Chapter 2:

NoSQL Databases

Outline

- History
- Concepts
  - ACID
  - BASE
  - CAP
- Data Models
  - Key-Value
  - Document
  - Column-based
  - Graph

History

60s: IBM developed the Hierarchical Database Model

- Tree-like structure
- Data stored as *records* connected by *links*
- Support only one-to-one and one-to-many relationships

Mid 80's: Rise of Relational Database Model

- Data stored in a collection of tables (rows and columns)
  → Strict relational scheme
- SQL became standard language (based on relational algebra)

→Impedance Mismatch!

History – Impedance Mismatch

Supply:
- Supplier:
  - LNR: L1
  - Lname: Meier
  - Status: 20
  - Sitz: Wetter
- Project:
  - PNR: P2
  - Pname: Pleite
  - Ort: Bonn
- Pieces:
  - TNR: T6
  - Tname: Schraube
  - Farbe: rot
  - Gewicht: 03
  - Menge: 700

LNR	Lname	Status	Sitz
…	…	…	…
…	…	…	…
…	…	…	…

PNR	Pname	Ort
…	…	…
…	…	…
…	…	…

TNR	Tname	Farbe	Gewicht
…	…	…	…
…	…	…	…
…	…	…	…

LNR	PNR	TNR	Menge
…	…	…	…
…	…	…	…
…	…	…	…

Given the LTP scheme from Datenbanksysteme I and an object of type Supply:

How to incorporate the data bundled in the object Supply into the DB?

History – Impedance Mismatch

Supply:
- Supplier:
  - LNR: L1
  - Lname: Meier
  - Status: 20
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- Project:
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LNR	Lname	Status	Sitz
…	…	…	…
…	…	…	…
L1	Meier	20	Wetter

PNR	Pname	Ort
…	…	…
…	…	…
P2	Pleite	Bonn

TNR	Tname	Farbe	Gewicht
…	…	…	…
…	…	…	…
T6	Schraube	rot	03

LNR	PNR	TNR	Menge
…	…	…	…
…	…	…	…
…	…	…	…

```
INSERT INTO L VALUES (Supply.getSupplier().getLNR(), ...);

INSERT INTO P VALUES (Supply.getProject().getPNR(), ...);

...
```

History – Impedance Mismatch

Supply:
Supplier:
LNR: L1
Lname: Meier
Status: 20
Sitz: Wetter
Project:
PNR: P2
Pname: Pleite
Ort: Bonn
Pieces:
TNR: T6
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LNR	Lname	Status	Sitz
…	…	…	…
…	…	…	…
L1	Meier	20	Wetter

PNR	Pname	Ort
…	…	…
…	…	…
P2	Pleite	Bonn

TNR	Tname	Farbe	Gewicht
…	…	…	…
…	…	…	…
T6	Schraube	rot	03

LNR	PNR	TNR	Menge
…	…	…	…
…	…	…	…
L1	P2	T6	700

```
INSERT INTO LTP VALUES (...);
```

- Object-oriented encapsulation vs. storing data distributed among several tables

  → Lots of data type maintenance by the programmer

History

Mid 90‘s: Trend of the Object-Relational Database Model

- Data stored as objects (including data and methods)
- Avoidance of object-relational mapping
  → Programmer-friendly
- But still Relational Databases prevailed in the 90‘s

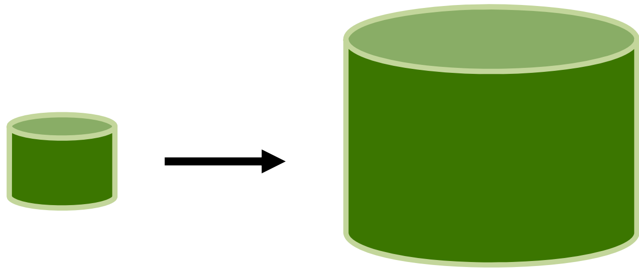
Mid 2000‘s: Rise of Web 2.0

- Lots of user generated data through web applications

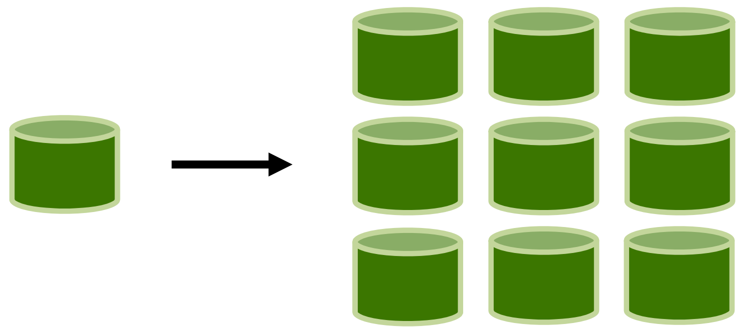
  → Storage systems had to become scaled up

Approaches to scale up storage systems

- Two opportunities to solve the rising storage system:
  - Vertical scaling
    Enlarge a single machine
    - Limited in space
    - Expensive



  - Horizontal scaling
    Use many commodity machines and form *computer clusters* or *grids*
    - Cluster maintenance

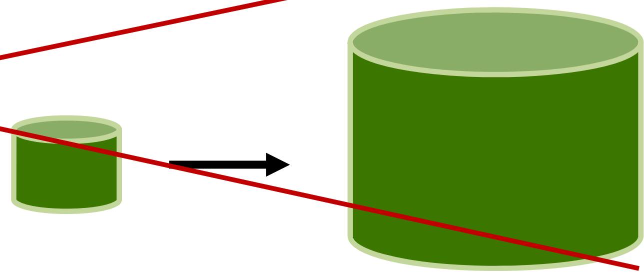


History

Approaches to scale up storage systems

- Two opportunities to solve the rising storage system:
  - ~~Vertical scaling~~

    ~~Enlarge a single machine~~
    - ~~Limited in space~~
    - ~~Expensive~~



  - Horizontal scaling

    Use many commodity machines and form *computer clusters* or *grids*
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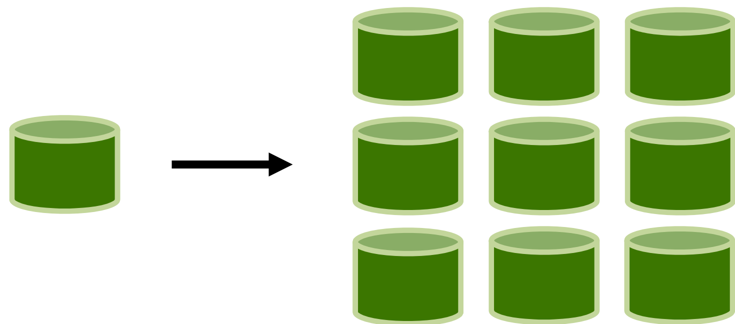


History

Mid 2000‘s: Birth of the NoSQL Movement

- Problem of computer clusters:
  Relational databases do not scale well horizontally

→ Big Players like Google or Amazon developed their own storage systems: NoSQL („Not-Only SQL“) databases were born

Today: Age of NoSQL

- Several different NoSQL systems available (>225)

Google Bigtable   redis   neo4j   HYPERTABLE

Cassandra   amazon DynamoDB   mongoDB   APACHE HBASE

Characterstics of NoSQL Databases

There is no unique definition but some characteristics for NoSQL Databases:

- Horizontal scalability (cluster-friendliness)
- Non-relational
- Distributed
- Schema-less
- Open-source (at least most of the systems)

About the concepts behind NoSQL Databases

ACID – The holy grail of RDBMSs:

- Atomicity: Transactions happen entirely or not at all. If a transaction fails (partly), the state of the database is unchanged.
- Consistency: Any transaction brings the database from one valid state to another and does not break one of the pre-defined rules (like constraints).
- Isolation: Concurrent execution of transactions results in a system state that would be obtained if transactions were executed serially.
- Durability: Once a transaction has been commited, it will remain so.

