

# Distributed Storage Systems

## Theory and practice

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# Introduction

# Overview

- The CAP Theorem
- Amazon Dynamo
- Apache HBase
- Apache Cassandra

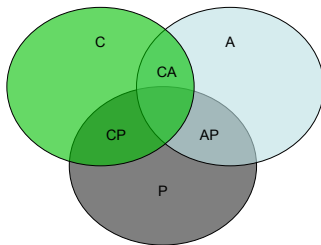
# The CAP Theorem

# The CAP Theorem

- **Frequently cited distributed systems theorem**
- **Relates the following three properties**
  - ▶ **C: Consistency**
    - ★ One-copy semantics, linearizability, atomicity, total order
    - ★ Every operation must appear to take effect in a single indivisible point in time between its invocation and response
  - ▶ **A: Availability**
    - ★ Every client's request is served (receives a response) unless a client fails (despite a strict subset of server nodes failing)
  - ▶ **P: Partition tolerance**
    - ★ A system functions properly even if the network is allowed to lose arbitrarily many messages sent from one node to another

## The CAP Theorem

- In the folklore interpretation, the theorem says:  
C, A, P: pick two



## Precautions: be careful with CA

- **Sacrificing P (partition tolerance)**
- **Negating:** A system functions properly even if the network is allowed to lose arbitrarily many messages sent from one node to another
- **Yields:** A system **does not** function properly even if the network is allowed to lose arbitrarily many messages sent from one node to another
  - ▶ This implies sacrificing C or A, *i.e.*, the system does not work

## Precautions: be careful with CA

- **Negating P:** A system function properly if the network is **not allowed** to lose arbitrarily many messages
- **However, in practice:** It is not possible to choose whether the network will lose messages! This either happens or not
- **One can argue that not “arbitrarily” many messages will be lost**
  - ▶ But “a lot” of them might be (before the network repairs)
  - ▶ In the meantime, either C or A is sacrificed



## CAP in practice

- **In practical distributed systems:**

- ▶ Partitions may occur
- ▶ This is not under your control, as a system designer

- **Designer's choice:**

- ▶ **You choose** whether you want your system in C or A, when/if (temporary) partitions occur

- **In summary:**

- ▶ CAP is a fundamental theorem stating the tradeoffs among different system properties
- ▶ **Practical distributed systems are either in CP or AP**
- ▶ **The choice (C vs. A) depends on your application logic**

## CAP in theory

- **Historical notes:**

- ▶ First stated by Eric Brewer at the PODC 2000 keynote
- ▶ Formally proved by Gilbert and Lynch, 2002

- **GL Theorems:**

- ▶ Asynchronous / partially synchronous network models
- ▶ Read/Write data objects
- ▶ Finer definitions of Availability and Consistency

- **Further readings:**

- ▶ (Fischer, Lynch and Patterson) FLP impossibility result
- ▶ t-connected CAP

## CAP: some illustrative choices

- **CP:**

- ▶ BigTable (Google), HBase, ...
- ▶ Coordination systems: ZooKeeper, etcd, ...

- **AP:**

- ▶ Amazon Dynamo, CouchDB, Cassandra, SimpleDB, Riak, Voldemort (LinkedIn), ...

# Amazon Dynamo

# Amazon Web Services

- **Amazon's cloud computing services**

- ▶ S3, EC2, RedShift, SimpleDB, Elastic MR, and many, many more
- ▶ Combined, they allow constructing Internet-scale applications

- **Infrastructure services requirements:**

- ▶ Security, scalability, availability, performance, cost-efficiency
- ▶ Serve millions of customers worldwide, continuously

# Amazon Web Services

- **Important observations**

- ▶ No emphasis on consistency
- ▶ AWS is in AP, sacrificing consistency

- **AWS follows the BASE philosophy**

- ▶ BASE vs. ACID
- ▶ Basically Available
- ▶ Soft state
- ▶ Eventually consistent

## Why favoring Availability over Consistency?

- **Even the shortest outage has significant financial consequences and impact customer trust**
- **Clearly, consistency violations may as well have a big impact**
  - ▶ But not in several Amazon's services
  - ▶ **Billing** is a separate story

# Amazon Dynamo

- **Works behind the scenes in the context of AWS**

- ▶ Used to power client-facing services such as S3, and others
- ▶ Used to power internal Amazon services such as: shopping cart, customer session management, product catalog, recommendations, order fulfillment, sales rank, fraud detection, ...

- **What is Dynamo?**

- ▶ Highly available key-value storage system
- ▶ Favors availability over consistency under failures



## What is a key-value store?

- **Think about Hash tables or dictionaries**

- ▶ Simple API: **get(key)**, **put(key, value)**
- ▶ Sometimes referred to read/write operations

- **Specifics of Dynamo API**

- ▶ Uses an additional argument to pass a “context”
- ▶ Context holds critical metadata
- ▶ Typically stores **small objects** (< 1 MB)

- **Specifics of services using Dynamo**

- ▶ Do not need transactions
- ▶ Often need only primary-key access to data

# Amazon Dynamo: Features

## ● Main characteristics

- ▶ Low latency
- ▶ Scalable (hundreds of machines)
- ▶ Always-on available (especially for writes)
- ▶ Partition/Fault tolerance
- ▶ **Eventually** consistent

## ● How such features are obtained

- ▶ General distributed systems toolbox
- ▶ We review some of them here

# Amazon Dynamo: Key Techniques (1)

- **Consistent hashing** [Karger97]
  - ▶ For data partitioning, replication and load balancing
- **Sloppy Quorums**
  - ▶ Boosts availability in presence of failures
  - ▶ May result in inconsistent versions of keys (data)

## Amazon Dynamo: Key Techniques (2)

- **Vector clocks** [Fidge88/Mantern88]
  - ▶ For tracking causal dependencies among different versions of the same key (data)
- **Gossip-based group membership**
  - ▶ For maintaining information about alive nodes
- **Anti-entropy protocol based on Merkle trees**
  - ▶ Background synchronization of divergent replicas

# Amazon Dynamo: Design Decisions

- **Always writable data store**

- ▶ E.g., think shopping cart service

- **How to handle data changes?**

- ▶ Replication, required for fault/disaster tolerance
- ▶ Allow multiple versions of data
- ▶ Reconcile and resolve conflicts **during reads**

- **How to reconcile data?**

- ▶ Application-side: depending on business logic
- ▶ Dynamo: deterministic, e.g., “last-write” wins

## Amazon Dynamo: Architecture

# Amazon Dynamo Architecture

- **Scalable and robust components for:**
  - ▶ **Load balancing and data partitioning**
  - ▶ **Membership, fault detection**
  - ▶ Failure recovery
  - ▶ **Replica synchronization**
  - ▶ Overload Handling
  - ▶ State transfer
  - ▶ Concurrency management
  - ▶ Scheduling
  - ▶ Request marshalling and routing
  - ▶ System monitoring
  - ▶ Configuration management

# Amazon Dynamo: Data Partitioning

## • Data partitioning

- ▶ Dynamic partitioning of **keys** over a set of storage **nodes**
- ▶ Technique used for DHTs, e.g., Chord

## • Consistent Hashing

- ▶ Hashes of keys give key  $m$ -bit identifiers
- ▶ Hashes of nodes give  $m$ -bit identifiers
- ▶ Identifiers are ordered in an identifier circle

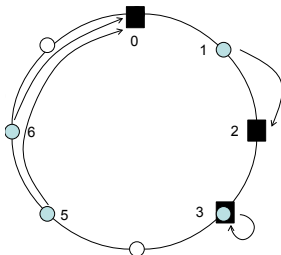
## • Key assignment to storage nodes

- ▶ A key is assigned to the closest **successor node** ID
- ▶ Key  $k$  is assigned to the first node whose ID  $\geq k$
- ▶ If such node does not exist, navigate the circle and find node with the smallest ID



## Consistent Hashing Example

- Assume:  $m = 3$  bit, 3 storage nodes (0,2,3), 4 keys (1,3,5,6)



## Consistent Hashing: Key Properties (1)

- **Dynamic membership management**

- ▶ Storage nodes can come and go
- ▶ Allows incremental scalability

- **Storage node arrival/departures**

- ▶  $n$  Joins: some (maybe many) keys previously assigned to node  $n$ 's successor are now assigned to  $n$
- ▶  $n$  Leaves: all keys currently assigned to node  $n$  are assigned to its successor

## Consistent Hashing: Key Properties (2)

- **Load balancing** [Karger97]

- ▶ Each node is responsible for at most  $(1 + \epsilon)K/n$  keys
- ▶ When a new node joins, only  $O(K/n)$  keys must be moved (optimal)

- **Virtual Nodes**

- ▶ Each physical storage node mapped multiple times to the circle
- Improves load balancing
- Allows heterogeneous storage nodes

## Amazon Dynamo: Data Replication

- **Goal: achieve high availability and durability**

- ▶ Each data item (key) replicated at  $N$  nodes
- ▶ Virtual nodes: same physical node skipped
- ▶  $N$  is a configurable parameter per Dynamo instance

- **Example:**

- ▶ Assume  $N = 3$
  - ▶ For key  $k$ ,  $B$  is the “coordinator” node
  - ▶  $B$  replicates  $k$  to  $N - 1$  other successor nodes ( $C$  and  $D$ )
- $B, C, D$  are a **preference list** for  $k$

