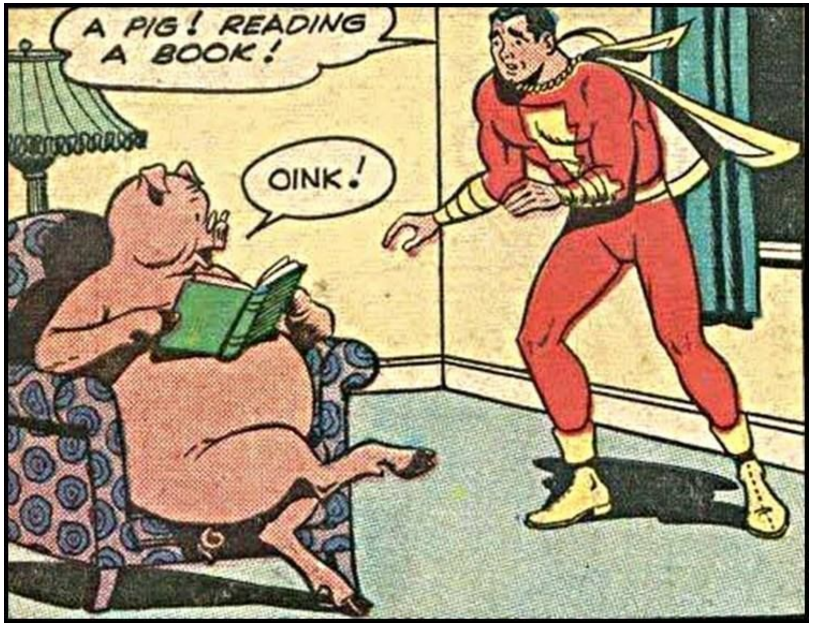
NoSQL
Document Databases

Weekend outage.

Problem Set #5 is
due on Tuesday

Problem Set #3 is graded and
should be posted by Thursday



NoSQL Databases and Data Types

1. Document databases
   - Structured text data - Hierarchical tree data structures
     - typically JSON, XML

2. Key-value stores:
   - Can store any (text or binary) data
     - often, if using JSON data, additional functionality is available

3. Columnar stores
   - Rows that have many columns associated with a row key
     - can be written as JSON

Unstructured Data Formats

- Binary Data
  - often, we want to store objects (class instances)
  - objects can be binary serialized (marshalled)
    - and kept in a key-value store
  - there are several popular serialization formats
    - Protocol Buffers, Apache Thrift
- Structured Text Data
  - JSON, BSON (Binary JSON)
    - JSON is currently number one data format used on the Web
  - XML: eXtensible Markup Language
  - RDF: Resource Description Framework

JSON: Basic Information

- Text-based open standard for data interchange
  - Serializing and transmitting structured data
- JSON = JavaScript Object Notation
  - Originally specified by Douglas Crockford in 2001
  - Derived from JavaScript scripting language
  - Uses conventions of the C-family of languages
- Filename: *.json
- Internet media (MIME) type: application/json
- Language independent

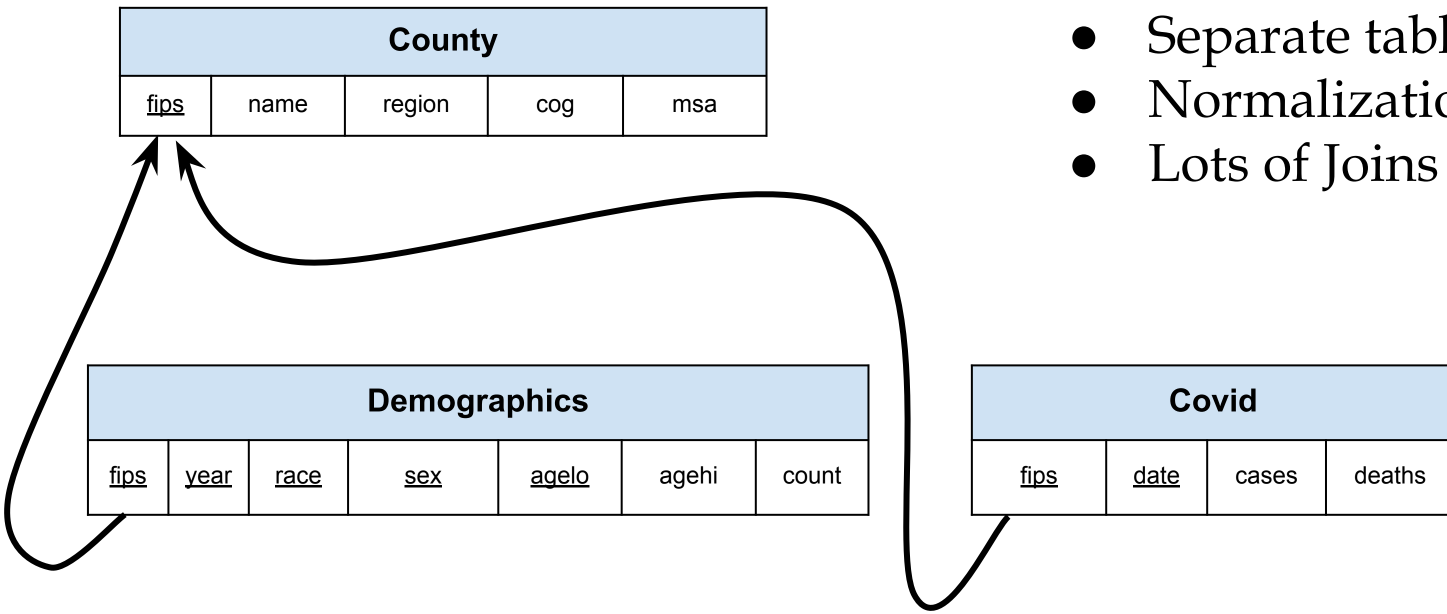
http://www.json.org

JSON:Example

A "list" of documents, that contains key-value pairs (dictionary) and lists of subdocuments.
Realated data is "localized"

```
[{
    "_id": 6059,
    "population": 3175692,
    "name": "Orange County",
    "state": "CA",
    "deaths": [{"date": "2020-03-27", "count": 1}, {"date": "2020-04-02", "count": 1},
               {"date": "2020-04-05", "count": 2}, {"date": "2020-04-07", "count": 1},
               {"date": "2020-10-26", "count": 1}, {"date": "2020-10-27", "count": 5},
               {"date": "2020-10-28", "count": 2}],
    "cases":  [{"date": "2020-01-26", "count": 1}, {"date": "2020-03-04", "count": 2},
               {"date": "2020-03-09", "count": 2}, {"date": "2020-03-11", "count": 1},
               {"date": "2020-10-26", "count": 152}, {"date": "2020-10-27", "count": 255},
               {"date": "2020-10-28", "count": 233}]
},
{
    "_id": 38019,
    "name": "Cavalier County",
    "state": "ND",
    "population": 3762,
    "deaths": [{"date": "2020-03-27", "count": 1}, {"date": "2020-04-02", "count": 1},
               {"date": "2020-04-05", "count": 2}, {"date": "2020-04-07", "count": 1},
               {"date": "2020-10-26", "count": 1}, {"date": "2020-10-27", "count": 5},
               {"date": "2020-10-28", "count": 2}],
    "cases":  [{"date": "2020-06-20", "count": 1}, {"date": "2020-06-22", "count": 1},
               {"date": "2020-07-02", "count": 1}, {"date": "2020-07-05", "count": 1},
               {"date": "2020-10-25", "count": 3}, {"date": "2020-10-27", "count": 1},
               {"date": "2020-10-28", "count": 3}]
}]
```

