Graph Databases

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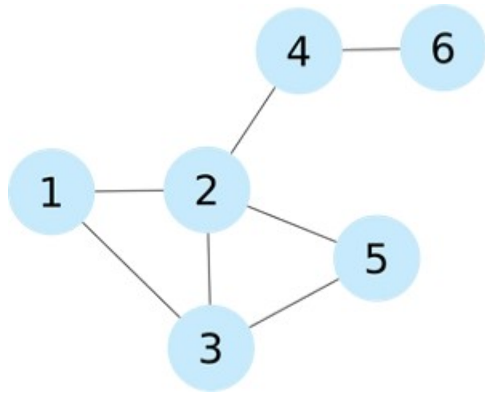
Some theory about graph theory

Graph Databases

- **Data**: a set of entities and their relationships
  - e.g., social networks, travelling routes, …
  - We need to efficiently represent graphs
- Basic **operations**: finding the neighbours of a node, checking if two nodes are connected by an edge, updating the graph structure, …
  - We need efficient graph operations
- $G = (V, E)$ is commonly modelled as
  - set of **nodes** (vertices) V
  - set of **edges** E
  - $n = |V|$, $m = |E|$
- Which data structure should be used?

Adjacency Matrix

- Bi-dimensional **array** *A* of *n x n* Boolean values
  - Indexes = node identifiers
  - *Aij* indicates whether the two nodes *i, j* are connected



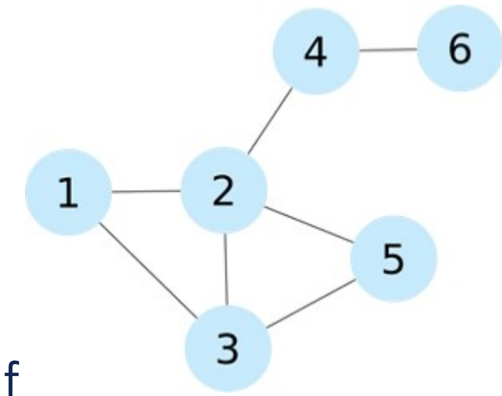
- **Pros**:
  - Checking if two nodes are connected
  - Adding/removing edges
- **Cons**:
  - Quadratic space with respect to *n*
    - We usually have sparse graphs (lots of 0)
  - Addition of nodes is expensive
  - Retrieval of all the neighbouring - *O(n)*

$$\begin{pmatrix} 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

- Other variants:
  - Directed graphs, Weighted graphs, …

Adjacency List

- A **set of lists** where each accounts for the neighbours of one node
  - A vector of *n* pointers to adjacency lists

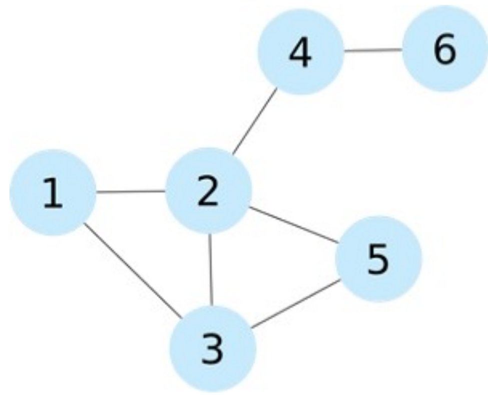


- Undirected graph:
  - An edge connects nodes *i* and *j* => the list of neighbours of *i* contains the node *j* and vice versa
- **Pros**:
  - Obtaining the neighbours of a node
  - Cheap addition of nodes to the structure
  - Compact representation of sparse matrices
- **Cons**:
  - Checking an edge between two nodes

N1 → {N2, N3}
N2 → {N1, N3, N5}
N3 → {N1, N2, N5}
N4 → {N2, N6}
N5 → {N2, N3}
N6 → {N4}

Incidence Matrix

- Bi-dimensional Boolean matrix of *n* rows and *m* columns
  - A **column** represents an **edge**
    - Nodes that are connected by a certain edge
  - A **row** represents a **node**
    - All edges that are connected to the node

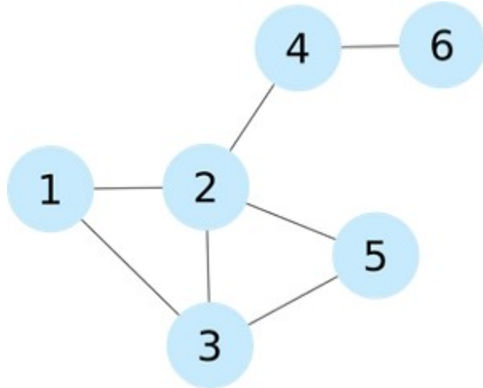


- **Pros**:
  - For representing hypergraphs, where one edge connects an arbitrary number of nodes
- **Cons**:
  - Requires *n x m* bits

$$\begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Laplacian Matrix

- Bi-dimensional **array** of *n x n* integers
  - Diagonal of the Laplacian matrix indicates the **degree** of the node
  - The rest of positions are set to -1 if the two vertices are connected, 0 otherwise



- **Pros:**
  - Allows analyzing the graph structure by means of spectral analysis
    - Calculates the eigenvalues

$$\begin{pmatrix} 2 & -1 & -1 & 0 & 0 & 0 \\ -1 & 4 & -1 & -1 & -1 & 0 \\ -1 & -1 & 3 & 0 & -1 & 0 \\ 0 & -1 & 0 & 2 & 0 & -1 \\ 0 & -1 & -1 & 0 & 2 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 \end{pmatrix}$$

