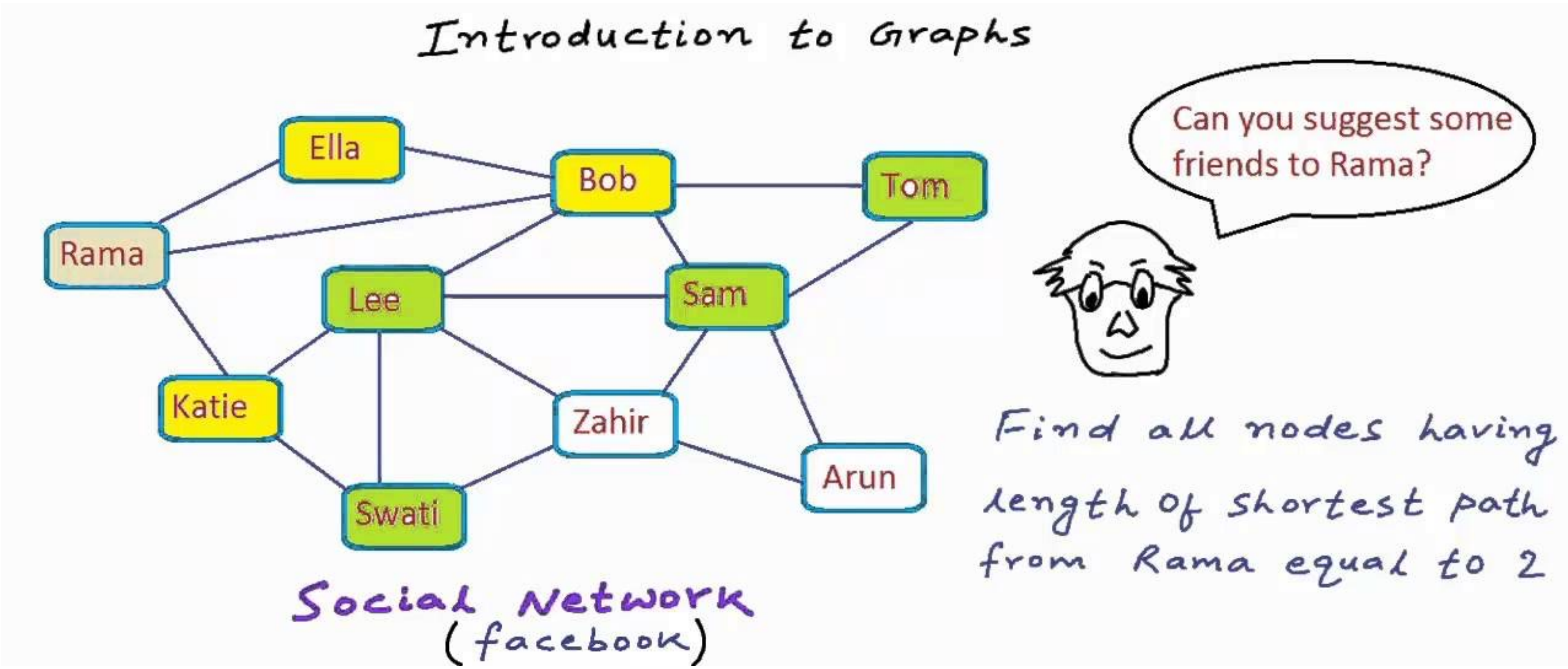
Graph Databases

UA.DETI.CBD
José Luis Oliveira / Carlos Costa

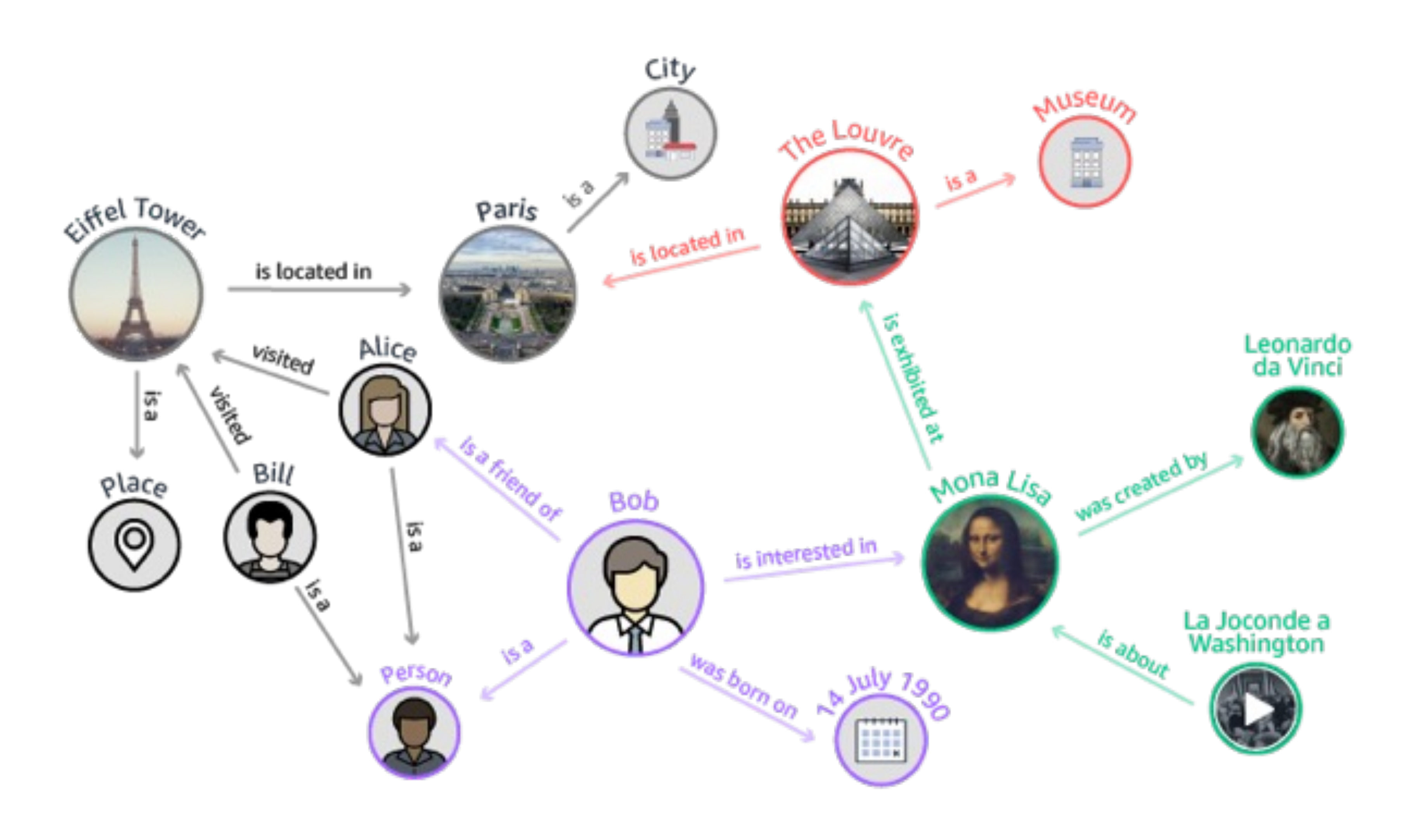
Some theory about graph theory

*“**Graphs are one of the unifying themes of computer science** - an abstract representation that describes the organization of transportation systems, human interactions, and telecommunication networks. That so many different structures can be modeled using a single formalism is a source of great power to the educated programmer.”*

