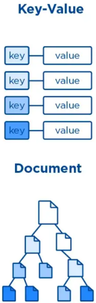
NoSQL Document Stores MongoDB CouchDB

Instructor: Dr. GP Saggese - gsaggese@umd.edu**
TAs: Krishna Pratardan Taduri, kptaduri@umd.edu Prahar Kaushikbhai Modi, pmodi08@umd.edu
with thanks to Prof. Alan Sussman Prof. Amol Deshpande Prof. Nguyen Vo (Utah State U.) Prof. Kathleen Durant (Northeastern U.)
v1.1

UMD DATA605 - Big Data Systems

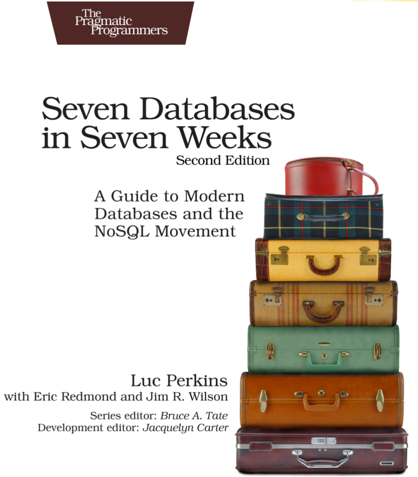
Key-Value Store vs Document DBs

- **Key-value stores**
  - Basically a map or a dictionary
    - E.g., HBase, Redis
  - Typically only look up values by key
    - Sometimes can do search in value field with a pattern
  - Uninterpreted value (e.g., binary blob) associated with a key
  - Typically one namespace for all key-values
- **Document DBs**
  - Collect sets of key-value pairs into *documents*
    - E.g., MongoDB, CouchDB
  - Documents represented in JSON, XML, or BSON (binary JSON)
  - Documents organized into *collections*
    - Similar to *tables* in relational DBs
    - Large collections can be partitioned and indexed



Resources

- All concepts in slides
- MongoDB tutorial
- Web
  - https://www.mongodb.com/
  - Official docs
  - pymongo
- Book
  - Seven Databases in Seven Weeks, 2e



MongoDB

- Developed by MongoDB Inc.
  - Founded in 2007
  - Based on DoubleClick experience with large-scale data
  - Mongo comes from "hu-mongo-us"
- One of the most used NoSQL DBs (if not the most used)
- **Document-oriented NoSQL database**
  - Schema-less
    - No Data Definition Language (DDL), like for SQL
    - You can store maps with any keys and values
    - Application tracks the schema, mapping between documents and their meaning
  - Keys are hashes stored as strings
    - Document Identifiers **_id** created for each document (field name reserved by Mongo)
  - Values use BSON format
    - Based on JSON (B stands for Binary)
- Written in C++
- Supports APIs (drivers) in many languages
  - E.g., JavaScript, Python, Ruby, Java, Scala, C++, ...

MongoDB: Example of Document

- **A document is a JSON data structure**
- It corresponds to a row in a relational DB
  - Without schema
  - Primary key is **_id**
  - Values nested to an arbitrary depth


```
{
   "_id" : ObjectId("4d0b6da3bb30773266f39fea"),
   "country" : {
      "$ref" : "countries",
      "$id" : ObjectId("4d0e6074deb8995216a8309e")
   },
   "famous_for" : [
      "beer",
      "food"
   ],
   "last_census" : "Sun Jan 07 2018 00:00:00 GMT -0700 (PDT)",
   "mayor" : {
      "name" : "Ted Wheeler",
      "party" : "D"
   },
   "name" : "Portland",
   "population" : 582000,
   "state" : "OR"
}
```

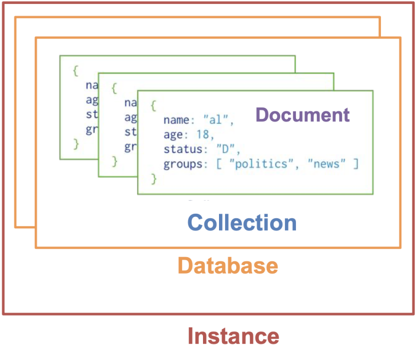

SCIENCE ACADEMY

MongoDB: Functionalities

- **Design goals**
  - Performance
  - Availability / scalability
  - Rich data storage (not rich querying!)
- **Dynamic schema**
  - No DDL (Data Definition Language)
  - Secondary indexes
  - Query language via an API
- **Several levels of data consistency**
  - E.g., atomic writes and fully-consistent reads (at document level)
- **No joins nor transactions across multiple documents**
  - Makes distributed queries easy and fast
- **High availability through replica sets**
  - E.g., primary replication with automated failover
- **Built-in sharding**
  - Horizontal scaling via automated range-based partitioning of data
  - Reads and writes distributed over shards

