NoSQL Databases

Acknowledgements

- Material from
  - Stanford courses (CS145 and CS347)
  - Washington University
  - Illinois University
  - Cattell’s paper and website

Contents

- Intro, motivation, key definitions
- Overview
- Systems
  - Cassandra
  - HBase
- Applications

Not every data management/analysis problem is best solved using a traditional DBMS

Database Management System (DBMS) provides….

… efficient, reliable, convenient, and safe multi-user storage of and access to massive amounts of persistent data.

Traditional DBMSs

These types of DBMSs show severe limitations due to challenges posed by big data.

One architectural feature that may not respond promptly is **consistency** (*the second of the ACID properties of transactions*)

Atomicity
Consistency
Isolation
Durability

Traditional DBMSs

Consistency Types

Strict: The changes to the data are atomic and appear to take effect instantaneously. This is the highest form of consistency.

Sequential: Every client sees all changes in the same order they were applied.

Causal: All changes that are causally related are observed in the same order by all clients.

Eventual: When no updates occur for a period of time, eventually all updates will propagate through the system and all replicas will be consistent.

Weak: No guarantee is made that all updates will propagate and changes may appear out of order to various clients.

NoSQL Systems

Alternative to traditional relational DBMS

- \+ Flexible schema
- \+ Quicker/cheaper to set up
- \+ Massive scalability
- \+ Relaxed consistency → higher performance & availability

- – No declarative query language → more programming
- – Relaxed consistency → fewer guarantees

NoSQL Systems

Several incarnations

- MapReduce framework
- **Key-value stores**
  - **Extensible record stores**
- **Document stores**
- Graph database systems

MapReduce Framework

Schemas and declarative queries are missed

Hive – schemas, SQL-like query language

Pig – more imperative but with relational operators

- Both compile to "workflow" of Hadoop (MapReduce) jobs

Key-Value Stores

Extremely simple interface

- Data model: (key, value) pairs
- Operations: Insert(key,value), Fetch(key),
  Update(key), Delete(key)

Implementation: efficiency, scalability, fault-tolerance

- Records distributed to nodes based on key
- Replication
- Single-record transactions, “eventual consistency”

Key-Value Stores

Extremely simple interface

- Data model: (key, value) pairs
- Operations: Insert(key,value), Fetch(key),
  Update(key), Delete(key)
- Some allow (non-uniform) columns within value
  - Extensible record stores
- Some allow Fetch on range of keys

Example systems

- Google BigTable, Amazon Dynamo, Cassandra, Voldemort, HBase, …

Document Stores

Like Key-Value Stores except value is document

- Data model: (key, document) pairs
- Document: JSON, XML, other semistructured formats
- Basic operations: Insert(key,document), Fetch(key),
  Update(key), Delete(key)
- Also Fetch based on document contents

Example systems

- CouchDB, MongoDB, SimpleDB, …

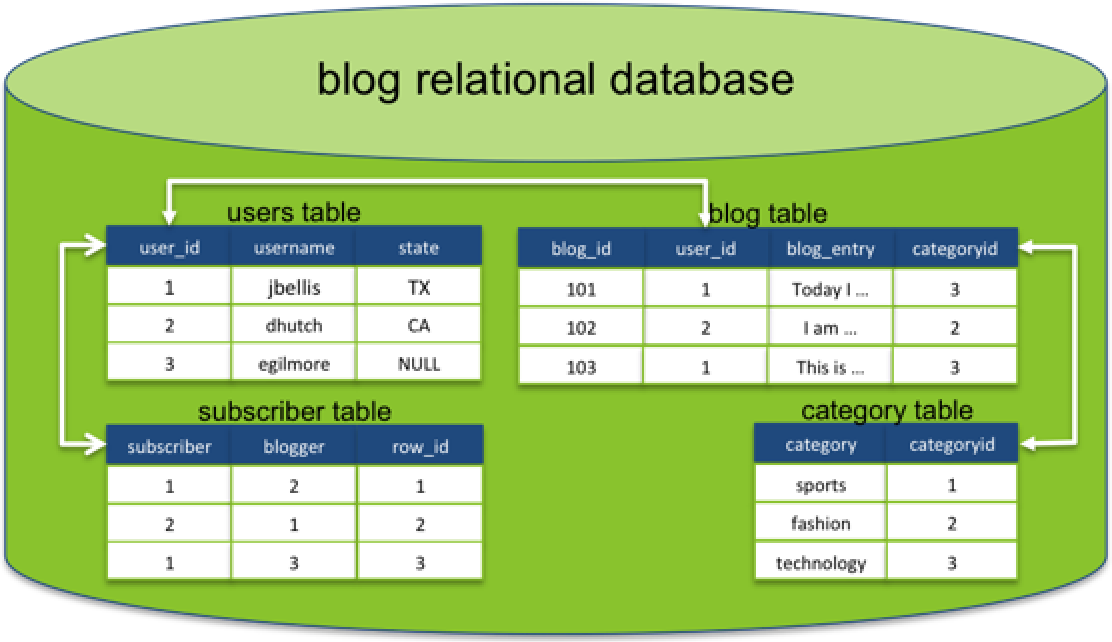
Why Key-value Store?

- (Business) Key -> Value
- (twitter.com) tweet id -> information about tweet
- (kayak.com) Flight number -> information about flight, e.g., availability
- (yourbank.com) Account number -> information about it
- (amazon.com) item number -> information about it

- Search is usually built on top of a key-value store

Isn’t that just a database?