The Algorithm Design Manual, by Steven S. Skiena (Springer)



Graphs



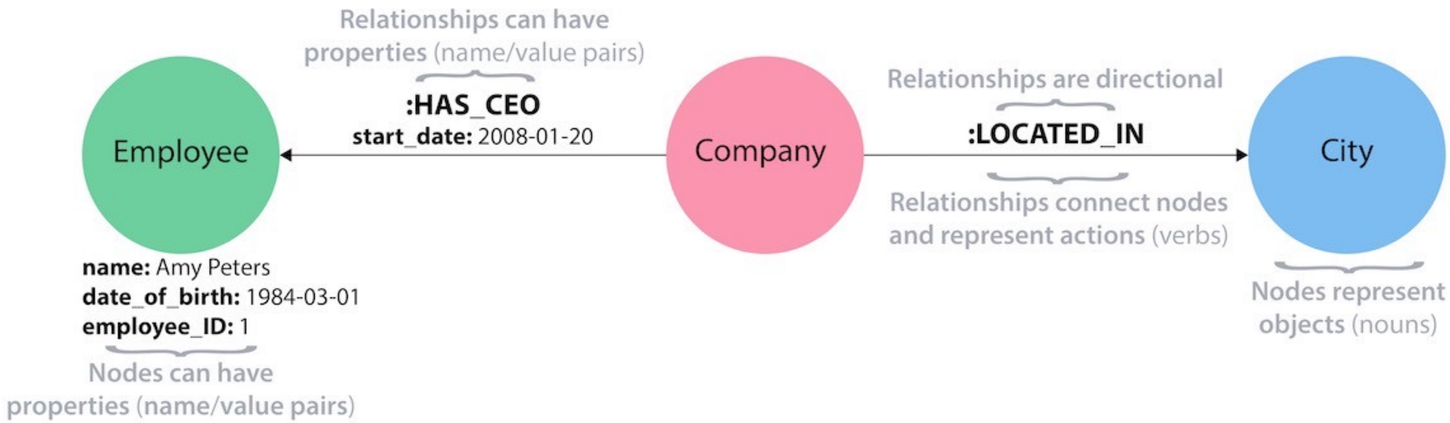
https://www.allthingsdistributed.com/2019/12/power-of-relationships.html

Graphs

- **Data**: a set of entities and their relationships
  - e.g., social networks, travelling routes, …
  - We need to efficiently represent graphs
- **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
  - $n = |V|$, $m = |E|$

