By Marina Barsky

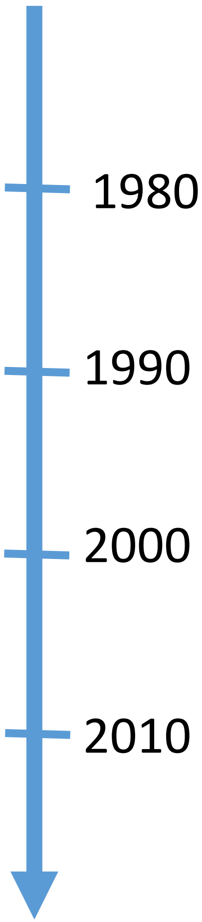
Introduction to NoSQL

Lecture 19

Outline

- Relational vs. NoSQL databases
  - the value of relational databases
  - new requirements and NoSQL features
  - flexible data models
- Types of NoSQL databases
  - key-value stores
  - document databases
  - column-family databases
  - graph databases
- Concurrency
- Usage patterns

History

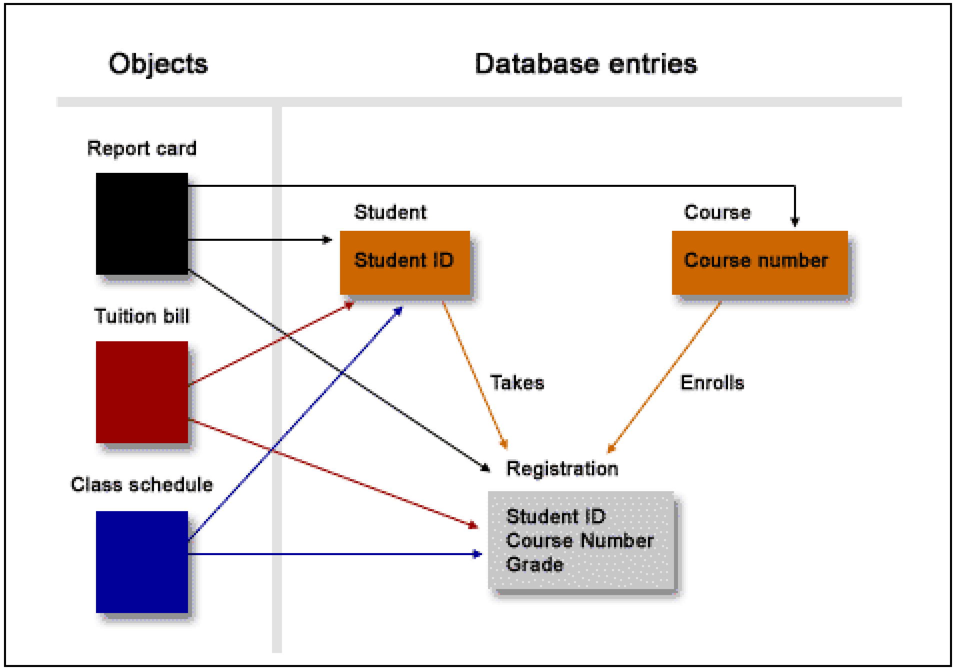


Relational databases

- A standard data model is basis for standard query language SQL
- Mature technologies:
    - Physical organization of data on disk
    - Indexes: B^+-Trees, hash indexes
    - Query optimization, operator implementations
- Concurrency control (ACID)
    - transactions: atomicity, consistency, isolation, durability
- Many reliable integration mechanisms
    - “shared database” integration of multiple applications

Impedance mismatch

- Mismatch between tables and data structures in memory
  - For object-oriented languages: invented Object-Relational Mapping (ORM)
  - For other languages (functional, c) – data structures just do not match



Object-oriented databases

1980

Relational databases

1990

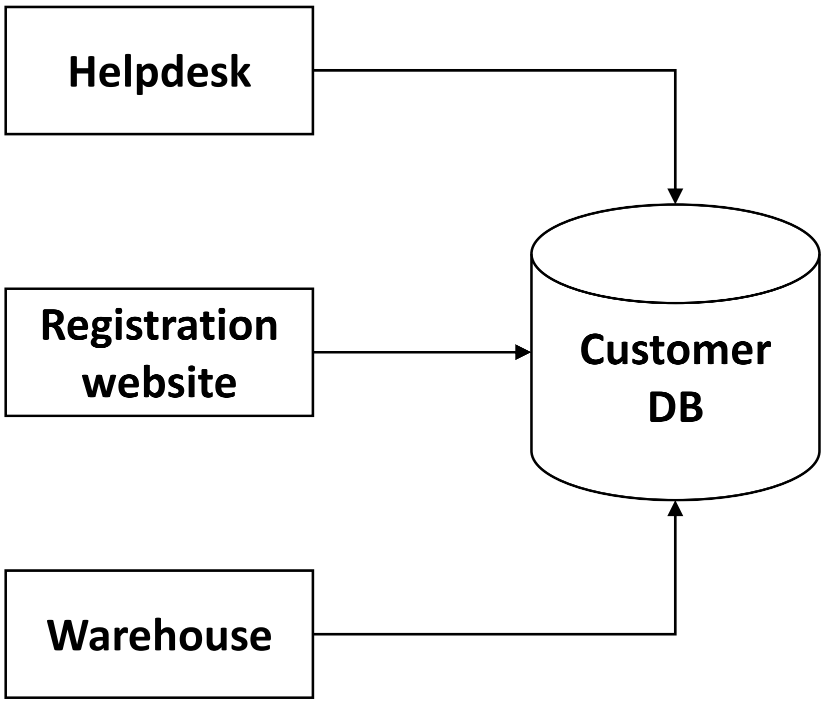
Object-oriented databases

2000

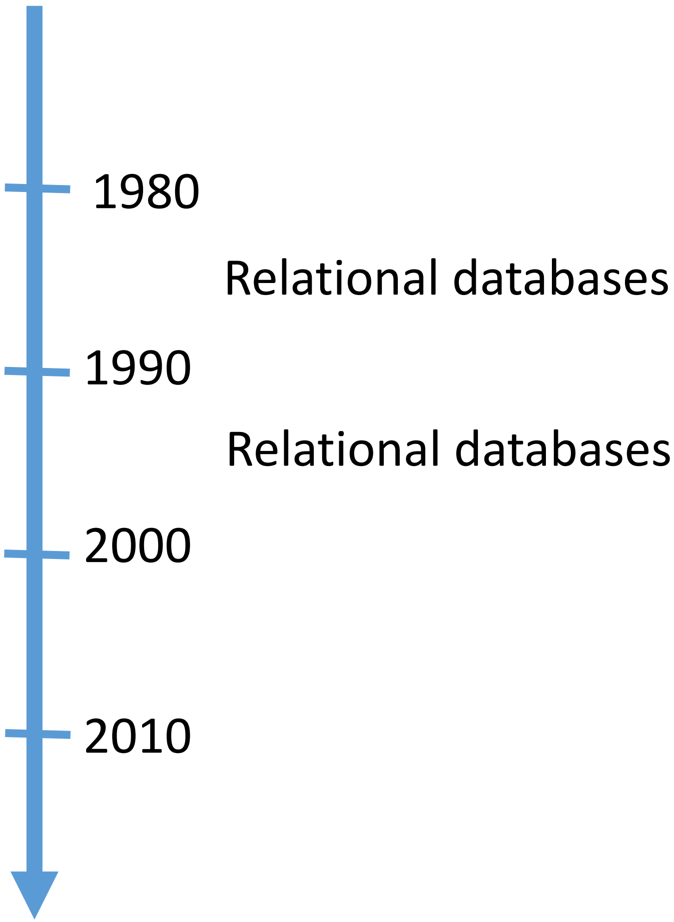
2010

Why object-oriented databases disappeared

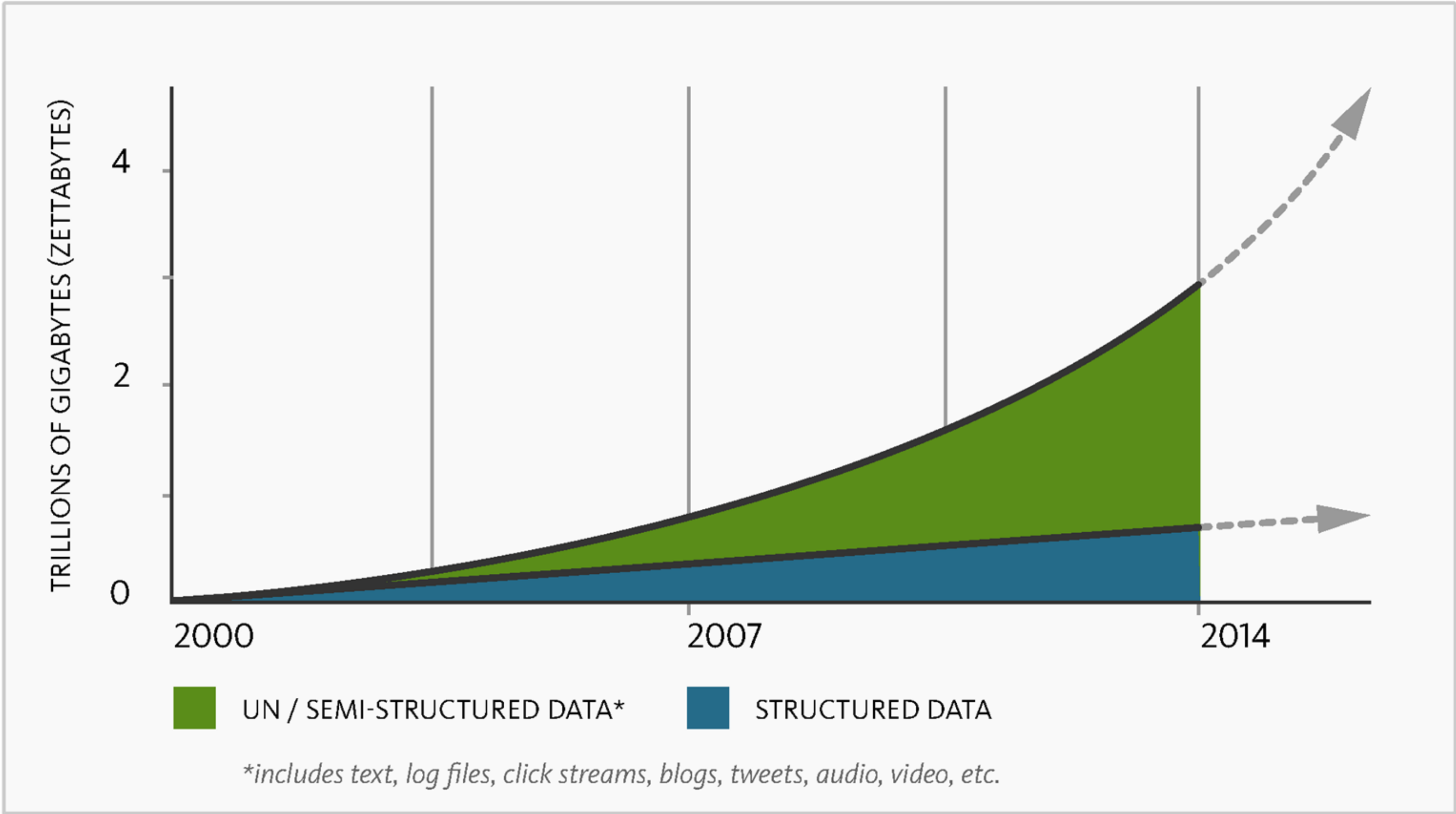
- They were not useful for integrating applications through databases
- For integration through databases, data should be broken into atomic datum – to be used by different applications



