Database Models: Beyond RDBMS

UA.DETI.CBD

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The Battle of the Data Models

- Data models are perhaps the most important part of developing software
- They have a profound effect on:
  - how the software is written
  - how we think about the problem that we are solving.
- There are many different kinds of data model
  - Each data model embodies assumptions about how it is going to be used.

- We will now look at a range of general-purpose data models for data storage and querying

When we have some data...

- **Relational Databases solve most data problems**

Why?

- **Persistence**
  – We can store data, and it will remain stored!
- **Integration**
  – We can integrate lots of different apps through a central DB
- **SQL**
  – Standard, well understood, very expressive
- **Transactions**
  – ACID transactions, strong consistency

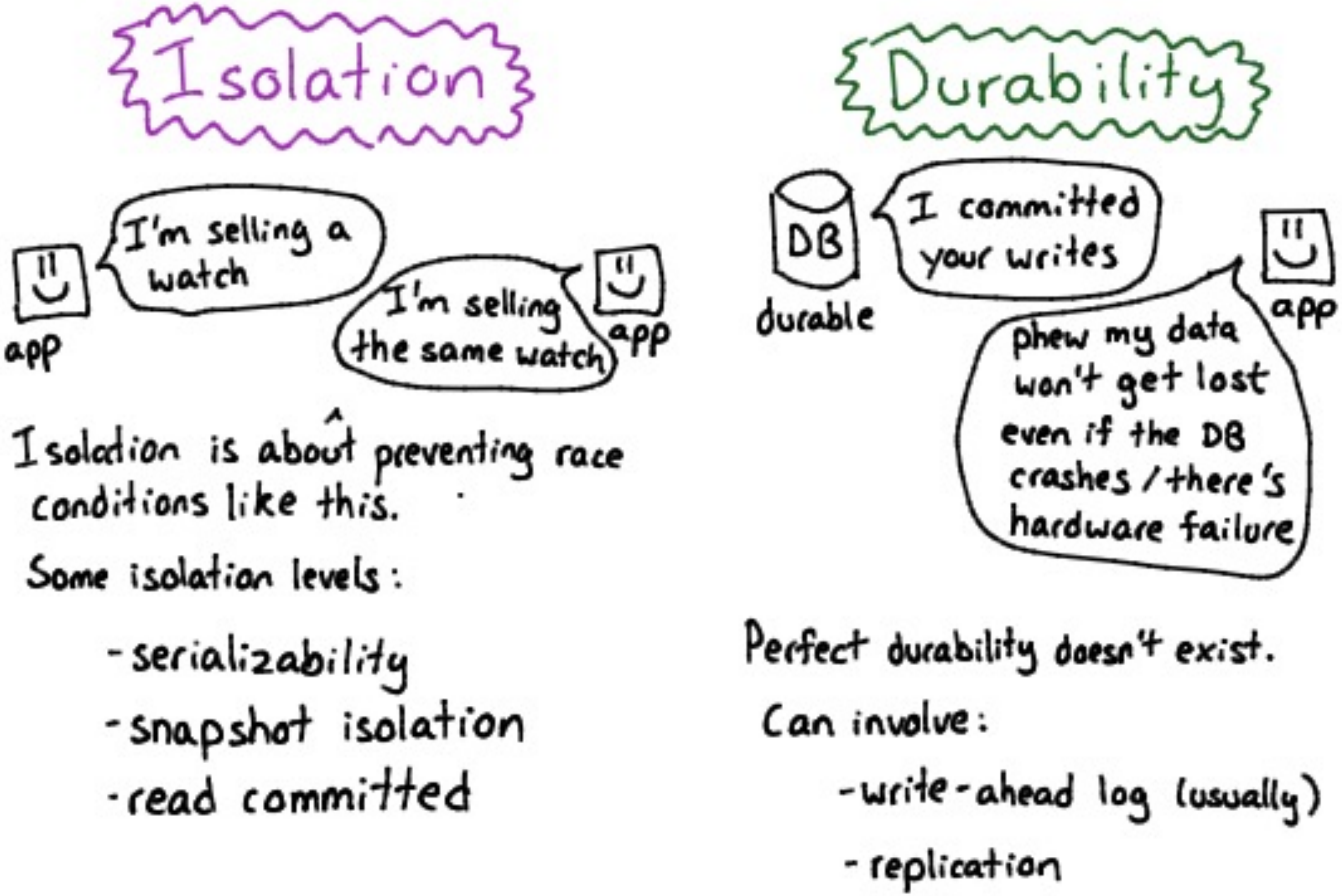
Transactions – ACID Properties

- **Atomic**
  - All of the work in a transaction completes (commit) or none of it completes
- **Consistent**
  - A transaction transforms the database from one consistent state to another consistent state. Consistency is defined in terms of constraints.
- **Isolated**
  - The results of any changes made during a transaction are not visible until the transaction has committed. Concurrent interactions behave as though they occurred serially
- **Durable**
  - The results of a committed transaction survive failures

ACID

https://jvns.ca/blog/2017/06/11/log-structured-storage/

ACID



https://jvns.ca/blog/2017/06/11/log-structured-storage/

The Relational Model

- The relational model, proposed by Edgar Codd in 1970, is still the best-known data model today.
  - data is organized into relations (in SQL: tables), where each relation is an unordered collection of tuples (rows).
- The dominance of relational databases has been around for +40 years.
  - An "eternity" in computing history.
- Other databases at that time forced application developers to think a lot about the internal representation of the data in the database.
  - The goal of the relational model was to hide that implementation detail behind a cleaner interface.

Rivals of the Relational Model

- Over the years, there have been many competing approaches to data storage and querying.
  - Object databases came and went again in the late 1980s and early 1990s.
  - XML databases appeared in the early 2000s, but have only seen niche adoption.
- Much of what you see on the web today is still powered by relational databases
  - Online publishing, discussion, social networking, e-commerce, games, software-as-a-service productivity applications, or much more.
- Now, NoSQL is the most recent attempt to overthrow the relational model's dominance.