- **Cons:**
  - = Adjacency Matrix

Graph Traversals

- Single step **traversal** from element *i* to element *j*, where $i,j \in (V \cup E)$
- Expose explicit **adjacencies** in the graph
  - e_{out} : traverse to the outgoing edges of the vertices
  - e_{in} : traverse to the incoming edges of the vertices
  - v_{out} : traverse to the outgoing vertices of the edges
  - v_{in} : traverse to the incoming vertices of the edges
  - e_{lab} : allow (or filter) all edges with the label
  - $\in$: get element property values for key r
  - e_p : allow (or filter) all elements with the property s for key r
  - $\in=$: allow (or filter) all elements that are the provided element

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Graph Traversals

- Single step traversals can **compose complex traversals** of arbitrary length
  - e.g., find all friends of Alberto
  - Traverse to the outgoing edges of vertex i (representing Alberto), then only allow those edges with the label friend, then traverse to the incoming (i.e. head) vertices on those friend-labeled edges. Finally, of those vertices, return their name property."

$$f(i) = (\in^{name} \circ v_{in} \circ e_{lab}^{friend} \circ e_{out})(i)$$

Types of Graphs

- **Single-relational**
  - Edges are homogeneous in meaning
    - e.g., all edges represent friendship
- **Multi-relational** (property) graphs
  - Edges are typed or labeled
    - e.g., friendship, business, communication
  - Vertices and edges in a property graph maintain a set of key/value pairs
    - Representation of non-graphical data (properties)
    - e.g., name of a vertex, the weight of an edge

Graph Databases

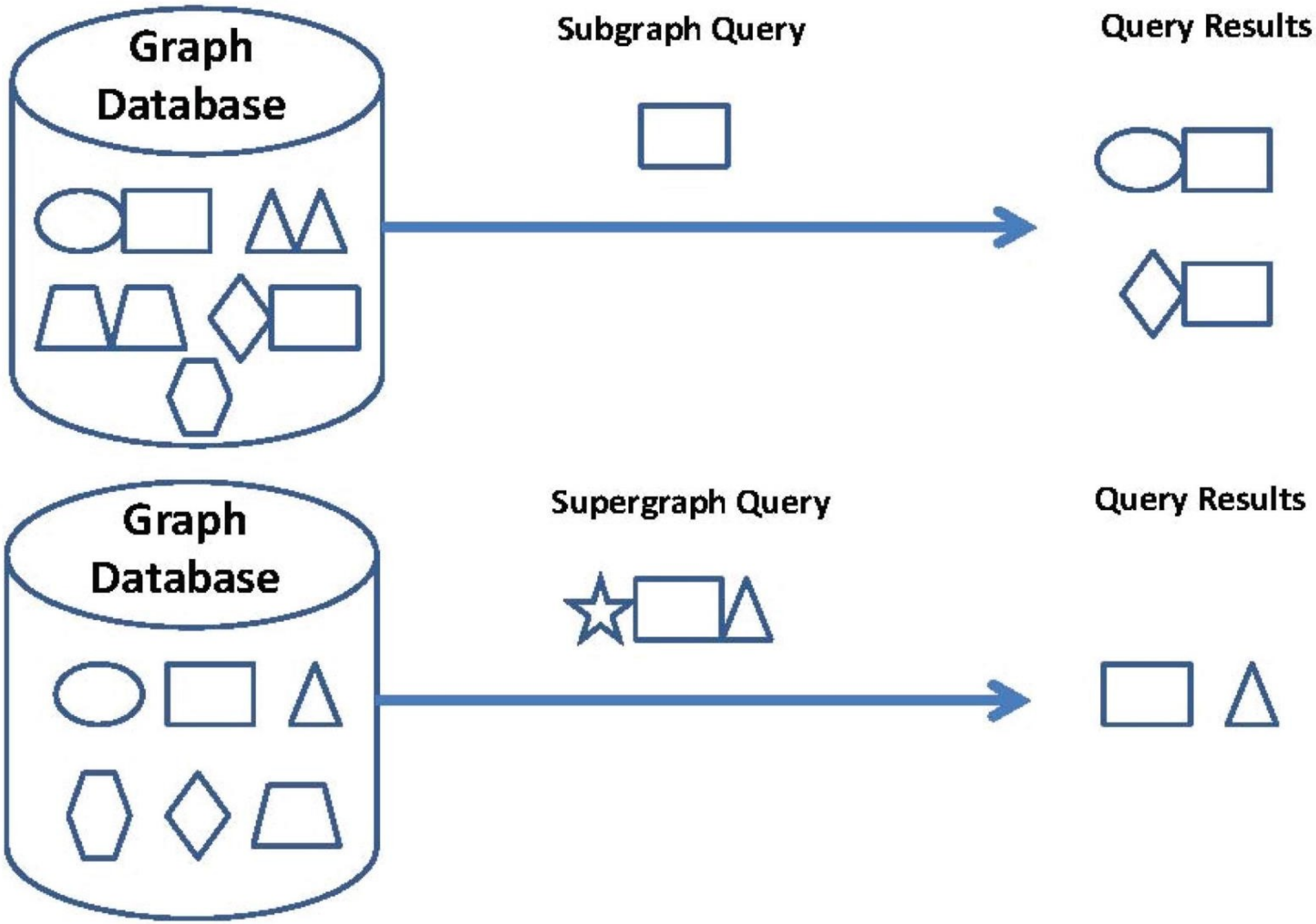
- A graph database = a set of graphs
- Types of graphs:
  - Directed-labeled graphs
    - e.g., XML, RDF, traffic networks
  - Undirected-labeled graphs
    - e.g., social networks, chemical compounds
- Types of graph databases:
  - Non-transactional = few numbers of very large graphs
    - e.g., Web graph, social networks, …
  - Transactional = large set of small graphs
    - e.g., chemical compounds, biological pathways, linguistic trees each representing the structure of a sentence…

