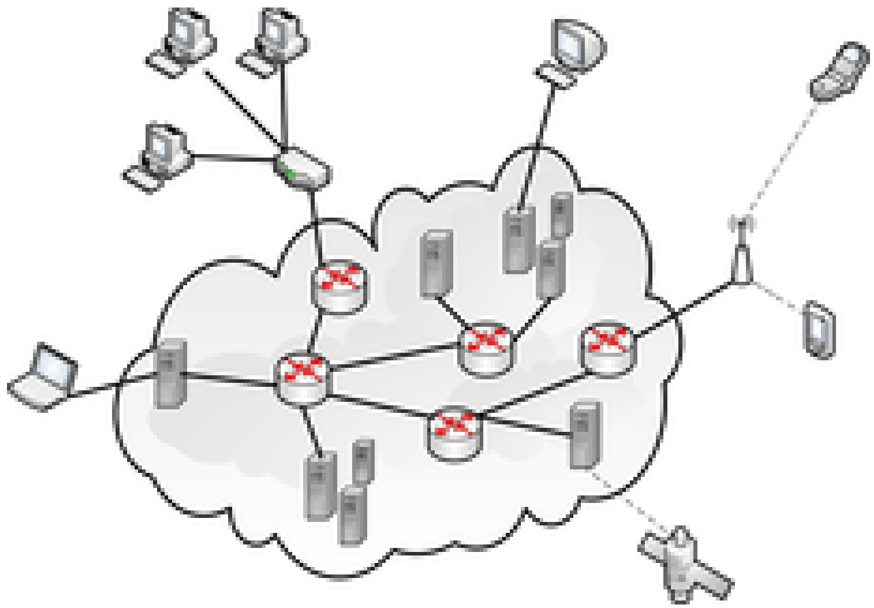
- Distributed systems overview
  - *Roadmap for semester*

- Administrative overview

- Course project (milestones)

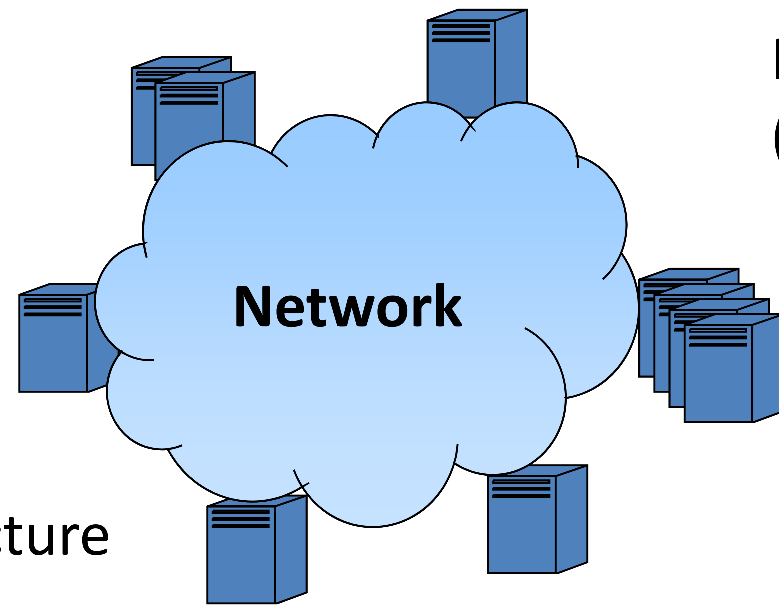
DISTRIBUTED SYSTEMS OVERVIEW

What is a Distributed System?



Working Definition

A distributed system is a system that is comprised of several **physically disjoint compute resources** interconnected by a **network**.



Peer-to-peer
(Bitcoin, BitTorrent)

MapReduce
(Hadoop)

World Wide Web
(Akamai CDN)

Google infrastructure
(BigTable)

Other Definitions & Views

- A distributed system is one in which **hardware** or **software components** located at **networked computers communicate** and **coordinate** their actions only by **passing messages**.
  - *By Coulouris et al.*

- A distributed system is a **collection of independent computers** that appears to its users as **a single coherent system**.
  - *By Tanenbaum & van Steen.*

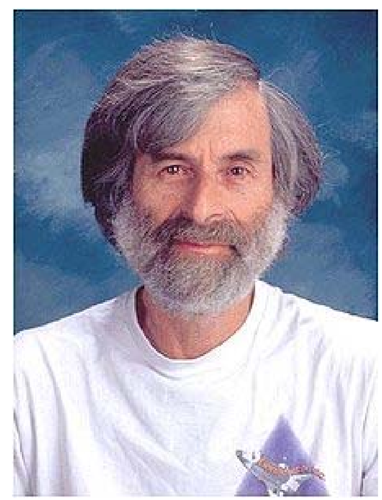
“Introduction to Distributed Systems Design”

- A distributed system is an **application** that executes a collection of **protocols** to **coordinate the actions** of multiple **processes** on a **network,** such that all components **cooperate** together to perform a **single** or small set of **related tasks**.
  - By Google Code University

Leslie Lamport's Anecdotal Remark

- *"A distributed system is one in which the failure of a computer you didn't even know existed can render your own computer unusable*. " (While at DEC SRC, 1985-2001)

- "Father" of distributed systems
  – Turing Award 2013
  – Inventor of LaTeX, ☺



Leslie Lamport

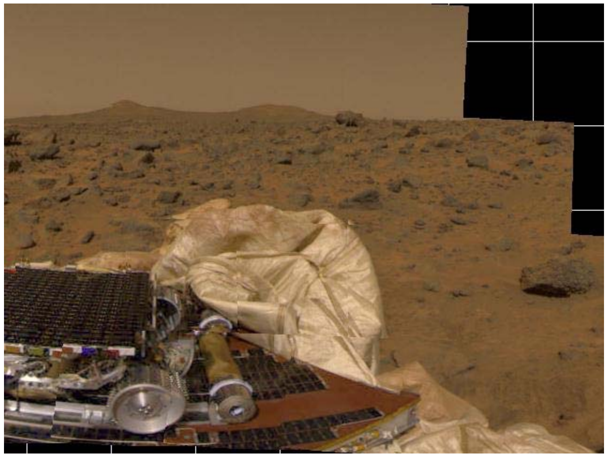
Why Build a Distributed System?

- Centralized system is simpler in all respects:
  - Local memory, storage
  - Failure model
  - Maintenance
  - Data security

Why Build a Distributed System?

But…

Mars Pathfinder, July 1997

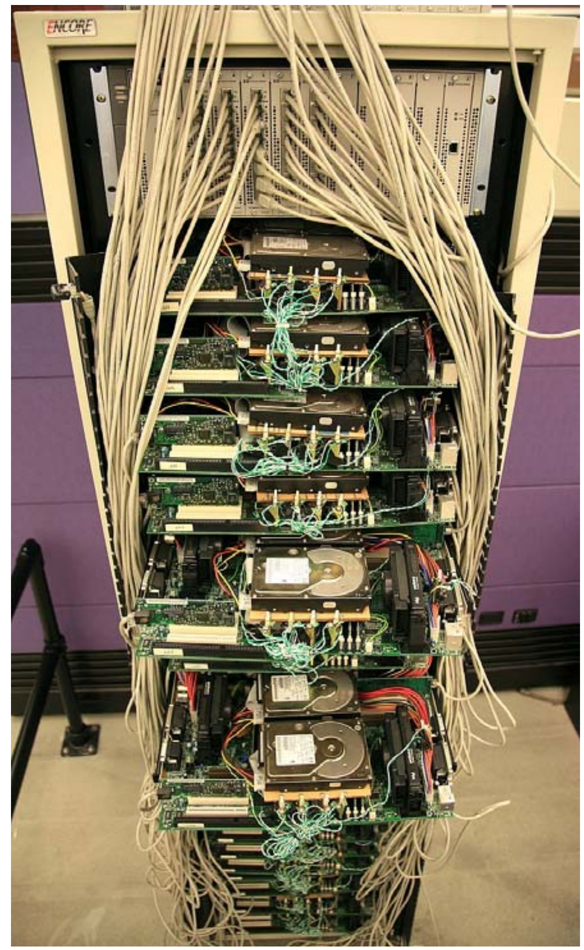


- **Vertical scaling** costs more than **horizontal scaling**
- Availability and redundancy
- Single point of failure