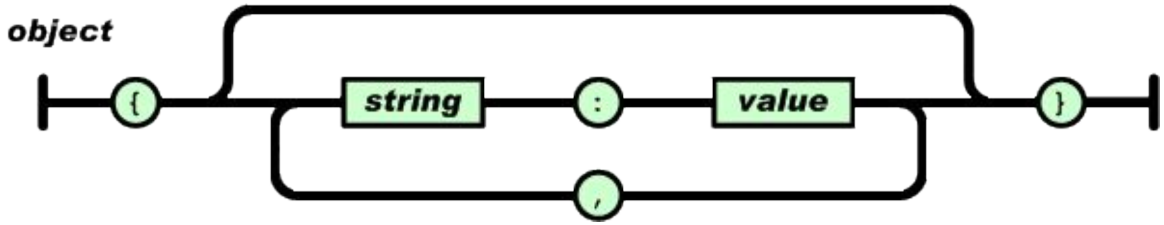
Compared to a Relational DB



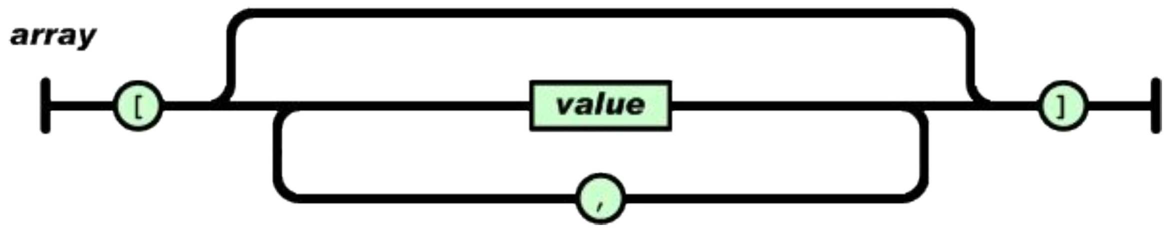
- Separate tables
- Normalization
- Lots of Joins

JSON: Data Types (1)

- object – an unordered set of name+value pairs
  - these pairs are called properties (members) of an object
  - syntax: { name: value, name: value, name: value, ...}

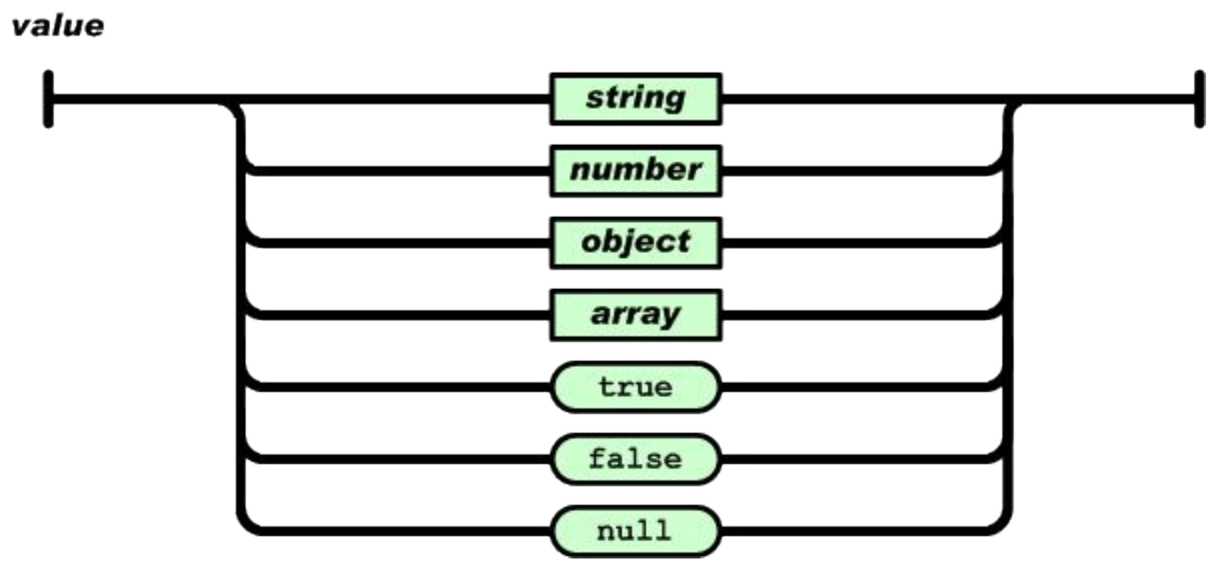


- array – an ordered collection of values (elements)
  - syntax: [comma-separated values]



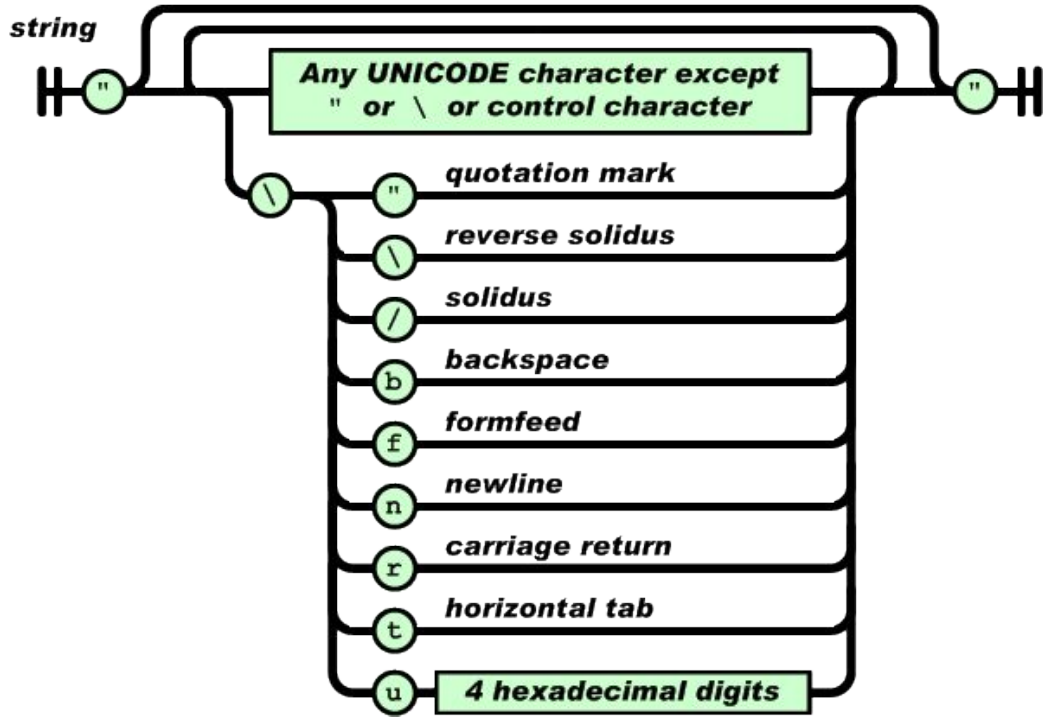
JSON: Data Types (2)

- value – string in double quotes / number / true or false (i.e., Boolean) / null / object / array



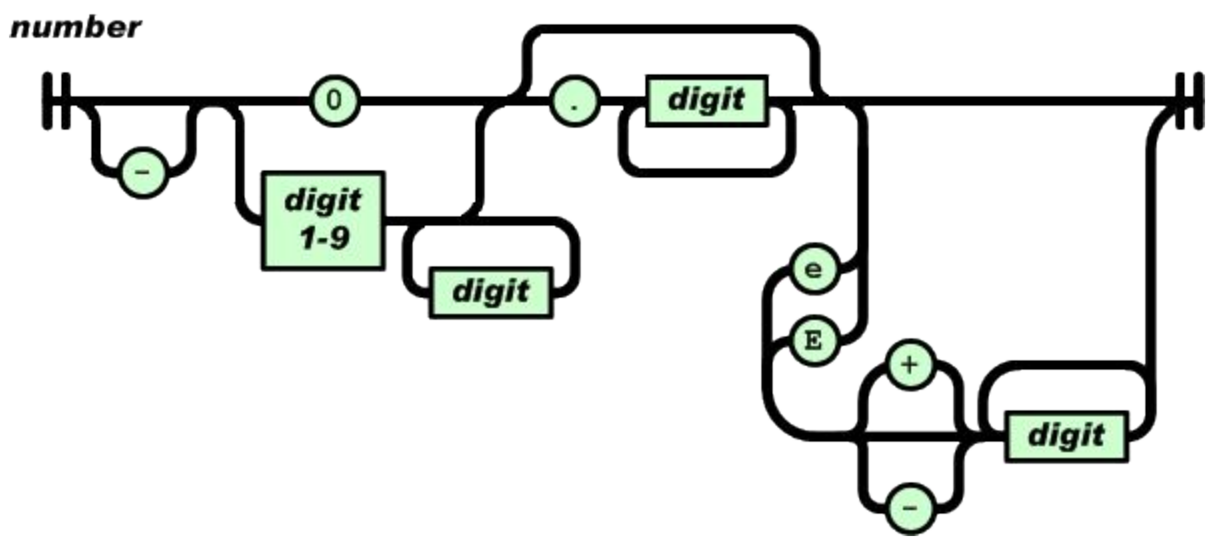
JSON: Data Types (3)

