Data & Cloud infrastructure

Sprint 2 | Week 3

INFO9023 - ML Systems Design

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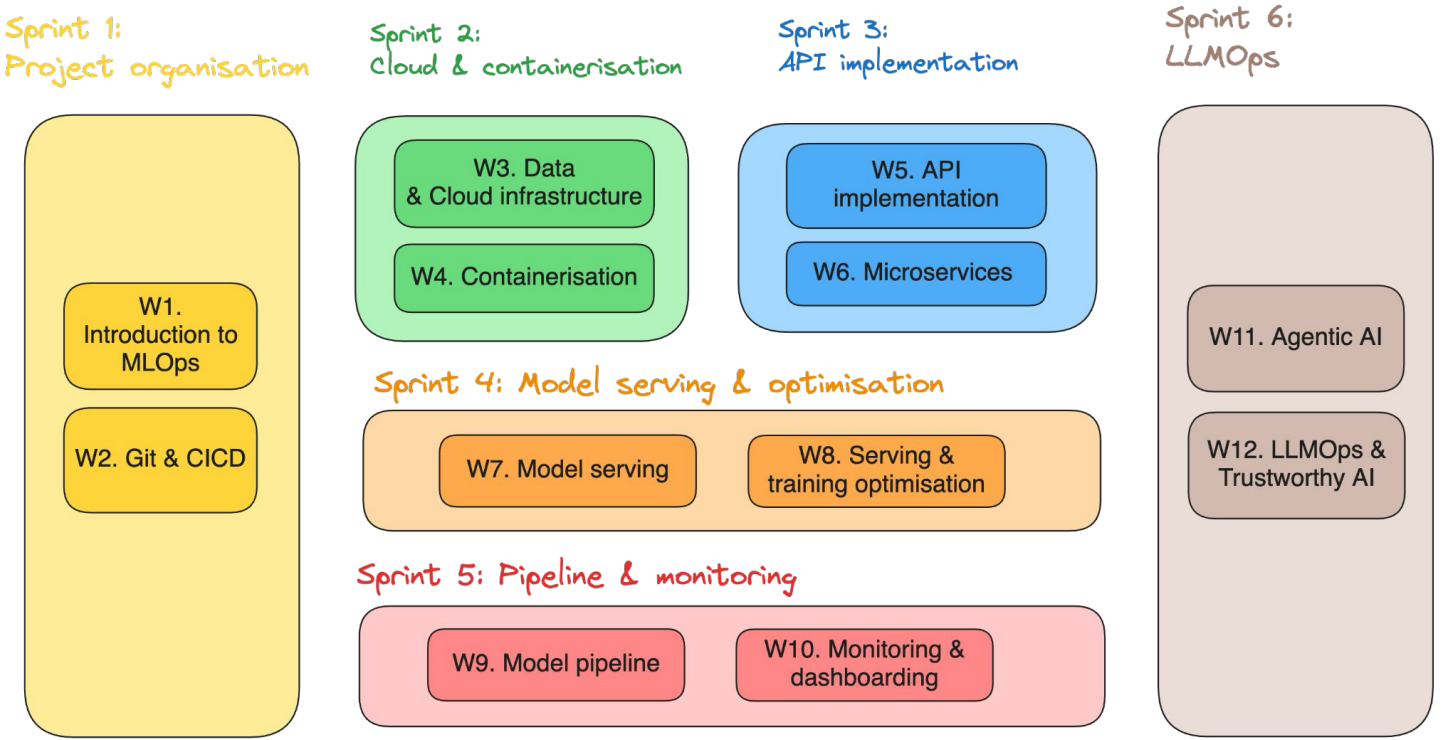
Status on our overall course roadmap




Always has been.
It’s all about data…
imgflip.com


ATARI

Agenda

What will we talk about today

Lecture

1. Data formats
2. Data models
3. Workload types
4. Extract, Transform and Load (ETL)

Guest lecture

5. Cloud infrastructure

Directed work

6. Cloud & data

Today’s objective and how to learn more about it

Objective: Overview of basic concepts as they relate to ML applications. Going in depth over database management is out of scope for this course.

Want to learn more about these topics? See:

- INFO0009: **Database**
  - Realization of computer systems centered on a database
  - Relational database, access, storage and more
- INFO9016: **Advanced Databases**
  - Distributed databases and their applications
  - Spatial databases, temporal databases, deductive databases, data warehousing, and NoSQL databases.
- INFO9014: **Knowledge representation and reasoning**
  - Ontologies, Knowledge Graphs, and Open Information Systems
  - Declarative approaches to reasoning and data integration
- INFO8002: **Topics in Distributed Systems**
  - Distributed File Systems and Distributed Programming
  - Hadoop, MapReduce, Spark

Project milestones

- **MS1**: You will pick a spot between the **2nd and the 5th of March**. The exact spot available will be announced later.
- **MS2**: You will pick a spot between the **30th of March and the 2nd of April**. The exact spot available will be announced later.
- **MS3**: Each group will present in the classroom, other groups can attend the presentation. It will be on the **11th of May**.