Current trends and Issues

- A few key trends and issues have motivated change in relational data storage technologies
  - …In use cases
  - …In technology

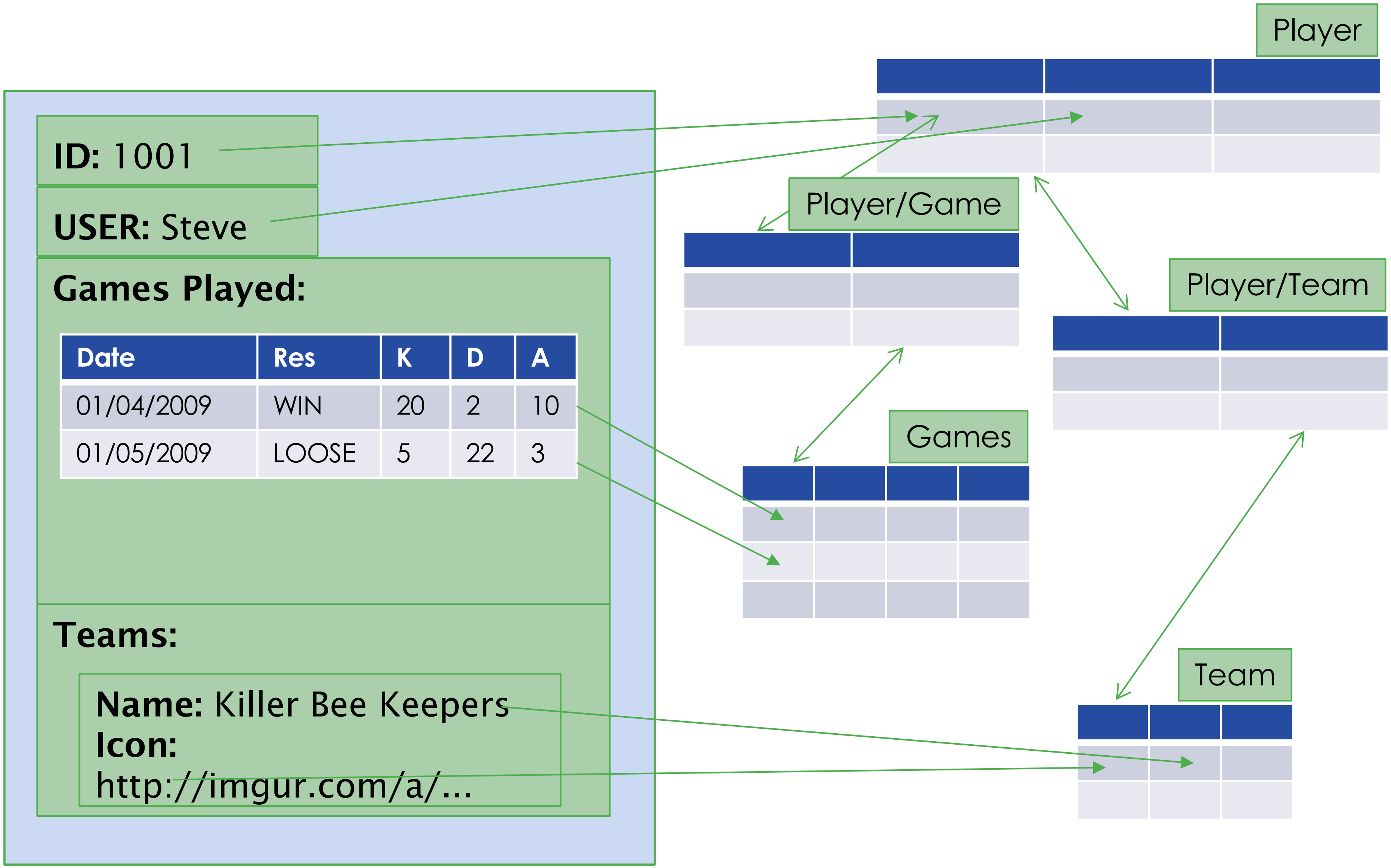
- Key trends include:
  - Increasing **volume of data and traffic**
  - More complex data connectedness
- Key Issues include:
  - The **impedance mismatch** problem

Impedance Mismatch

- **Object** Orientation
  - based on software engineering principles
- **Relational** Paradigms
  - based on mathematics and set theory
- Mapping from one world to the other has problems

- To store data persistently in modern programs a single logical structure must be split up
  - The nice word is **normalised**

Impedance Mismatch – example



Date	Res	K	D	A
01/04/2009	WIN	20	2	10
01/05/2009	LOOSE	5	22	3

Impedance Mismatch – example

http://www.linkedin.com/in/williamhgates

Bill Gates

Greater Seattle Area | Philanthropy

Summary

Co-chair of the Bill & Melinda Gates Foundation. Chairman, Microsoft Corporation. Voracious reader. Avid traveler. Active blogger.

Experience

Co-chair • Bill & Melinda Gates Foundation
2000 – Present

Co-founder, Chairman • Microsoft
1975 – Present

Education

Harvard University
1973 – 1975

Lakeside School, Seattle

Contact Info

Blog: thegatesnotes.com
Twitter: @BillGates

users table

user_id	first_name	last_name	summary
251	Bill	Gates	Co-chair of … blogger.

region_id	industry_id	photo_id
us:91	131	57817532

regions table

id	region_name
us:7	Greater Boston Area
us:91	Greater Seattle Area

industries table

id	industry_name
43	Financial Services
48	Construction
131	Philanthropy

positions table

id	user_id	job_title	organization
458	251	Co-chair	Bill & Melinda Gates F…
457	251	Co-founder, Chairman	Microsoft

education table

id	user_id	school_name	start	end
807	251	Harvard University	1973	1975
806	251	Lakeside School, Seattle	NULL	NULL