Transactional Graph Databases

Types of Queries

- **Sub-graph** queries
  - Searches for a specific pattern in the graph database
  - A small graph or a graph, where some parts are uncertain
    - e.g., vertices with wildcard labels
  - More general type: sub-graph isomorphism
- **Super-graph** queries
  - Searches for the graph database members of which their whole structures are contained in the input query
- **Similarity** (approximate matching) queries
  - Finds graphs which are similar, but not necessarily isomorphic to

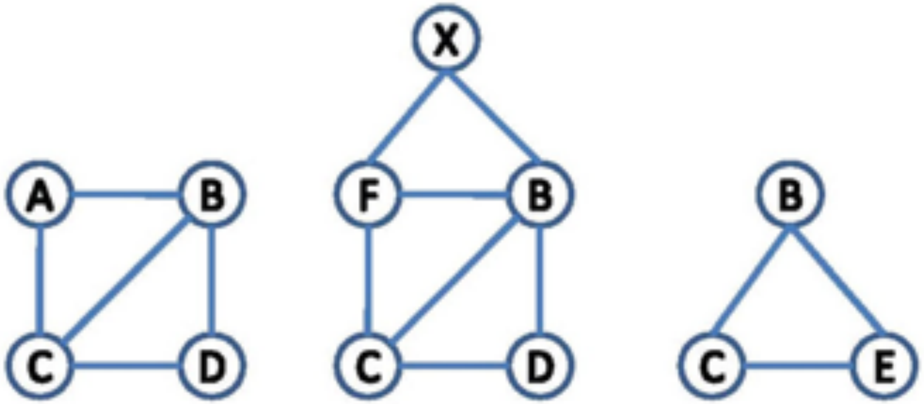
Graph queries



http://www.ksi.mff.cuni.cz/~svoboda/courses/171-B4M36DS2/

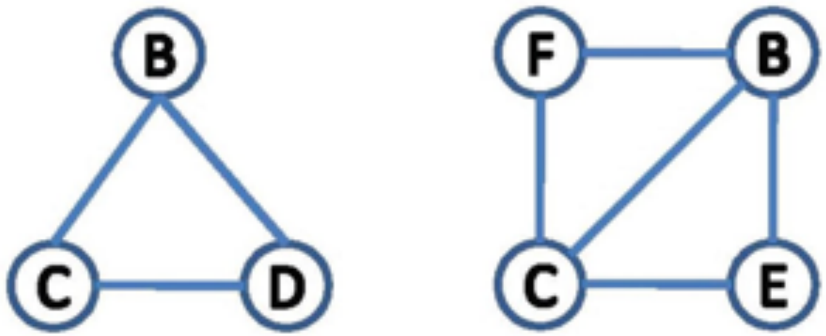
Graph queries

sub-graph:
q_1: g_1, g_2
q_2: $\varnothing$



g_1 g_2 g_3

super-graph:
q_1: $\varnothing$
q_2: g_3



q_1 q_2

Sub-graph Query Processing

Mining-Based Graph Indexing Techniques

- Idea: if features of query graph *q* do not exist in data graph G, then G cannot contain *q* as its sub-graph
- Graph-mining methods extract selected features (sub-structures) from the graph database members
  - An inverted index is created for each feature
- Answering a sub-graph query *q*:
  - Identifying the set of features of *q*
  - Using the inverted index to retrieve all graphs that contain the same features of *q*

Sub-graph Query Processing

Non Mining-Based Graph Indexing Techniques

- Focus on indexing whole constructs of the graph database
  - Instead of indexing only some selected features
- Cons:
  - Can be less effective in their pruning (filtering) power
  - May need to conduct expensive structure comparisons in the filtering process
- Pros:
  - Can handle graph updates with less cost
    - Do not rely on the effectiveness of the selected features
    - Do not need to rebuild whole indexes

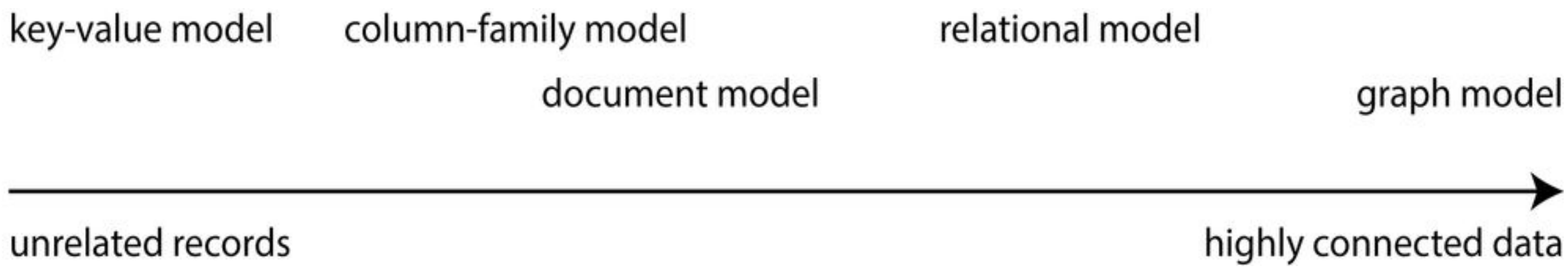
Graph Similarity Queries

- Find sub-graphs in the database that are *similar to query q*
  - Allows for node mismatches, node gaps, structural differences, …
- Usage: when graph databases are noisy or incomplete
  - Approximate graph matching query-processing techniques can be more useful and effective than exact matching

