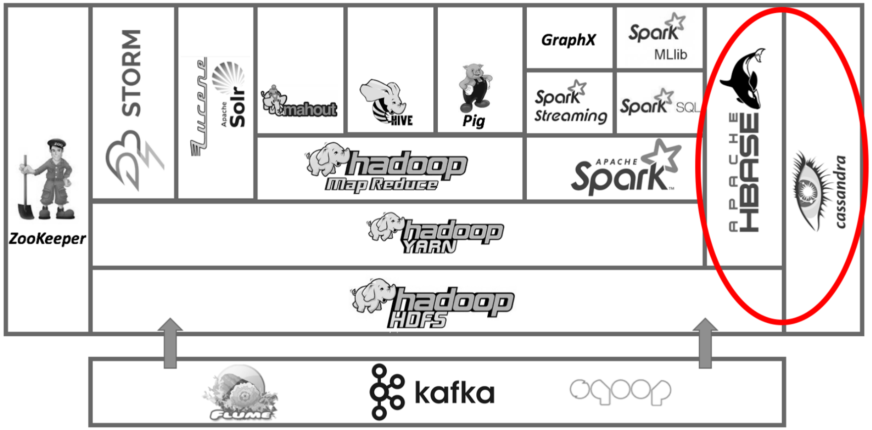
Large-scale Distributed Systems

Lecture 9: Distributed databases and NoSQL

Today

- Relational databases:
  - Quick recap
- Distributed relational databases.
  - Data placement
  - Distributed queries
  - Dsitributed transactions
- NoSQL databases.
  - CAP theorem



Relational databases

(Quick recap from INFO0009: Databases)

Databases

From Oxford dictionary:

- Database: an organized body of related information.
- Database system, Database management system (DBMS): a software system that facilitates the creation and maintenance and use of an electronic database

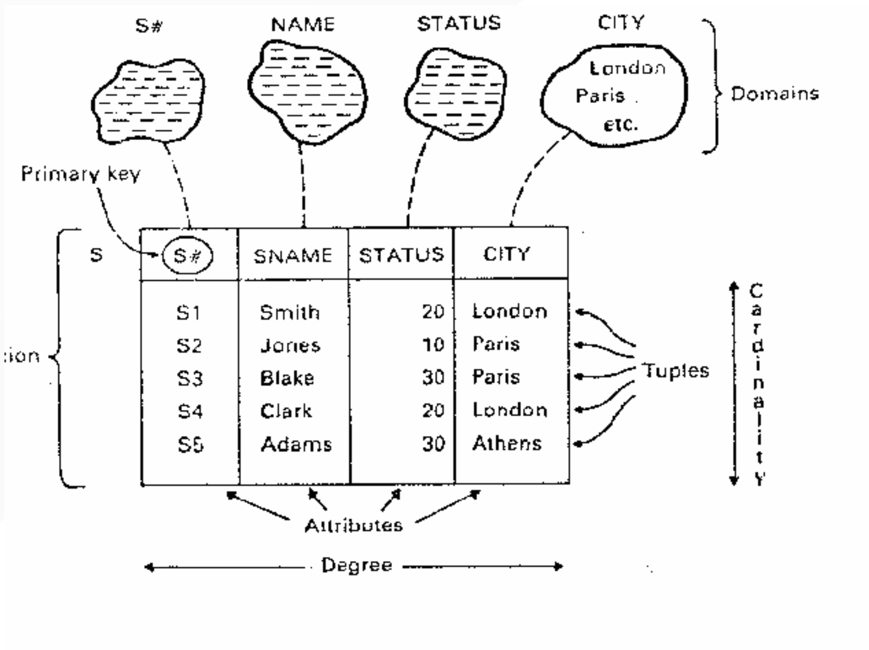
What do you want from a DBMS?

- Persistence: Keep data around.
- Queries: answer questions about data.
- Updates: add, modify, delete data.

[Q] Which database systems do you know?

Relational data model (1)

- A simple but general-purpose model.
- Data is stored in relations (i.e., a collection of tables).
  - a tuple is a row of a relation.
  - an attribute is a column of a relation.
  - a domain is a set of legal atomic values for an attribute.
    - this can be used to enforce semantic constraints.



