# Beyond relational databases

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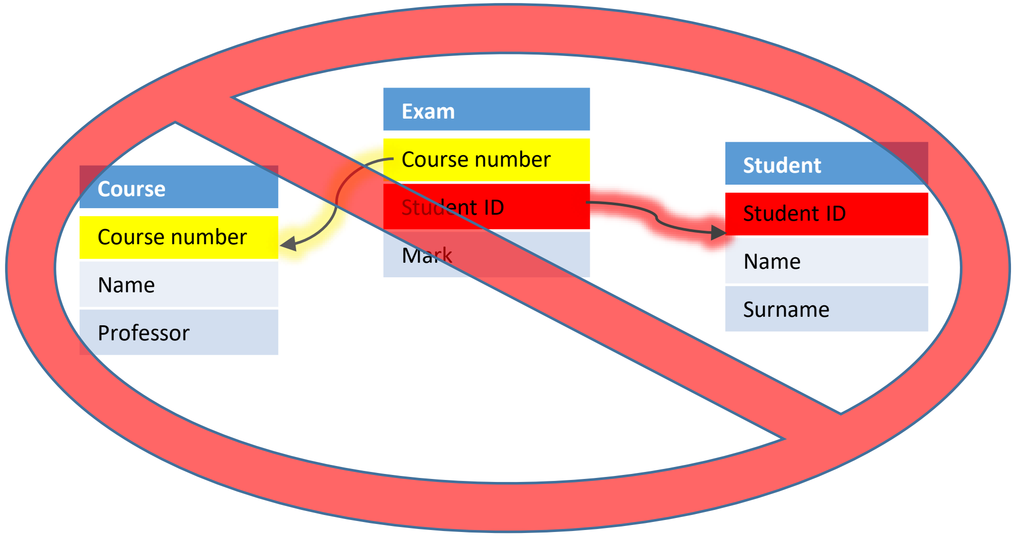
# «NoSQL» birth

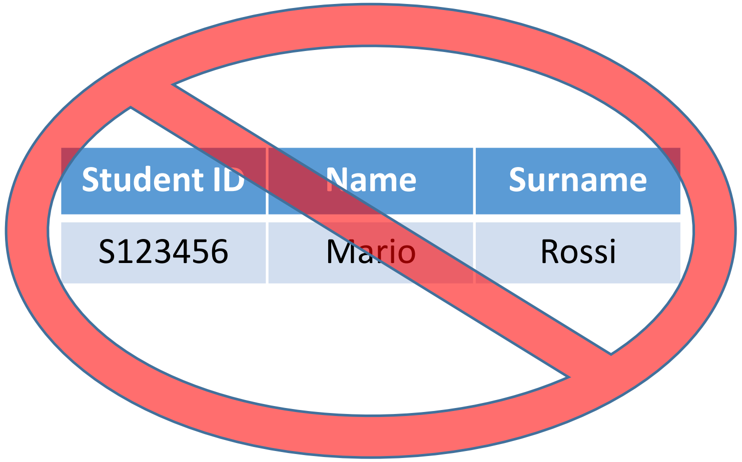
- In **1998** Carlo Strozzi’s lightweight, open-source relational database that did not expose the standard SQL interface
- In **2009** Johan Oskarsson’s (Last.fm) organizes an event to discuss recent advances on non-relational databases. A new, unique, short **hashtag** to promote the event on Twitter was needed: **#NoSQL**

# NoSQL main features

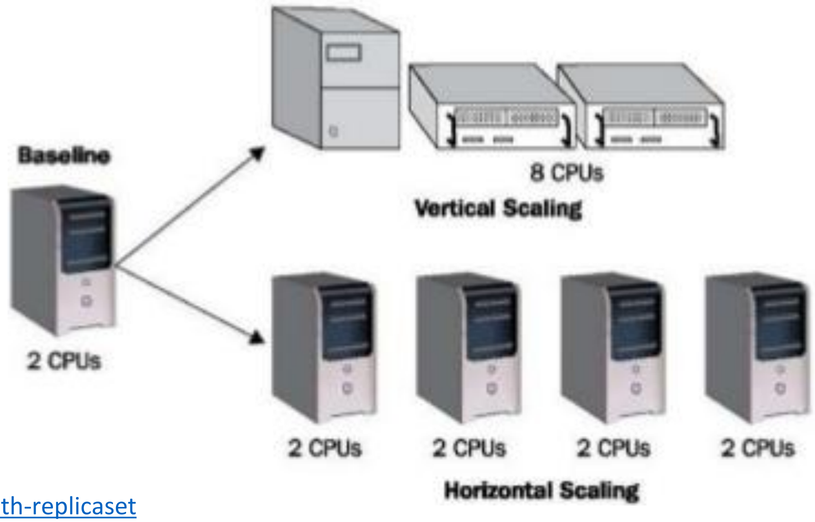
**no joins**




**schema-less**
(no tables, implicit schema)




**horizontal scalability**




http://www.slideshare.net/vivekparihar1/mongodb-scalability-and-high-availability-with-replicaset

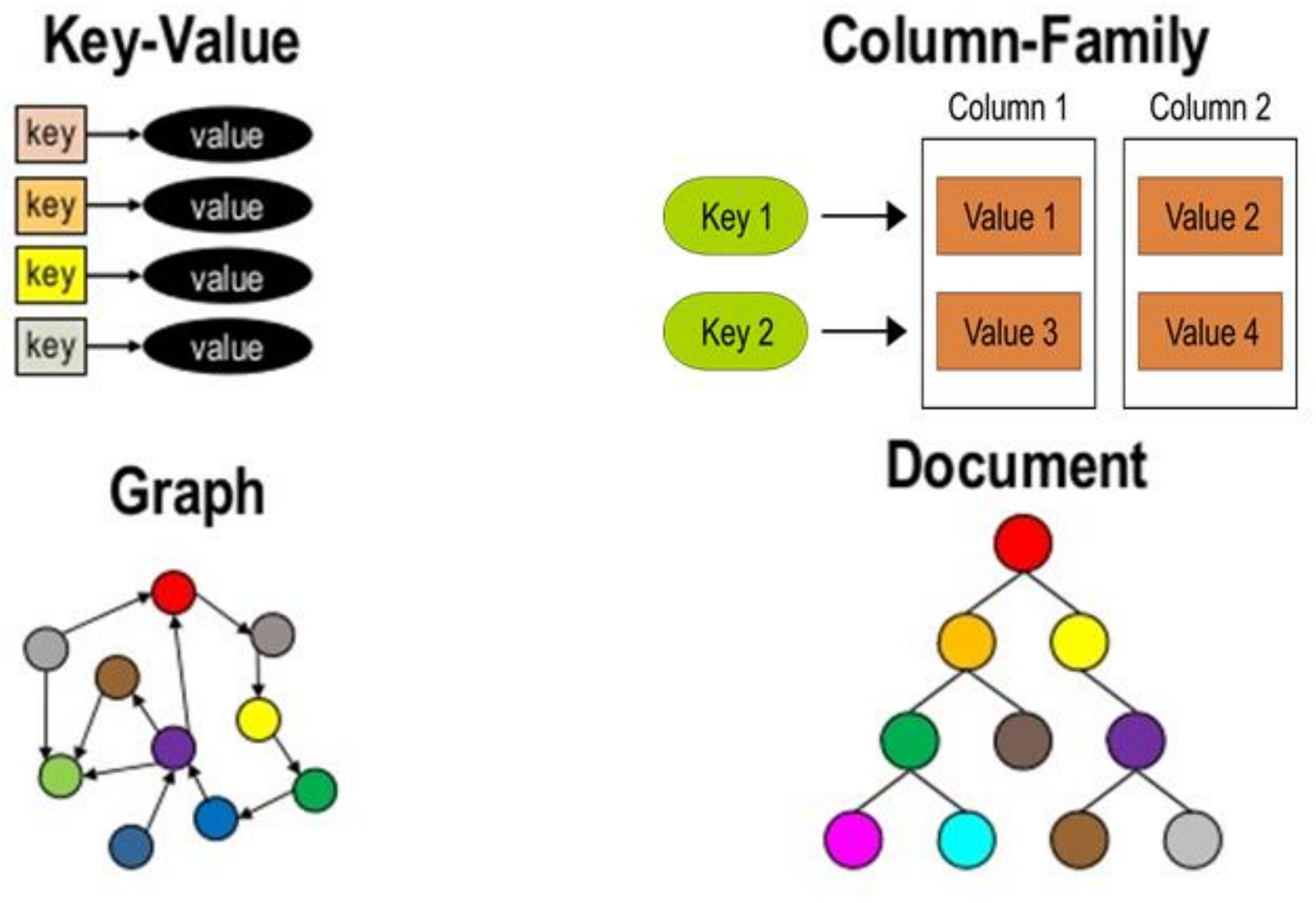
# Comparison

| Relational databases | Non-Relational databases |
|---|---|
| **Table**-based, each record is a structured row | **Specialized storage solutions**, e.g, document-based, key-value pairs, graph databases, columnar storage |
| Predefined **schema** for each table, changes allowed but usually blocking (expensive in distributed and live environments) | **Schema-less**, schema-free, schema change is dynamic for each document, suitable for semi-structured or **un-structured data** |
| **Vertically** scalable, i.e., typically scaled by increasing the power of the hardware | **Horizontally** scalable, NoSQL databases are scaled by increasing the databases servers in the pool of resources to reduce the load |
| Use **SQL** (Structured Query Language) for defining and manipulating the data, very powerful | **Custom query** languages, focused on collection of documents, graphs, and other specialized data structures |

# Comparison

| Relational databases | Non-Relational databases |
| --- | --- |
| Suitable for **complex queries**, based on data **joins** | **No standard** interfaces to perform complex queries, **no joins** |
| Suitable for **flat** and structured data storage | Suitable for complex (e.g., **hierarchical**) data, similar to JSON and XML |
| Examples: MySql, **Oracle**, Sqlite, Postgres and Microsoft SQL Server | Examples: **MongoDB**, BigTable, Redis, Cassandra, Hbase and CouchDB |

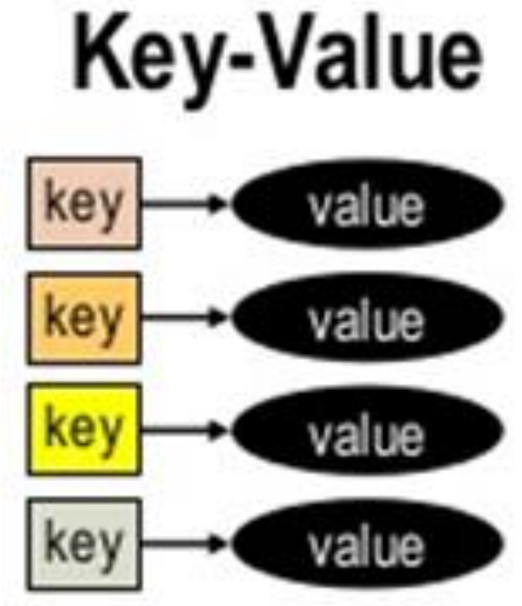
# Types of NoSQL databases




http://www.slideshare.net/Couchbase/webinar-making-sense-of-nosql-applying-nonrelational-databases-to-business-needs

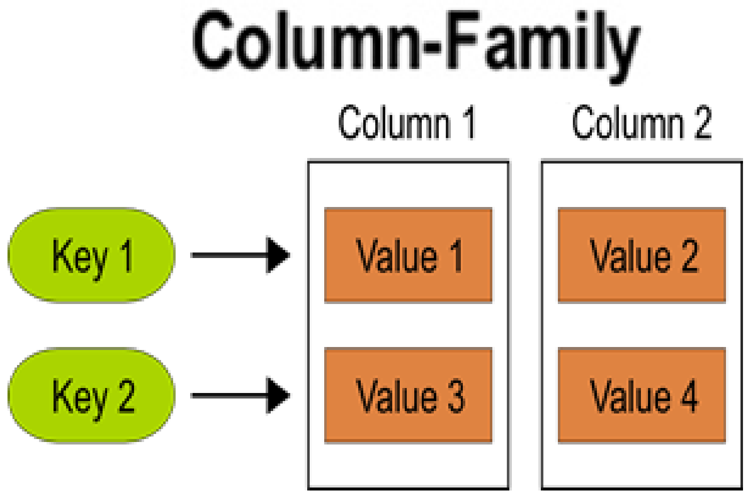
# Key-values databases

- **Simplest** NoSQL data stores
- Match keys with values
- No structure
- Great **performance**
- Easily scaled
- Very fast
- Examples: Redis, Riak, **Memcached**



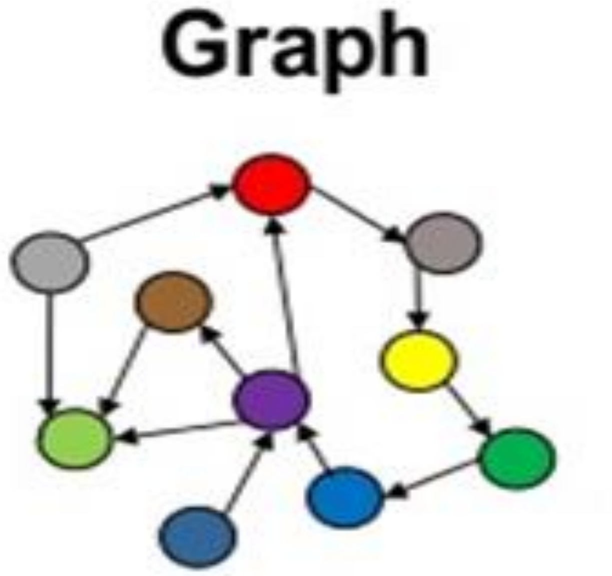
# Column-oriented databases

- Store data in **columnar** format
  - Name = "*Daniele*":row1,row3; "*Marco*":row2,row4; …
  - Surname = "*Apiletti*":row1,row5; "*Rossi*":row2,row6,row7…
- A column is a (possibly-complex) **attribute**
- Key-value pairs stored and retrieved on key in a parallel system (similar to **indexes**)
- **Rows** can be constructed from column values
- Column stores can produce row output (**tables**)
- Completely transparent to application
- Examples: Cassandra, Hbase, Hypertable, Amazon DynamoDB



# Graph databases

- Based on graph theory
- Made up by **Vertex** and **Edges**
- Used to store information about **networks**
- Good fit for several real world applications
- Examples: Neo4J, Infinite Graph, OrientDB



# Document databases

- Database stores and retrieves documents
- Keys are mapped to documents
- Documents are self-describing (**attribute=value**)
- Has hierarchical-tree nested data structures (e.g., maps, **lists**, datetime, …)
- **Heterogeneous** nature of documents
- Examples: **MongoDB**, CouchDB, RavenDB.

