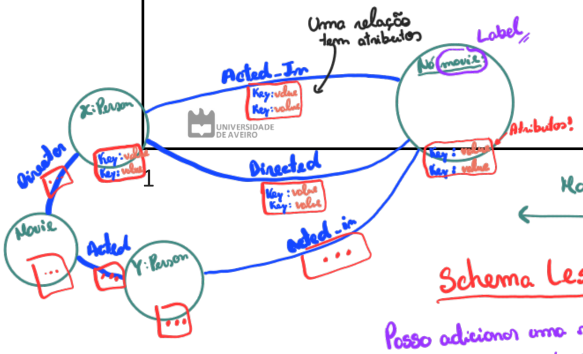
Graph Databases

UA.DETI.CBD
José Luis Oliveira / Carlos Costa



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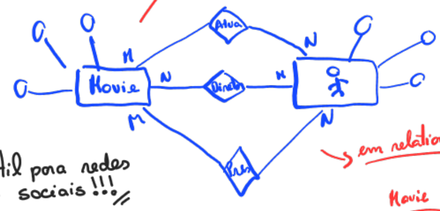
Modelo de grafos



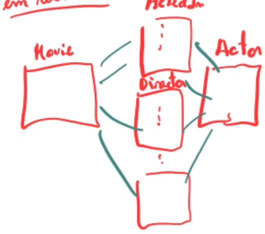
Cada nó seria um elemento de Movie e cada record tem vários atributos

Schema Less!

Posso adicionar uma nova relação e não preciso de alterar a base de dados...

Útil para redes sociais!!!

→ em relational:

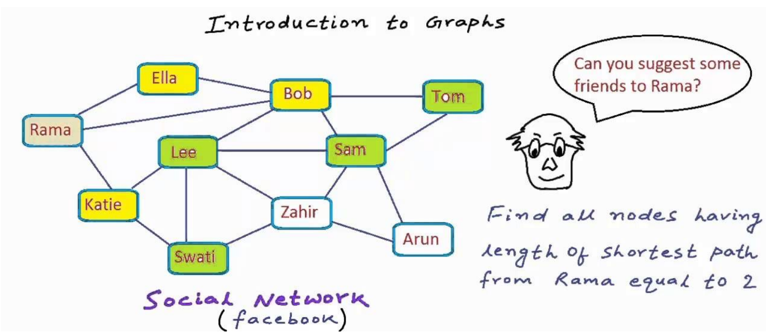


→ Muita complexidade!
→ Não aceita alterações dinâmicas

Some theory about graph theory

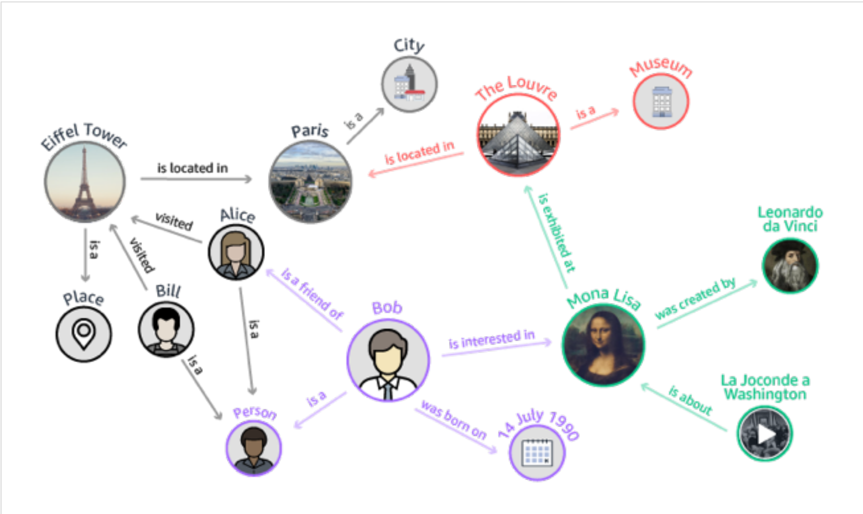
*"**Graphs are one of the unifying themes of computer science** - an abstract representation that describes the organization of transportation systems, human interactions, and telecommunication networks. That so many different structures can be modeled using a single formalism is a source of great power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

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



2

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

↳ ShortestPath!