Data formats

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Data formats

Serialisation: process of converting data structures (like python objects, dataframes, …) into a *format* that can be stored or transmitted and then later reconstructed (deserialized).

Types:

1. **Text format**: Data is encoded as readable characters (ASCII/UTF-8).
   - *Properties*: Humane readable, easy to debug/interpret, larger size, slower to parse…
   - *Examples:* CSV, JSON, …
2. **Binary format**: Data is encoded directly as raw bytes, not as readable characters.
   - *Properties*: More compact, less storage space, not readable, often optimise for specific workloads…
   - *Examples:* Parquet, pickle, …
3. **Binary primary format**: *Protocols* designed from the ground up for binary serialisation and data exchange. They are not “text formats converted to binary”
   - *Properties*: Schema based, strong typing, used for streaming or service-to-service systems…
   - *Examples:* Protobuf, avro, …

Text vs binary format

	Text files	**Binary files**
Examples	CSV, JSON	Parquet
Pros	Human readable	Compact
Store the number *1000000*?	7 characters -> 7 bytes	If stored as int32, only 4 bytes

You can unload the result of an Amazon Redshift query to your Amazon S3 data lake in Apache Parquet, an efficient open columnar storage format for analytics. Parquet format is up to 2x faster to unload and consumes up to 6x less storage in Amazon S3, compared with text formats. This enables you to save data transformation and enrichment you have done in

Data formats

	Format	Binary/Text	Human-readable	Example use cases
	JSON	Text	Yes	Everywhere
Row-major	**CSV**	**Text**	**Yes**	**Everywhere**
Column-major	**Parquet**	**Binary**	**No**	**Amazon Redshift**
	Avro	Binary primary	No	Hadoop
	Protobuf	Binary primary	No	TensorFlow (TFRecord)
	Pickle	Binary	No	Python, PyTorch serialization

Data formats

Row-major

Column-major

Format	Binary/Text	Human readable	Use cases	Example
JSON	Text	Yes	Everywhere	{ ‘foo’: [1,2,3, …]}
CSV	Text	Yes	Everywhere	name,age\nAlice,30
Parquet	Binary	No	Amazon Redshift	(Binary column chunks – not readable in editor)
Avro	Binary primary	No	Hadoop	Schema: {"type":"record","fields":[{"name":"age" ,"type":"int"}]}
Protobuf	Binary primary	No	TensorFlow (TFRecord)	proto\nmessage User { int32 age = 1; }\n
Pickle	Binary	No	Python, PyTorch serialization	b'\x80\x04\x95...'

Row-major vs column-major

Column-major

- Stored and retrieved column by column
- Good for accessing features or computing statistics

A = [[1, 2, 3],
[4, 5, 6]]
Stored ⇒ [1, 4, 2, 5, 3, 6]

Row-major

Stored and retrieved row by row
Good for accessing samples efficiently (uniquely or by rule)

A = [[1, 2, 3],
[4, 5, 6]]
Stored ⇒ [1, 2, 3, 4, 5, 6]

Column 1	Column 2	Column 3	...
Sample 1			
Sample 2			
Sample 3			
Sample 4			
…			

Row-major vs. column-major

Often leads to misuse of pandas…

- Pandas Dataframe is **column-major** while Numpy is **row-major**.
- Accessing a **column in pandas** is significantly **faster** than accessing a row
- Numpy is often faster than pandas

```
# Get the column `date`, 1000 loops
%timeit -n1000 df["Date"]

# Get the first row, 1000 loops
%timeit -n1000 df.iloc[0]
```

```
1.78 µs ± 167 ns per loop (mean ± std. dev. of 7 runs, 1000 loops each)
145 µs ± 9.41 µs per loop (mean ± std. dev. of 7 runs, 1000 loops each)
```

```
df_np = df.to_numpy()
%timeit -n1000 df_np[0]
%timeit -n1000 df_np[:,0]
```

```
147 ns ± 1.54 ns per loop (mean ± std. dev. of 7 runs, 1000 loops each)
204 ns ± 0.678 ns per loop (mean ± std. dev. of 7 runs, 1000 loops each)
```

Data models

Data models

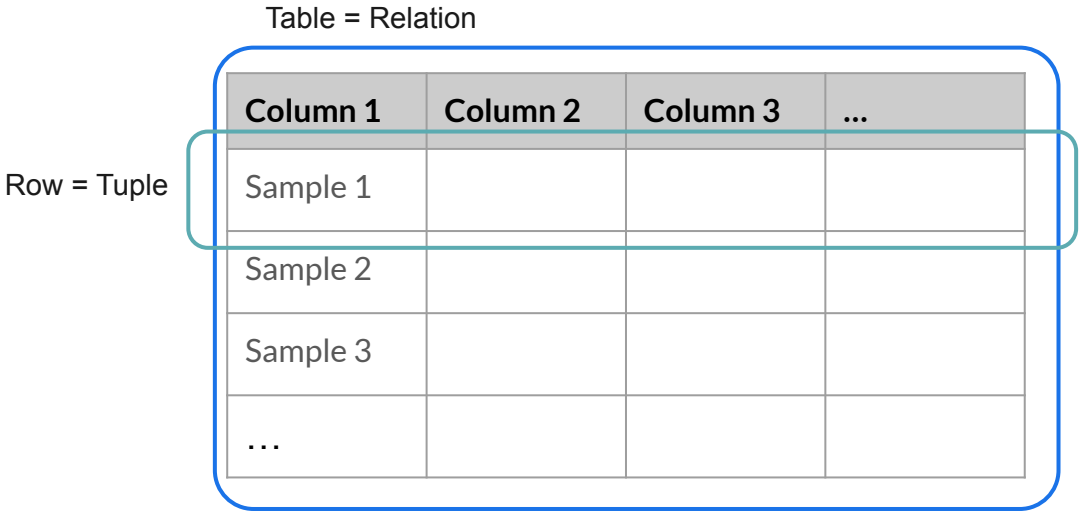
Data model: Describes the *representation* of data. Defines the structure, organisation and relationship of the data. It ensures it is retrieved efficiently.