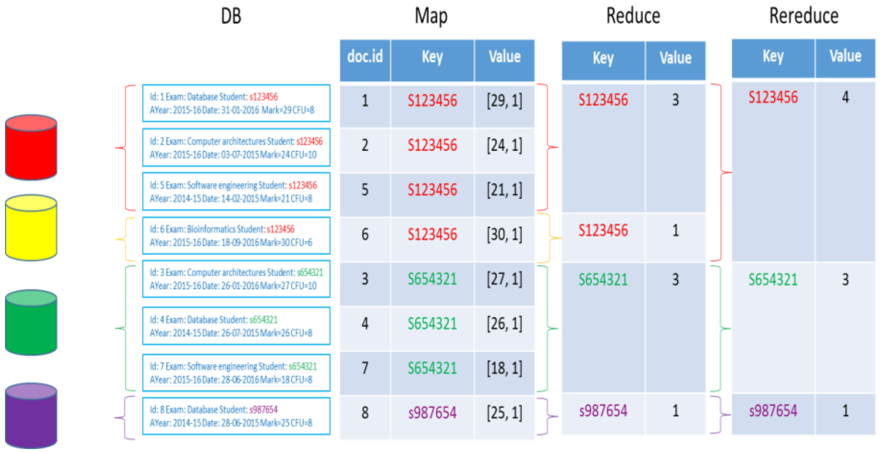
# a notable NoSQL example

**CouchDB**

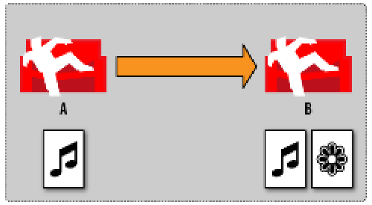
**C**luster **O**f **U**nreliable
**C**ommodity **H**ardware

# CouchDB original home page

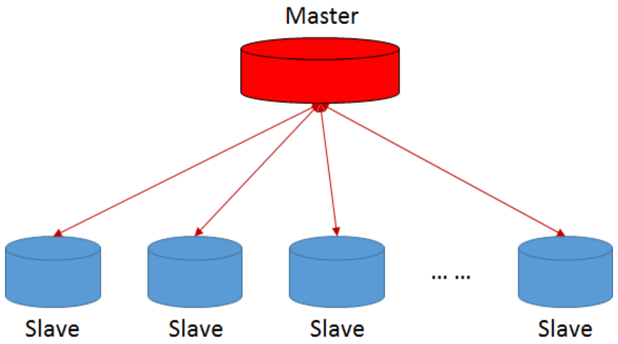
**Document-oriented** database can be queried and indexed in a **MapReduce** fashion



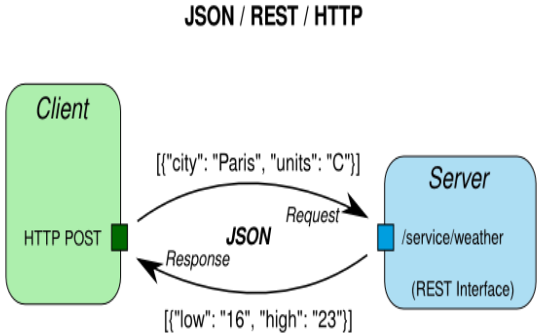

Offers incremental **replication** with bi-directional **conflict** detection and resolution




Written in Erlang, a robust functional programming language ideal for building **concurrent distributed systems**. Erlang allows for a flexible design that is **easily scalable** and readily extensible

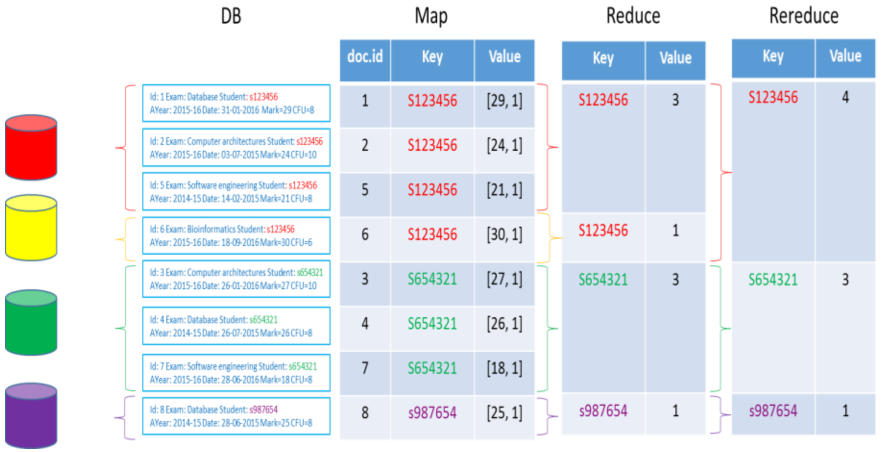



Provides a **RESTful JSON API** than can be accessed from any enviroment that allows **HTTP** requests



# CouchDB original home page

**Document-oriented** database can be queried and indexed in a **MapReduce** fashion

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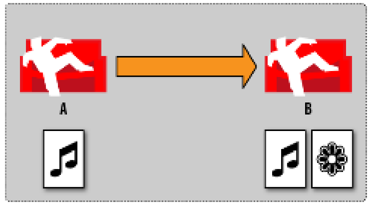


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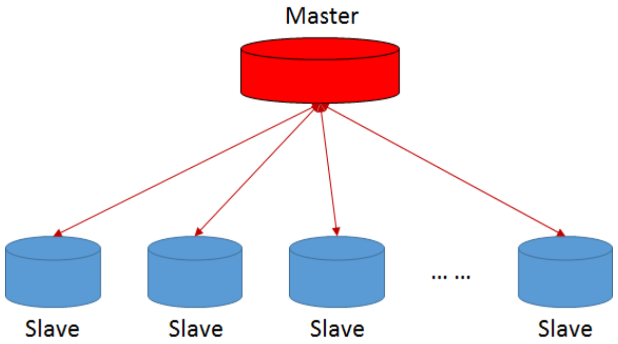


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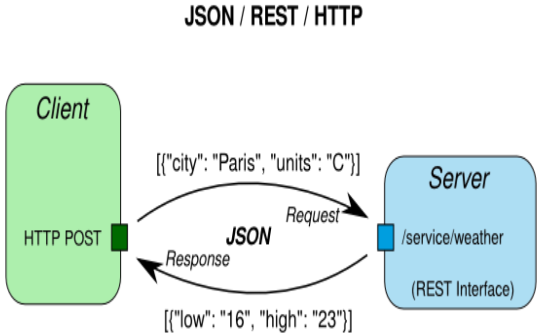


# MapReduce

a **scalable** distributed programming model to **process** Big Data

# MapReduce

- Published in **2004** by **Google**
  - J. Dean and S. Ghemawat, “MapReduce: Simplified Data Processing on Large Clusters”, OSDI'04: Sixth Symposium on Operating System Design and Implementation, San Francisco, CA, December, 2004
  - used to rewrite the production indexing system with 24 MapReduce operations (in August 2004 alone, 3288 TeraBytes read, 80k machine-days used, jobs of 10’ avg)
- **Distributed** programming model
- Process large data sets with parallel algorithms on a **cluster** of common machines, e.g., PCs
- Great for **parallel** jobs requiring pieces of computations to be executed on all data records
- **Move the computation** (algorithm) **to the data** (remote node, PC, disk)
- Inspired by the map and reduce functions used in **functional programming**
  - In functional code, the output value of a function depends only on the arguments that are passed to the function, so calling a function *f* twice with the same value for an argument *x* produces the same result *f(x)* each time; this is in contrast to procedures depending on a local or global state, which may produce different results at different times when called with the same arguments but a different program state.

# MapReduce: working principles

- Consists of two functions, a **Map** and a **Reduce**
  - The Reduce is optional
- **Map** function
  - Process each record (**docu**ment) → INPUT
  - Return a list of **key-value** pairs → OUTPUT
- **Reduce** function
  - for each **key**, reduces the list of its **values**, returned by the map, to a “single” value
  - Returned value can be a complex piece of data, e.g., a list, tuple, etc.

# Map

- Map functions are called once for each document:

```
function(doc) {
    emit(key1, value1); // key1 = fk1(doc); value1 = fv1(doc)
    emit(key2, value2); // key2 = fk2(doc); value2 = fv2(doc)
}
```

- The map function can choose to skip the document altogether or emit one or **more** key/value pairs
- Map function may **not** depend on any information **outside the document.** This independence is what allows CouchDB views to be generated incrementally and **in parallel**

# Map example

- Example database, a collection of docs describing university exam records

Id: 1
Exam: Database
Student: s123456
AYear: 2015-16
Date: 31-01-2016
Mark=29
CFU=8

Id: 2
Exam: Computer architectures
Student: s123456
AYear: 2015-16
Date: 03-07-2015
Mark=24
CFU=10

Id: 3
Exam: Computer architectures
Student: s654321
AYear: 2015-16
Date: 26-01-2016
Mark=27
CFU=10

Id: 4
Exam: Database
Student: s654321
AYear: 2014-15
Date: 26-07-2015
Mark=26
CFU=8

Id: 5
Exam: Software engineering
Student: s123456
AYear: 2014-15
Date: 14-02-2015
Mark=21
CFU=8

Id: 6
Exam: Bioinformatics
Student: s123456
AYear: 2015-16
Date: 18-09-2016
Mark=30
CFU=6

Id: 7
Exam: Software engineering
Student: s654321
AYear: 2015-16
Date: 28-06-2016
Mark=18
CFU=8

Id: 8
Exam: Database
Student: s987654
AYear: 2014-15
Date: 28-06-2015
Mark=25
CFU=8

# Map example (1)

- List of exams and corresponding marks

```
Function(doc){
    emit(doc.exam, doc.mark);
}
```

**Key** **Value**

Id: 2
Exam: Computer architectures
Student: s123456
AYear: 2015-16
Date: 03-07-2015
Mark=24
CFU=10

Id: 3
Exam: Computer architectures
Student: s654321
AYear: 2015-16
Date: 26-01-2016
Mark=27
CFU=10

Id: 4
Exam: Database
Student: s654321
AYear: 2014-15
Date: 26-07-2015
Mark=26
CFU=8

Id: 1
Exam: Database
Student: s123456
AYear: 2015-16
Date: 31-01-2016
Mark=29
CFU=8

Id: 5
Exam: Software engineering
Student: s123456
AYear: 2014-15
Date: 14-02-2015
Mark=21
CFU=8

Id: 8
Exam: Database
Student: s987654
AYear: 2014-15
Date: 28-06-2015
Mark=25
CFU=8

Id: 7
Exam: Software engineering
Student: s654321
AYear: 2015-16
Date: 28-06-2016
Mark=18
CFU=8

Id: 6
Exam: Bioinformatics
Student: s123456
AYear: 2015-16
Date: 18-09-2016
Mark=30
CFU=6

Result:

| doc.id | Key | Value |
|---|---|---|
| 6 | Bioinformatics | 30 |
| 2 | Computer architectures | 24 |
| 3 | Computer architectures | 27 |
| 1 | Database | 29 |
| 4 | Database | 26 |
| 8 | Database | 25 |
| 5 | Software engineering | 21 |
| 7 | Software engineering | 18 |

# Map example (2)

- Ordered list of exams, academic year, and date, and select their mark

```
Function(doc) {
        key = [doc.exam, doc.AYear]
        value = doc.mark
        emit(key, value);
}
```

| | | |
|---|---|---|
| Id: 2<br>Exam: Computer architectures<br>Student: s123456<br>AYear: 2015-16<br>Date: 03-07-2015<br>Mark=24<br>CFU=10 | Id: 3<br>Exam: Computer architectures<br>Student: s654321<br>AYear: 2015-16<br>Date: 26-01-2016<br>Mark=27<br>CFU=10 | Id: 4<br>Exam: Database<br>Student: s654321<br>AYear: 2014-15<br>Date: 26-07-2015<br>Mark=26<br>CFU=8 |
| Id: 1<br>Exam: Database<br>Student: s123456<br>AYear: 2015-16<br>Date: 31-01-2016<br>Mark=29<br>CFU=8 | | Id: 5<br>Exam: Software engineering<br>Student: s123456<br>AYear: 2014-15<br>Date: 14-02-2015<br>Mark=21<br>CFU=8 |
| Id: 8<br>Exam: Database<br>Student: s987654<br>AYear: 2014-15<br>Date: 28-06-2015<br>Mark=25<br>CFU=8 | Id: 7<br>Exam: Software engineering<br>Student: s654321<br>AYear: 2015-16<br>Date: 28-06-2016<br>Mark=18<br>CFU=8 | Id: 6<br>Exam: Bioinformatics<br>Student: s123456<br>AYear: 2015-16<br>Date: 18-09-2016<br>Mark=30<br>CFU=6 |

Result:

| doc.id | Key | Value |
|---|---|---|
| 6 | [Bioinformatics, 2015-16] | 30 |
| 2 | [Computer architectures, 2015-16] | 24 |
| 3 | [Computer architectures, 2015-16] | 27 |
| 4 | [Database, 2014-15] | 26 |
| 8 | [Database, 2014-15] | 25 |
| 1 | [Database, 2015-16] | 29 |
| 5 | [Software engineering, 2014-15] | 21 |
| 7 | [Software engineering, 2015-16] | 18 |

# Map example (3)

- Ordered list of students, with mark and CFU for each exam

```
Function(doc) {
    key = doc.student
    value = [doc.mark, doc.CFU]
    emit(key, value);
}
```

Id: 2
Exam: Computer architectures
Student: s123456
AYear: 2015-16
Date: 03-07-2015
Mark=24
CFU=10

Id: 3
Exam: Computer architectures
Student: s654321
AYear: 2015-16
Date: 26-01-2016
Mark=27
CFU=10

Id: 4
Exam: Database
Student: s654321
AYear: 2014-15
Date: 26-07-2015
Mark=26
CFU=8

Id: 1
Exam: Database
Student: s123456
AYear: 2015-16
Date: 31-01-2016
Mark=29
CFU=8

Id: 5
Exam: Software engineering
Student: s123456
AYear: 2014-15
Date: 14-02-2015
Mark=21
CFU=8

Id: 8
Exam: Database
Student: s987654
AYear: 2014-15
Date: 28-06-2015
Mark=25
CFU=8

Id: 7
Exam: Software engineering
Student: s654321
AYear: 2015-16
Date: 28-06-2016
Mark=18
CFU=8

Id: 6
Exam: Bioinformatics
Student: s123456
AYear: 2015-16
Date: 18-09-2016
Mark=30
CFU=6

Result:

| doc.id | Key | Value |
|---|---|---|
| 1 | S123456 | [29, 8] |
| 2 | S123456 | [24, 10] |
| 5 | S123456 | [21, 8] |
| 6 | S123456 | [30, 6] |
| 3 | S654321 | [27, 10] |
| 4 | S654321 | [26, 8] |
| 7 | S654321 | [18, 8] |
| 8 | s987654 | [25, 8] |

# Reduce

- Documents (key-value pairs) emitted by the map function are **sorted by key**
  - some platforms (e.g. Hadoop) allow you to specifically define a **shuffle phase** to manage the distribution of map results to reducers spread over different nodes, thus providing a fine-grained control over **communication costs**
- Reduce **inputs** are the map outputs: a **list** of key-value documents
- Each execution of the reduce function returns **one key-value document**
- The most simple SQL-equivalent operations performed by means of reducers are **«group by» aggregations**, but reducers are very flexible functions that can execute even **complex operations**
- **Re-reduce**: reduce functions can be called on their own results in CouchDB

# MapReduce example (1)

- Map - List of exams and corresponding mark

```
Function(doc){
    emit(doc.exam, doc.mark);
}
```

- Reduce - Compute the average mark for each exam

```
Function(key, values){
    S = sum(values);
    N = len(values);
    AVG = S/N;
    return AVG;
}
```

id: 1 **DOC**
Exam: Database
Student: s123456
AYear: 2015-16
Date: 31-01-2016
Mark=29
CFU=8

The reduce function receives:
- **key**=Bioinformatics, **values**=[30]
- …
- **key**=Database, **values**=[29,26,25]
- …

Map

| doc.id | Key | Value |
|---|---|---|
| 6 | Bioinformatics | 30 |
| 2 | Computer architectures | 24 |
| 3 | Computer architectures | 27 |
| 1 | Database | 29 |
| 4 | Database | 26 |
| 8 | Database | 25 |
| 5 | Software engineering | 21 |
| 7 | Software engineering | 18 |

Reduce

| Key | Value |
|---|---|
| Bioinformatics | 30 |
| Computer architectures | 25.5 |
| Database | 26.67 |
| Software engineering | 19.5 |

# MapReduce example (2)

- Map - List of exams and corresponding mark

```
Function(doc){
    emit(
      [doc.exam, doc.AYear],
      doc.mark
    );
}
```

- Reduce - Compute the average mark for each exam and academic year

```
Function(key, values){
    S = sum(values);
    N = len(values);
    AVG = S/N;
    return AVG;
}
```

