جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology

IBM

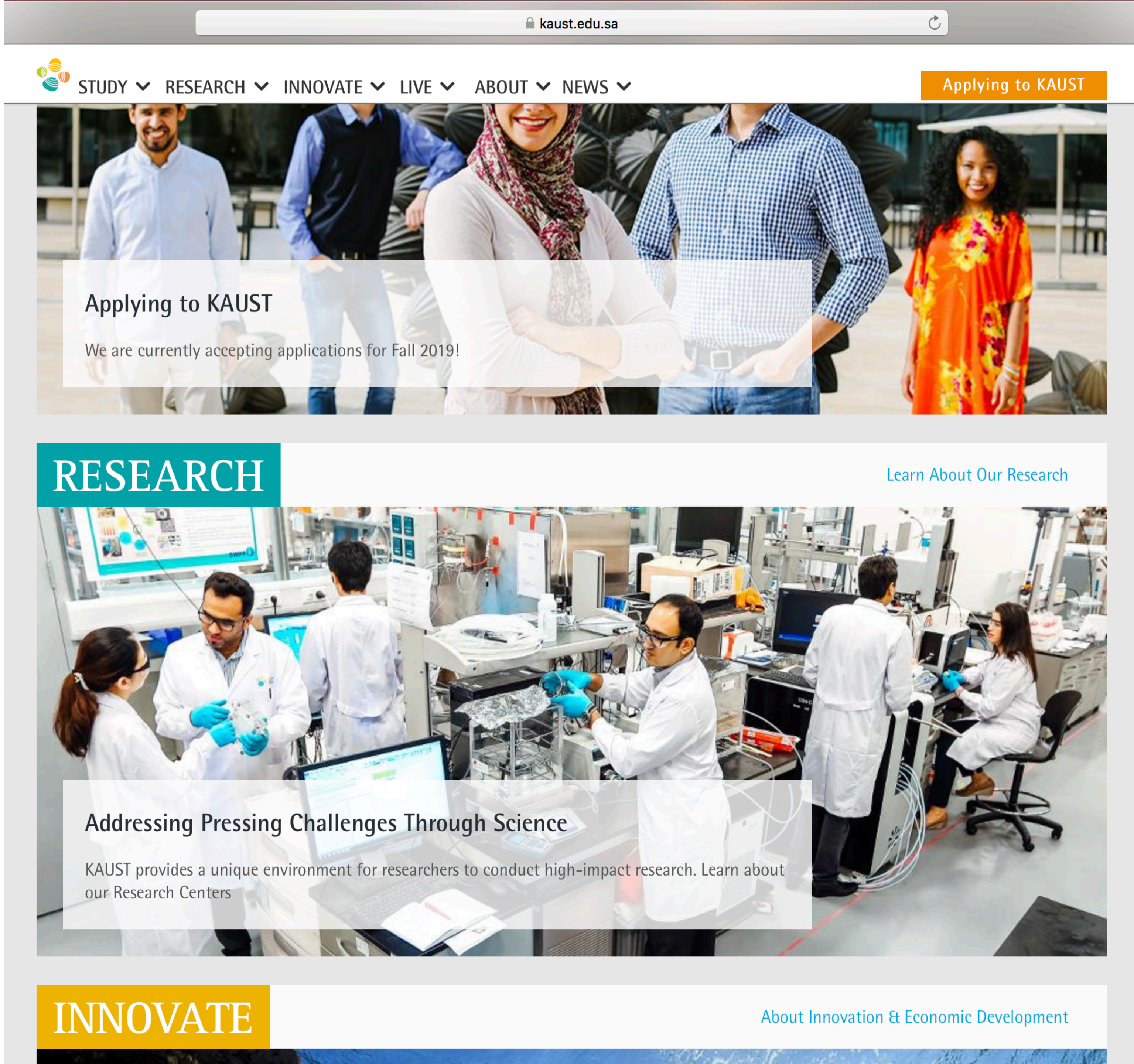
How to build scalable **SPARQL** engines for Big **RDF** data

Panos Kalnis

King Abdullah University of Science and Technology (KAUST)

KAUST.edu.SA


3 hours
Saudi Arabia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Info: **Panos.Kalnis**@kaust.edu.sa