- Many resources are inherently distributed
- Many resources used in a shared fashion

First Google Computer, Cluster

(http://www.computerhistory.org/collections/catalog/102662167)



Related Disciplines …

Networking
- Latency
- Communication

Databases
- Transactions
- Consistency

Distributed Systems

Security
- Faulty stacks
- *Privacy, encryption*

Parallel computing
- Concurrency
- Decomposition

Characteristics of distributed systems

- Reliable
- Fault-tolerant
- Highly available
- Recoverable
- Consistent
- Scalable
- Predictable performance
- Secure
- Heterogeneous
- Open

Also known as the ***ilities***

(non-functional requirements)

Many of them still pose ***significant challenges*** *in theory and in practice!*

Reliability

- Probability of a system to **perform** its **required functions** under **stated conditions** for a **specified period of time**.
- To run continuously without failure

- Expressed as
  Mean Time Between Failure
  (MTBF), failure rate

Availability & High-availability

- Proportion of time a system is in a **functioning state**, i.e., can be used, **(1 – unavailable).**
- **Ratio** of time usable over entire time
  - Informally, uptime / (uptime + downtime)
  - System that **can be used 100 hrs** out of **168 hrs** has **availability of 100/168**
- Specified as decimal or percentage
  - Five nines is 0.99999 or 99.999% available

Nines or Class of 9

# Nines	Avail. (%)	Downtime per			
		year	month	week	day
1 x 9	90	36.5 d	3 d	16.8 h	2.4 h
2 x 9	99	3.65 d	7.2 h	1.68 h	14.4 mins
4 x 9	99.99	52.56 min	4.32 min	60.48 s	8.64 s
5 x 9	99.999	5.256 min	25.92 s	6.048 s	864 ms
6 x 9	99.9999	31.536 s	2.592 s	604.8 ms	86.4 ms
9 x 9	99.9999999	31.536 ms	2.592 ms	604.8 µs	86.4 µs

Nines or Class of 9

- Frequently used for telecommunication systems et al.
- Favorite marketing term
- Does not capture impact or cost of downtime

*"According to Google, its Gmail service was **available** 99.984 percent of the time in 2010 …"* by P. Lilly

Availability ≠ Reliability

- System going down 1 ms every 1 hr has an availability of more than 99.9999%
  - Highly available, but also highly unreliable

- A system that never crashes, but is taken down for two weeks
  - Highly reliable, but only about 96% available

Distributed Systems Design Fallacies

- **Assumptions** (novice) designers of distributed systems often make **that turn out to be false**
- Originated in 1994 by Peter Deutsch, Sun Fellow, Sun Microsystems

- **The 8 fallacies**
  - 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

DISTRIBUTED SYSTEM EXAMPLE: BIGTABLE

Key-value stores

- *What is a key-value-store?*
- *Why is a key-value store needed*?
- Key-value-store client interface
- Key-value stores in practice
- Common features & non-features
- Apache HBase
- Apache Cassandra

What mechanisms make them work?

What are key-value stores?

- Container for key-value pairs (databases)
- Distributed, multi-component, systems
- NoSQL semantics (non-relational)
- KV-Stores offer **simpler query semantics** in exchange for **increased scalability**, **speed**, **availability**, and **flexibility**.

DBMS (SQL)

Students Table

Student	ID*
John Smith	084
Jane Bloggs	100
John Smith	182
Mark Antony	219

Activities Table

ID*	Activity*	Cost
084	Swimming	$17
084	Tennis	$36
100	Squash	$40
100	Swimming	$17
182	Tennis	$36
219	Golf	$47
219	Swimming	$15
219	Squash	$40

- Relational data schema
- Data types
- Foreign keys
- Full SQL support

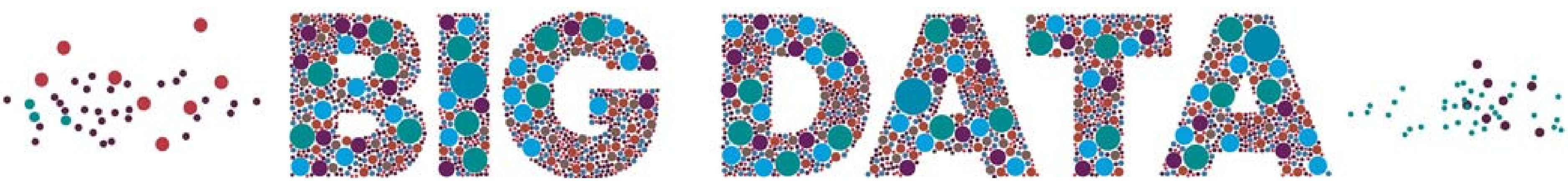
Key-value store

Key	Value
John Smith	{Activity:Name=Swimming}
Jane Bloggs	{Activity:Cost=57}
Mark Anthony	{ID=219}

- No data schema
- Raw byte access
- No relations
- Single-row operations

Why are key-value stores needed?

- Today's internet applications
  - Huge amounts of stored data (1 PB = 10^{15} bytes)
  - Huge number of Internet users (e.g., 3.4 billion)
  - Frequent updates
  - Fast retrieval of information
  - Rapidly changing data definitions
- Ever more users, ever more data



Why are key-value stores needed?

- Horizontal scalability
  - User growth, traffic patterns change
  - Adapt to number of requests, data size
- Performance
  - High speed for single-record read and write operations
- Flexibility
  - Adapt to changing data definitions

Why are key-value stores needed?

- Reliability
  - Thousands of components at play
  - Uses commodity hardware: failure is the norm
  - Provide failure recovery
- Availability and geo-distribution
  - Users are worldwide
  - Guarantee fast access

Key-value store client interface

- Main operations
  - Write/update **put**(key, value)
  - Read **get**(key)
  - Delete **delete**(key)

- Usually no aggregation, no table joins, no transactions!

Hbase: Key-value store client interface

```
Configuration conf = HBaseConfiguration.create();
conf.set("hbase.zookeeper.quorum", "192.168.127.129");

HTable table = new HTable(conf, „M

Put put = new Put(Bytes.toBytes("k                 ));
put.add(Bytes.toBytes("colfam1"), Bytes.toBytes(„value"), Bytes.toBytes(200));
table.put(put);

Get get = new Get(Bytes.toBytes("key1"));
Result result = table.get(get);
byte[] val = result.getValue(Bytes.toBytes("colfam1"), Bytes.toBytes(„value"));
System.out.println("Value: " + Bytes.toInt(val));
```

Initialization Using ZooKeeper

Column Family: “Schema”

Column: Defined at run-time (“wide column” stores)

Key-value store in practice

- BigTable
- Apache HBase
- Apache Cassandra
- Redis
- Amazon Dynamo
- Yahoo! PNUTS