Relational data model (2)

- A relation schema is a list of attributes.
  - A schema is the blueprint that describes how the data is structured in the relation.
- A relation is a set of tuples for a given relation schema.
  - Each tuple in a relation is unique and satisfies the schema.
  - Uniqueness is often controlled through a (primary) key attribute.
- A database schema is a collection of relation schemas.
- Relationships between relations (tables) are defined by matching one or more attributes (usually, the keys) across relations.
  - 1-to-1 relationships
  - 1-to-many relationships
  - many-to-many relationships

Querying data

- Data is retrieved, added or modified through an expressive declarative query language, SQL.

```
SELECT EmployeeName, City FROM Employees;
```

  - Can be used to access data across one or more relations, with arbitrarily complex constraints.
  - Programmer specifies what answers a query should return, but not how the query is executed.
  - DBMS transparently picks the best execution strategy, based on availability of indexes, data/workload, properties, etc.
    - As based on an often sophisticated query processing engine.
- This provides physical data independence.
  - Applications should not worry about how data is physically structured and stored.
  - Applications instead work with a logical data model and a declarative query language.
- Single most important reason behind the success of DBMSs today.

Concurrency

- DBMSs are multi-user, which raises concurrency issues.
- Example:
  - Both Homer and Marge concurrently execute, on the same bank account:

```
def withdraw(account, amount):
    balance = account.balance
    if balance - amount >= 0:
        balance = balance - amount
        dispense_cash(amount)
        account.balance = balance
```

  - Homer at ATM1 withdraws $100.
  - Marge at ATM2 withdraws $200.
  - Initial balance = $400.
  - What is the final balance?

[Q] Haven't we already studied a similar problem?

Fault-tolerance and recovery

- Example: balance transfer.
  - decrement the balance of account X by \$100.
  - increment the balance of account Y by \$100.
- Scenario 1: Power goes out after the first instruction.
- Scenario 2: DBMS buffers and updates data in memory (for efficiency), but power goes out before they are written back to disk.
- How can we deal with these failures?

ACID

ACID = key characteristics (most) relational databases use to ensure modifications are saved in a consistent, safe, and robust manner.

- Atomic: All parts of the transaction or none are committed.
- Consistent: A transaction either creates a new valid state of data, or, if any failure occurs, returns all data to its state before the transaction was started.
- Isolation: A transaction in process and not yet committed must remain isolated from any other transaction.
- Durable: Committed data is saved by the system such that, even in the event of a failure and system restart, the data is available in its correct state.

[Q] Don't some of these properties look familiar?

[Q] Assume the bank uses an ACID database. What does this mean for Homer and Marge?

Performance

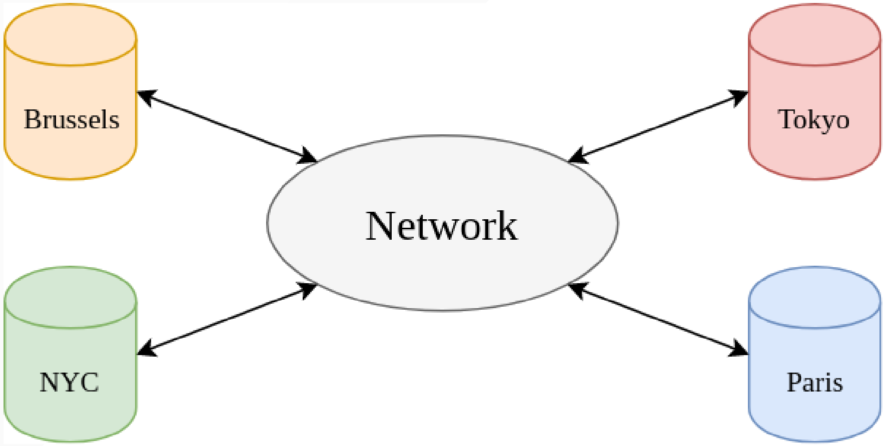
- DBMSs are designed to store massive amounts of data (TB, PB).
- High throughput is desired (thousands to millions transactions/hour).
- High availability ($\geq$ 99.999%).

[Q] How can we address these issues, at large-scale?

Distributed relational databases

Distributed relational databases

- A distributed database (DDBMS) is a database whose relations reside on different sites.
- Interface requirements:
  - Relational data model
  - ACID properties
  - Single system illusion



[Q] How is this different from/similar to a distributed file system?