## Amazon Dynamo: Data Versioning (1)

- **Data replication performed after an ACK is sent to a client put request**
  - ▶ **Asynchronous replication**
  - ▶ May result in inconsistencies under partitions
  - Read does not return the last value
- **Operations should not be lost!**
  - ▶ “Add to cart” should not be rejected but also not forgotten
  - ▶ If it is performed when the latest version is not available, then it is performed on a stale version of the data
  - We may have different versions of a key/value pair

## Amazon Dynamo: Data Versioning (2)

- **Precautions**

- ▶ Once a partition heals, versions are merged
- ▶ New versions subsume previous ones
- ▶ Applications **must be designed** with data versioning in mind

- **Key technique for versioning**

- ▶ Vector clocks, to capture causality between different versions of an object

## Vector Clocks (in Dynamo) (1)

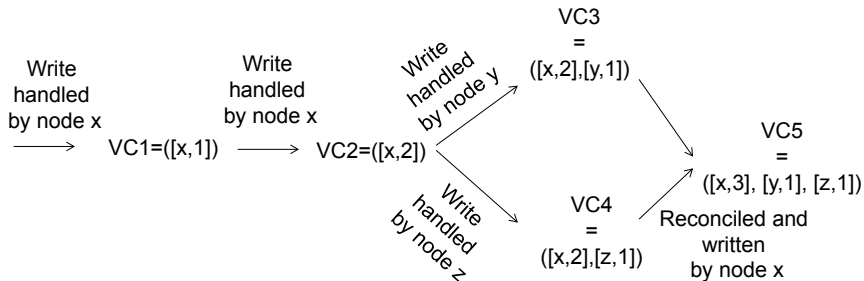
- **In theory:**

- ▶ Each `write` to a key  $k$  associated to a vector clock  $VC(k)$
- ▶  $VC(k)$  is an array (map) of integers
- ▶ In theory, one entry  $VC(k)[i]$  for each storage node  $i$
- ▶ When node  $i$  handles a write for key  $k$  it increments  $VC(k)[i]$

- **In practice:**

- ▶  $VC(k)$  will not have many entries  $\rightarrow$  only node from the preference list should have entries
- ▶ Dynamo truncates entries if more than a threshold

## Vector Clocks (in Dynamo) (2)



**NB: one VC per key**



## Anatomy of put and get operations

- **Storage nodes can receive requests for **any** key**

- ▶ Generic load balancer may choose a random node, not necessarily the coordinator
- ▶ Application may directly contact the coordinator in a preference list

- **Request routing**

- ▶ If request comes from load balancer
  - ★ Node serves request only if in preference list
  - ★ Otherwise, routes the request to the first node in preference list
- ▶ 0-hop DHT routing: all nodes know all other nodes
- Not the most scalable, but excellent for low-latency

- **Extended preference list**

- ▶ Accounts for node failures

## Amazon Dynamo: Quorums

- **Two important parameters**

- ▶ R: number of nodes involved in a get
- ▶ W: number of nodes involved in a put
- ▶ Quorum system:  $R + W > N$ , where  $N$  is the number of replicas

- **Handling put (by coordinator)**

- ▶ Generate new VC, write new version locally
- ▶ Send value, VC, to  $N$  nodes from preference list
- ▶ Wait for  $W - 1$  acknowledgments

- **Handling get (by coordinator)**

- ▶ Send get to  $N$  selected nodes from preference list
- ▶ Wait for  $R$  responses
- ▶ Select highest versions using VC, reconcile/merge different versions
- ▶ Writeback reconciled version

## Choosing $R, W$

- **$R, W$  smaller than  $N$** 
  - ▶ To decrease latency
  - ▶ Slowest replica dictates query latency
- **$W = 1$** 
  - ▶ Always available for writes
  - ▶ Yields  $R = N \rightarrow$  reads pay the penalty
- **Typical values in Dynamo**
  - ▶  $W, R, N = 2, 2, 3$

## Handling Failures

- **$N$  selected nodes are the first  $N$  healthy nodes**
  - ▶ Might change from request to request
  - ▶ Hence the term “sloppy” quorums
- **Sloppy vs. strict quorums**
  - ▶ Allow availability under a much wider range of partitions
  - ▶ Sacrifice consistency
- **Data-center wide failures**
  - ▶ Power outages, cooling failures, network failures, ...
  - ▶ Preference lists account for this

## Handling Temporary Failures

### ● Hinted Handoff

- ▶ If a replica in the preference list is down, then a new replica is created on a new node
- ▶ Coordinator selects a new replica node, but hints that the role is temporary
- ▶ When the new replica learns about failure recovery, it handles data to the node in the preference list

# Amazon Dynamo: Anti-Entropy Synchronization

- **Uses Merkle Trees**

- ▶ A tree in which every non-leaf node is labelled with the hash of the labels of its children nodes

- **Storage nodes**

- ▶ Keep a Merkle tree for each of its key ranges (virtual nodes)
- ▶ Compare root of the tree with replicas
- ▶ If equal, replicas are in sync
- ▶ Otherwise, traverse the tree and synchronize keys that differ

# Amazon Dynamo: Membership Management

- **Membership management initiated by administrator**
- **Gossip protocol to propagate membership changes**
  - ▶ Nodes contact a random node every second
  - ▶ 2 nodes reconcile membership information
  - ▶ Gossiping also used to handle metadata

# Failure Detection

- **Unreliable failure detection**

- ▶ Detection is triggered by read/write requests
- ▶ Called “in-band” failure detection
- No dedicated component

- **Example:**

- ▶ With steady load on node A
- ▶ Node A periodically checks the status of nodes in the extended preference list
- ▶ Does not make the distinction between faults and partitions



## Amazon Dynamo: Summary

- **Eventually consistent, highly available key value store**
  - ▶ In the CAP space, it is in AP
- **Focuses on low-latency**
  - ▶ Writes are super fast
  - ▶ Reconciliation in reads
- **Built atop of fundamental techniques in distributed systems**
  - ▶ Consistent hashing
  - ▶ Sloppy quorum-based replication
  - ▶ Merkle-tree based synchronization
  - ▶ Vector clocks, and gossip membership management

# HBASE

# Introduction

## Why yet another storage architecture?

- **Relational Database Management Systems (RDBMS):**

- ▶ Around since 1970s
- ▶ Countless examples in which they actually do make sense

- **The dawn of Big Data:**

- ▶ Previously: ignore data sources because no cost-effective way to store everything
  - ★ One option was to prune, by retaining only data for the last  $N$  days
- ▶ Today: store everything!
  - ★ Pruning fails in providing a base to build useful mathematical models

## Batch processing

- **Hadoop and MapReduce:**

- ▶ Excels at storing (semi- and/or un-) structured data
- ▶ Data interpretation takes place at analysis-time
- ▶ Flexibility in data classification

- **Batch processing: A complement to RDBMS**

- ▶ Scalable sink for data, processing launched when time is right
- ▶ Optimized for large file storage
- ▶ Optimized for “streaming” access

- **Random Access:**

- ▶ Users need to “interact” with data, especially that “crunched” after a MapReduce job
- ▶ This is historically where RDBMS excel: random access for structured data

## Column-Oriented Databases

- **Data layout:**

- ▶ Save their data grouped by columns
- ▶ Subsequent column values are stored contiguously on disk
- ▶ This is substantially different from traditional RDBMS, which save and store data by row

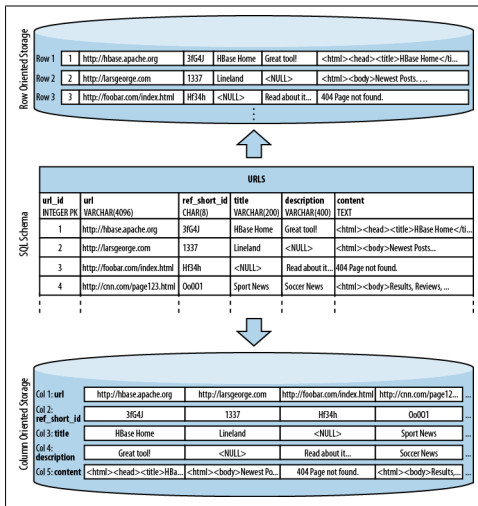
- **Specialized databases for specific workloads:**

- ▶ Reduced I/O
- ▶ Better suited for compression → Efficient use of bandwidth
  - ★ Indeed, column values are often very similar and differ little row-by-row
- ▶ Real-time access to data

- **Important NOTE:**

- ▶ HBase is not a column-oriented DB in the typical term
- ▶ HBase uses an on-disk column storage format
- ▶ Provides key-based access to specific cell of data, or a sequential range of cells

# Column-Oriented and Row-Oriented storage layouts



**Figure:** Example of Storage Layouts

## The Problem with RDBMS

- **RDBMS are still relevant**

- ▶ Persistence layer for frontend application
- ▶ Store relational data
- ▶ Works well for a limited number of records