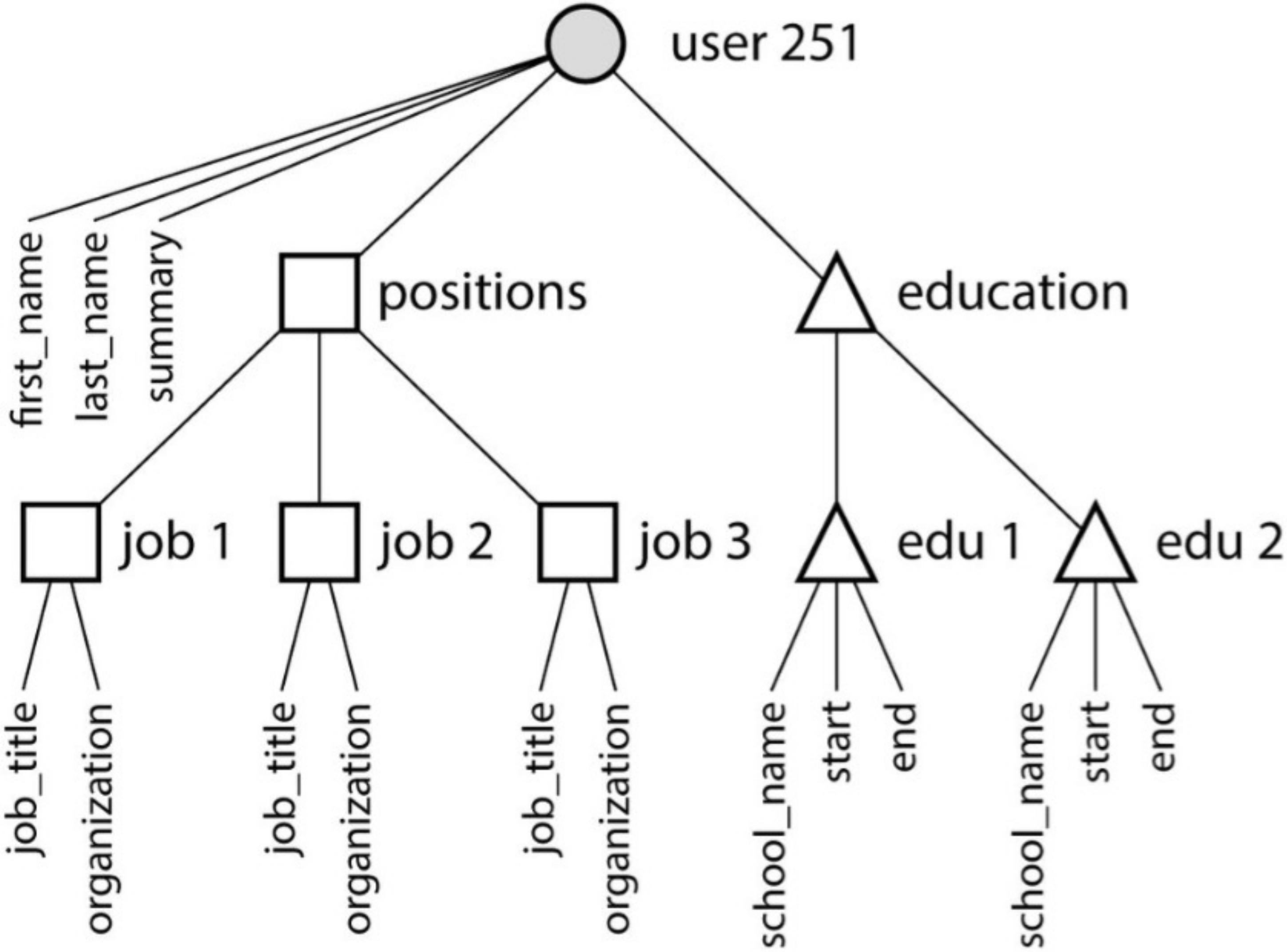
contact_info table

id	user_id	type	url
155	251	blog	http://thegatesnotes.com
156	251	twitter	http://twitter.com/BillGates

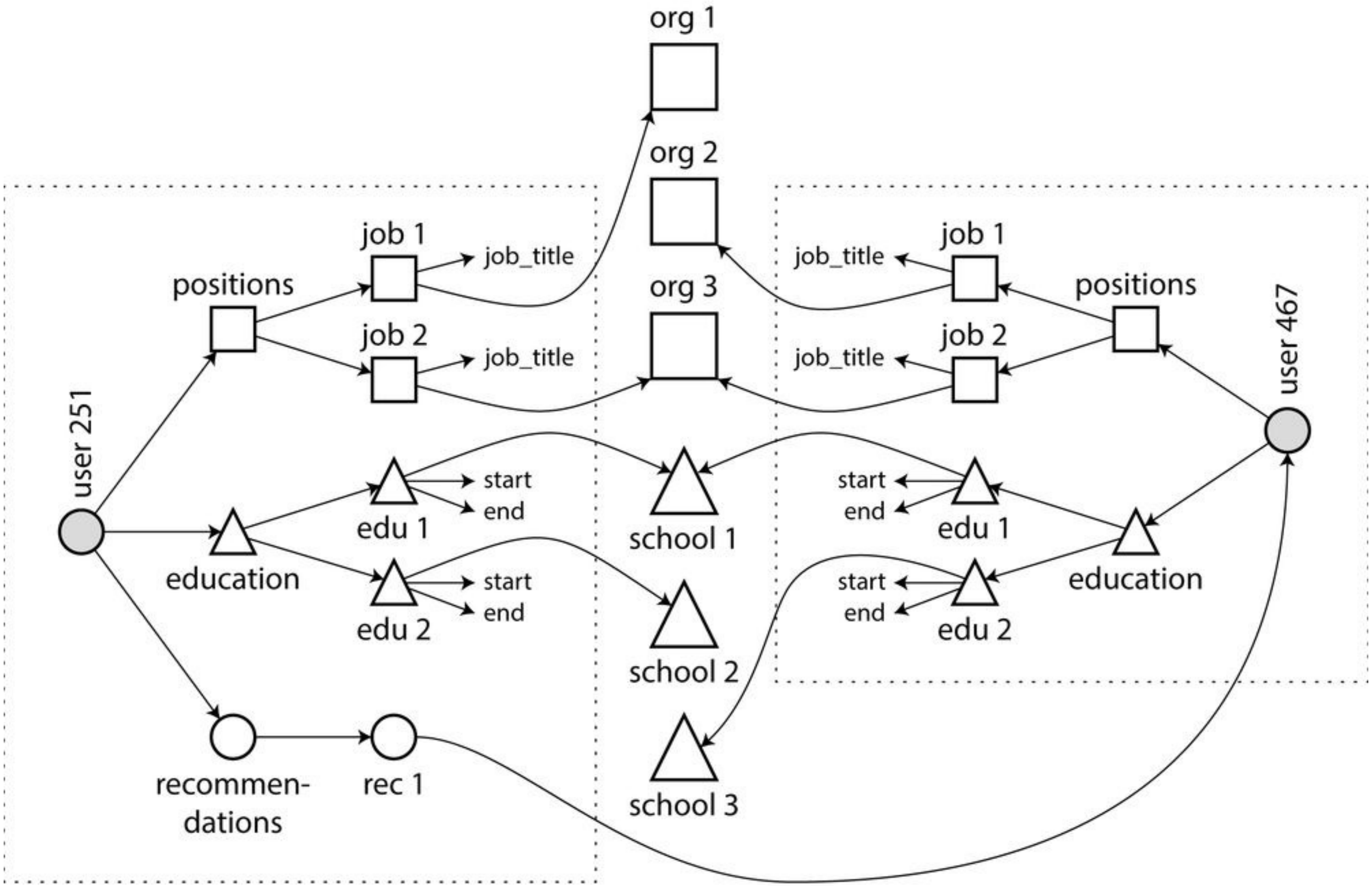
Normalization

- Why IDs (region_id, industry_id, ..) and not plain-text?
  - Consistent style and spelling across profiles,
  - Avoiding ambiguity, e.g. if there are several cities with the same name,
  - The name is stored only in one place, so it is easy to update,
  - Simplify translation into other languages,
- A database in which entities like region and industry are referred to by ID is called **normalized**.
- A database that duplicates the names and properties of entities on each document is **denormalized**.

