

## MIE-PDB.16: **Advanced Database Systems**

<http://www.ksi.mff.cuni.cz/~svoboda/courses/201-MIE-PDB/>

Lecture 1

# Introduction

**Martin Svoboda**

[martin.svoboda@fit.cvut.cz](mailto:martin.svoboda@fit.cvut.cz)

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**Charles University**, Faculty of Mathematics and Physics

**Czech Technical University in Prague**, Faculty of Information Technology

# Lecture Outline

## Big Data

- Characteristics
- Current trends

## NoSQL databases

- Motivation
- Features

## Overview of NoSQL database types

- **Key-value, wide column, document, graph, ...**

# What is Big Data?

**Buzzword? Bubble? Gold rush? Revolution?**



*Dan Ariely:*

**Big Data** is like teenage sex: **everyone talks about it, nobody really knows how to do it, everyone thinks everyone else is doing it, so everyone claims they are doing it.**

# What is Big Data?

No standard definition

- Gartner (*research and advisory company*):  
**High Performance Computing**

**Big Data** is **high volume**, **high velocity**, and/or **high variety** information assets that require **new forms of processing** to enable enhanced decision making, insight discovery and process optimization.

# Where is Big Data?

## Sources of Big Data

- **Social media and networks**
  - ...all of us are generating data
- **Scientific instruments**
  - ...collecting all sorts of data
- **Mobile devices**
  - ...tracking all objects all the time
- **Sensor technology and networks**
  - ...measuring all kinds of data

# Big Data Characteristics

## Volume (Scale)

**40 ZETTABYTES**

[ 43 TRILLION GIGABYTES ]  
of data will be created by  
2020, an increase of 300  
times from 2005



It's estimated that  
**2.5 QUINTILLION BYTES**

[ 2.3 TRILLION GIGABYTES ]  
of data are created each day

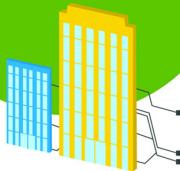


**6 BILLION PEOPLE**  
have cell  
phones



WORLD POPULATION: 7 BILLION

**Volume**  
SCALE OF DATA



Most companies in the  
U.S. have at least

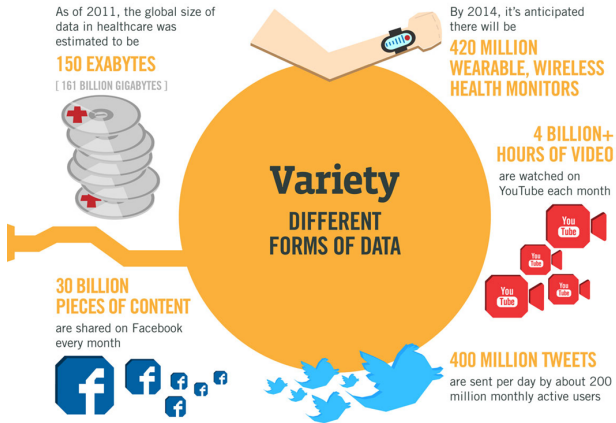
**100 TERABYTES**

[ 100,000 GIGABYTES ]  
of data stored

Source: <http://www.ibmbigdatahub.com/>

# Big Data Characteristics

## Variety (Complexity)



Source: <http://www.ibmbigdatahub.com/>

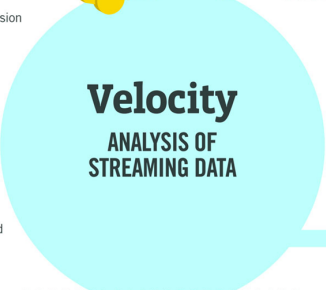
# Big Data Characteristics

## Velocity (Speed)

The New York Stock Exchange captures  
**1 TB OF TRADE INFORMATION**  
during each trading session



Modern cars have close to  
**100 SENSORS**  
that monitor items such as  
fuel level and tire pressure



By 2016, it is projected  
there will be  
**18.9 BILLION NETWORK CONNECTIONS**  
– almost 2.5 connections  
per person on earth