- **Example: Hush**

- ▶ Used throughout this course
- ▶ URL shortener service

- **Let's see the “scalability story” of such a service**

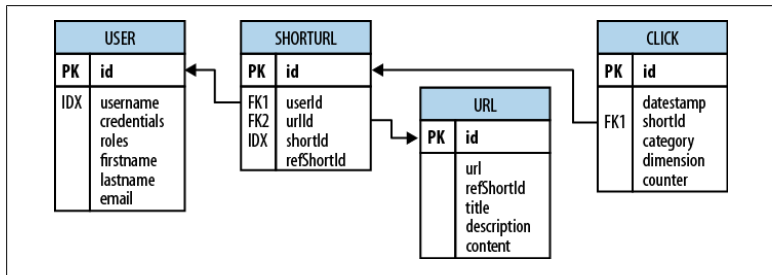
- ▶ Assumption: service must run with a reasonable budget



## The Problem with RDBMS

- **Few thousands users: use a LAMP stack**

- ▶ *Normalize data*
- ▶ Use foreign keys
- ▶ Use Indexes



**Figure:** The Hush Schema expressed as an ERD

## The Problem with RDBMS

- **Find all short URLs for a given user**

- ▶ JOIN `user` and `shorturl` tables
- ▶ Use the `WHERE` clause to select the given user

- **Stored Procedures**

- ▶ Consistently update data from multiple clients
- ▶ Underlying DB system guarantees coherency

- **Transactions**

- ▶ Make sure you can update tables in an *atomic* fashion
- ▶ RDBMS → *Strong Consistency* (ACID properties)
- ▶ *Referential Integrity*

## The Problem with RDBMS

- **Scaling up to tens of thousands of users**

- ▶ Increasing pressure on the database server
- ▶ Adding more application servers is easy: they share their state on the same central DB
- ▶ CPU and I/O start to be a problem on the DB

- **Master-Slave architecture**

- ▶ Add DB server so that `READS` can be served in parallel
- ▶ Master DB takes all the writes (which are fewer in the Hush application)
- ▶ Slaves DB replicate Master DB and serve all reads (but you need a load balancer)

# The Problem with RDBMS

- **Scaling up to hundreds of thousands**

- ▶ `READS` are still the bottlenecks
- ▶ Slave servers begin to fall short in serving clients requests

- **Caching**

- ▶ Add a caching layer, e.g. Memcached or Redis
- ▶ Offload `READS` to a fast in-memory system
- You lose consistency guarantees
- Cache invalidation is critical for having DB and Caching layer consistent

## The Problem with RDBMS

### ● Scaling up more

- ▶ `WRITES` are the bottleneck
- ▶ The master DB is hit too hard by `WRITE` load
- ▶ *Vertical scalability*: beef up your master server
- This becomes costly, as you may also have to replace your RDBMS

### ● SQL JOINS becomes a bottleneck

- ▶ Schema de-normalization
- ▶ Cease using stored procedures, as they become slow and eat up a lot of server CPU
- ▶ Materialized views (they speed up `READS`)
- ▶ Drop secondary indexes as they slow down `WRITES`

# The Problem with RDBMS

- **What if your application needs to further scale up?**
  - ▶ Vertical scalability vs. Horizontal scalability
- **Sharding**
  - ▶ Partition your data across multiple databases
    - ★ Essentially you break horizontally your tables and ship them to different servers
    - ★ This is done using fixed boundaries
    - Re-sharding to achieve load-balancing
  - This is an operational nightmare
    - ▶ Re-sharding takes a huge toll on I/O resources

## Non-Relational DataBases

- **They originally do not support SQL**

- ▶ In practice, this is becoming a thin line to make the distinction
- ▶ One difference is in the data model
- ▶ Another difference is in the consistency model (ACID and transactions are generally sacrificed)

- **Consistency models and the CAP Theorem**

- ▶ Strong: real-time global ordering of operations
- ▶ Sequential: global ordering of operations that respects client session ordering
- ▶ Causal: causally related changes are seen in the same order
- ▶ Eventual: eventual, steady state replicas convergence
- ▶ Weak: no guarantee

## Dimensions to classify NoSQL DBs

### • Data model

- ▶ How the data is stored: key/value, semi-structured, column-oriented, ...
- ▶ How to access data?
- ▶ Can the schema evolve over time?

### • Storage model

- ▶ In-memory or persistent?
- ▶ How does this affect your access pattern?

### • Consistency model

- ▶ Strong or eventual?
- ▶ This translates in how fast the system handles `READS` and `WRITES` [2]



## Dimensions to classify NoSQL DBs

- **Physical Model**

- ▶ Distributed or single machine?
- ▶ How does the system scale?

- **Read/Write performance**

- ▶ Top-down approach: understands well the workload!
- ▶ Some systems are better for `READS`, other for `WRITES`

- **Secondary indexes**

- ▶ Does your workload require them?
- ▶ Can your system emulate them?

## Dimensions to classify NoSQL DBs

### ● Failure Handling

- ▶ How does each data store handle server failures?
- ▶ Is it able to continue operating in case of failures?
  - ★ This is related to Consistency models and the CAP theorem
- ▶ Does the system support “hot-swap”?

### ● Compression

- ▶ Is the compression method pluggable?
- ▶ What type of compression?

### ● Load Balancing

- ▶ Can the storage system seamlessly balance load?

## Dimensions to classify NoSQL DBs

- **Atomic read-modify-write**

- ▶ Easy in a centralized system, difficult in a distributed one
- ▶ Prevent race conditions in multi-threaded or shared-nothing designs
- ▶ Can reduce client-side complexity

- **Locking, waits and deadlocks**

- ▶ Support for multiple client accessing data simultaneously
- ▶ Is locking available?
- ▶ Is it wait-free, hence deadlock free?

### Impedance Match

“One-size-fits-all” has been long dismissed: need to find the perfect match for your problem.

## Database (De-)Normalization

- **Schema design at scale**

- ▶ A good methodology is to apply the DDI principle [8]
  - ★ Denormalization
  - ★ Duplication
  - ★ Intelligent Key design

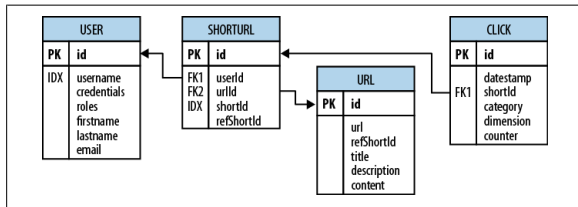
- **Denormalization**

- ▶ Duplicate data in more than one table such that at `READ` time no further aggregation is required

- **Next: an example based on Hush**

- ▶ How to convert a classic relational data model to one that fits HBase

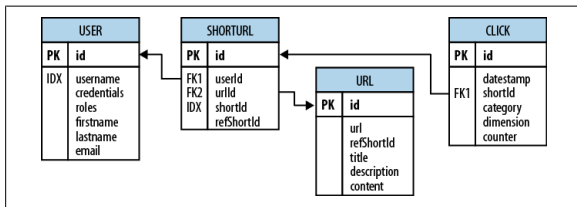
## Example: Hush - from RDBMS to HBase



**Figure:** The Hush Schema expressed as an ERD

- `shorturl` table: contains the short URL
- `click` table: contains click tracking, and other statistics, aggregated on a daily basis (essentially, a counter)
- `user` table: contains user information
- `URL` table: contains a replica of the page linked to a short URL, including META data and content (this is done for batch analysis purposes)

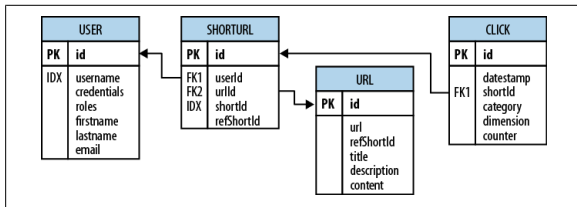
## Example: Hush - from RDBMS to HBase



**Figure:** The Hush Schema expressed as an ERD

- `user` table is indexed on the `username` field, for fast user lookup
- `shorturl` table is indexed on the short URL (`shortId`) field, for fast short URL lookup

## Example: Hush - from RDBMS to HBase



**Figure:** The Hush Schema expressed as an ERD

- `shorturl` and `user` tables are related through a foreign key relation on the `userId`
- `URL` table is related to `shorturl` table with a foreign key on the `URL id`
- `click` table is related to `shorturl` table with a foreign key on the `short URL id`
- **NOTE:** a web page is stored only once (even if multiple users link to it), but each users maintain separate statistics

## Example: Hush - from RDBMS to HBase

Table: shorturl		
Row Key:	shortId	
Family:	data:	Columns: url, refShortId, userId, clicks
	stats-daily: [ttl: 7days]	Columns: YYYYMMDD, YYYYMMDD\x00<country-code>
	stats-weekly: [ttl: 4weeks]	Columns: YYYYWW, YYYYWW\x00<country-code>
	stats-monthly: [ttl: 12months]	Columns: YYYYMM, YYYYMM\x00<country-code>

Table: url		
Row Key:	MD5(url)	
Family:	data: [compressed]	Columns: refShortId, title, description
	content: [compressed]	Columns: raw

Table: user-shorturl		
Row Key:	username\x00shortId	
Family:	data:	Columns: timestamp

Table: user		
Row Key:	username	
Family:	data:	Columns: credentials, roles, firstname, lastname, email

- `shorturl` table: stores each short URL, usage statistics (various time-ranges in separate *column-families* with distinct *TTL* settings)
  - ▶ Note the dimensional postfix appended to the time information
- `url` table: stores the downloaded page, and the extracted details
  - ▶ This table uses compression