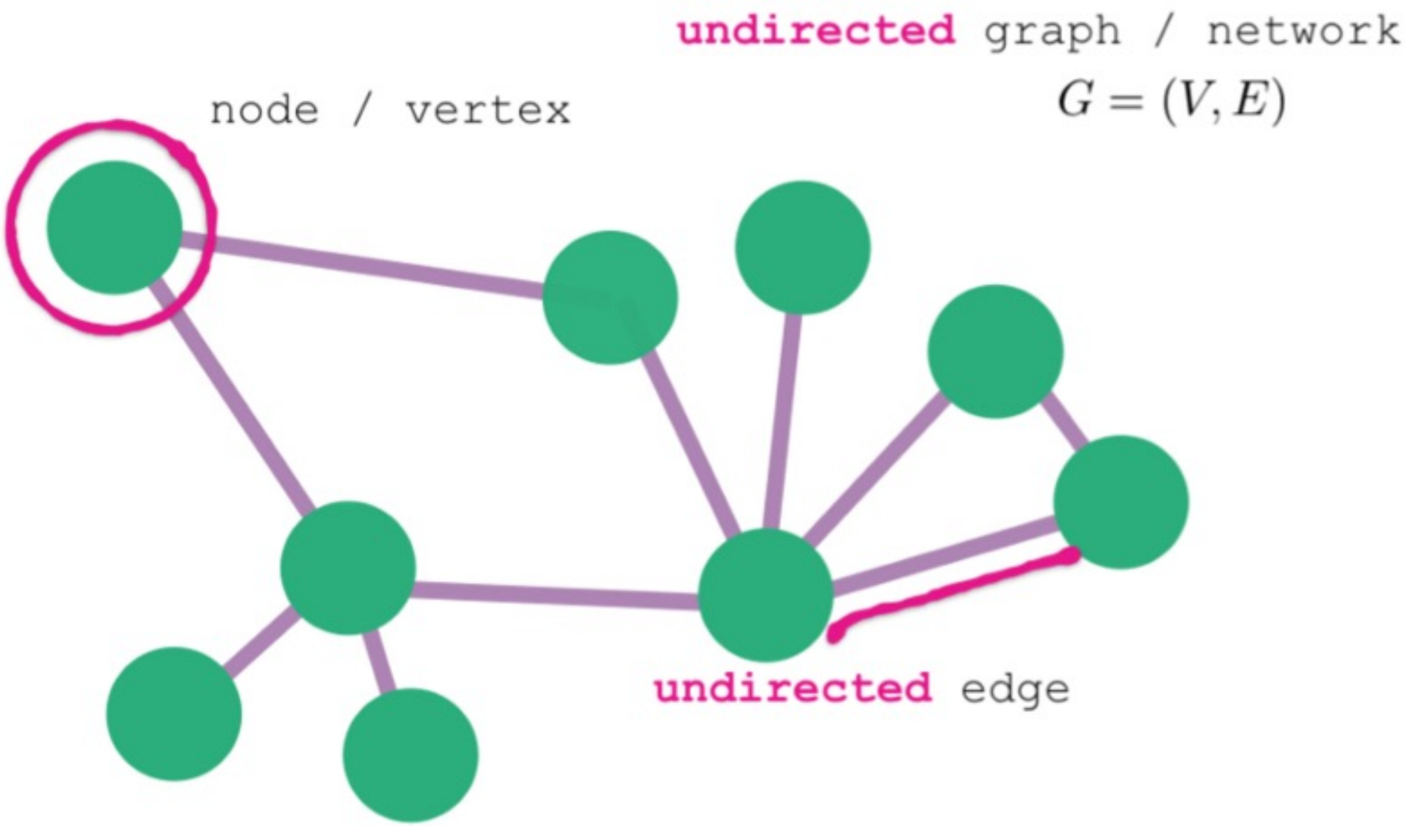
Types of Graphs

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



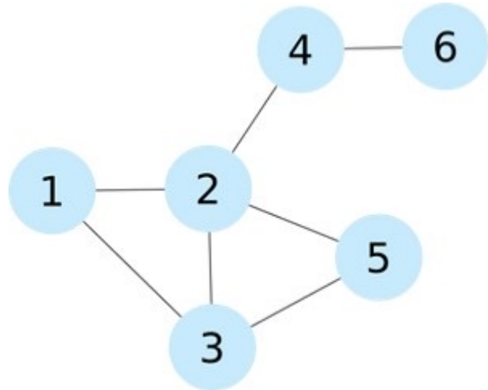
Graphs

❖ 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



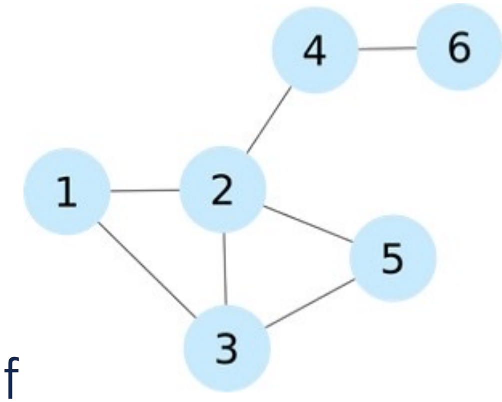
- **Pros:**
  – Checking if two nodes are connected
  – Adding/removing edges
- **Cons:**
  – Quadratic space with respect to *n*
    - We usually have sparse graphs (lots of 0)
  – Addition of nodes is expensive
  – Retrieval of all the neighbouring - *O(n)*

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

- 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}

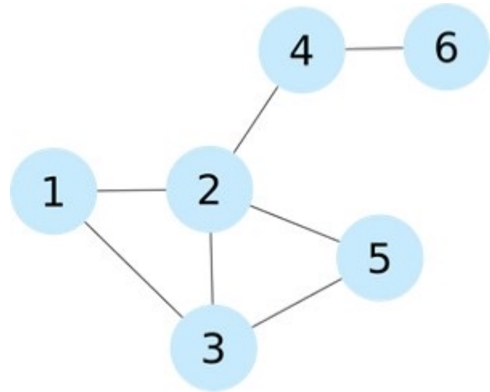
N4 → {N2, N6}

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

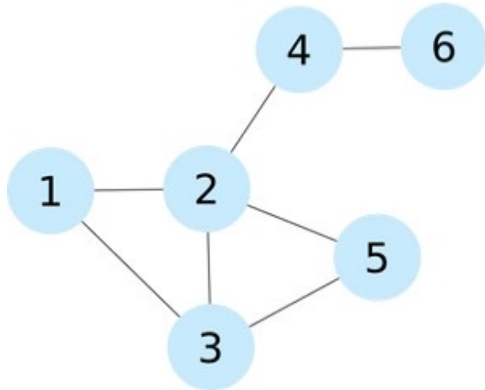


- **Pros**:
  - For representing hypergraphs, where one edge connects an arbitrary number of nodes
- **Cons**:
  - Requires *n* x *m* bits

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

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
  - **L = D – A**
    - where D is degree matrix of graph G and A is the adjacency matrix



- **Pros & Cons:**
  - = Adjacency Matrix
    - But, it retains more information
    - Allows analyzing the graph structure by means of spectral analysis

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

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-labelled edges.
  - Finally, of those vertices, return their name property.