Common elements of key-value stores

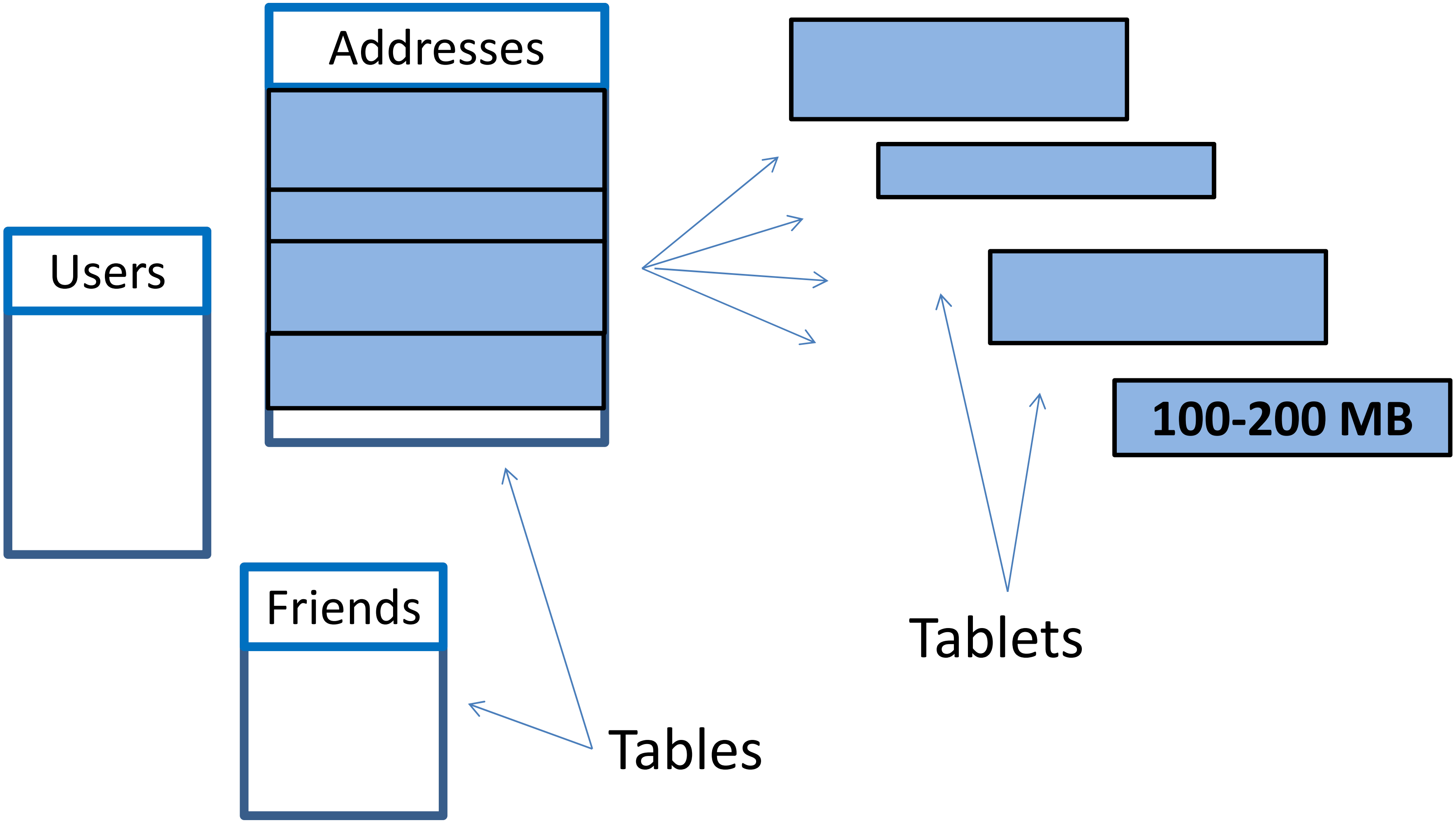
- Failure detection & failure recovery *(cf. DS Models Lecture)*
- Replication *(cf. Replication Lecture)*
  - Store and manage multiple copies of data
- Memory store & write ahead log (WAL) *(cf. Web Caching, Consistent Hashing Lecture)*
  - Keep data in memory for fast access
  - Keep a commit log as ground truth
- Versioning (*cf. Time in DS Lecture*)
  - Store different versions of data
  - Timestamping

BIGTABLE / HBASE

BigTable

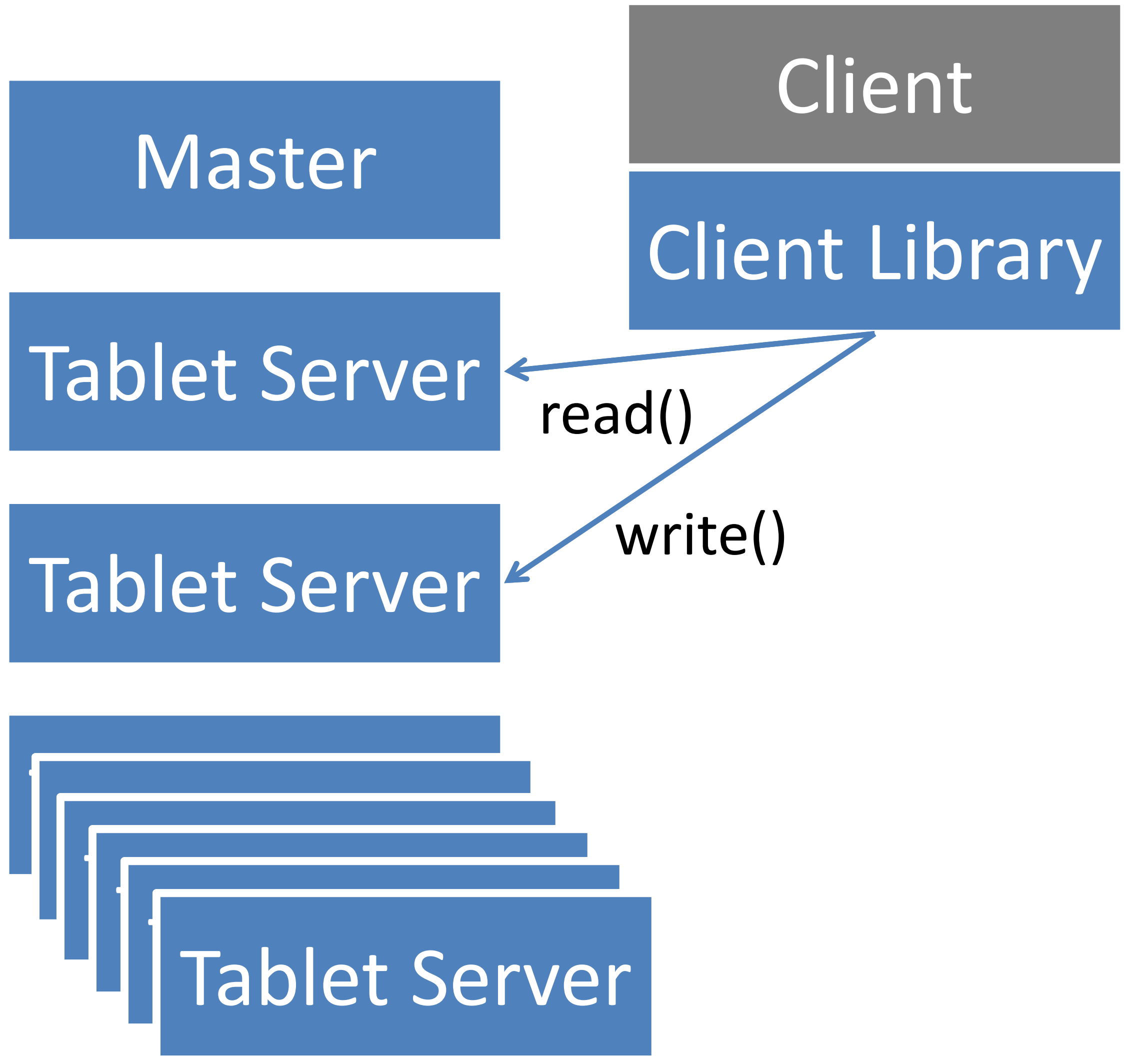
- Engineered at Google, 2004
- Designed for petabyte scale
- Internal use for web indexing, personalized search, Google Earth, Google Analytics, Google Finance
- Based on Google File System (GFS), *cf. GFS et al. Lecture*

BigTable: Tables & Tablets
(Logical Organization)