**Figure:** The Hush Schema in HBase



## Example: Hush - from RDBMS to HBase

Table: shorturl		
Row Key:	shortId	
Family:	data:	Columns: url, refShortId, userId, clicks
	stats-daily: [ttl: 7days]	Columns: YYYYMMDD, YYYYMMDD\x00<country-code>
	stats-weekly: [ttl: 4weeks]	Columns: YYYYWW, YYYYWW\x00<country-code>
	stats-monthly: [ttl: 12months]	Columns: YYYYMM, YYYYMM\x00<country-code>

Table: url		
Row Key:	MD5(url)	
Family:	data: [compressed]	Columns: refShortId, title, description
	content: [compressed]	Columns: raw

Table: user-shorturl		
Row Key:	username\x00shortId	
Family:	data:	Columns: timestamp

Table: user		
Row Key:	username	
Family:	data:	Columns: credentials, roles, firstname, lastname, email

- `user-shorturl` table: this is a lookup table (basically an index) to find all shortIDs for a given user

- ▶ Note that this table is filled at *insert time*, it's not automatically generated by HBase

- `user` table: stores user details

**Figure:** The Hush Schema in HBase

## Example: Hush - RDBMS vs HBase

- **Same number of tables**

- ▶ Their meaning is different
- ▶ `click` table has been absorbed by the `shorturl` table
- ▶ statistics are stored with the date as the key, so that they can be accessed *sequentially*
- ▶ The `user-shorturl` table is replacing the foreign key relationship, making user-related lookups faster

- **Normalized vs. De-normalized data**

- ▶ Wide tables and column-oriented design eliminates `JOINS`
- ▶ *Compound keys* are essential
- ▶ Data partitioning is based on keys, so a proper understanding thereof is essential

## HBase building blocks

- **The backdrop: BigTable**

- ▶ GFS, The Google FileSystem [6]
- ▶ Google MapReduce [4]
- ▶ BigTable [3]

- **What is BigTable?**

- ▶ BigTable is a distributed storage system for managing structured data designed to scale to a very large size
- ▶ BigTable is a sparse, distributed, persistent multi-dimensional sorted map

- **What is HBase?**

- ▶ Essentially it's an open-source version of BigTable
- ▶ Differences listed in [5]

## HBase building blocks

### Tables, Rows, Columns, and Cells

- **The most basic unit in HBase is a *column***

- ▶ Each column may have multiple versions, with each distinct value contained in a separate *cell*
- ▶ One or more columns form a *row*, that is addressed uniquely by a *row key*

- A table is a collection of rows

- ▶ All rows are always *sorted lexicographically* by their row key

```
hbase(main):001:0> scan 'table1'
ROW                                COLUMN+CELL
row-1                             column=cf1:, timestamp=1297073325971 ...
row-10                             column=cf1:, timestamp=1297073337383 ...
row-11                             column=cf1:, timestamp=1297073340493 ...
row-2                              column=cf1:, timestamp=1297073329851 ...
row-22                             column=cf1:, timestamp=1297073344482 ...
row-3                              column=cf1:, timestamp=1297073333504 ...
row-abc                            column=cf1:, timestamp=1297073349875 ...
7 row(s) in 0.1100 seconds
```

## HBase building blocks

### Tables, Rows, Columns, and Cells

- **Lexicographical ordering of row keys**

- ▶ Keys are compared on a binary level, byte by byte, from left to right
- ▶ This can be thought of as a primary index on the row key!
- ▶ Row keys are *always unique*
- ▶ Row keys can be any *arbitrary array of bytes*

- **Columns**

- ▶ Rows are composed of columns
- ▶ Can have millions of columns
- ▶ Can be compressed or tagged to stay in memory

## HBase building blocks

### Tables, Rows, Columns, and Cells

#### ● Column Families

- ▶ Columns are grouped into *column families*
- Semantical boundaries between data
- ▶ Column families and columns stored together in the same low-level storage file, called an *HFile*
- ▶ Defined when table is created
- ▶ Should not be changed too often
- ▶ The number of column families should be reasonable [WHY?]
- ▶ Column family name composed by printable characters

#### ● References to columns

- ▶ Column “name” is called *qualifier*, and can be any arbitrary number of bytes
- ▶ Reference: `family:qualifier` (also called the **column key**)

## HBase building blocks

### Tables, Rows, Columns, and Cells

- **A note on the `NULL` value**

- ▶ In RDBMS `NULL` cells need to be set and occupy space
- ▶ In HBase, `NULL` cells or columns are simply not stored

- **A *cell***

- ▶ Every column value, or cell, is timestamped (implicitly or explicitly)
  - ★ This can be used to save multiple versions of a value that changes over time
  - ★ Versions are stored in decreasing timestamp, most recent first
- ▶ Cell versions can be constrained by *predicate deletions*
  - ★ Keep only values from the last week

## HBase building blocks

### Tables, Rows, Columns, and Cells

- **Access to data**

- ▶ (Table, RowKey, Family, Column, Timestamp) → Value
- ▶ `SortedMap<RowKey, List<SortedMap<Column, List<Value, Timestamp>>>>`
- ▶ The first `SortedMap` is the table, containing a `List` of column families
- ▶ The families contain another `SortedMap`, representing columns and a `List` of value, timestamp tuples

- **A note on consistency:**

- ▶ Row data access is **atomic** and includes any number of columns
  - ▶ There is no further guarantee or transactional feature spanning multiple rows
- HBase is strongly consistent



# HBase building blocks

## Automatic Sharding

### ● Region

- ▶ This is the basic unit of scalability and load balancing
- ▶ Regions are contiguous ranges of rows “stored together” → they are the equivalent of *range partitions* in sharded RDBMS
- ▶ Regions are *dynamically split* by the system when they become too large
- ▶ Regions can also be merged to reduce the number of storage files

### ● Regions in practice

- ▶ Initially, there is one region
- ▶ System monitors region size: if a threshold is attained, `SPLIT`
  - ★ Regions are split in two at the *middle key*
  - ★ This creates roughly two equivalent (in size) regions

# HBase building blocks

## Automatic Sharding

- **Region Servers**

- ▶ Each region is served by *exactly one Region Server*
- ▶ Region servers can serve multiple regions
- ▶ The number of region servers and their sizes depend on the capability of a single region server

- **Server failures**

- ▶ Regions allow for fast recovery upon failure
- ▶ Fine-grained Load Balancing is also achieved using regions as they can be easily moved across servers

## HBase building blocks

### Storage API

- **No support for SQL**

- ▶ CRUD operations using a standard API, available for many “clients”
- ▶ Data access is not declarative but imperative

- **Scan API**

- ▶ Allows for fast iteration over ranges of rows
- ▶ Allows to limit the number and which column are returned
- ▶ Allows to control the version number of each cell

- **Read-modify-write API**

- ▶ HBase supports single-row transactions
- ▶ Atomic read-modify-write on data stored in a single row key

# HBase building blocks

## Storage API

### ● Counters

- ▶ Values can be interpreted as counters and **updated atomically**
- ▶ Can be read and modified in one operation
- Implement global, strongly consistent, sequential counters

### ● Coprocessors

- ▶ These are equivalent to stored-procedures in RDBMS
- ▶ Allow to push user code in the address space of the server
- ▶ Access to server local data
- ▶ Implement lightweight batch jobs, data pre-processing, data summarization

## HBase building blocks

### HBase implementation

- **Data Storage**

- ▶ *Store* files are called `HFiles`
- ▶ Persistent and ordered **immutable** maps from key to value
- ▶ Internally implemented as sequences of blocks with an index at the end
- ▶ Index is loaded when the `HFile` is opened and kept in memory

- **Data lookups**

- ▶ Since `HFiles` have a block index, lookup can be done with a single disk seek
- ▶ First, the block possibly containing a given lookup key is determined with a **binary search** in the in-memory index
- ▶ Then a block read is performed to find the actual key

- **Underlying file system**

- ▶ Many are supported, usually HBase deployed on top of HDFS

## HBase building blocks

### HBase implementation

- **WRITE operation**

- ▶ First, data is written to a commit log, called WAL (write-ahead-log)
- ▶ Then data is moved into memory, in a structure called `memstore`
- ▶ When the size of the `memstore` exceeds a given threshold it is flushed to an `HFile` to disk

- **How can HBase write, while serving READS and WRITES?**

- ▶ Rolling mechanism
  - ★ new/empty slots in the `memstore` take the updates
  - ★ old/full slots are flushed to disk
- ▶ Note that data in `memstore` is sorted by keys, matching what happens in the `HFiles`

- **Data Locality**

- ▶ Achieved by the system looking up for server hostnames
- ▶ Achieved through intelligent key design

## HBase building blocks

### HBase implementation

- **Deleting data**

- ▶ Since HFiles are immutable, how can we delete data?
- ▶ A delete marker (also known as *tombstone marker*) is written to indicate that a given key is deleted
- ▶ During the read process, data marked as deleted is skipped
- ▶ Compactions (see next slides) finalize the deletion process

- **READ operation**

- ▶ Merge of what is stored in the `memstores` (data that is not on disk) and in the `HFiles`
- ▶ The WAL is never used in the `READ` operation
- ▶ Several API calls to read, scan data

# HBase building blocks

## HBase implementation

### • Compactions

- ▶ Flushing data from `memstores` to disk implies the creation of new `HFiles` each time
- We end up with many (possibly small) files
- We need to do housekeeping [**WHY?**]

### • Minor Compaction

- ▶ Rewrites small `HFiles` into fewer, larger `HFiles`
- ▶ This is done using an  $n$ -way merge<sup>1</sup>

### • Major Compaction

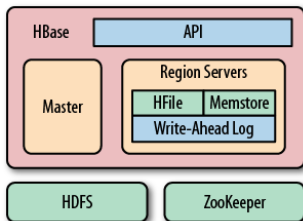
- ▶ Rewrites all files within a column family or a region in a new one
- ▶ Drop deleted data
- ▶ Perform predicated deletion (e.g. delete old data)

---

<sup>1</sup>What is MergeSort?