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

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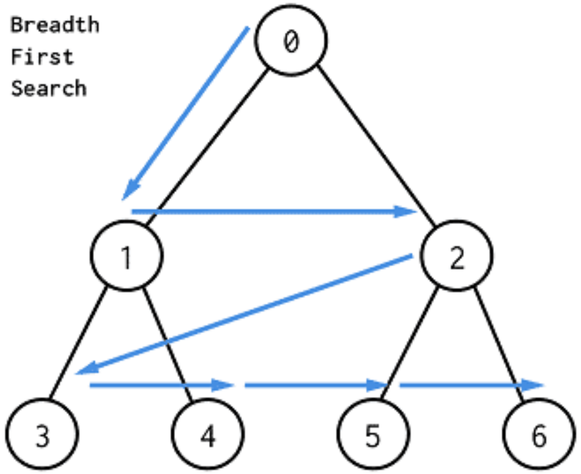
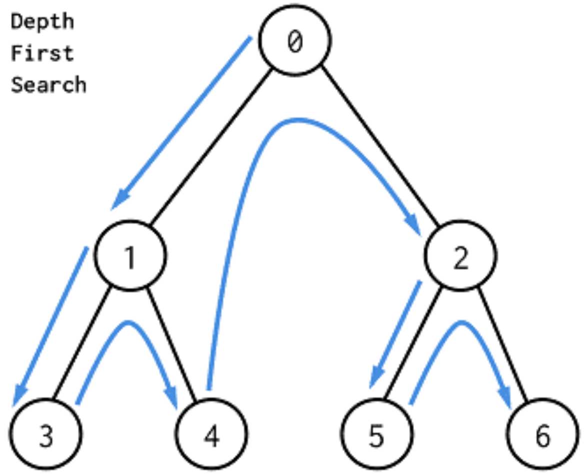
Graph Traversals

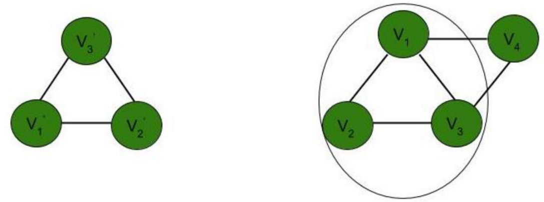
- **Breadth First Search (BFS)**
  - one node is selected and then all of the adjacent nodes are visited one by one.
  - it moves further to check another node.
- **Depth First Search (DFS)**
  - one starting vertex is given, and when an adjacent vertex is found, it moves to that adjacent vertex first and try to traverse in the same manner.