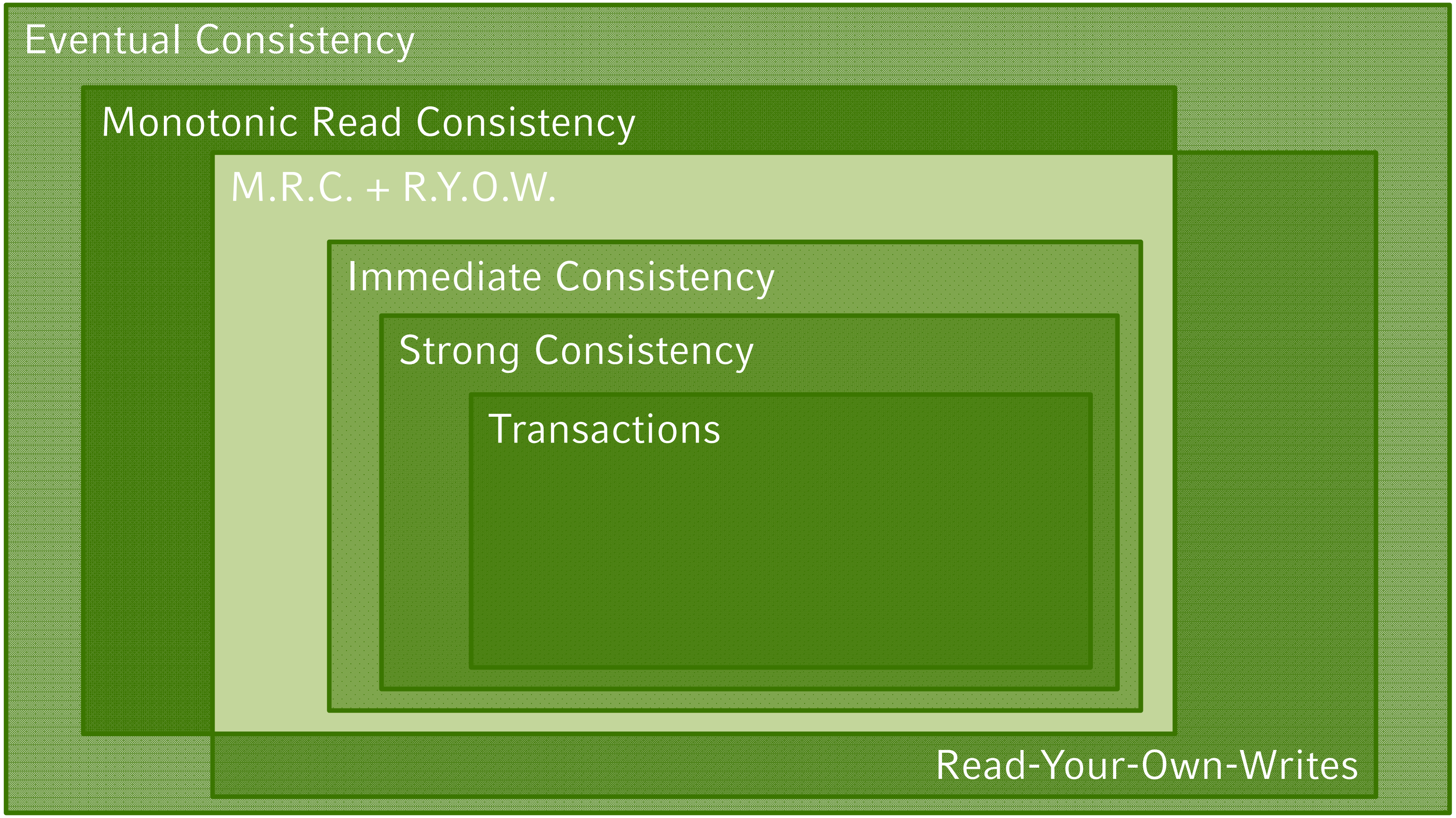
About the concepts behind NoSQL Databases

BASE – An artificial concept for NoSQL databases:

- Basically Available: The system is generally available, but some data might not at any time (e.g. due to node failures)
- Soft State: The system's state changes over time. Stale data may expire if not refreshed.
- Eventual consistency: The system is consistent from time to time, but not always. Updates are propagated through the system if there is enough time.

→ **BASE is settled on the opposite site to ACID when considering a „consistency-availability spectrum"**

Levels of Consistency:



About the concepts behind NoSQL Databases

Levels of Consistency:

- Eventual Consistency: Write operations are not spread across all servers/partitions immediately
- Monotononic Read Consistency: A client who read an object once will never read an older version of this object
- Read Your Own Writes: A client who wrote an object will never read an older version of this object
- Immediate Consistency: Updates are propagated immediately, but not atomic

About the concepts behind NoSQL Databases

Levels of Consistency:

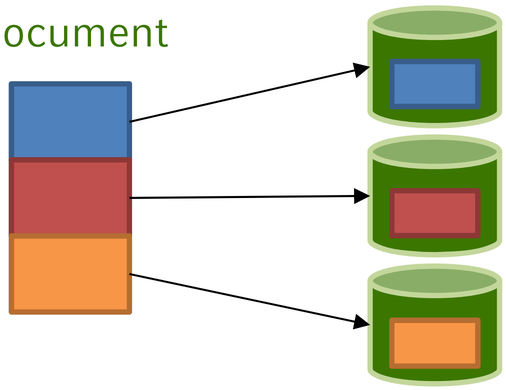
- <u>Strong consistency:</u> Updates are propagated immediately + support of atomic operations on single data entities (usually on master nodes)