- $G = (V, E)$ is commonly modelled as
  - set of **nodes** (vertices) V
  - set of **edges** E
  - $n = |V|$, $m = |E|$

Um grafo é definido por um set de vertices e arestas

Types of Graphs

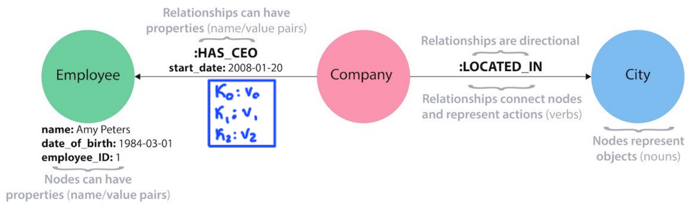
sem propriedades!

- **Single-relational**
  - Edges are homogeneous in meaning
    - e.g., all edges represent friendship

Simplesmente sem propriedades

Os que queremos

- **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



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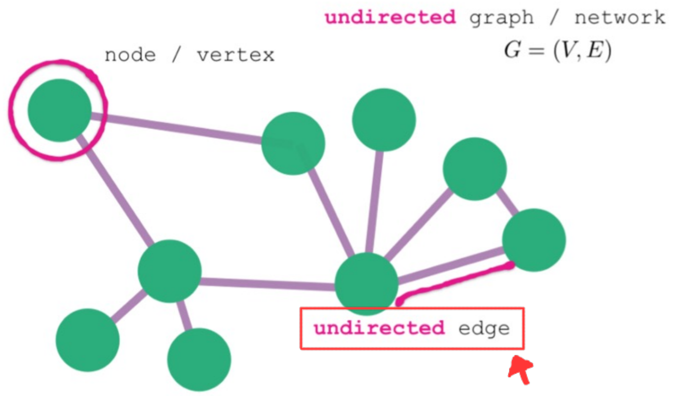
5

Graphs

- Which **data structure** should be used?



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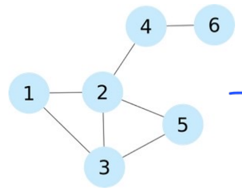
6

Adjacency Matrix

NxN

- Bi-dimensional **array** *A* of $\underbrace{n \times n}$ Boolean values
  - Indexes = node identifiers
  - *Aij* indicates whether the two nodes *i, j* are connected



→ Não existem ligações a eles próprios!
⇒ Diagonal a 0,,

- **Pros**:
  - basta ver
  - Checking if two nodes are connected
  - Adding/removing edges ← não é assim tão bom…
- **Cons**:
  - Quadratic space with respect to *n* $O(n^2)$
    - We usually have sparse graphs (lots of 0)
  - Addition of nodes is expensive
  - Retrieval of all the neighbouring - *O(n)*

Matrix de adjacência,,

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

→ Informação duplicada,,

bidirecional

Sem ligação interna

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

Já não seria espelhado!

Poderia meter peso por aresta!,,

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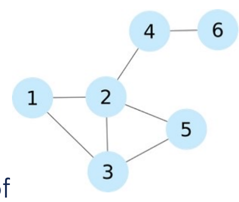
Adjacency List

- 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



Apenas guardamos os que estão ligados

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

- **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

↳ em Directed Graphs tenho de ver nas 2 listas

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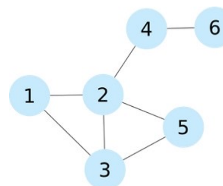
Incidence Matrix

- 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

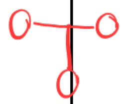


- **Pros**:
  - For representing hypergraphs, where one edge connects an arbitrary number of nodes

Grafos com mais do que 2 nós por relação!

Para hypergrafos é bom podemos ter 3 entidades numa única relação

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



- **Cons**:
  - Requires $\boxed{n \times m}$ bits

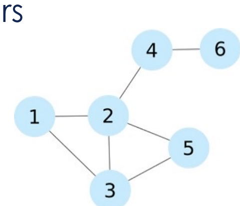
Tem maior dimensão!

Laplacian Matrix

Matriz de Adjacência!