One-to-Many relations



Many-to-Many relationships



Increased Data Volume

- We are creating, storing, processing more data than ever before!
  - *“From 2005 to 2020, the digital universe will grow by a factor of 300, from 130 exabytes to 40,000 exabytes, or 40 trillion gigabytes (more than 5,200 gigabytes for every man, woman, and child in 2020)".*
    - THE DIGITAL UNIVERSE IN 2020: Big Data, Bigger Digital Shadows, and Biggest Growth in the Far East, Dec 2012, John Gantz and David Reinsel
  - *"IDC predicts that the collective sum of the world’s data will grow from 33 zettabytes this year to a 175ZB by 2025."*
    - The Digitization of the World, From Edge to Core, Nov 2018
    - https://www.seagate.com/files/www-content/our-story/trends/files/idc-seagate-dataage-whitepaper.pdf

EB = 10^{18} ZB = 10^{21}

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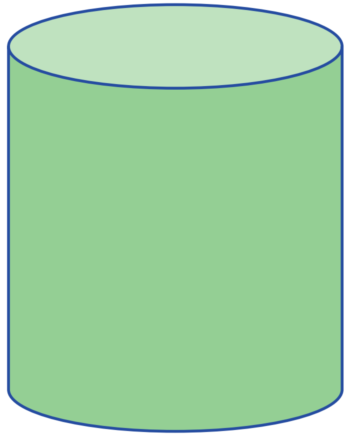
Increased Data Connectivity

- The data we're producing has fundamentally changed
  - from isolated Text Documents (early 1990s)
  - … to html pages with links (early web)
  - … to blogs with pingback, RSS feeds (web 2.0)
  - … to social networks (… add links between people)
  - … to massive linked open data sets (web 3.0… one of them anyway)

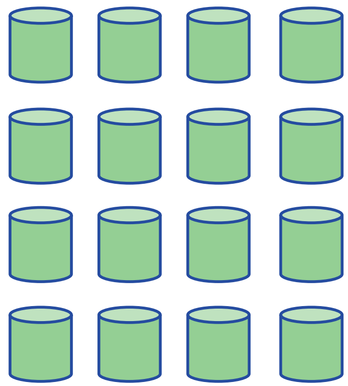
Dealing with data size Trends

- Two options when dealing with these trends:

- Build Bigger Database machines
  - This can be expensive
  - Fundamental limits to machine size



- Build Clusters of smaller machines
  - Lots of small machines (commodity machines)
  - Each machine is cheap, potentially unreliable
  - Needs a DBMS which understands clusters



RDBMS have fundamental issues

- In dealing with (horizontal) scale
  - Designed to work on single, large machines
  - Difficult to distribute effectively
- More subtle: An Impedance Mismatch
  - We create logical structures in memory
    - and then rip them apart to stick it in an RDBMS
  - The RDBMS data model often disjoint from its intended use
    - (Normalisation sucks sometimes)
  - Uncomfortable to program with (joins and ORM etc.)

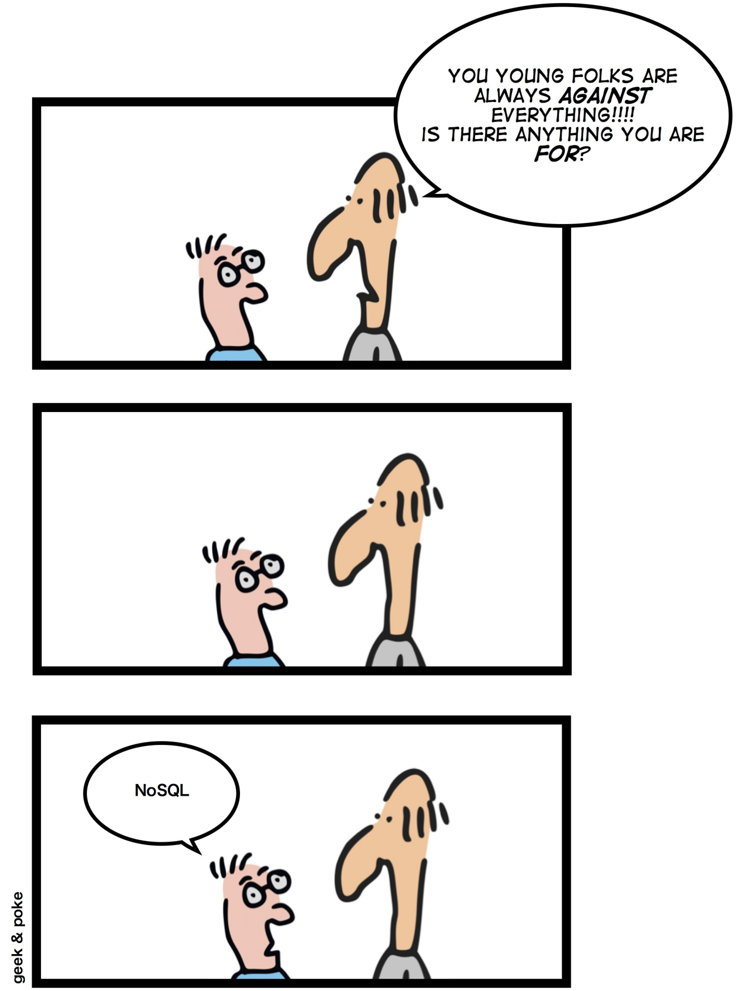
The NoSQL Movement

NoSQL

- The term NoSQL is unfortunate, since it doesn't refer to any technology
  - "Not only SQL"
- Nevertheless, the term struck a nerve, and quickly spread through the web startup community and beyond.
- Several interesting database systems are now associated with the #NoSQL hashtag.

The NoSQL movement

- Key attributes include:
  - **Non-Relational**
    - They can be, but aren't good at it
  - **Simple API**
    - No Join
  - **BASE** & **CAP** Theorem
    - No ACID requirements
  - **Schema-free**
    - Implicit schema, application side
  - **Inherently Distributed**
    - Some more so than others
  - **Open Source**
    - mostly



BASE Transactions

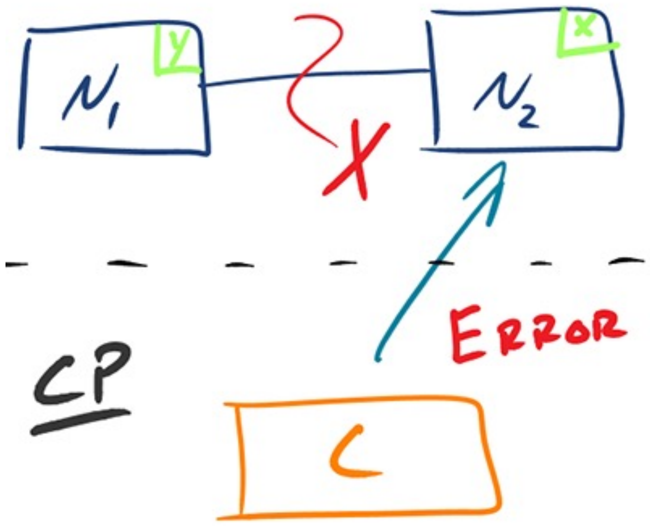
- Acronym contrived to be the opposite of ACID
  - Basic Availability
    - The database appears to work most of the time.
  - Soft-state
    - Stores don't have to be write-consistent, nor do different replicas have to be mutually consistent all the time.
  - Eventual consistency
    - Stores exhibit consistency at some later point (e.g., lazily at read time).
- Characteristics
  - Optimistic
  - Simpler and faster
  - Availability first
  - Best effort
  - Approximate answers OK