- <u>Transactions:</u> Full support of ACID transaction model

About the concepts behind NoSQL Databases

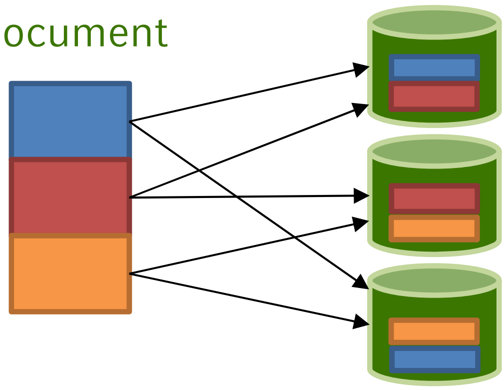
Data sharding

Document



Data replication

Document

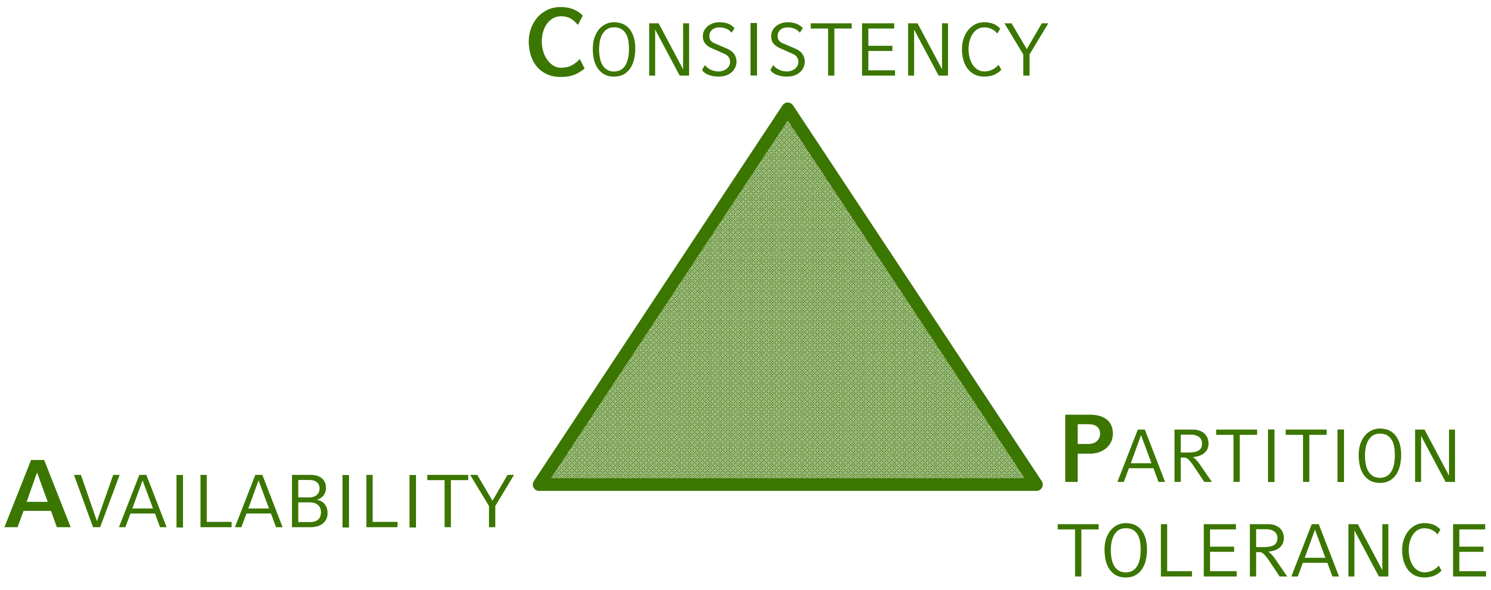


The two types of consistency:

- Logical consistency:
  Data is consistent within itself (Data Integrity)

- Replication consistency:
  Data is consistent across multiple replicas (on multiple machines)

Brewer's CAP Theorem:



Any networked shared-data system can have at most two of the three desired properties!

About the concepts behind NoSQL Databases

DB-Systems allowed by CAP Theorem:

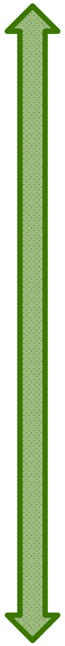
- **CP**-Systems: Fully consistent and partitioned systems renounce availability. Only consistent nodes are available.

- **AP**-Systems: Fully available and partitioned systems renounce consistency. All nodes answer to queries all the time, even if answers are inconsistent.

- **AC**-Systems: Fully available and consistent systems renounce partitioning. Only possible if the system is not distributed.

CAP Theorem:

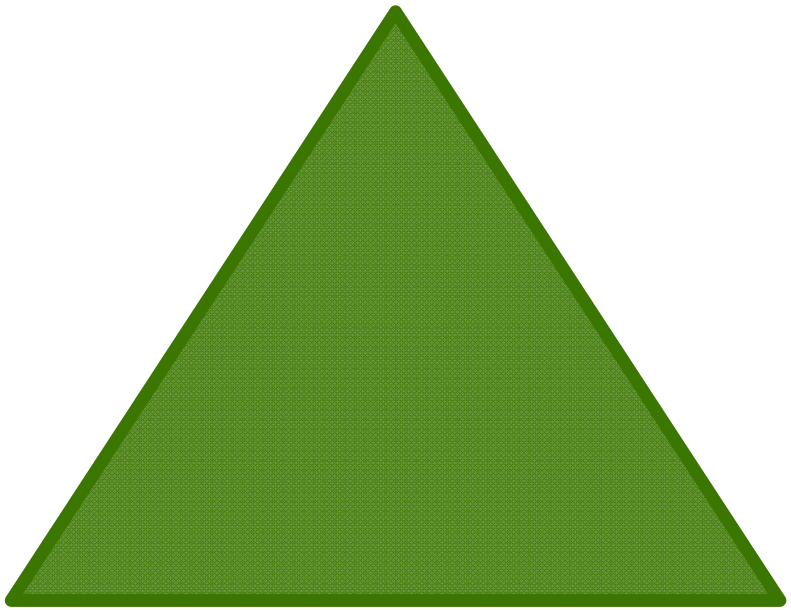
C



A

All clients always have the same view of the data

C



A

Each client can always read and write

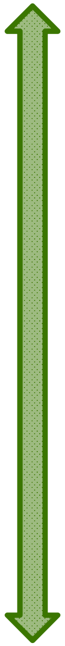
P

The system works well despite physical network partitions

Big Picture

CAP Theorem:

C



ACID

BASE

A

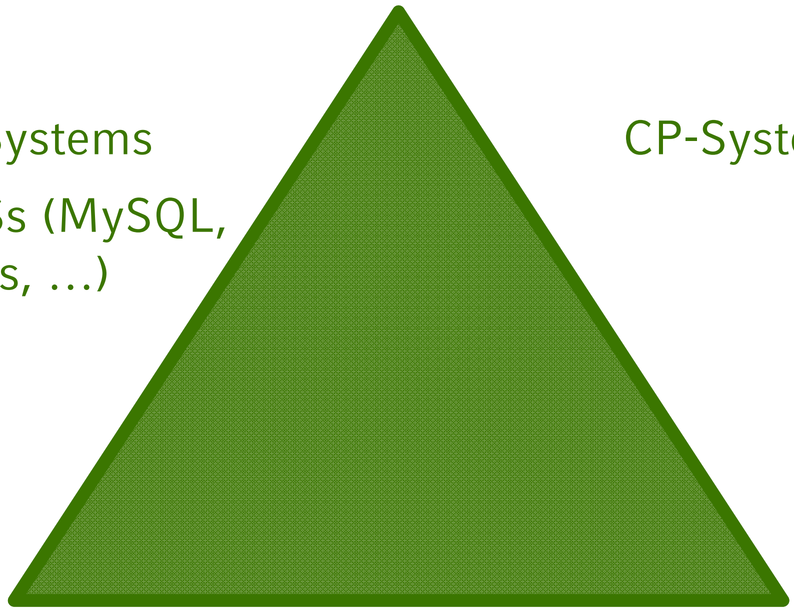
All clients always have the same view of the data

C

AC-Systems

- RDBMSs (MySQL, Postgres, ...)

CP-Systems



A

Each client can always read and write

AP-Systems

P

The system works well despite physical network partitions

NoSQL Data Models

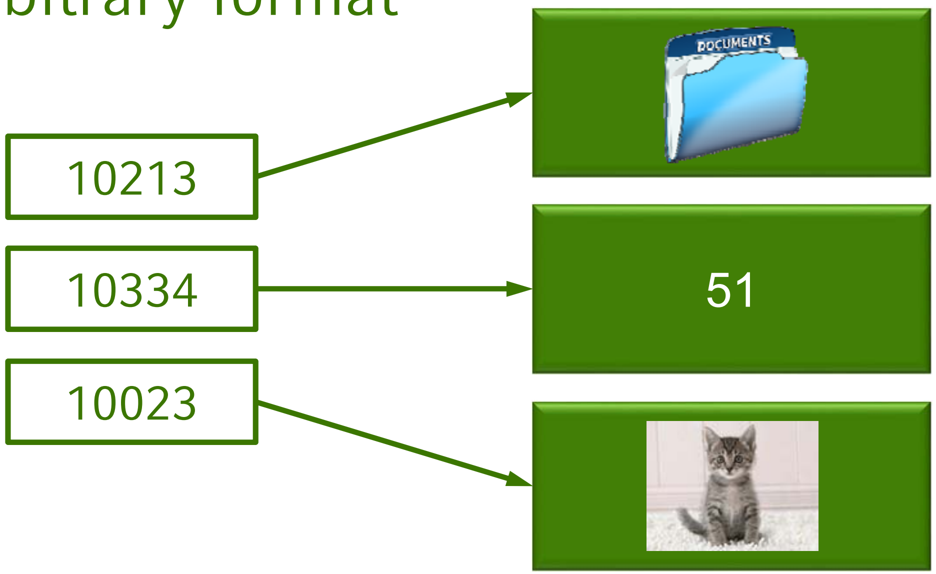
The 4 Main NoSQL Data Models:

- Key/Value Stores
- Document Stores
- Wide Column Stores
- Graph Databases

NoSQL Data Models

Key/Value Stores:

- Most simple form of database systems
- Store key/value pairs and retrieve values by keys
- Values can be of arbitrary format



Key/Value Stores:

- Consistency models range from *Eventual consistency* to *serializibility*
- Some systems support ordering of keys, which enables efficient querying, like range queries
- Some systems support in-memory data maintenance, some use disks

→ There are very heterogeneous systems

Key/Value Stores - Redis:

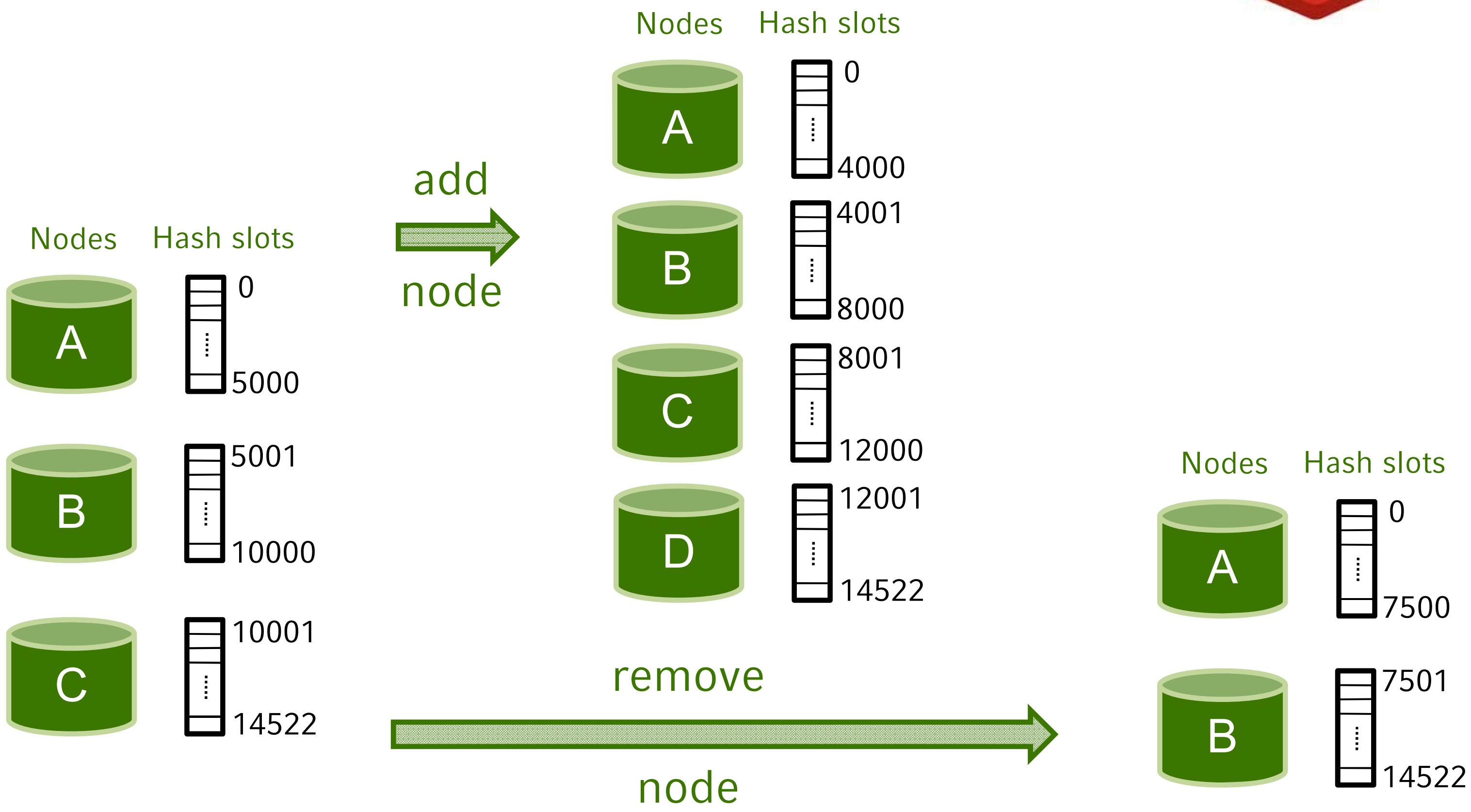
- In-memory data structure store with built-in replication, transactions and different levels of on-disk persistence
- Support of complex types like lists, sets, hashes, …
- Support of many *atomic* operations

```
>> SET val 1
>> GET val => 1
>> INCR val => 2
>> LPUSH my_list a (=> ‘a‘)
>> LPUSH my_list b (=> ‘b‘,‘a‘)
>> RPUSH my_list c (=> ‘b‘,‘a‘,‘c‘)
>> LRANGE my_list 0 1 => b,a
```

Key/Value Stores – The Redis cluster model:

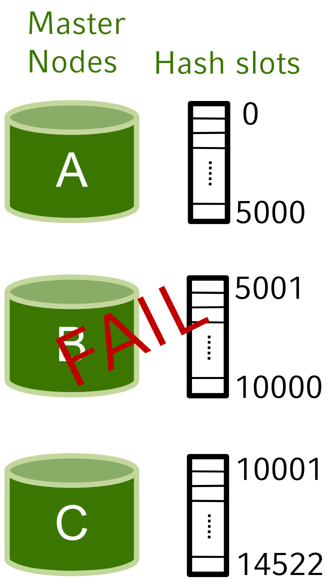
- Data is automatically sharded across nodes
- Some degree of availability, achieved by master-slave architecture (but cluster stops in the event of larger failures)
- Easily extendable

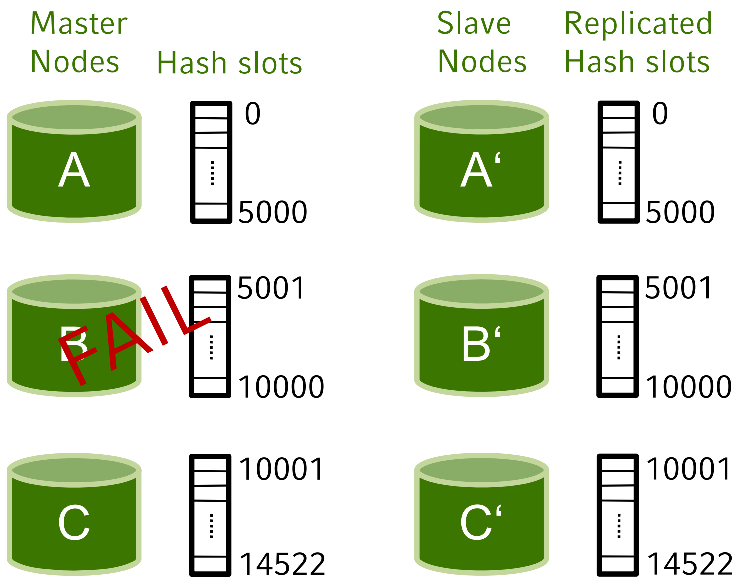
Key/Value Stores – The Redis cluster model:



Key/Value Stores – The Redis cluster model:

redis





Hash slots 5001 – 10000 cannot be used anymore

Slave node B‘ is promoted as the new master and hash slots 5001 – 10000 are still available