- Yes
- Relational Databases (RDBMSs) have been around for ages
- MySQL is the most popular among them
- Data stored in tables
- Schema-based, i.e., structured tables
- Queried using SQL



blog relational database

users table

user_id	username	state
1	jbellis	TX
2	dhutch	CA
3	egilmore	NULL

blog table

blog_id	user_id	blog_entry	categoryid
101	1	Today I ...	3
102	2	I am ...	2
103	1	This is ...	3

subscriber table

subscriber	blogger	row_id
1	2	1
2	1	2
1	3	3

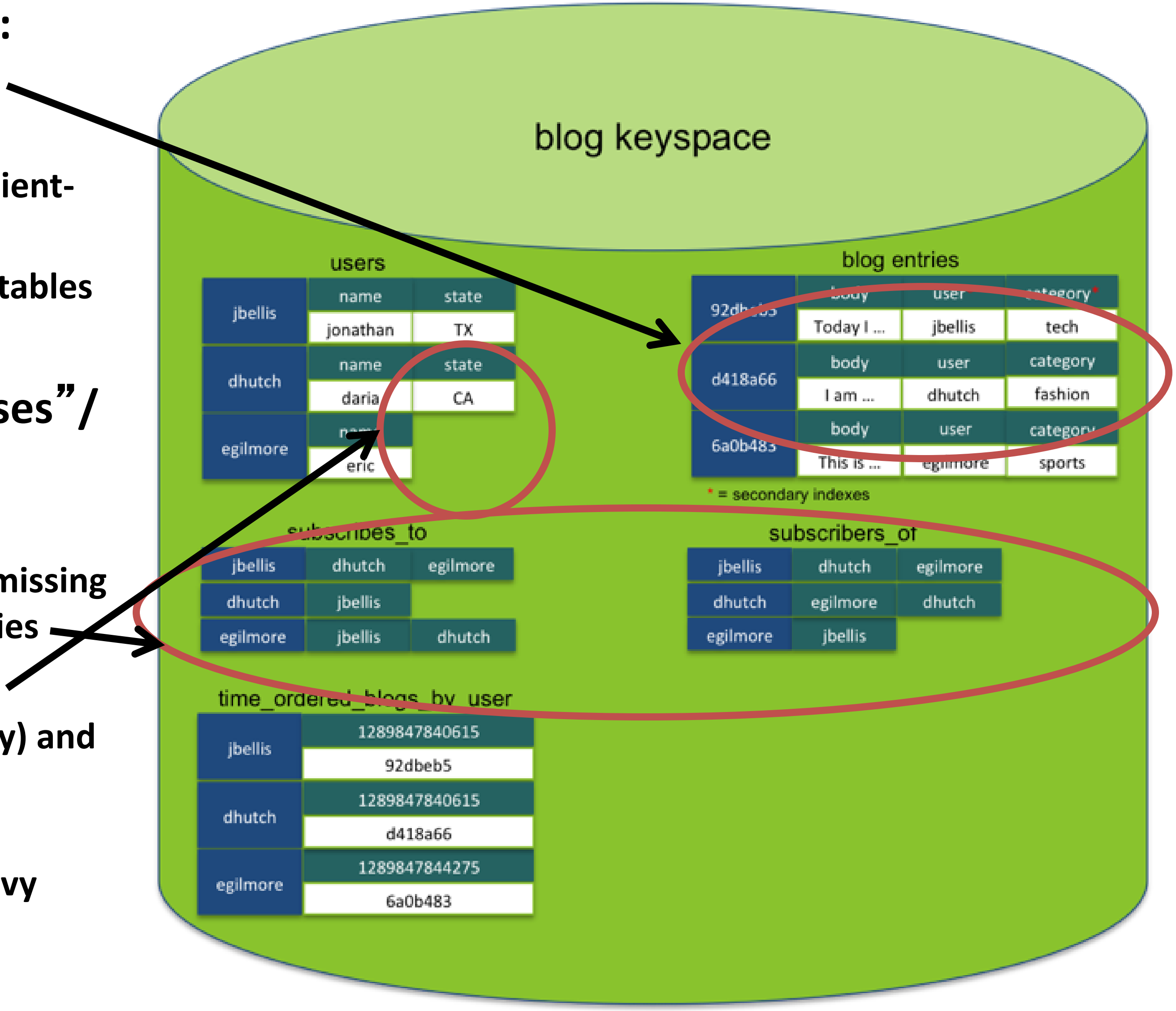
category table

category	categoryid
sports	1
fashion	2
technology	3

SQL queries: SELECT user_id from users WHERE username = “jbellis”

Cassandra Data Model

- **Column Families:**
  - **Like SQL tables**
  - **but may be unstructured (client-specified)**
  - **Can have index tables**
- **Hence "column-oriented databases"/ "NoSQL"**
  - **No schemas**
  - **Some columns missing from some entries**
  - **"Not Only SQL"**
  - **Supports get(key) and put(key, value) operations**
  - **Often write-heavy workloads**