Relational databases predominate

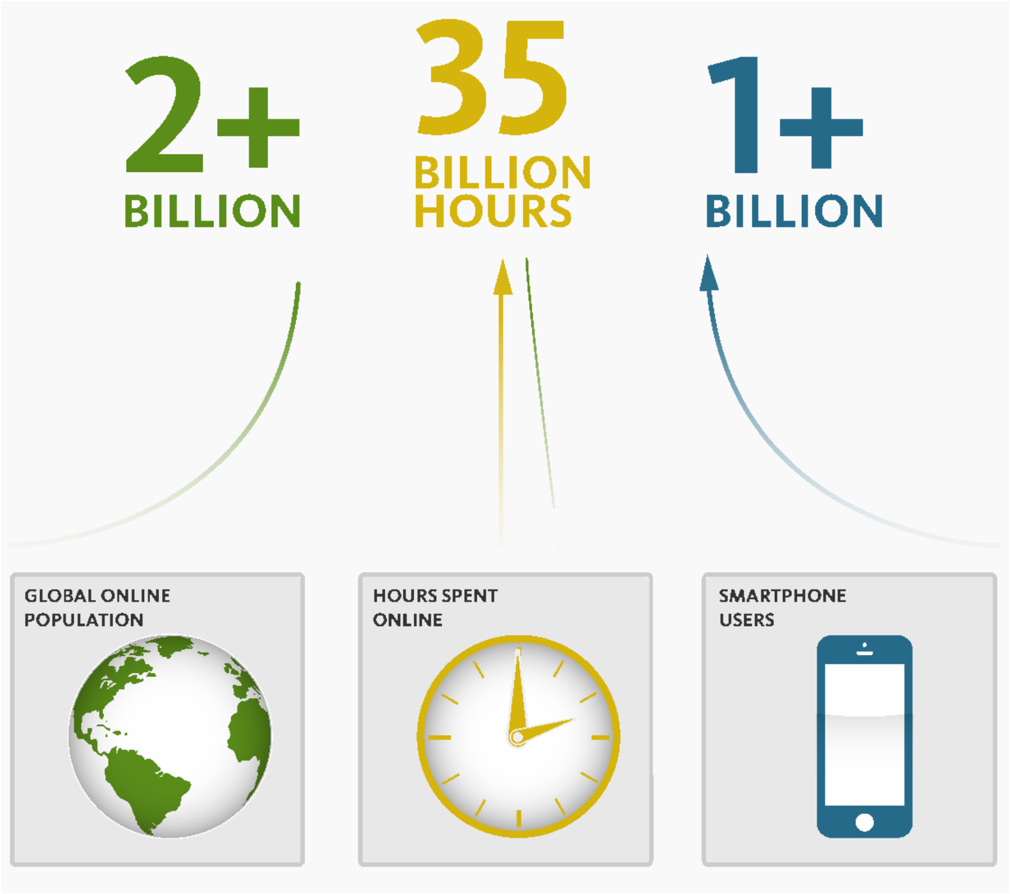


Current Trends: Big Data



source: http://www.couchbase.com/sites/default/files/uploads/all/whitepapers/NoSQL-Whitepaper.pdf

Current Trends: Lots of traffic



source: http://www.couchbase.com/sites/default/files/uploads/all/whitepapers/NoSQL-Whitepaper.pdf

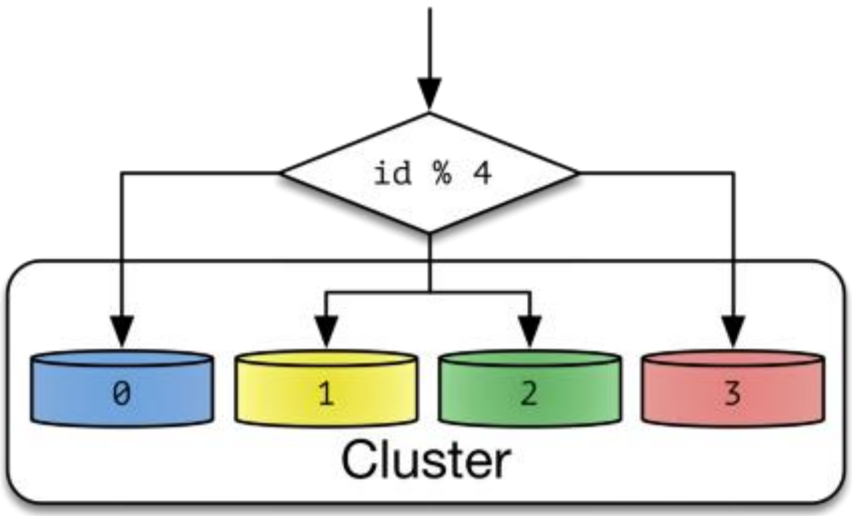
Current Trends: Cloud Computing

source: http://www.profitbricks.com/what-is-iaas

Scaling up

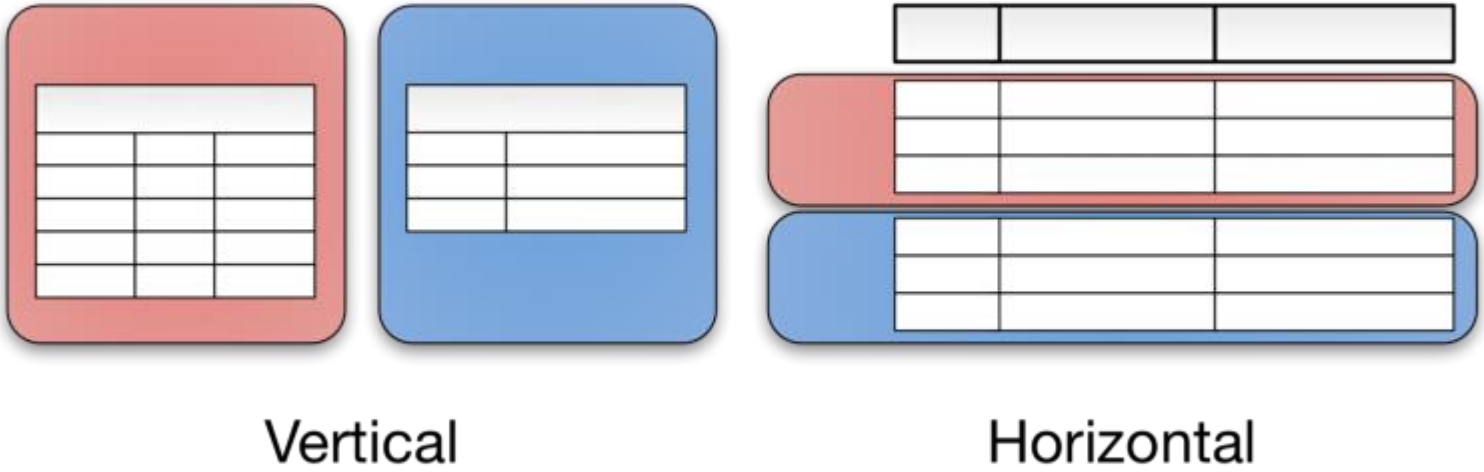
Two alternatives:

- Bigger servers
- Lots of little boxes in massive grids



Partitioning

- Vertical: normalization, splitting into smaller tables
- Horizontal: splitting single table into multiple sets of rows
  - Horizontal partitioning when rows are distributed across multiple nodes based on some attribute (for example, zip code) is called *sharding*



Parallelism is not natural for relational databases

- SQL designed to run as a single node
- Both vertical partitioning and horizontal partitioning introduce performance bottlenecks:
  - Increased latency when querying across more than one shard
  - Indexes are sharded by one dimension, so that some searches are optimal, and others are slow or impossible
  - Cross-shard consistency and durability is hard to achieve due to the more complex failure modes of a set of servers

New requirements on data management

Trends

- **Volume** of data
- **Cloud** comp. (IaaS)
- **Velocity** of data
- **Big** traffic
- **Variety** of data

Requirements

- Real **scalability**
  - massive database distribution
  - dynamic resource management
  - horizontally scaling systems
- Frequent **update** operations
- Massive **read** throughput
- **Flexible** database schema