- string – sequence of zero or more Unicode characters, wrapped in double quotes
  - Backslash escaping



JSON: Data Types (4)

- number – like a C, Python, or Java number
  - Integer or float
  - Octal and hexadecimal formats are not used



JSON Properties

- There are no comments in JSON
  - Originally, there was but they were removed for security
- No way to specify precision/size of numbers
  - It depends on the parser and the programming language
- There exists a standard "JSON Schema"
  - A way to specify the schema of the data
  - Field names, field types, required/optional fields, etc.
  - JSON Schema is written in JSON, of course
    - see example below

JSON Schema: Example

```
{
  "$schema": "http://json-schema.org/schema#",
  "type": "object",
  "properties": {
    "conferences": {
      "type": "array",
      "items": {
        "type": "object",
        "properties": {
          "name": { "type": "string" },
          "start": { "type": "string", "format": "date" },
          "end": { "type": "string", "format": "date" },
          "web": { "type": "string" },
          "price": { "type": "number" },
          "currency": { "type" : "string",
                "enum": ["CZK", "USD", "EUR", "GBP"] },
          "topics": {
            "type": "array",
            "items": {
              "type": "string"
            }
          },
```

```
          "venue": {
            "type": "object",
            "properties": {
              "name": { "type": "string" },
              "location": {
                "type": "object",
                "properties": {
                  "lat": { "type": "number" },
                  "lon": { "type": "number" }
                }
              }
            },
            "required": ["name"]
          }
        },
        "required": ["name", "start", "end",
                     "web", "price", "topics"]
      }
    }
  }
}
```

Document with JSON Schema

```json
{
  "conferences":
  [
    {
      "name": "XML Prague 2015",
      "start": "2015-02-13",
      "end": "2015-02-15",
      "web": "http://xmlprague.cz/",
      "price": 120,
      "currency": "EUR",
      "topics": ["XML", "XSLT", "XQuery", "Big Data"],
      "venue": {
        "name": "VŠE Praha",
        "location": {
          "lat": 50.084291,
          "lon": 14.441185
        }
      }
    },
    {
      "name": "DATAKON 2014",
      "start": "2014-09-25",
      "end": "2014-09-29",
      "web": "http://www.datakon.cz/",
      "price": 290,
      "currency": "EUR",
      "topics": ["Big Data", "Linked Data", "Open Data"]
    }
  ]
}
```

XML: Basic Information

- XML: eXtensible Markup Language
  - W3C standard (since 1996)
- Designed to be both human and machine readable
- example:

```xml
<?xml version="1.0"?>
<quiz>
 <qanda seq="1">
  <question>
   Who was the forty-second
   president of the U.S.A.?
  </question>
  <answer>
   William Jefferson Clinton
  </answer>
 </qanda>
 <!-- Note: We need to add
  more questions later.-->
</quiz>
```

XML

source: http://en.wikipedia.org/wiki/XML

XML: Features and Comparison

- Standard ways to specify XML document schema:
  - DTD, XML Schema, etc.
  - concept of Namespaces; XML editors (for given schema)
- Technologies for parsing: DOM, SAX
- Many associated technologies:
  - XPath, XQuery, XSLT (transformation)
- XML is good for configurations, meta-data, etc.
- XML databases are mature, not considered NoSQL
- Currently, JSON format rules:
  - compact, easier to write, meets most needs

NoSQL Document Databases

- Basic concept of data: *Document*
- Documents are self-describing pieces of data
  - Hierarchical tree data structures
  - Nested associative arrays (maps), collections, scalars
  - XML, JSON (JavaScript Object Notation), BSON, …
- Documents in a collection should be "similar"
  - Their schema can differ
- Often: Documents stored as values of key-value
  - Key-value stores where the values are examinable
  - Building search indexes on various keys/fields

Why Document Databases

- XML and JSON are popular for data exchange
  - Recently mainly JSON
- Data stored in document DB can be used directly

- Databases often store objects from memory
  - Using RDBMS, we must do Object Relational Mapping (ORM)
    - ORM is relatively demanding
  - JSON is much closer to structure of memory objects
    - It was originally for JavaScript objects
    - Object Document Mapping (ODM) is faster

Document Databases

mongoDB

Apache CouchDB relax

OrientDB

RAVENDB

terrastore

PostgreSQL

amazon DynamoDB

MS Azure DocumentDB

Example: MongoDB

- Initial release: 2009
  - Written in C++
  - Open-source
  - Cross-platform
- JSON documents

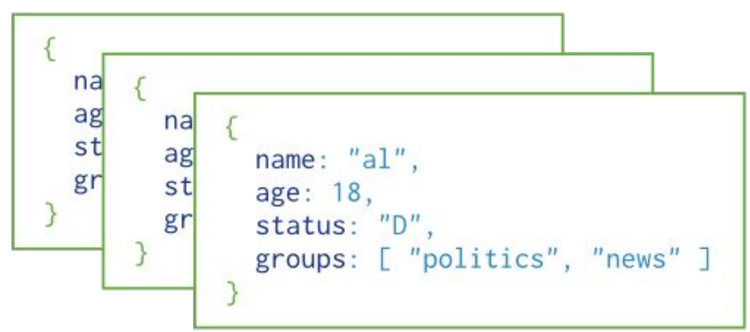
```
{
   name: "sue",                          ←— field: value
   age: 26,                              ←— field: value
   status: "A",                          ←— field: value
   groups: [ "news", "sports" ]          ←— field: value
}
```

- Basic features:
  - High performance – many indexes
  - High availability – replication + eventual consistency + automatic failover
  - Automatic scaling – automatic sharding across the cluster
  - MapReduce support

MongoDB: Terminology

RDBMS	MongoDB
database instance	MongoDB instance
schema	database
table	collection
row	document
rowid	_id

- each JSON document:
  - belongs to a collection
  - has a field _id
    - unique within the collection
- each collection:
  - belongs to a "database"



Collection

Documents

- Use JSON for API communication
- Internally: BSON
  - Binary representation of JSON
  - For storage and inter-server communication

- Document has a maximum size: 16MB (in BSON)
  - Not to use too much RAM
  - GridFS tool can divide larger files into fragments

Document Fields

- Every document must have field _id
  - Used as a primary key
  - Unique within the collection
  - Immutable
  - Any type other than an array
  - Can be generated automatically

- Restrictions on field names:
  - The field names cannot start with the $ character
    - Reserved for operators
  - The field names cannot contain the . character
    - Reserved for accessing sub-fields

Database Schema

- Documents have flexible schema
  - Collections do not enforce specific data structure
  - In practice, documents in a collection are similar

- Key decision of data modeling:
  - References vs. embedded documents

  - In other words: Where to draw lines between aggregates
    - Structure of data
    - Relationships between data

Schema: Embedded Docs

- Related data in a single document structure
  - Documents can have subdocuments (in a field or array)

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

Embedded sub-document (contact)