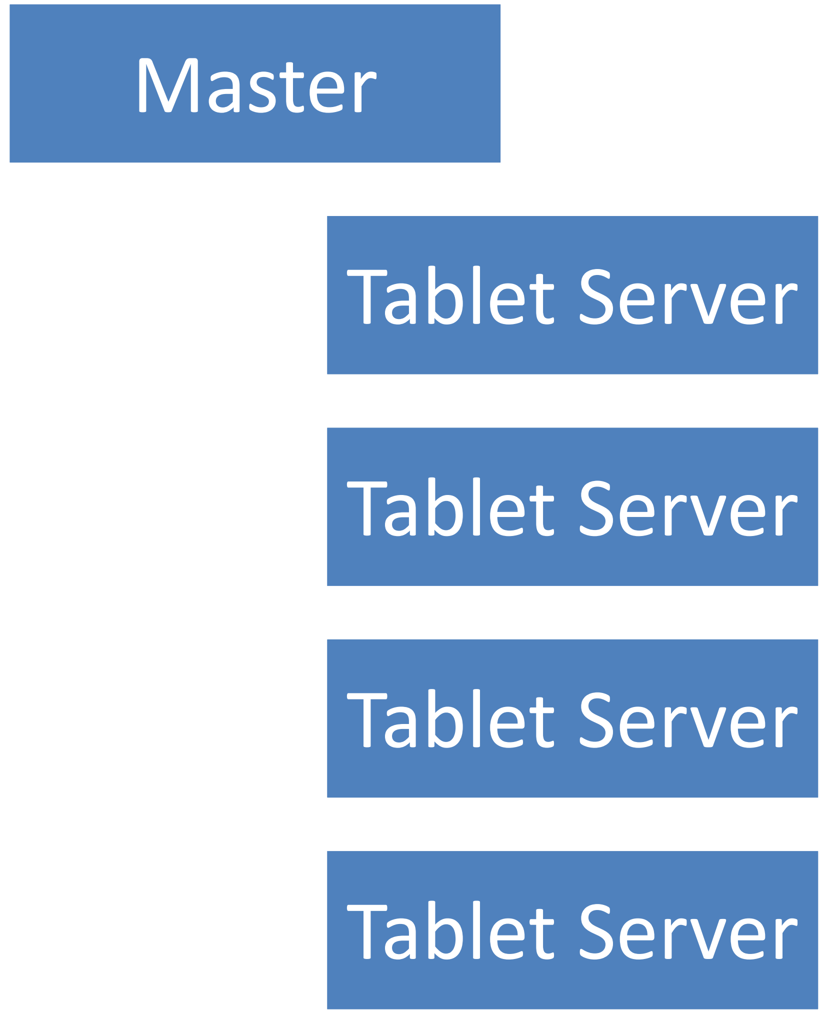
BigTable Components

- Client library
- Master
  - Metadata operations
  - Load balancing
- Tablet server
  - Data operations



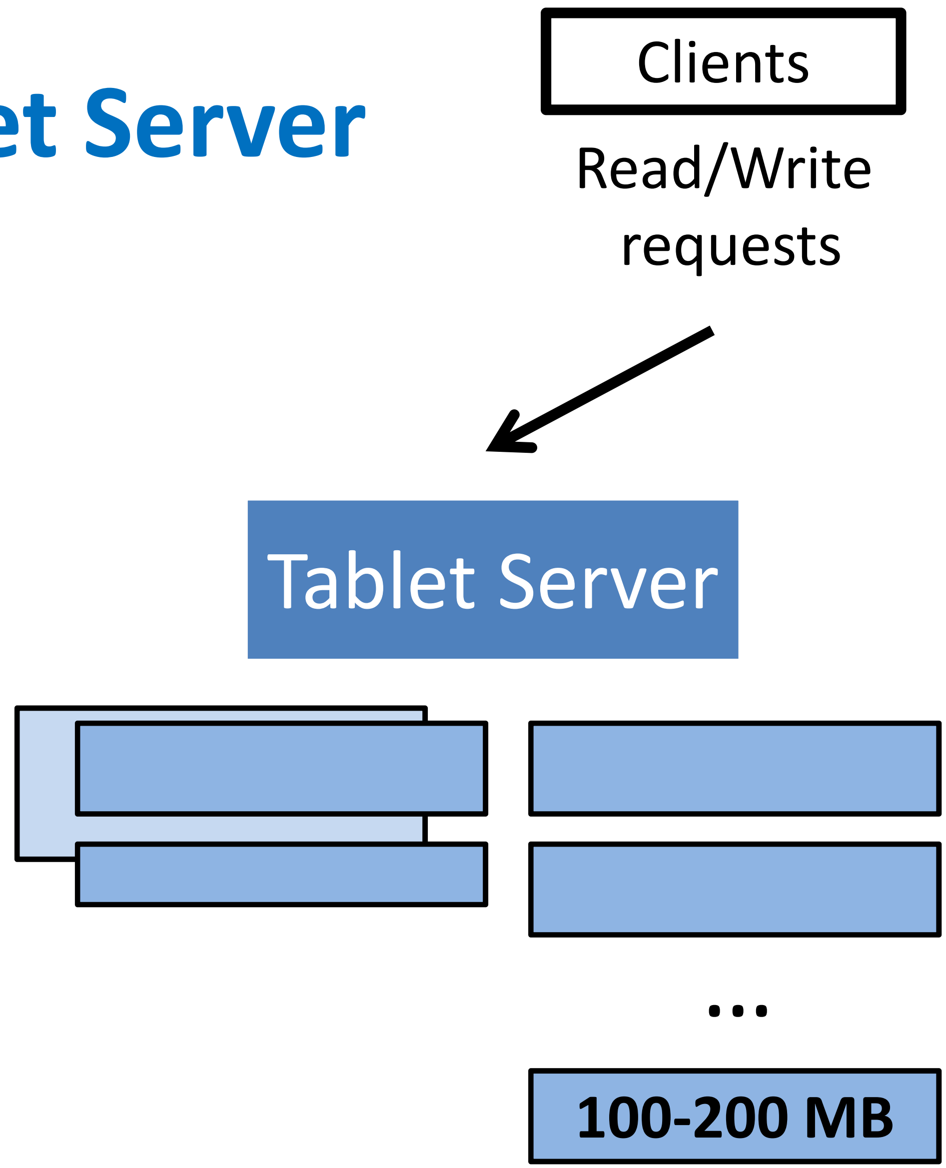
Master

- Assigns tablets to tablet servers
- Detects addition and expiration of tablet servers
- Balance tablet server load