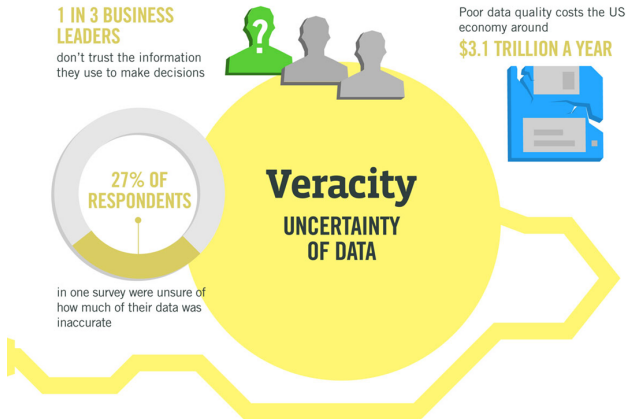


Source: <http://www.ibmbigdatahub.com/>



# Big Data Characteristics

## Veracity (Uncertainty)



Source: <http://www.ibmbigdatahub.com/>

# Big Data Characteristics

## Basic 4V

- **Volume** (Scale)
  - Data volume is increasing exponentially, not linearly
  - Even large amounts of small data can result into Big Data
- **Variety** (Complexity)
  - Various formats, types, and structures  
(from semi-structured XML to unstructured multimedia)
- **Velocity** (Speed)
  - Data is being generated fast and needs to be processed fast
- **Veracity** (Uncertainty)
  - Uncertainty due to inconsistency, incompleteness, latency, ambiguities, or approximations

# Big Data Characteristics

## Additional V and C

- **Value**
  - Business value of the data (needs to be revealed)
- **Validity**
  - Data correctness and accuracy with respect to the intended use
- **Volatility**
  - Period of time the data is valid and should be maintained
  
- **Cardinality**
- **Continuity**
- **Complexity**

# Big Data Characteristics

## Additional V



Source: <https://www.xenonstack.com/blog/big-data-engineering/ingestion-processing-big-data-iot-stream/>

# Relational Databases

## Data model

Instance → **database** → **table** → **row**

## Query languages

- Real-world: **SQL** (*Structured Query Language*)
- Formal: **Relational algebra**, relational calculi (domain, tuple)

## Query patterns

- **Selection** based on complex conditions, **projection**, **joins**, **aggregation**, derivation of new values, recursive queries, ...

## Representatives

- Oracle Database, Microsoft SQL Server, IBM DB2
- MySQL, PostgreSQL

# Relational Databases

## Representatives

**ORACLE**<sup>®</sup>  
DATABASE

  
Microsoft<sup>®</sup>  
SQL Server<sup>®</sup>

**IBM** DB2

  
MySQL<sup>®</sup>

 PostgreSQL

# Relational Databases

## Features: Normal Forms

### Model

- Functional dependencies
- **1NF, 2NF, 3NF, BCNF** (Boyce-Codd normal form)

### Objective

- **Normalization of database schema** to BCNF or 3NF
- Algorithms: decomposition or synthesis

### Motivation

- Diminish **data redundancy**, prevent update anomalies
- However:
  - Data is scattered into small pieces (high granularity), and so
  - these pieces have to be joined back together when querying!

# Relational Databases

## Features: Transactions

### Model

- **Transaction** = flat sequence of database operations (READ, WRITE, COMMIT, ABORT)

### Objectives

- Enforcement of ACID properties
- **Efficient parallel / concurrent execution** (slow hard drives, ...)

### ACID properties

- Atomicity – partial execution is not allowed (all or nothing)
- Consistency – transactions turn one valid database state into another
- Isolation – uncommitted effects are concealed among transactions
- Durability – effects of committed transactions are permanent



# Current Trends

## Big Data

- **Volume:** terabytes → zettabytes
- **Variety:** structured → structured and unstructured data
- **Velocity:** batch processing → streaming data
- ...

## Big users

- Population online, hours spent online, devices online, ...
- Rapidly growing companies / web applications
  - Even millions of users within a few months

# Current Trends

Everything is in **cloud**

- **SaaS**: Software as a Service
- **PaaS**: Platform as a Service
- **IaaS**: Infrastructure as a Service

Processing paradigms

- **OLTP**: Online Transaction Processing
- **OLAP**: Online Analytical Processing
- *...but also...*
- **RTAP**: Real-Time Analytical Processing

# Current Trends

## Data assumptions

- **Data format** is becoming unknown or inconsistent
- Linear growth → **unpredictable exponential growth**
- **Read requests** often prevail **write requests**
- Data updates are no longer frequent
- Data is expected to be replaced
- Strong **consistency** is no longer mission-critical

# Current Trends

⇒ **New approach is required**

- Relational databases simply do not follow the current trends

Key technologies

- Distributed **file systems**
- **MapReduce** and other programming models
- Grid computing, cloud computing
- **NoSQL databases**
- Data warehouses
- Large scale machine learning

# NoSQL Databases

What does **NoSQL** actually mean?