## HBase: a glance at the architecture



- **Master node: HMaster**

- ▶ Assigns regions to region servers using ZooKeeper
- ▶ Handles load balancing
- ▶ Not part of the data path
- ▶ Holds metadata and schema

- **Region Servers**

- ▶ Handle `READs` and `WRITEs`
- ▶ Handle region splitting

## Architecture

## Seek vs. Transfer

- **Fundamental difference between RDBMS and alternatives**

- ▶ B+Trees
- ▶ Log-Structured Merge Trees

- **Seek vs. Transfer**

- ▶ Random access to individual cells
- ▶ Sequential access to data

## B+ Trees

- **Dynamic, multi-level indexes**

- ▶ Efficient insertion, lookup and deletion
- ▶ **Q: What's the difference between a B+ Tree and a Hash Table?**
- ▶ Frequent updates may imbalance the trees → Tree optimization and re-organization is required (which is a costly operation)

- **Bounds on *page size***

- ▶ Number of keys in each branch
- ▶ Larger fanout compared to binary trees
- ▶ Lower number of I/O operations to find a specific key

- **Support for range scans**

- ▶ Leaves are linked and represent an in-order list of all keys
- ▶ No costly tree-traversal algorithms required

# LSM-Trees

## • Data flow

- ▶ Incoming data is first stored in a logfile, *sequentially*
- ▶ Once the log has the modification saved, data is pushed in memory
  - ★ In-memory store holds most recent updates for fast lookup
- ▶ When memory is “full”, data is flushed in a store file to disk, as a sorted list of `key`  $\rightarrow$  `record` pair
- ▶ At this point, the log file can be thrown away

## • How store files are arranged

- ▶ Similar idea of a B+ Tree, but optimized for sequential disk access
- ▶ All nodes of the tree try to be filled up completely
- ▶ Updates are done in a **rolling merge** fashion
  - ★ The system packs existing on-disk multi-page blocks with in-memory data until the block reaches full capacity

## LSM-Trees

### ● Clean-up process

- ▶ As flushes take place over time, a lot of store files are created
- ▶ Background process aggregates files into larger ones to limit disk seeks
- ▶ All store files are always sorted by key → no re-ordering required to fit new keys in

### ● Data Lookup

- ▶ Lookups are done in a merging fashion
  - ★ First lookup in the in-memory store
  - ★ If miss, the lookup in the on-disk store

### ● Deleting data

- ▶ Use a *delete marker*
- ▶ When pages are re-written, deleted markers and keys are eventually dropped
- ▶ Predicate deletion happens here

## B+ Tree vs. LSM-Trees

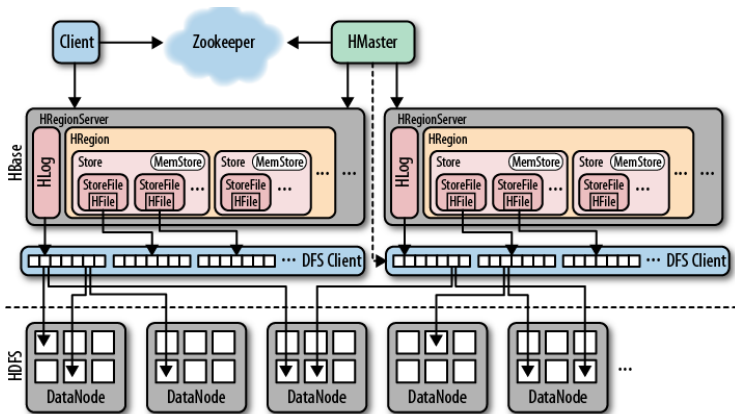
### ● B+ Tree [1]

- ▶ Work well when there are not so many updates
- ▶ The more and the faster you insert data at random locations the faster pages get fragmented
- ▶ **Updates and deletes are done at disk seek rates, rather than transfer rates**

### ● LSM-Tree [7]

- ▶ Work at disk transfer rate and scale better to huge amounts of data
- ▶ Guarantee a consistent insert rate
  - ★ They transform random into sequential writes
- ▶ Reads are independent from writes
- ▶ Optimized data layout which offers predictable boundaries on disk seeks

## Overview



**Figure:** Overview of how HBase handles files in the filesystem



# Storage

## Overview

- **HBase handles two kinds of file types**

- ▶ One is used for the WAL
- ▶ One is used for the actual data storage

- **Who does what**

- ▶ `HMaster`
  - ★ Low-level operations
  - ★ Assigns region servers to key space
  - ★ Keeps metadata
  - ★ Talks to ZooKeeper
- ▶ `HRegionServer`
  - ★ Handles the WAL and `HFiles`
  - ★ These files are divided in to blocks and stored into HDFS
  - ★ Block size is a parameter

# Storage

## Overview

### ● General communication flow

- ▶ A client contacts ZooKeeper when trying to access a particular row
- ▶ Recovers from ZooKeeper the server name that host the `-ROOT-` region
- ▶ Using the `-ROOT-` information the client retrieves the server name that host the `.META.` table region
  - ★ The `.META.` table region contains the row key in question
- ▶ Contact the reported `.META.` server and retrieve the server name that has the region containing the row key in question

### ● Caching

- ▶ Generally, lookup procedures involve caching row key locations for faster subsequent lookups

# Storage

## Overview

### ● Important Java Classes

- ▶ `HRegionServer` handles one or more regions and create the corresponding `HRegion` object
- ▶ When an `HRegion` object is opened it creates a `Store` instance for each `HColumnFamily`
- ▶ Each `Store` instance can have:
  - ★ One or more `StoreFile` instances
  - ★ A `MemStore` instance
- ▶ `HRegionServer` has a shared `HLog` instance

# Storage

## Write Path

- **External client insert data in HBase**

- ▶ Issues an `HTable.put(Put)` request to `HRegionServer`
- ▶ `HRegionServer` hands the request to the `HRegion` instance that matches the request [Q: What is the matching criteria?]

- **How the system reacts to a write request**

- ▶ Write data to the WAL, represented by the `HLog` class
  - ★ The WAL stores `HLogKey` instances in a HDFS `SequenceFile`
  - ★ These keys contain a sequence number and the actual data
  - ★ In case of failure, this data can be used to replay not-yet-persisted data
- ▶ Copy data in the `MemStore`
  - ★ Check if `MemStore` size has reached a threshold
  - ★ If yes, launch a *flush request*
  - ★ Launch a thread in the `HRegionServer` and flush `MemStore` data to an `HFile`

# Storage

## HBase Files

- **What and where are HBase files (including WAL, HFile,...) stored?**
  - ▶ HBase has a root directory set to “/hbase” in HDFS
  - ▶ Files can be divided into:
    - ★ Those that reside under the HBase root directory
    - ★ Those that are in the *per-table* directories
- /hbase
  - ▶ .logs
  - ▶ .oldlogs
  - ▶ .hbase.id
  - ▶ .hbase.version
  - ▶ /example-table

# Storage

## HBase Files

- /example-table
  - ▶ .tableinfo
  - ▶ .tmp
  - ▶ "...Key1..."
    - ★ .oldlogs
    - ★ .regioninfo
    - ★ .tmp
    - ★ colfam1/
- colfam1/
  - ▶ "...column-key1..."