MongoDB: Hierarchical Objects

- A Mongo **instance** has:
  - Zero or more "databases"
  - Mongo instance ~ Postgres instance
- A Mongo **database** has:
  - Zero or more "collections"
    - Mongo collection ~ Postgres tables
  - Mongo database ~ Postgres database
- A Mongo **collection** has:
  - Zero or more "documents"
    - Mongo document ~ Postgres rows
- A Mongo **document** has:
  - One or more "fields"
    - It has always primary key _id
    - Mongo field ~ Postgres columns



From
https://www.mongodb.com/docs/manual/core/data-modeling-introduction

Relational DBs vs MongoDB: Terms and Concepts

RDBMS Concept	MongoDB Concept	Meaning in MongoDB
database	database	Container for collections
relation / table / view	collection	Group of documents
row / instance	document	Group of fields
column / attribute	field	A name-value pair
index	index	Automatic
primary keys	_id field	Always the primary key
foreign key	reference	Pointers
table joins	embedded documents	Nested name-value pairs

```
{
   "_id" : ObjectId("4d0b6da3bb30773266f39fea"),
   "country" : {
      "$ref" : "countries",
      "$id" : ObjectId("4d0e6074deb8995216a8309e")
   },
   "famous_for" : [
      "beer",
      "food"
   ],
   "last_census" : "Sun Jan 07 2018 00:00:00 GMT -0700 (PDT)",
   "mayor" : {
      "name" : "Ted Wheeler",
      "party" : "D"
   },
   "name" : "Portland",
   "population" : 582000,
   "state" : "OR"
}
```

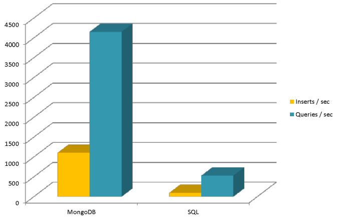
SCIENCE
ACADEMY

Relational vs Document DB: Workflows

- **Relational DBs**
  - E.g., PostgreSQL
  - Know what you want to store
    - Tabular data
  - Do not know how to use it
    - Static schema allows query flexibility (e.g., joins)
  - Complexity is at insertion time
    - Decide how to represent the data (i.e., schema)
- **Document DBs**
  - E.g., MongoDB
  - No assumptions on what to store
    - E.g., irregular JSON data
  - Know a bit how to access data
    - You want to access the data by key
    - E.g., it's a nested key-value map
  - Complexity is at access time
    - Get the data from the server
    - Process data on the client side

Why Use MongoDB?

- Simple to query
  - Do the work on client side
- It's fast
  - 2-10x faster than Postgres
- Data model / functionalities suitable for most web applications
  - Semi-structured data
  - Quickly evolving systems
- Easy and fast integration of data
- Not well suited for heavy and complex transactions systems
  - E.g., banking system



SCIENCE ACADEMY

MongoDB: Data Model

- **Documents** are composed of field and value pairs
  - **Field names** are strings
  - **Values** are any BSON type
    - Arrays of documents
    - Native data types
    - Other documents
- E.g.,
  - _id holds an ObjectId
  - name holds a document that contains the fields first and last
  - birth and death are of Date type
  - contribs holds an array of strings
  - views holds a value of the NumberLong type

MongoDB: Data Model

- Documents can be nested
  - Embedded sub-document
- **Denormalized data models**
  - Store multiple related pieces of information in the same record
  - Conceptually is the result of a join operation
- **Normalized data models**
  - Eliminate duplication
  - Represent many-to-many relationships

```
{
  _id: <ObjectId1>,
  username: "123xyz",
  contact: {
              phone: "123-456-7890",
              email: "xyz@example.com"
            },
  access: {
             level: 5,
             group: "dev"
           }
}
```

Embedded sub-document

Embedded sub-document

user document

```
{
  _id: <ObjectId1>,
  username: "123xyz"
}
```

contact document

```
{
  _id: <ObjectId2>,
  user_id: <ObjectId1>,
  phone: "123-456-7890",
  email: "xyz@example.com"
}
```