Graph-oriented Database

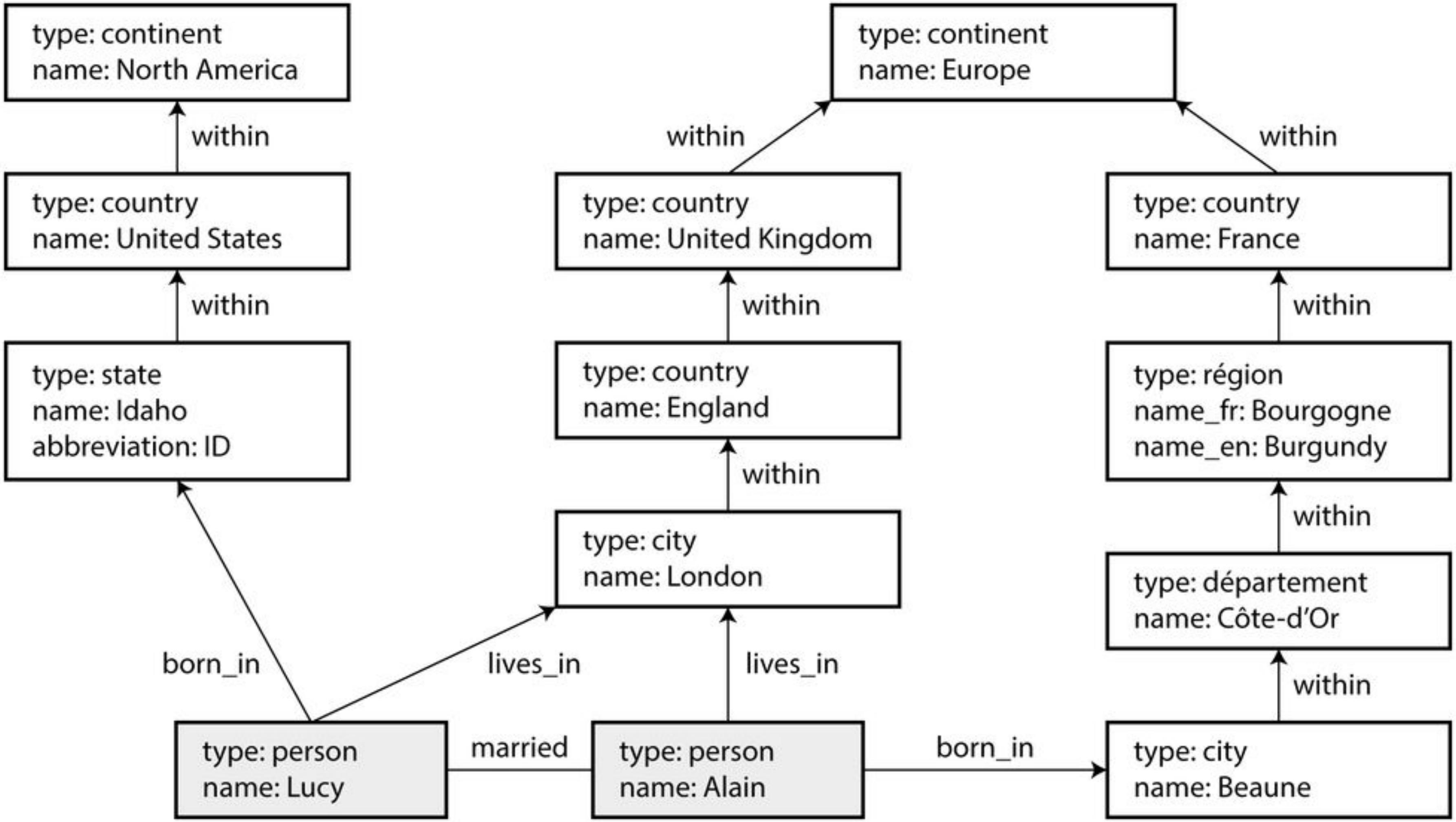
Graph-like Data Models

- Many-to-many relationships are an important distinguishing feature between different data models.



- The relational model can handle simple cases of many-to-many relationships, but
  - as the connections become more complex, it becomes more natural to start modeling as a graph.

Graph-like Data Models

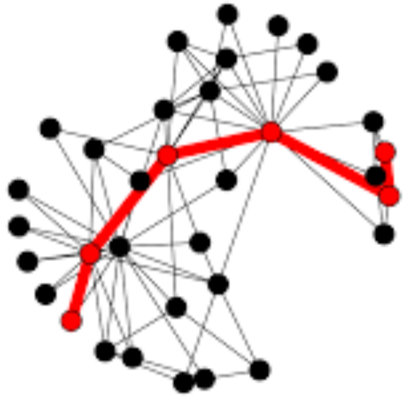


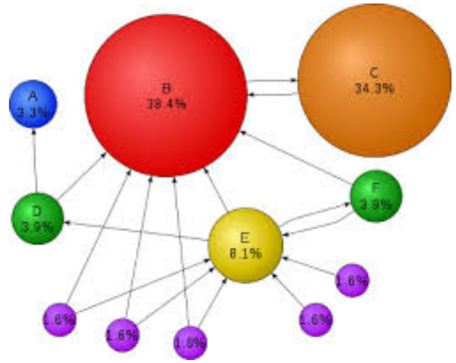
Graph-like Data Models

- A graph consists of two kinds of object:
  - **vertices** (also known as nodes or entities)
  - **edges** (also known as relationships).
- Many kinds of data can be modelled as a graph:
  - **Social graphs** – vertices are people, edges indicate which people know each other.
  - The **web graph** – vertices are web pages, edges indicate HTML links to other pages.
  - Road or rail **networks** – vertices are junctions, and edges represent the roads or railway lines between them.