Big Picture

CAP Theorem:

Key/Value Stores

C

ACID

BASE

A

All clients always have the same view of the data

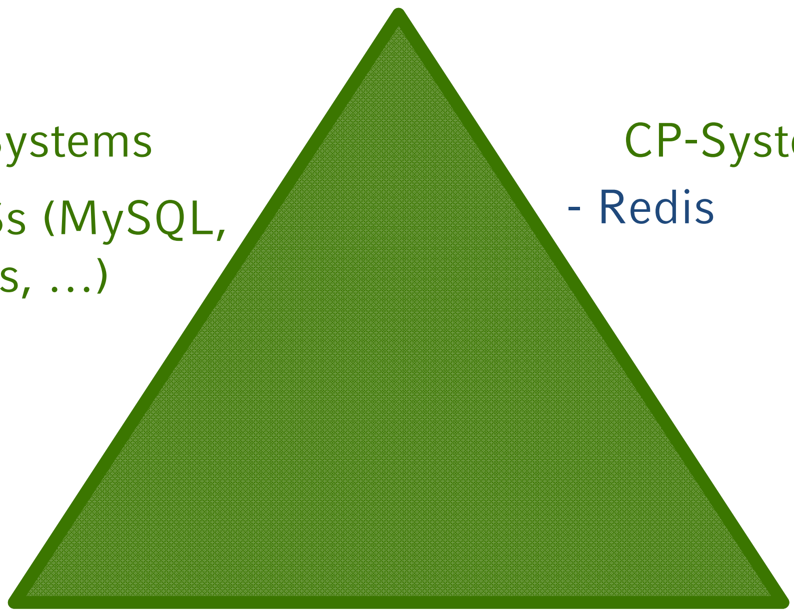
C

AC-Systems

- RDBMSs (MySQL, Postgres, …)

CP-Systems

- Redis



A

Each client can always read and write

AP-Systems

- Dynamo

P

The system works well despite physical network partitions

NoSQL Data Models

Document Stores:

- Store documents in form of XML or JSON
- Semi-structured data records that do not have a homogeneous structure
- Columns can have more than one value (arrays)
- Documents include internal structure, or metadata
- Data structure enables efficient use of indexes

Document Stores:

Given following text:

Max Mustermann
Musterstraße 12
D-12345 Musterstadt

```
<contact>
   <first_name>Max</first_name>
   <last_name>Mustermann</last_name>
   <street>Musterstraße 12</street>
   <city>Musterstadt</city>
   <zip>12345</zip>
   <country>D</country>
</contact>
```

→ Find all <contact>s where <zip> is “12345“

NoSQL Data Models

Document Stores:

- Data stored as documents in binary representation (BSON)
- Similarly structured documents are bundled in collections
- Provides own ad-hoc query language
- Supports ACID transactions on document level

Document Stores: mongoDB

MongoDB Data Management:

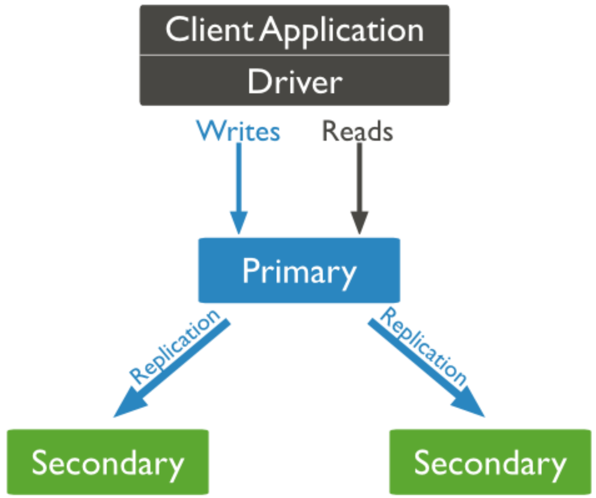
- Automatic data sharding
- Automatic re-balancing

- Multiple sharding policies:
  - Hash-based sharding: Documents are distributed according to an MD5 hash → uniform distribution
  - Range-based sharding: Documents with shard key values close to one another are likely to be co-located on the same shard → works well for range queries
  - Location-based sharding: Documents are partitioned wrt to a user-specified configuration that associates shard key ranges with specific shards and hardware

Document Stores: mongoDB

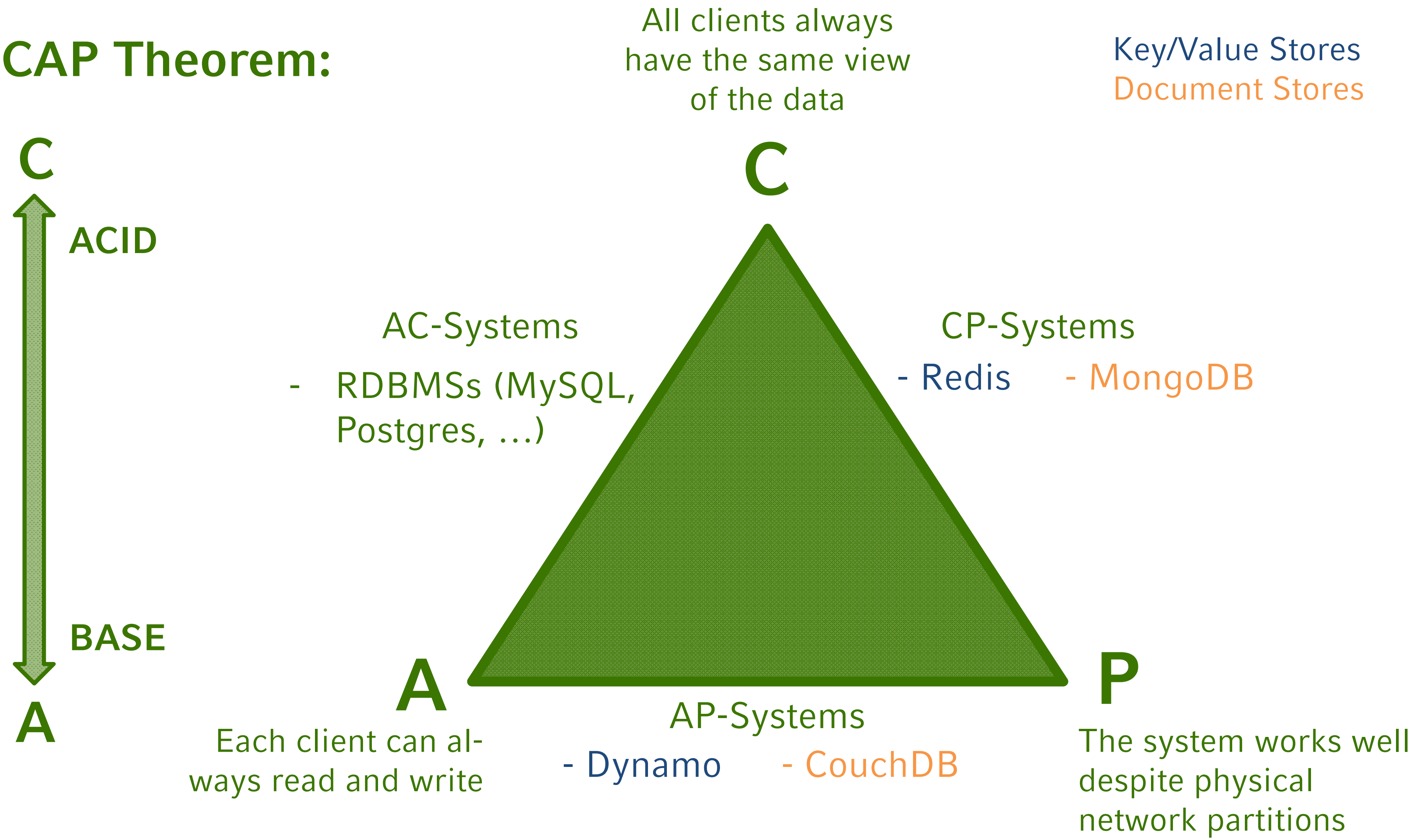
MongoDB Consistency & Availabilty:

- Default: Strong consistency (but configurable)
- Increased availability through replication
  - *Replica sets* consist of one *primary* and multiple *secondary members*
  - MongoDB applies writes on the primary and then records the operations on the primary's *oplog*



Big Picture

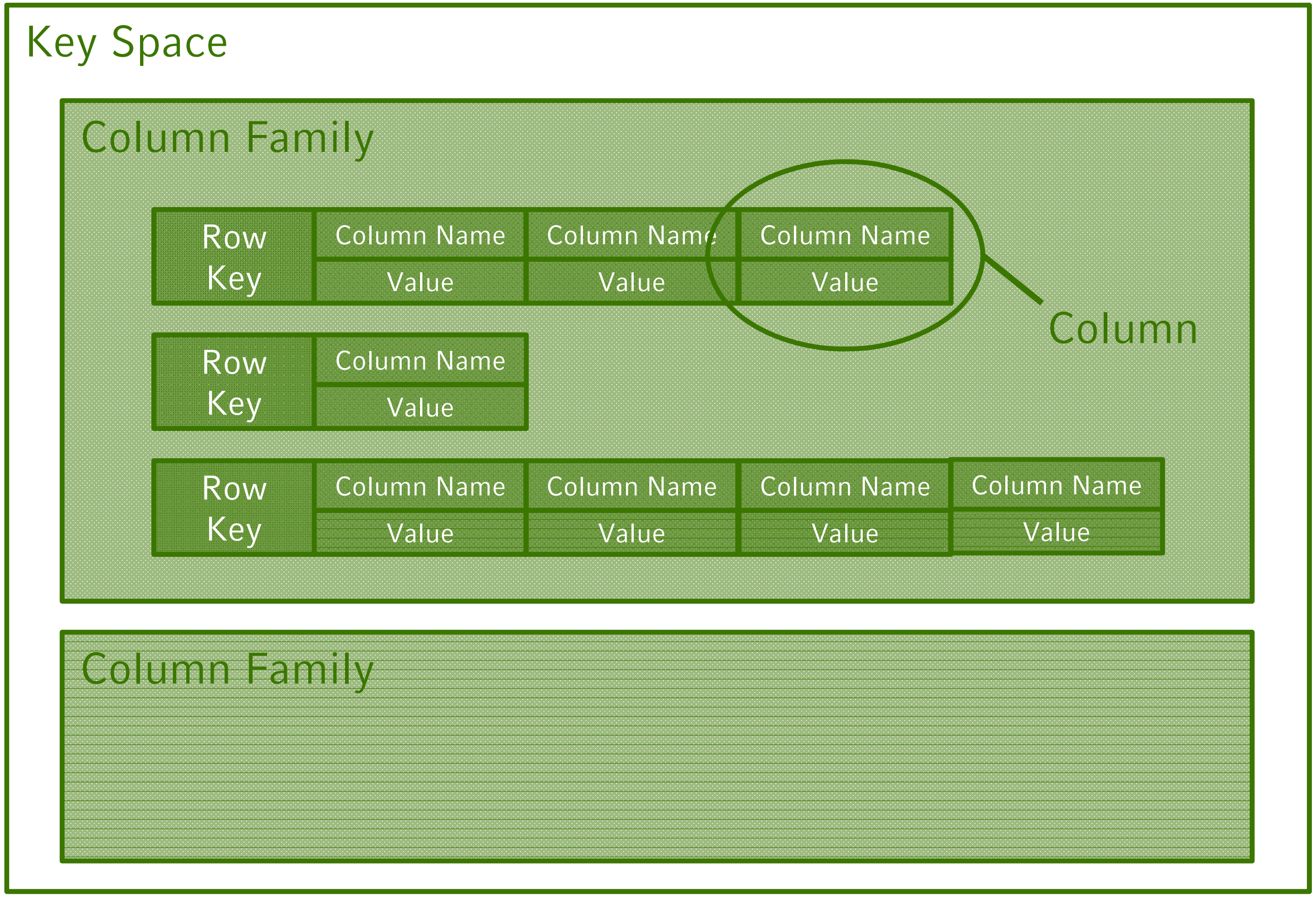
CAP Theorem:



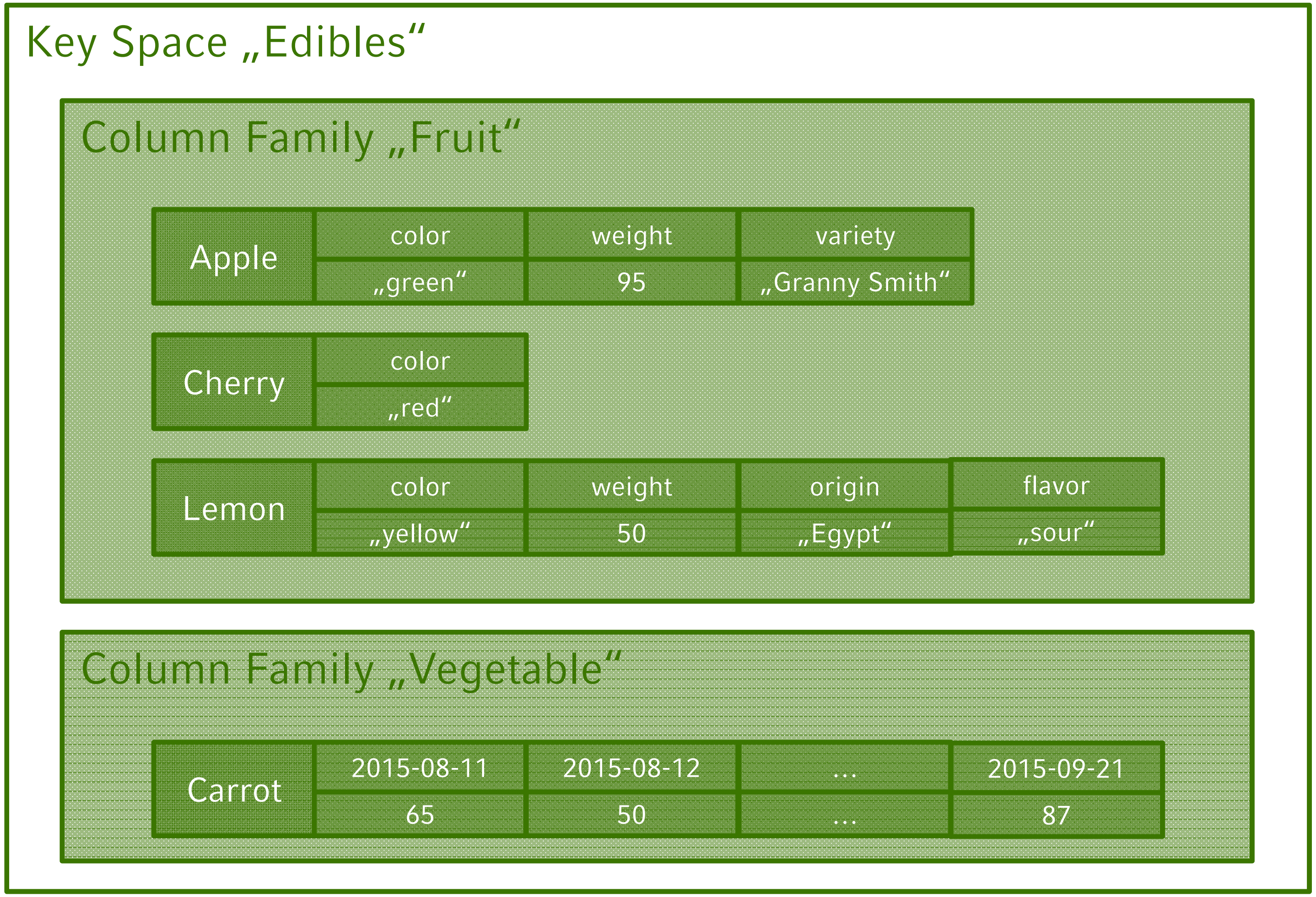
Wide Column Stores:

- Rows are identified by keys
- Rows can have different numbers of columns (up to millions)
- Order of rows depend on key values (locality is important!)
- Multiple rows can be summarized to *families* (or *tablets*)
- Multiple families can be summarized to a *key space*

Wide Column Stores:



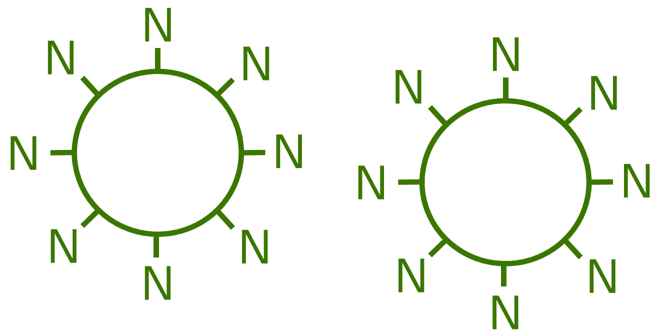
Wide Column Stores:



NoSQL Data Models

Wide Column Stores: Cassandra

- Developed by Facebook, Apache project since 2009
- Cluster Architecture:
  - P2P system (ordered as rings)
  - Each node plays the same role (decentralized)
  - Each node accepts read/write operations



- User access through nodes via *Cassandra Query Language (CQL)*

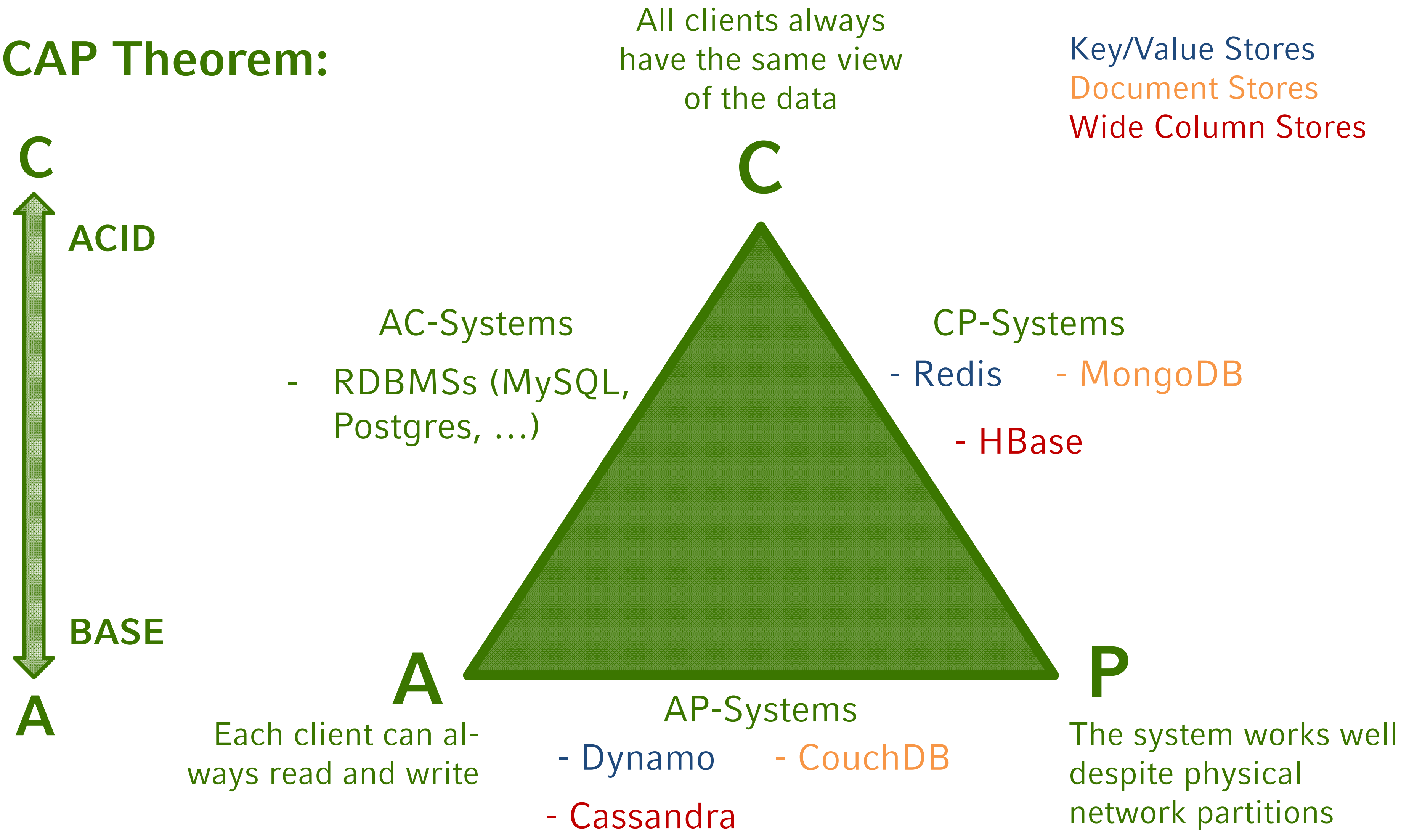
Wide Column Stores: Cassandra

Consistency

- Tunable Data Consistency (choosable per operation)
- Read repair: if stale data is read, Cassandra issues a read repair → find most up-to-date data and update stale data
- Generally: Eventually consistent
- Main focus on availability!

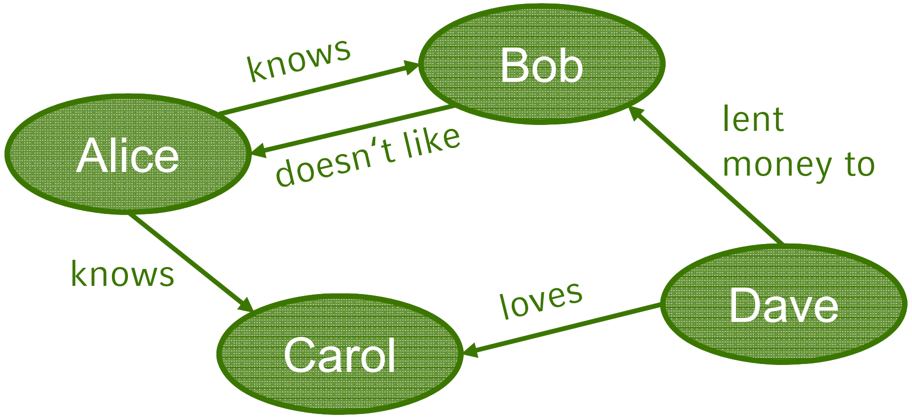
Big Picture

CAP Theorem:



Graph Databases:

- Use graphs to store and represent relationships between entities
- Composed of *nodes* and *edges*
- Each node and each edge can contain *properties* (*Property-Graphs*)