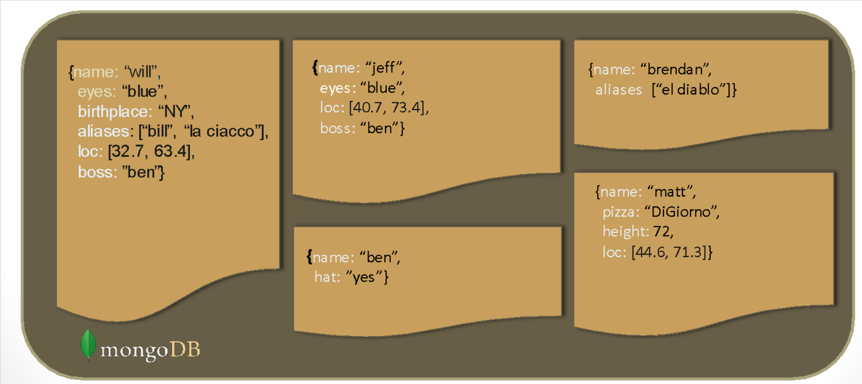
access document

```
{
  _id: <ObjectId3>,
  user_id: <ObjectId1>,
  level: 5,
  group: "dev"
}
```

Schema Free

- MongoDB does not need any pre-defined data schema
- Every **document** in a **collection** can have different fields and values
  - No need for NULL values / union of fields like in relational DBs
- E.g., dishomogeneous data instances

Document **Document** **Collection**



JSON Format

- JSON = JavaScript Object Notation
- Data is stored in field / value pairs
- A field / value pair consists of:
  - A field name (always a string)
  - Followed by a colon :
  - Followed by a typed value "name": "R2-D2"
- **Data in documents is separated by commas ,**

  "name": "R2-D2", race : "Droid"

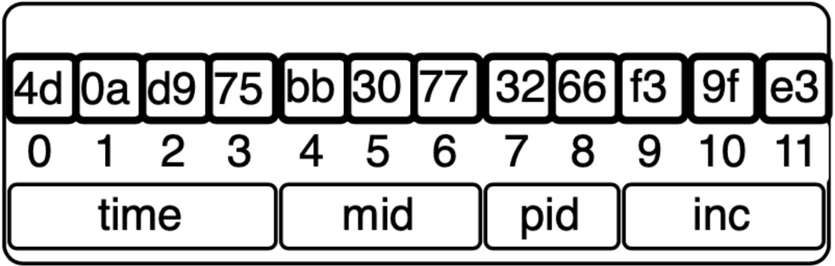
- Curly braces {} hold documents {"name": "R2-D2", race : "Droid", affiliation: "rebels"}
- An array is stored in brackets [] [{"name": "R2-D2", race: "Droid", affiliation: "rebels"}, {"name": "Yoda", affiliation: "rebels"}]
- Supports:
  - Embedding of nested objects within other objects
  - Just references

BSON Format

- Binary-encoded serialization of JSON-like documents
  - https://bsonspec.org
- Zero or more key/value pairs are stored as a single entity
  - Each entry consists of:
    - a field name (string)
    - a data type
    - a value
- Similar to Protocol Buffer, but more schema-less
- Large elements in a BSON document are prefixed with a length field to facilitate scanning
- MongoDB understands the internals of BSON objects, even nested ones
  - Can build indexes and match objects against query expressions for BSON keys

ObjectID

- Each JSON data contains an _id field of type ObjectId
  - Same as a SERIAL constraint incrementing a numeric primary key in PostgreSQL
- An ObjectId is 12 bytes, composed of:
  - a timestamp
  - client machine ID
  - client process ID
  - a 3-byte auto-incremented counter
- Each Mongo process can handle its own ID generation without colliding
  - Mongo has a distributed nature
- Details here



Indexes

- **Primary index**
    - Automatically created on the _id field
    - B+ tree indexes
- **Secondary index**
- Users can create secondary indexes to:
    - Improve query performance
    - Enforce unique values for a particular field
- Single field index and compound index (like SQL)
    - Order of the fields in a compound index matters
- Sparse property of an index
    - The index contains only entries for documents that have the indexed field
    - Ignore records that do not have the field defined
- Reject records with duplicate key value if an index is unique and sparse
- Details at https://www.mongodb.com/docs/manual/indexes/