Transactional Graph Databases

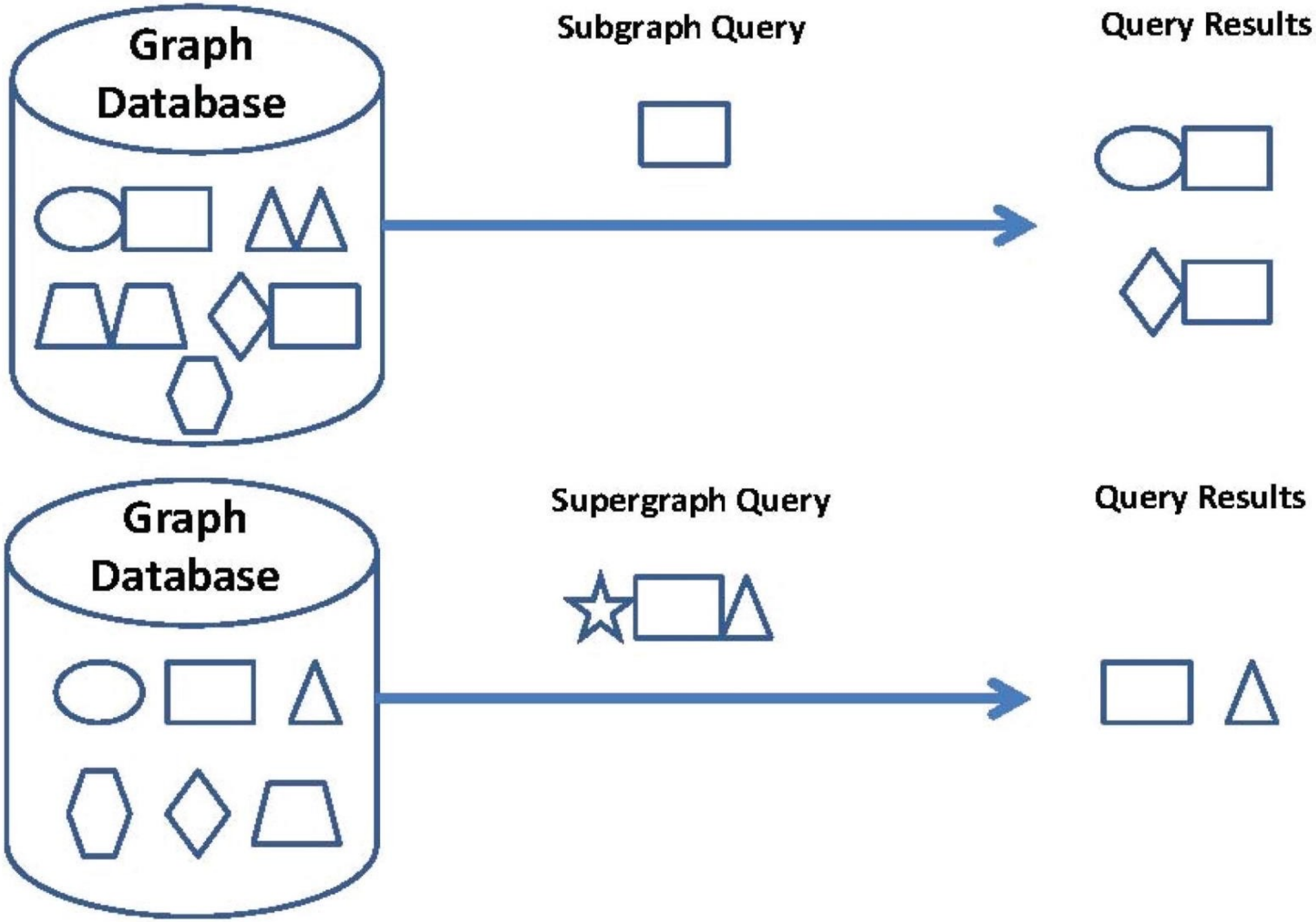
Types of Queries



Graph G_1 Graph G_2

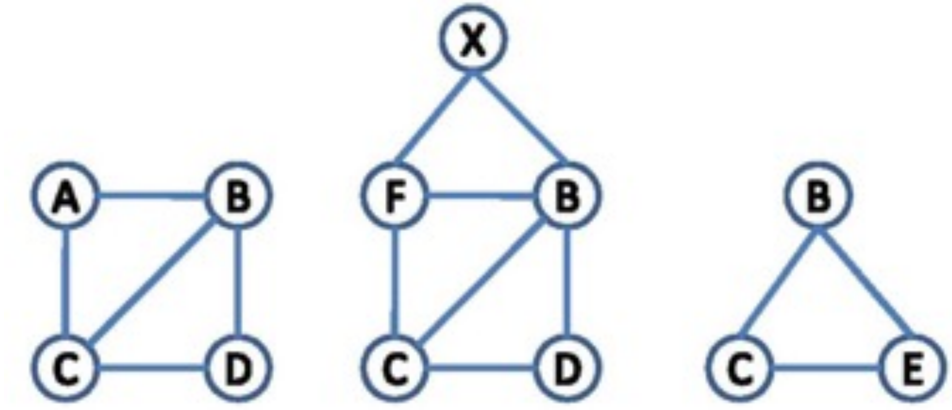
- **Sub-graph** queries
  - More general type: sub-graph isomorphism
  - Searches for a specific pattern in the graph database
  - A small graph or a graph, where some parts are uncertain
    - e.g., vertices with wildcard labels
- **Super-graph** queries
  - Searches for the graph database members of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