History

1980

Relational databases

1990

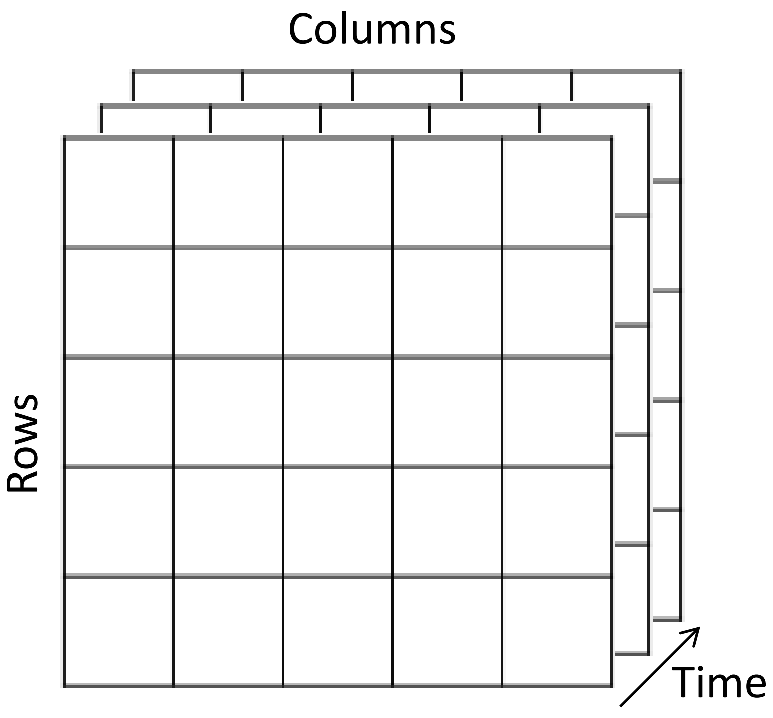
2000

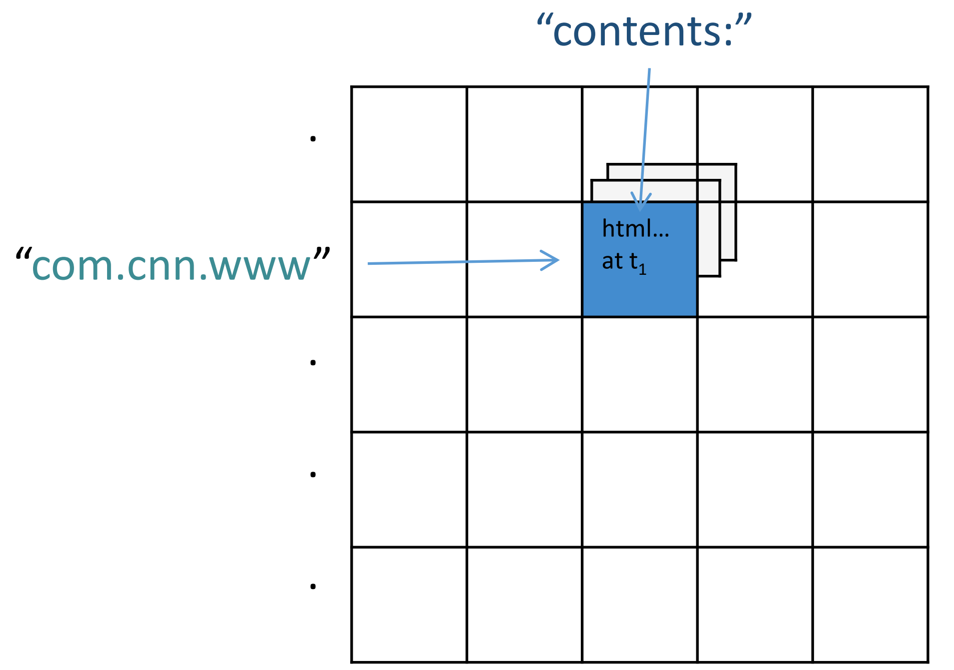
NoSQL databases

2010

Google BigTable (2006)

- Data model: three-dimensional indexed sorted map
  - Input (row, column, timestamp) → Output (cell contents)

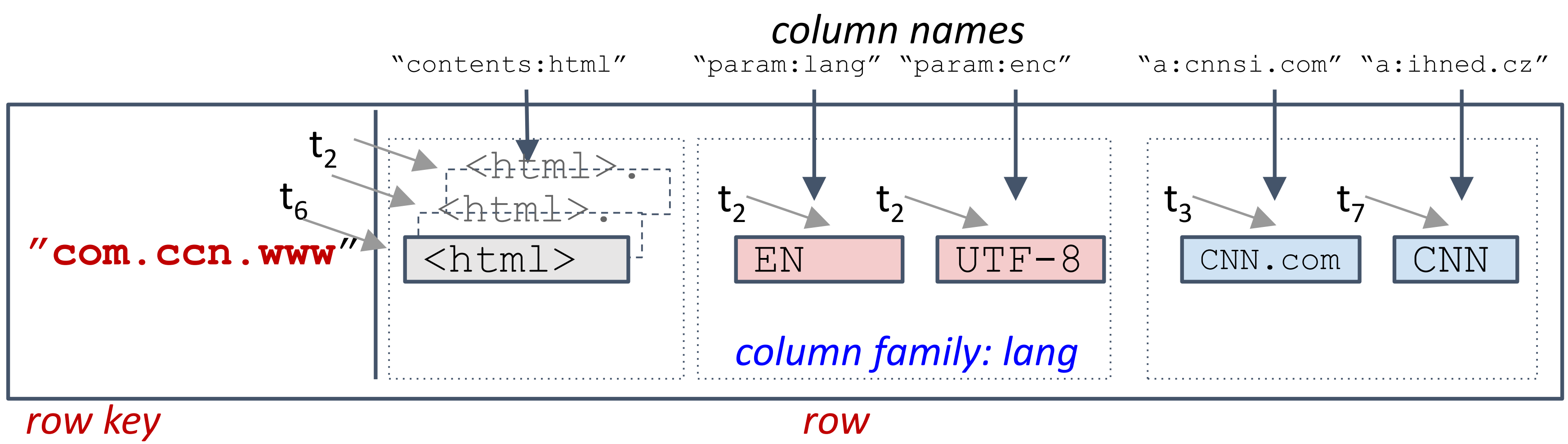




http://static.googleusercontent.com/media/research.google.com/en//archive/bigtable-osdi06.pdf

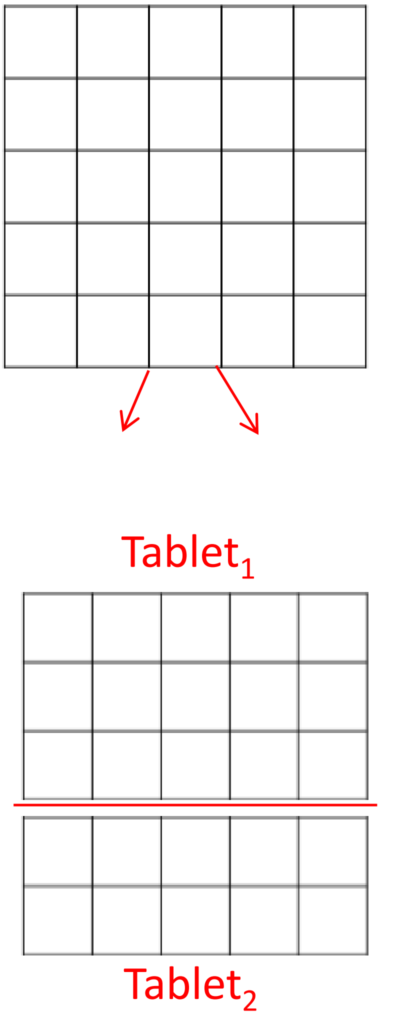
Column-family

- Columns are grouped in column-families
- Different fields describing html documents are stored in different column-families: for fast search and ranking



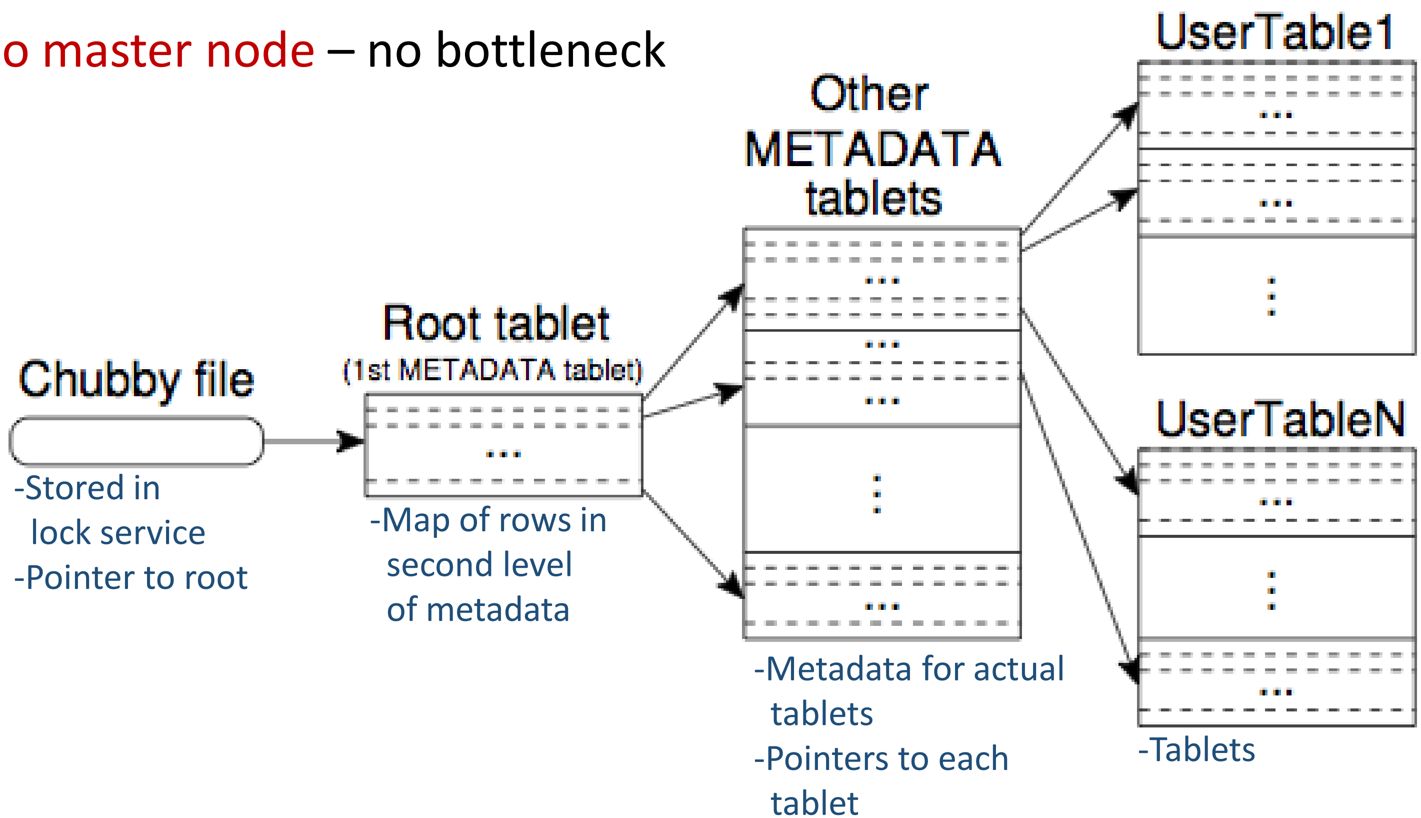
Partitioning: tablets

- The entire BigTable is split into tablets of contiguous ranges of rows
  - Approximately 100MB to 200MB each
- One machine services 100 tablets
  - Fast recovery in event of tablet failure
  - Fine-grained load balancing
  - 100 tablets are assigned non-deterministically to avoid hot spots of data being located on one machine
- Tablets are split as their size grows



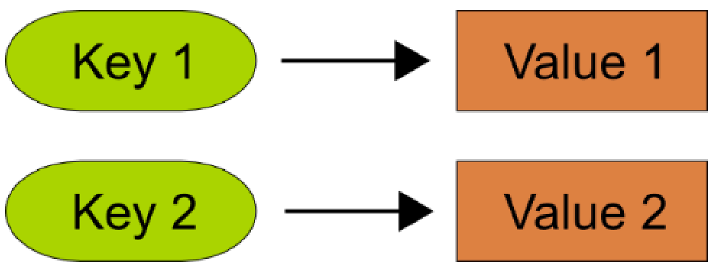
Locating Tablets

- Metadata for tablet locations
- Similar to B-tree index: row ids are sorted: interval is a key, and an IP of a corresponding tablet is a value
- No master node – no bottleneck



Amazon: Dynamo DB (2007)