Graph-like Data Models

- Well-known **algorithms** can operate on these graphs: for example,
  - the **shortest path** in a road network is useful for routing.
  - **PageRank** on the web graph to determine the popularity of a web page.
  - Closeness, betweenness, etc.





Graph-like Data Models

- There are several different, but related, ways of **structuring** and querying data in graphs. Two examples:
  - **property graph** model
    - implemented by Neo4j, Titan, InfiniteGraph
  - the **triple-store** model
    - implemented by Datomic, AllegroGraph and others.
- Some declarative **query languages** for graphs
  - Cypher
  - SPARQL
  - Datalog

Property graphs

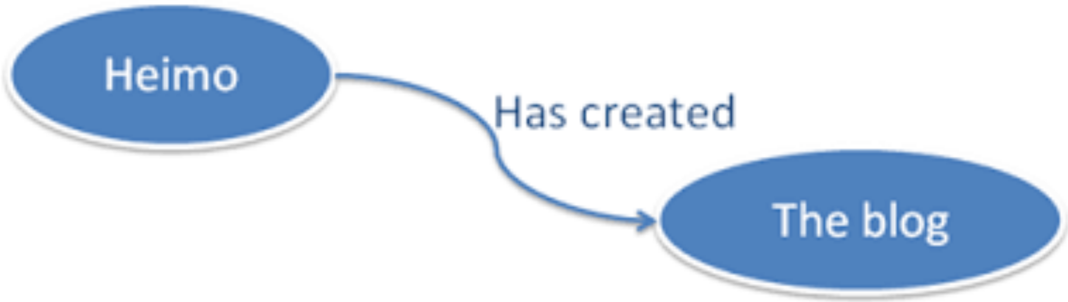
- Each **vertex** consists of:
  - a unique identifier,
  - a set of outgoing edges,
  - a set of incoming edges, and
  - a collection of properties (key-value pairs).
- Each **edge** consists of:
  - a unique identifier,
  - the vertex at which the edge starts (the tail vertex),
  - the vertex at which the edge ends (the head vertex),
  - a label to describe the type of relationship between the two vertices, and
  - a collection of properties (key-value pairs).

Property graphs

- Any vertex can have an edge connecting it with any other vertex.
  - There is no schema that restricts which kinds of things can or cannot be associated.
- Given any vertex,
  - We can efficiently find both incoming and outgoing edges.
  - Traverse the graph.
- Different labels for different kinds of relationship
  - Allow storing several different kinds of information in a single graph, while still maintaining a clean data model.

Triple-stores

- The **triple-store model** is mostly equivalent to the property graph model
  - using different words to describe the same ideas.
- Information is stored in the form of very simple three-part statements:
  - **subject**, **predicate**, **object**.



Triple-stores

- The **subject** of a triple is equivalent to a vertex in a graph.

- The **object** is one of two things:
  - a value in a primitive datatype, such as a string or a number.
    - In that case, the **predicate** and object of the triple are equivalent to the key and value of a property on the subject vertex.
    - For example, (lucy, age, 33) is like a vertex lucy with properties {"age":33}.
  - another vertex in the graph.
    - In that case, the **predicate** is an edge in the graph, the subject is the tail vertex and the object is the head vertex.
    - For example, in (lucy, marriedTo, alain).

Triples examples

- Using *Turtle*, a format that is a subset of *Notation3* (*N3*).

```
@prefix : <urn:x-example:>.
_:lucy     a :Person;   :name "Lucy";          :bornIn _:idaho.
_:idaho    a :Location; :name "Idaho";         :type "state";   :within _:usa.
_:usa      a :Location; :name "United States"; :type "country"; :within _:namerica.
_:namerica a :Location; :name "North America"; :type "continent".
```