Brewer's CAP Theorem

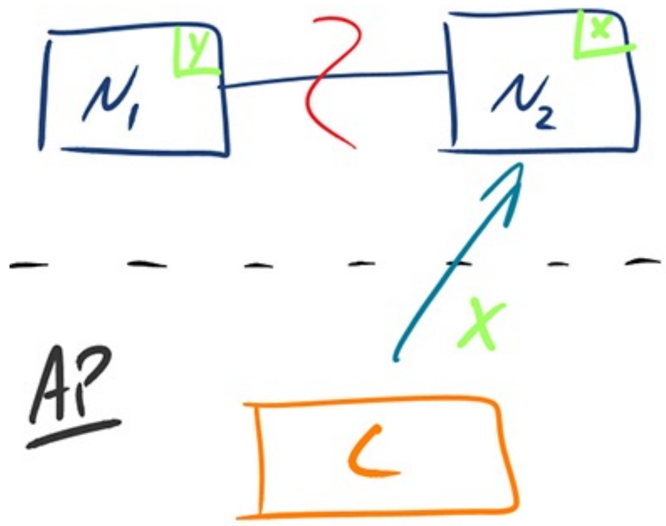
- A distributed system can support only two of the following characteristics:
  - **Consistent**
    - writes are atomic, all subsequent requests retrieve the new value
  - **Available**
    - The database will always return a value so long as the server is running
  - **Partition Tolerant**
    - The system will still function even if the cluster network is partitioned (i.e. the cluster loses contact with parts of itself)
- The overly stated well cited issue is:
  - We can only ever build an algorithm which satisfies 2 of 3.
    - But .. horizontal scaling strategy is based on data partitioning;
    - Therefore, designers are forced to decide between consistency and availability.

Brewer's CAP Theorem

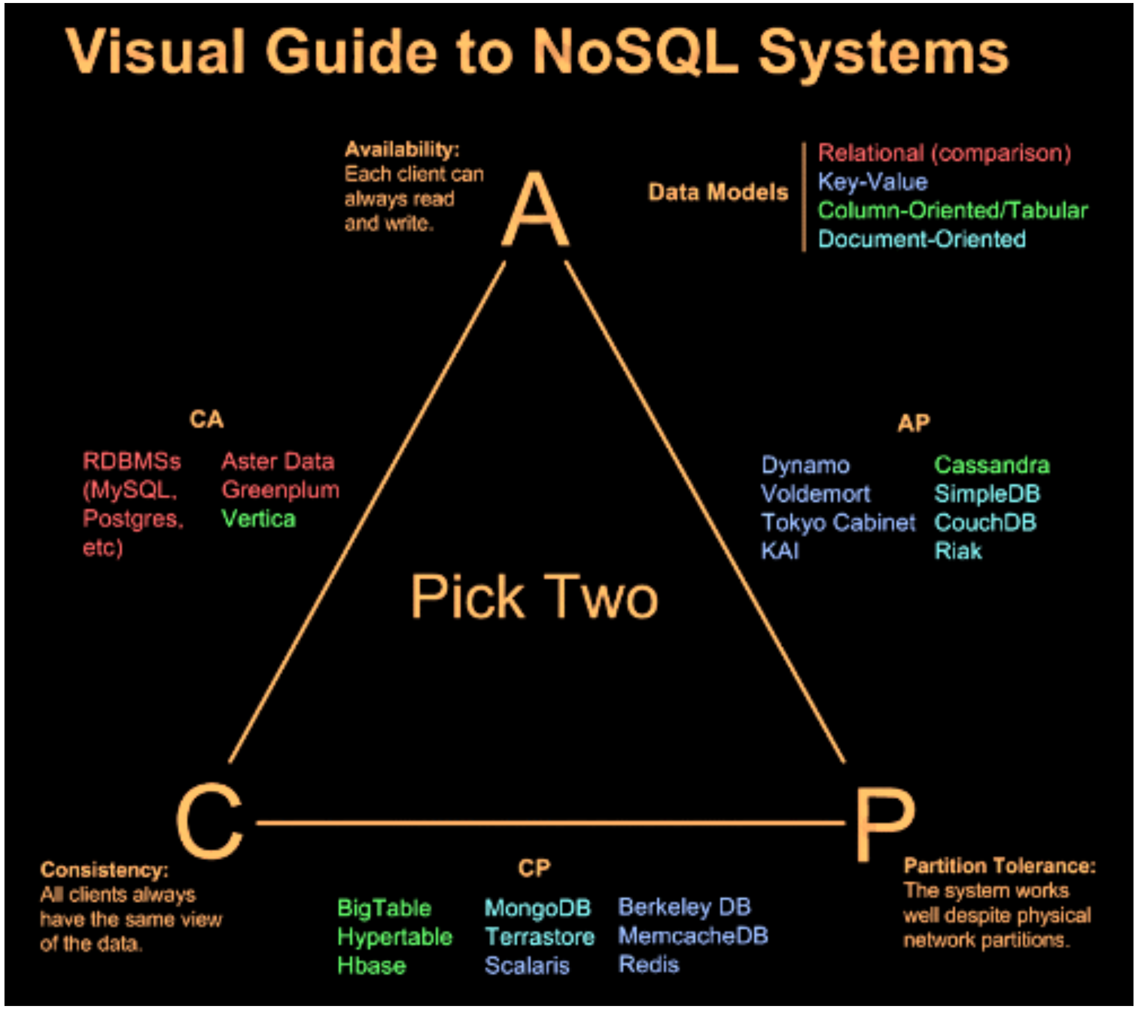
- **CP** - Consistency/Partition Tolerance



- **AP** - Availability/Partition Tolerance



CAP Theorem



Visual Guide to NoSQL Systems
Availability:
Each client can always read and write.
A
Data Models
Relational (comparison)
Key-Value
Column-Oriented/Tabular
Document-Oriented
CA
RDBMSs (MySQL, Postgres, etc)
Aster Data
Greenplum
Vertica
AP
Dynamo
Voldemort
Tokyo Cabinet
KAI
Cassandra
SimpleDB
CouchDB
Riak
Pick Two
C
P
Consistency:
All clients always have the same view of the data.
CP
BigTable
Hypertable
Hbase
MongoDB
Terrastore
Scalaris
Berkeley DB
MemcacheDB
Redis
Partition Tolerance:
The system works well despite physical network partitions.