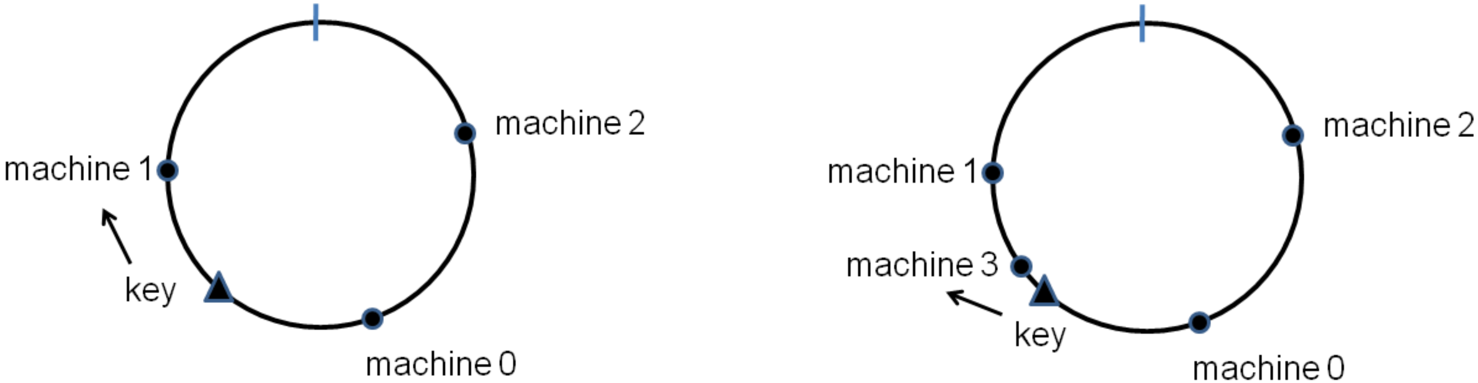
- Data model:
  simple hash table (map): key-value data store



http://www.allthingsdistributed.com/files/amazon-dynamo-sosp2007.pdf

Dynamo: architecture

- Implemented as distributed hash table (DHT) based on consistent hashing – hashing into the place on the ring
- Elastic scalability: able to scale out one node at a time, with minimal impact on the system
- Decentralization



General definition of NoSQL databases

- What is "NoSQL"?
  - term used in late 90s for a different type of technology: Carlo Strozzi: http://www.strozzi.it/cgi-bin/CSA/tw7/I/en_US/NoSQL/
  - "Not Only SQL"?
    - but many RDBMS are also "not just SQL"

- "NoSQL is an accidental term with no precise definition"
  - first used at an informal meetup in 2009 in San Francisco (presentations from Voldemort, Cassandra, Dynomite, HBase, Hypertable, CouchDB, and MongoDB)

Common characteristics

- Not relational
- Cluster-friendly
- Schema-less

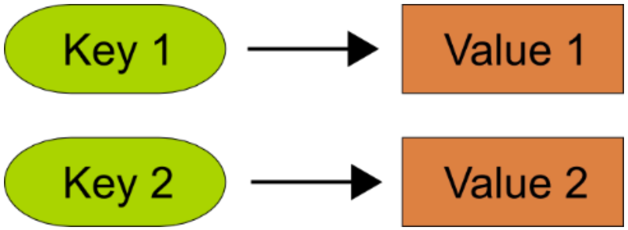
- Open source

Data models

1. Key - value (hash table)
2. Key - document
3. Wide-column
4. Graph

1. Key-value stores

- Value can be anything
- Search only by key – no structure inside the value
- Basic operations:
  Get the value for the key `value:= get(key)`
  Put a value for a key `put(key, value)`
  Delete a key-value `delete(key)`



Key-value Stores: Representatives

redis

MEMCACHED

riak

LevelDB

MapDB

ORACLE BERKELEY DB 12c

ORACLE NOSQL DATABASE

Infinispan

amazon DynamoDB

Project Voldemort

Ranked list: http://db-engines.com/en/ranking/key-value+store

2. Document stores

- Also key-value pairs
- But value is a semi-structured text 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, …
- Can query inside document: building search indexes on various keys/fields

Data Formats

- 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

- 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

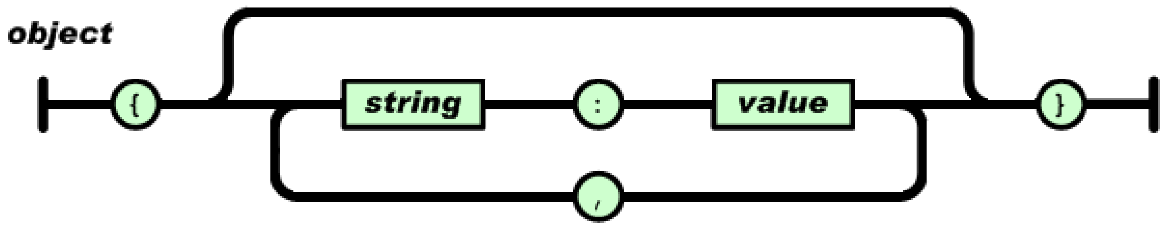
JSON: Basic Information

- 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

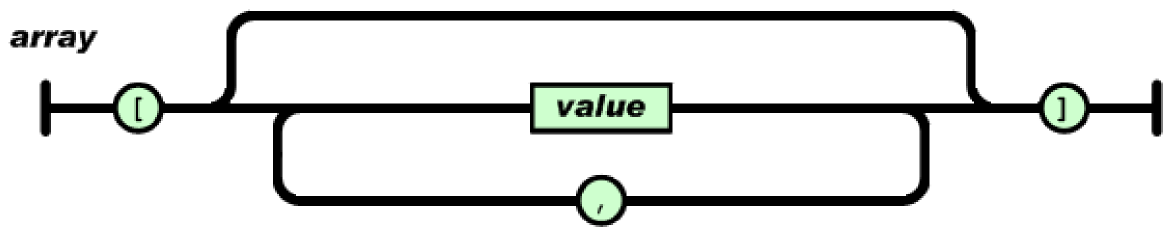
http://www.json.org

JSON: Data Types (1)

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

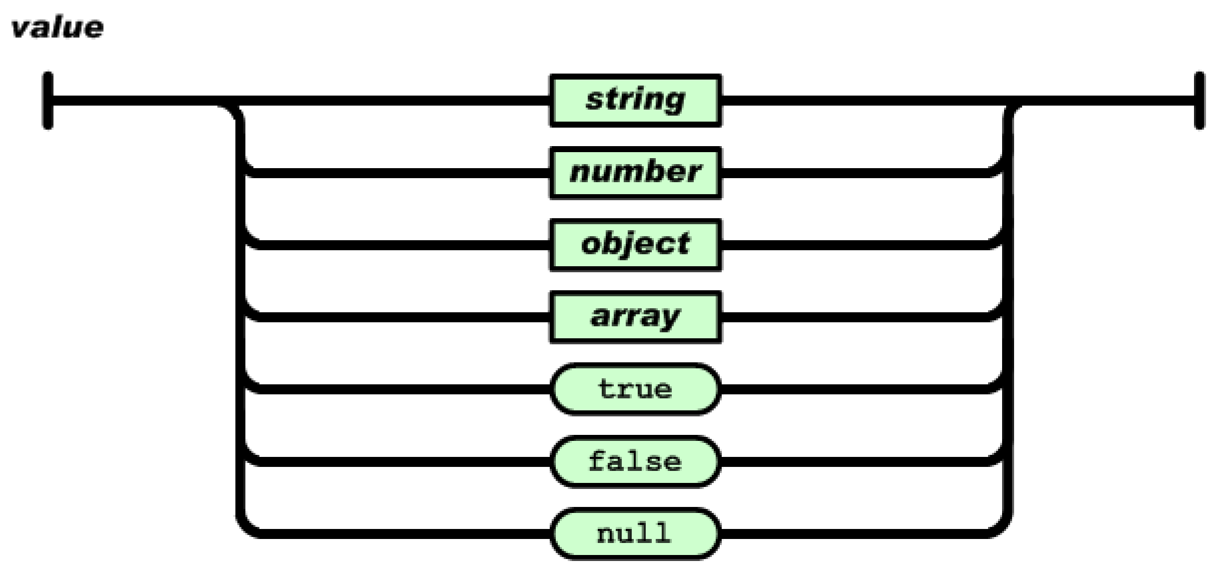


- array – an ordered collection of values (elements)
  - syntax: [comma-separated values]



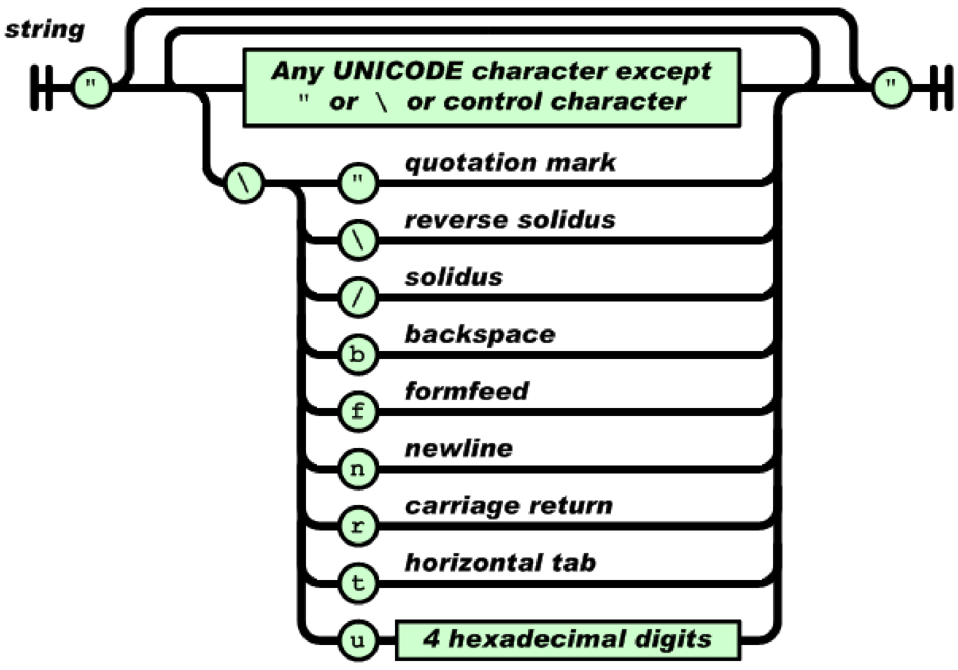
JSON: Data Types (2)