Data models we will cover:

1. Relational
2. Document
3. Key-value
4. Graph
5. Wide-column

1. Relational model

- Persistent idea in computer science, introduced by Edgar F. Codd in 1970.
- Data is organized into **relations** (tables) where each relation is a set of **tuples** (rows)
- Rigid **schema**



Normalisation

Normalisation is the act of reducing repetition of data by separating a table into multiple connected tables.

Title	Author	Format	Publisher	Country	Price
Harry Potter	J.K. Rowling	Paperback	Banana Press	UK	$20
Harry Potter	J.K. Rowling	E-book	Banana Press	UK	$10
Sherlock Holmes	Conan Doyle	Paperback	Guava Press	US	$30
The Hobbit	J.R.R. Tolkien	Paperback	Banana Press	US	$30
Sherlock Holmes	Conan Doyle	Paperback	Guava Press	US	$15

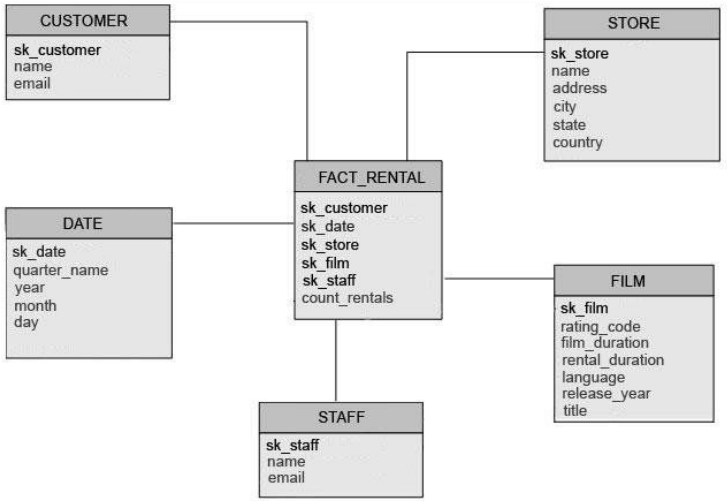
Title	Author	Format	Publisher ID	Price
Harry Potter	J.K. Rowling	Paperback	1	$20
Harry Potter	J.K. Rowling	E-book	1	$10
Sherlock Holmes	Conan Doyle	Paperback	2	$30
The Hobbit	J.R.R. Tolkien	Paperback	1	$30
Sherlock Holmes	Conan Doyle	Paperback	2	$15

Publisher ID	Publisher	Country
1	Banana Press	UK
2	Guava Press	US

Normalisation

1. **Fact tables** | The “center”
   - Contains quantitative data, the “business transactions or events”(e.g., sales amount, revenue)
   - And foreign keys linking to dimension tables
2. **Dimension tables** | The “leafs”
   - Contains attribute and descriptive text for the facts (e.g., product category, customer demographics)

Splitting your data between fact and dimension tables is called **normalisation**. It reduces redundancy for tables with high cardinality.



Borges, Clemente & Macías, José. (2014). Facilitating the Interaction with Data Warehouse Schemas through a Visual Web-Based Approach. Computer Science and Information Systems. 11. 481-501. 10.2298/CSIS131130032B.

Forms of normalisation

Normalisation of relational data models exists in different forms

1. First Normal Form (1NF)
2. Second Normal Form (2NF)
3. Third Normal Form (3NF)
4. Boyce-Codd Normal Form (BCNF)
5. Fourth Normal Form (4NF)
6. Fifth Normal Form (5NF) / Project-Join Normal Form (PJNF)
7. Sixth Normal Form (6NF)

https://learn.microsoft.com/en-us/office/troubleshoot/access/database-normalization-description

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7. Sixth Normal Form (6NF)

Covered in this course

"[Higher form of normalisation] do exist but are rarely considered in practical design. Disregarding these rules may result in less-than-perfect database design but shouldn't affect functionality."

https://learn.microsoft.com/en-us/office/troubleshoot/access/database-normalization-description

Forms of normalisation

Starting with a base example

Title	Author	Author Nationality	Format	Price	Subject	Pages	Thickness	Publisher	Publisher Country	Genre ID	Genre Name
Beginning MySQL Database Design and Optimization	Chad Russell	American	Hardcover	49.99	MySQL Database Design	520	Thick	Apress	USA	1	Tutorial

Forms of normalisation

First normal form (1NF)

First normal form: each field contains a single value. A field may not contain a set of values or a nested record.