CRUD Operations

- CRUD = Create, Read, Update, Delete
- **Create** **db.collection.insert(<document>)**
  db.collection.update(<query>, <update>, upsert: true) Upsert = update (if exists) or insert (if it doesn't)
- **Read** **db.collection.find(<query>, <projection>)**
  db.collection.findOne(<query>, <projection>)
- **Update** **db.collection.update(<query>, <update>, <options>)**
- **Delete** **db.collection.remove(<query>, <justOne>)** Details at
  https://www.mongodb.com/docs/manual/crud/

Create Operations

- **db.collection** specifies the collection (like an SQL table) to store the document **db.collection.insert(<document>)**
  - Without **_id** field, MongoDB generates a unique key **db.parts.insert(type: "screwdriver", quantity: 15)**
  - Use **_id** field if it has a special meaning **db.parts.insert(_id: 10, type: "hammer", quantity: 1)**
- Update 1 or more records in a collection satisfying **query** **db.collection.update(<query>, <update>, upsert: true)**
- Update an existing record or create a new record **db.collection.save(<document>)**
- A more modern OOP-like syntax than the COBOL / FORTRAN-inspired SQL

Read Operations

- **find** provides functionality similar to **SQL SELECT** command
  db.collection.find(<query>, <projection>).cursor with:
  - = WHERE condition
  - = fields in result set
- **db.parts.find(parts: "hammer").limit(5)**
  - Return cursor to handle a result set
  - Can modify the query to impose limits, skips, and sort orders
  - Can specify to return the ‘top’ number of records from the result set
- **db.collection.findOne(<query>, <projection>)**

More Query Examples

- Mongo has a functional programming flavor
  - E.g., composing operators, like \textcolor{red}{$or}

SQL

```
SELECT * FROM users WHERE age>33

SELECT * FROM users WHERE age!=33

SELECT * FROM users WHERE name
LIKE "%Joe%"

SELECT * FROM users WHERE a=1 and b='q'

SELECT * FROM users WHERE a=1 or b=2

SELECT * FROM foo
WHERE name='bob' and (a=1 or b=2 )

SELECT * FROM users
WHERE age>33 AND age<=40
```

Mongo

```
db.users.find({age: {$gt: 33}})

db.users.find({age: {$ne: 33}})

db.users.find({name: /Joe/})

db.users.find({a: 1, b: 'q'})

db.users.find({$or: [{a: 1}, {b: 2}]})

db.foo.find({name: "bob",
$or: [{a: 1}, {b: 2}]})

db.users.find({'age':
{$gt: 33, $lte: 40}})
```

SCIENCE ACADEMY

Query Operators

Command	Description
$regex	Match by any PCRE-compliant regular expression string (or just use the // delimiters as shown earlier)
$ne	Not equal to
$lt	Less than
$lte	Less than or equal to
$gt	Greater than
$gte	Greater than or equal to
$exists	Check for the existence of a field
$all	Match all elements in an array
$in	Match any elements in an array
$nin	Does not match any elements in an array
$elemMatch	Match all fields in an array of nested documents
$or	or
$nor	Not or
$size	Match array of given size
$mod	Modulus
$type	Match if field is a given datatype
$not	Negate the given operator check

Update Operations

- db.collection.insert(<document>)
  - Omit the _id field to have MongoDB generate a unique key
  - db.parts.insert(type: "screwdriver", quantity: 15)
  - db.parts.insert(_id: 10, type: "hammer", quantity: 1)
- db.collection.save(<document>)
  - Updates an existing record or creates a new record
- db.collection.update(<query>, <update>, upsert: true)
  - Will update 1 or more records in a collection satisfying query
- db.collection.findAndModify(<query>, <sort>, <update>, <new>, <fields>, <upsert>)
  - Modify existing record(s)
  - Retrieve old or new version of the record

Delete Operations

- **db.collection.remove(<query>, <justone>)**
  - Delete all records from a collection or matching a criterion
  - **<justone>** specifies to delete only 1 record matching the criterion
- Remove all records in **parts** with **type** starting with h
  - **db.parts.remove(type: /h/)**
- Delete all documents in the **parts** collection
  - **db.parts.remove()**