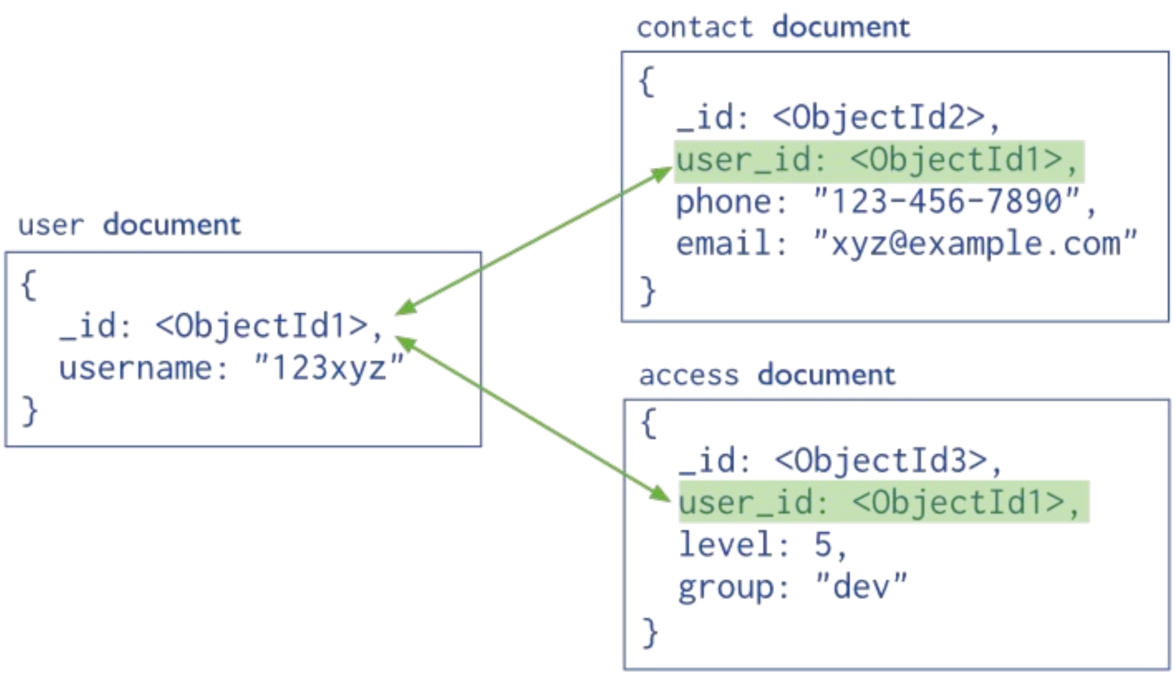
Embedded sub-document (access)

Schema: Embedded Docs (2)

- Denormalized schema
- Main advantage:
  Manipulate related data in a single operation
- Use this schema when:
  - One-to-one relationships: one doc "contains" the other
  - One-to-many: if children docs have one parent document
- Disadvantages:
  - Documents may grow significantly during the time
  - Impacts both read/write performance
    - Document must be relocated on disk if its size exceeds allocated space
    - May lead to data fragmentation on the disk

Schema: References

- Links/references from one document to another
- Normalization of the schema



Schema: References (2)

- More flexibility than embedding
- Use references:
  - When embedding would result in duplication of data
    - and only insignificant boost of read performance
  - To represent more complex many-to-many relationships
  - To model large hierarchical data sets
- Disadvantages:
  - Can require more roundtrips to the server
    - Documents are accessed one by one

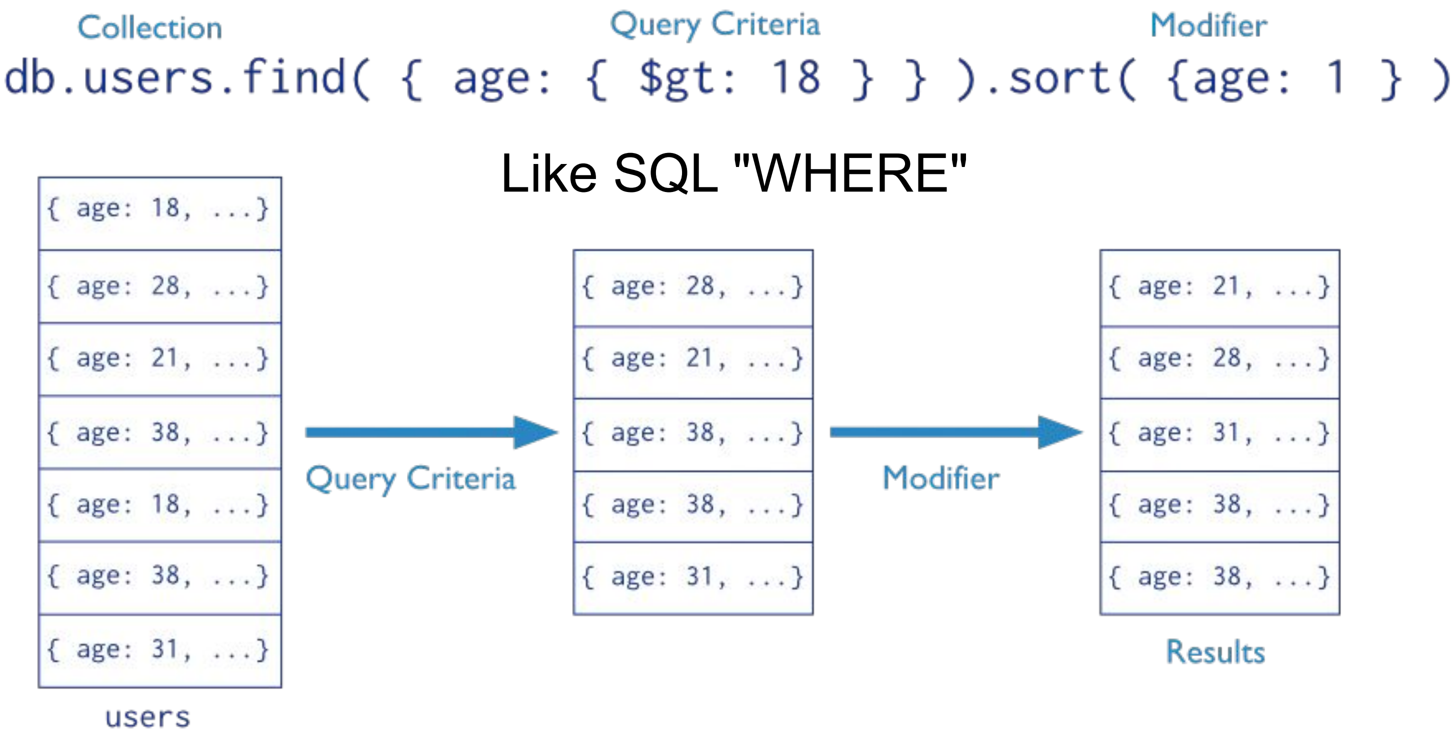
Querying: Basics

- Mongo query language
- A MongoDB query:
  - Targets a specific collection of documents
  - Specifies criteria that identify the returned documents
  - May include a projection to specify returned fields
  - May impose limits, sort, orders, …

- Basic query - all documents in the collection:

```
db.users.find()      -- Like SELECT *
db.users.find( {} )
```

Querying: Example



Querying: Selection

```
db.inventory.find({ type: "snacks" })
```

- All documents from collection inventory where the type field has the value snacks

```
db.inventory.find(
   { type: { $in: [ 'food', 'snacks' ] } } )
```

- All inventory docs where the type field is either food or snacks

```
db.inventory.find(
   { type: 'food', price: { $lt: 9.95 } } )
```

- All ... where the type field is food and the price is less than 9.95

Inserts

```
db.inventory.insert( { _id: 10, type: "misc",
item: "card", qty: 15 } )
```

- Inserts a document with three fields into collection inventory
  - User-specified _id field

```
db.inventory.insert(
    { type: "book", item: "journal" } )
```

- The database generates `_id` field

```
$ db.inventory.find()
{ "_id": ObjectId("58e209ecb3e168f1d3915300"),
type: "book", item: "journal" }
```

Updates

```
db.inventory.update(
    { type: "book", item : "journal" },
    { $set: { qty: 10 } },
    { upsert: true }  )
```