- Bi-dimensional **array** of $\boxed{n \times n}$ 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

Se estão ligados fica -1



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

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

número de relações

liga

Grau de relacionamento de um determinado nó!!

⇒ Na Matriz de Adj. era só zeros...

Graph Traversals

percorrer!

- Single step **traversal** from element *i* to element *j*, where *i,j* ∈ *(V ∪ 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
  - ∈ : get element property values for key r
  - e_p : allow (or filter) all elements with the property s for key r
  - ∈= : allow (or filter) all elements that are the provided element

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.

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

todos os que têm determinada direção

extrair name

incoming

são do tipo friend?

todos os que saem

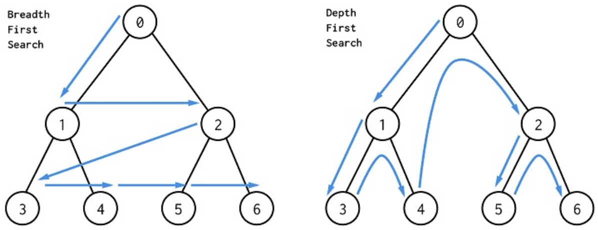
lab = friend

Vin $\xrightarrow{e_{out}}$ e_{out}

name

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.



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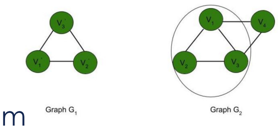
13

13

Transactional Graph Databases

Encontrar subgrafos

Types of Queries



- **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 → Se dentro da base de dados tem algum subgrafo neste supergrafo
  - 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

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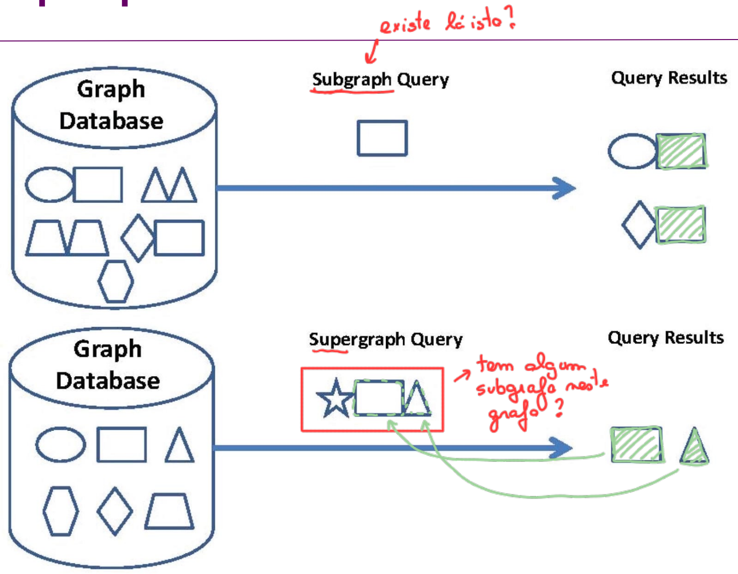
15

15

Graph queries

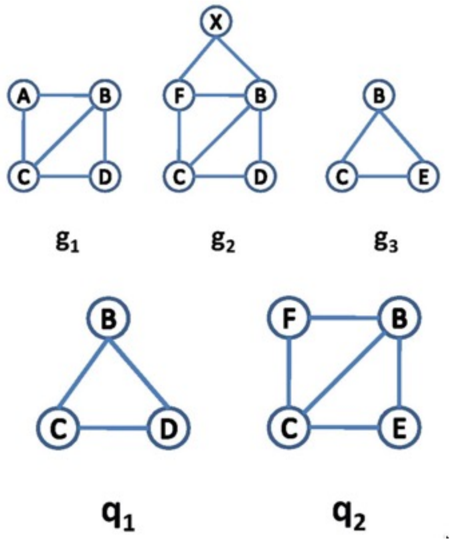


http://www.ksi.mff.cuni.cz/~svoboda/courses/171-B4M36DS2/ 16

16

Graph queries

sub-graph:
q_1: g_1, g_2
q_2: ∅



super-graph:
q_1: ∅
q_2: g_3

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17

Graph-oriented Database

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21

Graph-like Data Models

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

key-value model   column-family model   relational model   graph model

document model

unrelated records → highly connected data

Neo4j dá propriedades ACID

Sai no teste

!!!