Graph queries



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

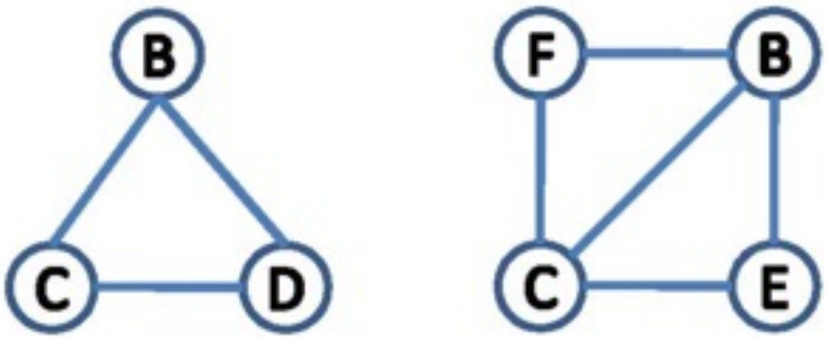
Graph queries



g_1 g_2 g_3

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

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

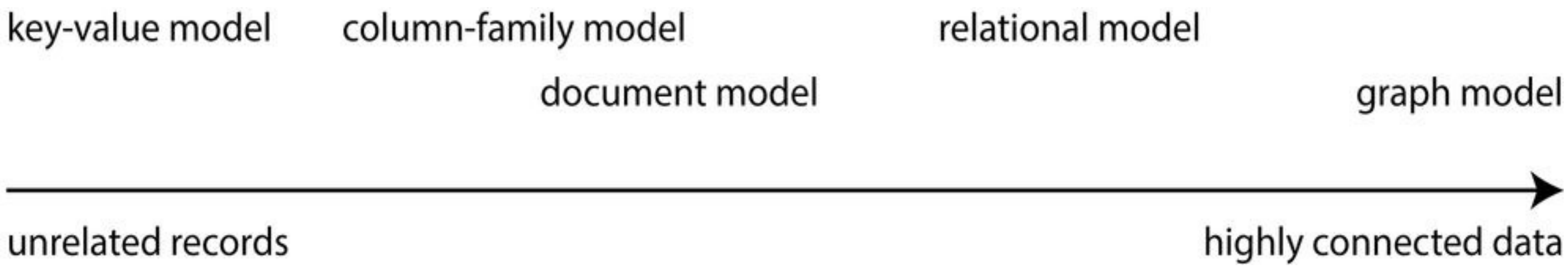


q_1 q_2

Graph-oriented Database

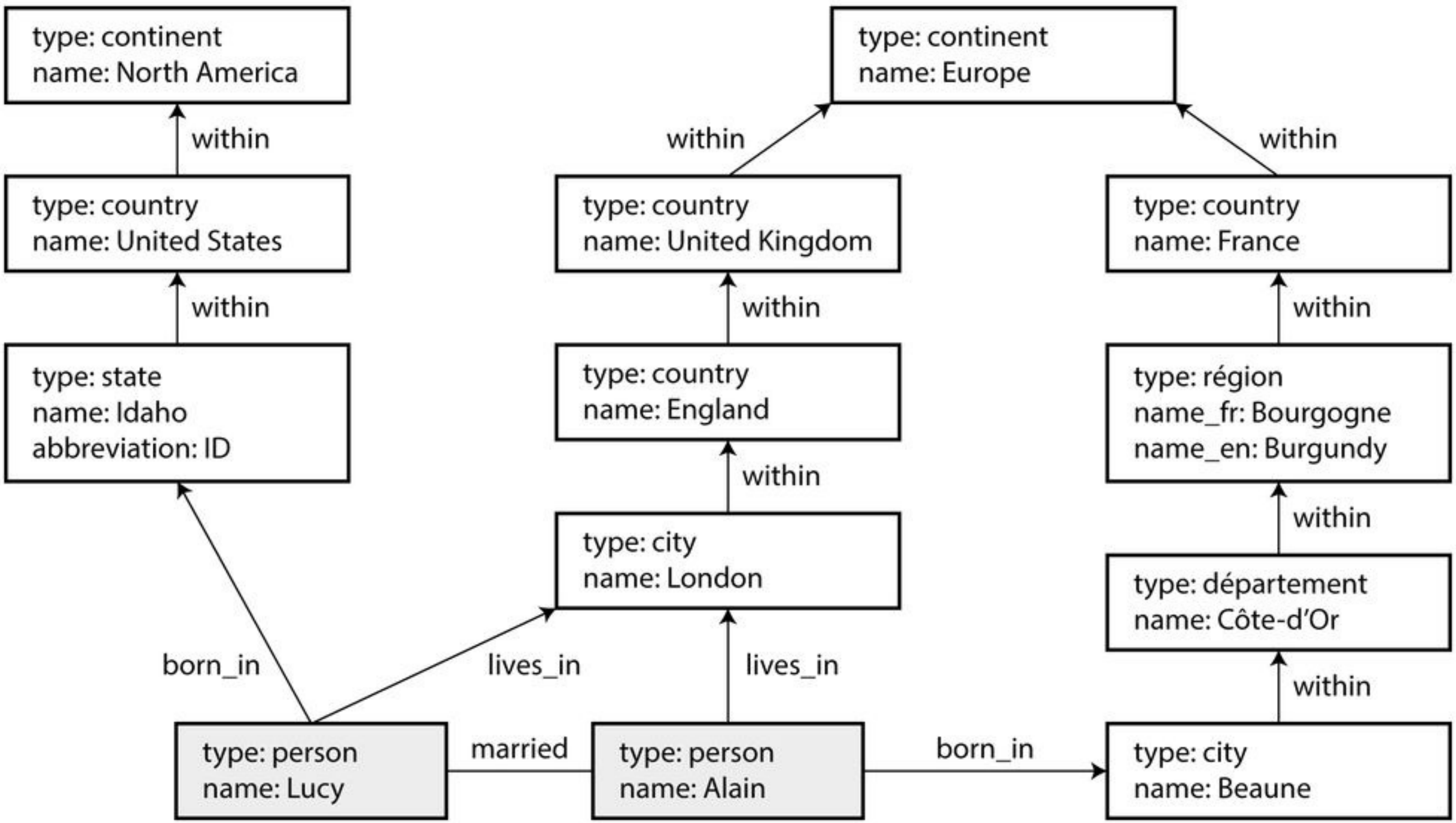
Graph-like Data Models

- 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 modelling as a graph.

Graph-like Data Models

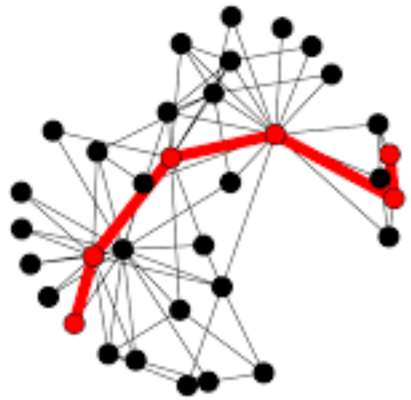


Graph-like Data Models

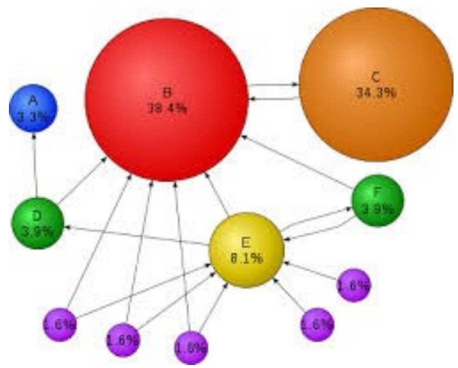
- A graph consists of two kinds of object:
  - **vertices** (also known as nodes or entities)
  - **edges** (also known as relationships).
- Many kinds of data can be modelled as a graph:
  - **Social graphs** – vertices are people, edges indicate which people know each other.
  - The **web graph** – 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

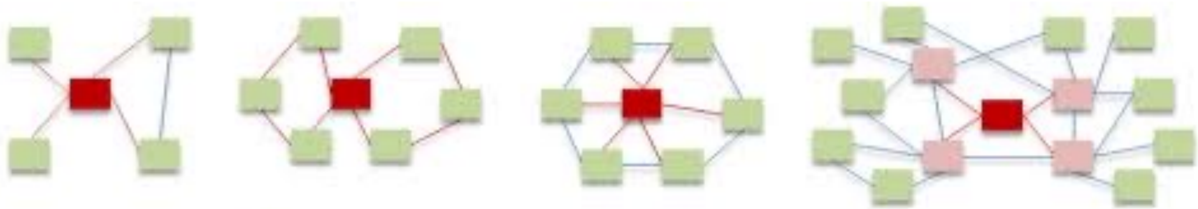
- Well-known **algorithms** can operate on these graphs: for example,
  - the **shortest path** in a road network is useful for routing.