A bit of history ...

- 1998
  - First used for a relational database that omitted usage of SQL
- 2009
  - First used during a conference to advocate non-relational databases

So?

- Not: *no to SQL*
- Not: *not only SQL*
- NoSQL is an **accidental term with no precise definition**

# NoSQL Databases

What does **NoSQL** actually mean?

**NoSQL movement** = The whole point of **seeking alternatives** is that you need to solve a problem that **relational databases are a bad fit for**

**NoSQL databases** = Next generation databases mostly addressing some of the points: being **non-relational, distributed, open-source** and **horizontally scalable**. The original intention has been modern web-scale databases. Often more characteristics apply as: **schema-free, easy replication support, simple API, eventually consistent, a huge data amount, and more.**

# Types of NoSQL Databases

## Core types

- **Key-value** stores
- **Wide column** (column family, column oriented, ...) stores
- **Document** stores
- **Graph** databases

## Non-core types

- **Object** databases
- Native **XML** databases
- **RDF** stores
- ...

# Key-Value Stores

## Data model

- The most simple NoSQL database type
  - Works as a simple hash table (mapping)
- **Key-value pairs**
  - **Key** (id, identifier, primary key)
  - **Value**: binary object, black box for the database system

## Query patterns

- Create, update or remove value for a given key
- **Get value** for a given key

## Characteristics

- Simple model  $\Rightarrow$  **great performance, easily scaled, ...**
- Simple model  $\Rightarrow$  **not for complex queries nor complex data**



# Key-Value Stores

## 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**
- **Set operations** involving multiple key-value pairs

## Representatives

- **Redis**, **MemcachedDB**, **Riak KV**, Hazelcast, Ehcache, Amazon SimpleDB, Berkeley DB, Oracle NoSQL, Infinispan, LevelDB, Ignite, Project Voldemort
- *Multi-model*: OrientDB, ArangoDB

# Key-Value Stores

## Representatives



redis



hazelcast



EHCache



SimpleDB



ArangoDB

# Document Stores

## Data model

- **Documents**
  - Self-describing
  - **Hierarchical tree structures** (JSON, XML, ...)
    - Scalar values, maps, lists, sets, nested documents, ...
  - Identified by a **unique identifier** (key, ...)
- Documents are **organized into collections**

## Query patterns

- Create, update or remove a document
- **Retrieve documents according to complex query conditions**

## Observation

- Extended key-value stores where the value part is examinable!

# Document Stores

## 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

# Document Stores

## Representatives

- **MongoDB, Couchbase**, Amazon **DynamoDB**, **CouchDB**, RethinkDB, RavenDB, Terrastore
- *Multi-model*: **MarkLogic**, **OrientDB**, OpenLink Virtuoso, ArangoDB

# Document Stores

## Representatives



# Wide Column Stores

## 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

# Wide Column Stores

## Query patterns

- Create, update or remove a row within a given column family
- **Select rows according to a row key or simple conditions**

## Warning

- Wide column stores are not just a special kind of RDBMSs with a variable set of columns!



# Wide Column Stores

## Suitable use cases

- Event logging, content management systems, blogs, ...
  - I.e. **for structured flat data with similar schema**

## When not to use

- **ACID transactions** are required
- **Complex queries**: aggregation (SUM, AVG, ...), joining, ...
- Early prototypes: i.e. when **database design may change**

## Representatives

- Apache **Cassandra**, Apache **HBase**, Apache Accumulo, Hypertable, **Google Bigtable**

# Wide Column Stores

## Representatives



# Graph Databases

## Data model

- **Property graphs**
  - **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 be associated with additional **properties**

## Types of databases

- **Non-transactional** = small number of very large graphs
- **Transactional** = large number of small graphs

# Graph Databases

## 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)

## Representatives

- **Neo4j**, **Titan**, Apache Giraph, InfiniteGraph, FlockDB
- *Multi-model*: **OrientDB**, OpenLink **Virtuoso**, **ArangoDB**

# Graph Databases

## Suitable use cases

- Social networks, routing, dispatch, and location-based services, recommendation engines, chemical compounds, biological pathways, linguistic trees, ...
  - I.e. simply **for graph structures**