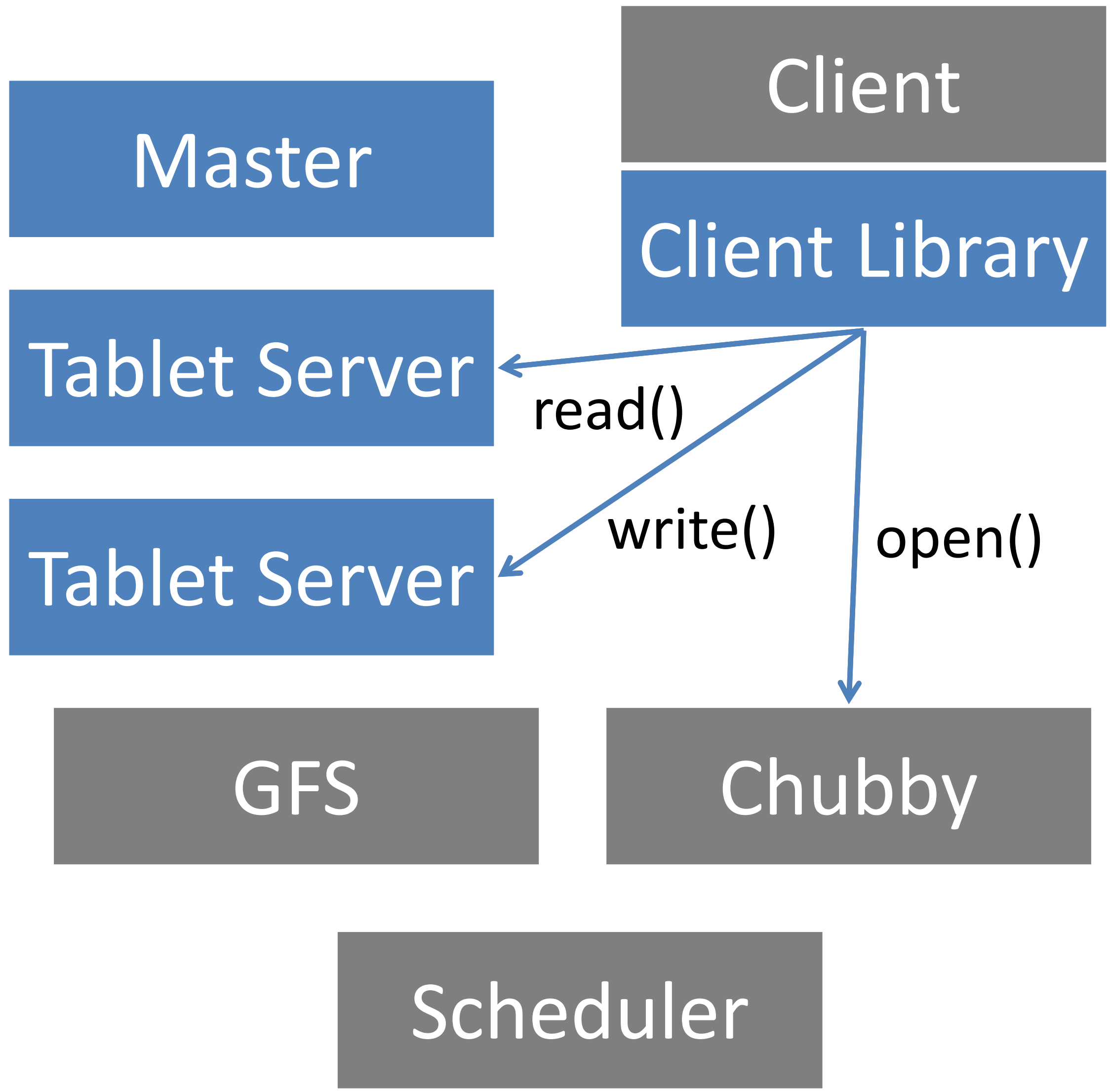
Tablet Server

- Manages a set of tablets (up to a thousand)
- Handles read and write requests for the tablets it manages
- Splits tablets that have grown too large



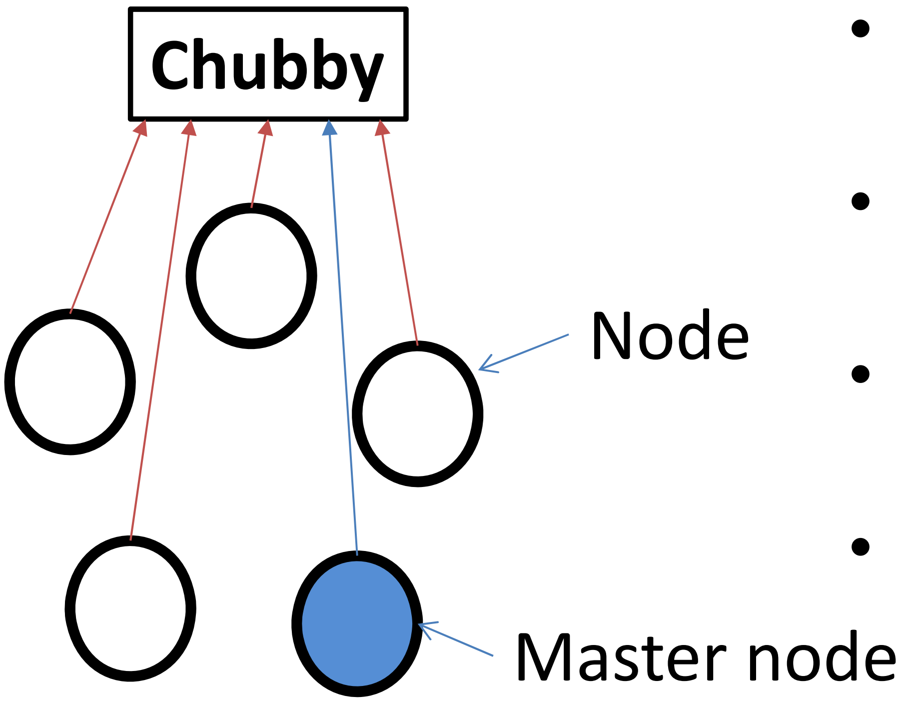
BigTable Building Blocks

- Chubby *(cf. Paxos Lecture)*
  - Lock service
  - Metadata storage
- GFS *(cf. GFS et al. Lecture)*
  - Data, log storage
  - Replication
  - Uses Sorted Strings Table files (SSTables)
- Scheduler
  - Monitoring
  - Failover



Chubby Lock Service

Highly-available, persistent, distributed lock, coordination service



Sample use in BigTable

- Ensure at most one active BigTable master at any time
- Store bootstrap location of data (root tablet)
- Discover tablet servers (manage their lifetime)
- Store schema information

Chubby Lock Service

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Cf. Coordination and Agreement Lecture

Cf. The Paxos Consensus Algorithm Lecture

Cf. Coordination with Zookeeper Lecture

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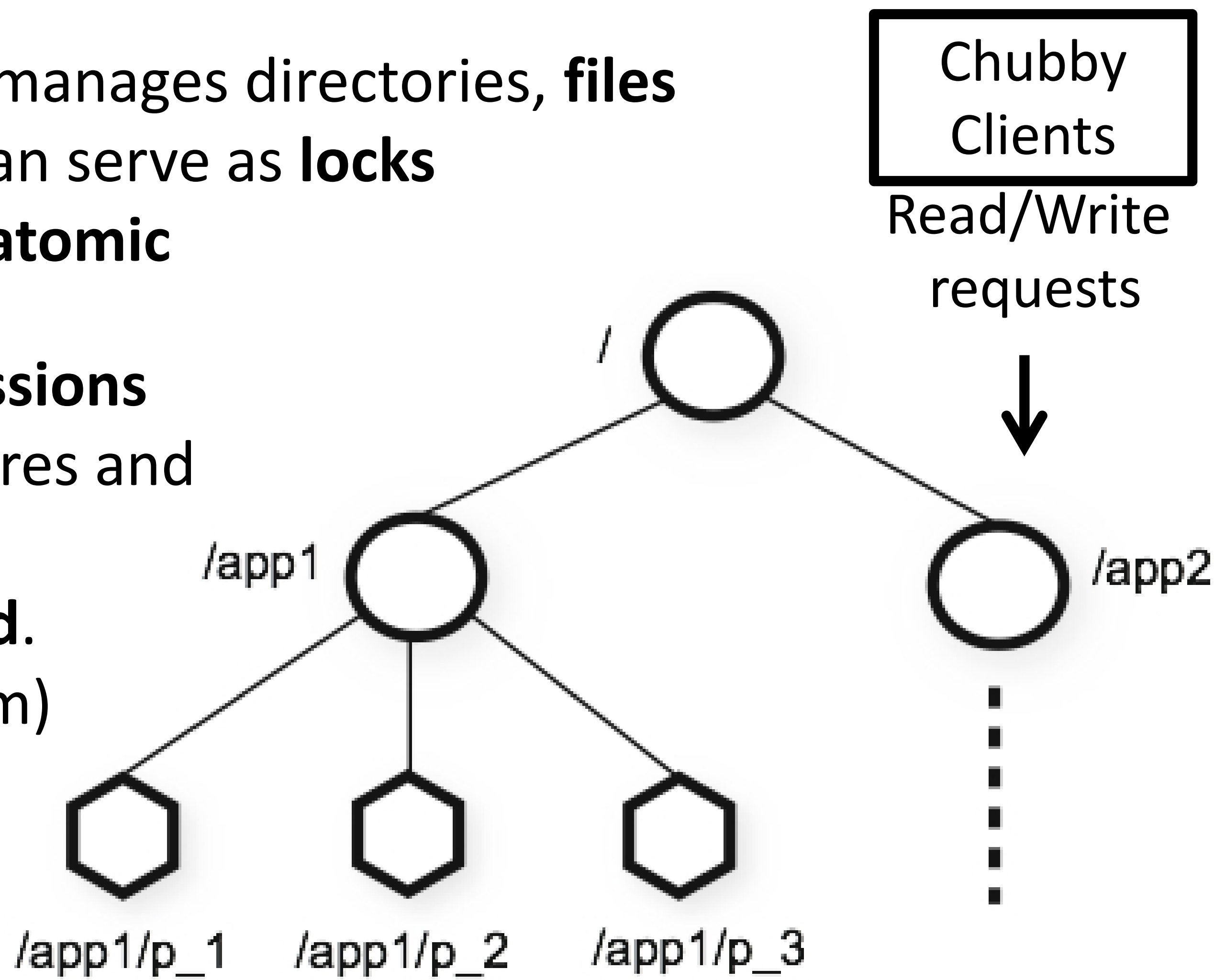
Lock Service Operational Model