Data placement

- The data placement strategy, i.e. the distribution of the relations over the sites, and its implications form the main part in the design of a DDBMS.
- Aim to improve:
  - reliability
  - availability
  - efficiency (e.g., reduced communication costs or better load balancing)
  - security.
- Key considerations:
  - Fragmentation: relations may be divided into a number of sub-relations which are distributed.
  - Allocation: each fragment is stored at site with optimal placement.
  - Replication: copy of fragment may be maintained at several sites.

Fragmentation

- Break a relation into smaller relations or fragments, which are then distributed at different sites.
- Main kinds of fragmentation:
    - Horizontal: partition a relation along its tuples.
        - e.g., identify fragments to selection queries.
    - Vertical: partition a relation along its attributes.
        - e.g., identify fragments to projection queries.
    - Mixed: partition horizontally and vertically.

TID	eid	name	city	age	sal
t1	53666	Jones	Madras	18	35
t2	53688	Smith	Chicago	18	32
t3	53650	Smith	Chicago	19	48
t4	53831	Madayan	Bombay	11	20
t5	53832	Guldu	Bombay	12	20

Vertical Fragment

Horizontal Fragment

Correctness rules of fragmentation

A fragmentation strategy should satisfy the following properties:

- Completeness: If a relation R is decomposed into fragments $R_1, ..., R_n$, each data item that can be found in R must appear in a least one fragment.
- Reconstruction: Must be possible to define a relation operation that will reconstruct R from its fragments.
  - Union to combine horizontal fragments
  - Join to combine vertical fragments
- Disjointness: If data item d appears in fragment R_i, then it should not appear in any other fragment (at the exception for primary keys).
  - For horizontal fragmentation, data item is a tuple.
  - For vertical fragmentation, data item is an attribute.

Allocation

- Ideally, fragments should be allocated such that queries that are frequently performed locally at sites are fast.
    - e.g., store tuples of Belgian employees at Brussels' site, but tuples of Japanese employees at Tokyo's.
- Optimization problem:
    - Givens:
        - fragments $f_1, ..., f_n$
        - sites $s_1, ..., s_m$
        - applications $q_1, ..., q_k$
    - Find the optimal assignment of fragments to sites such that the total cost of all applications is minimized and the performance is maximized.
        - Application costs: communication, storage, processing.
        - Performance: response time, throughput.
    - Constraints: per site constraints (storage and processing)
    - Problem is in general NP-complete, but good heuristics exist.
        - Reduce to a knapsack problem.

Replication

- Storing a same fragment at distinct sites increases availability and efficiency.
- Replication modes:
  - fully replicated: each fragment at each site.
  - partially replicated: each fragment at one or more sites.
- Rule of thumb: if read-only queries / update queries ≥ 1, then replication is advantageous, otherwise it may cause problems.
- The optimal partial replication policy can be determined jointly with the allocation problem.

[Q] Doesn't replication violate disjoitness?

Distributed query processing

- For centralized regular DBMSs, all data is local and queries are mainly optimized to limit disk accesses.
- In DDBMSs, the data is distributed across several sites. This has the following consequences:
  - The query processing engine must communicate with all sites holding fragments involved in the query.
    - The cost of data transmission becomes a dominant factor when optimizing the query.
  - The engine must orchestrate the execution of sub-queries to compute the original query.
  - Independent sub-queries can be scheduled concurrently.

Non-joins

tid	sid	sname	rating	age	
1			5		Tokyo
2			9		Tokyo
3			4		Brussels

```sql
SELECT AVG(S.age)
FROM Sailors AS S
WHERE S.rating > 3 AND
      S.rating < 7
```

- Horizontal fragmentation: Tuples with ratings < 5 at Brussels, ≥ 5 at Tokyo.
  - Must compute sub-queries `SUM(S.age)` and `COUNT(s.age)` at both sites, before union and aggregation.
  - If the `WHERE` clause contained just `S.rating > 6`, then the query could be processed at one site only.
- Vertical fragmentation:
  - Must reconstruct relation by join on `tid`, then evaluate the query.

Joins

- Joins in DDBMSs can be very expensive if relations are stored at different sites.
- Consider three relations `account`, `depositor` and `branch`.
    - We want to compute their join `account`$\bowtie$`depositor`$\bowtie$`branch`.
        - `account` is stored at site 1.
        - `depositor` is stored at site 2.
        - `branch` is stored at site 3.
    - A query issued at site 1 must produce a result at site 1.
- Possible strategies:
    - Ship copies of all three relations to site 1 and process the query locally.
    - Ship a copy of `account` to site 2, compute `temp1=account`$\bowtie$`depositor`. Ship `temp1` from site 2 to site 3, compute `temp2=temp1`$\bowtie$`branch`. Ship `temp2` to site 1.

