A Brief Introduction to Graph Databases

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Theoretical Foundations

Foundations of Graph Databases

- Topic of research since at least 30 years
- Typical questions of interest:
  - Expressiveness
  - Complexity of evaluation
  - Containment problem

Expressiveness

- Let *L1* and *L2* be query languages
- *L1* is at least as expressive as *L2* if for every query in *L2*, there exists a semantically equivalent query in *L1*
- *L1* is strictly more expressive than *L2* if *L1* is at least as expressive as *L2* and there exists a query in *L1* for which there does not exist a semantically equivalent query in *L2*

Complexity of Evaluation

- Let *L* be a query language
- *L*-EVAL: Given a graph database *G*, a query *Q* in *L*, and a result element *μ* of the right type for *L*, does *μ* belong to the result of *Q* over *G*?
  - Combined complexity

Complexity of Evaluation (cont.)

- EVAL(Q) for a fixed query Q in L: Given a graph database G and a result element μ of the right type for L, does μ belong to the result of Q over G?
- Let C be a complexity class
- If for every query Q in L, the problem EVAL(Q) is in C, then L-EVAL is in C in data complexity
- L-EVAL is C-hard in data complexity if there exists a query Q in L such that EVAL(Q) is C-hard
- L-EVAL is C-complete in data complexity if a) it is in C and b) it is C-hard in data complexity

Containment Problem

- Let *L* be a query language
- *L*-CONT: Given two queries *Q* and *Q'* in *L*, is the result of *Q* over *G* a subset of the result of *Q'* over *G* for every graph database *G*?

Data Model

- Prevalent data model: directed, edge-labeled graph
  - Given a finite alphabet Σ, a *graph database* over Σ is a pair (V,E) where V is a finite set of node ids and E is a subset of $V \times \Sigma \times V$
- A *path* is a sequence $\rho = v_0\, a_0\, v_1\, a_1 \ldots v_{k-1}\, a_{k-1}\, v_k$ such that (v_{i-1}, a_{i-1}, v_i) in E for each i in $\{1, \ldots, k\}$
- The *label* of ρ is the string $a_0\, a_1 \ldots a_{k-1}$
  - Label of the empty path v is the empty string
- A path is *simple* if it does not go through the same node twice

Types of Queries

- Conjunctive queries (subgraph matching)

$$ans(z_1, \ldots, z_n) \leftarrow \bigwedge_{1 \leq i \leq m} (x_i, a_i, y_i)$$

- Regular path queries (RPQs)

$$ans(x, y) \leftarrow (x, r, y)$$

- Conjuctive RPQs (CRPQs)

$$ans(z_1, \ldots, z_n) \leftarrow \bigwedge_{1 \leq i \leq m} (x_i, r_i, y_i)$$

- RPQs with inverse (2RPQ) and C2RPQ
- RPQs with label variables (RPQVs)
- Unions of C2RPQs
- RPQs with nested regular expression
- Extended CRPQs