- Knows about and manages directories, **files**
- Directories, files can serve as **locks**
- Reads, writes are **atomic**

Clients maintain **sessions**
If session lease expires and can't be renewed, **locks** are **released**.
(timeout mechanism)



Lock Service Availability

- Comprised of **five** active **replicas**
  - **Consistently replicate writes (***cf. Replication Lecture***)**
- One replica is designated as master
  - Need to **elect** master (**leader**) (*cf. Coordination Lecture*)
  - Chubby master is different from BigTable master!
- Service is up when:
  - Majority of replicas are running and
    - A **quorum** of replicas is established
  - Can communicate with one another

Core Mechanisms

- Ensure one active BigTable master at any time
  - **Leader election**, but in a distributed setting
  - *Cf. Coordination and Agreement Lecture*
- Keep replicas consistent in face of failures
  - **Paxos algorithm** based on replicated state machines (RSM)
  - Atomic broadcast
  - *Cf. Paxos Lecture, Replication Lecture*

Chubby Example: leader election

- Electing a leader node: supported by acquiring an exclusive lock on a file (**clients represent partaking nodes**)
- Clients concurrently **open a file** and attempt to acquire the file lock in write mode
- One client **succeeds** (i.e., becomes the **leader**) and writes its name to the file
- Other clients **fail** (i.e., become **replicas**) and discover the name of the leader by reading the file

Chubby Example: leader election

```
Open("/ls/cell1/somedir/file1",
      "write mode")

if (successful) {   // leader
      setContents(primary_identity)
} else {            // replica
      Open("/ls/cell1/somedir/file1",
            "read mode",
            "file-modification event")
      On modification notification
            primary = getContentsAndStat()
}
```

obtain file handle

write to file

subscribe to modification event

read from file

Apache HBase

- Open-source implementation of BigTable
- E.g., Facebook Messenger uses Hbase

- Different names for similar components
  - GFS → HDFS
  - Chubby → Zookeeper
  - BigTable → Hbase
  - MapReduce → Hadoop

BigTable vs. MapReduce

BigTable

- Layered on top of GFS
- Data storage and access
- BigTable: read/write web data

MapReduce

- Layered on top of GFS
- Batch analytics
- MapReduce: offline batch processing *(cf. MapReduce Lecture)*

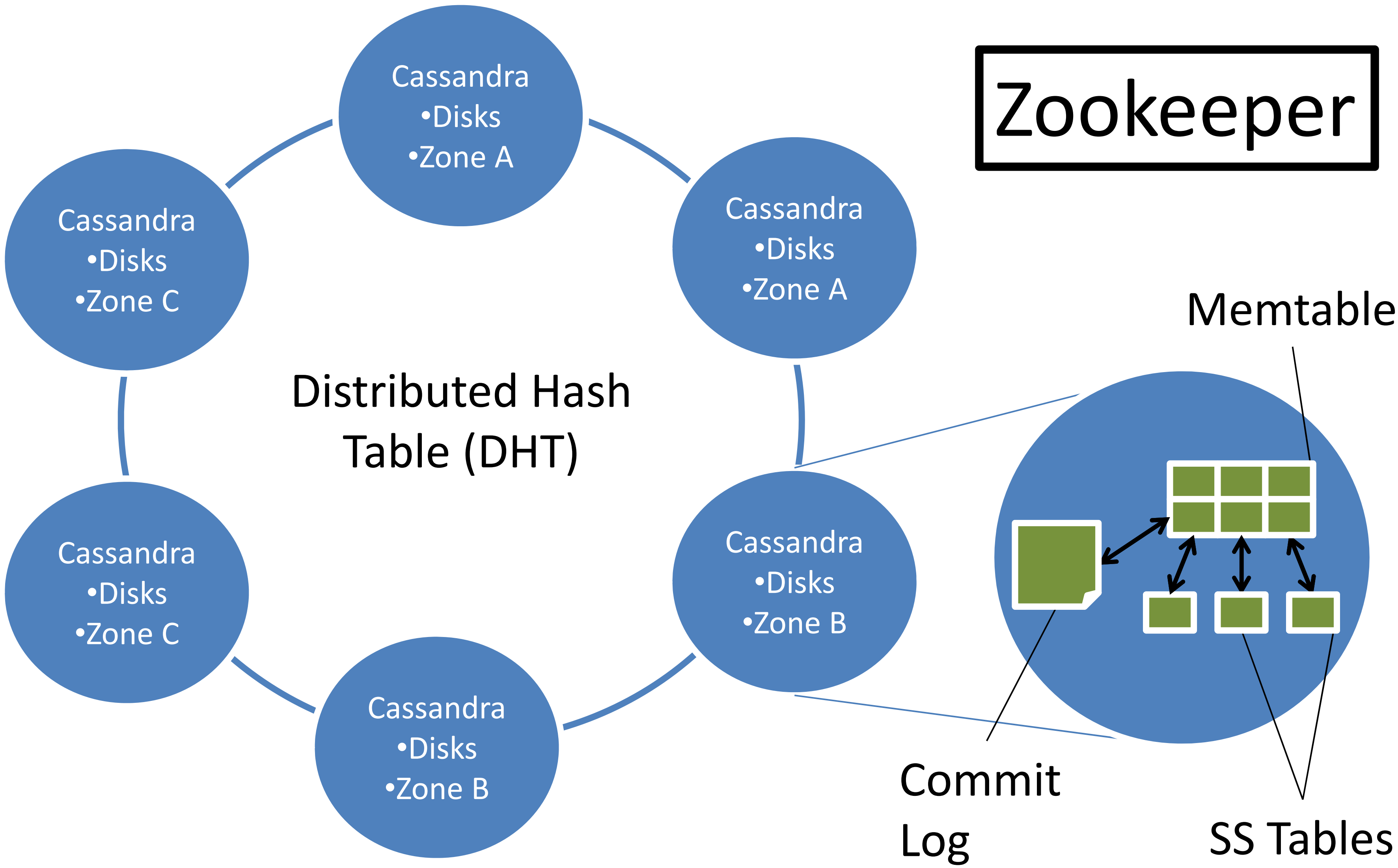
Google File System: common persistent storage layer *(cf. GFS et al. Lecture)*