- Finds all docs matching query `{ type: "book", item : "journal" }`
- and sets the field `{ qty: 10 }`

- `upsert: true`
  - if no document in the inventory collection matches
  - creates a new document (generated _id)
    - it contains fields _id, type, item, qty

MapReduce

```
collection "accesses":
{
  "user_id": <ObjectId>,
  "login_time": <time_the_user_entered_the_system>,
  "logout_time": <time_the_user_left_the_system>,
  "access_type": <type_of_the_access>
}
```

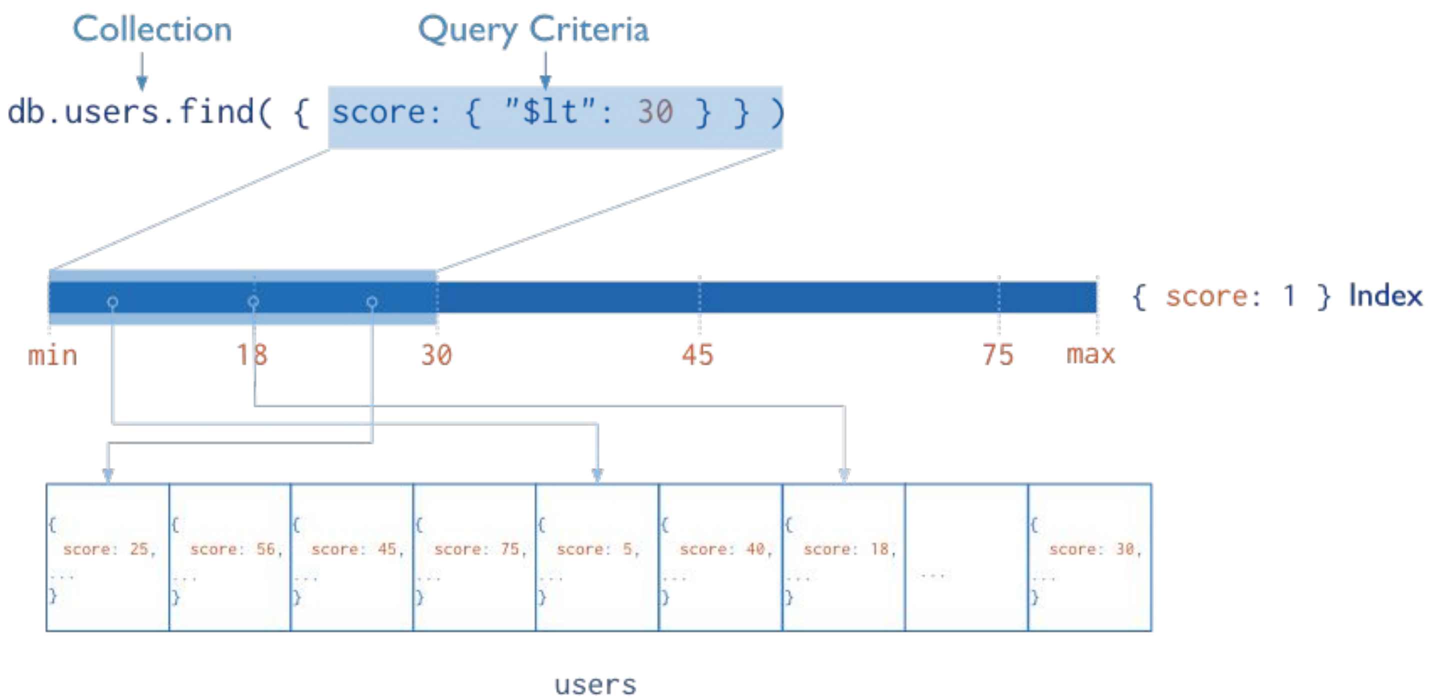
- How much time did each user spend logged in
  - Counting just accesses of type “regular”

```
db.accesses.mapReduce(
  function() { emit (this.user_id, this.logout_time - this.login_time); },
  function(key, values) { return Array.sum( values ); },
  {
    query: { access_type: "regular" },
    out: "access_times"
  }
)
```

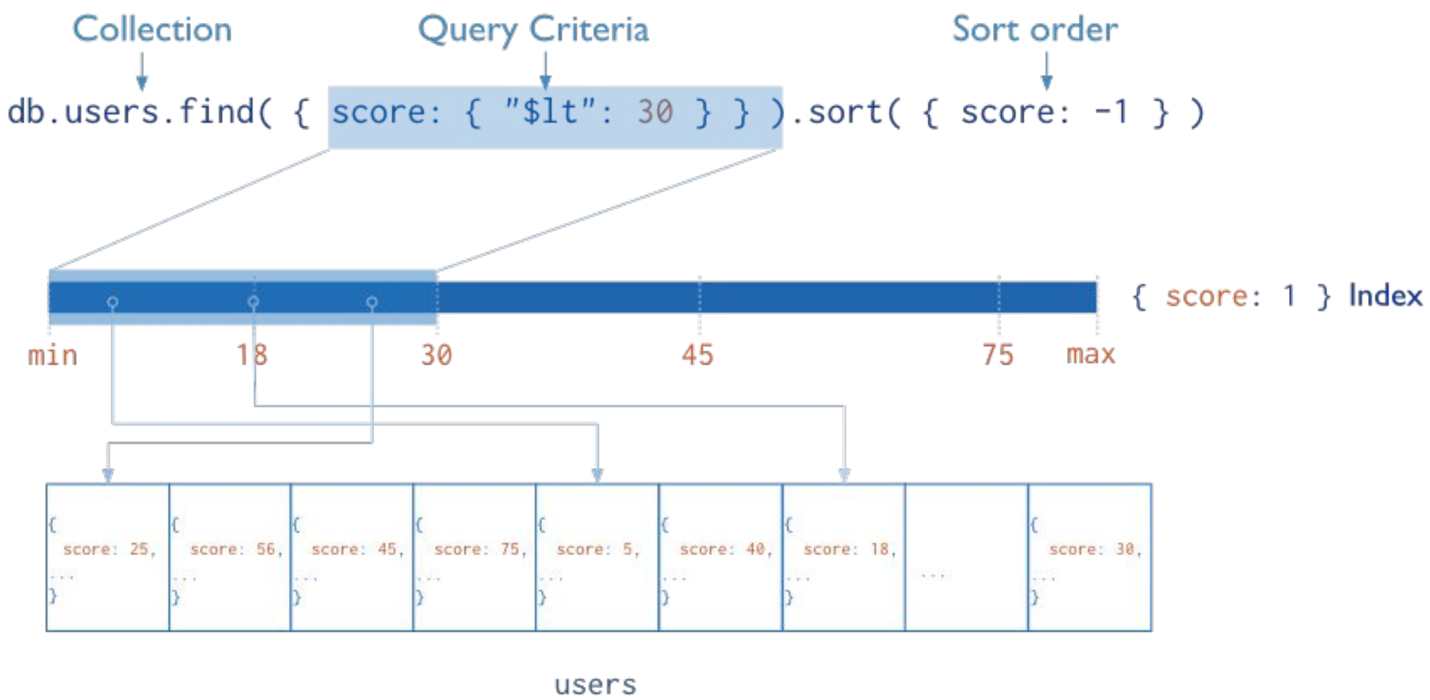
MongoDB Indexes

- Indexes are the key for MongoDB performance
  - Without indexes, MongoDB must scan every document in a collection to select matching documents
- Indexes store some fields in easily accessible form
  - Stores values of a specific field(s) ordered by the value
- Defined per collection
- Purpose:
  - To speed up common queries
  - To optimize performance of other specific operations