# Storage

## HBase: Root-level files

- **.logs directory**

- ▶ WAL files handled by `HLog` instances
- ▶ Contains a subdir for each `HRegionServer`
- ▶ Each subdir contains many `HLog` files
- ▶ All regions from that `HRegionServer` share the same `HLog` files

- **.oldlogs directory**

- ▶ When data is persisted to disk (from `Memstores`) log files are decommissioned to the `.oldlogs` dir

- **hbase.id and hbase.version**

- ▶ Represent the unique ID of the cluster and the file format version

# Storage

## HBase: Table-level files

- **Every table has its own directory**

- ▶ `.tableinfo`: stores the serialized `HTableDescriptor`
  - ★ This include the table and column family schema
- ▶ `.tmp` directory
  - ★ Contains temporary data



## Storage

### HBase: Region-level files

- **Inside each table dir, there is a separate dir for every region in the table**
  - ▶ The name of each of these dirs is the MD5 hash of a region name
    - ★ Inside each region there is a directory for each column family
    - ★ Each column family directory holds the actual data files, namely `HFiles`
    - ★ Their name is just an arbitrary random number
  - ▶ Each region directory also has a `.regioninfo` file
    - ★ Contains the serialized information of the `HRegionInfo` instance
- **Split Files**
  - ▶ Once the region needs to be split, a `splits` directory is created
    - ★ This is used to stage two daughter regions
    - ★ If split is successful, daughter regions are moved up to the table directory

## Storage

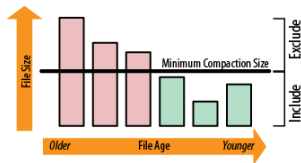
### HBase: A note on region splits

- **Splits triggered by store file (region) size**
  - ▶ Region is split in two
  - ▶ Region is closed to new requests
  - ▶ `.META.` is updated
- **Daughter regions initially reside on the same server**
  - ▶ Both daughters are compacted
  - ▶ Parent is cleaned up
  - ▶ `.META.` is updated
- **Master schedules new regions to be moved off to other servers**

## Storage

### HBase: Compaction

- **Process that takes care of re-organizing store files**
  - ▶ Essentially to conform to underlying filesystem requirements
  - ▶ Compaction check when memstore is flushed
- **Minor and Major compactions**
  - ▶ Always from the oldest to the newest files
  - ▶ Avoid all servers to perform compaction concurrently

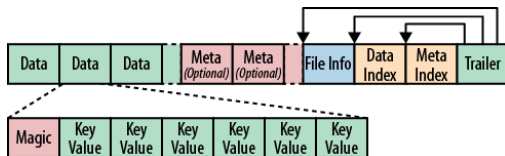


**Figure:** A set of store files showing the minimum compaction threshold

# Storage

## HFile format

- **Store files are implemented by the `HFile` class**
  - ▶ Efficient data storage is the goal
- **HFiles consist of a variable number of blocks**
  - ▶ Two fixed blocks: *info* and *trailer*
  - ▶ *index* block: records the offsets of the *data* and *meta* blocks
  - ▶ Block size: *large* → sequential access; *small* → random access



**Figure:** The HFile structure

# Storage

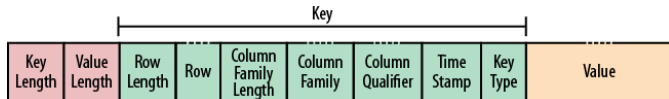
## HFile size and HDFS block size

- **HBase uses any underlying filesystem**
- **In case HDFS is used**
  - ▶ HDFS block size is generally 64MB
  - ▶ This is 1,024 times the default `HFile` block size (64 KB)
  - There is no correlation between HDFS block and HFile sizes

## Storage

### The KeyValue Format

- **Each KeyValue in the HFile is a low-level byte array**
  - ▶ It allows for *zero-copy* access to the data
- **Format**
  - ▶ Fixed-length preamble indicates the length of the key and value
    - ★ This is useful to offset into the array to get direct access to the value, ignoring the key
  - ▶ Key format
    - ★ Contains row key, column family name, column qualifier...
    - ★ [TIP]: consider small keys to avoid overhead when storing small data



**Figure:** The KeyValue Format

## The Write-Ahead Log

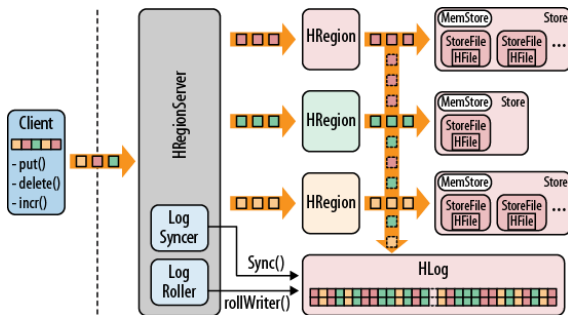
- **Main tool to ensure resiliency to failures**

- ▶ Region servers keep data in-memory until enough is collected to warrant a flush
- ▶ What if the server crashes or power is lost?

- **WAL is a common approach to address fault-tolerance**

- ▶ Every data update is first written to a log
- ▶ Log is persisted (and replicated, since it resides on HDFS)
- ▶ Only when log is written, client is notified a successful operation on data

## The Write-Ahead Log



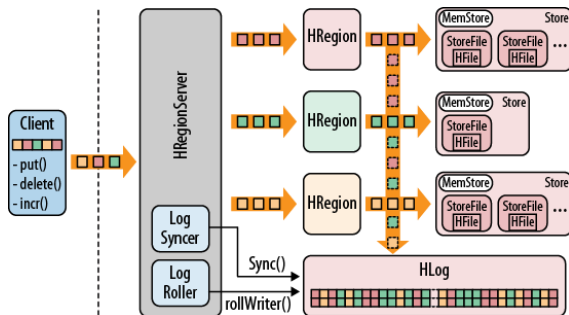
**Figure:** The write path of HBase

- **WAL records all changes to data**

- ▶ Can be replayed in case of server failure
- ▶ If write to WAL fails, the whole operations has to fail



# The Write-Ahead Log



## Write Path

- ▶ Client modifies data (`put()`, `delete()`, `increment()`)
- ▶ Modifications are wrapped into a **KeyValue** object
- ▶ Objects are batched to the corresponding **HRegionServer**
- ▶ Objects are routed to the corresponding **HRegion**
- ▶ Objects are written to **WAL** and in the **MemStore**

## Read Path

- **HBase uses multiple store files per column family**
  - ▶ These can be either in-memory and/or materialized on disk
  - ▶ Compactions and clean-up background processes take care of store files maintenance
  - ▶ Store files are immutable, so deletion is handled in a special way
- **The anatomy of a get command**
  - ▶ HBase uses a `QueryMatcher` in combination with a `ColumnTracker`
  - ▶ First, an exclusion check is performed to filter skip files (and eventually tombstone labelled data)
  - ▶ Scanning data is implemented by a `RegionScanner` class which retrieves a `StoreScanner`
  - ▶ `StoreScanner` includes both the `MemStore` and `HFiles`
  - ▶ Read/Scans happen in the same order as data is saved

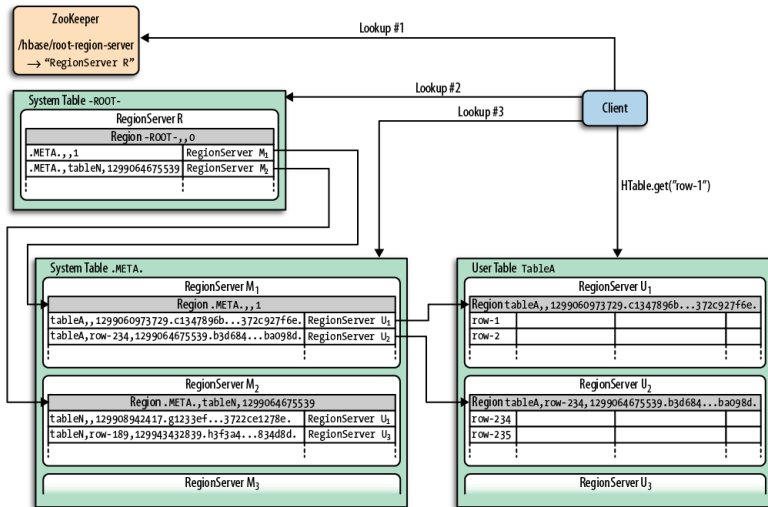
## Region Lookups

- **How does a client find the region server hosting a specific row key range?**
  - ▶ HBase uses two special catalog tables, `-ROOT-` and `.META.`
  - ▶ The `-ROOT-` table is used to refer to all regions in the `.META.` table
- **Three-level B+ Tree -like operation**
  - ▶ Level 1: a node stored in ZooKeeper, containing the location (region server) of the `-ROOT-` table
  - ▶ Level 2: Lookup in the `-ROOT-` table to find a matching meta region
  - ▶ Level 3: Retrieve the table region from the `.META.` table

## Region Lookups

- **Where to send requests when looking for a specific row key?**
  - ▶ This information is cached, but the first time or when the cache is stale or when there is a miss due to compaction, the following procedure applies
- **Recursive discovery process**
  - ▶ Ask the region server hosting the matching `.META.` table to retrieve the row key address
  - ▶ If the information is invalid, it backs out: asks the `-ROOT-` table where the relevant `.META.` region is
  - ▶ If this fails, ask ZooKeeper where the `-ROOT-` table is

# Region Lookups



## Key Design

# Concepts

- **HBase has two fundamental key structures**

- ▶ Row key
- ▶ Column key

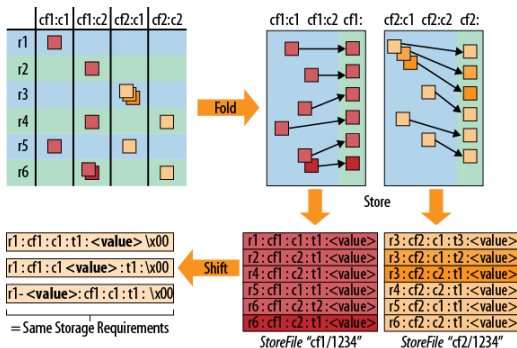
- **Both can be used to convey meaning**

- ▶ Because they store particularly meaningful data
- ▶ Because their sorting order is important