- Paid internships for undergrads
- Scholarships for Master’s & PhDs
- PostDoc
- Faculty positions

- Big Data, Analytics
- Cloud, Parallel, Distributed, HPC
- Machine Learning, **AI**
- Visual Computing
- Bio-Informatics
- Cyber-Security

Systems for Big Data & Machine Learning

Greece Italy USA France S. Arabia Egypt Taiwan Belgium Mexico India China

Systems for Big Data & Machine Learning

Materials Science
Hang

Software Engineering
Chen-Yu Kostas

Distributed Systems
Marco

Big Data
Panos

Algorithms
Atal

Mathematical Optimization
Aritra Elhoucine

Networks
Ahmed

Paid **Remote** Internships

- Final year undergraduates, or Master's
- 3 – 6 months, start anytime
- US$ **1000 / month**
- Meetings via Zoom
- Can be combined with final year project
  - **Διπλωματική / Πτυχιακή εργασία**

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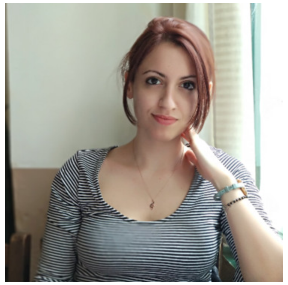
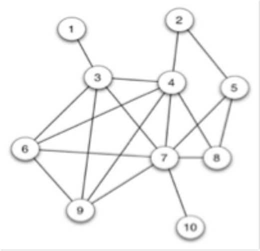
Klearchos Kosmanos
MSc – Aristotle Univ. Thessaloniki