Types of NoSQL Databases

- Core types
  - **Key-value** stores
  - **Document** stores
  - **Column** stores
  - **Graph** databases
- Non-core types
  - **Object** databases
  - Native **XML** databases
  - **RDF** stores
  - …

Key-Value Databases – Basics

- Data model
  - The most simple NoSQL database type
  - Works as a simple hash table (mapping)
- Key-value pairs
  - **Key** (id, identifier, primary key) – usually a string.
  - **Value**: can be anything (text, structure, image, etc.) – a black box for the database system.
- Query patterns
  - Create, update or remove value for a given key
  - Get value for a given key
- Characteristics
  - great performance, easily scaled, …
  - not for complex queries nor complex data

Key-Value Databases – Basics

- Suitable use cases
  - Session data, user profiles, user preferences, shopping carts, …
    - I.e. when values are only accessed via keys
- When not to use
  - Relationships among entities
  - Queries requiring access to the content of the value part
- Examples
  - Redis, MemcachedDB, Riak KV, Amazon SimpleDB, Berkeley DB, Oracle NoSQL, LevelDB, Project Voldemort
  - *Multi-model*: OrientDB, ArangoDB

Document Databases – Basics

- Data model - Documents
  - Self-describing complex data structure
  - **Hierarchical tree structures** (JSON, XML, …)
    - Scalar values, maps, lists, sets, nested documents, …
  - Identified by a unique identifier (key, …)
- Document data stores understand their documents
  - Queries can run against values of document fields
  - Indexes can be constructed for document fields
- Query patterns
  - Create, update or remove a document
  - Retrieve documents according to complex queries
- Difference from Key-Value stores
  - Extended key-value stores. The value part is examinable!

Document Databases – Basics

```
{
"_id": "1",
  "name": "steve",
  "games_owned": [
    {"name":"Super Meat Boy"},
    {"name":"FTL"},
  ],
}
```

```
{
  "_id": "2",
  "name": "darren",
  "handle":"zerocool",
  "games_owned": [
    {"name":“FTL"},
    {"name":“Assassin’s Creed 3“, “dev”: “ubisoft”},
  ],
}
```

Document Databases – Basics

- Suitable use cases
  - Event logging, content management systems, blogs, web analytics, e-commerce applications, …
  - I.e. for **structured documents with similar schema**
- When not to use
  - Set operations involving multiple documents
  - Design of document structure is constantly changing
    - I.e. when the required level of granularity would outbalance the advantages of aggregates
- Examples
  - MongoDB, Couchbase, Amazon DynamoDB, CouchDB, RethinkDB, RavenDB, Terrastore
  - *Multi-model:* MarkLogic, OrientDB, OpenLink Virtuoso, ArangoDB

Column Databases – Basics

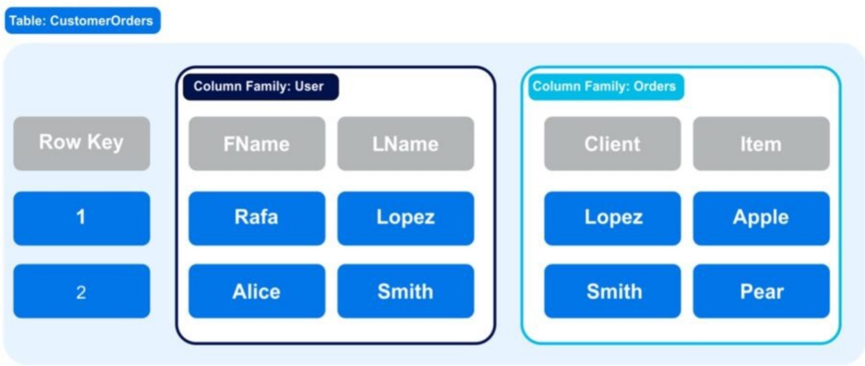
- Data model
  - Column family (table)
    - Table is a collection of similar rows (not necessarily identical)
  - Row
    - Row is a collection of columns - should encompass a group of data that is accessed together
    - Associated with a unique row key
  - Column
    - Column consists of a column name and column value (and possibly other metadata records)
    - Scalar values, but also flat sets, lists or maps may be allowed
- Query patterns
  - Create, update or remove a row within a given column family
  - Select rows according to a row key or simple conditions

Column Databases – Basics

- Suitable use cases
  - Event logging, content management systems, blogs, …
    - I.e. for structured flat data with similar schema
  - Batch processing via mapreduce
- When not to use
  - ACID transactions are required
  - Complex queries: aggregation (SUM, AVG, …), joining, …
  - Early prototypes: i.e. when database design may change
- Examples
  - Apache Cassandra, Apache HBase, Apache Accumulo, Hypertable, Google Bigtable

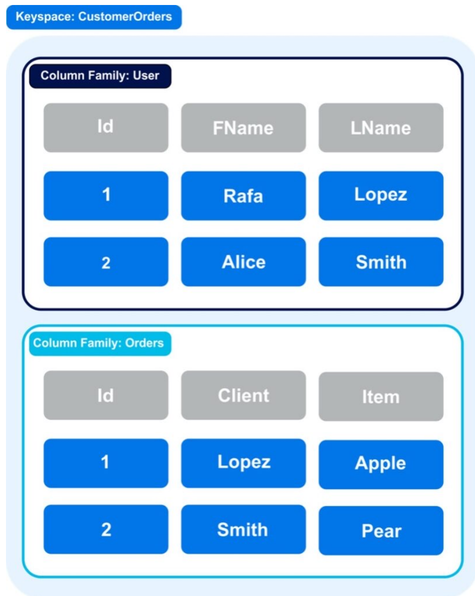
Column Databases – Approaches

- Apache HBase versus Apache Cassandra
  - **HBase**
    - data model is the column-oriented table
    - rows are divided into related columns of data called column families




```
> get 'CustomerOrders ', '1'
COLUMN                    CELL
User: FName timestamp = 1675123184293, value = Rafa
User: LName timestamp = 1675123184293, value = Lopez
Orders: Client timestamp = 1675123388213, value = Lopez
Orders: Client timestamp = 1675123388214, value = Apple
4 row(s) in 0.0260 seconds
```

  - **Cassandra**:
    - data model is best described as a partitioned row store
    - at top-level data model, keyspaces are column-families