[Q] Does the ordering matter? Can we do better?

Semijoins

- We do not need to exchange the whole relations! Semijoins are sufficient:
  - At site 2, project `depositor` onto join columns with `branch` and ship to site 3.
  - At site 3, join the projection with `branch`. Project the resulting relation onto the join columns with `account` and ship to site 1.
  - At site 1, join the projection with `account`.
- Tradeoff the cost of computing and shipping projection for cost of shipping full relation.

Distributed transactions

```
def send(A, B, amount):
    begin_transaction()
    if A.balance - amount >= 0:
        A.balance = A.balance - amount
        B.balance = B.balance + aount
        commit_transaction()
    else:
        abort_transaction()
```

- All copies of the fragments involved in a transaction must be updated before the modifying transaction commits.
- How does one guarantee that all of the fragments commit the transactions or none do?

[Q] What algorithm have we seen that could solve this?

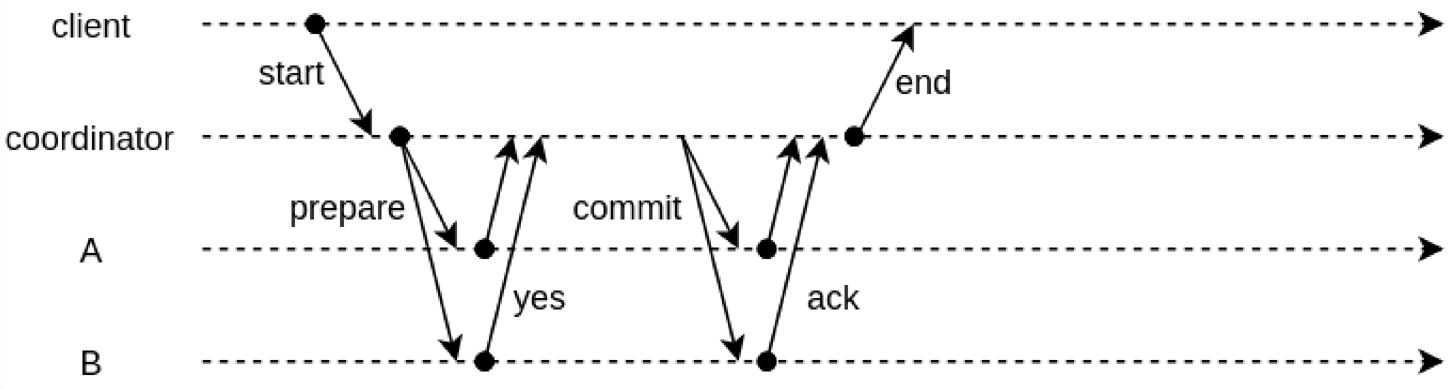
Two-phase commit (1)

- Goal: general-purpose distributed agreement on some action, with failures.
- Running example: transfer money from A to B.
  - Debit at A, credit at B, tell the client OK.
  - Require both banks to do it, or neither.
  - Require that a bank never acts alone.
- This is a form of consensus:
  - The value to agree upon is whether or not the transaction should be committed.
  - We require agreement, validity and termination.

Two-phase commit (2)

- Site at which transaction originates is the coordinator.
- Other sites at which it executes are the participants.
- Two rounds of communication:
  - Phase 1 (request phase):
    - Prepare messages are sent from coordinator to all participants asking if ready to commit.
    - Yes/No replies from the participants to the coordinator.
      - If yes, the participant might have prepared locks on the local resources that need to be modified.
    - To commit, all subordinates must say yes.
  - Phase 2 (commit phase):
    - If yes from all participants, coordinator sends out commit messages, otherwise send abort instructions.
    - Participants do so, and send back an acknowledgement.
    - When the coordinator receives all acknowledgements, the transaction has committed.
- Efficient protocol: $4n$ messages are exchanged in total. Seem difficult to do better.

Two-phase commit (3)



[Q] What if a node fails?

Two-phase commit (4)

What if nodes fail?

- If a participant fails in the request phase, then this can be detected and the transaction may be aborted.
    - If a participant fails in the commit phase, then the other participants commit anyway!
- If the coordinator crashes, than all processes are blocked.
    - If the coordinator crashes after some correct process has committed, then the decision can be recovered from this correct process.
    - If the coordinator crashes in the request phase, then the transaction is blocked!