## When not to use

- **Extensive batch operations** are required
  - Multiple nodes / relationships are to be affected
- **Only too large graphs** to be stored
  - Graph distribution is difficult or impossible at all

# Graph Databases

## Representatives



# Native XML Databases

## 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)

## Representatives

- **Sedna**, **Tamino**, BaseX, eXist-db
- *Multi-model*: **MarkLogic**, OpenLink **Virtuoso**

# Native XML Databases

## Representatives



Native XML Database System





# RDF Stores

## 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*

## Representatives

- Apache **Jena**, **rdf4j** (Sesame), Algebraix
- *Multi-model*: **MarkLogic**, OpenLink **Virtuoso**

# RDF Stores

## Representatives



# Features of NoSQL Databases

## Data model

- Traditional approach: relational model
- (New) possibilities:
  - **Key-value, document, wide column, graph**
  - Object, XML, RDF, ...
- Goal
  - Respect the real-world nature of data (i.e. data structure and mutual relationships)

# Features of NoSQL Databases

## Aggregate structure

- **Aggregate** definition
  - Data unit with a complex structure
  - **Collection of related data pieces we wish to treat as a unit** (with respect to data manipulation and data consistency)
- Examples
  - **Value** part of key-value pairs in key-value stores
  - **Document** in document stores
  - **Row** of a **column family** in wide column stores

# Features of NoSQL Databases

## Aggregate structure

- Types of systems
  - **Aggregate-ignorant**: relational, graph
    - It is not a bad thing, it is a feature
  - **Aggregate-oriented**: key-value, document, wide column
- Design notes
  - No universal strategy how to draw **aggregate boundaries**
  - **Atomicity** of database operations:  
just a single aggregate at a time

# Features of NoSQL Databases

## Elastic scaling

- Traditional approach: **scaling-up**
  - Buying bigger servers as database load increases
- New approach: **scaling-out**
  - Distributing database data across multiple hosts
    - Graph databases (unfortunately): difficult or impossible at all

## Data distribution

- **Sharding**
  - Particular ways how database data is split into separate groups
- **Replication**
  - Maintaining several data copies (performance, recovery)

# Features of NoSQL Databases

## Automated processes

- Traditional approach
  - Expensive and highly trained database administrators
- New approach: **automatic recovery, distribution, tuning, ...**

## Relaxed consistency

- Traditional approach
  - **Strong consistency** (ACID properties and transactions)
- New approach
  - **Eventual consistency** only (BASE properties)
  - I.e. we have to make trade-offs because of the data distribution

# Features of NoSQL Databases

## Schemalessness

- Relational databases
  - Database schema present and **strictly enforced**
- NoSQL databases
  - **Relaxed schema** or **completely missing**
  - Consequences: **higher flexibility**
    - Dealing with **non-uniform data**
    - **Structural changes** cause no overhead
  - However: there is (usually) an **implicit schema**
    - We must know the data structure at the application level anyway



# Features of NoSQL Databases

## Open source

- Often community and enterprise versions (with extended features or extent of support)

## Simple APIs

- Often state-less application interfaces (HTTP)

# Features of NoSQL Databases

## Current State: Five advantages

- **Scaling**
  - Horizontal distribution of data among hosts
- **Volume**
  - High volumes of data that cannot be handled by RDBMS
- **Administrators**
  - No longer needed because of the automated maintenance
- **Economics**
  - Usage of cheap commodity servers, lower overall costs
- **Flexibility**
  - Relaxed or missing data schema, easier design changes

# Features of NoSQL Databases

## Current State: Five challenges

- **Maturity**
  - Often still in pre-production phase with key features missing
- **Support**
  - Mostly open source, limited sources of credibility
- **Administration**
  - Sometimes relatively difficult to install and maintain
- **Analytics**
  - Missing support for business intelligence and ad-hoc querying
- **Expertise**
  - Still low number of NoSQL experts available in the market

# Conclusion

## The end of relational databases?

- Certainly no
  - They are still suitable for most projects
  - 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**

# Lecture Conclusion

## Big Data

- 4V characteristics: volume, variety, velocity, veracity

## NoSQL databases

- (New) **logical models**
  - Core: key-value, wide column, document, graph
  - Non-core: XML, RDF, ...
- (New) **principles and features**
  - Horizontal scaling, data sharding and replication, eventual consistency, ...