Graph Data Systems and their Data Models

Categories of Graph Data Systems

- **Triple stores**
  - Typically, pattern matching queries and in
  - Data model: RDF
- **Graph databases**
  - Typically, navigational queries
  - Prevalent data model: property graphs
- **Graph processing systems**
  - Typically, complex graph analysis tasks
  - Prevalent data model: generic graphs
- **Graph dataflow systems**
  - Typically, complex graph analysis tasks in combination with general dataflow tasks
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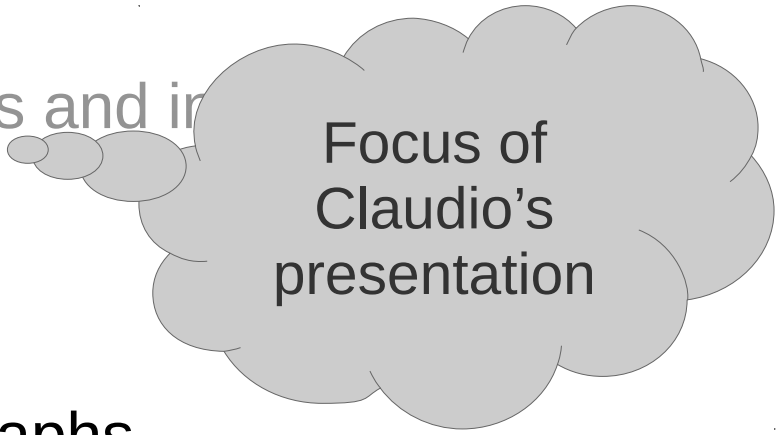
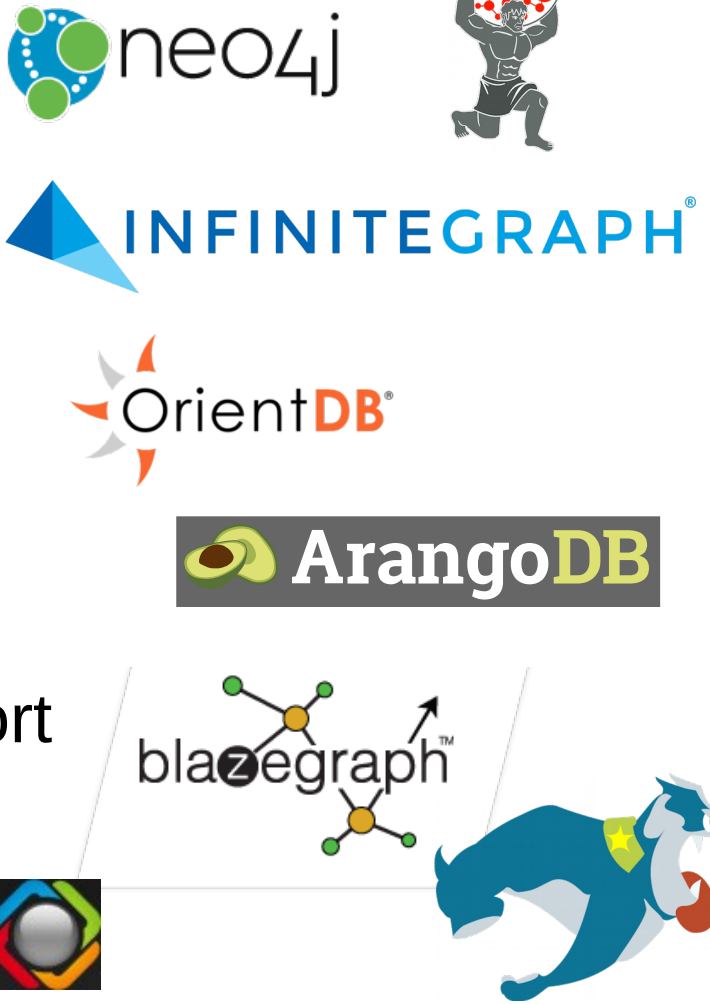
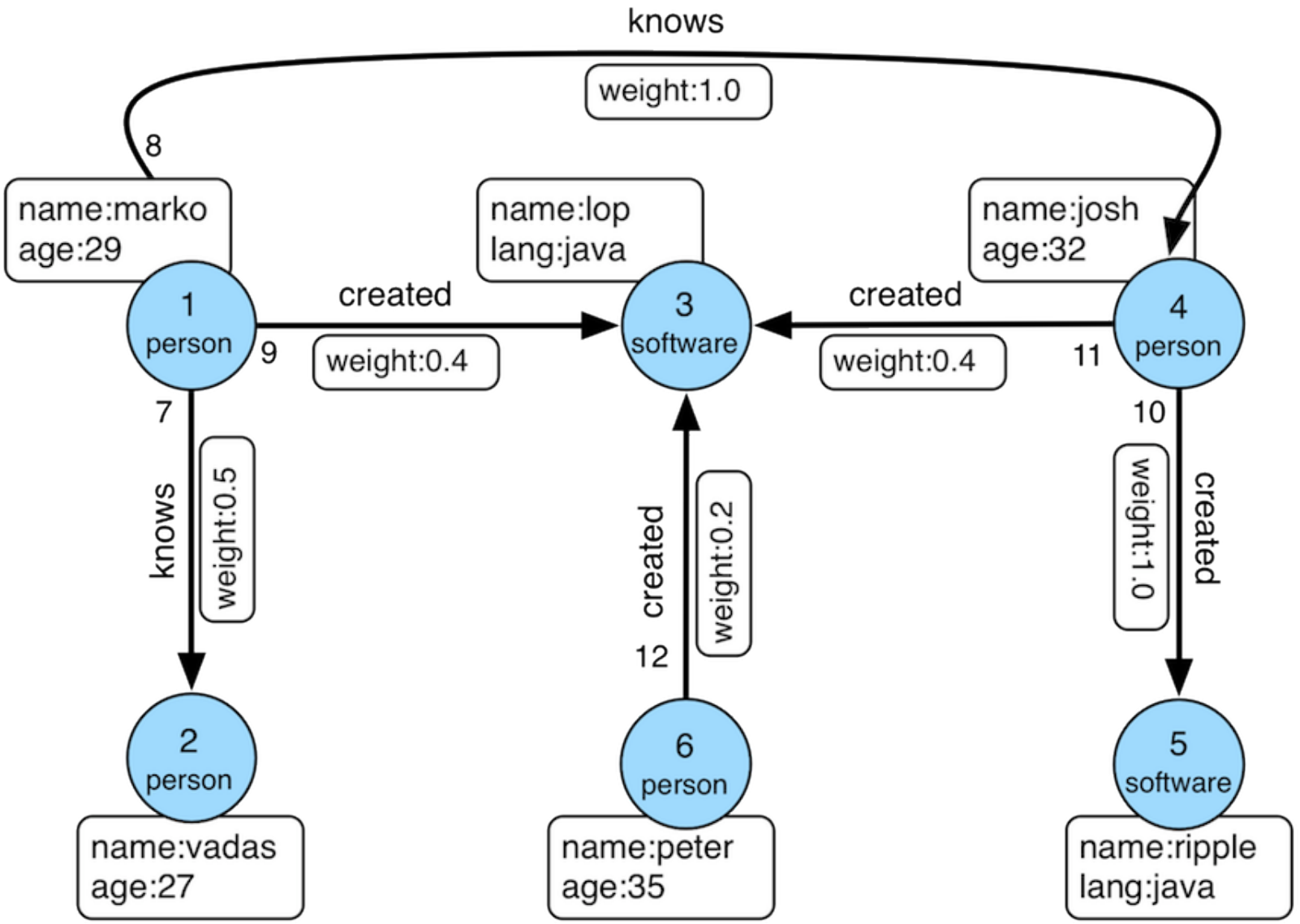