Book

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Beginning MySQL Database Design and Optimization	Chad Russell	American	Hardcover	49.99	520	Thick	Apress	USA	1	Tutorial

Title - Subject

Title	Subject name
Beginning MySQL Database Design and Optimization	MySQL
Beginning MySQL Database Design and Optimization	Database
Beginning MySQL Database Design and Optimization	Design

Forms of normalisation

Second normal form (2NF)

Second normal form: all key attribute must be fully determinant to all non-key attributes. You must not be able to reduce key information. Mostly relevant for composite-keys that can be simplified.

Does not satisfy 2NF.

Composite key {title, format} is not **determinant**.
Some subset of facts can be determined only on part of the composite key (only “price” is dependent on “format”)

Book

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Beginning MySQL Database Design and Optimization	Hardcover	Chad Russell	American	49.99	520	Thick	Apress	USA	1	Tutorial
Beginning MySQL Database Design and Optimization	E-book	Chad Russell	American	22.34	520	Thick	Apress	USA	1	Tutorial
The Relational Model for Database Management: Version 2	E-book	E.F.Codd	British	13.88	538	Thick	Addison-Wesley	USA	2	Popular science
The Relational Model for Database Management: Version 2	Paperback	E.F.Codd	British	39.99	538	Thick	Addison-Wesley	USA	2	Popular science

Forms of normalisation

Second normal form (2NF)

Second normal form: all key attribute must be fully determinant to all non-key attributes. You must not be able to reduce key information. Mostly relevant for composite-keys that can be simplified.

To conform to 2NF:

- all attributes that are determined based on {title} are in the *book* table
- all the attributes dependent on {title, format} are in the *price* table

Book

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The Relational Model for Database Management: Version 2	Paperback	39.99

Forms of normalisation

Third normal form (3NF)

Third normal form: no transitive functional dependencies between attributes.
Transitive functional dependency: non-key attribute in a database table is functionally dependent on another non-key attribute, rather than directly on the primary key.

Does not satisfy 3NF.

Many transitive dependencies:

- Title → Author → Author nationality
- Title → Publisher → Publisher country
- Title → Genre ID → Genre name

Transitive functional dependency

Book

Title	Author	Author Nationality	Pages	Thickness	Publisher	Publisher Country	Genre ID	Genre Name
Beginning MySQL Database Design and Optimization	Chad Russell	American	520	Thick	Apress	USA	1	Tutorial
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Forms of normalisation

Third normal form (3NF)

Satisfies 3NF ! ✅

Book

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Genre

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Forms of normalisation

Pros & Cons

Pros	Cons
● Removes redundancy - memory efficient ● Consistency - standardised values ● Easy to update a value throughout all occurrences ● More security flexibility by restricting access to certain information	● Data spread across multiple relations ● Query performance - Joining can be an expensive/slow operation ● More complexity ● More maintenance

SQL query language

- SQL is a **query language**, it allows you to query most relational data models (and more!)
- SQL is a **declarative language**
  - You describe the outputs you want and the computer figures out the steps needed to retrieve it and how to optimize them.
  - By opposition languages such as Python are **imperative languages**
    - You declare the exact steps that the computer should execute.

```
SELECT
  EXTRACT(YEAR FROM starttime) AS year,
  EXTRACT(MONTH FROM starttime) AS month,
  COUNT(starttime) AS number_one_way
FROM
  mydb.return_transactions
WHERE
  start_station_name != end_station_name
GROUP BY year, month
ORDER BY year ASC, month ASC
```

Dividing SQL into sublanguages

SQL operations are divided into multiple **sub-languages** such as:

- **Data Query Language (DQL)** is responsible for reading, or querying, data from a database. In SQL, this corresponds to the `SELECT`
- **Data Manipulation Language (DML)** is responsible for adding, editing or deleting data from a database. In SQL, this corresponds to the `INSERT`, `UPDATE`, and `DELETE`
- **Data Definition Language (DDL)** is responsible for defining the way data is structured in a database. In SQL, this corresponds to manipulating tables through the `CREATE TABLE`, `ALTER TABLE`, and `DROP TABLE`
- **Data Control Language (DCL)** is responsible for the administrative tasks of controlling the database itself, most notably granting and revoking database permissions for users. In SQL, this corresponds to the `GRANT`, `REVOKE`, and `DENY` commands (among other things)

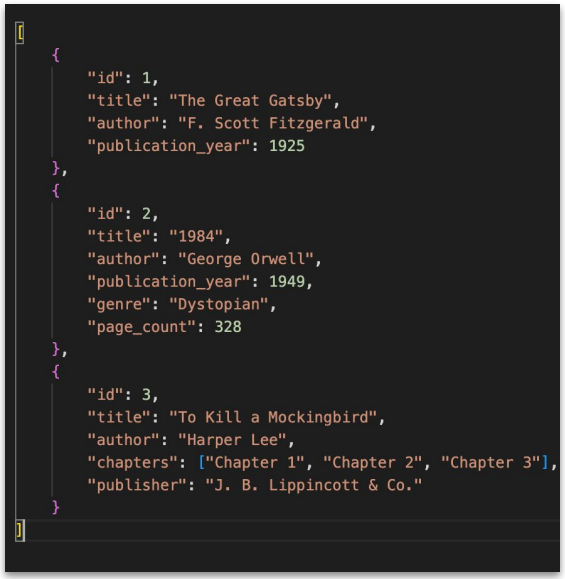
SQL is so popular that DQL and DML influence many NoSQL databases.