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



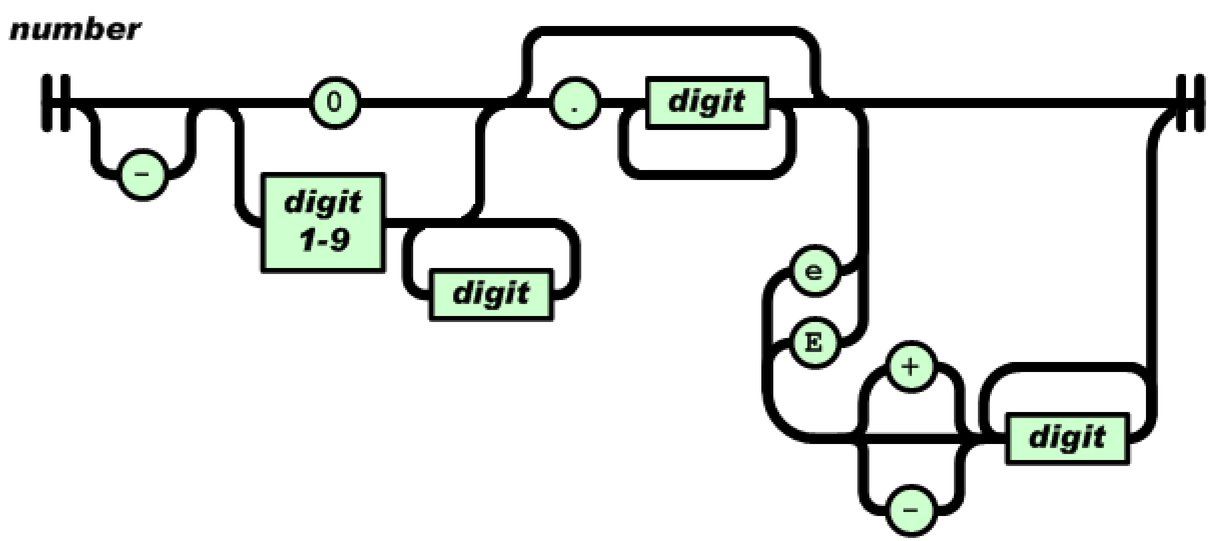
JSON: Data Types (3)

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



JSON: Data Types (4)

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

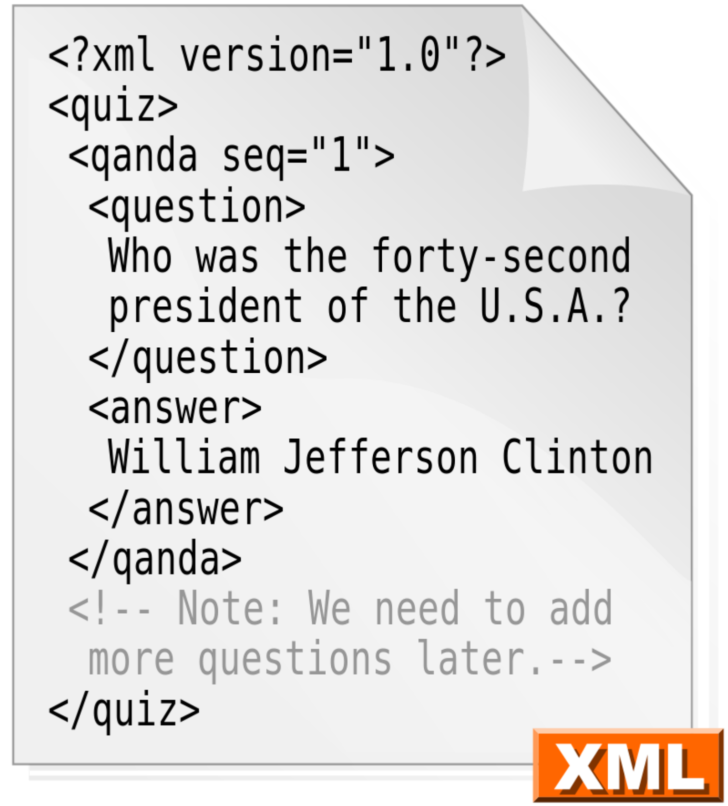


JSON data: Example


```
{
    "firstName": "John",
    "lastName": "Smith",
    "age": 25,
    "address": {
        "streetAddress": "21 2nd Street",
        "city": "New York",
        "state": "NY",
        "postalCode": 10021
    },
    "phoneNumbers": [
        {
            "type": "home",
            "number": "212 555-1234"
        },
        {
            "type": "fax",
            "number": "646 555-4567"
        }
    ]
}
```

XML basics

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



<element attribute="value">content</element>

rule of thumb: data = element tag, metadata = attribute

XML example: books.xml

```xml
<?xml version="1.0" encoding="UTF-8"?>
<bookstore>
  <book category="cooking">
    <title lang="en">Everyday Italian</title>
    <author>Giada De Laurentiis</author>
    <year>2005</year><price>30.00</price>
  </book>

  <book category="children">
    <title lang="en">Harry Potter</title>
    <author>J K. Rowling</author>
    <year>2005</year><price>29.99</price>
  </book>

  <book category="computers">
    <title lang="en">Learning XML</title>
    <author>Erik T. Ray</author>
    <year>2003</year><price>39.95</price>
  </book>
</bookstore>
```

XML prologue

XML document tag (analogous to HTML)

Custom tag

Custom attribute

Equivalent representation of books.xml using JSON

```
{
 "bookstore":
 [
   {"category": "cooking", "year": 2005, "price": 30.00,
   "title": "Everyday Italian", "author": "Giada De Laurentiis"},
   {"category": "computers", "year": 2003, "price": 49.99,
   "title": "XQuery Kick Start", "author": "James McGovern"},
   {"category": "children", "year": 2005, "price": 29.99,
   "title": "Harry Potter", "author": "J K. Rowling"},
   {"category": "computers", "year": 2003, "price": 39.95,
   "title": "Learning XML", "author": "Erik T. Ray"}
 ]
}
```

XML Features

- Document may be valid according to a schema:
  - DTD, XML Schema, etc.
- Technologies for parsing: DOM, SAX
- Advanced search technologies:
  - XPath, XQuery, XSLT (transformation)

- XML is great for configurations, meta-data, etc.
- XML databases are not widely used
- Currently, JSON format rules:
  - compact, easier to write, has all features typically needed

Two main properties of structured documents: both JSON and XML

- Schema-less – can add new attributes “on-the-fly”
- Self-describing data – data and metadata are stored in the same document

Binary Data

- Data objects to be stored often originate from memory structures (objects, class instances)

- Before storing, these objects must be serialized
  - Key-value stores can store a binary *value*

- Serialization (marshalling) can be done
  - By your own proprietary (de)serializator
  - Using "standard" language-specific way (Java serialization)
  - Using a cross-language standard: ProtoBuf, Apache Thrift

Protocol Buffers

- Technique for serializing structured data
- Developed by Google since 2008
  - BSD Licence

- Philosophy:
  1. Define the structure of the data
     - Using an ProtoBuf *interface description language*
  2. Automatically create source code in multiple programming languages for (de)serialization of such data
     - Compilers for Java, C++, Python, JavaScript, PHP, …

Protocol Buffers: Example

```
// file: addressbook.proto
message Person {
  required string name = 1;
  required int32 id = 2;
  optional string email = 3;

  enum PhoneType {
    MOBILE = 0; HOME = 1; WORK = 2;
  }
  message PhoneNumber {
    required string number = 1;
    optional PhoneType type = 2 [default = HOME];
  }

  repeated PhoneNumber phone = 4;
}

message AddressBook {
  repeated Person person = 1;
}
```

source: https://developers.google.com/protocol-buffers/

Protocol Buffers: Example 2 - Java

- Compile this source by:

```
protoc --java_out=jdir addressbook.proto
protoc --cpp_out=cppdir addressbook.proto
protoc --python_out=pdir addressbook.proto
```

- Result looks like this (Java):

https://github.com/jgilfelt/android-protobuf-example/blob/master/src/com/example/tutorial/AddressBookProtos.java

Most documents have JSON format

```
key=3 ->  { "personID": "3",
            "firstname": "Martin",
            "likes": [ "Biking","Photography" ],
            "lastcity": "Boston",
            "visited": [ "NYC", "Paris" ] }

key=5 ->  { "personID": "5",
            "firstname": "Pramod",
            "citiesvisited": [ "Chicago", "London","NYC" ],
            "addresses": [
               { "state": "AK",
                 "city": "DILLINGHAM" },
               { "state": "MH",
                 "city": "PUNE" }  ],
            "lastcity": "Chicago" }
```

Document store: sample query

Example in MongoDB syntax

- Query language expressed via JSON
- clauses: where, sort, count, sum, etc.

SQL: `SELECT * FROM users`
MongoDB: `db.users.find()`

```
SELECT * FROM users WHERE personID = "3"
db.users.find({"personID":"3"})
```

```
SELECT firstname,lastcity FROM users WHERE personID=5
db.users.find({"personID":"5"},{firstname:1,lastcity:1})
```

Schema-less?

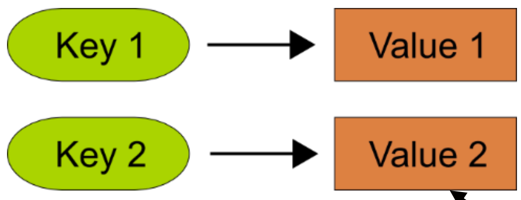
```
anOrder ["price"]*anOrder["qty"]
```

- Need to know the names of attributes
- Implicit schema: figure out the meaning of data

Document Databases: Representatives

Ranked list: http://db-engines.com/en/ranking/document+store

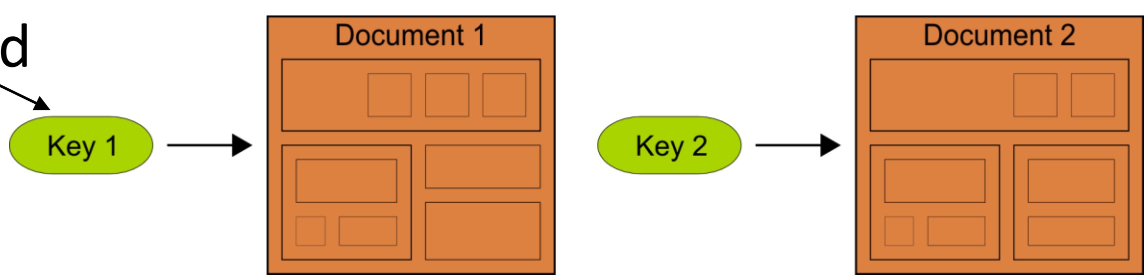
Key-value vs document: boundaries are blurry



Indexes metadata about the value

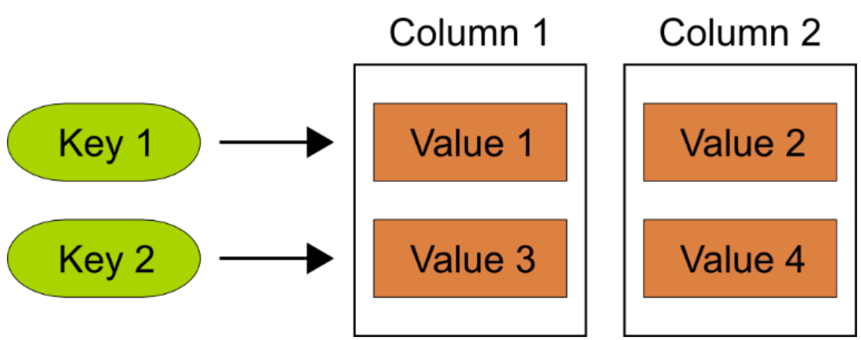
Customer_id: 7231

Document – may have id



3. Column-family Stores

- Also called: wide-column, columnar
- Data model: rows that have many columns associated with a row key. Data is **physically stored by column families**
- Column families are groups of related data (columns) that are often accessed together
  - e.g., for a customer we typically access all profile information at the same time, but not customer's orders