Examples of Graph DB Systems

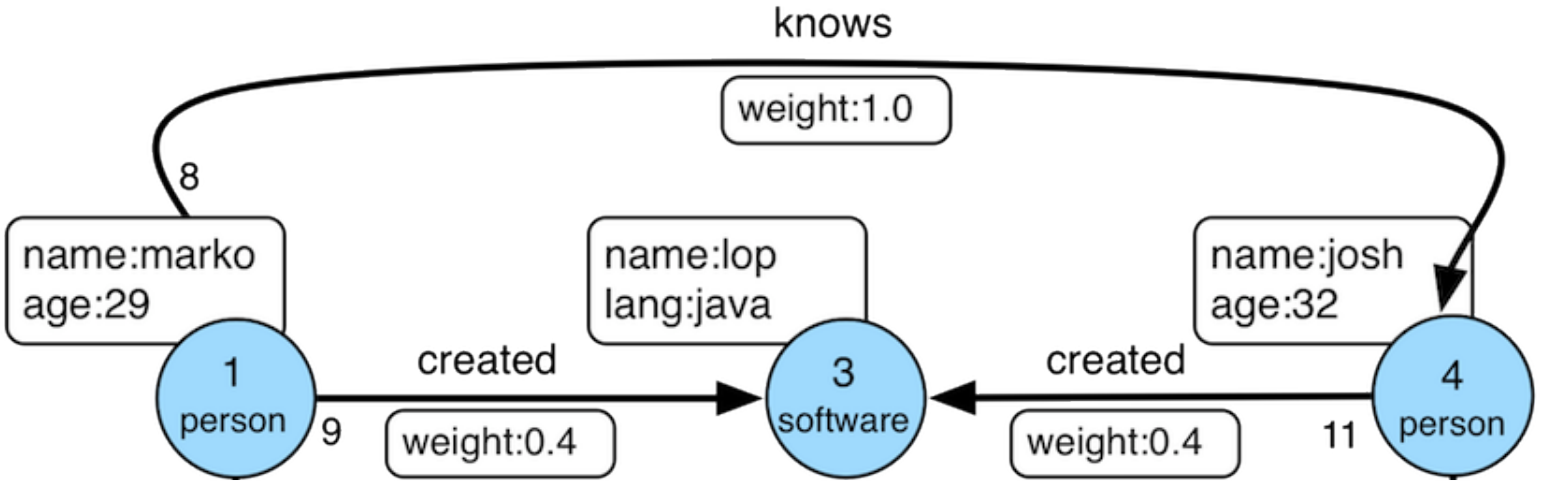
- System that focus on graph databases
  - Neo4j
  - Sparksee
  - Titan
  - InfiniteGraph
- Multi-model NoSQL stores with support for graphs:
  - OrientDB
  - ArangoDB
- Triple stores with TinkerPop support
  - Blazegraph
  - Stardog
  - IBM System G



Property Graph



Property Graph (cont'd)



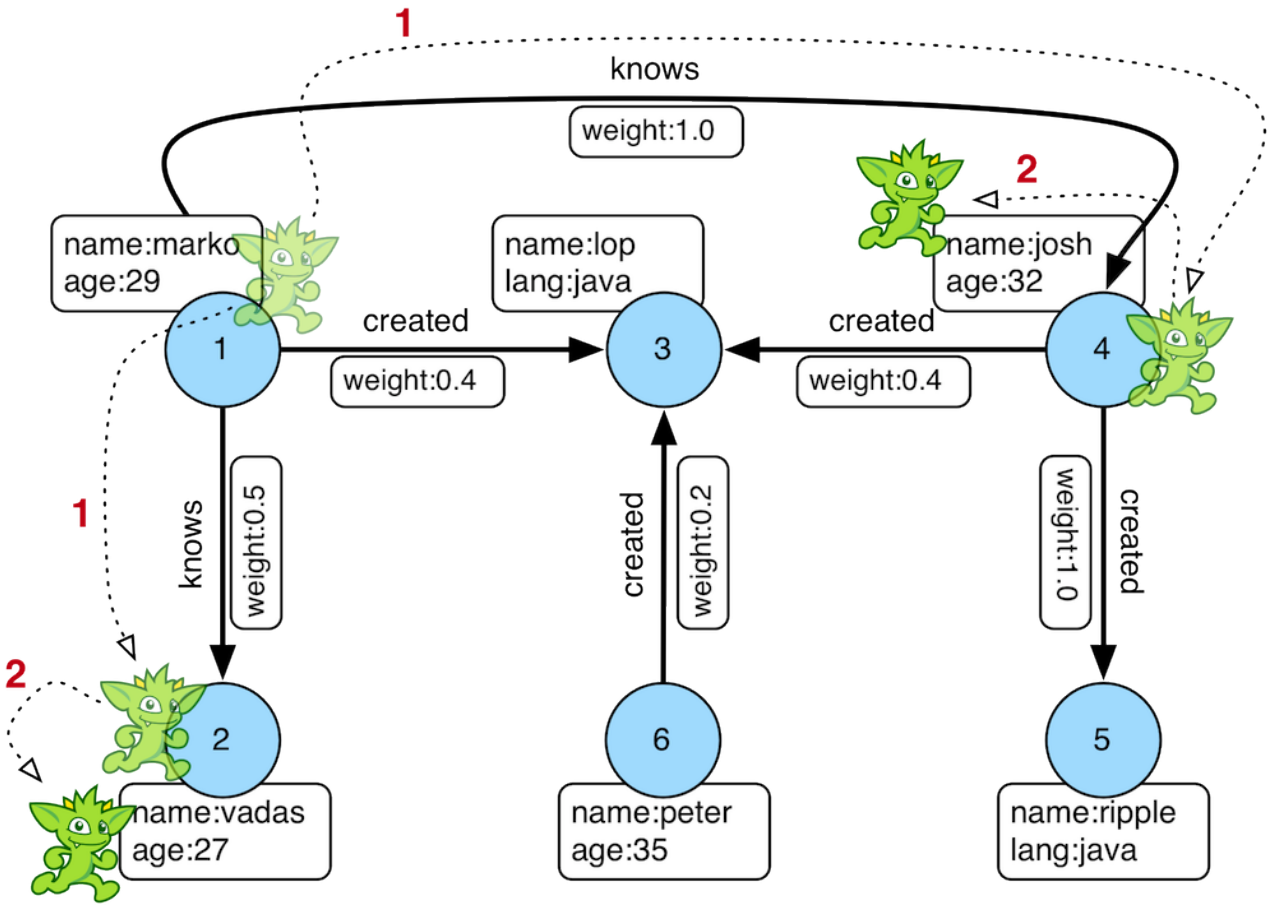
- Directed multigraph
  - multiple edges between the same pair of nodes
- Any node and any edge may have a label
- Additionally, any node and any edge may have an arbitrary set of key-value pairs (“properties”)