Kelly Kostopoulou
PhD – Columbia Univ. New York

Stamatis Anoustis
PhD - KAUST

Graphs are Everywhere…



PubChem

UniProt

…But processing is expensive

- E.g., subgraph isomorphism, NP

"Big": CPU vs. Big size

RDF Data

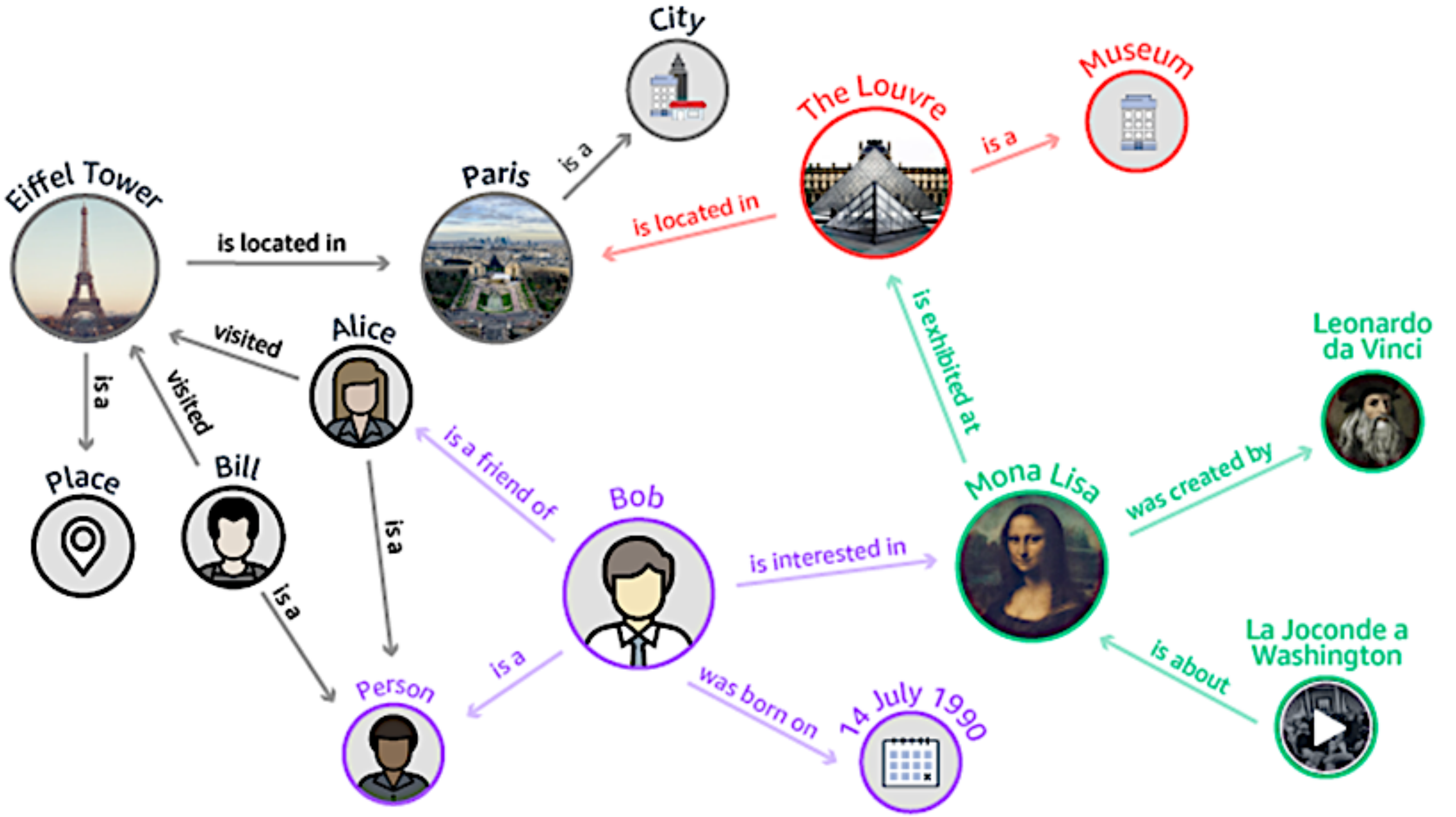


Image from: https://aws.amazon.com/blogs/apn/exploring-knowledge-graphs-on-amazon-neptune-using-metaphactory/

BIO2RDF

11 Billion

DBpedia

23 Billion

PubChem

130 Billion

RDF and SPARQL

RDF: Set of triples:

< **S**ubject	**P**redicate	**O**bject >
James	gradFrom	MIT
EE	subOrgOf	MIT
James	worksFor	CS
CS	subOrgOf	MIT
Lisa	advisor	Bill
John	advisor	Bill
	…	
	…	

RDF and SPARQL

RDF: Set of triples: or Directed edge-labelled graph

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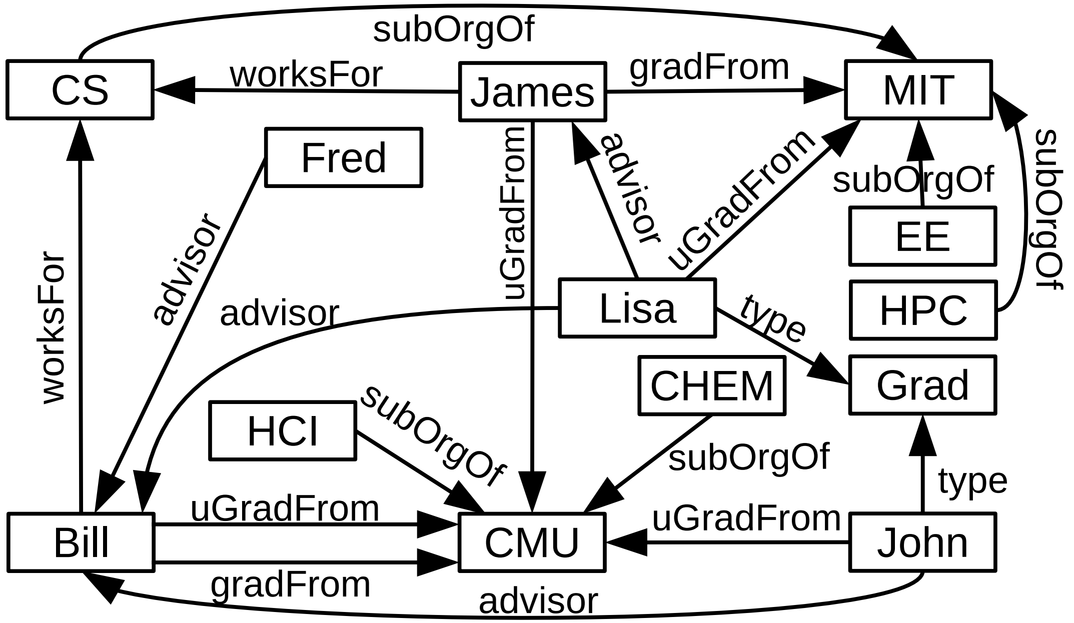
	…	