- 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.

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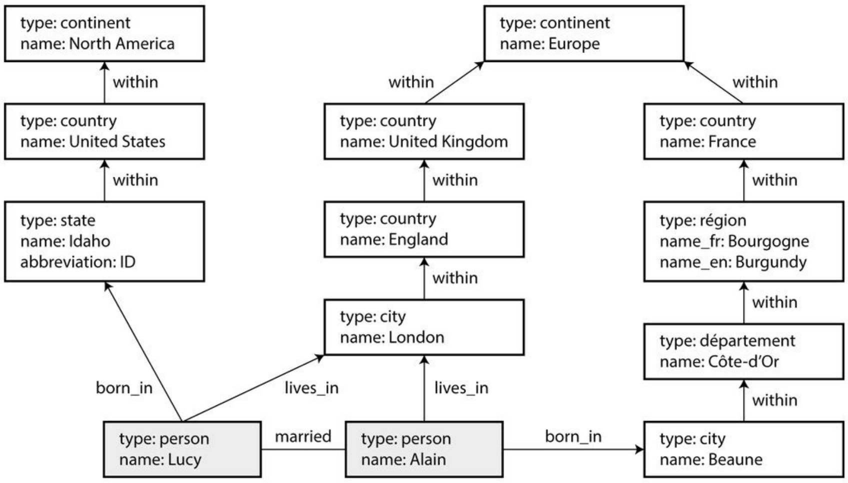
22

Graph-like Data Models



23

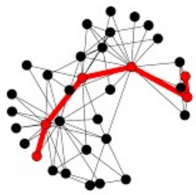
Graph-like Data Models

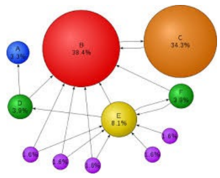
- A graph consists of two kinds of object:
  - **vertices** (also known as nodes or entities)
  - **edges** (also known as relationships).
- Many kinds of data can be modelled as a graph:
  - **Social graphs** – vertices are people, edges indicate which people know each other.
  - The **web graph** –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

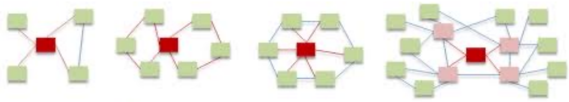
24

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.







Vetor próprio

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25

25

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 ← Neo4J
  - SPARQL ← Para web semântica!!
  - Datalog

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26

26

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).

O vertice tem propriedades

- 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).

As relações têm propriedades !

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27

27

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.

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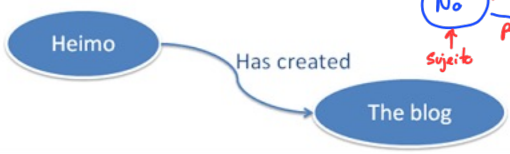
28

28

Triple-stores { é quase igual

- 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**.



29

Triple-stores

Nó do gráfico

- 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. predicado é o edge e o objeto é o nó
    - 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).

30

Graph Databases

neo4j

OrientDB

TITAN

ArangoDB

APACHE GIRAPH

INFINITEGRAPH

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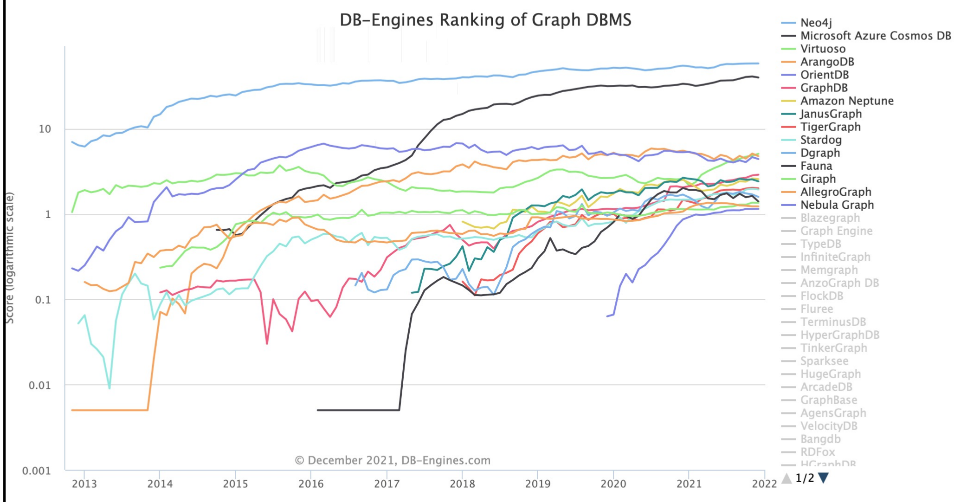
32