Gremlin Graph Traversal Language

- Part of the Apache TinkerPop framework
- Powerful domain-specific language (DSL) for which embeddings in various programming languages exist
- Expressions specify a concatenation of traversal steps

Gremlin Example

g.V().has('name','marko').out('knows').values('name')



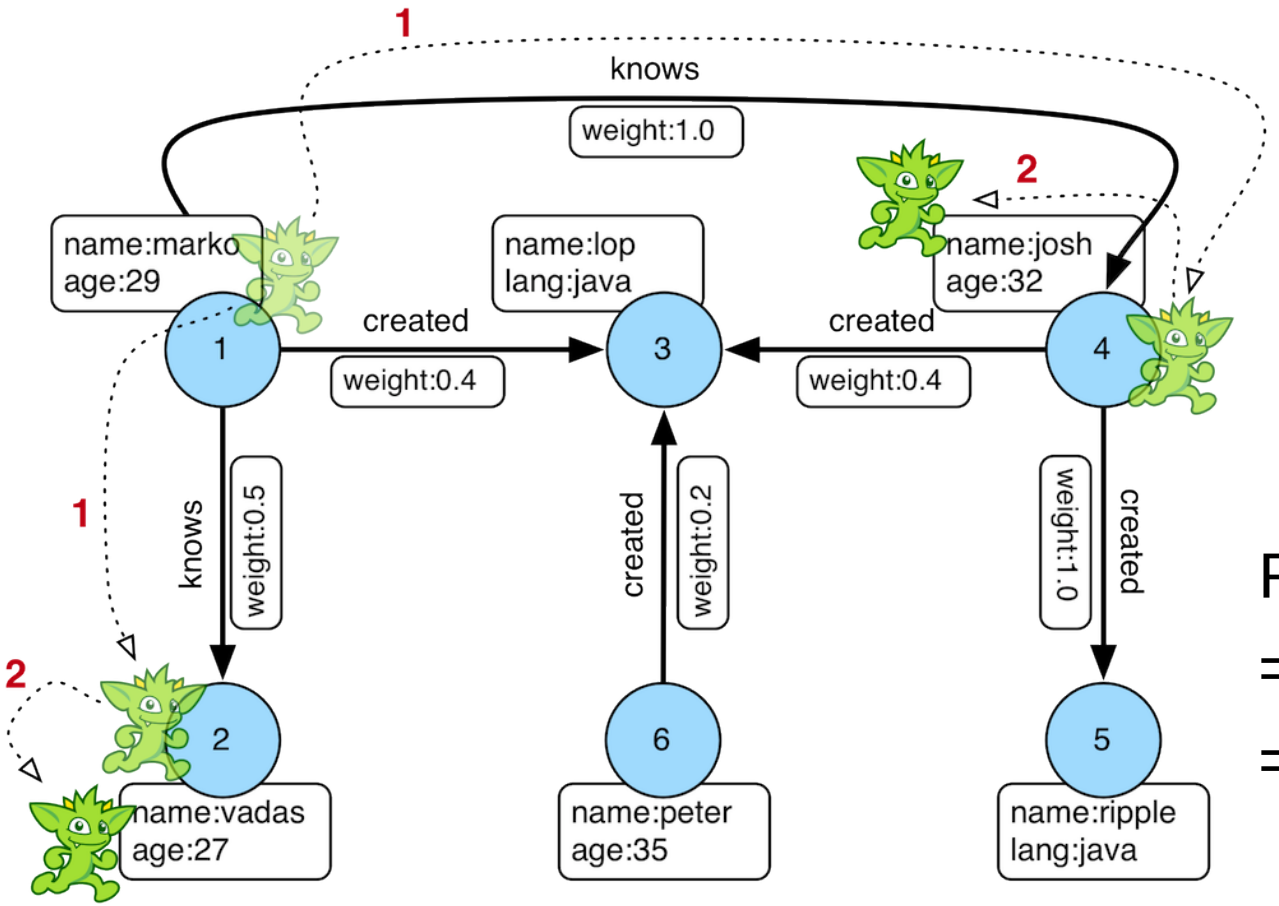
Result:

==>vadas

==>josh

Gremlin Example

g.V().has('name','marko').out('knows').values('name').path()



Result:

==>[v[1],v[2],vadas]

==>[v[1],v[4],josh]

Cypher

- Declarative graph database query language
- Proprietary (used by Neo4j)
- The OpenCypher project aims to deliver an open specification

- Example
  - Recall our initial Gremlin example:

```
g.V().has('name','marko').out('knows').values('name')
```

  - In Cypher we could express this query as follows:

```
MATCH ( {name:'marko'} )-[:knows]->( x )
RETURN x.name
```

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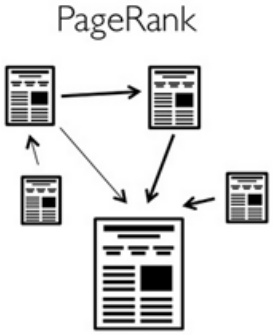
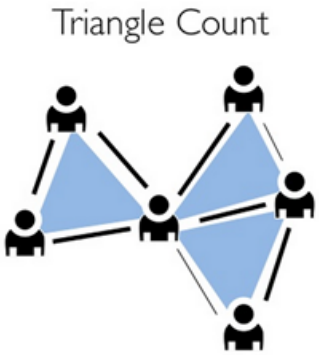
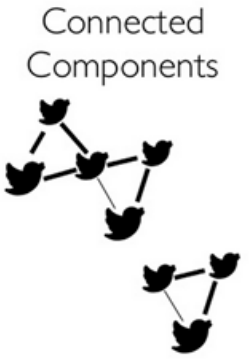
Complex Graph Analysis Tasks???