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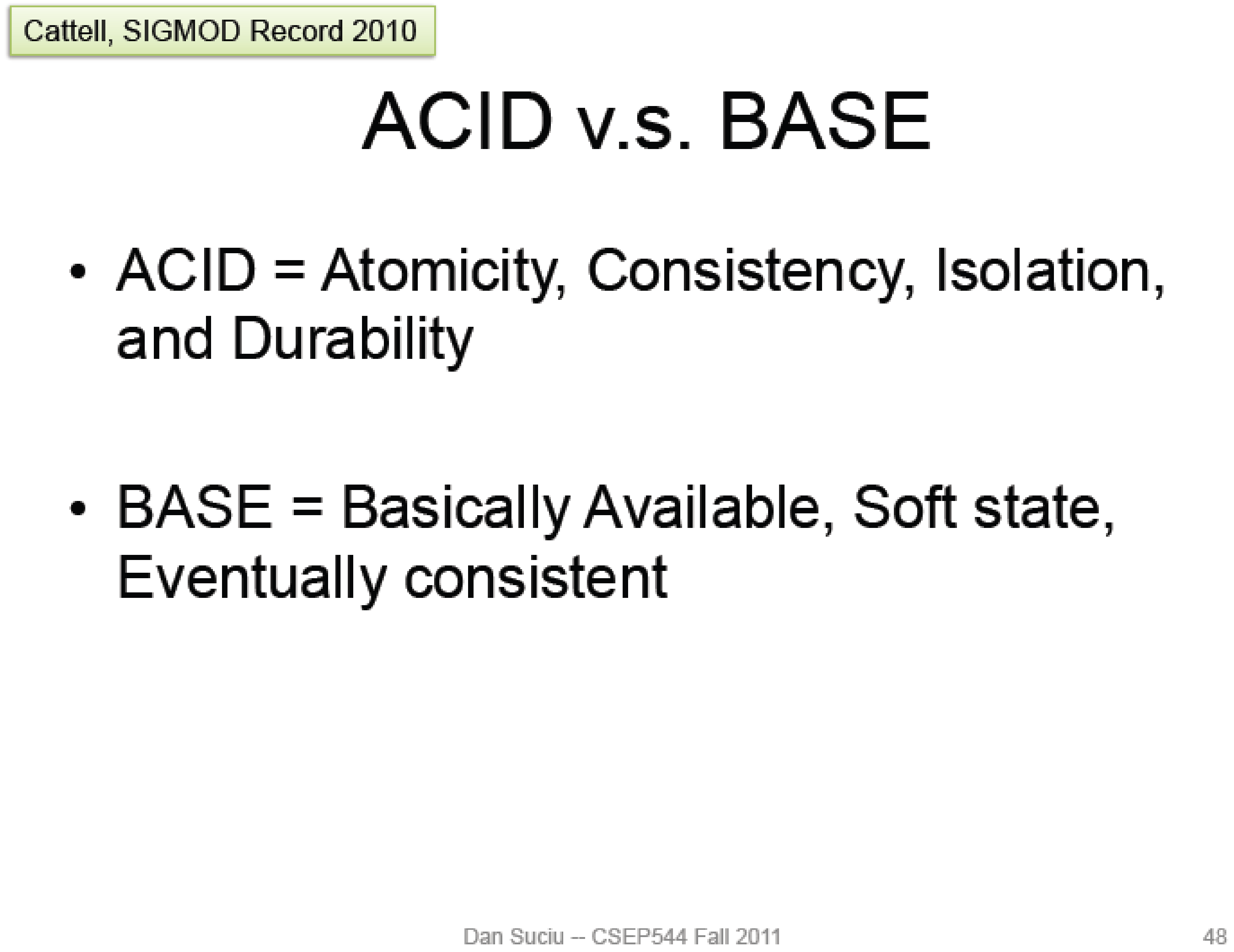
Early "Proof of Concepts"

- Memcached: demonstrated that in-memory indexes (DHT) can be highly scalable
- Dynamo: pioneered *eventual consistency* for higher availability and scalability
- BigTable: demonstrated that persistent record storage can be scaled to thousands of nodes



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ACID v.s. BASE

- ACID = Atomicity, Consistency, Isolation, and Durability
- BASE = Basically Available, Soft state, Eventually consistent

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Data Model

- Tuple = row in a relational db
- Document = nested values, extensible records (think XML or JSON)
- Extensible record = families of attributes have a schema, but new attributes may be added
- Object = like in a programming language, but without methods

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1. Key-value Stores

Think “file system” more than “database”

- Persistence,
- Replication
- Versioning,
- Locking
- Transactions
- Sorting

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1. Key-value Stores

- Voldemort, Riak, Redis, Scalaris, Tokyo Cabinet, Memcached/Membrain/Membase

- Consistent hashing (DHT)
- Only primary index: lookup by key
- No secondary indexes
- Transactions: single- or multi-update TXNs
  - locks, or MVCC

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2. Document Stores

- A "document" = a pointerless object = e.g. JSON = nested or not = schema-less

- In addition to KV stores, may have secondary indexes

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2. Document Stores

- SimpleDB, CouchDB, MongoDB, Terrastore
- Scalability:
  - Replication (e.g. SimpleDB, CounchDB – means entire db is replicated),
  - Sharding (MongoDB);
  - Both

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3. Extensible Record Stores

- Typical Access: Row ID, Column ID, Timestamp

- Rows: sharding by primary key
  - BigTable: split table into *tablets* = units of distribution
- Columns: "column groups" = indication for which columns to be stored together (e.g. customer name/address group, financial info group, login info group)

- HBase, HyperTable, Cassandra, PNUT, BigTable

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4. Scalable Relational Systems

- Means RDBS that are offering sharding
- Key difference: NoSQL make it difficult or impossible to perform large-scope operations and transactions (to ensure performance), while scalable RDBMS do not *preclude* these operations, but users pay a price only when they need them.
- MySQL Cluster, VoltDB, Clusterix, ScaleDB, Megastore (the new BigTable)

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The Dawn of NOSQL

There are several features that may be different from system to system:

- data model
- storage model
- consistency model
- physical model
- failure handling
- secondary indices
- compression
- load balancing
- atomic operations
- locking policy

Cassandra

- Originally designed at Facebook
- Open-sourced
- Some of its myriad users:

Adobe

AppScale

IBM

twitter

Symantec.

ebay

PBS KIDS

hp

Spotify

NETFLIX

ERICSSON

Cassandra

- “Apache Cassandra is an open-source, distributed, decentralized, elastically scalable, highly available, fault-tolerant, tunably consistent, column-oriented database that bases its distribution design on Amazon’s dynamo and its data model on Google’s Big Table.”
- Clearly, it is buzz-word compliant!!

Basic Idea: Key-Value Store

Table T:

key	value
k1	v1
k2	v2
k3	v3
k4	v4

Basic Idea: Key-Value Store

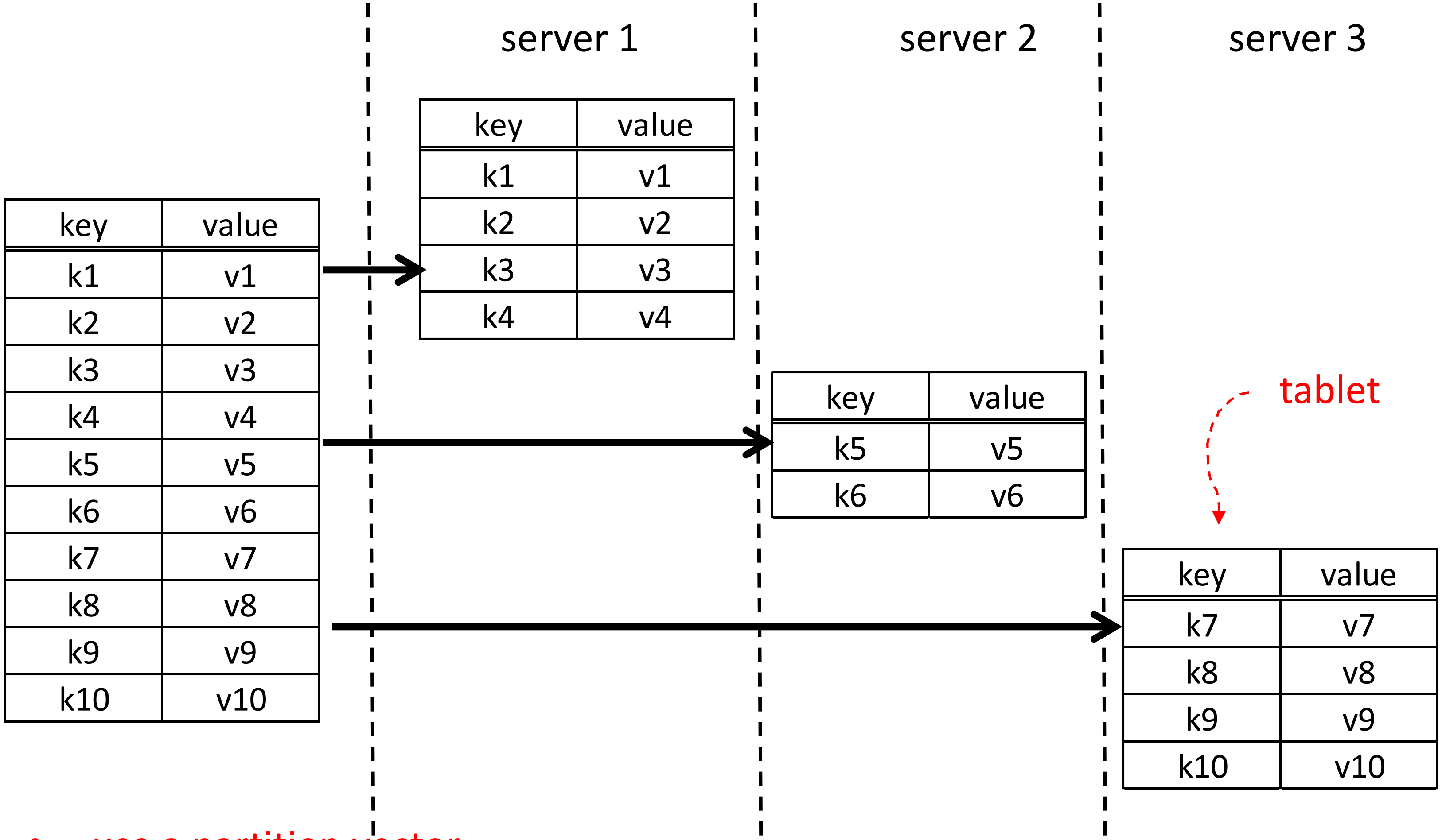
Table T:

key	value
k1	v1
k2	v2
k3	v3
k4	v4

keys are sorted

- API:
  - lookup(key) → value
  - lookup(key range) → values
  - getNext → value
  - insert(key, value)
  - delete(key)
- Each row has timestemp
- Single row actions atomic
  (but not persistent in some systems?)
- No multi-key transactions
- No query language!

Fragmentation (Sharding)



key	value
k1	v1
k2	v2
k3	v3
k4	v4
k5	v5
k6	v6
k7	v7
k8	v8
k9	v9
k10	v10

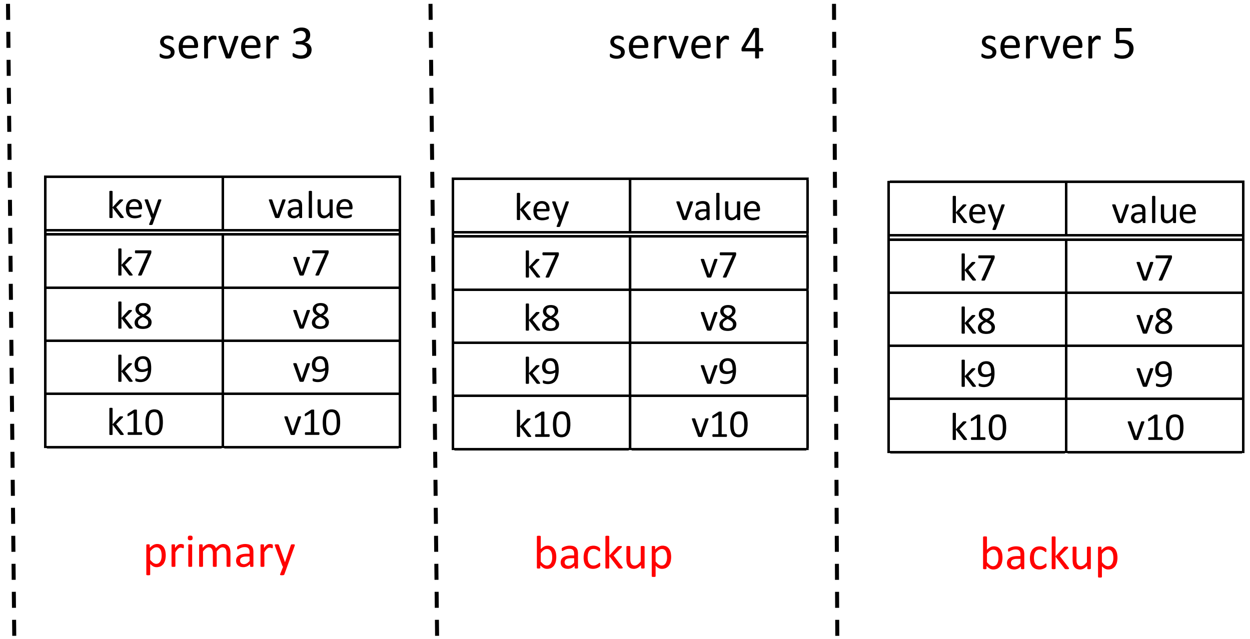
key	value
k1	v1
k2	v2
k3	v3
k4	v4

key	value
k5	v5
k6	v6

key	value
k7	v7
k8	v8
k9	v9
k10	v10

- use a partition vector
- "auto-sharding": vector selected automatically

Tablet Replication



server 3

key	value
k7	v7
k8	v8
k9	v9
k10	v10

primary

server 4

key	value
k7	v7
k8	v8
k9	v9
k10	v10

backup

server 5

key	value
k7	v7
k8	v8
k9	v9
k10	v10

backup

- <u>Cassandra:</u>
  Replication Factor (# copies)
  R/W Rule: One, Quorum, All
  Policy (e.g., Rack Unaware, Rack Aware, ...)
  Read all copies (return fastest reply, do repairs if necessary)
- <u>HBase:</u> Does not manage replication, relies on HDFS

Need a “directory”

- Table Name: Key → Server that stores key
  → Backup servers
- Can be implemented as a special table.