SQL is prevalent in data management!
Important to learn 🧠

2. Document model

Document model: Organizes data in a *semi-structured* format like JSON or BSON.

- Unlike relational models, there is no fixed schema. It is more flexible!
- Each observation (“document”) includes both the data and the metadata (keys)
- Often documents are represented in text format (JSON, XML, …)
- Observations can be retrieved through declarative queries on non-key values
  - Often with “SQL like” languages
- Complex operations (e.g. joins) are less efficient than for relational databases




```sql
SELECT
    id, date_time, user_type, prediction
FROM
    `my_project.my_dataset.my_documents`
WHERE
    publication_year BETWEEN '1960' AND '1980'
    AND publisher != 'lorem ipsum';
```

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2. Document model

Pros	Cons
Flexible schema allows easy modifications	Not optimized for complex relationships (joins)
Supports hierarchical and nested data structures	Indexing large documents can be challenging
Good for applications requiring varied data formats (e.g., user information, chatbot messages, …)	Query performance can degrade if documents grow too large

3. Graph model

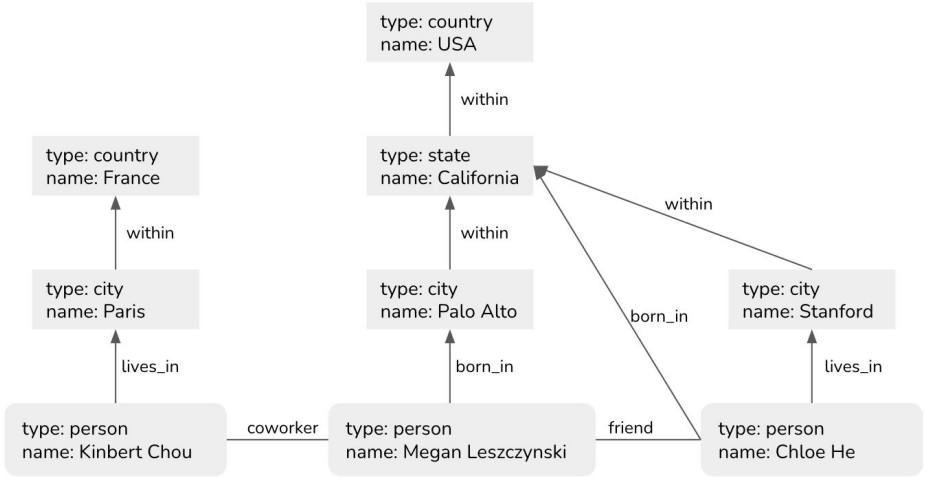
A **graph** consists of **nodes** and **edges.**

The edges describe the relationship between the nodes.

Fast to query based on relationships

- Find all people born in the US
  - Follow the edges linked to US
  - In relational database we would have to do a full search on the “born_in” field
  - Document database would be even worst…

Neo4j is a popular database for Graph models.



4. Key-value model

Key-value: data is stored as a collection of key-value pairs. The key is a unique identifier, and the value can be a simple data type (string, integer) or a more complex object (JSON, BLOB).

The “value” of each data point is opaque to the database. You cannot query against it.

It is extremely fast at querying against keys.

Pros	Cons
Extremely fast read/write operations when querying on keys (O(1) complexity)	Limited querying capabilities (no structured search)
Simple to scale horizontally	Cannot perform complex filtering, sorting, or aggregations efficiently
Highly efficient for caching, session storage, and configuration management	Keys must be known in advance for efficient lookups

5. Wide-column model

Wide-column: It stores data in column families rather than rows. Often described as a two-dimensional key-value map.

Designed to handle petabytes of data across thousands of machines with high write throughput.

Often used for Internet of Things (IoT) or large time series data.

Pros	**Cons**
Massive scalability, can scale horizontally across thousands of commodity servers	No complex querying - typically doesn't support complex "joins" or multi-table relationships
High write throughput, ideal for high velocity streamin devices	Mostly efficient on *primary* keys. The columns used for querying (look-ups) should be set at the beginning
Performance for aggregation due to the data being store by column	Cost and maintenance complexity

Workload types

Workload types

Data model: Describes the *representation* of data. Defines the structure, organisation and relationship of the data. It ensures it is retrieved efficiently.

Workload types: Describes the *operational patterns* of a system. Defines whether a database is optimised for high-volume individual *transactions* or complex *analytical* processing.