**Reduce is the same as before**

id: 1 **DOC**
Exam: Database
Student: s123456
AYear: 2015-16
Date: 31-01-2016
Mark=29
CFU=8

The reduce function receives:
- **key**=[Database, 2014-15], **values**=[26,25]
- **key**=[Database, 2015-16], **values**=[29]
- …

Map

| doc.id | Key | Value |
|---|---|---|
| 6 | Bioinformatics, 2015-16 | 30 |
| 2 | Computer architectures, 2015-16 | 24 |
| 3 | Computer architectures, 2015-16 | 27 |
| 4 | Database, 2014-15 | 26 |
| 8 | Database, 2014-15 | 25 |
| 1 | Database, 2015-16 | 29 |
| 5 | Software engineering, 2014-15 | 21 |
| 7 | Software engineering, 2015-16 | 18 |

Reduce

| Key | Value |
|---|---|
| [Bioinformatics, 2015-16] | 30 |
| [Computer architectures, 2015-16] | 25.5 |
| [Database, 2014-15] | 25.5 |
| [Database, 2015-16] | 29 |
| [Software engineering, 2014-15] | 21 |
| [Software engineering, 2015-16] | 18 |

# Rereduce in CouchDB

- Average mark the for each exam (**group level=1**) – **same Reduce** as before

**DB**

Id: 1
Exam: Database
Student: s123456
AYear: 2015-16
Date: 31-01-2016
Mark=29
CFU=8

Id: 8
Exam: Database
Student: s987654
AYear: 2014-15
Date: 28-06-2015
Mark=25
CFU=8

Id: 6
Exam: Bioinformatics
Student: s123456
AYear: 2015-16
Date: 18-09-2016
Mark=30
CFU=6

Id: 4
Exam: Database
Student: s654321
AYear: 2014-15
Date: 26-07-2015
Mark=26
CFU=8

Id: 5
Exam: Software engineering
Student: s123456
AYear: 2014-15
Date: 14-02-2015
Mark=21
CFU=8

Id: 7
Exam: Software engineering
Student: s654321
AYear: 2015-16
Date: 28-06-2016
Mark=18
CFU=8

Id: 3
Exam: Computer architectures
Student: s654321
AYear: 2015-16
Date: 26-01-2016
Mark=27
CFU=10

Id: 2
Exam: Computer architectures
Student: s123456
AYear: 2015-16
Date: 03-07-2015
Mark=24
CFU=10

**Map**

| doc.id | Key | Value |
|---|---|---|
| 6 | Bioinformatics, 2015-16 | 30 |
| 2 | Computer architectures, 2015-16 | 24 |
| 3 | Computer architectures, 2015-16 | 27 |
| 4 | Database, 2014-1015 | 26 |
| 8 | Database, 2014-15 | 25 |
| 1 | Database, 2015-16 | 29 |
| 5 | Software engineering, 2014-15 | 21 |
| 7 | Software engineering, 2015-16 | 18 |

**Reduce**

| Key | Value |
|---|---|
| [Bioinformatics, 2015-16] | 30 |
| [Computer architectures, 2015-16] | 25.5 |
| [Database, 2014-15] | 25.5 |
| [Database, 2015-16] | 29 |
| [Software engineering, 2014-15] | 21 |
| [Software engineering, 2015-16] | 18 |

**Rereduce**

| Key | Value |
|---|---|
| Bioinformatics | 30 |
| Computer architectures | 25.5 |
| Database | 27.25 |
| Software engineering | 19.5 |

# MapReduce example (3a)

id: 1 **DOC**
Exam: Database
Student: s123456
AYear: 2015-16
Date: 31-01-2016
Mark=29
CFU=8

## Average CFU-weighted mark for each student

- Map

The reduce function receives:
- **key**=
  **values**=
- …
- **key**=
- **values**=

- Reduce

The reduce function results:
- **key**=
  **values**=
- …
- **key**=
- **values**=

Map

| doc.id | Key | Value |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

Reduce

| Key | Value |
|---|---|
| | |
| | |
| | |

# MapReduce example (3a)

- Map - Ordered list of students, with mark and CFU for each exam

```
Function(doc) {
    key = doc.student
    value = [doc.mark, doc.CFU]
    emit(key, value);
}
```

- Reduce - Average CFU-weighted mark for each student

```
Function(key, values){
    S = sum([ X*Y for X,Y in values ]);
    N = sum([ Y for X,Y in values ]);
    AVG = S/N;
    return AVG;
}
```

**key** = S123456,
**values** = [(29,8), (24,10), (21,8)…]
**X** = 29, 24, 21, … → mark
**Y** = 8, 10, 8, … →CFU

The reduce function receives:

- **key**=S123456,
  **values**=[(29,8), (24,10), (21,8)…]
- …
- **key**=s987654, **values**=[(25,8)]

Map

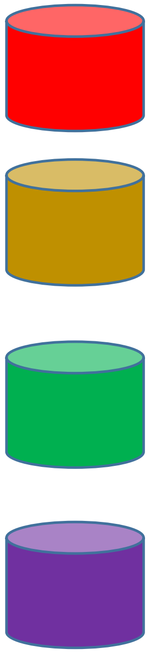
| doc.id | Key | Value |
|---|---|---|
| 1 | S123456 | [29, 8] |
| 2 | S123456 | [24, 10] |
| 5 | S123456 | [21, 8] |
| 6 | S123456 | [30, 6] |
| 3 | S654321 | [27, 10] |
| 4 | S654321 | [26, 8] |
| 7 | S654321 | [18, 8] |
| 8 | s987654 | [25, 8] |

Reduce

| Key | Value |
|---|---|
| S123456 | 25.6 |
| S654321 | 23.9 |
| s987654 | 25 |

# MapReduce example (3b)

- Compute the number of exams for each student
- Technological view of data distribution among different nodes



DB

- Id: 1 Exam: Database Student: s123456
  AYear: 2015-16 Date: 31-01-2016 Mark=29 CFU=8
- Id: 2 Exam: Computer architectures Student: s123456
  AYear: 2015-16 Date: 03-07-2015 Mark=24 CFU=10
- Id: 5 Exam: Software engineering Student: s123456
  AYear: 2014-15 Date: 14-02-2015 Mark=21 CFU=8
- Id: 6 Exam: Bioinformatics Student: s123456
  AYear: 2015-16 Date: 18-09-2016 Mark=30 CFU=6
- Id: 3 Exam: Computer architectures Student: s654321
  AYear: 2015-16 Date: 26-01-2016 Mark=27 CFU=10
- Id: 4 Exam: Database Student: s654321
  AYear: 2014-15 Date: 26-07-2015 Mark=26 CFU=8
- Id: 7 Exam: Software engineering Student: s654321
  AYear: 2015-16 Date: 28-06-2016 Mark=18 CFU=8
- Id: 8 Exam: Database Student: s987654
  AYear: 2014-15 Date: 28-06-2015 Mark=25 CFU=8

Map

| doc.id | Key | Value |
|---|---|---|
| 1 | S123456 | [29, 1] |
| 2 | S123456 | [24, 1] |
| 5 | S123456 | [21, 1] |
| 6 | S123456 | [30, 1] |
| 3 | S654321 | [27, 1] |
| 4 | S654321 | [26, 1] |
| 7 | S654321 | [18, 1] |
| 8 | s987654 | [25, 1] |

Reduce

| Key | Value |
|---|---|
| S123456 | 3 |
| S123456 | 1 |
| S654321 | 3 |
| s987654 | 1 |

Rereduce

| Key | Value |
|---|---|
| S123456 | 4 |
| S654321 | 3 |
| s987654 | 1 |

# Views (indexes)

- The only way to **query** CouchDB is to build a view on the data
- A view is produced by a MapReduce
- The predefined view for each database has
  - the document ID as **key**,
  - the whole document as **value**
  - no Reduce
- CouchDB views are **materialized** as values **sorted by key**
  - allows the same DB to have **multiple primary indexes**
- When writing CouchDB map functions, your primary goal is to build an index that **stores related data under nearby keys**

# Replication

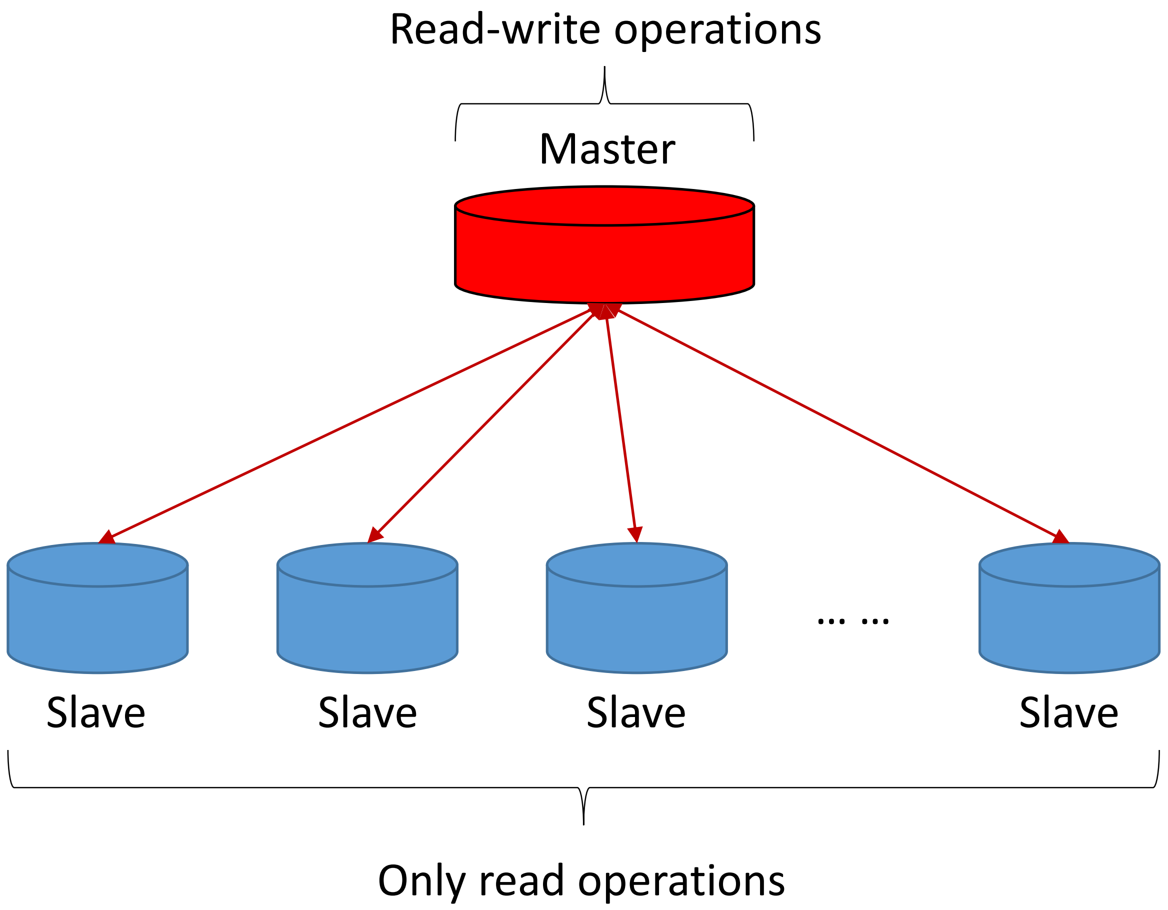
**Same** data
in **different** places
(content and schema)

# Replication

- **Same** data
    - portions of the whole dataset (chunks)
- in **different** places
    - local and/or remote servers, clusters, data centers
- Goals
    - Redundancy helps surviving failures (availability)
    - Better performance
- Approaches
    - Master-Slave replication
    - A-Synchronous replication

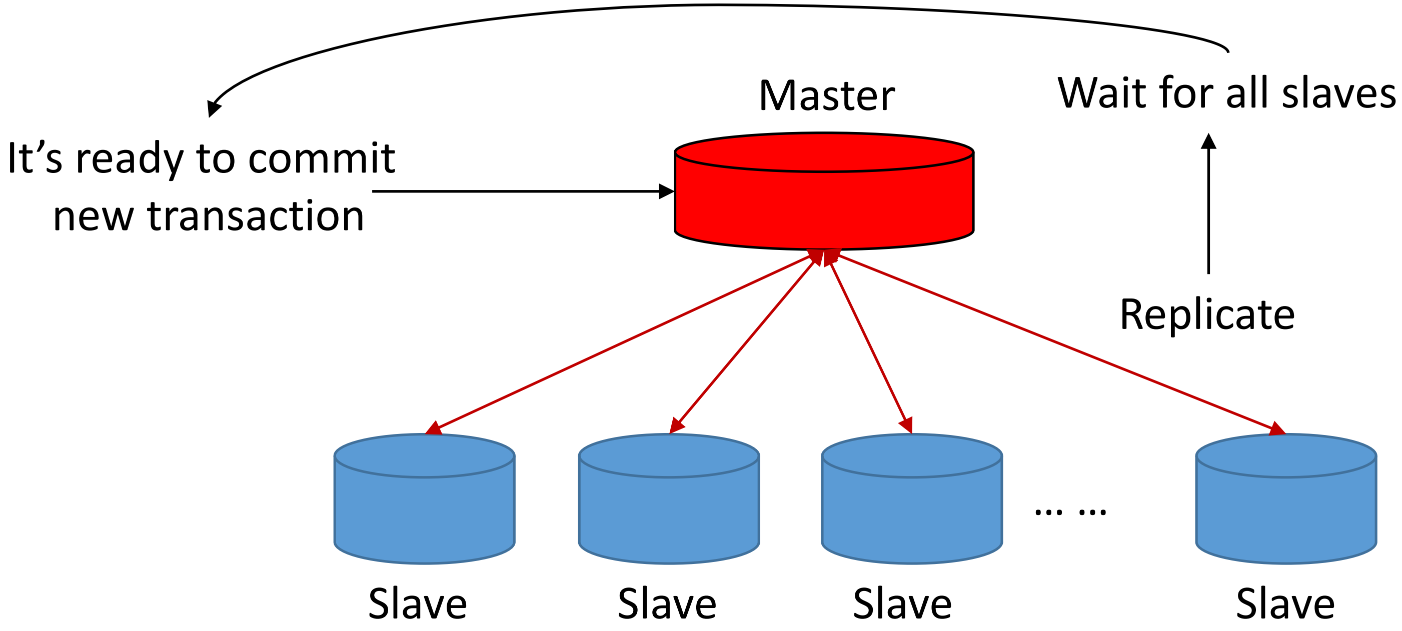
# Master-Slave replication

- Master-Slave
  - A **master** server takes all the writes, updates, inserts
  - One or more **Slave** servers take all the reads (they can't write)
  - Only read **scalability**
  - The master is a single point of **failure**
- CouchDB supports Master-Master replication