SCIENCE ACADEMY

MongoDB Features

- Document-oriented NoSQL store
- Rich querying
  - Full index support (primary and secondary)
- Fast in-place updates
- Agile and scalable
  - Replication and high availability
  - Auto-sharding
  - Map-reduce functionality
- Scale horizontally over commodity hardware
  - Horizontally = add more machines
  - Commodity hardware = relatively inexpensive servers

MongoDB vs Relational DBs

- Keep the functionality that works well in RDBMSs
    - Ad-hoc queries
    - Fully featured indexes
    - Secondary indexes
- Do not offer RDBMS functionalities that don't scale up
    - Long running multi-row transactions
    - ACID consistency
    - Joins

MongoDB Tutorial

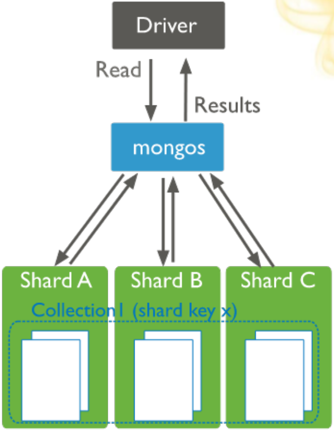
Tutorial is at GitHub The instructions are here:

```
> cd $GIT\_REPO/tutorials/tutorial\_mongodb
```

```
> vi tutorial\_mongo.md
```

MongoDB Processes and Configuration

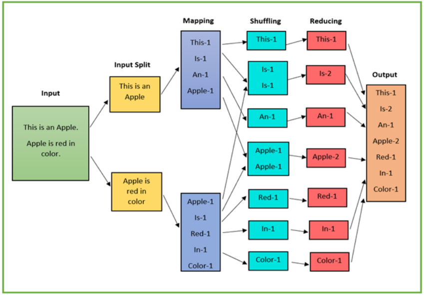
- **mongod**: database instance (i.e., a server process)
- **mongosh**: interactive shell (i.e., a client)
  - Fully functional JavaScript environment for use with a MongoDB
- **mongos**: database router
  - Process all requests
  - Decide how many and which **mongod** instances should receive the query (sharding / partitioning)
  - Collate the results
  - Send result back to the client
- You should have:
  - One **mongos** (router) for the whole system no matter how many **mongod**s you have; or
  - One local **mongos** for every client if you wanted to minimize network latency

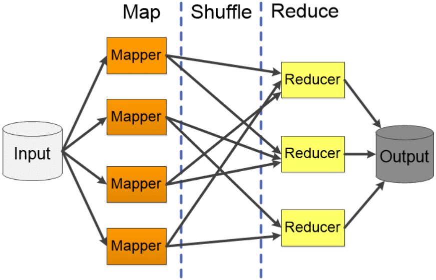


MapReduce Functionality

- Perform map-reduce computation given a collection of (keys, value) pairs
- Must provide at least a map function, reduction function, and the name of the result set

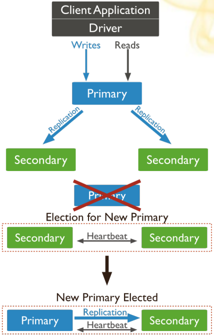
```
db.collection.mapReduce(
<map\_function>,
<reduce\_function>,
{
out: <collection>,
query: <document>,
sort: <document>,
limit: <number>,
finalize: <function>,
scope: <document>,
jsMode: <boolean>,
verbose: <boolean>
```





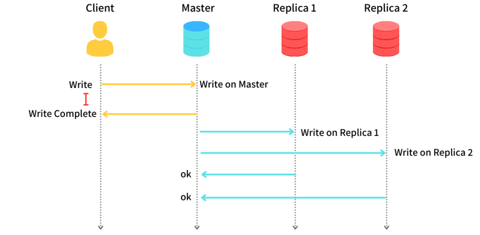
Data Replication

- **Data replication** ensure:
  - Redundancy
  - Backup
  - Automatic failover
- Replication occurs through groups of servers known as **replica sets**
  - **Primary set**: set of servers that client asks direct updates to
  - **Secondary set**: set of servers used for duplication of data
  - Different properties can be associated with a secondary set,
    - E.g., secondary-only, hidden delayed, arbiters, non-voting
- If the primary fails the secondary sets "vote" to elect the new primary set