Two workload types considered:

- OnLine Transaction Processing (OLTP)
- OnLine Analytical Processing (OLAP)

OnLine Transaction Processing (OLTP)

OnLine Transaction Processing (OLTP): Perform high volumes of low complexity *transactions*, which can be a sequence of operations such as insert, update, delete, or retrieve.

Brings *low latency* and *high availability.*

OLTP database perform **ACID transactions**:

- **Atomicity**: Every single operation in a transaction must succeed, otherwise none are applied (“all-or-nothing” rule).
- **Consistency**: All the transactions coming through must follow predefined rules. For example, a transaction must be made by a valid user or follow specific data types.
- **Isolation**: Concurrent transactions execute as if they were sequential, preventing interference.
- **Durability**: Once a transaction is “committed” (saved), its changes persist even in the event of a system failure or power outage.

https://www.ibm.com/blog/olap-vs-oltp/

OnLine Analytical Processing (OLAP)

OnLine Analytical Processing (OLAP): Perform complex *analytical* operations over a large amount of rows. Compute a lower volume of heavier jobs that require to perform calculations over data.

E.g.

- *What is the average purchase amount for users of a specific age?*
- *What is the maximum house price in a specific location for a specific date range?*
- *…*

Optimised for *complex aggregation queries*. *High throughput*, designed to scan millions or billions of row to generate insights. Usually *column major*.

In ML, primarily used for *offline training* and *batch feature engineering* where historical data is aggregated.

https://www.jedox.com/en

Workload types

Workload type	OnLine Transaction Processing (OLTP)	OnLine Analytical Processing (OLAP)
Goal	Fast updates & lookups. ACID transactions	Deep analysis & aggregation
ML Use	Real-time *serving* (fetch 1 user)	Offline *training* (scan all users, produce features through aggregations)
Storage	Usually Row-major	Often Column-major
Models	Relational, Document, Key-Value	Relational, Wide-Column

Optimising a relational database.

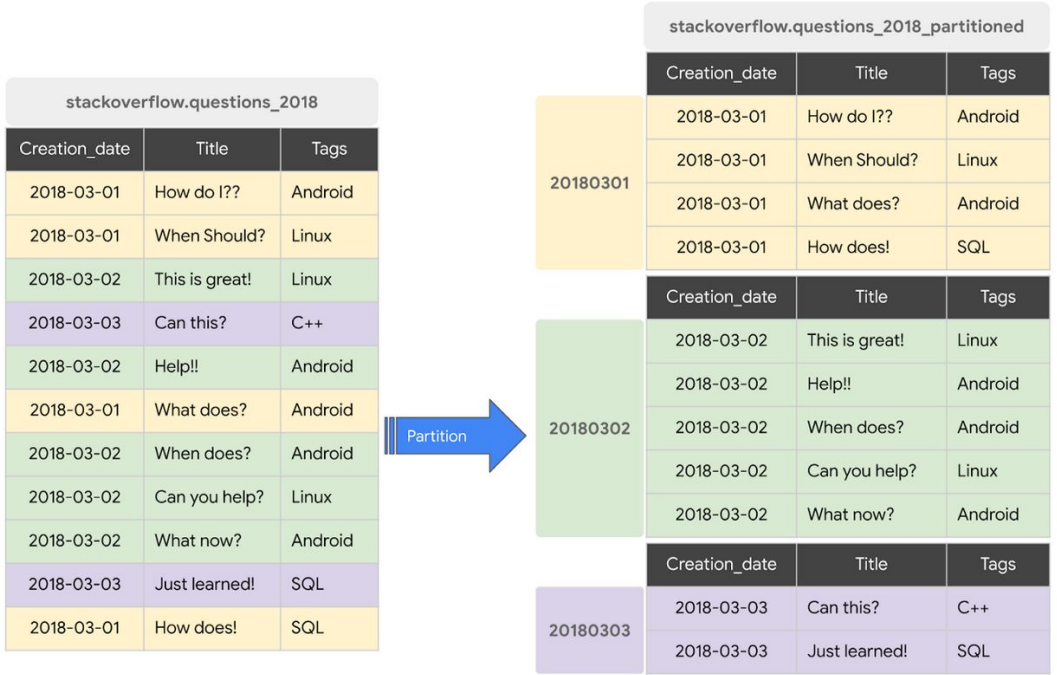
- **Indexing**: Data structure applied to one (or multiple) key columns to organise and speed the data retrieval operations applied on this column. Avoids searching the entire column for specific values. A downside of it is a higher memory consumption.
- **Query optimisation**: Selecting only required columns, using `WHERE` operations effectively. Know how the query is constructed and operated.
- **Caching**: Store frequently accessed results in RAM. Important for more complex systems (e.g. data/ML pipeline).
- **Hardware optimisation**: Obviously some hardware upgrade can significantly improve your database performance (e.g. faster CPU or SSDs). Sometimes abstracted away when using managed Cloud database.
- **Partitioning**: … ⬇️

Efficiency example: Partitioning your data

Divide table into segments, called **partitions**, that make it easier to manage and query your data.

Split large tables into many smaller partitions using TIMESTAMP/DATE column or an INTEGER column (e.g. if you will often apply operations on specific time frames).