## Concepts

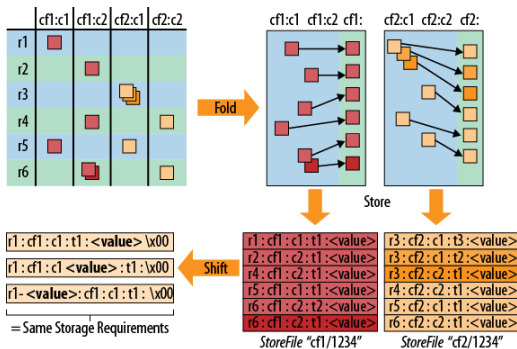
### ● Logical vs. on-disk layout of a table

- ▶ Main unit of separation within a table is the *column family*
- ▶ The actual columns (as opposed to other column-oriented DBs) are not used to separate data
- ▶ Although cells are stored logically in a table format, rows are stored as linear sets of the cells
- ▶ Cells contain all the vital information inside them





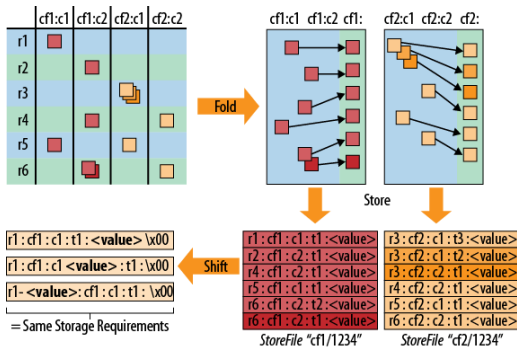
# Concepts



## Logical Layout (Top-Left)

- ▶ Table consists of rows and columns
- ▶ Columns are the combination of a column family name and a column qualifier
- `<cf name: qualifier>` is the **column key**
- ▶ Rows have a **row key** to address all columns of a single logical row

# Concepts



## ● Folding the Logical Layout (Top-Right)

- ▶ The cells of each row are stored one after the other
- ▶ Each column family are stored separately
- On disk all cells of one family reside on an individual `StoreFile`
- ▶ HBase does not store unset cells
- **Row and column key is required to address every cell**

# Concepts

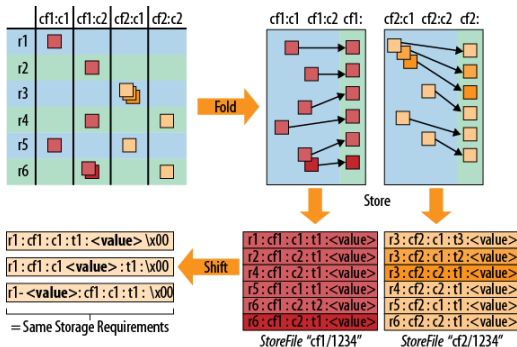
## ● Versioning

- ▶ Multiple versions of the same cell stored consecutively, together with the *timestamp*
- ▶ Cells are sorted in descending order of timestamp
- Newest value first

## ● KeyValue object

- ▶ The entire cell, with all the structural information, is a `KeyValue` object
- ▶ Contains: `row key, <column family: qualifier> → column key, timestamp and value`
- ▶ Sorted by row key first, then by column key

# Concepts



## Physical Layout (Lower-Right)

- ▶ Select data by row key
  - ★ This reduces the amount of data to scan for a row or a range of rows
- ▶ Select data by row key and column key
  - ★ This focuses the system on an individual storage file
- ▶ Select data by column qualifier
  - ★ Exact lookups, including filters to omit useless data

## Concepts

- Summary of key lookup properties

Key Value	Key				Value
	Row	Column Family	Column Qualifier	Timestamp	
Skip Rows	✓	X	X	X	X
Skip Store Files	✓	✓	X	✓	X
Filter Compatible	✓	✓	✓	✓	✓

← Performance

Increased Cardinality →

## Tall-Narrow vs. Flat-Wide Tables

- **Tall-Narrow Tables**

- ▶ Few columns
- ▶ Many rows

- **Flat-Wide Tables**

- ▶ Many columns
- ▶ Few rows

- **Given the query granularity explained before**

- Store parts of the cell data in the row key
  - ▶ Furthermore, HBase splits at row boundaries
- It is recommended to go for Tall-Narrow Tables

## Tall-Narrow vs. Flat-Wide Tables

### ● Example: email data - version 1

- ▶ You have all emails of a user in a single row (e.g. `userID` is the row key)
- ▶ There will be some outliers with orders of magnitude more emails than others
- A single row could outgrow the maximum file/region size and work against split facility

### ● Example: email data - version 2

- ▶ Each email of a user is stored in a separate row (e.g. `userID:messageID` is the row key)
- ▶ On disk this makes no difference (see the disk layout figure)
  - ★ If the `messageID` is in the column qualifier or the row key, each cell still contains a single email message
- The table can be split easily and the query granularity is more fine-grained

## Partial Key Scans

- **Partial Key Scans reinforce the concept of Tall-Narrow Tables**

- ▶ From the email example: assume you have a separate row per message, across all users
- ▶ If you don't have an exact combination of user and message ID you cannot access a particular message

- **Partial Key Scan solves the problems**

- ▶ Specify a *start* and *end* key
- ▶ The start key is set to the exact `userID` only, with the end key set at `userID+1`
- This triggers the internal lexicographic comparison mechanism
  - ★ Since the table does not have an exact match, it positions the scan at:  
`<userID>:<lowest-messageID>`
- ▶ The scan will then iterate over all the messages of an exact user, parse the row key and get the `messageID`



## Partial Key Scans

- **Composite keys and atomicity**

- ▶ Following the email example: a single user inbox now spans many rows
- ▶ It is no longer possible to modify a single user inbox in one atomic operation

- **If this is acceptable or not, depends on the application at hand**

## Time Series Data

- **Stream processing of events**

- ▶ E.g. data coming from a sensor, stock exchange, monitoring system ...
- ▶ Such data is a time series → **The row key represents the event time**
- HBase will store all rows sorted in a distinct range, namely regions with specific start and stop keys

- **Sequential monotonously increasing nature of time series data**

- ▶ All incoming data is written to the same region (and hence the same server)
- **Regions become HOT!**
- ▶ Performance of the whole cluster is bound to that of a single machine

## Time Series Data

### ● Solution to achieve load balancing: Salting

- ▶ We want data to be spread over all region servers
- ▶ This can be done, e.g., by prefixing the row key with a non-sequential number

### Salting example

```
byte prefix = (byte) (Long.hashCode(timestamp) % <number of  
region servers>);  
byte[] rowkey = Bytes.add(Bytes.toBytes(prefix),  
Bytes.toBytes(timestamp));
```

- Data access needs to be *fanned out* across many servers
- + Use multiple threads to read for I/O performance: e.g. use the Map phase of MapReduce

## Time Series Data

- **Solution to achieve load balancing: Field swap/promotion**
  - ▶ Move the timestamp field of the row key or prefix it with another field
    - ★ If you already have a composite row key, simply *swap* elements
    - ★ Otherwise if you only have the timestamp, you need to *promote* another field
  - ▶ The sequential, monotonously increasing timestamp is moved to a secondary position in the row key
- You can only access data (especially time ranges) for a given swapped or promoted field (but this could be a feature)
- + You achieve load balancing

## Time Series Data

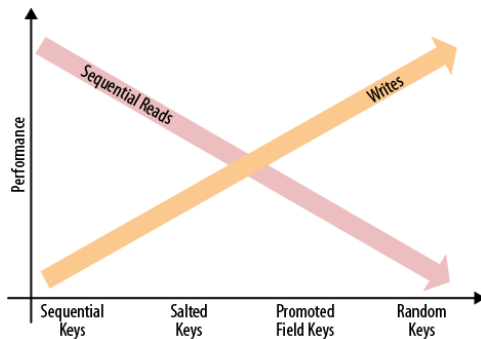
- **Solution to achieve load balancing: Randomization**

- ▶ `byte[] rowkey = MD5(timestamp)`
- ▶ This gives you a random distribution of the row key across all available region servers

- Less than ideal for range scans
- + Since you can re-hash the timestamp, this solution is good for **random access**

# Time Series Data

- Summary



# Cassandra

## Cassandra: Overview (1)

- **Distributed key value store**

- ▶ Stores large amounts of data
- ▶ Linear scalability, high availability, no SPOF

- **Tunable consistency**

- ▶ Often eventually consistent, hence in AP
- ▶ Can guarantee strong consistency, shifting it to CP

- **Column-oriented data model**

- ▶ One key per row



## Cassandra: Overview (2)

- **Combines techniques from Amazon Dynamo and HBase**

- ▶ HBase data model
  - ★ One key per row
  - ★ Columns, column families
- ▶ Dynamo-like architecture
  - ★ Partitioning, placement (using consistent hashing)
  - ★ Replication, gossip-based membership, anti-entropy

- **Some key differences**

- ▶ Many of them recently added

# Data Partitioning

- **Uses consistent hashing**

- ▶ Random Partitioner
- ▶ ByteOrdered Partitioner

- **Partitioning strategy can be changed on-the-fly**

- ▶ **All** data needs to be reshuffled
- ▶ Needs to be chosen carefully

## Random Partitioner

- **Hash-based identifiers for keys (data) and storage nodes**
  - ▶ Supports virtual nodes
- **Consistent hashing + load monitoring per ring**
  - ▶ Lightly loaded nodes move on the ring to alleviate heavily loaded ones
  - ▶ Make deterministic choices about load balancing, e.g., divides the hash-ring evenly w.r.t. to number of nodes
- **Node addition / suppression**
  - ▶ Requires re-balancing the cluster if no virtual nodes