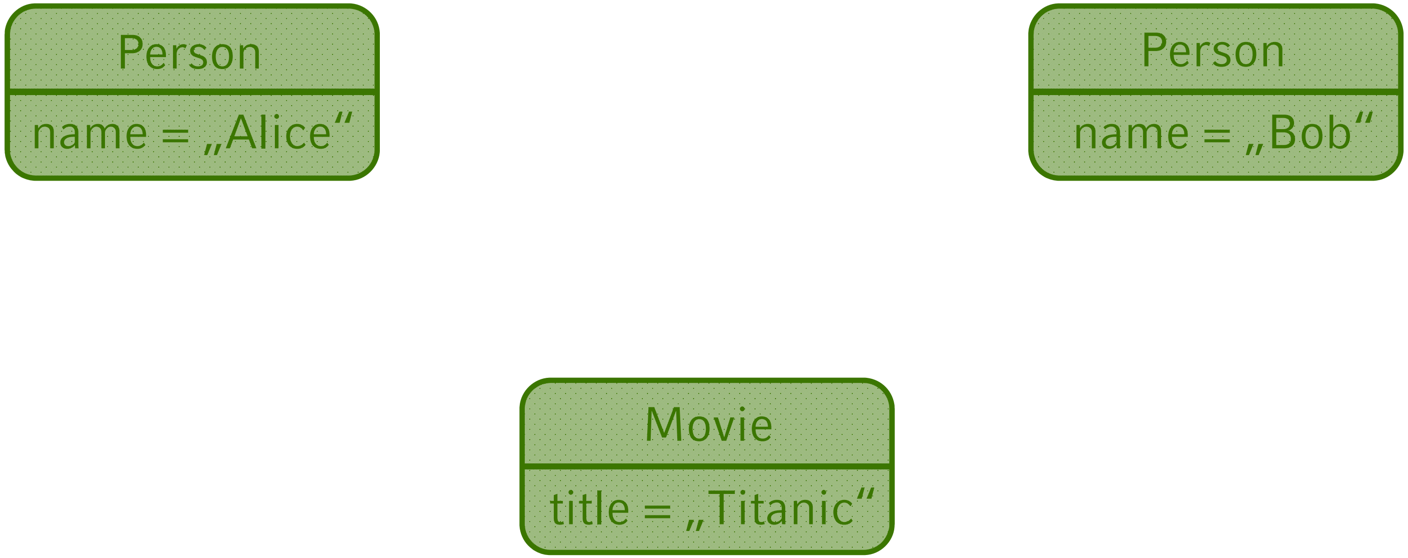
NoSQL Data Models

Graph Databases: neo4j

Alice is a friend of Bob and vice versa. They both love the movie „Titanic“.

Graph Databases:

Alice is a friend of Bob and vice versa. They both love the movie „Titanic".



Graph Databases:

neo4j

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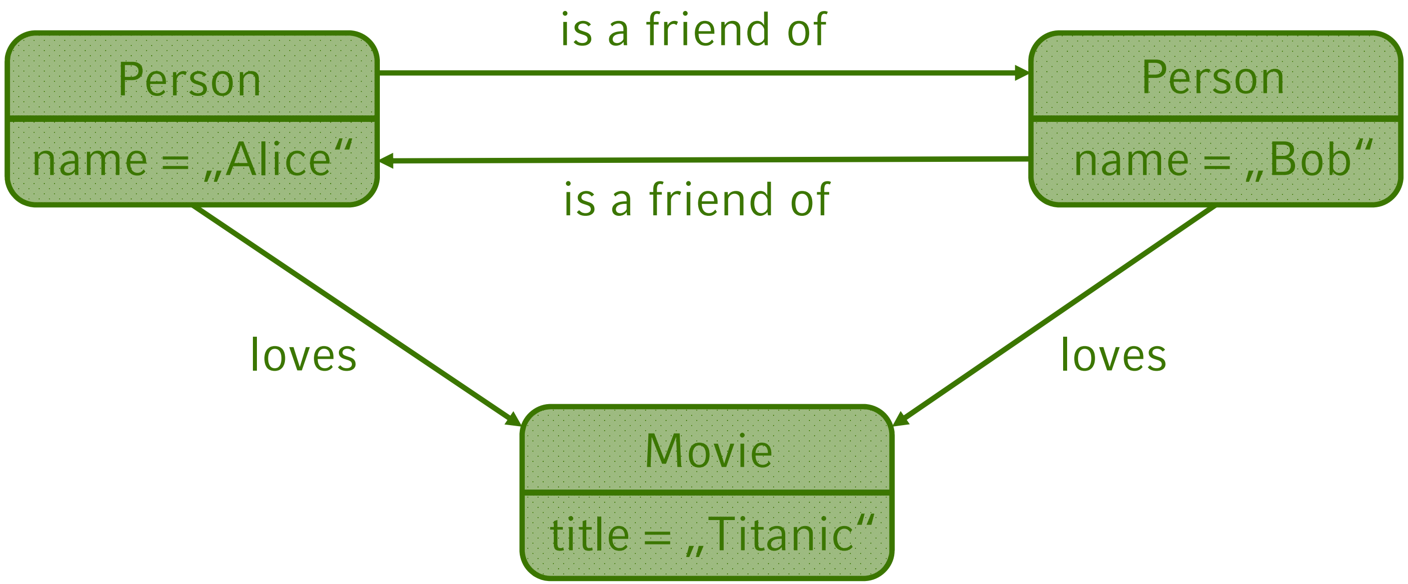


NoSQL Data Models

Graph Databases:

neo4j

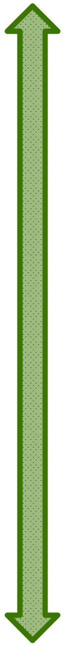
- Master-Slave Replication (no partitioning!)
- Consistency: Eventual Consistency (tunable to Immediate Consistency)
- Support of ACID Transactions
- Cypher Query Language
- Schema-optional

Big Picture

CAP Theorem:

Key/Value Stores
Document Stores
Wide Column Stores
Graph Databases

C



ACID

BASE

A

All clients always have the same view of the data

C

AC-Systems

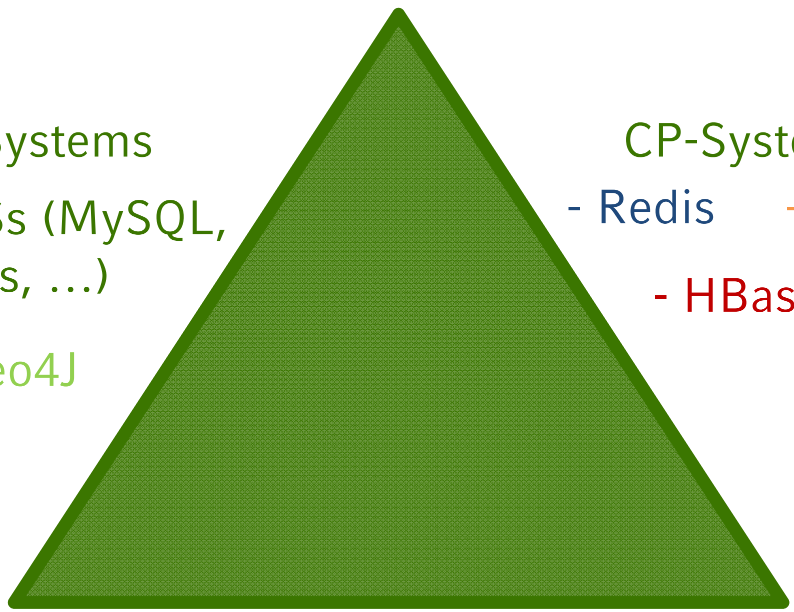
- RDBMSs (MySQL, Postgres, …)

- Neo4J

CP-Systems

- Redis - MongoDB

- HBase



A

Each client can always read and write

AP-Systems

- Dynamo - CouchDB

- Cassandra

P

The system works well despite physical network partitions