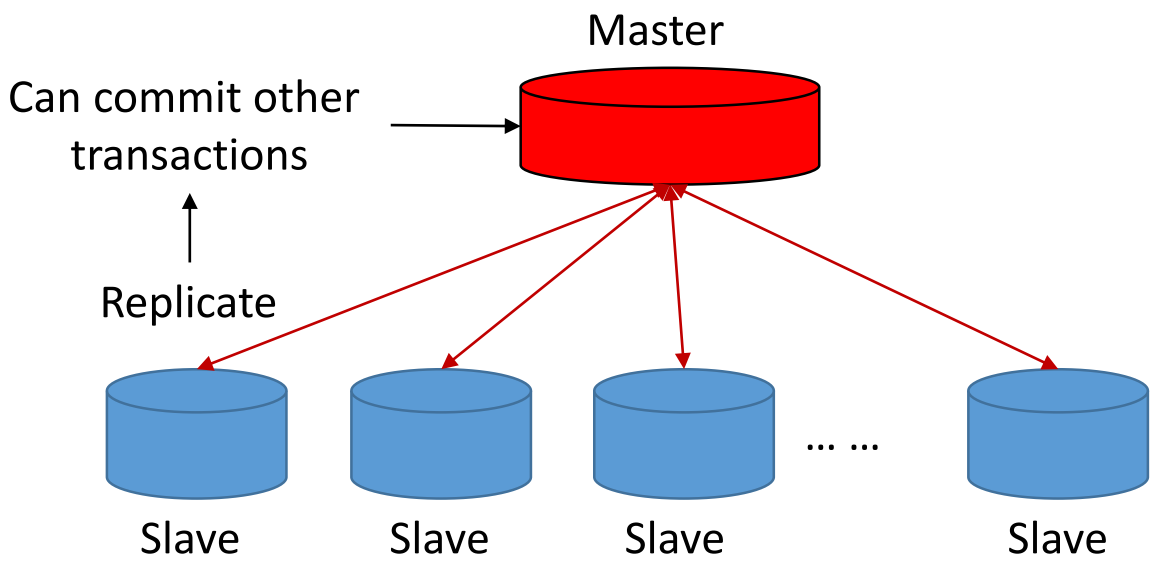
# Synchronous replication

- Before committing a transaction, the Master **waits** for (all) the Slaves to commit
- Similar in concept to the **2-Phase Commit** in relational databases
- **Performance** killer, in particular for replication in the cloud
- Trade-off: wait for a subset of Slaves to commit, e.g., the **majority** of them



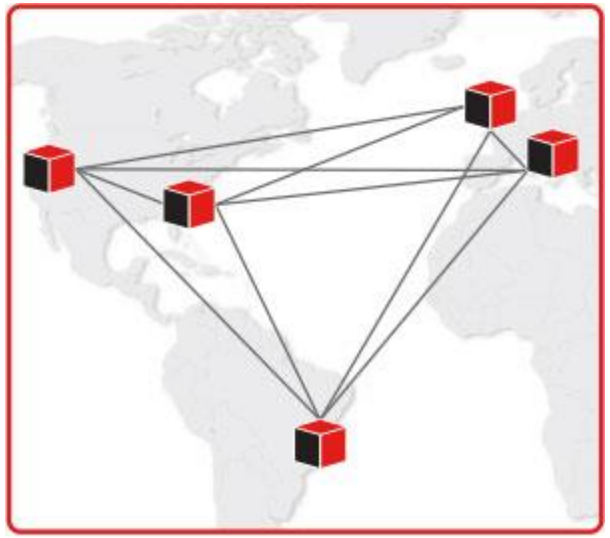
# Asynchronous replication

- The Master commits **locally**, it does not wait for any Slave
- Each Slave independently fetches updates from Master, which may **fail**…
  - IF no Slave has replicated, then you've **lost the data** committed to the Master
  - IF some Slaves have replicated and some haven't, then you have to **reconcile**
- Faster and **un**reliable



# Distributed databases

**Different** autonomous machines, working **together** to manage the same **dataset**

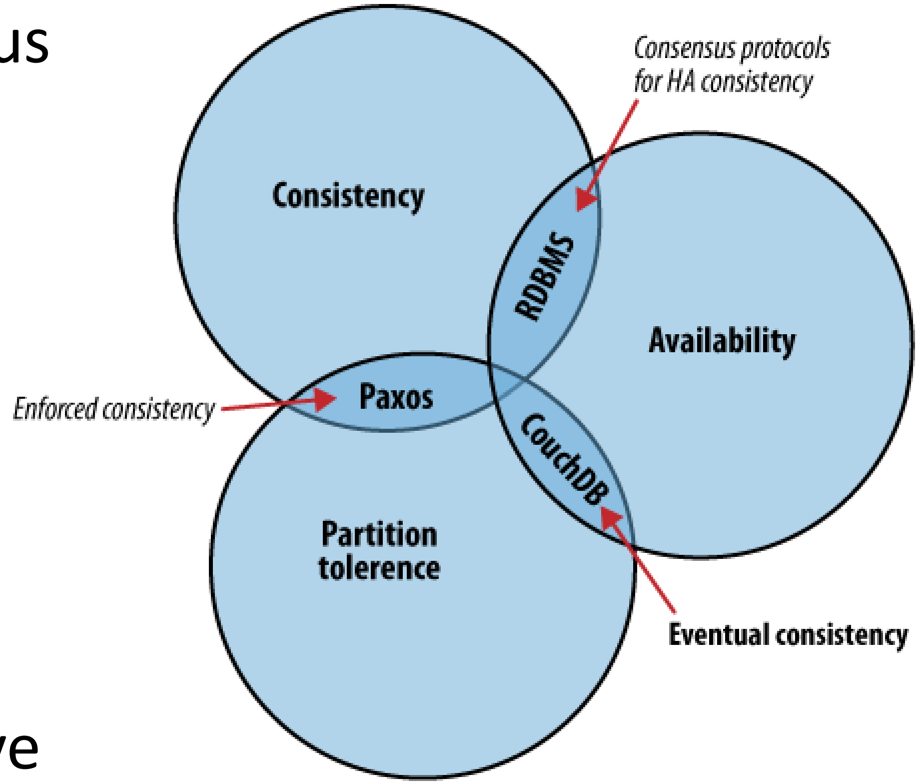


# Key features of distributed databases

- There are 3 typical problems in distributed databases:
  - **Consistency**
    - All the distributed databases provide the same data to the application
  - **Availability**
    - Database failures (e.g., master node) do not prevent survivors from continuing to operate
  - **Partition** tolerance
    - The system continues to operate despite arbitrary message loss, when connectivity failures cause network partitions

# CAP Theorem

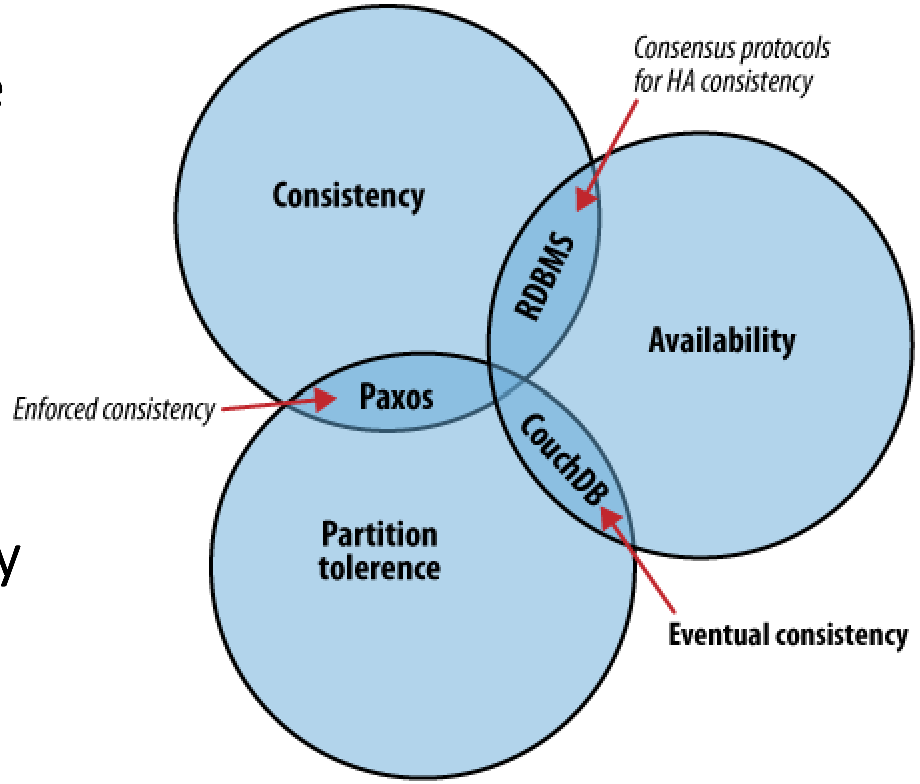
- The CAP theorem, also known as Brewer's theorem, states that it is **impossible** for a distributed system to **simultaneously** provide **all three** of the previous guarantees
- The theorem began as a **conjecture** made by University of California in 1999-2000
  - Armando Fox and Eric Brewer, “Harvest, Yield and Scalable Tolerant Systems”, Proc. 7th Workshop Hot Topics in Operating Systems (HotOS 99), IEEE CS, 1999, pg. 174-178.
- In 2002 a formal proof was published, establishing it as a **theorem**
  - Seth Gilbert and Nancy Lynch, “Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services”, ACM SIGACT News, Volume 33 Issue 2 (2002), pg. 51-59
- In 2012, a follow-up by Eric Brewer, “CAP twelve years later: How the "rules" have changed”
  - IEEE Explore, Volume 45, Issue 2 (2012), pg. 23-29.




http://guide.couchdb.org/editions/1/en/consistency.html#figure/1

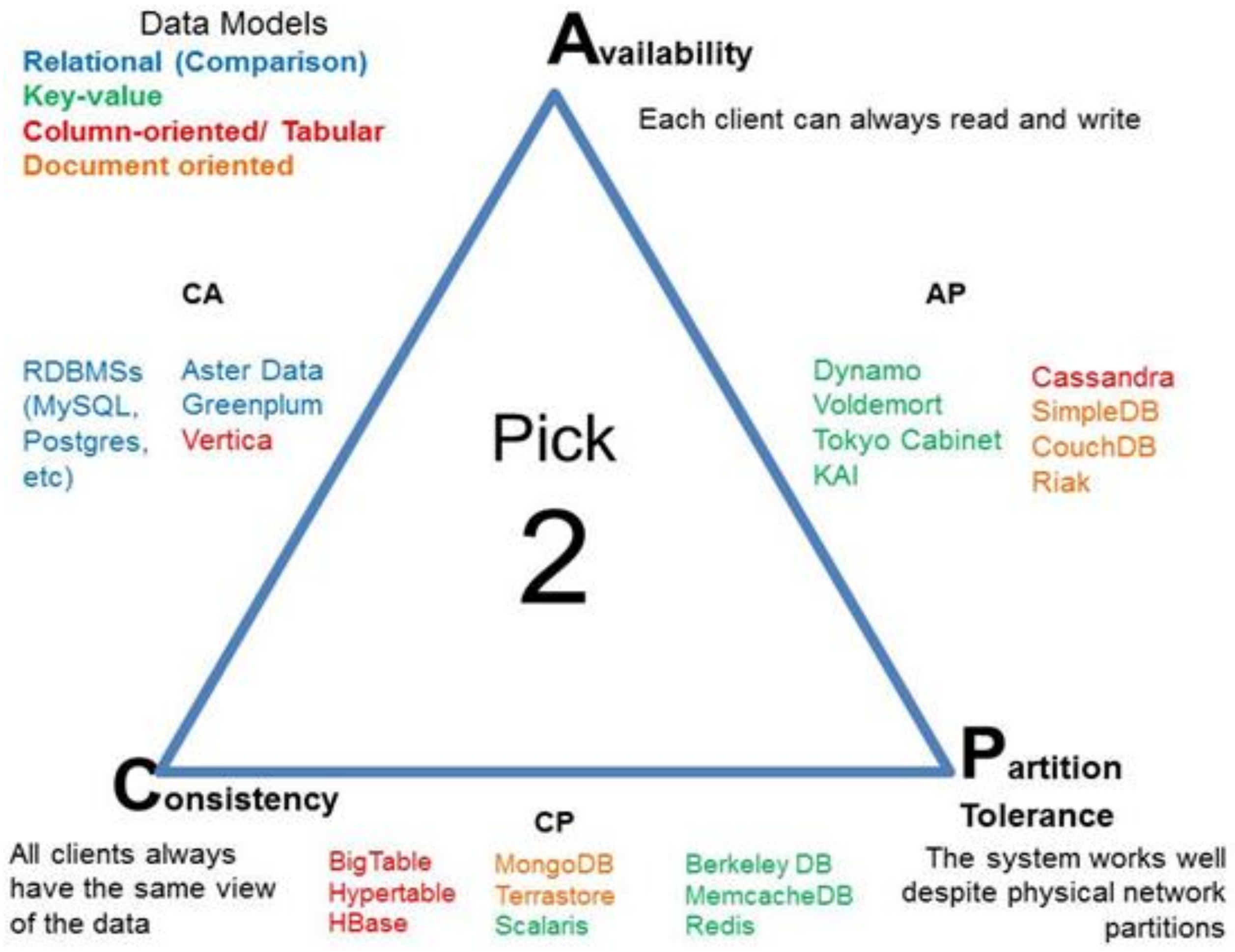
# CAP Theorem

- The easiest way to understand CAP is to think of **two nodes** on opposite sides of a **partition**.
- Allowing at least one node to update state will cause the nodes to become **inconsistent**, thus forfeiting C.
- If the choice is to preserve consistency, one side of the partition must act as if it is **unavailable**, thus forfeiting A.
- Only when no network **partition** exists, is it possible to preserve both consistency and availability, thereby forfeiting P.
- The general belief is that for wide-area systems, **designers cannot forfeit P** and therefore have a difficult choice between C and A.




http://www.infoq.com/articles/cap-twelve-years-later-how-the-rules-have-changed

# CAP Theorem




http://blog.flux7.com/blogs/nosql/cap-theorem-why-does-it-matter

# CA without P (local consistency)

- **Partitioning** (communication breakdown) causes a failure.
- We can still have **Consistency** and **Availability** of the data shared by agents **within each Partition**, by ignoring other partitions.
  - Local rather than global consistency / availability
- Local consistency for a partial system, 100% availability for the partial system, and no partitioning does not exclude several partitions from existing with their own "internal" CA.
- So partitioning means having **multiple independent systems** with 100% CA that do not need to interact.

# CP without A (transaction locking)

- A system is allowed to *not* answer requests at all (turn off "A").
- We claim to tolerate **partitioning/faults**, because we simply block all responses if a partition occurs, assuming that we cannot continue to function correctly without the data on the other side of a partition.
- Once the partition is healed and **consistency** can once again be verified, we can restore availability and leave this mode.
- In this configuration there are global consistency, and global correct behaviour in partitioning is to **block access to replica sets** that are not in synch.
- In order to tolerate P at any time, we must sacrifice A at any time for global consistency.
- This is basically the **transaction lock**.

# AP without C (best effort)

- If we don't care about **global consistency** (i.e. simultaneity), then every part of the system can make available what it knows.
- Each part might be able to answer someone, even though the system as a whole has been broken up into incommunicable regions (**partitions**).
- In this configuration without consistency means without the assurance of global consistency **at all times**.

# A consequence of CAP

“Each node in a system should be able to make decisions purely based on **local state**. If you need to do something under high load with **failures** occurring and you need to reach agreement, you’re lost. If you’re concerned about **scalability**, any algorithm that forces you to run agreement will eventually become your **bottleneck**. Take that as a given.”

*Werner Vogels, Amazon CTO and Vice President*

# Beyond CAP

- The "2 of 3" view is misleading on several fronts.
- First, because **partitions** are rare, there is little reason to forfeit C or A when the system is not partitioned.
- Second, the **choice between C and A** can occur many times within the same system at very fine granularity; not only can subsystems make different choices, but the choice can change according to the operation or even the specific data or user involved.
- Finally, all three **properties are more continuous than binary**. Availability is obviously continuous from 0 to 100 percent, but there are also many levels of consistency, and even partitions have nuances, including disagreement within the system about whether a partition exists.