32

Graph Databases Popularity



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33

33

Graph Databases

- **Suitable** use cases → Muitos relações!
  - 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

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35

Neo4j Graph Database

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36

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

Tem indexes também!

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37

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.

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38

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.

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39

39

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.

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40

40

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 id
  - Can be associated with a set of **labels** → O tipo do nó! ≠
    - Allow us to categorize nodes
  - Can also be associated with a set of **properties** → As propriedades do nó!
    - Allow us to store additional data together with nodes

Data Model

Relacionamento: apenas a um tipo
Nó: pode estar associado a vários tipos
X: Movie, Serie

- Graph **relationship** id
  - 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

$\boxed{V_0 \text{ ou } [V_0, V_1, V_2]}$

- 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

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43

43

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

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44

44

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)
```
nós
- 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)
```
label
podia usar where!

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

- 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)
```
Um nó pode ter multiplos labels!//

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Cypher – Relationships

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

```
[RELATION]
-, ->, <-
<-[RELATION]->
```
direção obrigatória!

❖ 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)
```

2 labels

```
CREATE (leo:person:player)

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

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

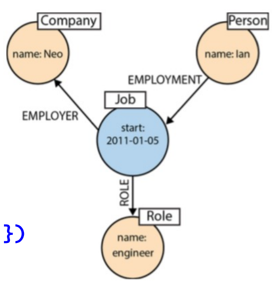
Creating Relationships

Representação Visual

```
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)
```

Difícil de Ler

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

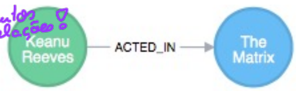


Cypher – Patterns

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

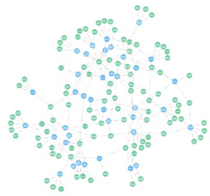
```
MATCH (matrix:Movie {title:"The Matrix"} )
  <-[role:ACTED_IN {roles:["Neo"]}]-
  (keanu:Person {name:"Keanu Reeves"})
RETURN matrix, role, keanu
```

Atributos nas relações!



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
```



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
```

UPDATE →

```
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**

Um qualquer

```
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
```

  - ?? Atores que tenham atuado num filme com Tom Hanks Mesmo nó que...

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

e que tenha dirigido outro filme

  - ??

```
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
```

  - ??

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51

51

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;
```

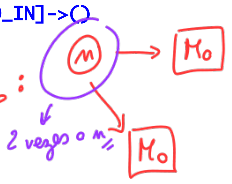
crescente!

1902
1901
1900

- List all actors, ordered by age

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

Para não termos:



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52

52

Variable Length Paths

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

- Relationships that traverse any depth are:
  (a)-[*]->(b)
- Specific depth of relationships
  Máxima!
  (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)
  Label
- Relationships of type KNOWS or LIKES from 2 levels distance:
  2 ou mais!
  (a)-[:KNOWS|:LIKES*2..]->(b) e.g.: amigos de 2.º grau

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53

Indexes

- Neo4j use indexes to speed up the finding of starting points by value, textual prefix or range
- To search efficiently people by name:
  $\boxed{\texttt{CREATE INDEX ON :Person(name);}}$
- 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);

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54

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

Coleção em lista →

↳ Filme [A_0, A_1, A_2, ...]

```
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

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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
```

Qualquer relação que tenha p

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

quebra as ligações!

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

  - delete all nodes and relationships

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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) });
```

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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

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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, …

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59

59

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/

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60

60