  - **PageRank** on the web graph to determine the popularity of a web page.



  - Degree, Betweenness, Closeness, 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

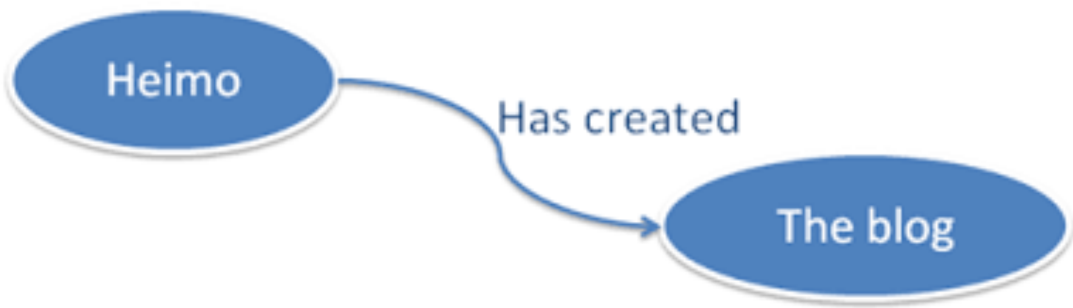
- Each **vertex** consists of:
  - a unique identifier,
  - a set of outgoing edges,
  - a set of incoming edges, and
  - a collection of properties (key-value pairs).
- Each **edge** consists of:
  - a unique identifier,
  - the vertex at which the edge starts (the tail vertex),
  - the vertex at which 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**.

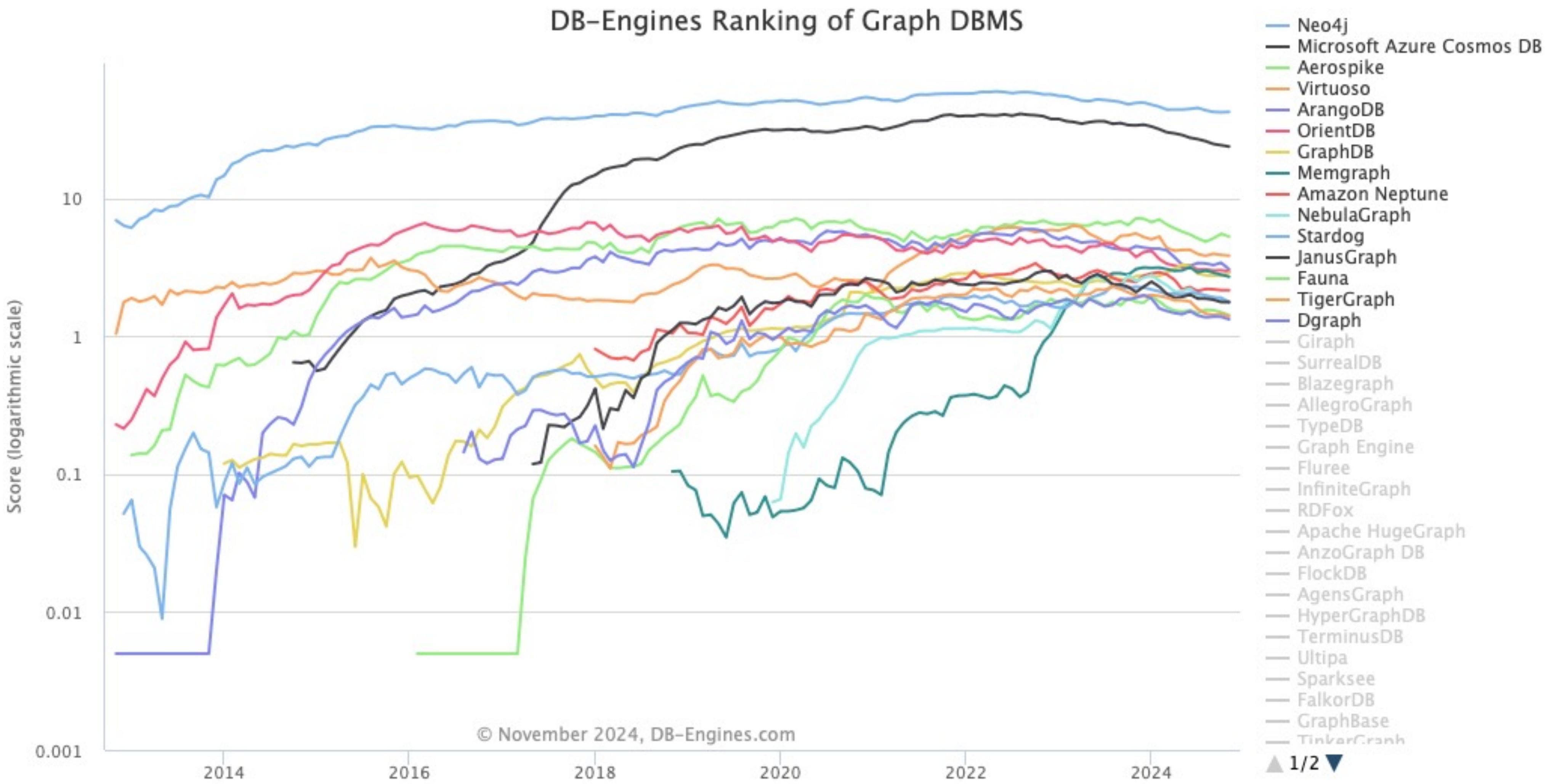


Triple-stores

- 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).