# ACID versus BASE

- ACID and BASE represent two design philosophies at opposite ends of the consistency-availability spectrum
- ACID properties focus on **consistency** and are the traditional approach of databases
- BASE properties focus on high **availability** and to make explicit both the choice and the spectrum
- **BASE**: Basically Available, Soft state, Eventually consistent, work well in the presence of **partitions** and thus promote **availability**

# ACID

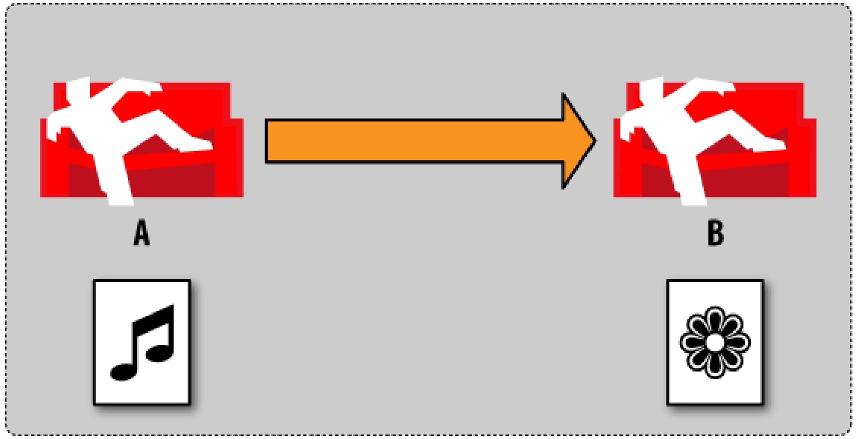
- The four ACID properties are:
  - **Atomicity (A)** All systems benefit from atomic operations, the database transaction must completely succeed or fail, partial success is not allowed
  - **Consistency (C)** During the database transaction, the database progresses from a valid state to another. In ACID, the C means that a transaction pre-serves all the database rules, such as unique keys. In contrast, the C in CAP refers only to single copy consistency.
  - **Isolation (I)** Isolation is at the core of the CAP theorem: if the system requires ACID isolation, it can operate on at most one side during a partition, because a client's transaction must be isolated from other client's transaction
  - **Durability (D)** The results of applying a transaction are permanent, it must persist after the transaction completes, even in the presence of failures.

# BASE

- **Basically Available**: the system provides availability, in terms of the CAP theorem
- **Soft state:** indicates that the state of the system may change over time, even without input, because of the eventual consistency model.
- **Eventual consistency:** indicates that the system will become consistent over time, given that the system doesn't receive input during that time
- Example: DNS – Domain Name Servers
  - DNS is not multi-master

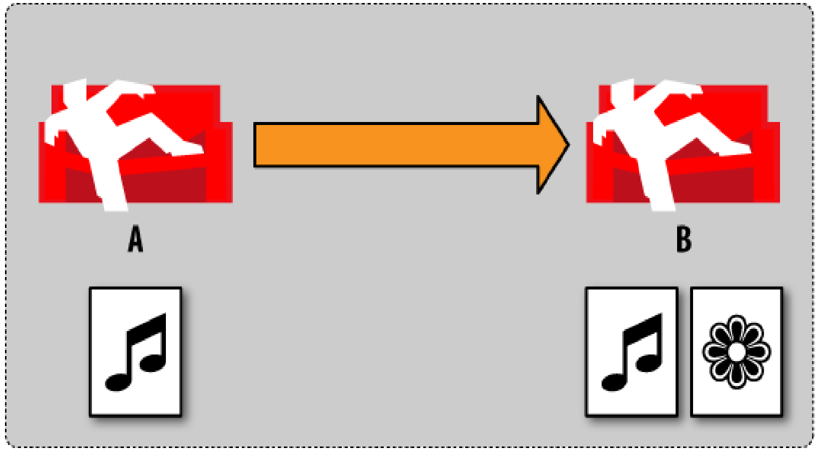
# Conflict resolution problem

- There are two customers, **A** and **B**
- **A** books a hotel room, the last available room
- **B** does the same, on a different node of the system, which was **not consistent**



# Conflict resolution problem

- The hotel room document is affected by two **conflicting updates**
- Applications should solve the conflict with custom logic (it's a business decision)
- The database can
  - **Detect** the conflict
  - Provide a local **solution**, e.g., latest version is saved as the winning version



# Conflict

- CouchDB guarantees that **each instance** that sees the **same conflict** comes up with the **same winning** and losing **revisions**.
- It does so by running a **deterministic algorithm** to pick the winner.
  - The revision with the longest revision history list becomes the winning revision.
  - If they are the same, the _rev values are compared in ASCII sort order, and the highest wins.

# HTTP API

a «**web**» database,

no ad-hoc **client** required

# HTTP RESTful API

- How to **get** a document? Use your browser and write its **URL**
  - [http://localhost:5984/test/some_doc_id](http://localhost:5984/test/some_doc_id)
- Any application and language can access **web data**
  - GET /somedatabase/some_doc_id HTTP/1.0
  - HEAD /somedatabase/some_doc_id HTTP/1.0
    - HTTP/1.1 200 OK
- **Write** a document by means of PUT HTTP request (specify revision to avoid conflicts)
  - PUT /somedatabase/some_doc_id HTTP/1.0
    - HTTP/1.1 201 Created
    - HTTP/1.1 409 Conflict

# MongoDB

The **leading** NoSQL database currently on the market

# MongoDB - intro

- Full of **features**, beyond NoSQL
- High **performance** and natively **scalable**
- Open source
- 311$ millions in funding
- 500+ employees
- **2000+ customers**


http://www.slideshare.net/mongodb/introduction-to-mongodb-56807822

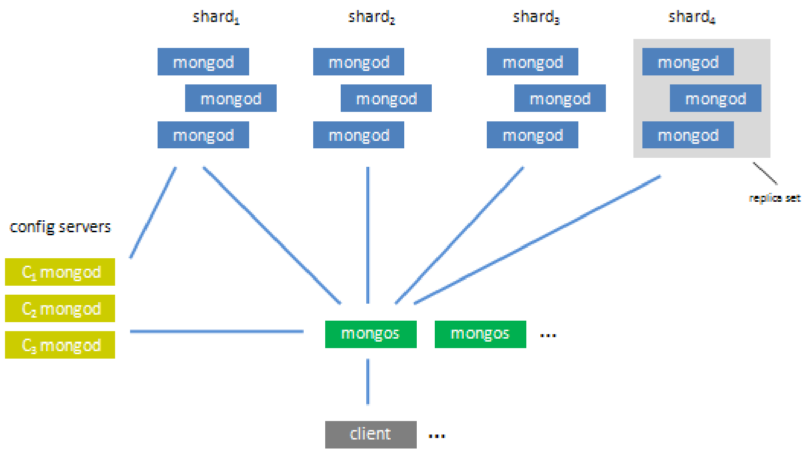
# MongoDB - why

## Why MongoDB?

| What? | Why? |
|---|---|
| JSON | End to End |
| No Schema | “No DBA”, Just Serialize |
| Write | 10K Inserts/sec on virtual machine |
| Read | Similar to MySQL |
| HA | 10 min to setup a cluster |
| Sharding | Out of the Box |
| LBS | Great for that |
| No Schema | None: no downtime to create new columns |
| Buzz | Trend is with NoSQL |

http://blogs.microsoft.co.il/blogs/vprnd
http://top-performance.blogspot.com



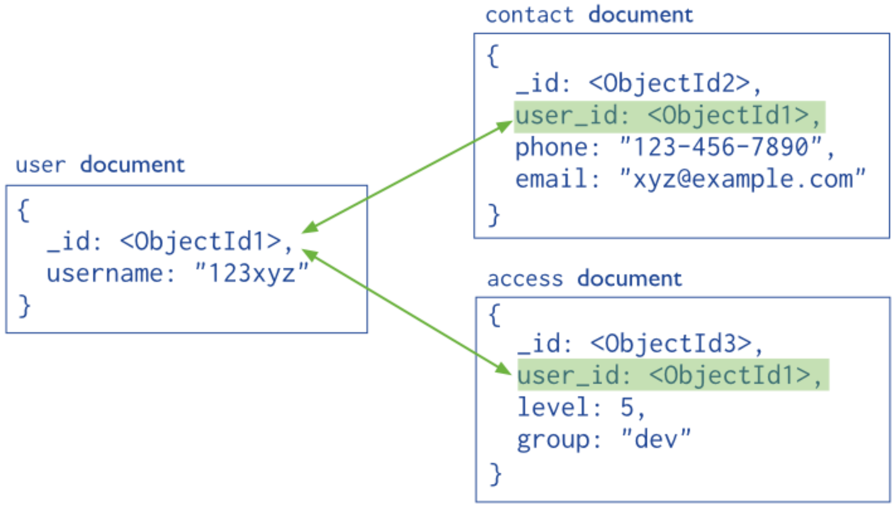



```
Fri Apr 26 22:49:38.567 [initandlisten] connection accepted from 127.0.0.1:4824
5 #7 (1 connection now open)
> use project
switched to db project
> db.posts.getIndexes()
[
        {
                "v" : 1,
                "key" : {
                        "_id" : 1
                },
                "ns" : "project.posts",
                "name" : "_id_"
        }
]
> 
```

# MongoDB – Document Data Design

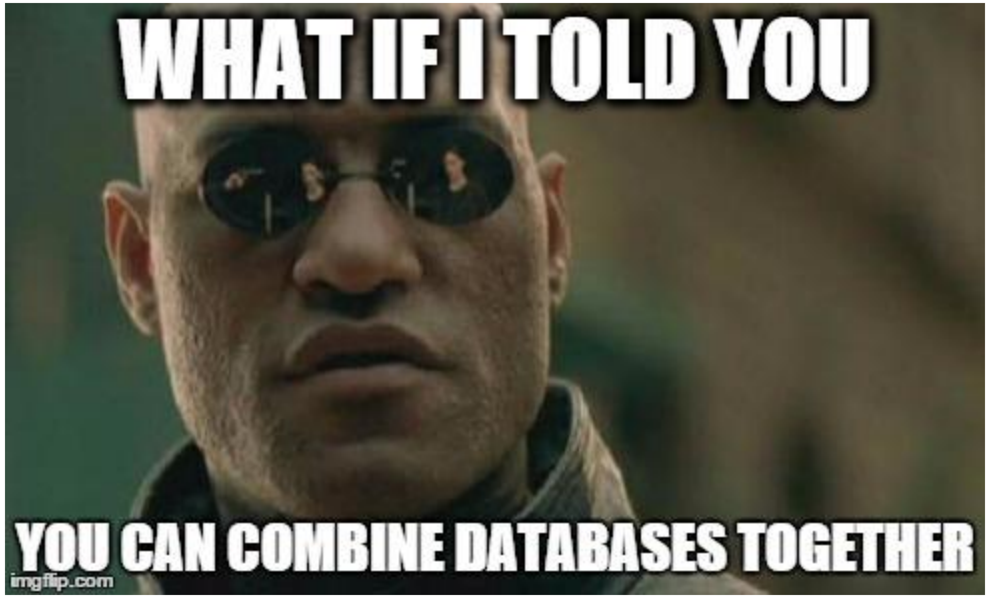
- High-level, business-ready representation of the data
- Flexible and rich, adapting to most use cases
- Mapping into developer-language objects
    - year, month, day, timestamp,
    - lists, sub-documents, etc.


- BUT
- Relations among documents / records are inefficient, and leads to de-normalization
    - Object(ID) reference, with **no native join**
- Temptation to go too much schema-free / non-relational even with structured relational data



# «So, which database should I choose?»

- If you're building an app today, then there might be a need for **using two or more databases** at the same time
- If your app does (text) search you might have to implement **ElasticSearch**
- for non-relational data-storage, **MongoDB** works the best
- if you're building an IoT which has sensors pumping out a ton of data, shoot it into **Cassandra**
- Implementing multiple databases to build one app is called "**Polyglot Persistence**"

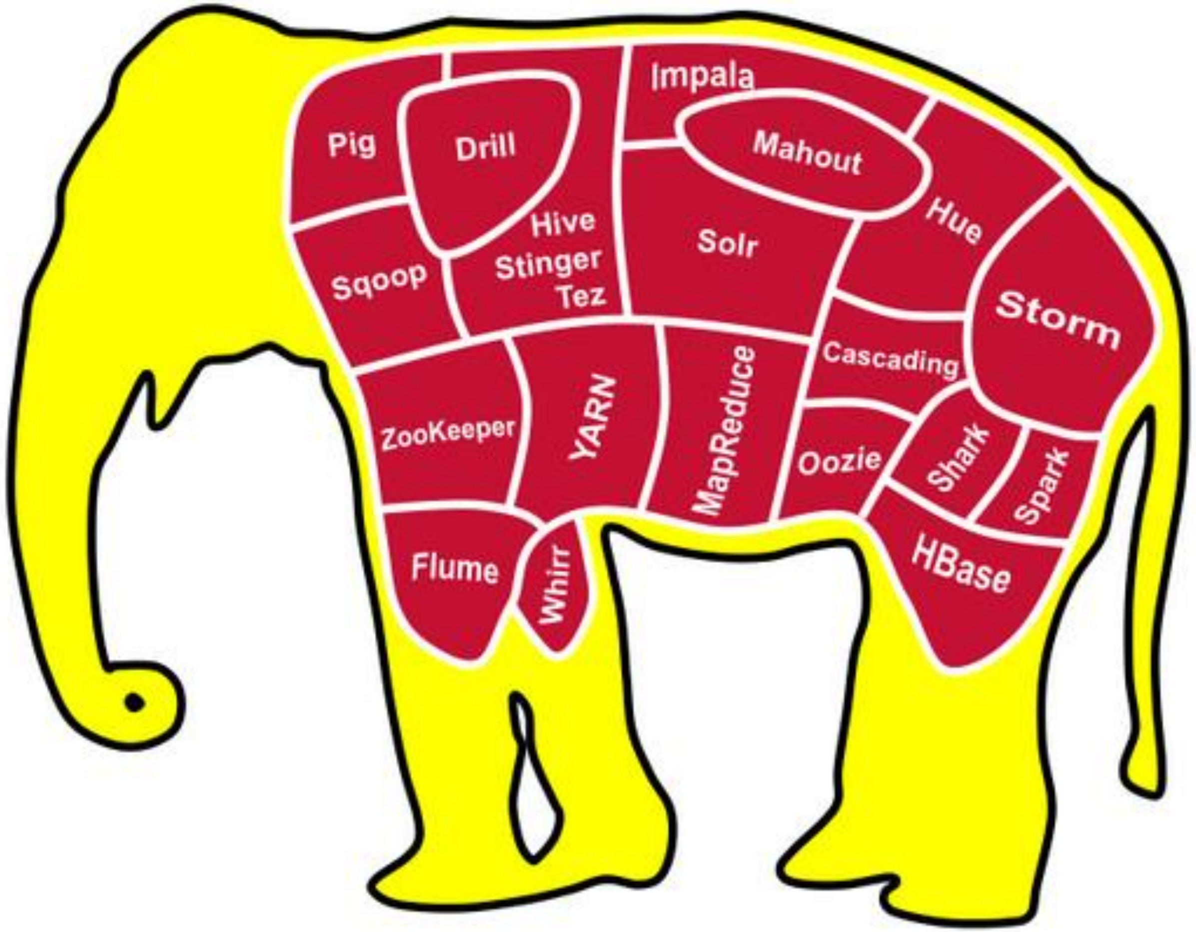



https://blog.cloudboost.io/why-you-should-not-use-only-mongodb/

# Hadoop

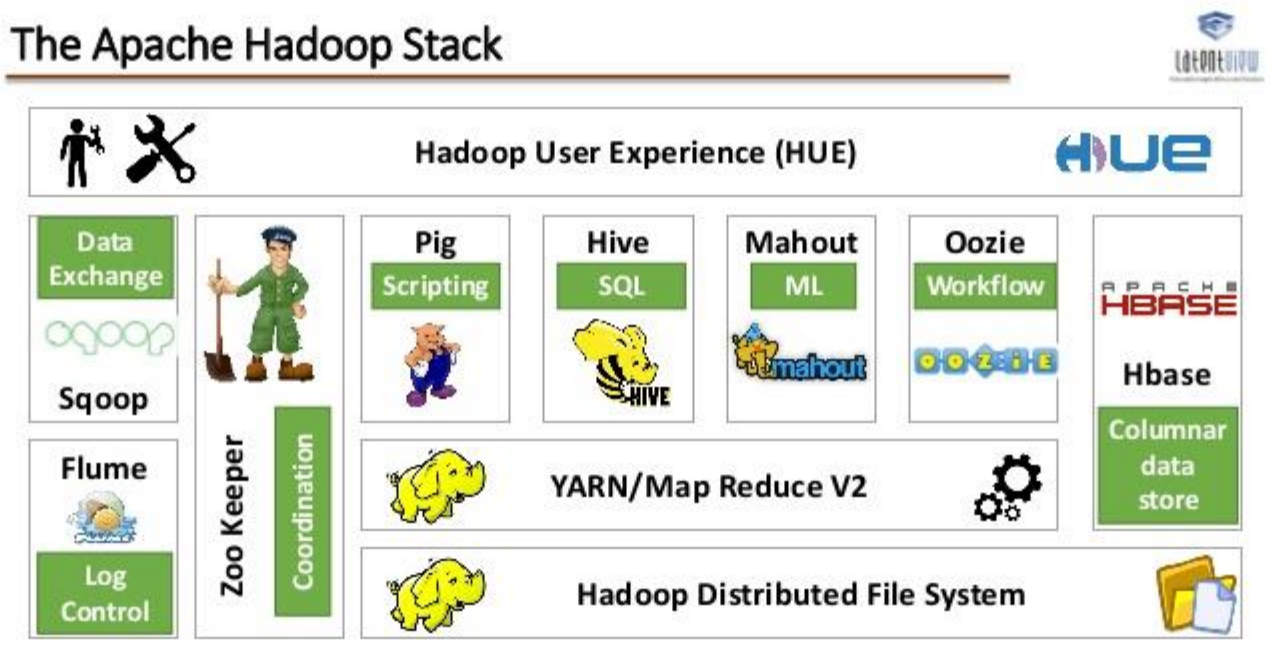
The de facto standard
**Big Data platform**