Tablet Internals

key	value
k3	v3
k8	v8
k9	delete
k15	v15

memory

---

key	value
k2	v2
k6	v6
k9	v9
k12	v12

key	value
k4	v4
k5	delete
k10	v10
k20	v20
k22	v22

disk

Design Philosophy (?): Primary scenario is where all data is in memory.
Disk storage added as an afterthought

Tablet Internals

tombstone

key	value
k3	v3
k8	v8
k9	delete
k15	v15

memory

flush periodically

key	value
k2	v2
k6	v6
k9	v9
k12	v12

key	value
k4	v4
k5	delete
k10	v10
k20	v20
k22	v22

disk

- tablet is merge of all segments (files)
- disk segments imutable
- writes efficient; reads only efficient when all data in memory
- periodically reorganize into single segment

Column Family

K	A	B	C	D	E
k1	a1	b1	c1	d1	e1
k2	a2	null	c2	d2	e2
k3	null	null	null	d3	e3
k4	a4	b4	c4	e4	e4
k5	a5	b5	null	null	null

Column Family

K	A	B	C	D	E
k1	a1	b1	c1	d1	e1
k2	a2	null	c2	d2	e2
k3	null	null	null	d3	e3
k4	a4	b4	c4	e4	e4
k5	a5	b5	null	null	null

- for storage, treat each row as a single “super value”
- API provides access to sub-values
  (use family:qualifier to refer to sub-values
  e.g., price:euros, price:dollars)
- Cassandra allows “super-column”:
  two level nesting of columns
  (e.g., Column A can have sub-columns X & Y)

Vertical Partitions

K	A	B	C	D	E
k1	a1	b1	c1	d1	e1
k2	a2	null	c2	d2	e2
k3	null	null	null	d3	e3
k4	a4	b4	c4	e4	e4
k5	a5	b5	null	null	null

can be manually implemented as

K	A
k1	a1
k2	a2
k4	a4
k5	a5

K	B
k1	b1
k4	b4
k5	b5

K	C
k1	c1
k2	c2
k4	c4

K	D	E
k1	d1	e1
k2	d2	e2
k3	d3	e3
k4	e4	e4

Vertical Partitions

K	A	B	C	D	E
k1	a1	b1	c1	d1	e1
k2	a2	null	c2	d2	e2
k3	null	null	null	d3	e3
k4	a4	b4	c4	e4	e4
k5	a5	b5	null	null	null

K	A
k1	a1
k2	a2
k4	a4
k5	a5

K	B
k1	b1
k4	b4
k5	b5

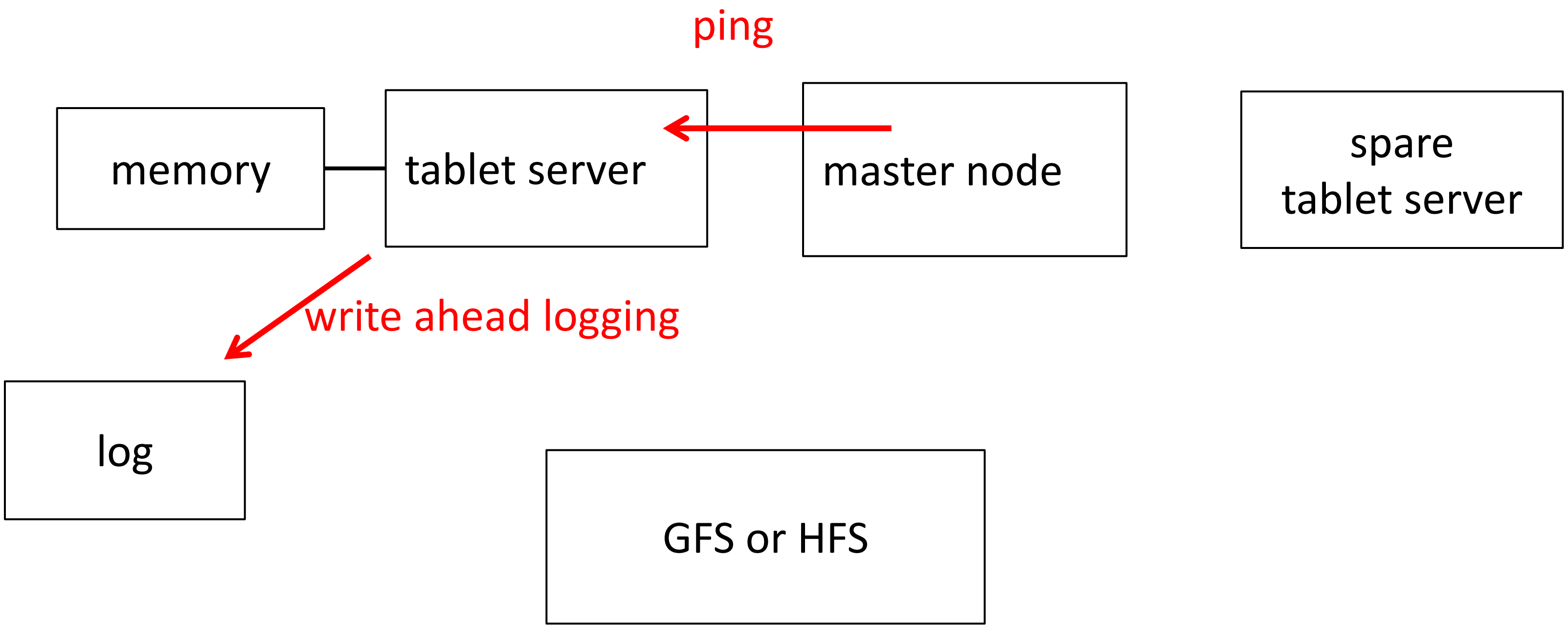
K	C
k1	c1
k2	c2
k4	c4

column family

K	D	E
k1	d1	e1
k2	d2	e2
k3	d3	e3
k4	e4	e4

- good for sparse data;
- good for column scans
- not so good for tuple reads
- API supports actions on full table; mapped to actions on column tables
- To decide on vertical partition, need to know access patterns