Graph Databases

Graph Databases Popularity



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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

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 **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, we can create and query any graph data.
- **Drivers** – Neo4j can work with
  - It supports two kinds of Java API: Cypher API and Native Java API to develop Java applications.
  - 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.
- **Indexing** – Neo4j supports Indexes by using Apache Lucene.

Data Model

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

- Property graph = directed labelled 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 pairs
  - 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)

- 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, etc) are represented as a list of key/value pairs, enclosed within a pair of braces

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

Cypher – Relationships

- Cypher uses a pair of square brackets and arrows to represent relationships

```
[RELATION]
-, ->, <-
<-[RELATION]->
```

- 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)
```

  - matches all nodes Person that had a relationship type ACTED_IN with other nodes Movie.

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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"})
```

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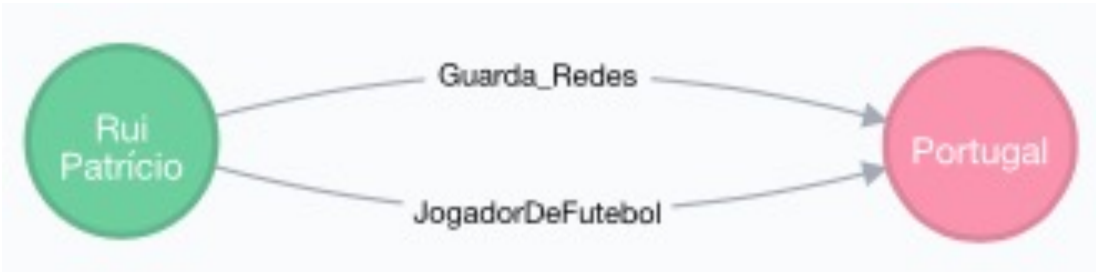
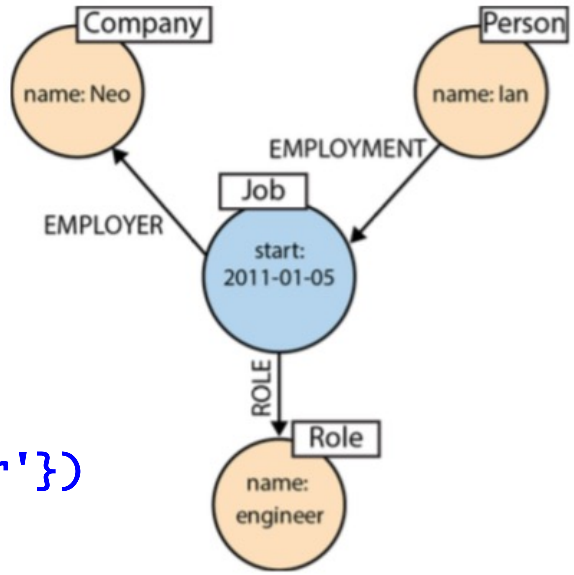
Creating Relationships

```
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)
```



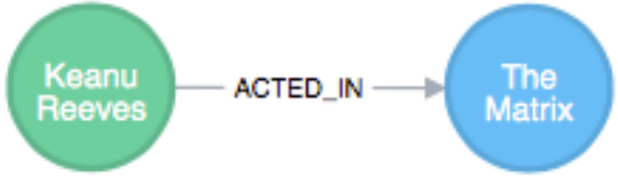

```
CREATE (:Person {name:'Ian'})
   -[:EMPLOYMENT]->
   (employment:Job    {start_date:'2011-01-05'})
   -[:EMPLOYER]->
   (:Company {name:'Neo'}),
   (employment) -[:ROLE]-> (:Role {name:'engineer'})
```



Cypher – Patterns

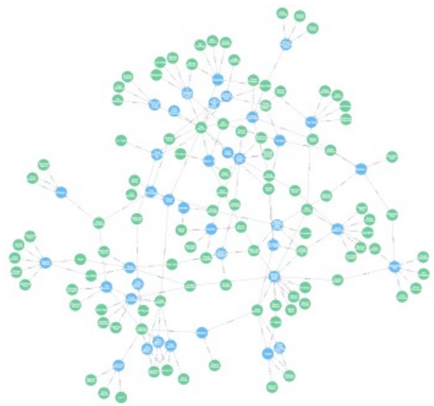
- Combining the syntax for nodes and relationships, we can express patterns.

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

- Generic format, from node1 to node2.

```
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**, **SKIP**, **DISTINCT**

- Return the five oldest people in the database

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

- List all actors, ordered by age

```
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 use indexes to speed up the finding of 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 more movies

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:"Trump"})
DELETE p
```

- Remove node "Trump". Error if it has relations

```
MATCH (p:Person {name:"Trump"})
OPTIONAL MATCH (p)-[r]-()
DELETE p,r
```

- Remove node "p" with *name*= "*Trump*" and all nodes with any relationship with "p".

```
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/