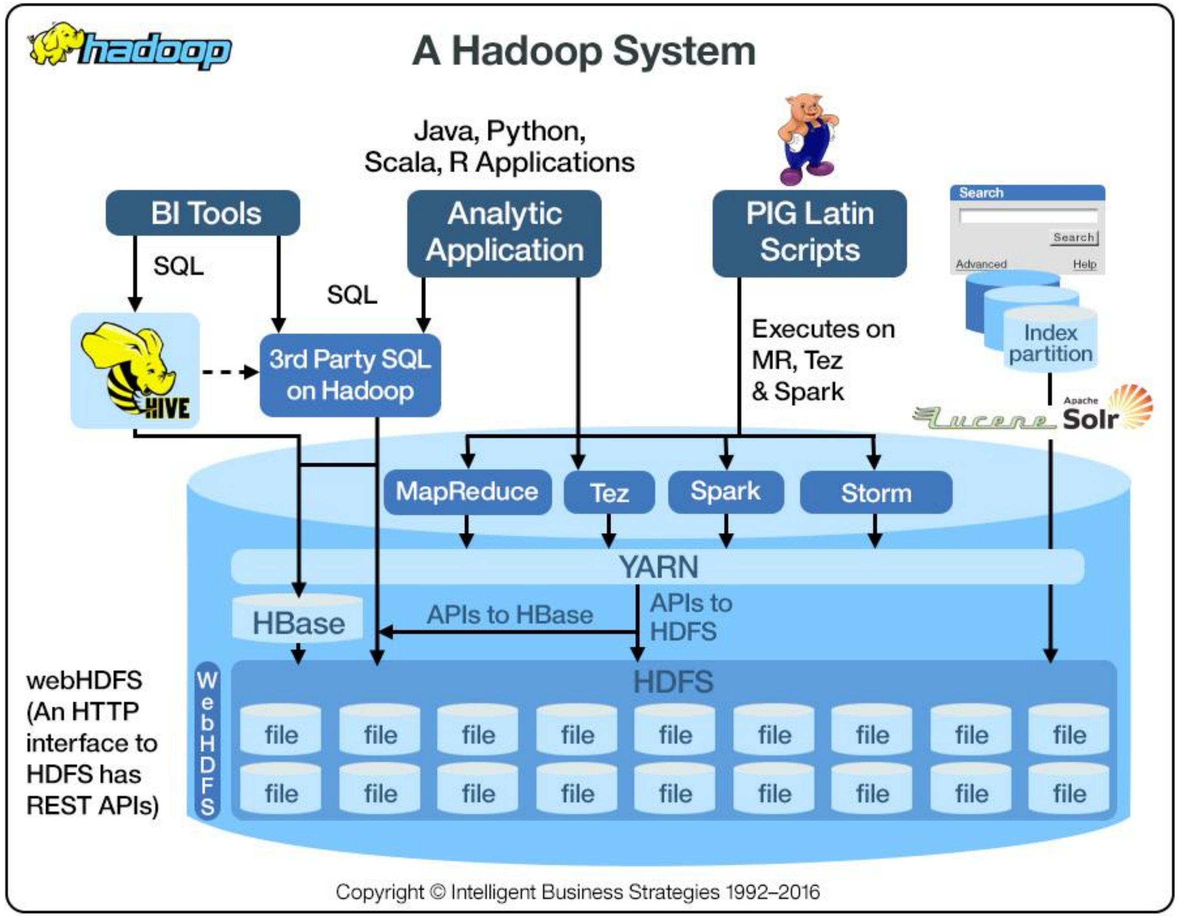
# Hadoop, a Big-Data-everything platform



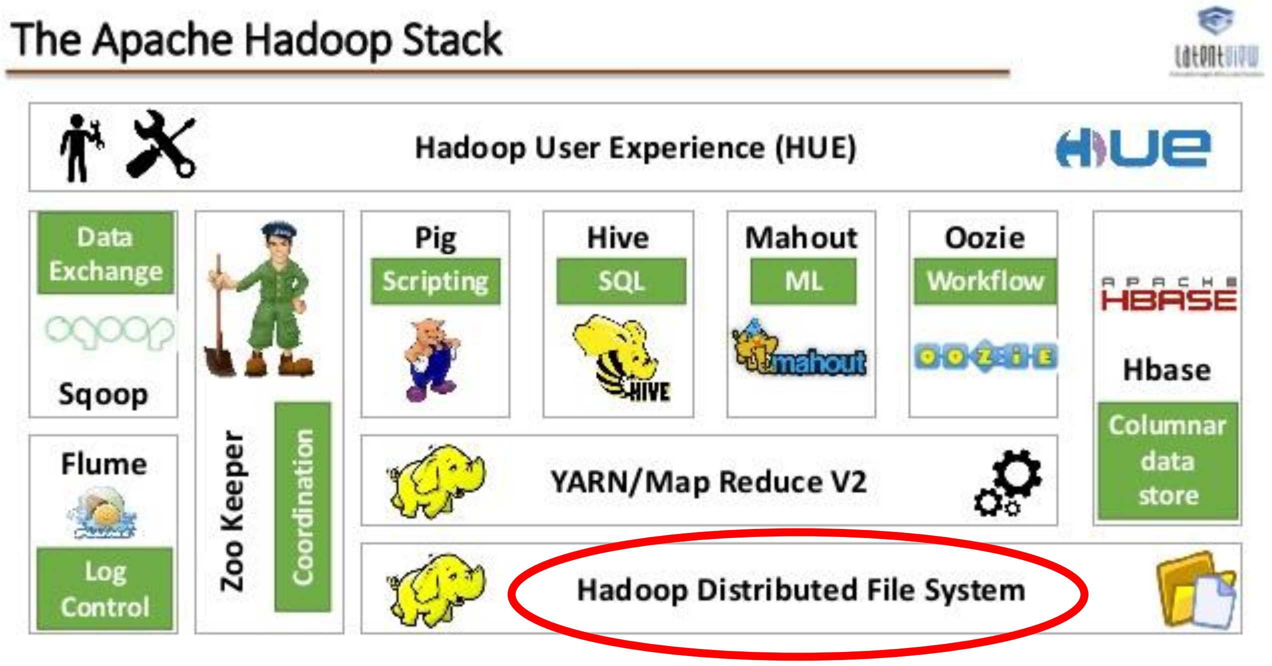

- **2003**: Google File System
- **2004**: MapReduce by Google (Jeff Dean)
- **2005**: Hadoop, funded by Yahoo, to power a search engine project
- **2006**: Hadoop migrated to Apache Software Foundation
- **2006**: Google BigTable
- **2008**: Hadoop wins the Terabyte Sort Benchmark, sorted 1 Terabyte of data in 209 seconds, previous record was 297 seconds
- **2009**: additional components and sub-projects started to be added to the Hadoop platform