Failure Recovery (BigTable, HBase)



ping

memory

tablet server

master node

spare
tablet server

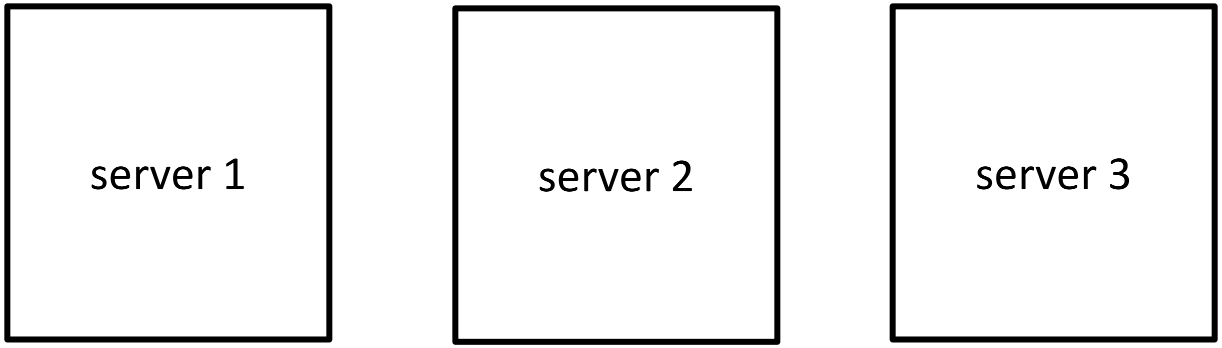
write ahead logging

log

GFS or HFS

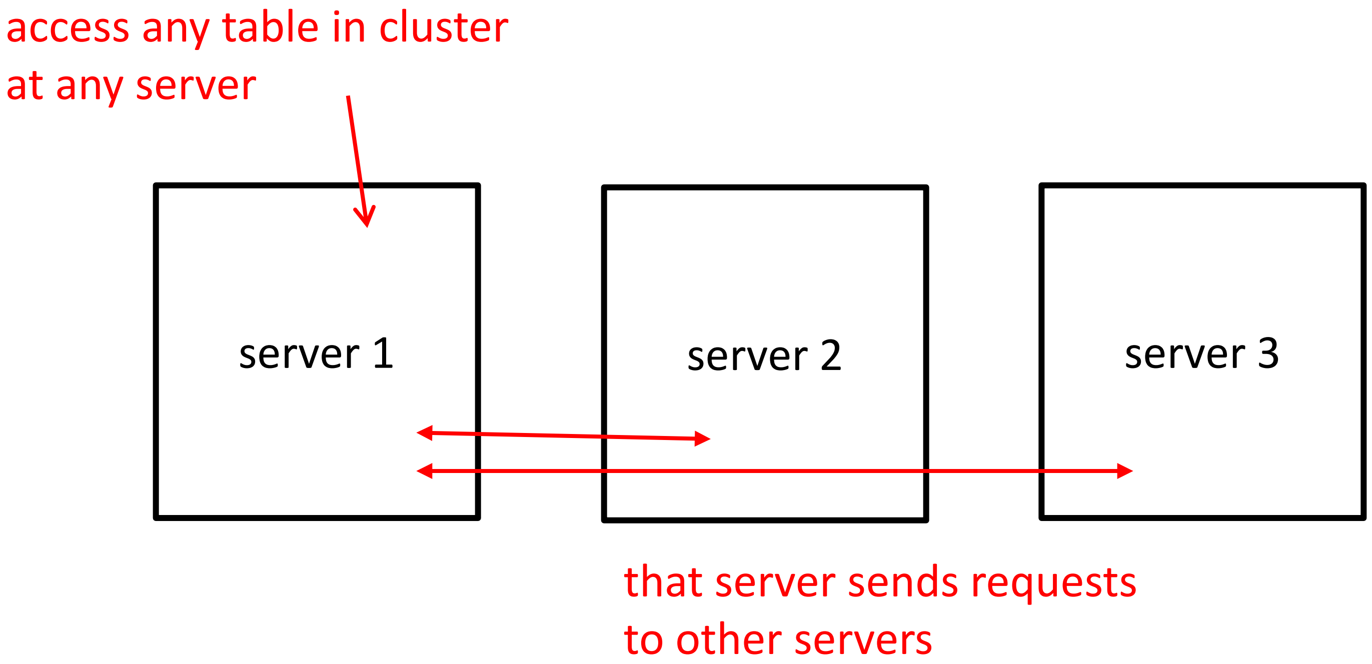
Failure recovery (Cassandra)

- No master node, all nodes in “cluster” equal



Failure recovery (Cassandra)

- No master node, all nodes in "cluster" equal



access any table in cluster at any server

that server sends requests to other servers

Cassandra Vs. SQL

- MySQL is the most popular (and has been for a while)
- On > 50 GB data
- MySQL
  - Writes 300 ms avg
  - Reads 350 ms avg
- Cassandra
  - Writes 0.12 ms avg
  - Reads 15 ms avg

Cassandra Summary

- While RDBMS provide ACID (Atomicity Consistency Isolation Durability)
- Cassandra provides BASE
  - Basically Available Soft-state Eventual Consistency
  - Prefers Availability over consistency
- Other NoSQL products
  - MongoDB, Riak (look them up!)
- Next: HBase
  - Prefers (strong) Consistency over Availability

Brewer's CAP Theorem

Brewer's CAP theorem states that a distributed system is not possible to guarantee all three of the following properties simultaneously:

Consistency: all nodes see the same data at the same time

Availability: a guarantee that every request receives a response about whether it succeeded or failed

Partition Tolerance (the system continues to operate despite arbitrary message loss or failure of part of the system)

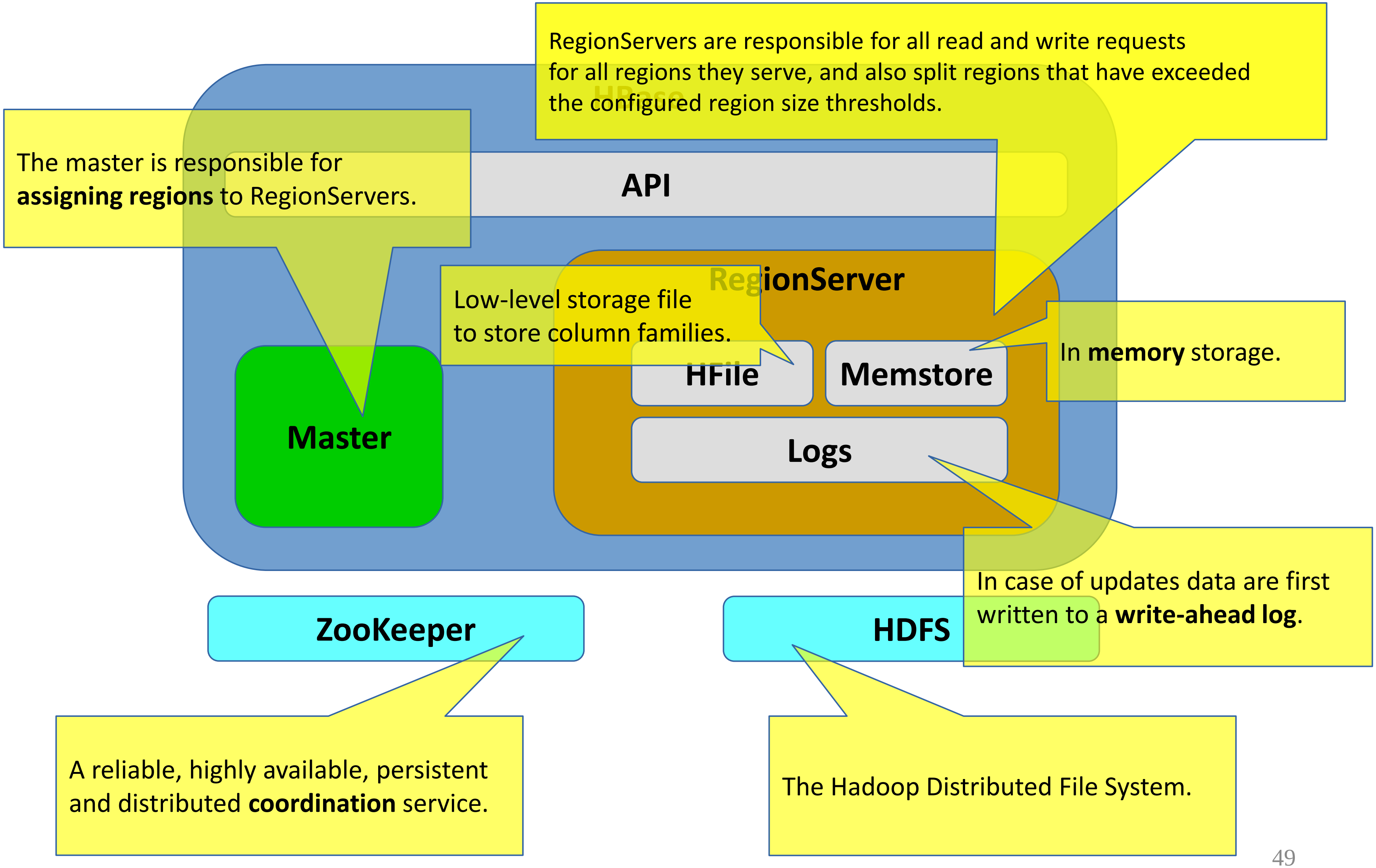
HBase

- Google’s BigTable was first “blob-based” storage system
- Yahoo! Open-sourced it → HBase
- Major Apache project today
- Facebook uses HBase internally
- API
  - Get/Put(row)
  - Scan(row range, filter) – range queries
  - MultiPut

HBase Storage hierarchy

- HBase Table
  - Split it into multiple regions: replicated across servers
    - One Store per ColumnFamily (subset of columns with similar query patterns) per region
- HFile
  - SSTable from Google's BigTable

HBase Architecture



RegionServers are responsible for all read and write requests for all regions they serve, and also split regions that have exceeded the configured region size thresholds.

The master is responsible for **assigning regions** to RegionServers.

Low-level storage file to store column families.

In **memory** storage.

In case of updates data are first written to a **write-ahead log**.

A reliable, highly available, persistent and distributed **coordination** service.

The Hadoop Distributed File System.

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Application 1

- Web application that needs to display lots of customer information; the users data is rarely updated, and when it is, you know when it changes because updates go through the same interface. Store this information persistently using a KV store.

Key-value store

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Application 2

- Department of Motor Vehicle: lookup objects by multiple fields (driver's name, license number, birth date, etc); "eventual consistency" is ok, since updates are usually performed at a single location.

Document Store

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Application 3

- eBay stile application. Cluster customers by country; separate the rarely changed "core" customer information (address, email) from frequently-updated info (current bids).