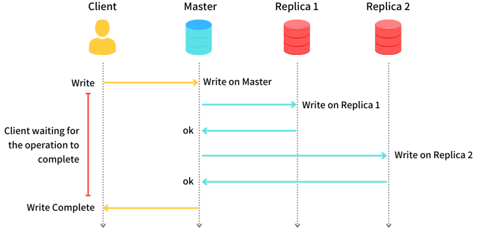


Sync vs Async Replication

- **Synchronous replication**: updates are propagated to other replicas as part of a single transaction
- Implementations
  - 2-Phase Commit (2PC)
  - Paxos
  - Both solutions are complex / expensive
- **Asynchronous replication**
  - The primary node propagates updates to replicas
  - The transaction is completed before replicas are updated (even if there are failures)
  - Commits are quick at cost of consistency



Asynchronous Replication



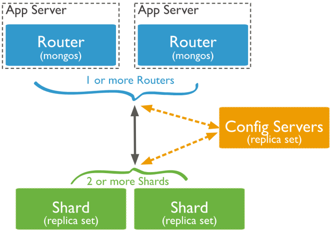
Synchronous Replication

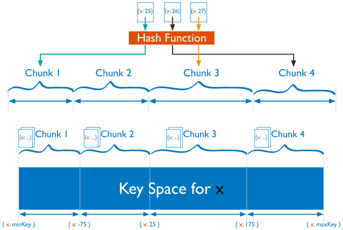
Data Consistency

- **Client decides how to enforce consistency for reads**
- Reads to a primary have **strict consistency**
  - Reads reflect the latest changes to the data
  - All writes and *consistent* reads go to the primary
- Reads to a secondary have **eventual consistency**
  - Updates propagate gradually
  - Client may read a previous state of the database
  - All *eventually consistent* reads are distributed among the secondaries

MongoDB: Sharding

- **Shard** = subset of data
  - A collection is split in pieces based on the shard key
  - Data distributed based on shard key or intervals [a, b)
- **Sharding** = method for distributing data across different machines
- **Horizontal scaling** can be achieved through sharding
  - Divide data and workload over multiple servers
  - Complexity in infrastructure and maintenance
- **mongos** acts as a query router interfacing clients and sharded cluster
  - Each shard can be deployed as a replica set
  - Config servers store metadata and configuration settings for cluster





SCIENCE ACADEMY

RDMBS Internals

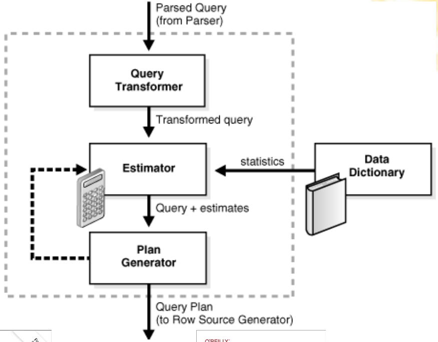
Storage hierarchy - How are tables mapped to files? - How are tuples mapped to disk blocks?

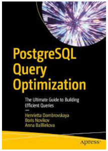
Buffer Manager - Bring pages from disk to memory - Manage the limited memory

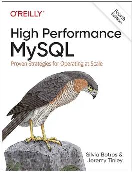
Query Processing Engine - Given a user query, decide how to "execute" it - Specify sequence of pages to be brought in memory - Operate upon the tuples to produce results

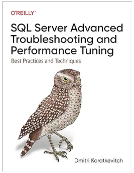
Query Optimizer

- **RDBMSs: query optimizer is static**
  - Assign a cost to each query plan
  - Estimate some cost params (e.g., time to access data)
  - Search for the best query
  - At least traditional RDBMs



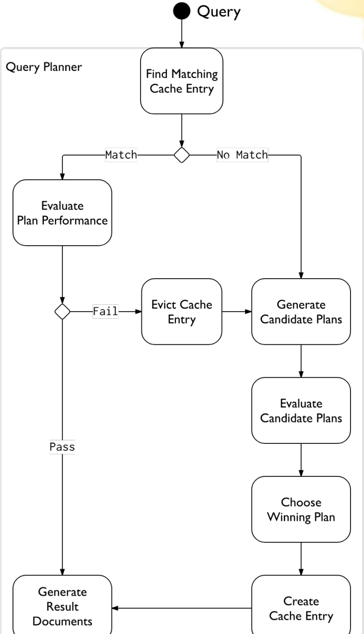






Query Optimizer

- **MongoDB: query optimizer is dynamic**
  - Try different query plans and learn which ones perform well
  - The space of query plans is not so large, because there are no joins
  - When testing new plans
    - Execute multiple query plans in parallel
    - As soon as one plan finishes, terminate the other plans
  - Cache the result
  - If a plan that was working well starts performing poorly try again different plans
    - E.g, data in the DB has changed, parameter values to a query are different