Column-family Stores: Representatives

Cassandra

H·BASE

HYPERTABLE

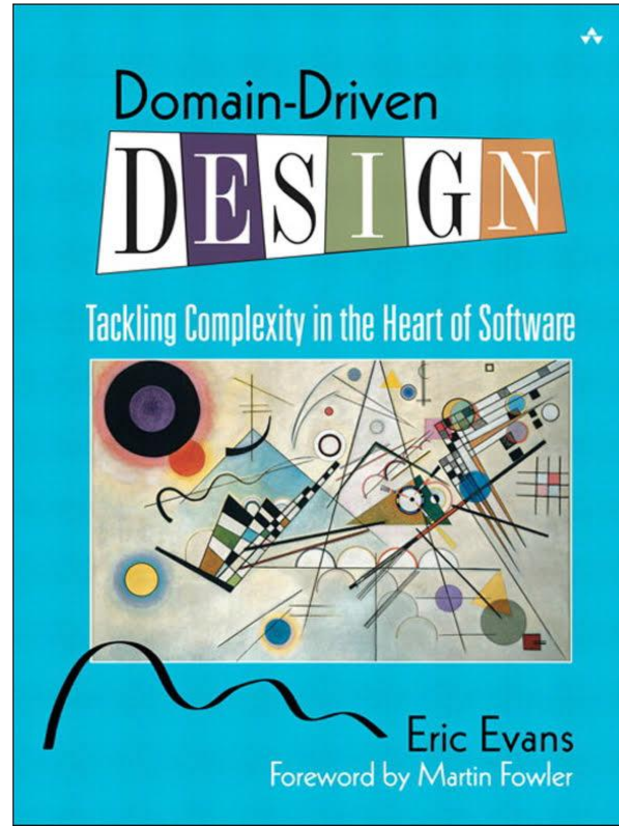
accumulo™

Ranked list: http://db-engines.com/en/ranking/wide+column+store

Common for key-value, key-document, row-col_family: aggregates

- We often operate in the world of clusters of objects

- Aggregate: complex structure that you can save as a single unit, retrieve as a single unit and work with it as a single unit
- A value, a document, a column-family is a single unit - aggregate



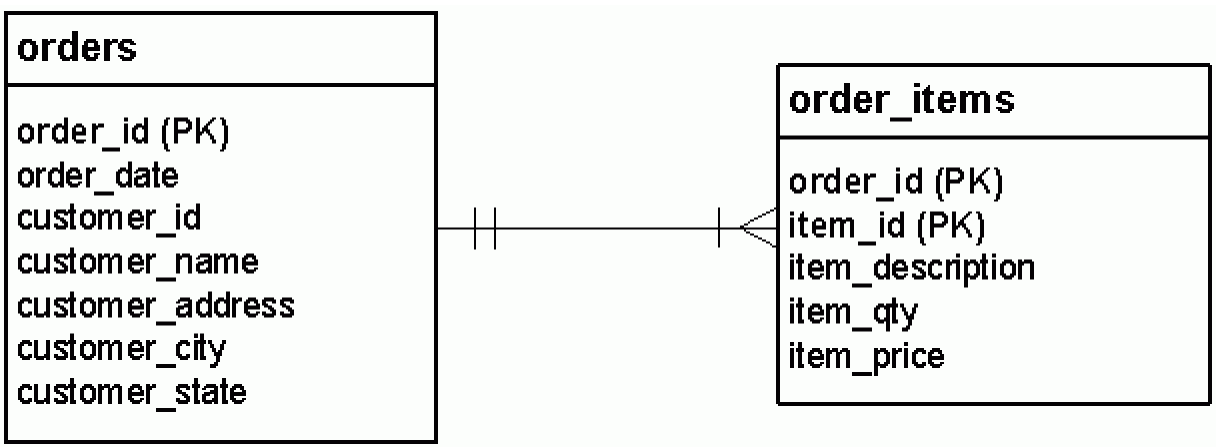
Aggregate-oriented databases

- There is no general strategy to set aggregate boundaries
- Aggregates give the database information about which bits of data will be manipulated together
- These should be stored on the same cluster node

Relational model: aggregate ignorant

- Relational databases are aggregate-ignorant
  - It is not a bad thing, it is a feature
  - Allows to easily look at the data in different ways
  - Best choice when there is no primary structure for data manipulation

Aggregate example: order



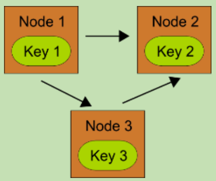
What if we want to calculate how many units are sold in total?

New classification of NoSQL

Aggregate databases:

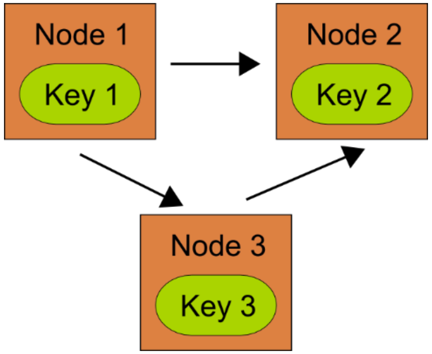
Key-value
Document
Wide-column

Graph databases

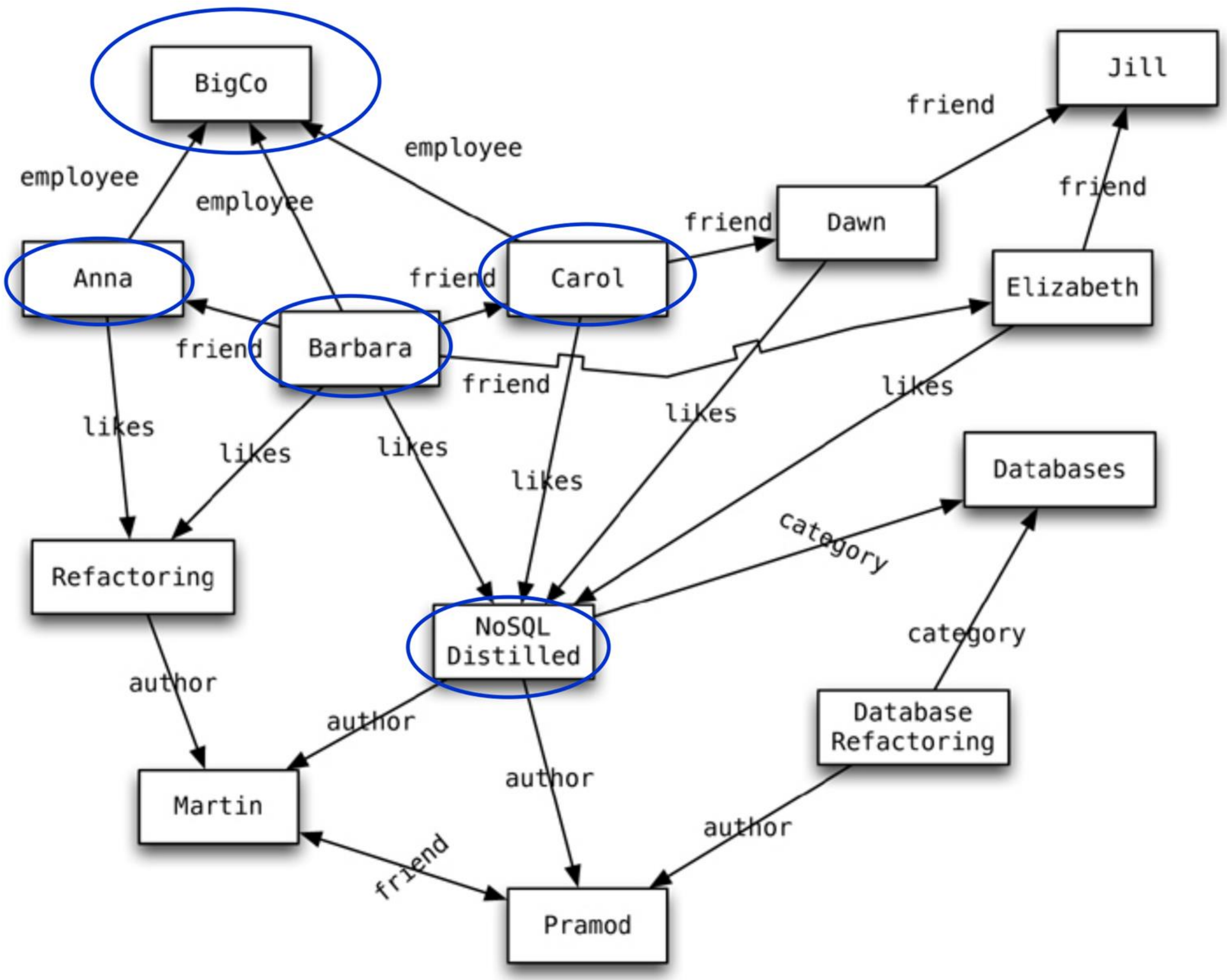


4. Graph databases

- Not aggregated: Very hard to model relationships between aggregates in aggregate-oriented databases
- Break things apart into smaller units
- Moving across multiple relationships in relational databases: – too many joins cause very bad performance



Graph database example



Graph databases: mission

- To store entities and relationships between them
  - Nodes are instances of objects
  - Nodes have properties, e.g., name
  - Edges have directional significance
  - Edges have types e.g., likes, friend, …

- Nodes are organized by relationships
  - Allow to find interesting patterns
  - example: Get all nodes that are “employee” of “Big Company” and that “likes” “NoSQL Distilled”

Graphs in RDBMS

- When we store a graph-like structure in RDBMS, it is for a single type of relationship
  - “Who is my manager”
- Adding another relationship usually means a lot of schema changes
- In RDBMS we model the graph beforehand based on the traversal we want
  - If the traversal changes, the data will have to change
  - Graph DBs: the relationship is not calculated but persisted

Graph Databases: Representatives

Neo4j

OrientDB®

APACHE GIRAPH

TITAN

InfiniteGraph

Ranked list: http://db-engines.com/en/ranking/graph+dbms

Consistency and concurrency

Consistency

- RDBMSs need ACID transactions – because data is in pieces
- We cannot afford that data is updated in chunks and parts of it are overridden
- We use transactions to wrap things together
- Graph databases do ACID updates