RDF and SPARQL

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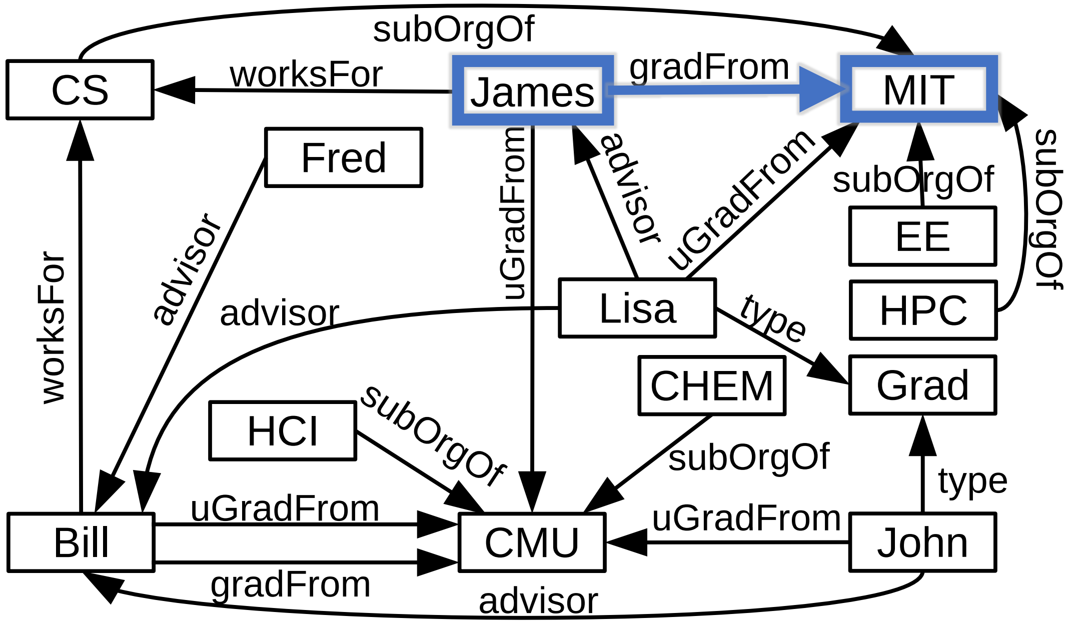

RDF and SPARQL

SPARQL: query language for RDF

```
SELECT ?prof ?stud WHERE {
   ?prof   worksFor   CS     .
   ?stud   advisor    ?prof  .
}
```

Return all professors who work for CS department, and their students

RDF and SPARQL

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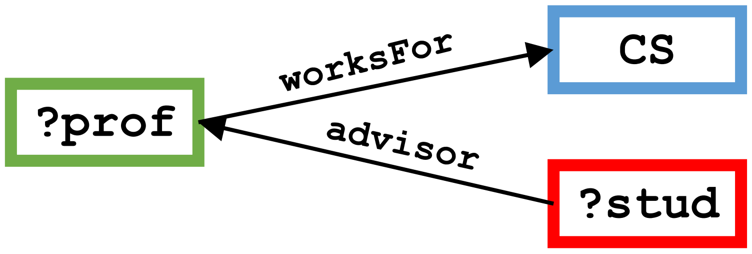