Graph Databases

neo4j

OrientDB®

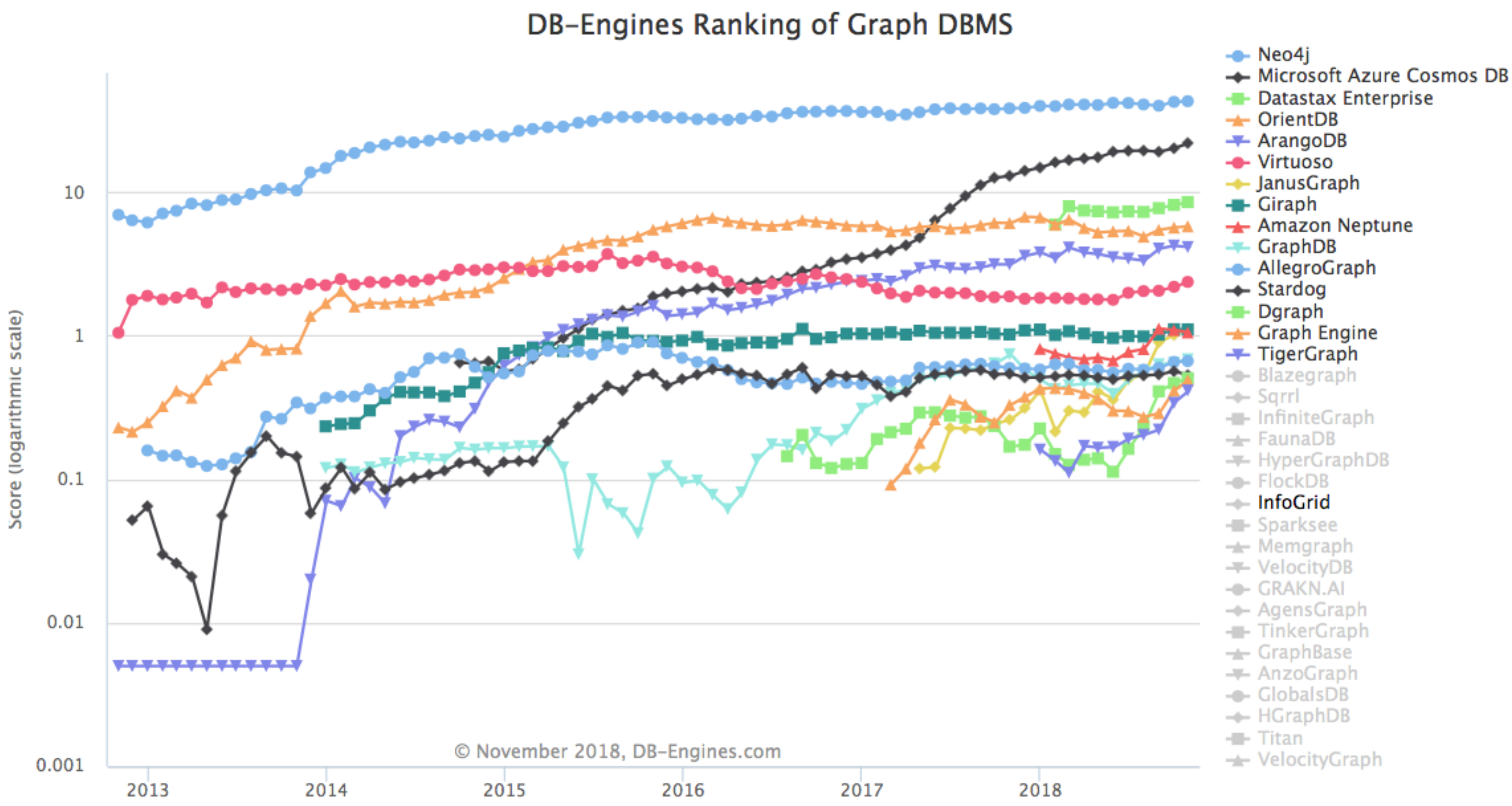
TITAN

ArangoDB

APACHE GIRAPH

INFINITEGRAPH®

Graph Databases Popularity



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

Neo4j Graph Database

Neo4j

- Graph database
  - https://neo4j.com/
- Features
  - Open source, massively scalable (billions of nodes), high availability, fault-tolerant, master-slave replication, ACID transactions, embeddable, …
  - Expressive graph query language (Cypher), traversal framework
- Developed by Neo Technology
- Implemented in Java
- Operating systems: cross-platform
- Initial release in 2007

Features of Neo4j

- **Data model (flexible schema)**
  - Neo4j follows a data model named native property graph model.
  - The graph contains **nodes** (entities) and these nodes are connected with each other (depicted by **relationships**). Nodes and relationships store data in key-value pairs known as **properties**.
  - In Neo4j, there is no need to follow a fixed schema.
- **ACID properties**
  - Neo4j supports full ACID (Atomicity, Consistency, Isolation, and Durability) rules.

Features of Neo4j

- Scalability and reliability
  - You can scale the database by increasing the number of reads/writes, and the volume without affecting the query processing speed and data integrity.
  - Neo4j also provides support for **replication** for data safety and reliability.
- **Cypher Query Language**
  - Neo4j provides a powerful declarative query language known as Cypher.
  - It uses ASCII-art for depicting graphs.
  - Cypher is easy to learn and can be used to create and retrieve relations between data without using the complex queries like Joins.

Features of Neo4j

- **Built-in web application**
  - Neo4j provides a built-in **Neo4j Browser** web application. Using this, you can create and query your graph data.
- **Drivers** – Neo4j can work with
  - REST API to work with programming languages such as Java, Spring, Scala etc.
  - Java Script to work with UI MVC frameworks such as Node JS.
  - It supports two kinds of Java API: Cypher API and Native Java API to develop Java applications.
- **Indexing** – Neo4j supports Indexes by using Apache Lucene.

Data Model

- Database system structure
  - **Instance → single graph**

- Property graph = directed labeled multigraph
  - Collection of vertices (nodes) and edges (relationships)

- Graph **node**
  - Has a unique (internal) identifier
  - Can be associated with a set of **labels**
    - Allow us to categorize nodes
  - Can also be associated with a set of **properties**
    - Allow us to store additional data together with nodes

Data Model

- Graph **relationship**
  - Has a unique (internal) identifier
  - Has a **direction**
    - Relationships are equally well traversed in either direction!
    - Directions can be ignored when querying
  - Always has a start and end node
    - Can be recursive (i.e. loops are allowed)
  - Is associated with exactly one type
  - Can also be associated with a set of **properties**

Data Model

- Node and relationship **properties**
  - Key-value pair
    - Key is a string
    - Value is an atomic value of any primitive data type, or an array of atomic values of one primitive data type
- Primitive **data types**
  - **`boolean`** – boolean values **`true`** and **`false`**
  - **`byte`**, **`short`**, **`int`**, **`long`** – integers (1B, 2B, 4B, 8B)
  - **`float`**, **`double`** – floating-point numbers (4B, 8B)
  - **`char`** – one Unicode character
  - **`String`** – sequence of Unicode characters