- Tasks that require an *iterative processing* of the *entire graph* or large portions thereof
- Examples:
  - Centrality analysis (e.g., PageRank)
  - Clustering, connected components
  - Graph coloring
  - Diameter finding
  - All-pairs shortest path
  - Graph pattern mining (e.g., frequent subgraphs, community detection)
  - Machine learning (e.g., belief propagation, Gaussian non-negative matrix factorization)





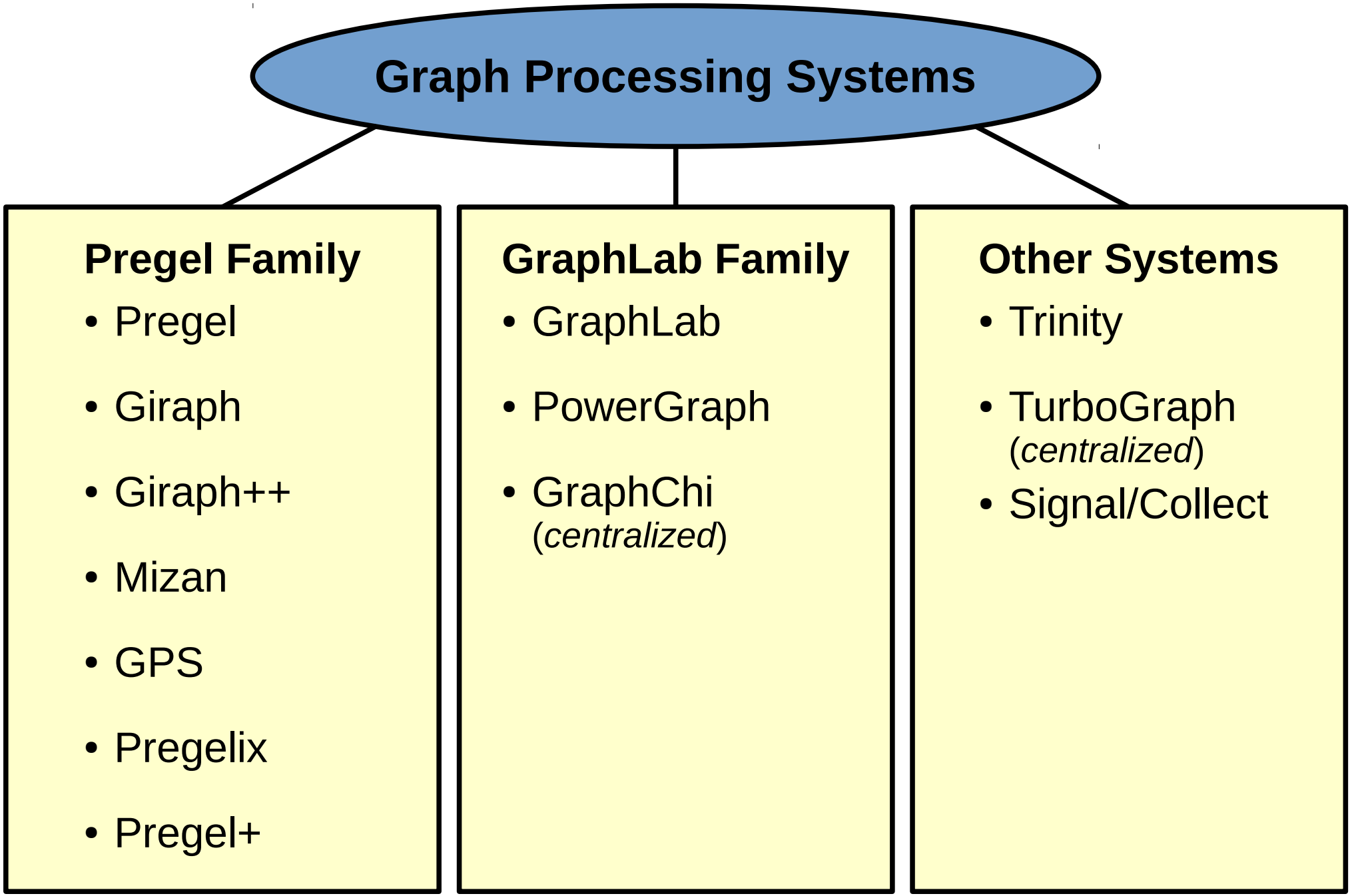


Generic Graphs

- Data model
  - Directed multigraphs
  - Arbitrary user-defined data structure can be used as value of a vertex or an edge (e.g., a Java object)
- Example (Flink Gelly API):