[Q] How to detect failures?

Asynchronous transactions

- Synchronous transactions:
  - Before the update transaction can commit, it must obtain locks on all copies of the modified fragment.
  - This acquisition may take time.
  - But data distribution is transparent to user.
- Asynchronous transactions:
  - Copies of a modified fragment are only periodically updated. Different copies may get out of sync in the meantime.
  - More efficient than synchronized distribution transactions.
  - But users must be aware of data distribution.

Google Cloud Spanner

- Spanner: widely distributed database engine
  - General-purpose transactions (ACID)
  - SQL query language
  - Semi-relational data model
  - Scale to millions of machines
- Technical details:
  - Paxos replicated state machines
  - Adds a very accurate distributed clock to each process.
    - i.e., a global wall clock time, with bounded uncertainty.
    - make it possible to order transactions, and to guarantee consistent non-blocking reads.
  - Make use of two-phase commits

Spanner: Google's Globally-Distributed Database

James C. Corbett, Jeffrey Dean, Michael Epstein, Andrew Fikes, Christopher Frost, JJ Furman, Sanjay Ghemawat, Andrey Gubarev, Christopher Heiser, Peter Hochschild, Wilson Hsieh, Sebastian Kanthak, Eugene Kogan, Hongyi Li, Alexander Lloyd, Sergey Melnik, David Mwaura, David Nagle, Sean Quinlan, Rajesh Rao, Lindsay Rolig, Yasushi Saito, Michal Szymaniak, Christopher Taylor, Ruth Wang, Dale Woodford

Google, Inc.

Google Cloud Spanner

NoSQL databases

NoSQL

- Many of the new generation databases are referred to as NoSQL data stores.
    - e.g., HBase, Cassandra, MongoDB, Dynamo, etc.
    - NoSQL is rarely a useful term by itself.
- NoSQL data stores are typically designed for non-relational data.
- Requirements are often relaxed, which often allows to gain in efficiency and scalability.

[Q] What kind of NoSQL database system have we already covered?

NoSQL main features

- Horizontal scaling of simple operations throughput over many servers.
- Replication and to data distribution (partitioning) over many servers.
- A simple call level interface or protocol (in contrast to SQL).
- A weaker concurrency model than ACID transactions of most relational DBMSs.
- Efficient use of distributed indexes and RAM for data storage.
- The ability to dynamically add new attributes to data records.

Brewer's CAP theorem

- It is impossible for a distributed data store to simultaneously provide more than two out of the following three guarantees:
  - Consistency: Every read receives the most recent write or returns an error.
  - Availability: Every request receives a (non-error) response (without the guarantee that it contains the most recent write).
  - Partition tolerance: The system continues to operate despite a partition of the network.
- Note that in the absence of a network partition, both consistency and availability can be satisfied simultaneously.
- Relational DBMSs designed with traditional ACID guarantees often choose consistency over availability.

BASE

- NoSQL systems typically do not provide ACID guarantees.
- Instead, the characteristics of a NoSQL systems are defined in terms BASE properties, which favors availability over consistency:
  - Basically Available: The system is guaranteed to be available for querying by all users.
  - Soft state: The state of the system may change over time, even without input.
    - This is because of eventually consistency, see below.
  - Eventually consistent: The system will eventually become consistent with time, given that the system does not receive input during that time.
- BASE properties are much loser than ACID properties.

Taxonomy (1)

When studying a new NoSQL system, it is often worth considering how it differs from a relational DBMS in terms of:

- Concurrency control:
  - Locks:
    - Some systems provide one-user-at-a-time read or update locks.
  - Multiversion concurrency control
    - Guarantee a read-only consistent view
    - May result in multiple conflicting versions of an entity if concurrent writes.
  - No control:
    - Some systems do not provide atomicity.
    - Multiple users can edit in parallel a same entity.
    - No guarantee which version is read.
  - ACID:
    - Modern systems pre-analyze transactions to avoid conflicts.
      - No deadlocks and no wait on locks.

Taxonomy (2)

- Data storage medium:
  - Designed for storage in RAM:
    - Fast but not persistent.
    - Often requires snapshots or replication saved on disk.
    - Poor performance when RAM overflows.
  - Designed for disk storage:
    - Slow but persistent.
    - Often requires caching in RAM.
- Replication:
  - Whether mirror copies are always in sync.
  - Synchronous
    - Provides consistency, but usually slower.
  - Asynchronous
    - Provides only eventual consistency, but usually faster.