Indexes: Example of Use

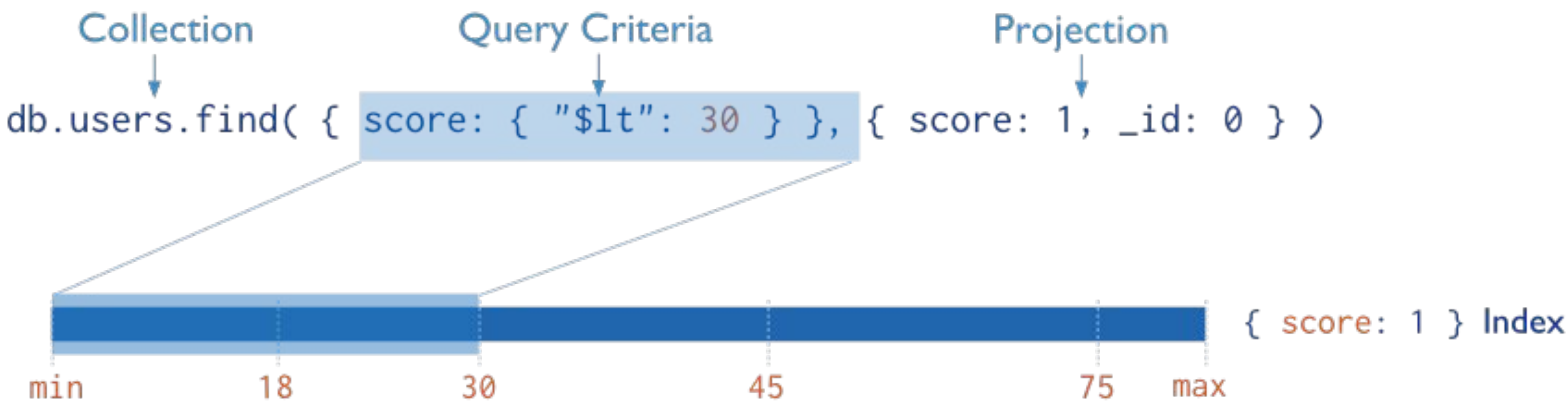


Indexes: Example of Use (2)



- The index can be traversed in order to return sorted results (without sorting)

Indexes: Example of Use (3)

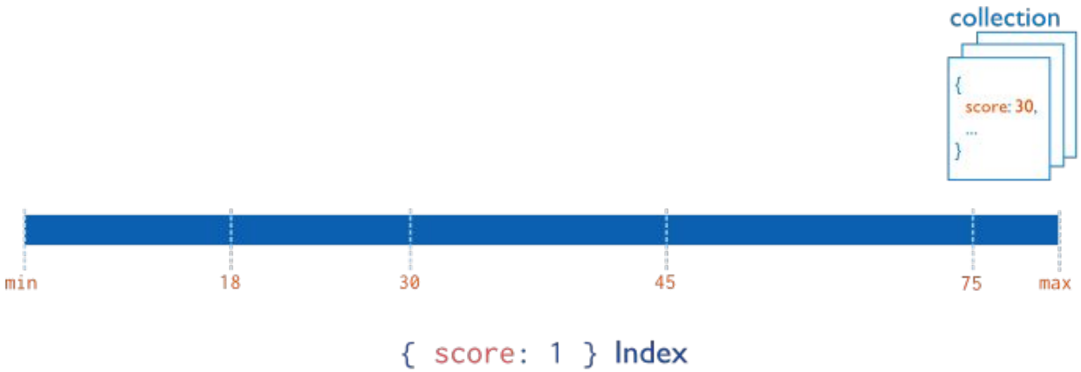


- MongoDB does not need to inspect data outside of the index to fulfill the query

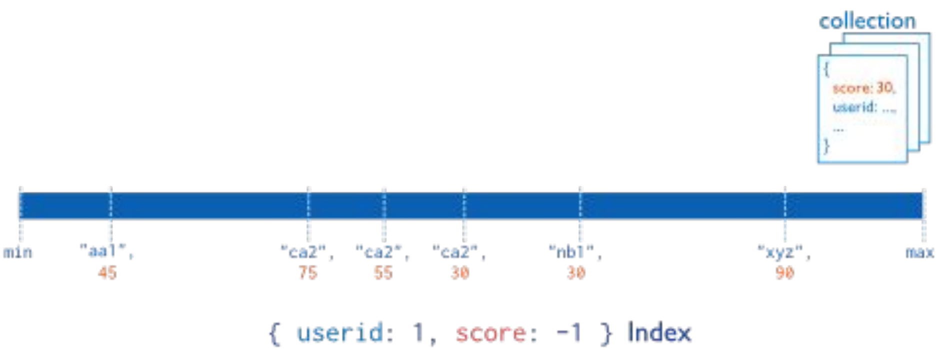
Index Types

- **Default:** _id
  - Exists by default
    - If applications do not specify _id, it is created.
  - Unique
- **Single Field**
  - User-defined indexes on a single field of a document
- **Compound**
  - User-defined indexes on multiple fields
- **Multikey index**
  - To index the content stored in arrays
  - Creates separate index entry for each array element

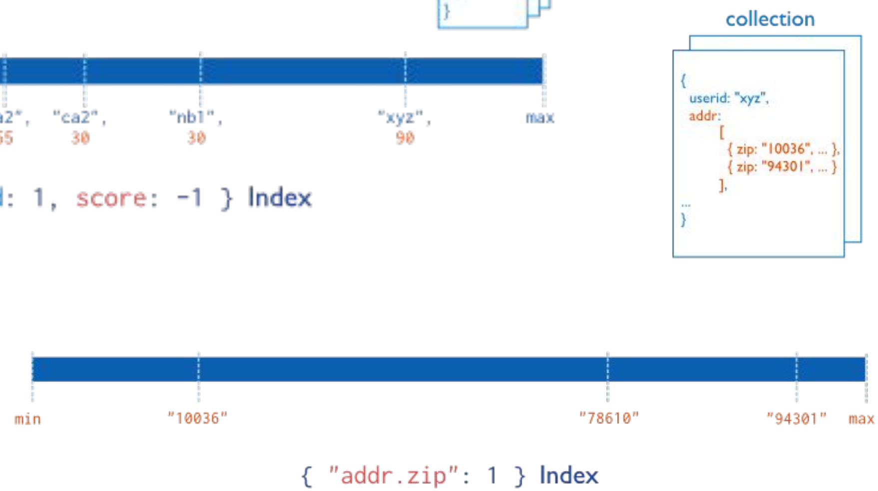
Index Types (2)



- Index on score field (ascending)



- Compound Index on userid (ascending) AND score field (descending)



- Multikey index on the addr.zip field

Index Types (3)

- **Ordered** Index
  - B-Tree (see above)
- **Hash** Indexes
  - Fast *O*(1) indexes the hash of the value of a field
    - Only equality matches
- **Geospatial** Index
  - 2d indexes = use planar geometry when returning results
    - For data representing points on a two-dimensional plane
  - 2sphere indexes = spherical (Earth-like) geometry
    - For data representing longitude, latitude
- **Text** Indexes
  - Searching for string content in a collection

MongoDB: Behind the Curtain

- BSON format
- Distribution models
  - Replication
  - Sharding
  - Balancing
- MapReduce
- Transactions
- Journaling

BSON (Binary JSON) Format

- Binary-encoded serialization of JSON documents
  - Representation of documents, arrays, JSON simple data types + other types (e.g., date)

```
{"hello": "world"}          →  "\x16\x00\x00\x00\x02hello\x00
                                 \x06\x00\x00\x00world\x00\x00"

                               "\x31\x00\x00\x00\x04BSON\x00\x26\x00
                                 \x00\x00\x020\x00\x08\x00\x00
{"BSON": ["awesome",             \x00awesome\x00\x011\x00\x33\x33\x33
5.05, 1986]}                →  \x33\x33\x33
                                 \x14\x40\x102\x00\xc2\x07\x00\x00
                                 \x00\x00"
```

http://www.bsonspec.org/

BSON: Basic Types

- `byte` – 1 byte (8-bits)
- `int32` – 4 bytes (32-bit signed integer)
- `int64` – 8 bytes (64-bit signed integer)
- `double` – 8 bytes (64-bit IEEE 754 floating point)

http://www.bsonspec.org/

BSON Grammar

```
document ::= int32 e_list "\x00"
```

- BSON document
- `int32` = total number of **bytes** in document

```
e_list ::= element e_list | ""
```