DYNAMO / CASSANDRA

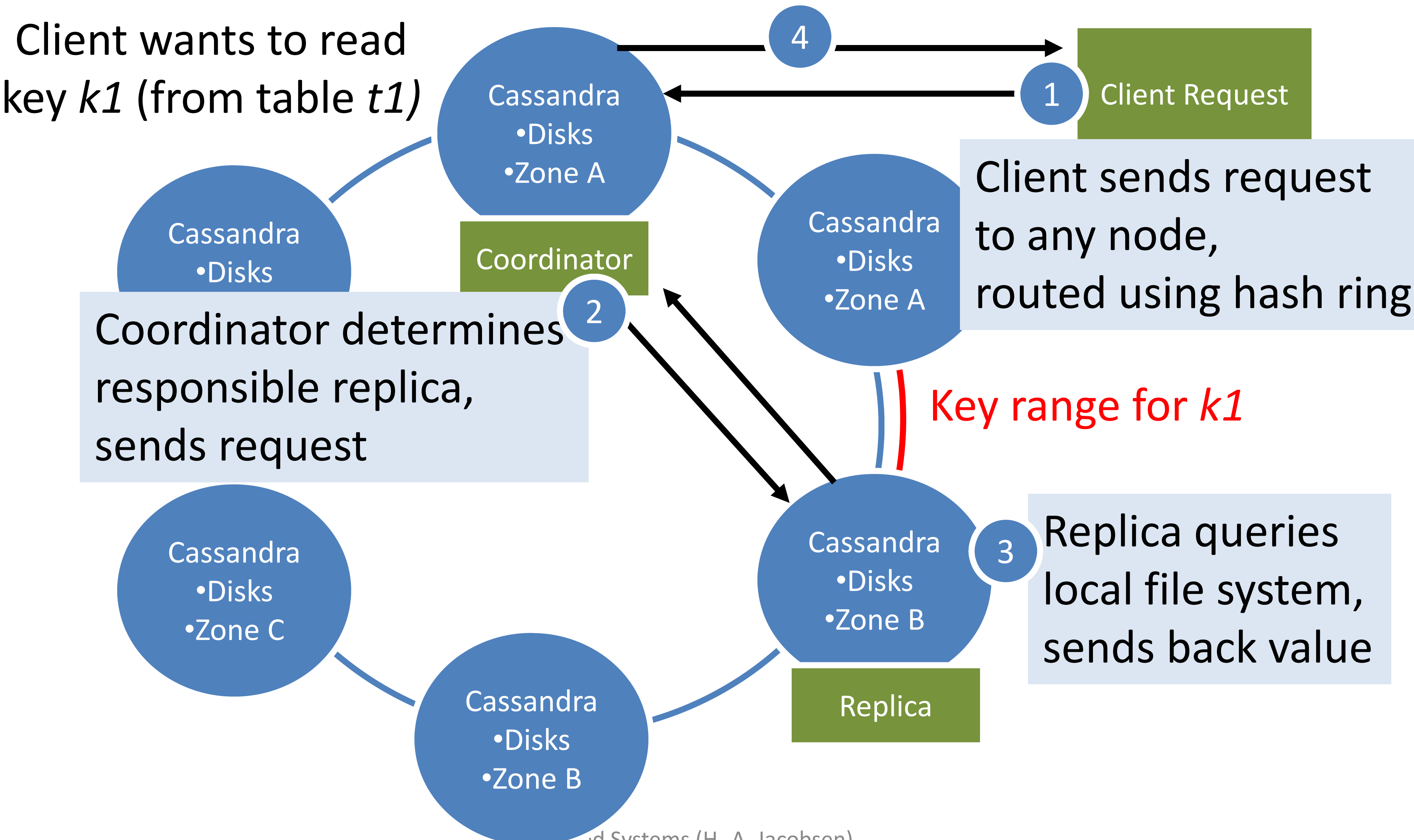
Cassandra

- Developed by Facebook
- Based on Amazon Dynamo (but open-source)
- Structured storage nodes (**no GFS** used)
- **Decentralized** architecture (no master assignment)
- **Consistent hashing** for load balancing
- Eventual consistency
- **Gossiping** to exchange information