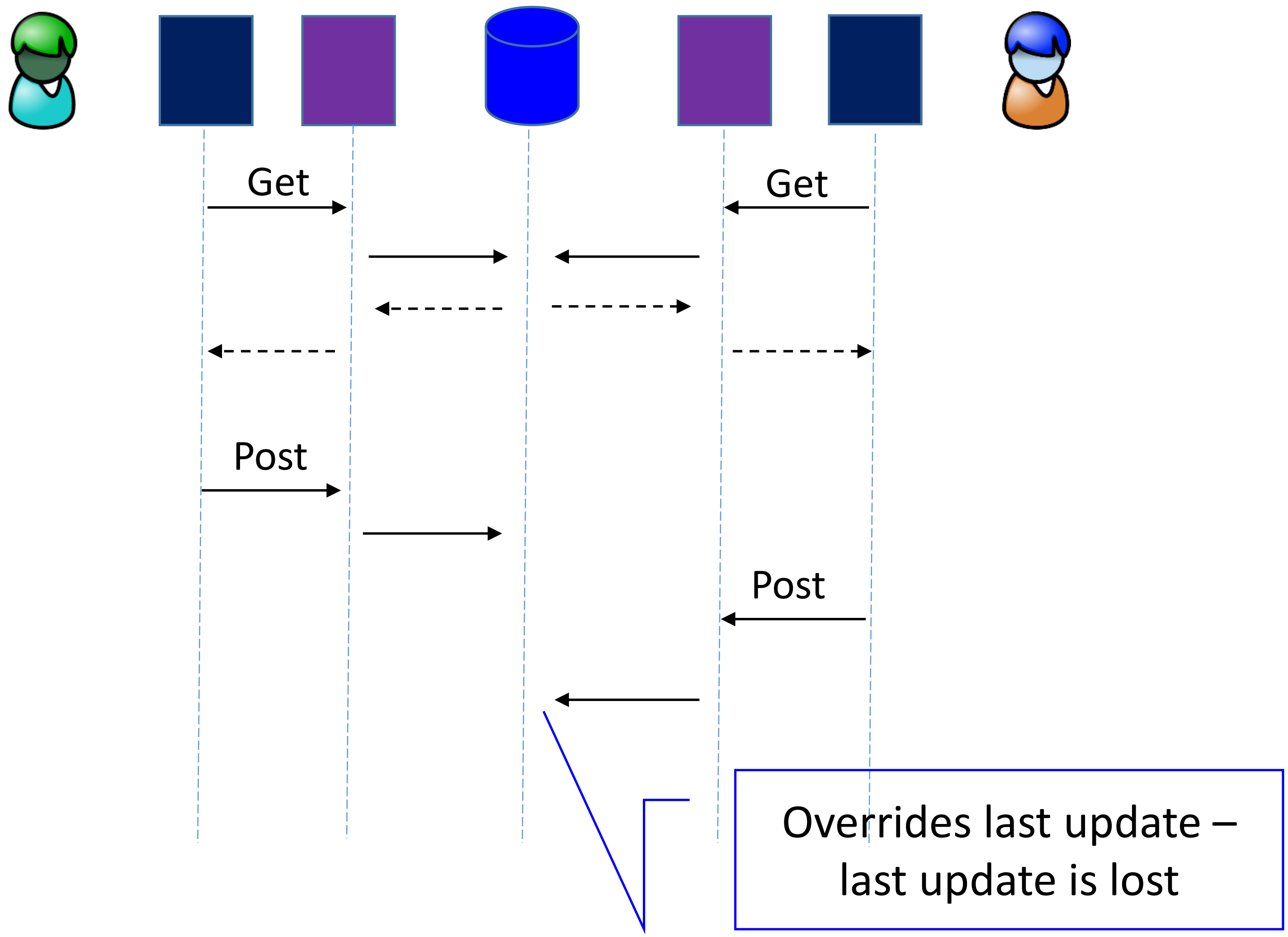
Aggregate consistency

- Aggregates themselves are transaction boundaries
- Isolated atomic update of an aggregate, not between 2 aggregates

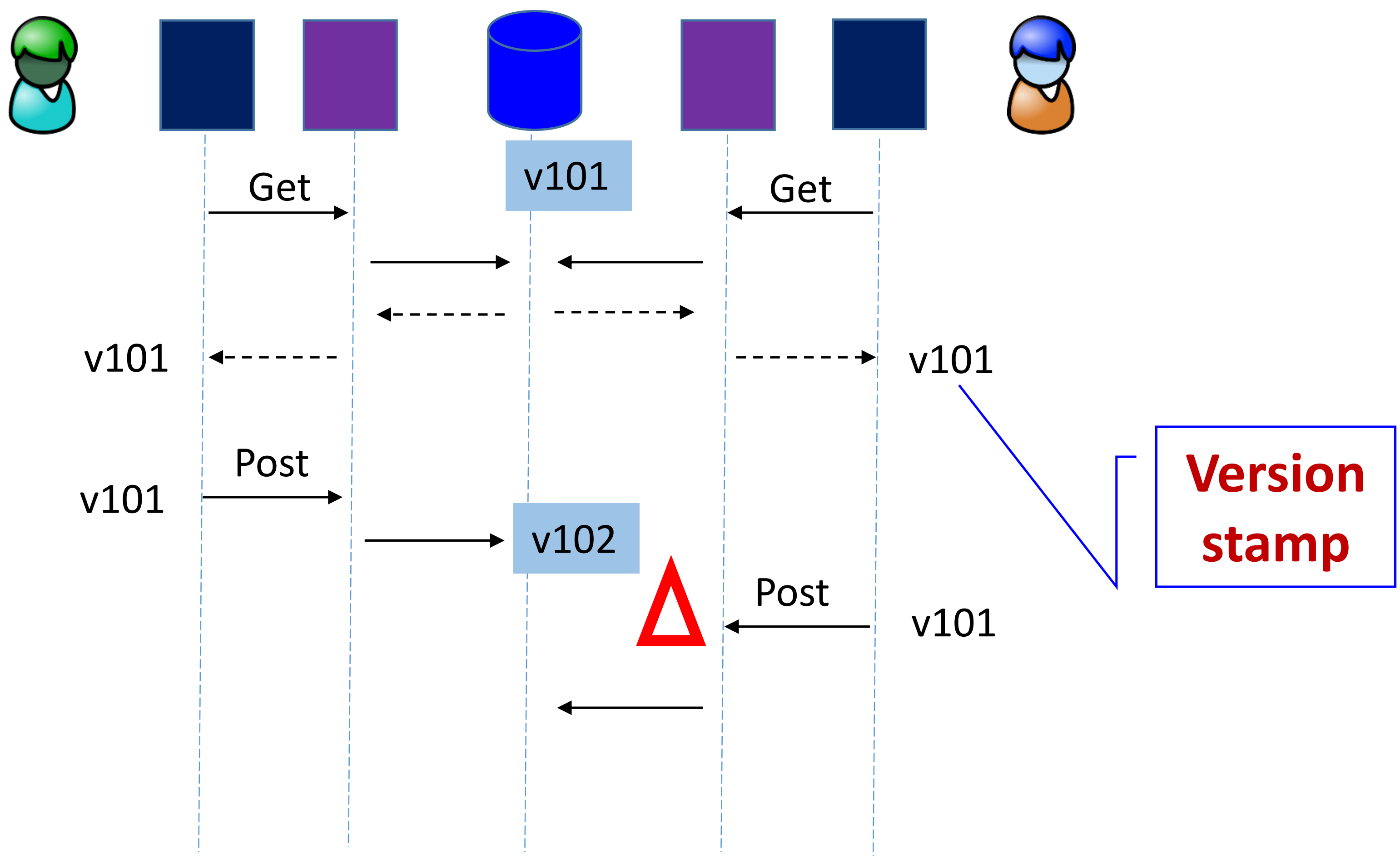
Multi-client system

- ACID requires additional handling, because we cannot lock the entire table in web app domain
- Holding a transaction open – degrades performance

Offline lock



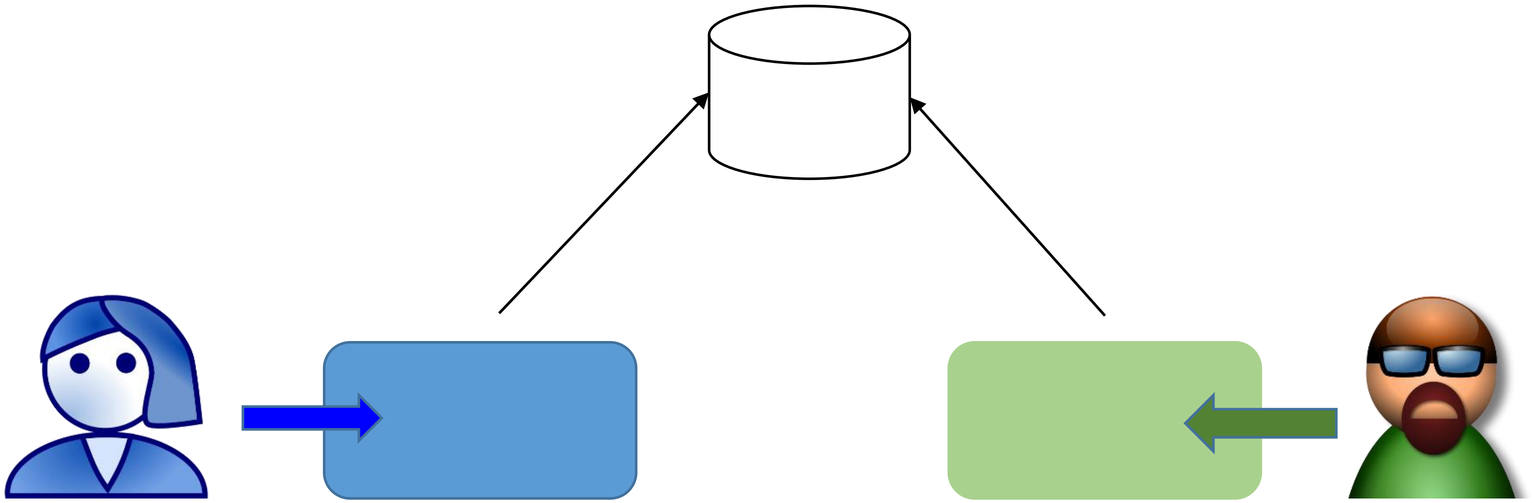
Offline lock



Consistency

- Logical consistency: when the same piece of data is broken into multiple chunks
- Multi-client consistency: performance vs. resilience

Example: booking hotel rooms



- If the connection is temporarily lost at time of booking
- 2 alternatives
  - Prohibit
  - Allow double-booking

- Consistency vs availability
- This is a business choice, not a technical choice