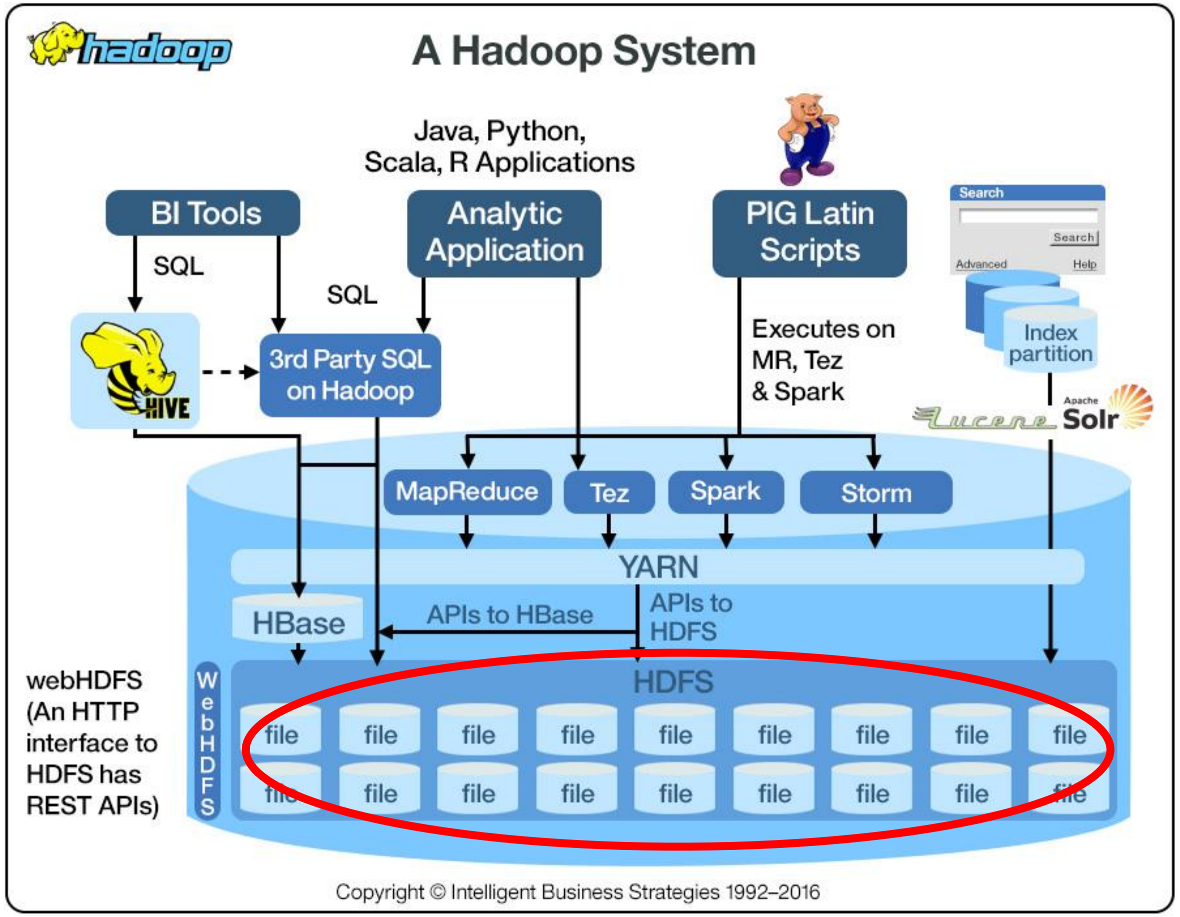
# Hadoop, platform overview



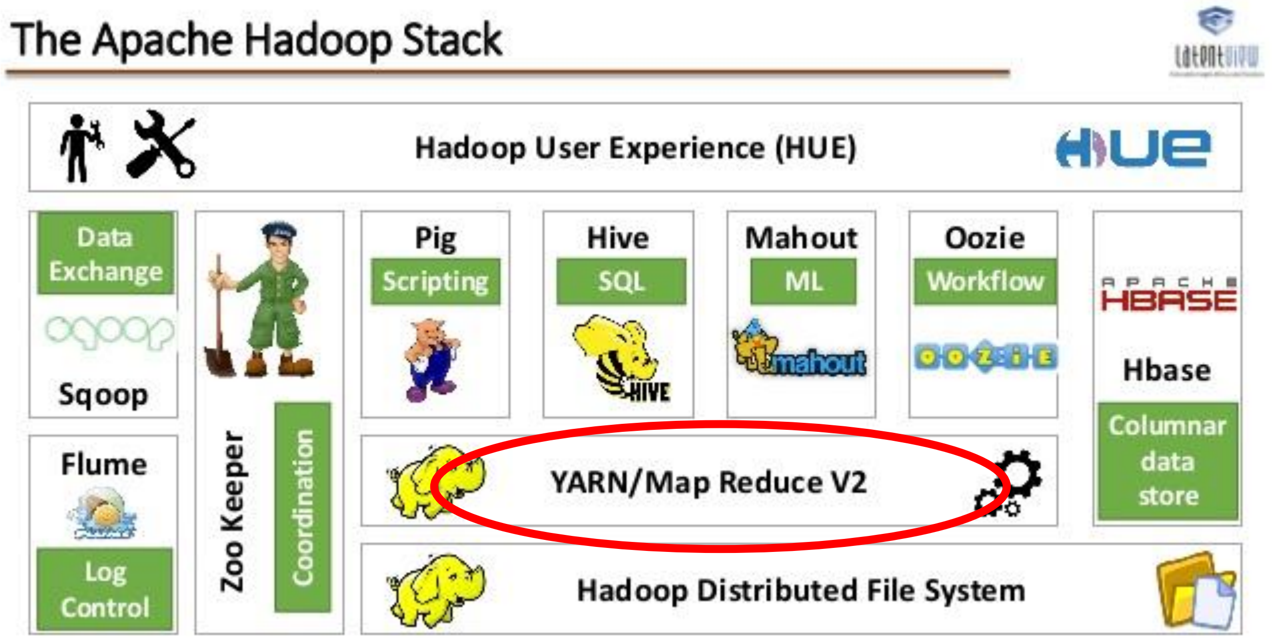



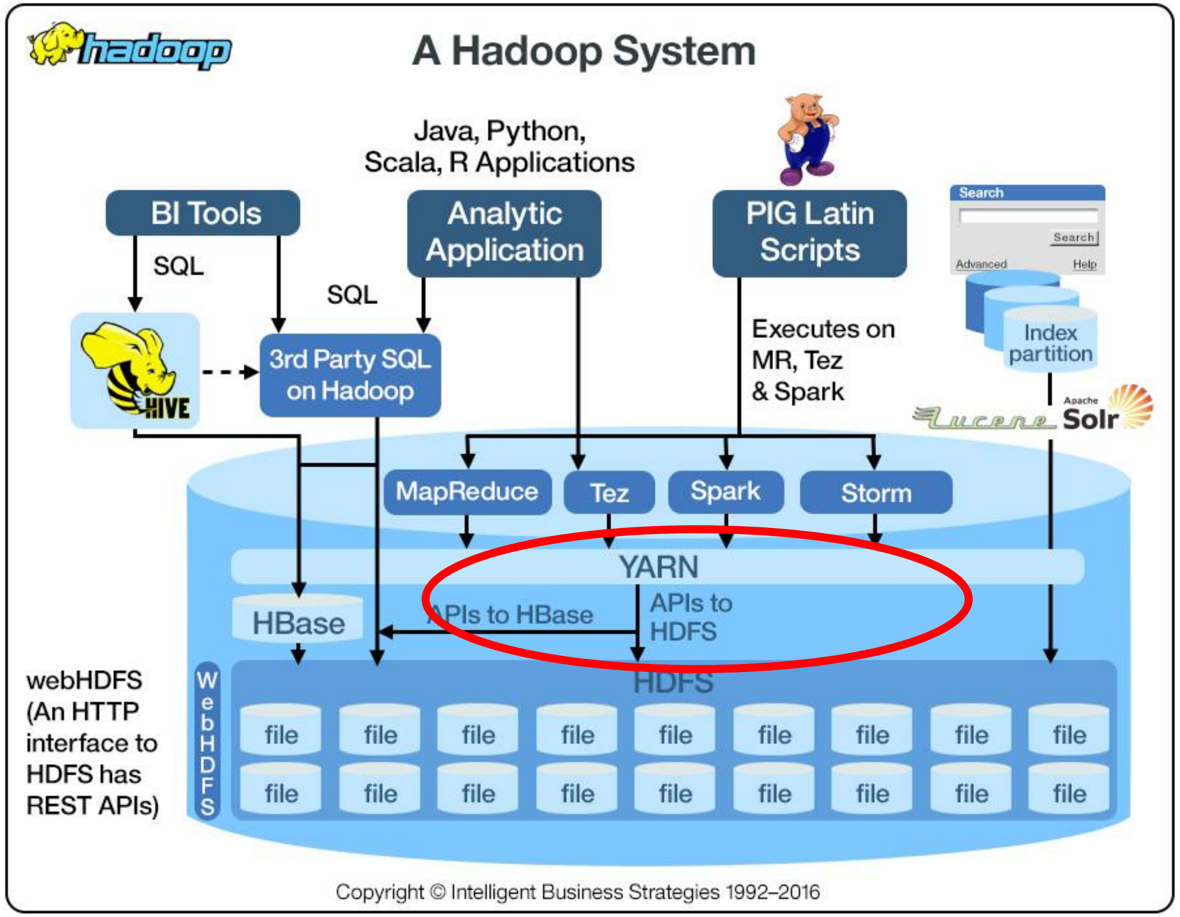
# Hadoop, platform overview



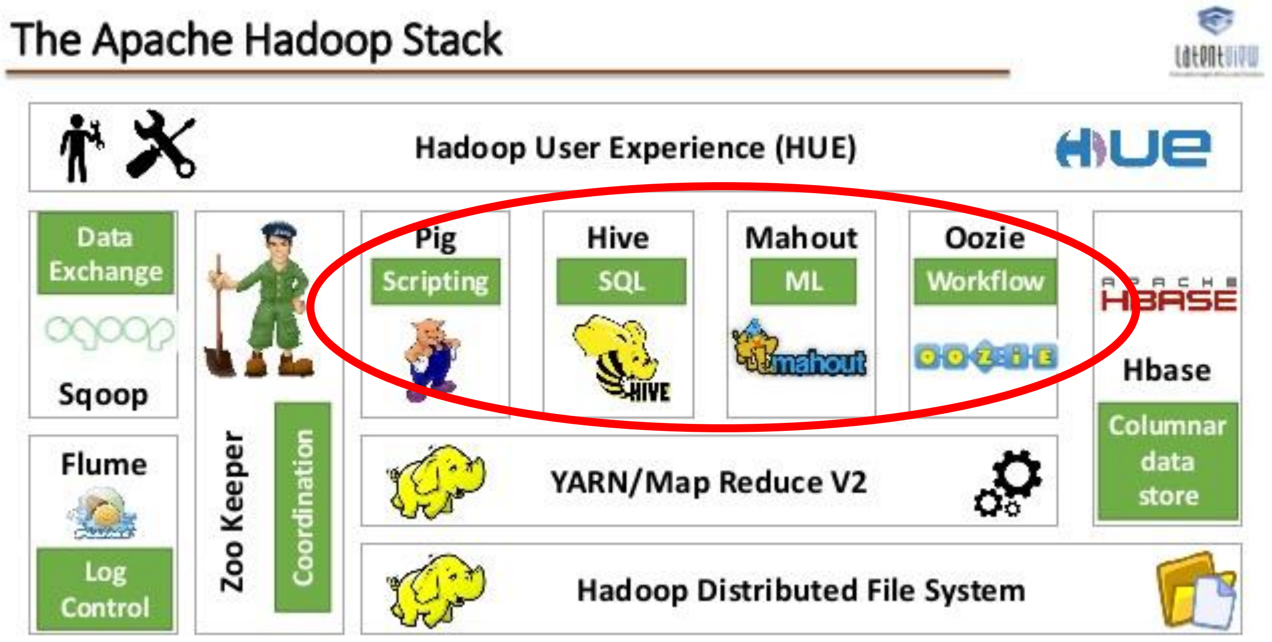



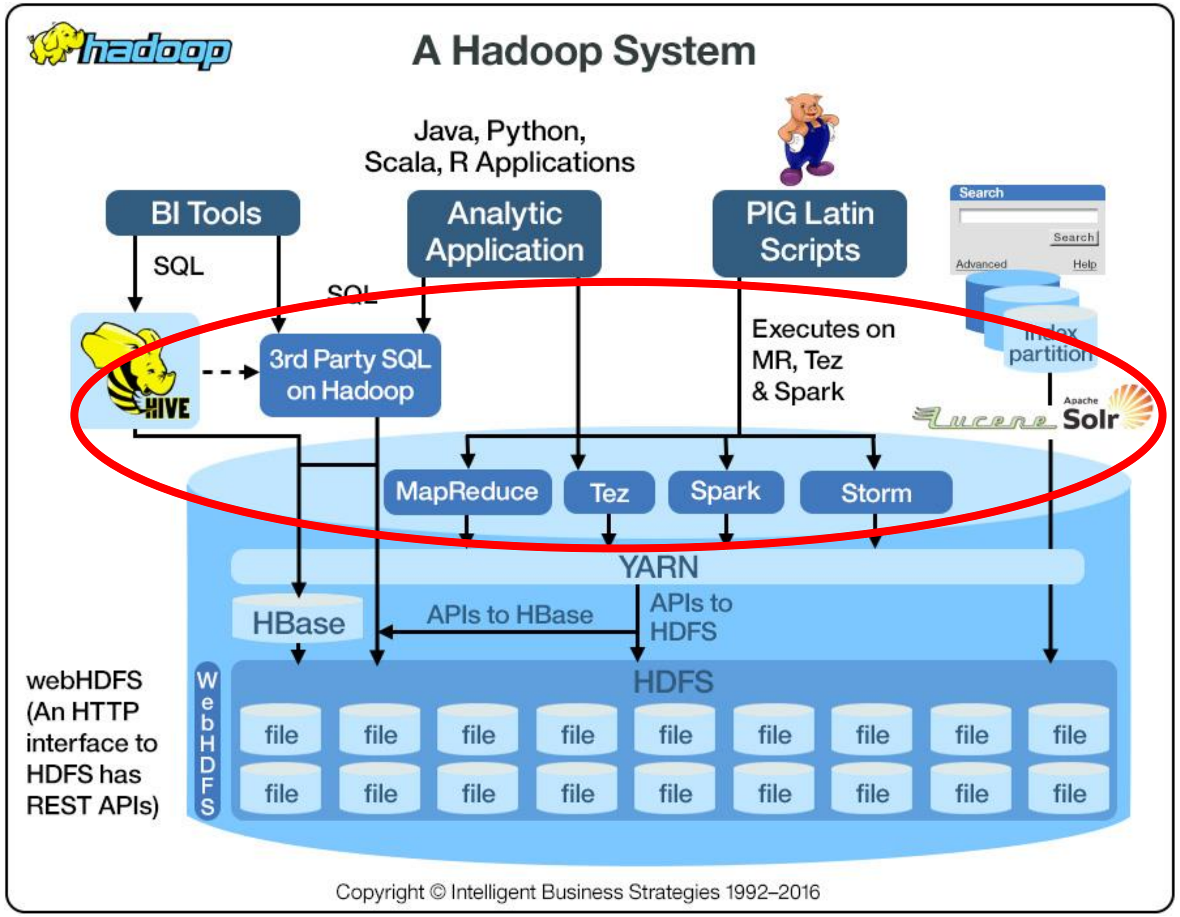
# Hadoop, platform overview



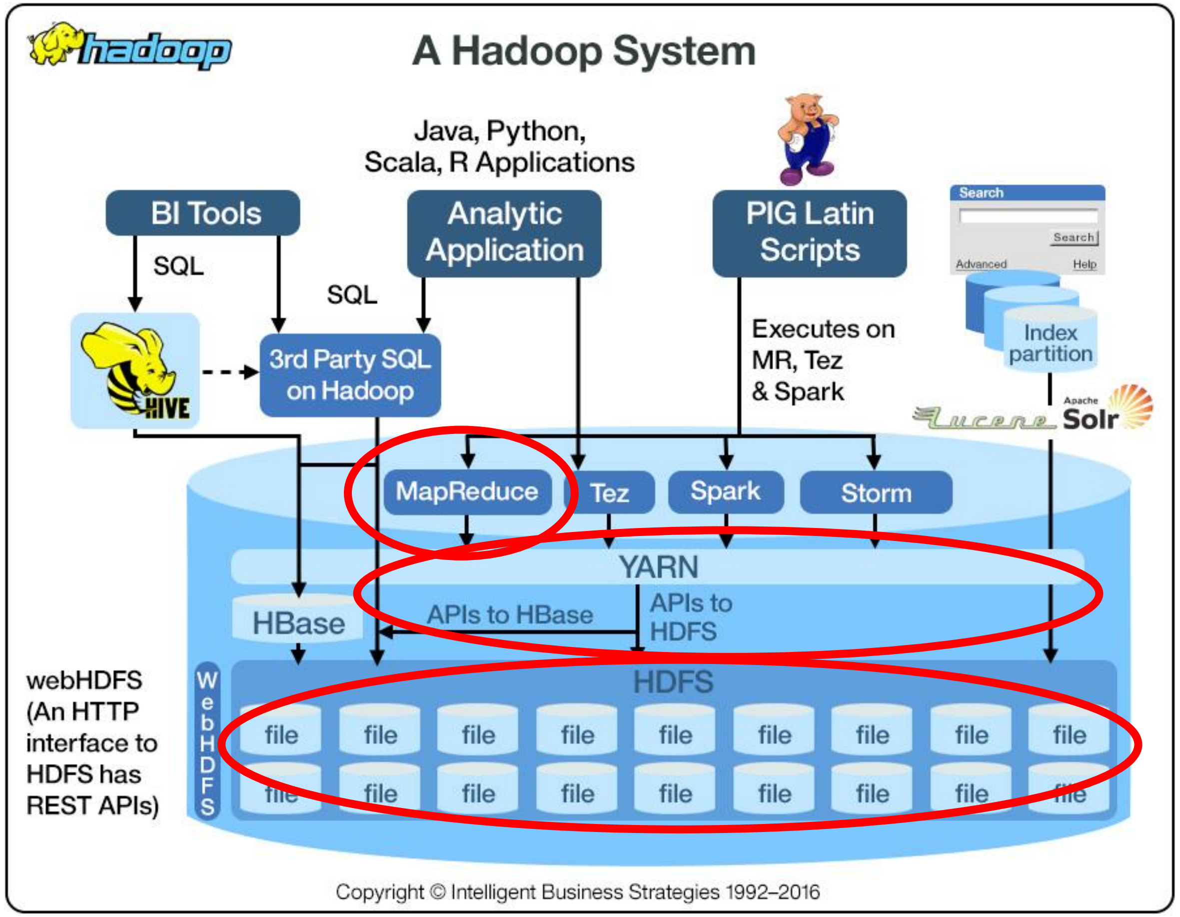
# Hadoop, platform overview



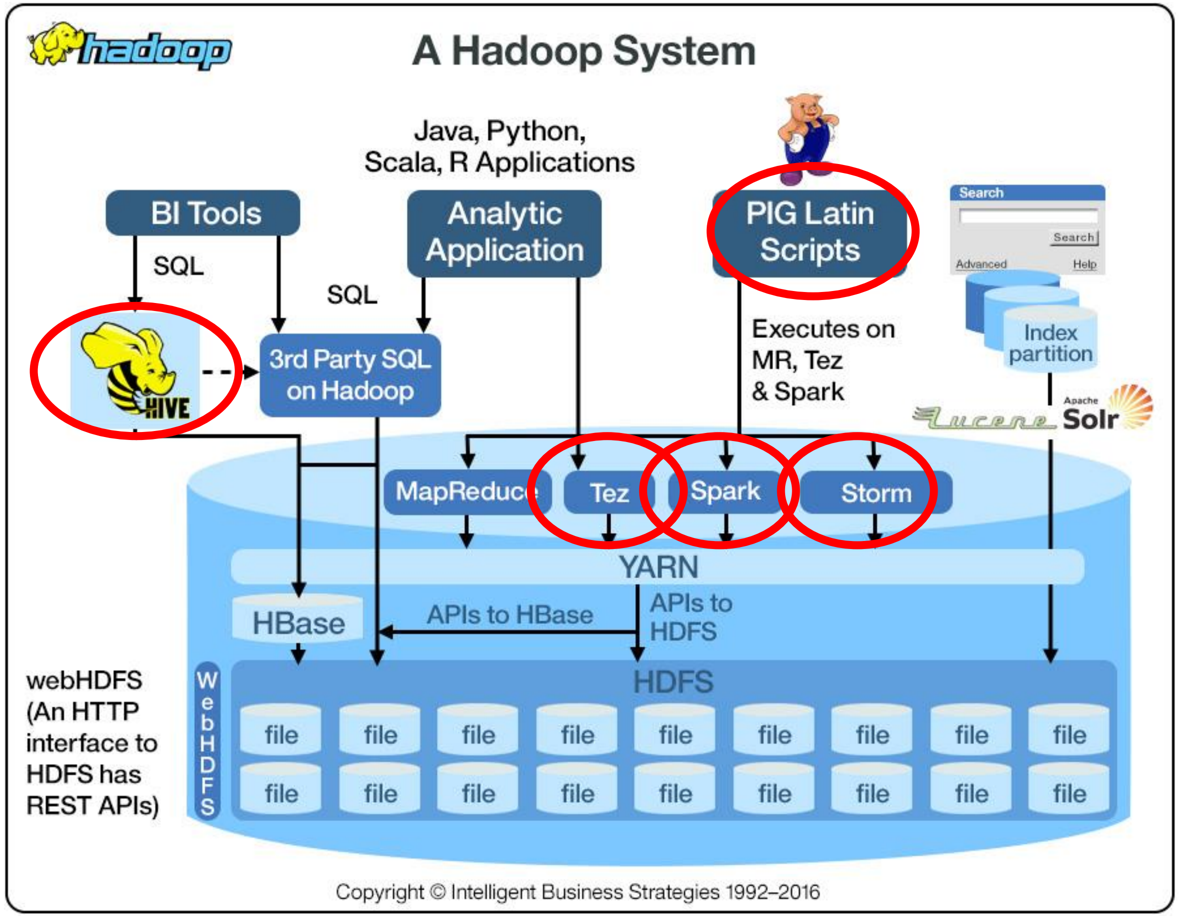
# Apache Hadoop, core components

- **Hadoop Common**: The common utilities that support the other Hadoop modules.
- **Hadoop Distributed File System (HDFS™)**: A distributed file system that provides high-throughput access to application data.
- **Hadoop YARN**: A framework for job scheduling and cluster resource management.
- **Hadoop MapReduce**: A YARN-based system for parallel processing of large data sets.