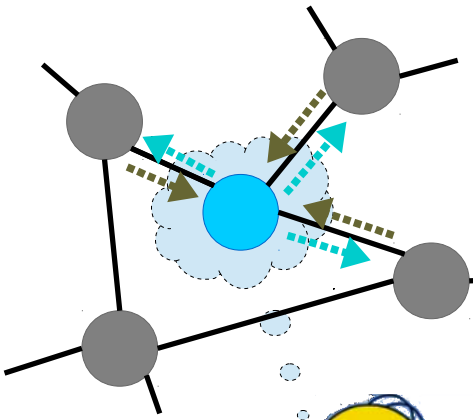
```
// create new vertexes with a Long ID and a String value
Vertex<Long, String> v1 = new Vertex<Long, String>(1L, "foo");
Vertex<Long, String> v2 = new Vertex<Long, String>(2L, "bar");

Edge<Long, Double> e = new Edge<Long, Double>(1L, 2L, 0.5);
```

- Advantage: give users maximum flexibility
- Drawback: systems cannot provide built-in operators related to vertex data or edge data


Graph Processing Systems
Pregel Family
• Pregel
• Giraph
• Giraph++
• Mizan
• GPS
• Pregelix
• Pregel+
GraphLab Family
• GraphLab
• PowerGraph
• GraphChi (centralized)
Other Systems
• Trinity
• TurboGraph (centralized)
• Signal/Collect

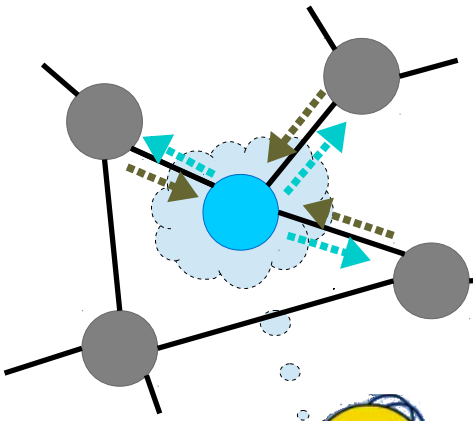
Vertex-Centric Abstraction

- Many such algorithms iteratively propagate data along the graph structure by transforming intermediate vertex and edge values
  - These transformations are defined in terms of functions on the values of adjacent vertexes and edges
  - Hence, such algorithms can be expressed by specifying a function that can be applied to any vertex separately
- “Think like a vertex”



Vertex-Centric Abstraction (cont'd)

- Vertex compute function consists of three steps:
  1. Read all incoming messages from neighbors
  2. Update the value of the vertex
  3. Send messages to neighbors
- Additionally, function may “vote to halt” if a local convergence criterion is met



- Overall execution can be parallelized
  - Terminates when all vertexes have halted and no messages in transit

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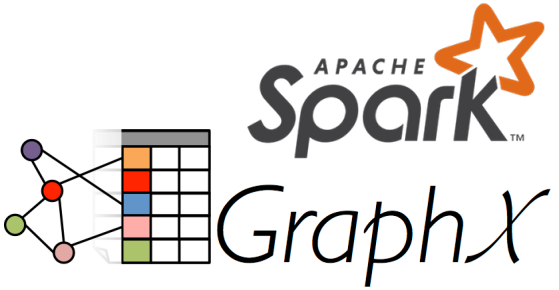

Acknowledgements:
- Some of the slides about graph processing systems are from a slideset of Sherif Sakr. Thanks Sherif!

Image sources:
- Example Property Graph http://tinkerpop.apache.org/docs/current/tutorials/getting-started/
- BSP Illustration https://en.wikipedia.org/wiki/Bulk_synchronous_parallel
- Smiley https://commons.wikimedia.org/wiki/File:Face-smile.svg
- Frowny https://commons.wikimedia.org/wiki/File:Face-sad.svg
- Powerlaw charts http://www9.org/w9cdrom/160/160.html

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