Cypher

- Declarative graph query language
  - Allows for expressive and efficient querying and updates
  - Inspired by SQL (query clauses) and SPARQL (pattern matching)
- OpenCypher
  - Ongoing project aiming at Cypher standardization http://www.opencypher.org/
- Clauses
  - E.g. MATCH, RETURN, CREATE, …
  - Clauses are (almost arbitrarily) chained together
  - Intermediate result of one clause is passed to a subsequent one

Cypher – Nodes

- Cypher uses a pair of parentheses to represent Nodes
  - Like a circle or a rectangle with rounded corners.

```
()
```

- Represents an anonymous, uncharacterized **node**.

```
(matrix)
```

- If we want to refer to the node elsewhere, we can add an variable

```
(:Movie)
```

- The Movie **label** declares the node's type or role

```
(matrix:Movie)
(matrix:Movie {title: "The Matrix"})
(matrix:Movie {title: "The Matrix", released: 1999})
```

- The node's **properties** (title, released, et cetera) are represented as a list of key/value pairs, enclosed within a pair of braces

```
(matrix:Movie:Promoted)
```

Cypher – Relationships

- Cypher uses arrows to represent relationships

  `-, ->, <-`

  - Relationships are arrows pointing from one node to another

  `(node1)-[:REL_TYPE]->(node2)`

  - General relation, from node1 to node2

  `(actor:Person)-[:ACTED_IN]->(movie:Movie)`

  - Retrieve all nodes that had a relationship type ACTED_IN with other nodes.

- Query examples

  ```
  MATCH (node1)-[rel:TYPE]->(node2)
  RETURN rel.property
  ```

  - Generic format, from node to node2.

  ```
  MATCH (actor:Person)-[rel:ACTED_IN]->(movie:Movie)
  RETURN rel.roles
  ```

  - Roles of actors that acted in any movie.

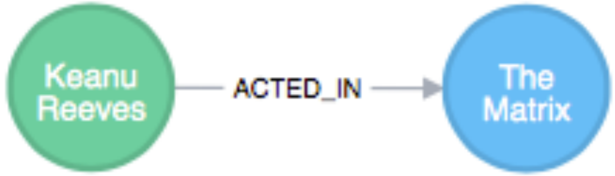
  ```
  MATCH (n)-->(m) RETURN n, m;
  ```

  - every pair of nodes with a relationship going from n to m.

Cypher – Patterns

- Combining the syntax for nodes and relationships, we can express patterns.

```
MATCH (matrix:Movie {title:"The Matrix"} )
   <-[role:ACTED_IN {roles:["Neo"]}]-
   (keanu:Person {name:"Keanu Reeves"})
RETURN matrix, role, keanu
```



matrix	role	keanu
{ "title": "The Matrix", "tagline": "Welcome to the Real World", "released": 1999 }	{ "roles": ["Neo"] }	{ "name": "Keanu Reeves", "born": 1964 }

```
MATCH cast = (:Person)-[:ACTED_IN]->(:Movie)
RETURN cast
```

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Cypher – Selection

MATCH

```
MATCH (n) RETURN n
```

- all nodes

```
MATCH (me:Person) WHERE me.name="My Name" RETURN me.name
MATCH (me:Person {name:"My Name"}) RETURN me.name
```

```
MATCH (movie:Movie)
WHERE movie.title = "Mystic River"
SET movie.released = 2003
RETURN movie.title AS title, movie.released AS released
```

title	released
Mystic River	2003

Cypher – Filtering

- **WHERE**

```
MATCH (tom:Person)-[:ACTED_IN]->()<-[:ACTED_IN]-(actor:Person)
WHERE tom.name="Tom Hanks" AND actor.born < tom.born
RETURN DISTINCT actor.name AS Name
```

  - ??

```
MATCH (gene:Person)-[:ACTED_IN]->()<-[:ACTED_IN]-(other:Person)
WHERE gene.name="Gene Hackman" AND exists( (other)-[:DIRECTED]->() )
RETURN DISTINCT other
```

  - ??

```
MATCH (gene:Person {name:"Gene Hackman"})-[:ACTED_IN]->(movie:Movie),
   (other:Person)-[:ACTED_IN]->(movie),
   (robin:Person {name:"Robin Williams"})
WHERE NOT exists( (robin)-[:ACTED_IN]->(movie) )
RETURN DISTINCT other
```

  - ??

Cypher – Ordering

- **ORDER BY**, **LIMIT**, **SKYP**, **DISTINCT**

- Return the five oldest people in the database

```
MATCH (person:Person)
RETURN person
ORDER BY person.born
LIMIT 5;
```

- List of the oldest actors

```
MATCH (actor:Person)-[:ACTED_IN]->()
RETURN DISTINCT actor
ORDER BY actor.born
```

Variable Length Paths

```
MATCH (node1)-[*]-(node2)
```

- Relationships that traverse any depth are:
  `(a)-[*]->(b)`
- Specific depth of relationships
  `(a)-[*depth]->(b)`
- Relationships from one to four levels deep
  `(a)-[*1..4]->(b)`
- Relationships of type KNOWS at 3 levels distance:
  `(a)-[:KNOWS*3]->(b)`
- Relationships of type KNOWS or LIKES from 2 levels distance:
  `(a)-[:KNOWS|:LIKES*2..]->(b)`

Indexes

- Neo4j doesn't use indexes to speed up JOINs
  - They are useful for finding the starting points by value, textual prefix or range

- To search efficiently people by name:

```
CREATE INDEX ON :Person(name);
```

- Now, the lookup of "Gene Hackman" will be faster

```
MATCH (gene:Person)-[:ACTED_IN]->(movie),
  (other:Person)-[:ACTED_IN]->(movie)
WHERE gene.name="Gene Hackman"
RETURN DISTINCT other;
```