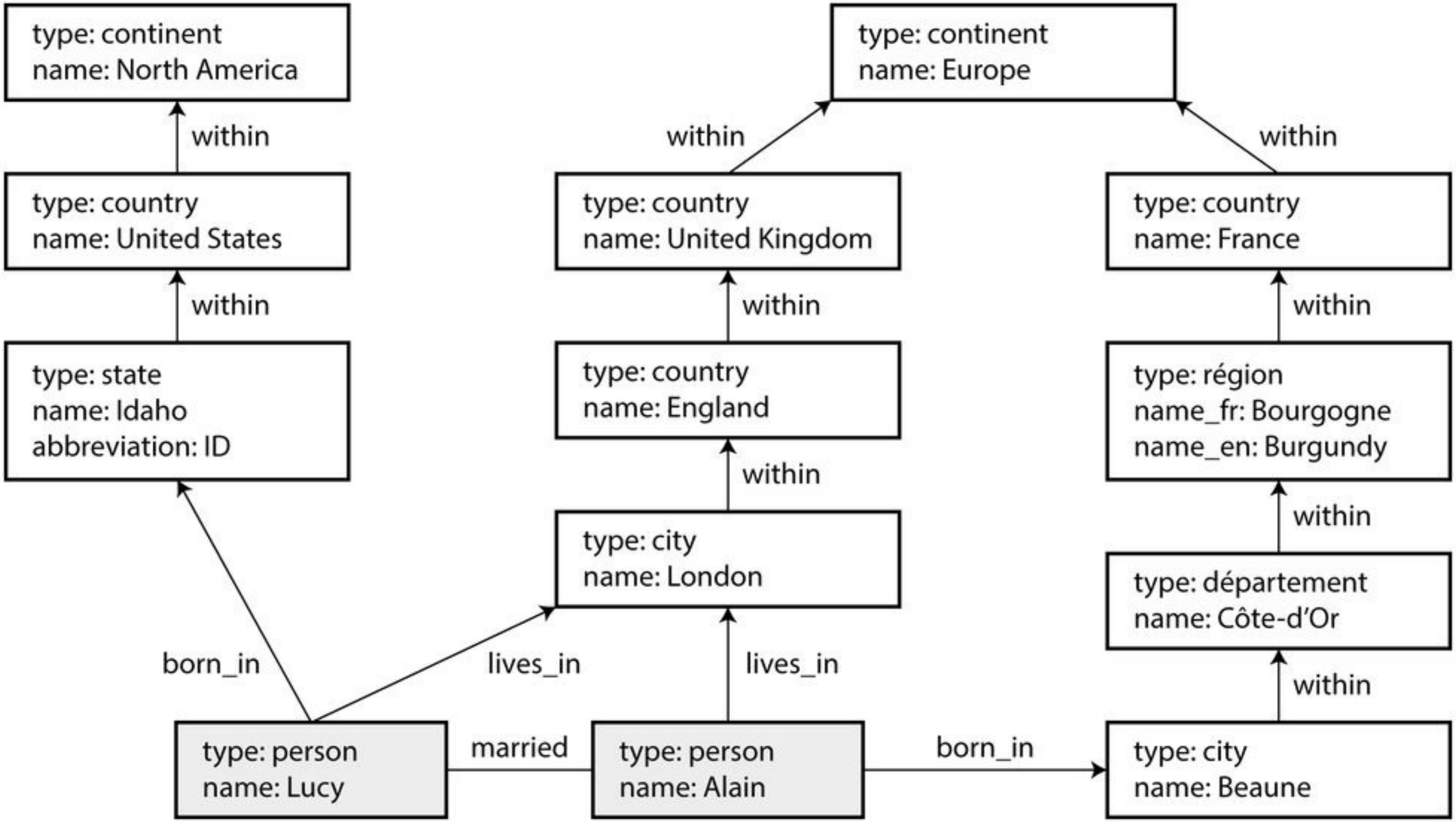



```
cqlsh> select * from User;
id |  fname | lname
--------+-----------+---------
    1 | Rafa    |    Lopez
    2 | Alice   |    Smith
(2 rows)
```

Graph Databases – Basics

- Data Model
  - Focus on modelling graphs' structure and properties
  - Directed / undirected graphs, i.e. collections of …
    - nodes (vertices) for real-world entities, and
    - relationships (edges) between these nodes
  - Both the nodes and relationships can have properties
- Query patterns
  - Create, update or remove a node / relationship in a graph
    - Graph algorithms (shortest paths, spanning trees, …)
    - General graph traversals
    - Sub-graph queries or super-graph queries
    - Similarity based queries (approximate matching)

Graph Databases – Basics



Graph Databases – Basics

- Suitable use cases
  - Social networks, routing, dispatch, and location-based services, recommendation engines, chemical compounds, biological pathways, linguistic trees, …
- When not to use
  - Extensive batch operations are required
    - Multiple nodes / relationships are to be affected
  - Too large graphs to be stored
    - Graph distribution is difficult or impossible at all
- Examples
  - Neo4j, Titan, Apache Giraph, InfiniteGraph, FlockDB
  - *Multi-model*: OrientDB, OpenLink Virtuoso, ArangoDB

Native XML Databases – Basics

- Data model
  - XML documents
  - **Tree structure** with nested elements, attributes, and text values (beside other less important constructs)
  - Documents are organized into collections
- Query languages
  - **XPath**: XML Path Language (navigation)
  - **XQuery**: XML Query Language (querying)
  - **XSLT**: XSL Transformations (transformation)
- Examples
  - Sedna, Tamino, BaseX, eXist-db
  - *Multi-model*: MarkLogic, OpenLink Virtuoso

RDF Databases – Basics

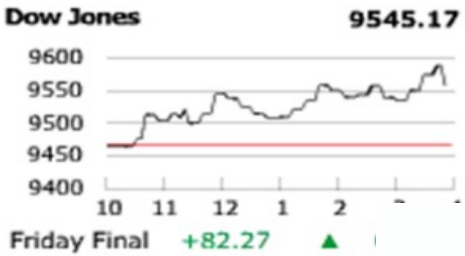
- Data model
  - RDF **triples**
    - Components: **subject**, **predicate**, and **object**
    - Each triple represents a statement about a real-world entity
  - Triples can be viewed as graphs
    - Vertices for subjects and objects
    - Edges directly correspond to individual statements
- Query language
  - **SPARQL**: SPARQL Protocol and RDF Query Language
- Examples
  - Apache Jena, rdf4j (Sesame), Algebraix
  - *Multi-model*: MarkLogic, OpenLink Virtuoso