- Sequence of elements

BSON Grammar (2)

`element ::= "\x01" e_name double`	Floating point
`| "\x02" e_name string`	UTF-8 string
`| "\x03" e_name document`	Embedded document
`| "\x04" e_name document`	Array
`| "\x05" e_name binary`	Binary data
`| …`	…

```
e_name ::= cstring
```

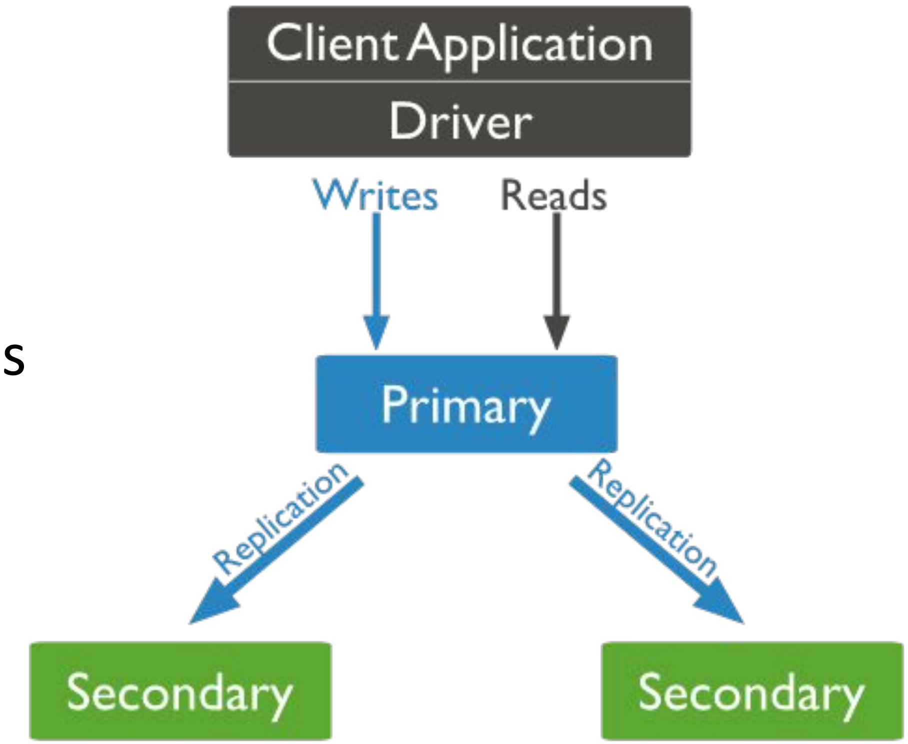
- Field key

```
cstring ::= (byte*) "\x00"
string ::= int32 (byte*) "\x00"
```

etc.…

Data Replication

- Master/slave replication
- Replica set = group of instances that host the same data set
  - **primary** (master) – handles all write operations
  - **secondaries** (slaves) – apply operations from the primary so that they have the same data set



Replication: Read & Write

- **Write operation:**
  1. Write operation is applied on the primary
  2. Operation is recorded to primary's oplog (operation log)
  3. Secondaries replicate the oplog + apply the operations to their data sets

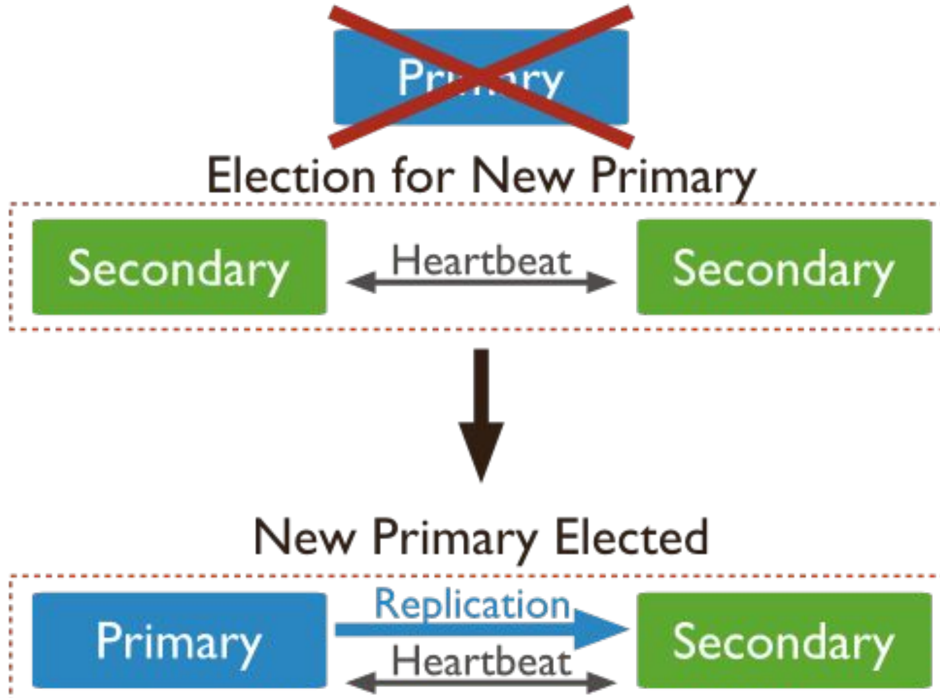
- **Read:** All replica set members can accept reads
  - By default, application directs its reads to the primary
    - Guaranties the latest version of a document
    - Decreases read throughput
  - Read preference mode can be set
    - See below

Replication: Read Modes

Read Preference Mode	Description
`primary`	operations read from the primary of the replica set
`primaryPreferred`	operations read from the primary, but if unavailable, operations read from secondary members
`secondary`	operations read from the secondary members
`secondaryPreferred`	operations read from secondary members, but if none is available, operations read from the primary
`nearest`	operations read from the nearest member (= shortest ping time) of the replica set

Replica Set Elections

- If the primary becomes unavailable, an election determines a new primary
  - Elections need some time
  - No primary => no writes