- To remove the index:

```
DROP INDEX ON :Person(name);
```

Aggregation

- Cypher provides support for a number of aggregate functions
  - **count(x)** Count the number of occurrences
  - **min(x)** Get the lowest value
  - **max(x)** Get the highest value
  - **avg(x)** Get the average of a numeric value
  - **sum(x)** Sum up values
  - **collect(x)** Collect all the values into an collection

```
MATCH (person:Person)-[:ACTED_IN]->(movie:Movie)
RETURN person.name, count(movie)
ORDER BY count(movie) DESC
LIMIT 10;
```

- Top ten actors who acted in the most movies

Creating Nodes

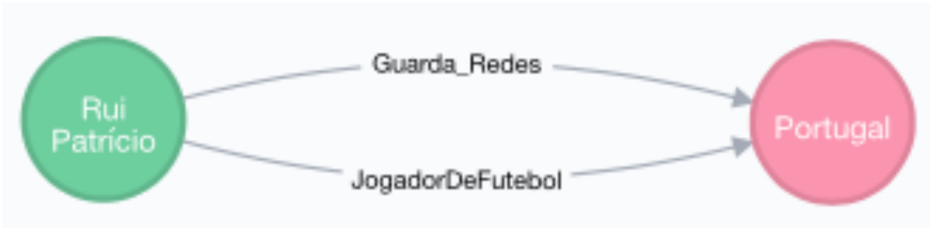
- **CREATE**

```
CREATE (node:label { key1: value, key2: value, ... })
```

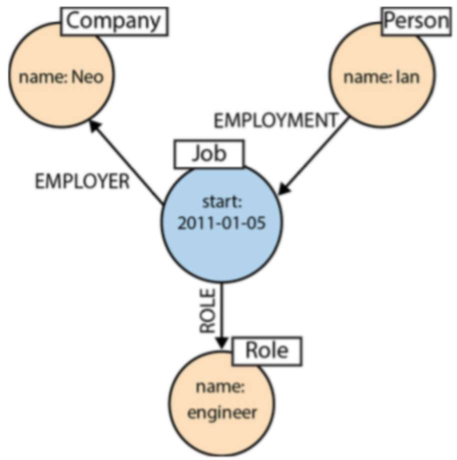
```
CREATE (Aveiro)

CREATE (Porto),(Coimbra),(Espinho)

CREATE (ric:person:player)

CREATE (leo:person:player)

CREATE (aveiro:cidade{name:"Aveiro"})

CREATE (ricg:player{name: "Ricardo Gomes",
YOB: 1985, POB: "Porto"})
```

Creating Relationships

```
CREATE (RuiPatricio:player{name: "Rui Patrício", YOB: 1988, POB:
"Leiria"})
CREATE (PT:Country {name: "Portugal"})
CREATE (RuiPatricio)-[r:Guarda_Redes]->(PT)
CREATE (RuiPatricio)-[:JogadorDeFutebol]->(PT)
RETURN RuiPatricio, PT
```




```
CREATE (:Person {name:'Ian'})-[:EMPLOYMENT]->
   (employment:Job
      {start_date:'2011-01-05'}) -[:EMPLOYER]->
   (:Company {name:'Neo'}), (employment)-[:ROLE]->
   (:Role {name:'engineer'})
```



Removing nodes/relationships

DELETE

- Removes nodes, relationships or paths from the data graph
- Relationships must be removed before the nodes
  - Unless the DETACH modifier is specified

```
MATCH (p:Person {name:"My Name"})
DELETE p
```

- Remove node "My name". Error if it has relations

```
MATCH (me:Person {name:"My Name"})
OPTIONAL MATCH (me)-[r]-()
DELETE me,r
```

- Remove me (node "My name") and any relationships with "me"..

```
MATCH (n) DETACH DELETE n
```

- delete all nodes and relationships

Importing Data

- **LOAD CSV**

- Content of "movies.csv"

```
id,title,country,year
1,Wall Street,USA,1987
2,The American President,USA,1995
3,The Shawshank Redemption,USA,1994
```

- In Cypher:

```
LOAD CSV WITH HEADERS
FROM "http://neo4j.com/docs/stable/csv/intro/movies.csv"
AS line
CREATE (movie:Movie
   { id:line.id, title:line.title, released:toInt(line.year) });
```

Other Write Clauses

- **SET** clause
  - allows to…
    - set a value for a property, or remove a property when NULL is assigned
    - replace all the current properties with new ones
    - add new properties to the existing ones
    - add labels to nodes
  - Cannot be used to set relationship types
- **REMOVE** clause
  - Allows to…
    - remove a particular property remove labels from nodes
    - Cannot be used to remove relationship types

Summary

- Graph theory
  - brief concepts
- Graph-oriented databases
  - Property graphs
- Neo4j graph database
- Cypher (graph query language)
  - Read (sub-)clauses: MATCH, WHERE, …
  - Write (sub-)clauses: CREATE, DELETE, SET, REMOVE, …
  - General (sub-)clauses: RETURN, WITH, ORDER BY, LIMIT, …

Resources

- Pramod J Sadalage and Martin Fowler, ***NoSQL Distilled***. Addison-Wesley, 2012
- Ian Robinson, Jim Webber and Emil Eifrem, ***Graph Databases***, O'Reilly's, 2013
    - https://neo4j.com/graph-databases-book/
- Neo4j
    - https://neo4j.com/developer/
- Martin Svoboda, "B4M36DS2: Database Systems"
    - http://www.ksi.mff.cuni.cz/~svoboda/courses/171-B4M36DS2/