Time Series Databases – basics

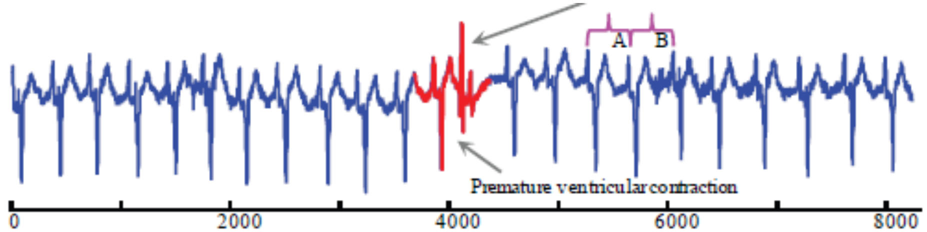
- Data model
  - Stores pairs "Time:Value"
- Query language
  - **Proprietary**: InfluxQL, …
  - **SQL:** some multi-model engines
- Usage
  - store profiles, curves, traces or trends
  - fewer relationships between data entries
  - long sets of data
  - data patterns are "appreciated"
    - compression algorithms to manage the data efficiently
- Examples
  - InfluxDB, Prometheus, Graphite
  - *Multi-model*: Kdb, TimescaleDB

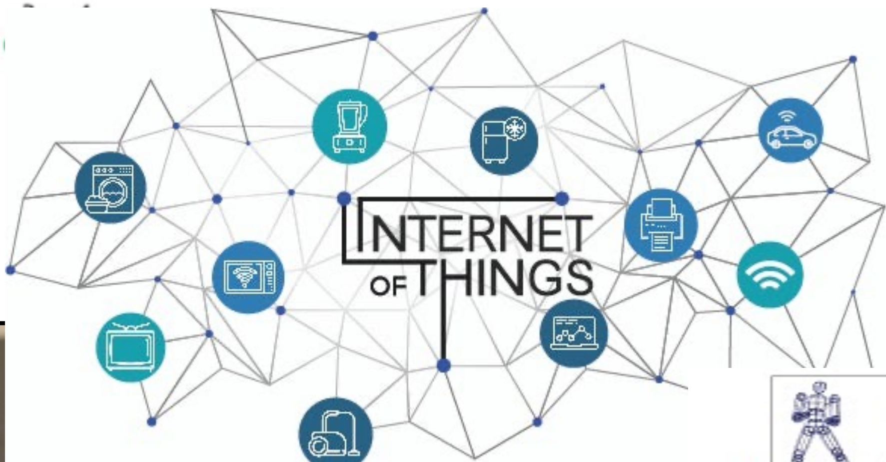
Time Series Examples

Stocks Data

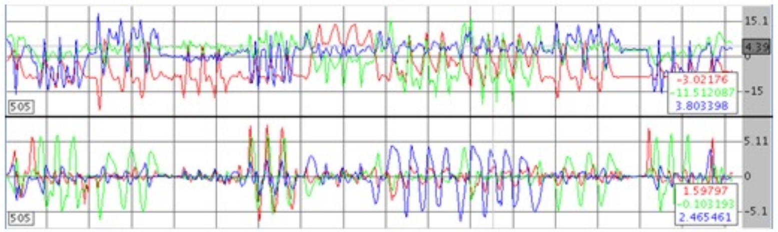


Vital Signals: ECG, EEG,...

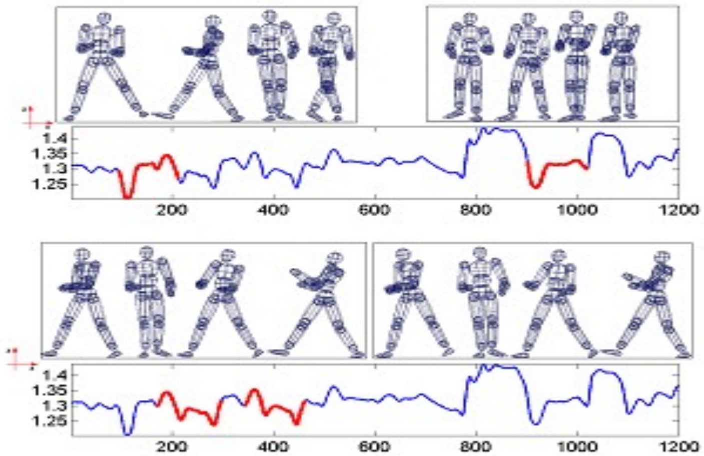




Sensors



Motion Data



NoSQL Databases

- The end of relational databases?

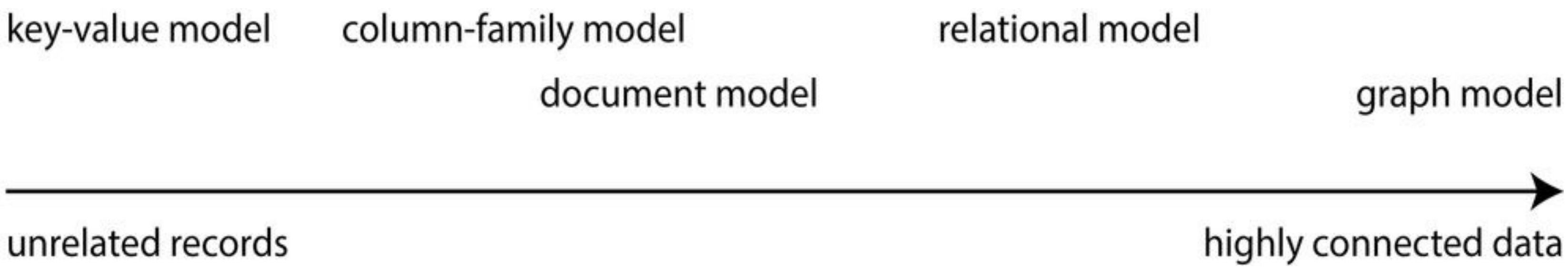
- **Certainly no!**
  - They are still suitable for most projects (90%)
  - Familiarity, stability, feature set, available support, …

- However, we should also consider different database models and systems
  - **Polyglot persistence** = usage of different data stores in different circumstances

Databases and data connectivity

- Relational model

- NoSQL models
  - Key-value stores
  - Document stores
  - Column stores
  - Graph databases



What next?

- Basic principles
  - Data formats: JSON, YAML, XML, RDF, …
  - Distribution, scaling, sharding, replication, consistency
  - Parallelism, transactions, visualization, processing of graphs
- NoSQL technologies: principles, models, interfaces, languages, …
  - Core databases: Redis, MongoDB, Cassandra, Neo4j
  - MapReduce: Apache Hadoop

Resources

- Martin Kleppmann, ***Designing Data-Intensive Applications***, O'Reilly Media, Inc., 2017.
- Pramod J Sadalage and Martin Fowler, ***NoSQL Distilled*** Addison-Wesley, 2012.
- Eric Redmond, Jim R. Wilson. ***Seven databases in seven weeks***, Pragmatic Bookshelf, 2012.
- Hector Garcia-Molina, Jeffrey D. Ullman, Jennifer Widom, ***Database systems: the complete book*** *(2nd Ed.)*, Pearson Education, 2009.