Extensible Record Store

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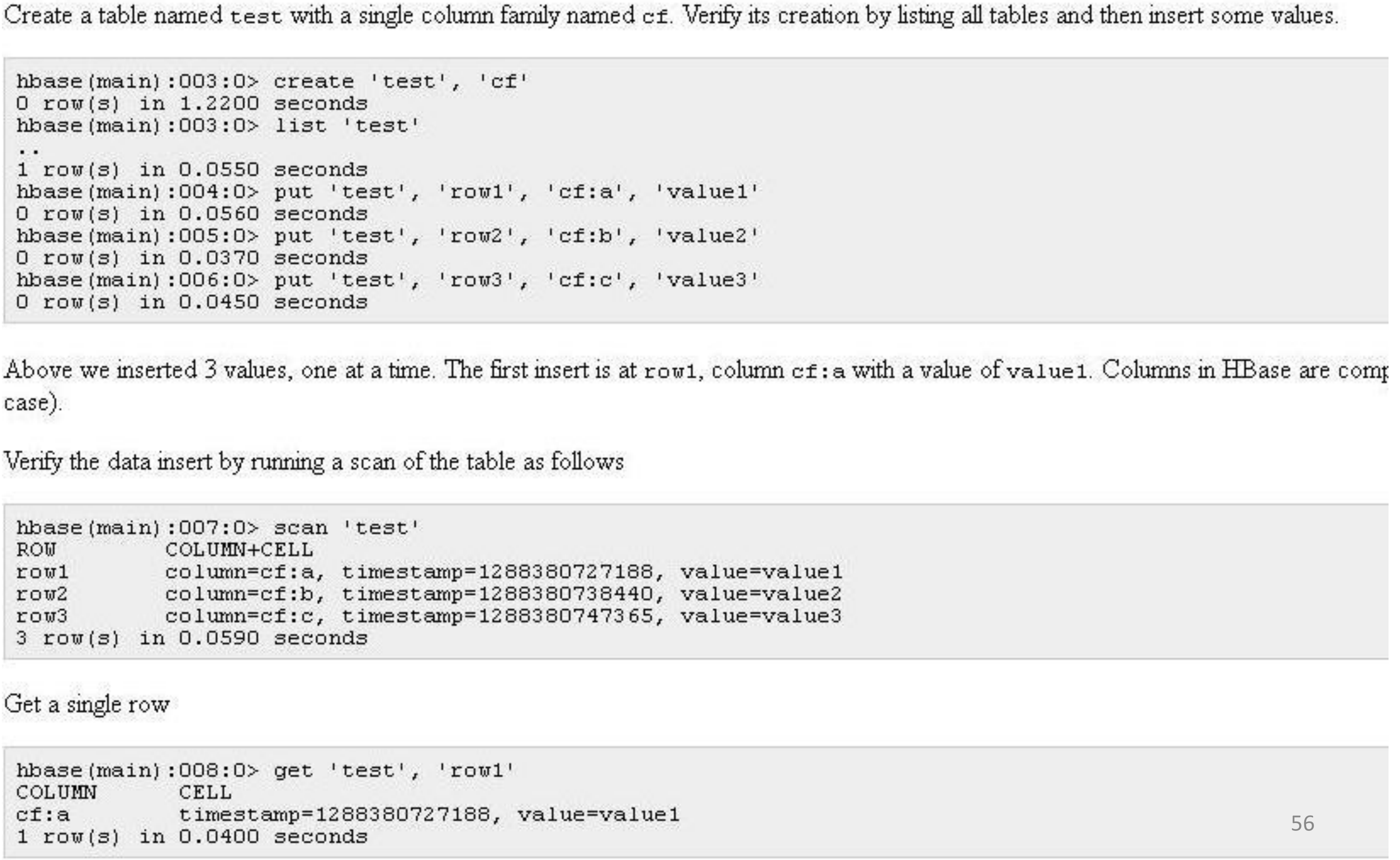
Application 4

- Everything else (e.g. a serious DMV application)

Scalable RDBMS

HBase

Shell



Create a table named `test` with a single column family named `cf`. Verify its creation by listing all tables and then insert some values.

```
hbase(main):003:0> create 'test', 'cf'
0 row(s) in 1.2200 seconds
hbase(main):003:0> list 'test'
..
1 row(s) in 0.0550 seconds
hbase(main):004:0> put 'test', 'row1', 'cf:a', 'value1'
0 row(s) in 0.0560 seconds
hbase(main):005:0> put 'test', 'row2', 'cf:b', 'value2'
0 row(s) in 0.0370 seconds
hbase(main):006:0> put 'test', 'row3', 'cf:c', 'value3'
0 row(s) in 0.0450 seconds
```

Above we inserted 3 values, one at a time. The first insert is at `row1`, column `cf:a` with a value of `value1`. Columns in HBase are comp
case).

Verify the data insert by running a scan of the table as follows

```
hbase(main):007:0> scan 'test'
ROW          COLUMN+CELL
row1         column=cf:a, timestamp=1288380727188, value=value1
row2         column=cf:b, timestamp=1288380738440, value=value2
row3         column=cf:c, timestamp=1288380747365, value=value3
3 row(s) in 0.0590 seconds
```

Get a single row

```
hbase(main):008:0> get 'test', 'row1'
COLUMN        CELL
cf:a          timestamp=1288380727188, value=value1
1 row(s) in 0.0400 seconds
```

Hbase Java Client

```
import org.apache.hadoop.hbase.util.*;
import org.apache.hadoop.conf.Configuration;
import org.apache.hadoop.hbase.HBaseConfiguration;
import org.apache.hadoop.hbase.client.HTable;
import org.apache.hadoop.hbase.client.Result;
import org.apache.hadoop.hbase.client.ResultScanner;
import org.apache.hadoop.hbase.client.Scan;
import org.apache.hadoop.hbase.util.Bytes;
import java.io.IOException;

public class TestHBase {


public static void main(String[] arg) throws IOException {
   Configuration config = HBaseConfiguration.create();
```

Cont’d

```
 //read values of cf:a
byte[] family = Bytes.toBytes("cf");
 byte[] qual = Bytes.toBytes("a");

HTable testTable = new HTable(config, "test");

Scan scan = new Scan();
 scan.addColumn(family, qual);
 ResultScanner rs = testTable.getScanner(scan);
 for (Result r = rs.next(); r != null; r = rs.next()) {
     byte[] valueObj = r.getValue(family, qual);
     String value = new String(valueObj);
     System.out.println(value);
 }
```

Cont’d

```
//add a row with key “newtest”
// and value of cf:a “new-value”
Put put = new Put(Bytes.toBytes("newtest"));
put.add(Bytes.toBytes("cf"), Bytes.toBytes("a"),
   Bytes.toBytes("new-value"));
testTable.put(put);
```