## ByteOrdered Partitioner

- **Supports range queries**

- ▶ Ensures row keys to be stored in sorted order
- ▶ Very different from consistent hashing

- **Key partitioning**

- ▶ There is still a ring
- ▶ Keys are ordered lexicographically along the ring by their value<sup>2</sup>

- **Precautions**

- ▶ Might be bad for load balancing
- ▶ Range scan can be obtained by using column family indexes

---

<sup>2</sup>The key value is different from the value associated to a key

## Data Replication

### ● Asynchronous replication

- ▶ Walk down the ring and choose  $N - 1$  successor nodes as replicas
- ▶ Builds a **preference list**

### ● Replication strategies

- ▶ Simple Strategy:
  - ★ Main replica = node responsible for a key
  - ★ Additional  $N - 1$  replicas placed on successor nodes, clockwise in the ring, w/o rack or datacenter information
- ▶ NetworkTopology Strategy
  - ★ Allows better performance when knowledge of the datacenter layout is available
  - ★ Reads served locally
  - ★ Replica placement is independent in each datacenter
  - ★ Rack-aware placement like in HDFS

## Data Replication Strategies: Implications

- **Focus on the NetworkTopology strategy**

- ▶ Requires **Snitches**<sup>3</sup> and optionally Zookeeper
- ▶ Mechanism to discover the underlying cluster configuration

- **Potential problems**

- ▶ Unbalanced load across datacenter
- ▶ Consider datacenter-specific key rings

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<sup>3</sup>We don't cover the details here: refer to the official documentation or the additional slides provided in the lecture notes.

# Data Model

## KeySpace

### Column Family

Sorted by Key ↓

Key	Column Name	Column Name	Column Name
	Value	Value	Value

Key	Column Name	Column Name
	Value	Value

Key	Column Name	Column Name	Column Name	Column Name
	Value	Value	Value	Value

### Column Family

Sorted by Key ↓

Key	Column Name	Column Name	Column Name
	Value	Value	Value

Key	Column Name	Column Name
	Value	Value

column_name
value
timestamp

Provided by  
Application

## Data Model: Special Columns

### ● Counter columns

- ▶ Store counters
- ▶ Timestamp information automatically generated (use NTP!)

### ● Expiring columns

- ▶ Specify a TTL value after which, data is removed
- ▶ Tombstone marker, as for HBase

### ● Super columns

- ▶ Additional nesting levels
- ▶ Group multiple columns on a common lookup value
  - ★ E.g.: “home address” super column, grouping “street”, “city”, “ZIP” columns
- ▶ No timestamps



# Anatomy of Read/Write Operations

## ● Request routing

- ▶ Proxy-based mechanism (coordinator, in Cassandra terms)
- ▶ Proxy route request to **any** replica

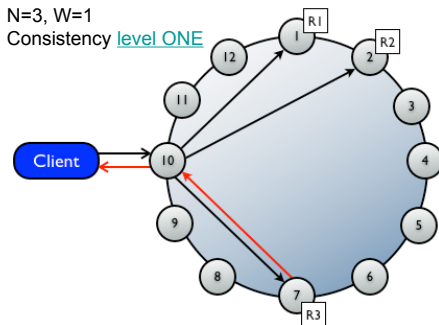
## ● Proxy nodes

- ▶ Handle interaction between a client and Cassandra
- ▶ First, determine replicas for a given key
- ▶ ZooKeeper may be useful here

## Write Requests (1)

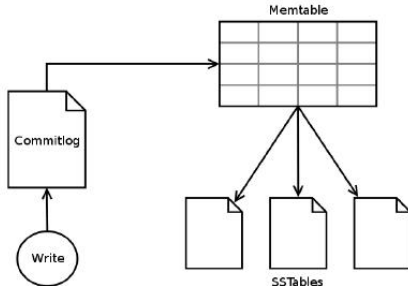
- **Proxy nodes forward write requests**

- ▶ Request routed to **all**  $N$  replicas
- ▶ This is true, regardless of consistency configuration



## Write Requests (2)

- **Write request:** similar mechanism to HBase
  - ▶ Write to the commit log
  - ▶ Write to in-memory data structure (`memtable`)
  - Write is considered successful now
  - ▶ Writes are batched and periodically flushed to a persistent data structure called a sorted string table (`SSTable`)



## Write Requests (3)

- **Memtables**

- ▶ Organized in sorted order by row key
- ▶ Flushed to SSTables sequentially, no random seeks

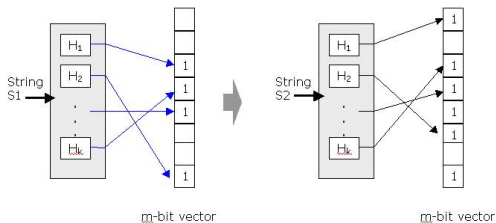
- **SSTables**

- ▶ Immutable (no rewrite after flushing)
- ▶ A single row can be stored in many SSTables
- At **read time**, rows must be combined from all SSTables (on disk or from memtables) to produce the requested data
- ▶ Use **Bloom Filters** to optimize the process

## Bloom Filters (1)

### • Bloom Filters in a nutshell

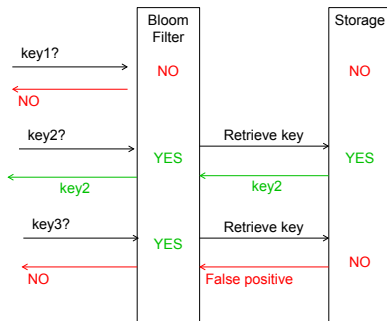
- ▶ Used to check for set membership
- ▶  $k$  hash functions hashing into the same  $m$ -bit space



## Bloom Filters (2)

- **One bloom filter per SSTable**

- ▶ Used in combining from row data from multiple “sources”
- ▶ Check if a requested row key exists in the SSTables, before doing any disk seeks



## Read Requests (1)

- **Similar mechanism to Dynamo**

- ▶ Proxy initiates a read repair (a.k.a. writeback) if it detects inconsistent replicas
- ▶ This is done in the background, after the read has been served to the client

- **The number of replicas contacted upon a read request depend on the consistency level**

- ▶ Proxy routes the requests to the closest replica
- ▶ Proxy routes requests to all replicas and wait for a quorum

## Read Requests (2)

- **When a node receives a read request**

- ▶ Row must be combined from all SSTables on that node
- ▶ Data not yet flushed to SSTables, i.e. stored in memtables, must be considered as well
- This produces the requested data

- **Key techniques to achieve high performance**

- ▶ Row-level column index
- ▶ Bloom filters

- **Cutting read latency**

- ▶ Combining data before serving it can be slow
- ▶ Read cache (in memory)
- ▶ Advanced topics: cache invalidation, consistency...



## Consistency

- **Consistency in Cassandra is tunable**

- ▶ Hence is availability, as per CAP
- ▶ Read and Write consistency levels can be independent

- **Given  $N$  replicas in the preference list**

- ▶ **Write request**: all  $N$  replicas are contacted
  - ★ Ends when  $W$  respond (i.e. acknowledgment)
- ▶ **Read request**: only  $R$  replicas are contacted
  - ★ This is optimistic, may need to contact all  $N$  replicas

- **Choices of  $W$  and  $R$  define consistency level**

- ▶ Dynamo:  $W + R > N$  (recall extended preference list + sloppy quorum)
- ▶ Cassandra:  $W + R > N$  not mandatory

## Consistency Levels: ONE

- $W = 1$ 
  - ▶ One replica must write to commit log and memtable
- $R = 1$ 
  - ▶ Returns a response from the closest replica (as determined by the snitch)
  - ▶ By default, a read repair runs in the background to make the other replicas consistent
- **This is true regardless of the replication factor  $N$**

## Consistency Levels: QUORUM

### ● QUORUM

- ▶  $W = \text{floor}(N/2 + 1)$ : a majority
  - ★ A write is written to the commit log and memtable on a quorum of  $W$  replicas
- ▶  $R = \text{floor}(N/2 + 1)$ : a majority
  - ★ Read returns the record with the most recent timestamp, once a quorum of size  $R$  has responded
  - ★ Timestamp = application timestamp

### ● LOCAL\_QUORUM

- ▶ Restricted to a local datacenter

### ● EACH\_QUORUM

- ▶ QUORUM invariant must be satisfied across datacenters

## Consistency Levels: ALL, ANY

### • ALL

- ▶  $W = N$ : all replica nodes must acknowledge
- ▶  $R = N$ : returns the record with the most recent timestamp across all replicas

### • ANY

- ▶ Additional consistency for writes
- ▶ Allow writes to complete even if all  $N$  replicas are down
- ▶ Hinted handoff mechanism

# Lightweight Transactions

- **Simple mechanism at the single key level**

- ▶ Single object transactions
- ▶ No support for multi-key transactions
- ▶ “Consistency” level: SERIAL

- **Compare and Swap (CAS) mechanism**

- ▶ Enhancements available in Cassandra 2.0
- ▶ Paxos based mechanism
- ▶ Address the problem of solving the agreement for 2 processes, that requires using locks

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