Taxonomy (3)

- Transaction mechanisms:
  - Supported.
  - Not supported.
  - In between:
    - E.g., only for local transactions.

Comparison

Table 1. System Comparison (grouped by category)

System	Conc Contol	Data Storage	Repli-cation	Tx
Redis	Locks	RAM	Async	N
Scalaris	Locks	RAM	Sync	L
Tokyo	Locks	RAM or disk	Async	L
Voldemort	MVCC	RAM or BDB	Async	N
Riak	MVCC	Plug-in	Async	N
Membrain	Locks	Flash + Disk	Sync	L
Membase	Locks	Disk	Sync	L
Dynamo	MVCC	Plug-in	Async	N
SimpleDB	None	S3	Async	N
MongoDB	Locks	Disk	Async	N
Couch DB	MVCC	Disk	Async	N
Terrastore	Locks	RAM+	Sync	L
HBase	Locks	Hadoop	Async	L
HyperTable	Locks	Files	Sync	L
Cassandra	MVCC	Disk	Async	L
BigTable	Locks+stamps	GFS	Sync+ Async	L
PNUTs	MVCC	Disk	Async	L
MySQL Cluster	ACID	Disk	Sync	Y
VoltDB	ACID, no lock	RAM	Sync	Y
Clustrix	ACID, no lock	Disk	Sync	Y
ScaleDB	ACID	Disk	Sync	Y
ScaleBase	ACID	Disk	Async	Y
NimbusDB	ACID, no lock	Disk	Sync	Y

From 2011. Many of those have already died, many other systems have appeared.

Data store categories

- Data stores are often grouped according to their data model.
- Key-value stores:
  - store key-value pairs.
  - e.g., Voldemort, Riak, Redis, Scalaris, Cabinet, Memcached, etc.
- Document stores:
  - store documents, which are indexed, with a simple query mechanism.
  - e.g., Amazon SimpleDB, CouchDB, MongoDB, Terrastore, etc.
- Extensible record stores:
  - store extensible records that can be partitioned vertically and horizontally across nodes.
  - e.g., HBase, HyperTable, Cassandra, etc.
- Relational databases:
  - store tuples, that are indexed and can be queried.
  - e.g., MySQL cluster, VoltDB, Clustrix, ScaleDB, etc.

RDBMS benefits

- Relational DBMSs have taken and retained majority market share over other competitors in the past 30 years.
- While no "one size fits all" in the SQL products, there is a common interface with SQL, transactions, and relational schema that give advantages in training, continuity, and data interchange.
- Successful relational DBMSs have been built to handle other specific application loads in the past:
  - read-only or read-mostly data warehousing, OLTP on multi-core multi-disk CPUs, in-memory databases, distributed databases, etc.

NoSQL benefits

- NoSQL may scale better than RDBMs.
- A NoSQL system is probably a better solution when:
  - one only requires a lookup of objects based on a single key.
  - the application requires a flexible schema.
- A relational DBMS usually make expensive operations easy to write.
  - On the other hand, a NoSQL system make them difficult for programmers.
- New systems are slowly gaining market shares, but still no clear winner.

[Q] What would you pick?

Case study: HBase

APACHE HBASE

- Apache HBase™ is the Hadoop database, a sparse, consistent, distributed, scalable, multi-dimensional sorted map.
- Why using HBase?
  - Open source
  - Distributed storage across cluster of machines
  - Random, online read and write data access
  - Schemaless data model (NoSQL)
  - Self-managed data partitions
- Based on Google's BigTable paper.