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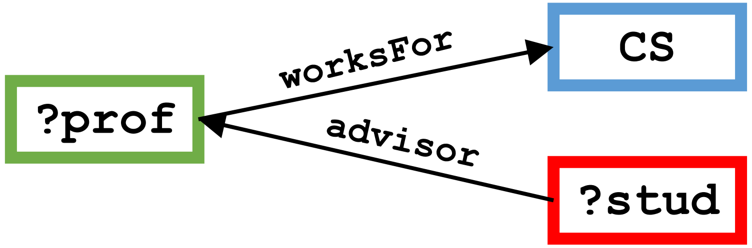
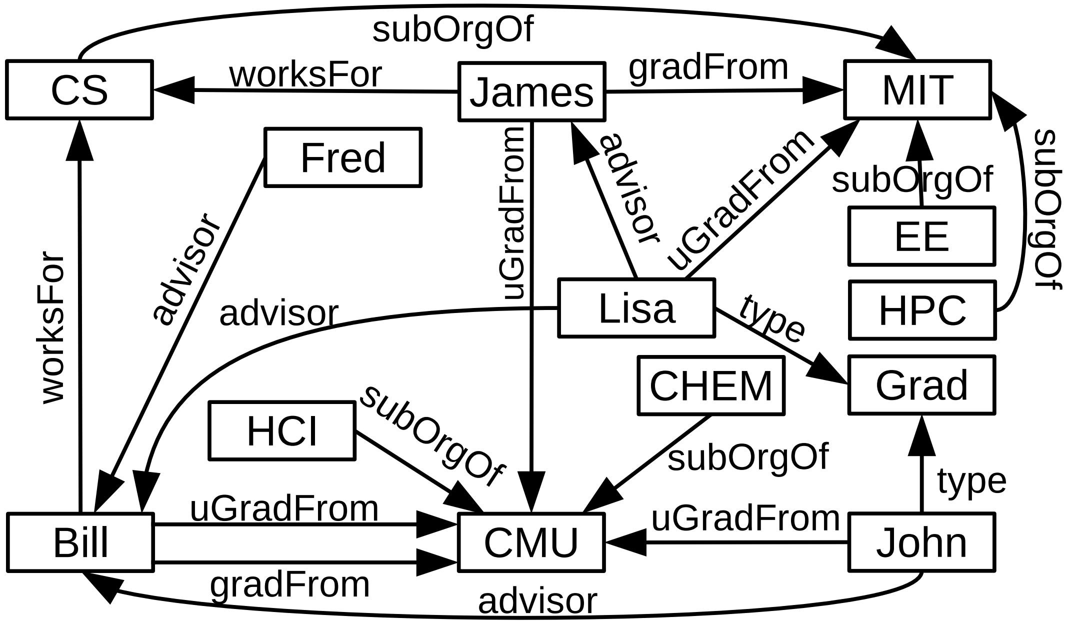


RDF: Directed edge-labelled graph



RDF and SPARQL

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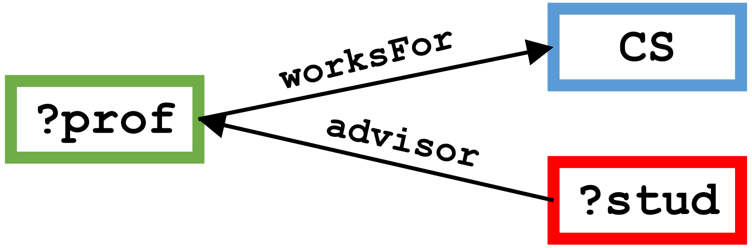
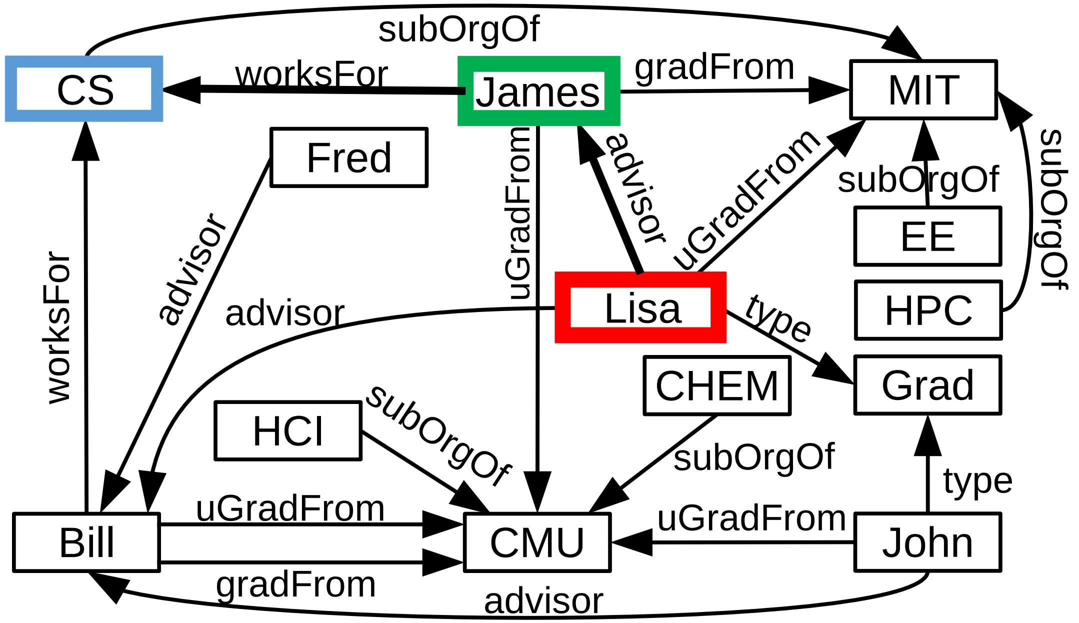