Minimize the amount of data that slot workers read from disk, typically for column majors.



https://cloud.google.com/blog/topics/developers-practitioners/bigquery-explained-storage-overview

Decision flow

4. Visualizing the Decision Flow

You might consider adding a slide with a simplified "Decision Tree" to help students choose a database for their ML System:

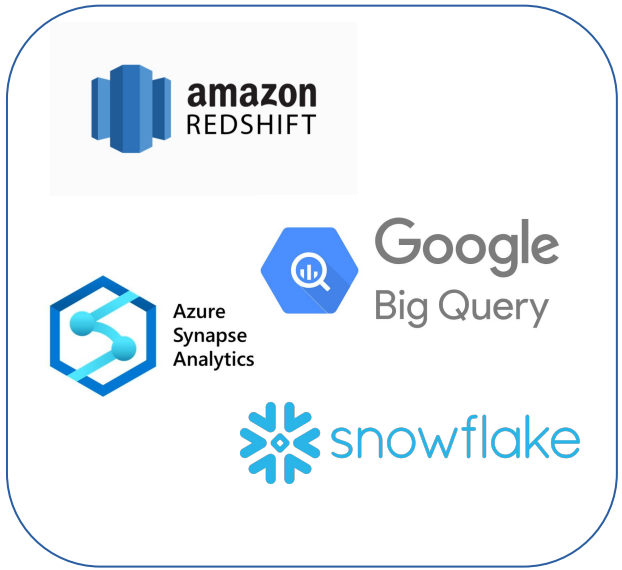
1. **Is your data highly relational with complex links?** $\rightarrow$ **Graph** or **Relational**.
2. **Do you need to store massive features for real-time ML serving?** $\rightarrow$ **Key-Value** (Memorystore) or **Wide-Column** (Bigtable).
3. **Are you performing "Offline" training on billions of rows?** $\rightarrow$ **OLAP** (BigQuery).
   +1
4. **Is your data format changing rapidly (unstructured)?** $\rightarrow$ **Document** (Firestore).
   +1

Example database services

Relational model

OLTP databases

OLAP databases



Example database services

Other models

Document model

Firestore
(Google Cloud)

DocumentDB
(AWS)

CosmosDB
(Azure)

MongoDB
(Self-managed)

Wide-column model

Cloud Bigtable
(Google Cloud)

Apache Cassandra
(Self-managed)

Graph model

Key-value model

MongoDB
(Self-managed)

Memorystore
(Google Cloud)

DynamoDB
(AWS)

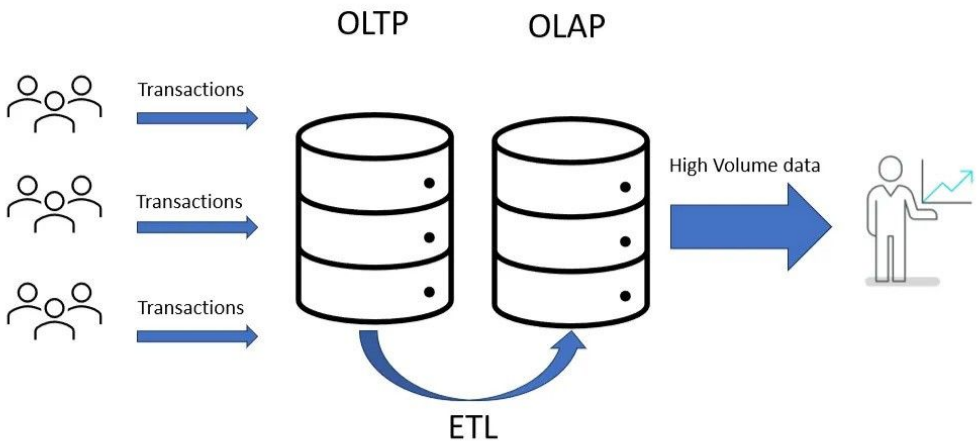
Cache for Redis
(Azure)

Extract, Transform and Load (ETL)

Extract, Transform and Load (ETL)

Extract, Transform and Load (ETL): Process of extracting data from a source, transforming it into a desired format, and loading it into a destination system. How to “move” and “transform” data between two systems.

Often, in ML, data will be moved from OLTP to OLAP databases in frequent batch jobs.



Extract, Transform and Load (ETL)

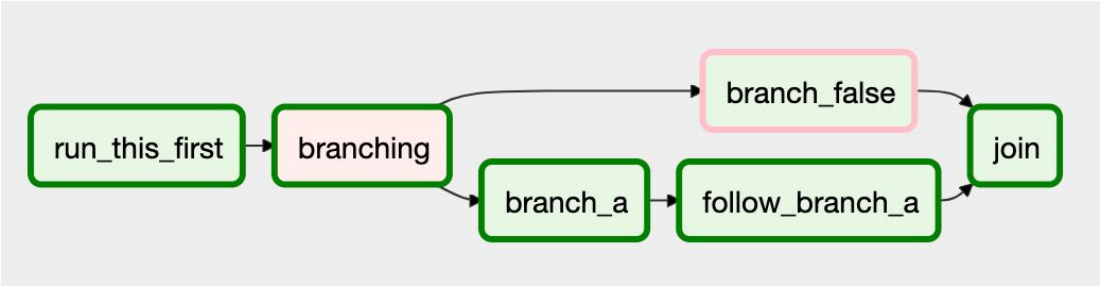
Extract, Transform and Load (ETL): Process of extracting data from a source, transforming it into a desired format, and loading it into a destination system. How to “move” and “transform” data between two systems.