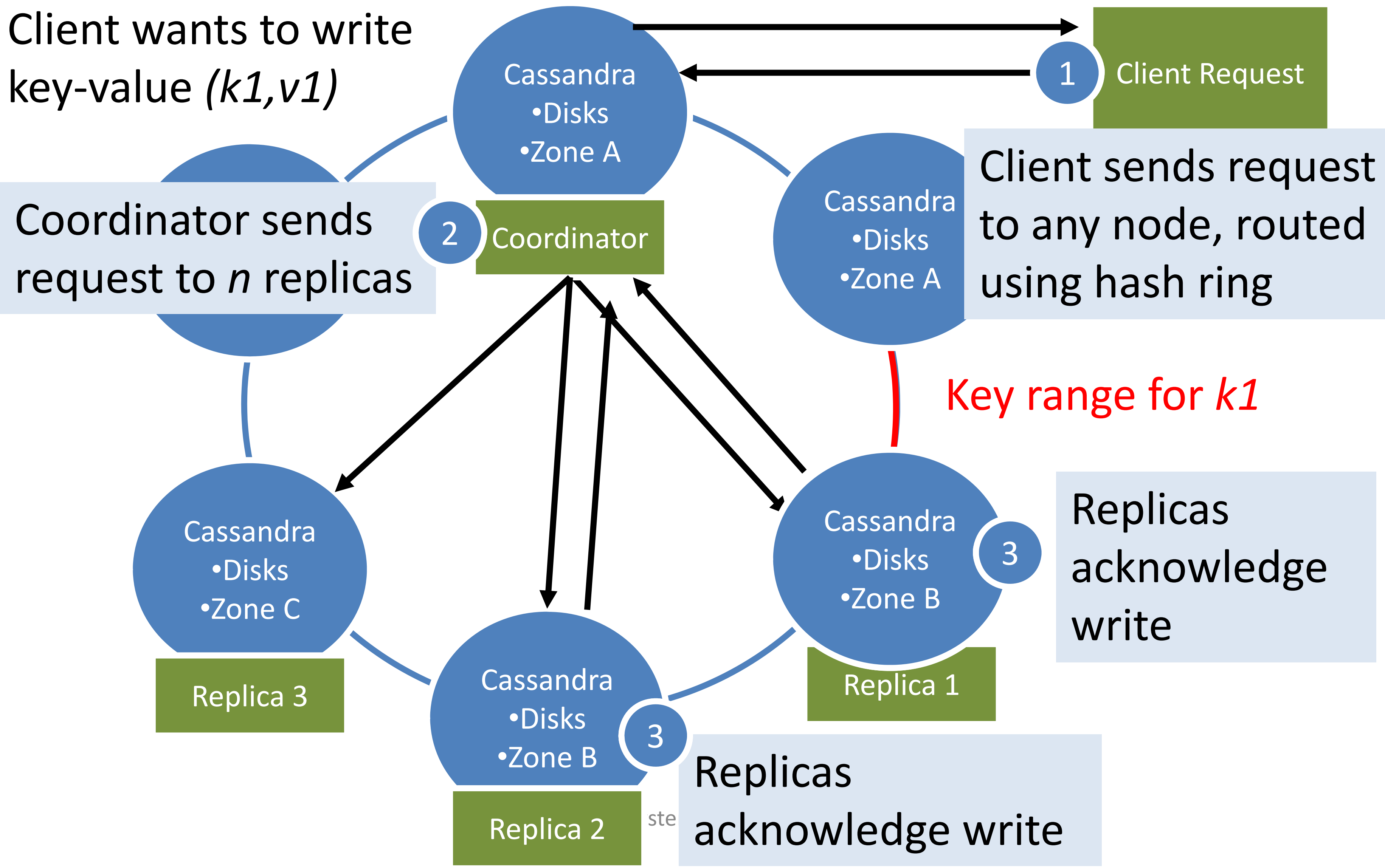
Cassandra Architecture Overview



Cassandra global read-path

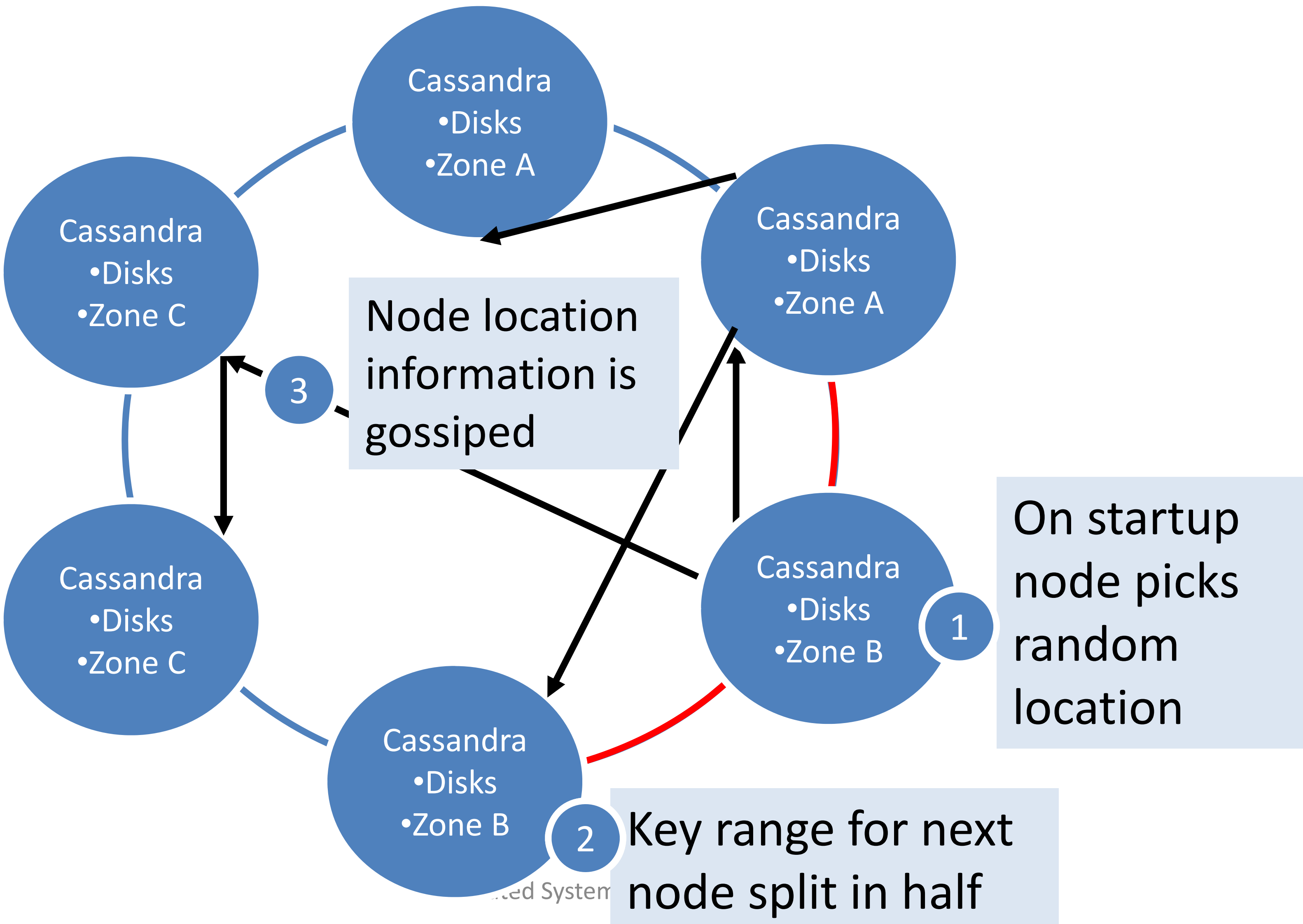


Cassandra Global Write-path

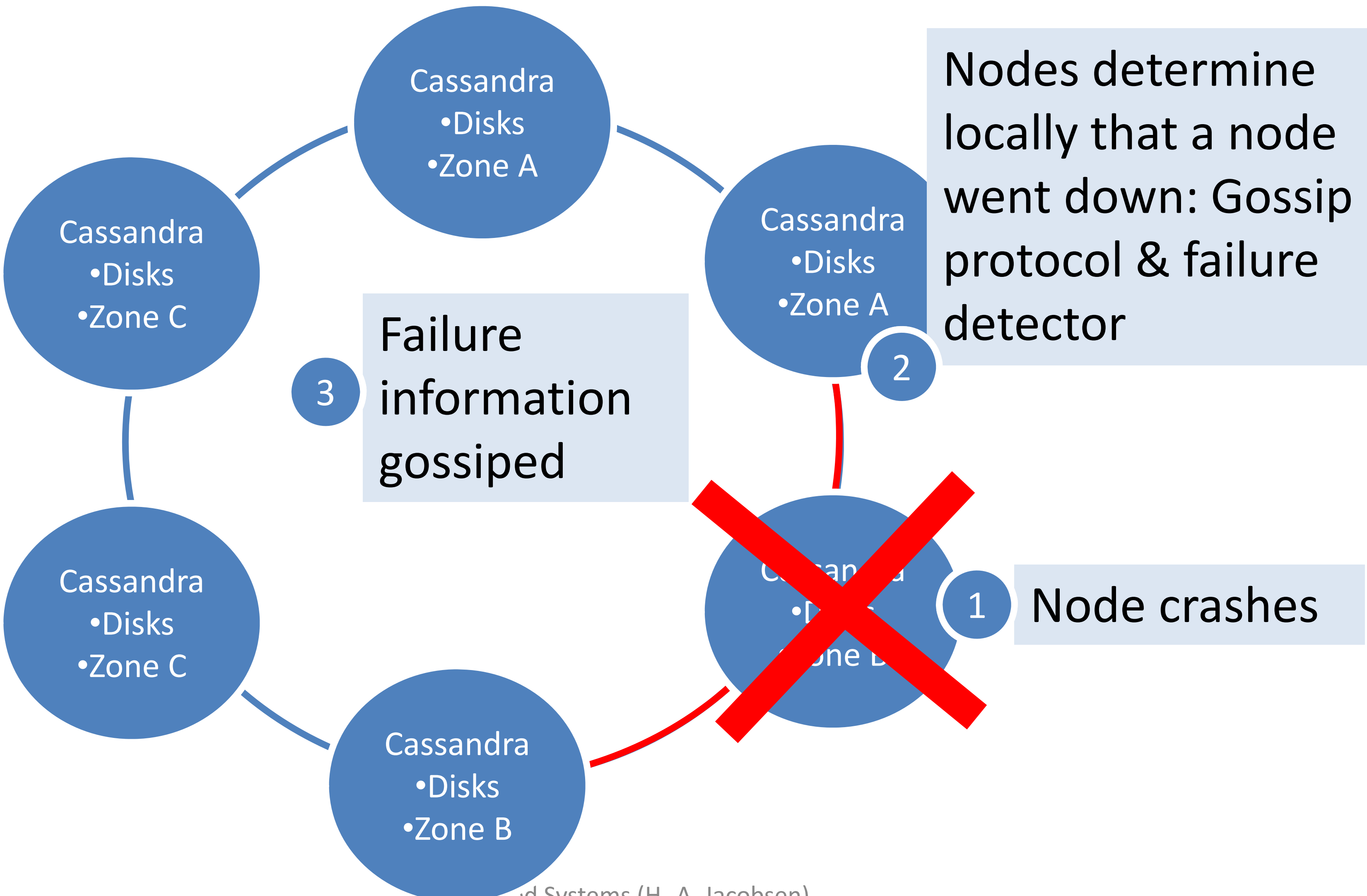


Incremental Scaling in Cassandra

(i.e., adding a storage unit)



Storage Unit Failure



Core Mechanisms

- Decentralized load balancing and scalability
  - *Cf. Consistent Hashing Lecture*
- Read/write reliability
  - *Cf. Replication Lecture*
- Membership management
  - *Cf. Gossip in Replication Lecture*
- Eventual consistency model
  - *Cf. Consistency Lecture*

Tentative Course Outline

- **Time** in distributed systems
- **Coordination** and **agreement**
- **Consensus** with Paxos
- **Replication**
- **Consistency** and transactions
- Consistent hashing, **CAP theorem**, web caching
- Distributed file systems (GFS)
- **MapReduce**, Spark
- Peer-to-peer systems, **distributed hash tables (DHTs)**
- **Blockchains**