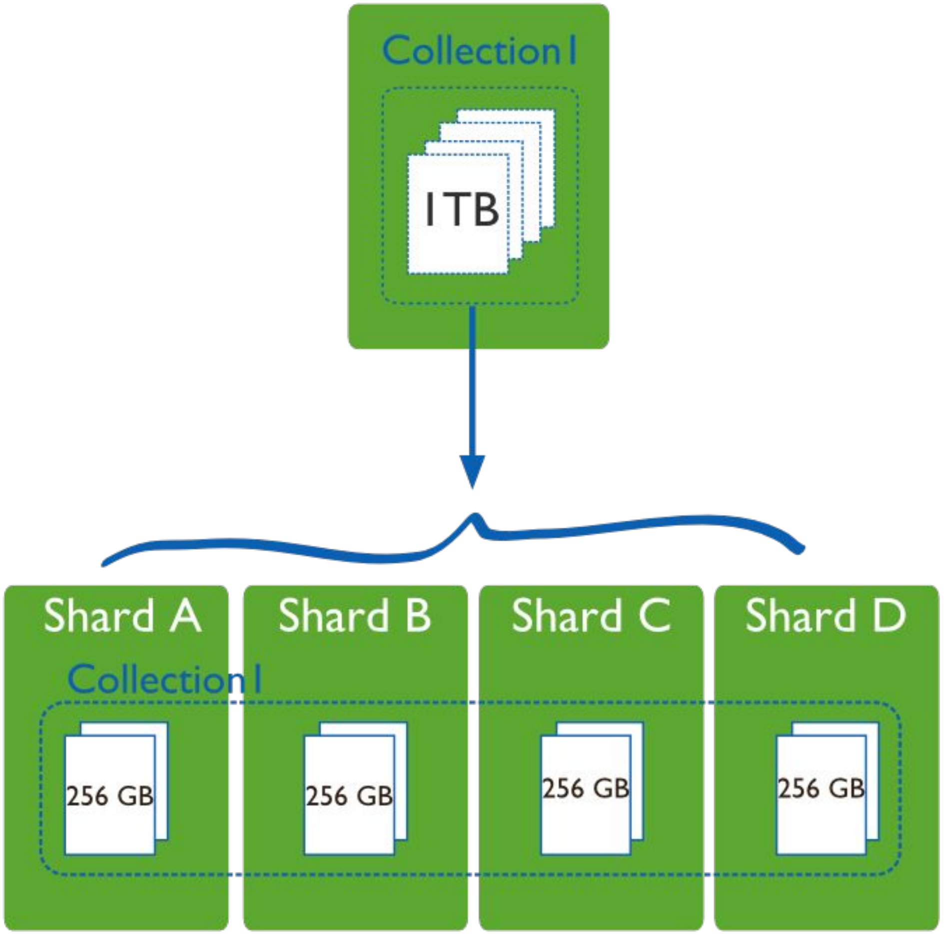


Replica Set: CAP

- Let us have three nodes in the replica set
  - Let's say that the master is disconnected from the other two
    - The distributed system is partitioned
  - The master finds out, that it is alone
    - Specifically, that can communicate with less than half of the nodes
    - And it steps down from being master (handles just reads)
  - The other two slaves "think" that the master failed
    - Because they form a partition with more than half of the nodes
    - And elect a new master
- In case of just two nodes in RS
  - Both partitions will become read-only
    - Similar case can occur with any even number of nodes in RS
  - Therefore, we can always add an arbiter node to an even RS

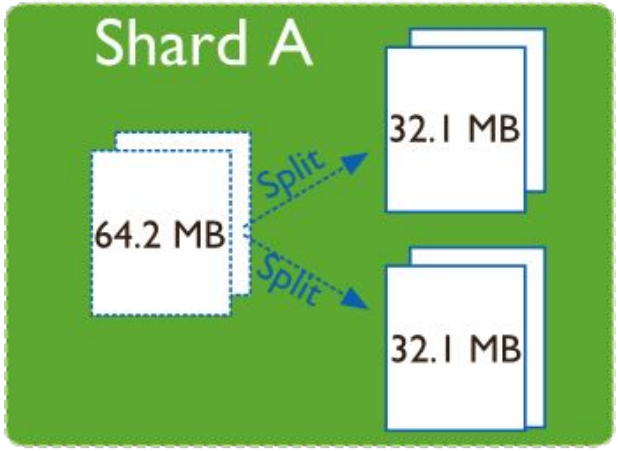
Sharding

❖ MongoDB enables collection partitioning (sharding)



Collection Partitioning

- Mongo partitions collection's data by the shard key
  - Indexed field(s) that exist in each document in the collection
    - Immutable
  - Divided into chunks, distributed across shards
    - **Range-based** partitioning
    - **Hash-based** partitioning
  - When a chunk grows beyond the size limit, it is split
    - Metadata change, no data migration

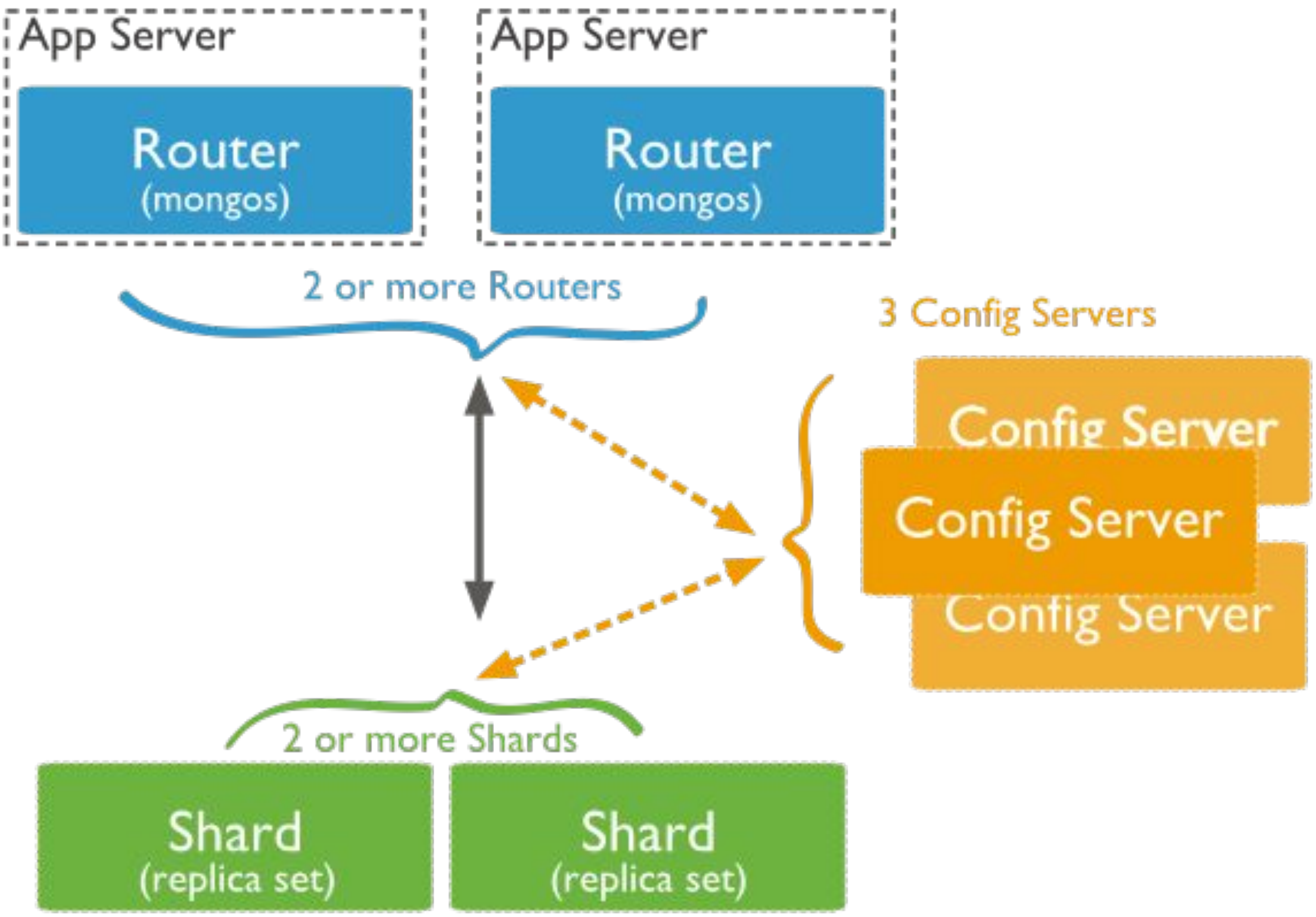


- Data balancing:
  - Background chunk migration

Sharding: Components

- MongoDB runs in cluster of different node types:
- Shards – store the data
  - Each shard is a replica set
    - Can be a single node
- Query routers – interface with client applications
  - Direct operations to the relevant shard(s)
    - + return the result to the client
  - More than one => to divide the client request load
- Config servers – store the cluster's metadata
  - Mapping of the cluster's data set to the shards
  - Recommended number: 3

Sharding: Diagram



Journaling

- **Write** operations are applied in memory and into a journal before done in the data files (on disk)
  - To restore consistent state after a hard shutdown
  - Can be switched on/off

- **Journal directory** – holds journal files
- **Journal file** = write-ahead redo logs
  - Append only file
  - Deleted when all the writes are durable
  - When size > 1GB of data, MongoDB creates a new file
    - The size can be modified
- Clean shutdown removes all journal files

Transactions

- Write ops: atomic at the level of single document
  - Including nested documents
  - Sufficient for many cases, but not all
  - When a write operation modifies multiple documents, other operations may interleave

- **Transactions**:
  - Isolation of a write operation that affects multiple docs

```
db.foo.update( { field1 : 1 , $isolated : 1 }, { $inc
: { field2 : 1 } } , { multi: true } )
```

  - Two-phase commit
    - Multi-document updates