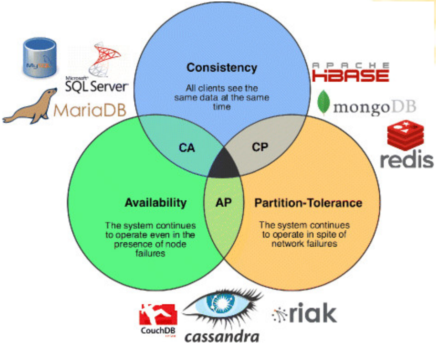


MongoDB: Strengths

- Provide a flexible and modern query language
- High-performance
  - Implemented in C++
- Very rapid development, open source
  - Support for many platforms
  - Many language drivers
- Built to address a distributed database system
  - Sharding
  - Replica sets of data
- Tunable consistency
- Useful for working with a huge quantity of data not requiring a relational model
  - The relationships between the elements does not matter
  - What matters is the ability to store and retrieve great quantities of data

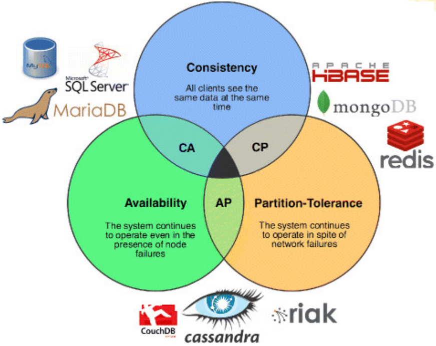
MongoDB: Limitations

- No referential integrity
  - Aka foreign key constraint
- Lack of transactions and joins
- High degree of denormalization
  - Need to update data in many places instead of one
- Lack of predefined schema is a double- edged sword
  - You must have a data model in your application
  - Objects within a collection can be completely inconsistent in their fields
- CAP Theorem: targets consistency and partition tolerance, giving up on availability



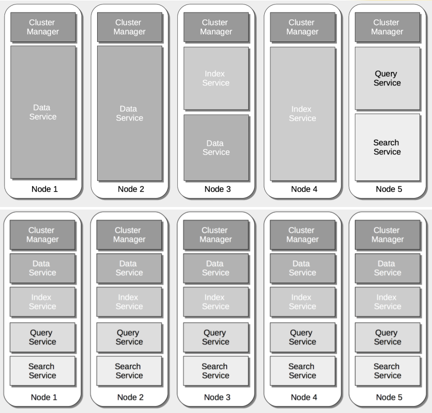
Couchbase

- NoSQL document-oriented DB (like MongoDB)
- Couchbase = merge of CouchDB and membase
  - *CouchDB*
    - Open source document store
    - HTTP RESTful API to add, update, delete documents
    - Support all 4 ACID properties
  - *membase*
    - Distributed key-value store (like Redis)
    - Designed to scale both up and down
    - Highly available and partition tolerant
  - Uses HTTP protocol to query and interact with objects in the DB
    - No query language
  - Objects stored in *buckets*
    - Collection of JSON docs, with no special relation to



Architecture

- Every Couchbase node consists of **different services**:
  - Data service
  - Index service
  - Query service
  - Cluster manager component
- Services can run on separate nodes of the cluster, if needed
- **Data replication**
  - Across nodes of a cluster
  - Across data centers
- **Data service**
  - Writes data *asynchronously* to disk after acknowledging to the client
  - Optionally *synchronous:* ensure data is written to more than one server before acknowledging a write



SCIENCE ACADEMY

Queries

- **Can create multiple views over documents**
  - Views are optimized / indexed by Couchbase for fast queries
  - Re-indexed when underlying documents changes
  - Can do full-text searches using the indexes
- **Perform well when:**
  - There are infrequent changes to the structure of documents
  - Know in advance what kinds of queries you want to execute
- **Query**
  - Uses a custom query language called N1QL ("nickel")
  - Extends SQL to JSON documents
  - Queries over multiple documents using (server-side) joins
- **Map-reduce support**
  - (Map) First define a view with the columns of the document your are interested in
  - (Reduce) Optionally define aggregate functions over the data