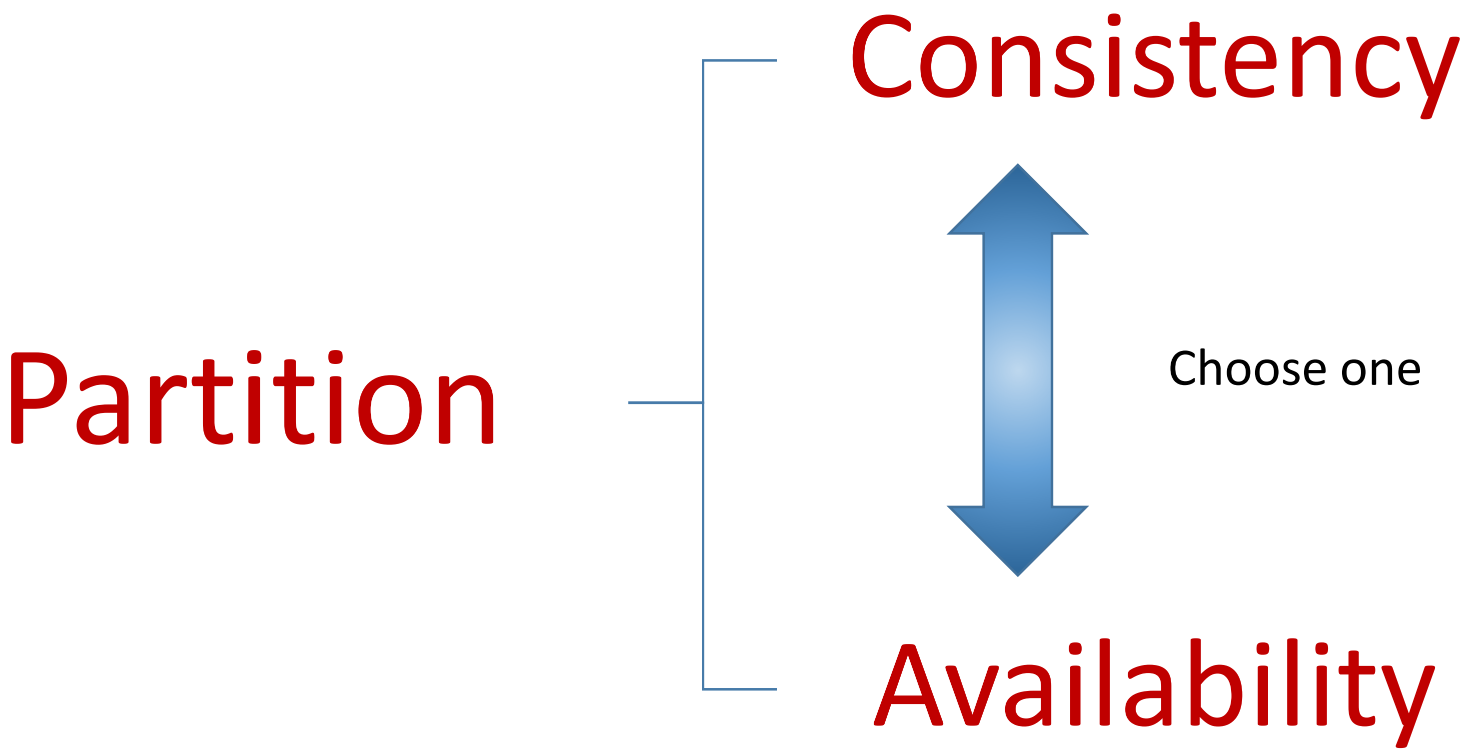
CAP theorem

- Tradeoff between:
  - Consistency
  - Availability
  - Partition tolerance

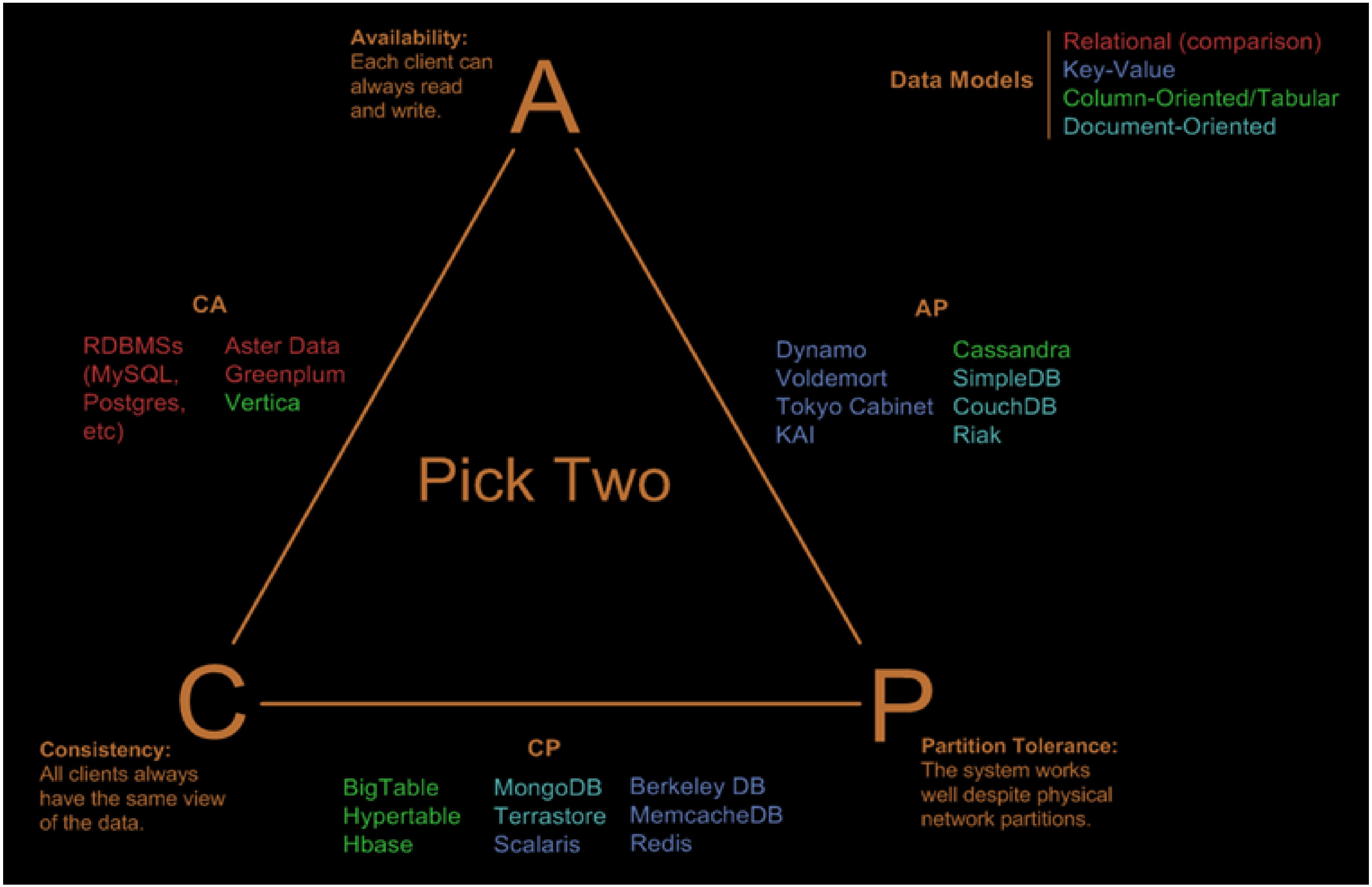
- Can have only 2 out of 3

- Consistency vs response time of your server
- Even if all the nodes are available – want fast response

In partitioned systems



CAP theorem and DBMSs



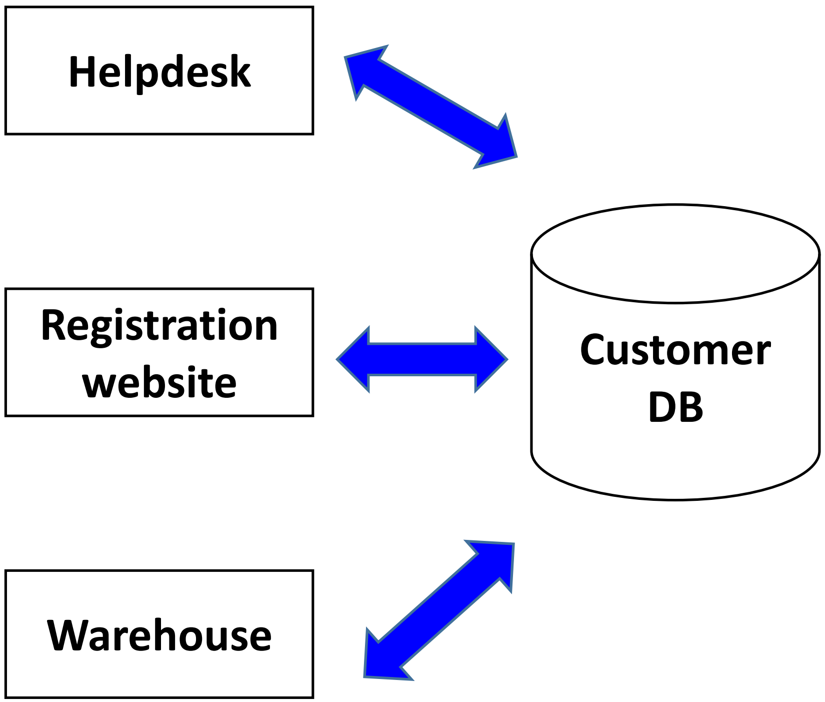
When to use NoSQL

- Large amounts of data
- Complex evolving schema
- The domain matches graph or document
- Ease of development: rapid time to market
- Projects that give you a strategic advantage

http://www.tim-wellhausen.de/papers/NoSQL-Patterns/NoSQL-Patterns.html

What with the application integration?

- This has changed too
- Integration through database:
  - Not safe
  - Resistance to schema change – multiple apps are affected
  - Business logic split across applications
- Now integrating data is achieved through web services (REST)



Future?

1980

Relational databases

1990

2000

NoSQL databases

2010

Polyglot persistence

One Example of NoSQL Usage: Facebook

Facebook statistics (Spring 2014)

- 1.28 billion users (1.23B active monthly)
- 300 PB of user data stored
- 10 billion messages sent daily
- 250 billion stored photos (350 million uploaded daily)

2009: 10,000 servers
2010: 30,000 servers
2012: 180,000 servers (estimated)

source: http://expandedramblings.com/index.php/by-the-numbers-17-amazing-facebook-stats/

Database Technology Behind Facebook

Apache Hadoop http://hadoop.apache.org/

- Hadoop File System (HDFS)
  - over 100 PB in a single HDFS cluster
- an open source implementation of MapReduce:
  - Enables efficient calculations on massive amounts of data

Apache Hive http://hive.apache.org/

- SQL-like access to Hadoop-stored data
- integration of MapReduce query evaluation

sources: http://goo.gl/SZ6jia http://royal.pingdom.com/2010/06/18/the-software-behind-facebook/

Database Technology Behind Facebook II

Apache HBase http://hbase.apache.org/

- a Hadoop column-family database
- used for e-mails, instant messaging and SMS
- replacement for MySQL and Cassandra

Memcached http://memcached.org/

- distributed key-value store
- used as a cache between web servers and MySQL servers since the beginning of FB

sources: http://goo.gl/SZ6jia http://royal.pingdom.com/2010/06/18/the-software-behind-facebook/

Database Technology Behind Facebook III

Apache Giraph http://giraph.apache.org/

- graph database
- facebook users and connections is one very large graph
- used since 2013 for various analytic tasks

RocksDB http://rocksdb.org/

- high-performance key-value store
- developed internally in FB, now open-source

sources: https://code.facebook.com/posts/509727595776839/scaling-apache-giraph-to-a-trillion-edges/ http://goo.gl/XNtG6p