Tool	Category	Description
Apache Airflow	Orchestration	An open-source tool used to schedule and monitor workflows as Directed Acyclic Graphs (DAGs).
Apache Spark	Compute (Batch)	A distributed computing engine designed for large-scale data processing using fast, in-memory computation.
Apache Beam	Compute (Stream)	A unified programming model for defining both Batch and Streaming data processing pipelines.

Airflow

An open-source platform used to schedule, monitor, and manage complex workflows using *Directed Acyclic Graphs (DAGs)*

- Workflows can be defined in *Python code*, allowing for dynamic pipeline generation and version control
- Easily scheduled or triggered
- Integrates well with cloud services and modern data stacks



Spark

An open-source, distributed computing engine designed for large-scale data processing.

Mostly used for *batch* heavy jobs.

Key features

- In-memory computing → Data is kept in the system's active memory (RAM). Faster execution than disk-based systems.
- Lazy evaluation → Delays the execution of an operation until its result is explicitly required by an "Action" (like .count() or .show()). Optimized execution plans for efficiency.

ML Use Case: Processing a years' worth of raw transaction logs in Cloud Storage to create a unified feature table for offline training.

Google Cloud
Dataproc

Beam

Unified programming model for defining both Batch and Streaming data processing pipelines

Flexible data pipeline, that allows the same code to handle historical data (Batch) and real-time events (Streaming).

- Abstracts away the underlying execution engine, allowing you to focus on the data logic rather than the infrastructure.

ML Use Case: Real-time feature engineering, such as calculating a user's "average clicks in the last 10 minutes" as they browse your app.

Cloud infrastructure

Wrap-up

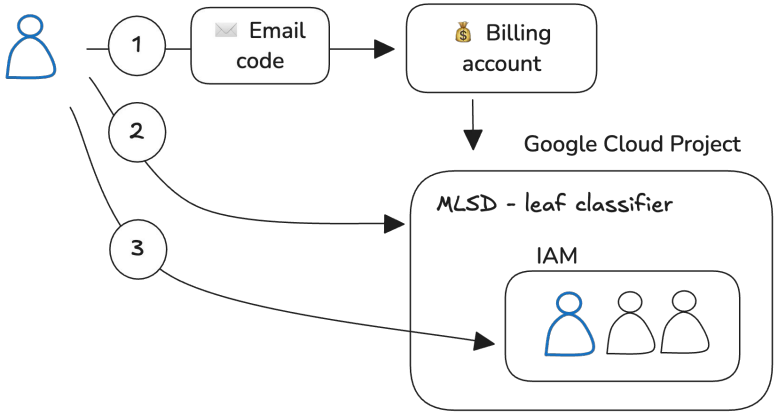
Cloud & credits

How to activate credits and manage projects

Only **one student** per group needs to create a project and activate the credits. If you run out of credits you can use the ones of someone else on your team.

Steps to setting up a project

1. Click on the link received by email to redeem credits and attach them to a billing account
2. Create a Google Cloud Project and link it to the billing account you created
3. Grant access to the other members of your team to this project through the IAM portal



Project objective for sprint 2

This course focuses on what comes **around** your ML model.
Do **not** spend significant time optimising your data or model.
No grading on the **accuracy** of the model itself.

#	Week	Work package
2.1	W03	Prepare your data and run an Exploratory Data Analysis (EDA).
2.2	W03	Train and evaluate your ML model.
2.3	W03	Make sure to document the result of your EDA and model evaluation (e.g. through slides or a markdown file in your "docs/" folder)
2.4	W03	Prepare your Cloud environment. That means creating a Cloud project, granting correct access rights to all members of your group and setting up a billing account. **Attention**: You can have free credits for the Cloud, as explained during the course.
2.5	W03	Store your data to the cloud and modify your training script so that it can automatically run with the data you stored on the cloud. Carefully select the database service you will use on the cloud, and document this choice. Different options might be more appropriate: • Relational SQL database (BigQuery) • NoSQL database (firestore) • Blob storage (cloud storage) If data storage or the choice of database is not trivial for your use case, make sure to discuss it with the teaching staff.

Lecture summary

Topic	Concepts	To know for…	
		Project	Exam
Data formats	• Data format (row-major vs column-major; text vs binary)		Yes
Data models	• Data models (relational, document, key-value, graph, wide-column)		Yes
Workload types	• OnLine Transactional Processing (OLTP) and OnLine Analytical Processing (OLAP)		Yes
Extract, Transform and Load (ETL)	• Airflow, Spark and Beam		Yes
Cloud infrastructure	• Introduction to the Cloud	Yes	

That’s it for today!

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