Logical data model

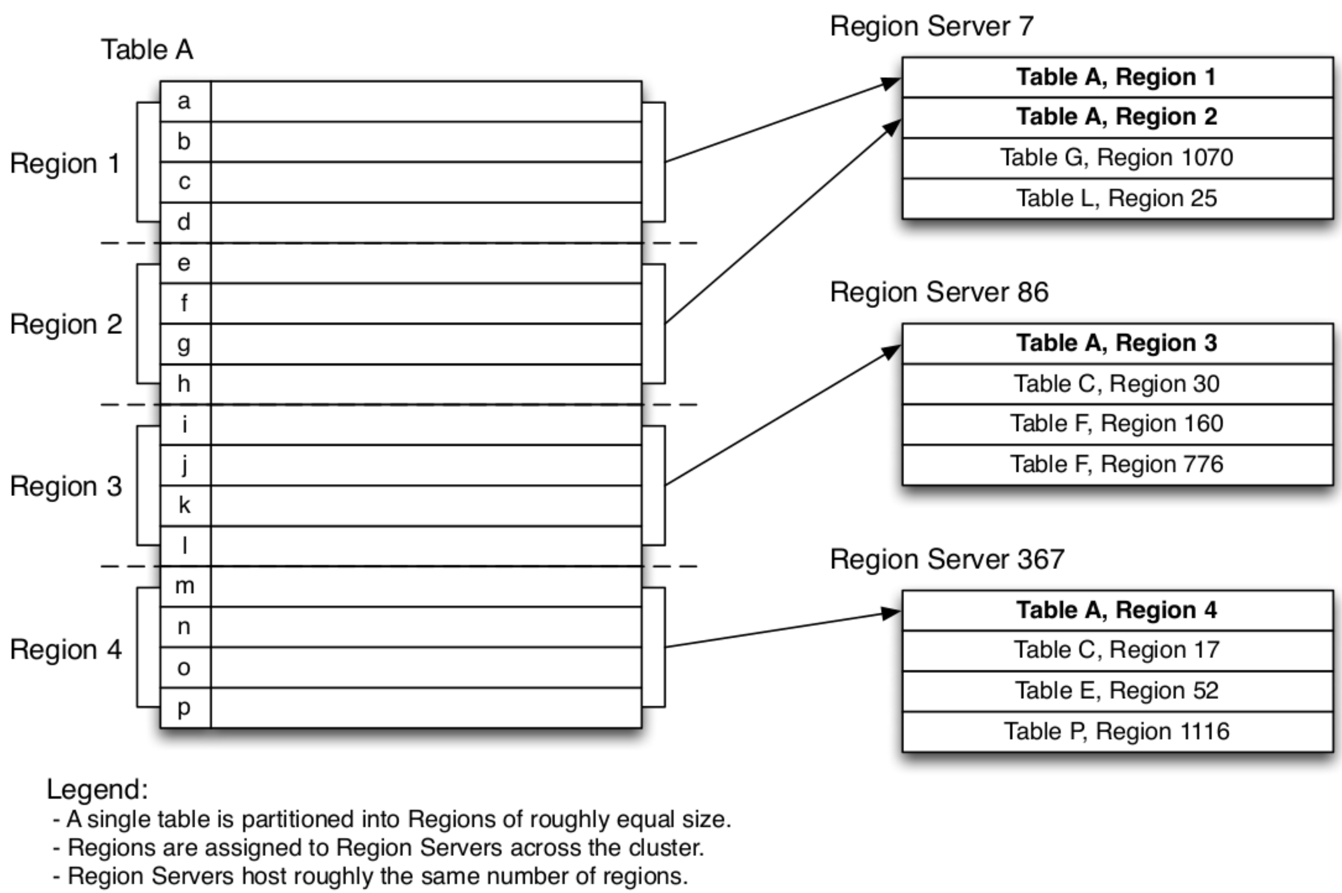
Table A

rowkey	column family	column qualifier	timestamp	value
a	cf1	"bar"	1368394583	7
			1368394261	"hello"
		"foo"	1368394583	22
			1368394925	13.6
			1368393847	"world"
	cf2	"2011-07-04"	1368396302	"fourth of July"
		1.0001	1368387684	"almost the loneliest number"
b	cf2	"thumb"	1368387247	[3.6 kb png data]

Legend:
- Rows are sorted by rowkey.
- Within a row, values are located by column family and qualifier.
- Values also carry a timestamp; there can me multiple versions of a value.
- Within a column family, data is schemaless. Qualifiers and values are treated as arbitrary bytes.