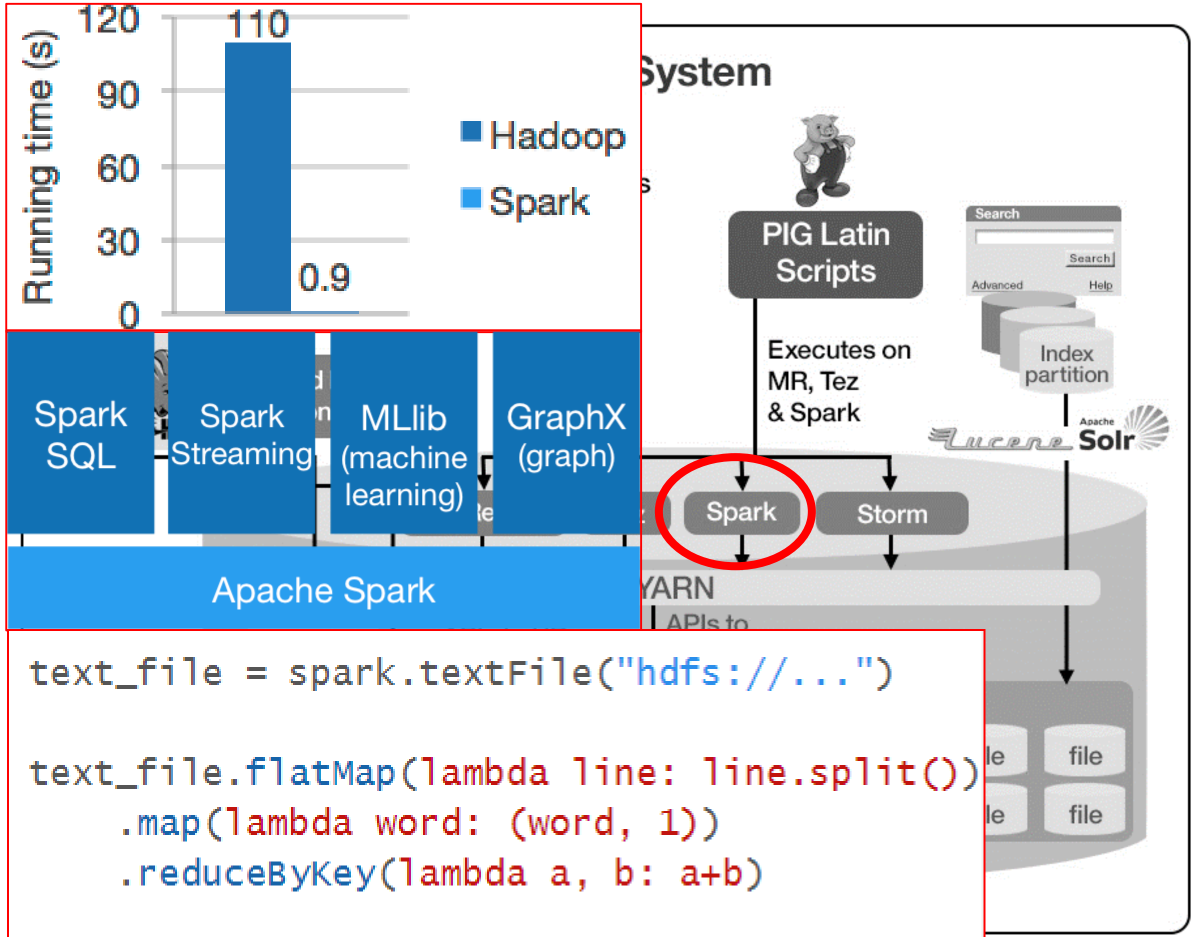
# Hadoop-related projects at Apache

- Ambari™: A web-based tool for provisioning, managing, and monitoring Apache Hadoop clusters which includes support for Hadoop HDFS, Hadoop MapReduce, Hive, HCatalog, HBase, ZooKeeper, Oozie, Pig and Sqoop. Ambari also provides a dashboard for viewing cluster health such as heatmaps and ability to view MapReduce, Pig and Hive applications visually alongwith features to diagnose their performance characteristics in a user-friendly manner.
- Avro™: A data serialization system.
- Cassandra™: A scalable multi-master database with no single points of failure.
- Chukwa™: A data collection system for managing large distributed systems.
- HBase™: A scalable, distributed database that supports structured data storage for large tables.
- Hive™: A data warehouse infrastructure that provides data summarization and ad hoc querying.
- Mahout™: A Scalable machine learning and data mining library.
- Pig™: A high-level data-flow language and execution framework for parallel computation.
- Spark™: A fast and general compute engine for Hadoop data. Spark provides a simple and expressive programming model that supports a wide range of applications, including ETL, machine learning, stream processing, and graph computation.
- Tez™: A generalized data-flow programming framework, built on Hadoop YARN, which provides a powerful and flexible engine to execute an arbitrary DAG of tasks to process data for both batch and interactive use-cases. Tez is being adopted by Hive™, Pig™ and other frameworks in the Hadoop ecosystem, and also by other commercial software (e.g. ETL tools), to replace Hadoop™ MapReduce as the underlying execution engine.
- ZooKeeper™: A high-performance coordination service for distributed applications.



# Apache Spark

- A **fast** and general engine for **large-scale data processing**
- **Speed**
  - Run programs up to 100x faster than Hadoop MapReduce in memory, or 10x faster on disk.
  - Apache Spark has an advanced DAG execution engine that supports acyclic data flow and in-memory computing.
- Ease of Use
  - Write applications quickly in **Java, Scala, Python, R**.
  - Spark offers over 80 **high-level operators** that make it easy to build parallel apps. And you can use it ***interactively*** from the Scala, Python and R shells.
- **Generality**
  - Combine SQL, streaming, and complex analytics.
  - Spark powers a stack of libraries including SQL and DataFrames, **MLlib** **for machine learning**, GraphX, and Spark Streaming. You can combine these libraries seamlessly in the same application.
- **Runs Everywhere**
  - Spark runs on **Hadoop**, Mesos, **standalone**, or in the cloud. It can access diverse data sources including HDFS, Cassandra, HBase, and S3.

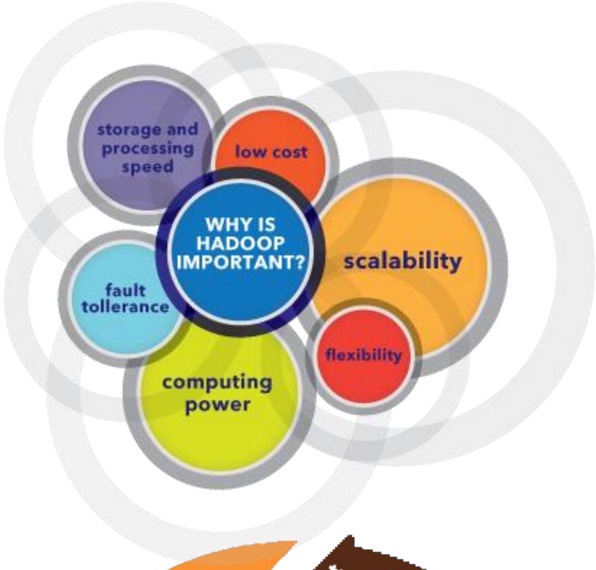


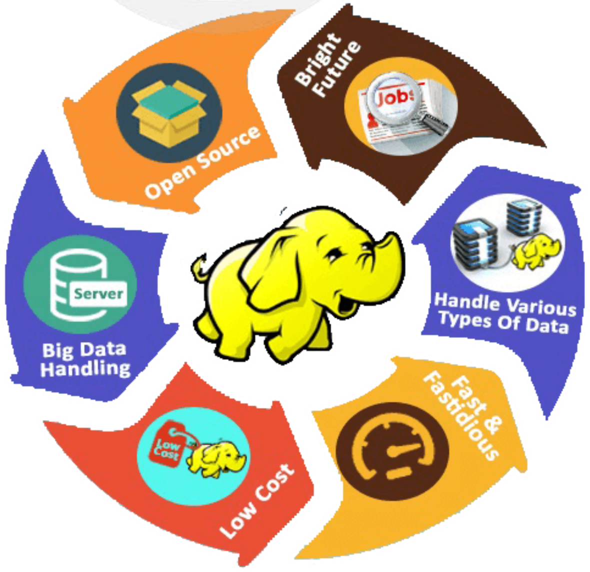

```
text_file = spark.textFile("hdfs://...")

text_file.flatMap(lambda line: line.split())
    .map(lambda word: (word, 1))
    .reduceByKey(lambda a, b: a+b)
```

Word count in Spark's Python API

# Hadoop - why

- **Storage**
  - distributed,
  - fault-tolerant,
  - heterogenous,
  - Huge-data storage engine.
- **Processing**
  - Flexible (multi-purpose),
  - parallel and scalable,
  - high-level programming (Java, Python, Scala, R),
  - batch and real-time, historical and streaming data processing,
  - complex modeling and basic KPI analytics.
- **High availability**
  - Handle failures of nodes by design.
- **High scalability**
  - Grow by adding low-cost nodes, not by replacement with higher-powered computers.
- **Low cost.**
  - Lots of commodity-hardware nodes instead of expensive super-power computers.



# A design recipe


A notable example of NoSQL design

# Design recipe: banking account


- Banks are serious business
- They need serious databases to store serious transactions and serious account information
- They can’t lose or create money
- A bank **must** be in balance **all the time**

# Design recipe: banking example

Say you want to give $100 to your cousin Paul for Christmas.

You need to:

decrease your account balance by 100$

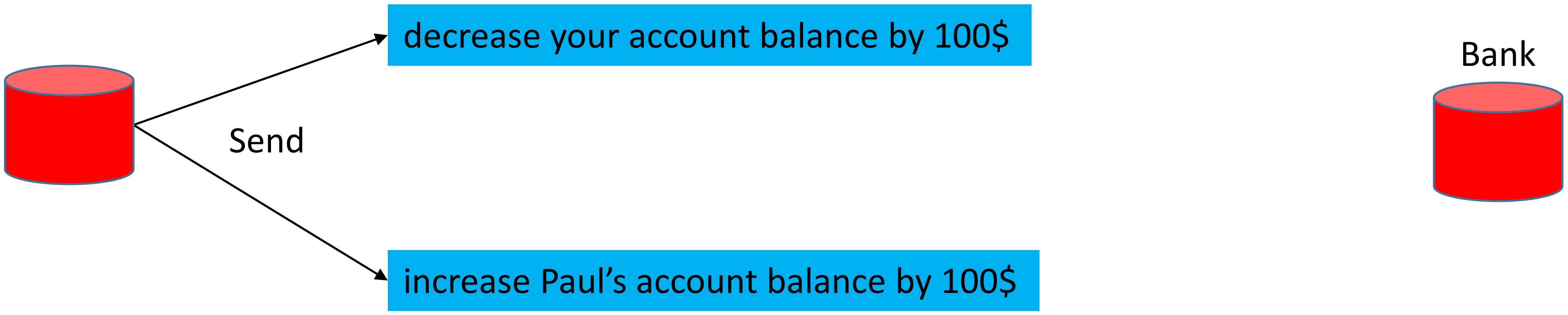
```
{
_id: "account_123456",
account:"bank_account_001",
balance: 900,
timestamp: 1290678353,45,
categories: ["bankTransfer"…],
…
}
```

increase Paul's account balance by 100$

```
{
_id: "account_654321",
account:"bank_account_002",
balance: 1100,
timestamp: 1290678353,46,
categories: ["bankTransfer"…],
…
}
```

# Design recipe: banking example

- What if some kind of failure occurs between the two separate updates to the two accounts?



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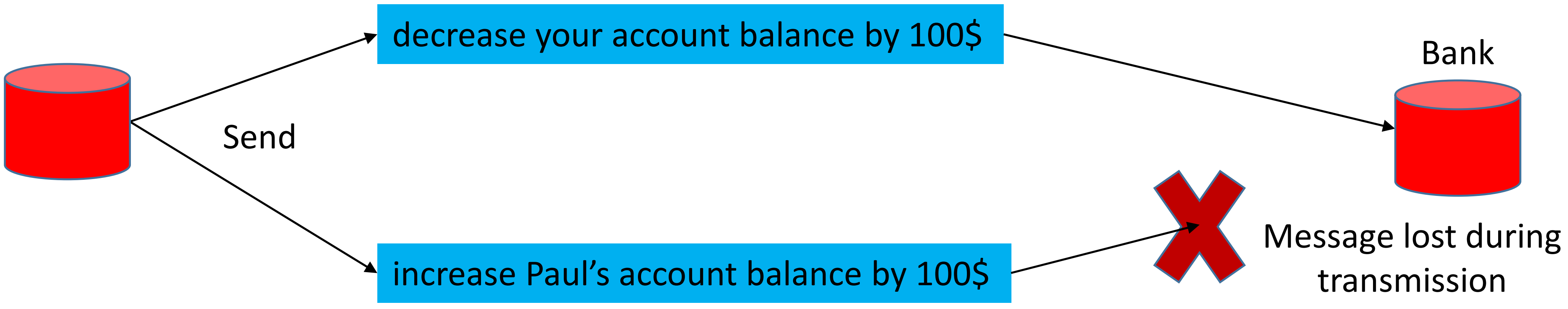

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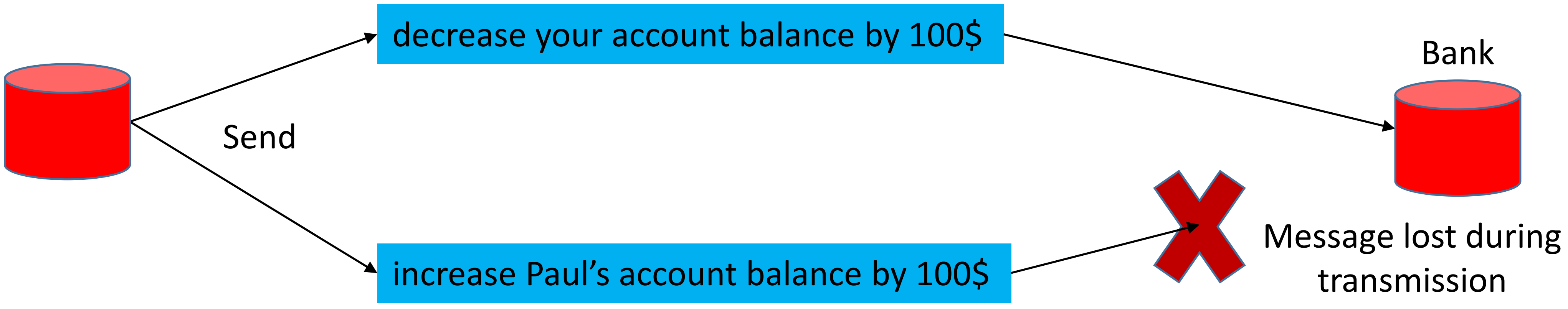


- CouchDB **cannot guarantee the bank balance**.
- A different strategy (design) must be adopted.

# Banking recipe solution

- What if some kind of failure occurs between the two separate updates to the two accounts?
- CouchDB cannot guarantee the bank balance.
- A different strategy (design) must be adopted.

id: transaction001
**from**: "**bank_account_001**",
**to**: "**bank_account_002**",
**qty: 100**,
when:1290678353.45,
…

# Design recipe: banking example

- How do we read the current account balance?
- Map

```
function(transaction){
 emit(transaction.from, transaction.amount*-1);
 emit(transaction.to, transaction.amount);
}
```

- Reduce

```
function(key, values){
 return sum(values);
}
```

- Result

{rows: [ {key: "**bank_account_001**", value: **900**} ]

{rows: [ {key: "**bank_account_002**", value: **1100**} ]

The reduce function receives:

- **key**= bank_account_001, **values**=[1000, -100]
- …
- **key**= bank_account_002, **values**=[1000, 100]
- …

# Beyond relational databases

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