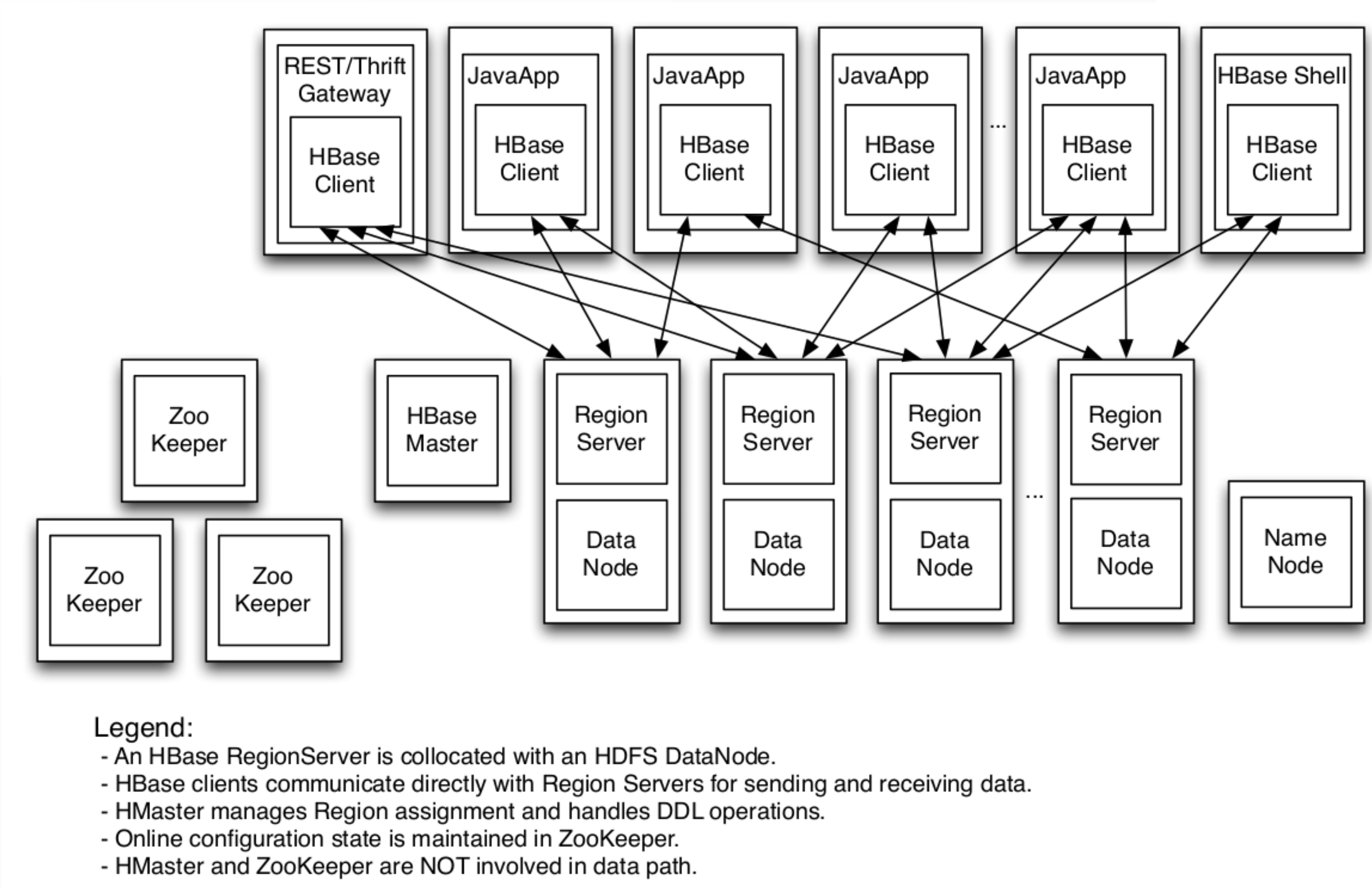
Credits: Nick Dimiduk, "HBase for architects".

Logical architecture



Credits: Nick Dimiduk, "HBase for architects".

Physical architecture



Credits: Nick Dimiduk, "HBase for architects".

When should you use HBase?

- HBase is good for:
  - Random access
  - Large datasets
  - Sparse datasets
  - Loosely coupled (denormalized) records
  - Lots of concurrent clients
- However, try avoid:
  - Sequential access
  - Small datasets
  - Highly relational records
  - Schema design requiring transactions

Credits: Nick Dimiduk, "HBase for architects".

Summary

- Relational databases can be distributed over many sites.
  - Fragmentation, allocation and replication are key considerations.
  - Distributed databases has consequences for:
    - query processing
    - transactions
- NoSQL databases trade off consistency for availability.
- RDBMs remain a strong and efficient technology.
- CAP theorem helps classify distributed data stores behavior choices.
- NoSQL databases have benefits over RDBMs, but this should be evaluated on a case by case basis.

References

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