RDF: Directed edge-labelled graph



RDF and SPARQL

SPARQL: query language for RDF

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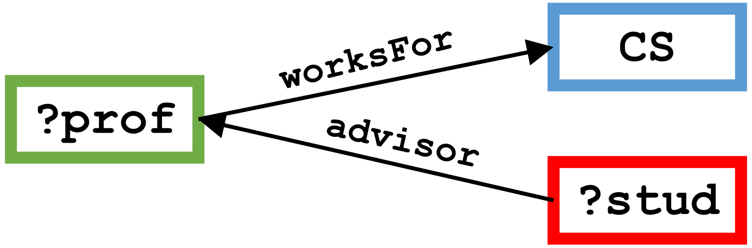
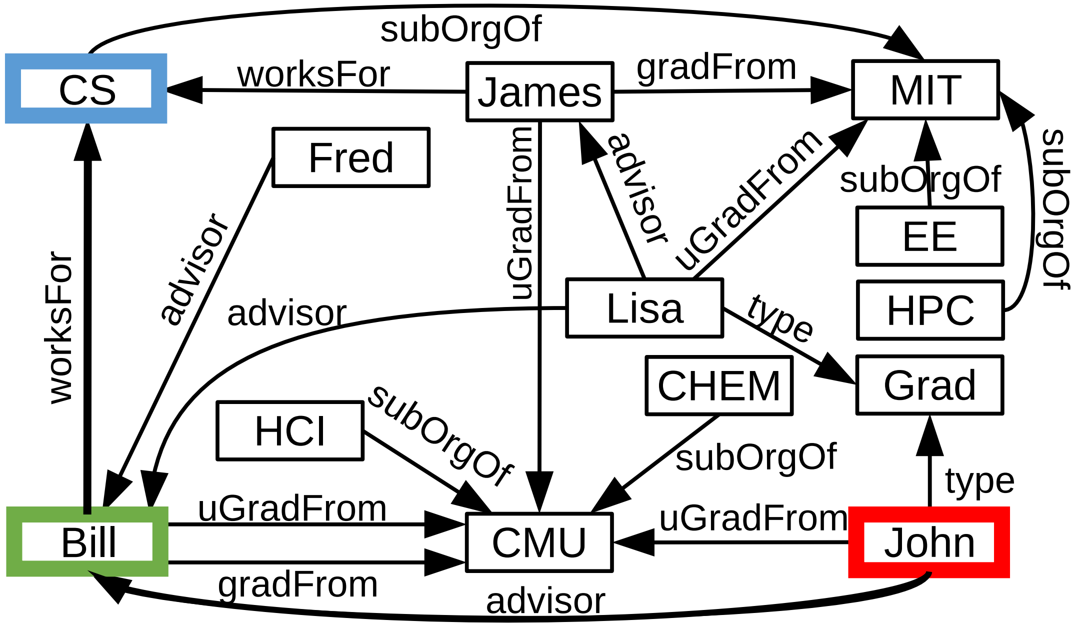
```

Return all professors who work for CS department, and their students



RDF: Directed edge-labelled graph

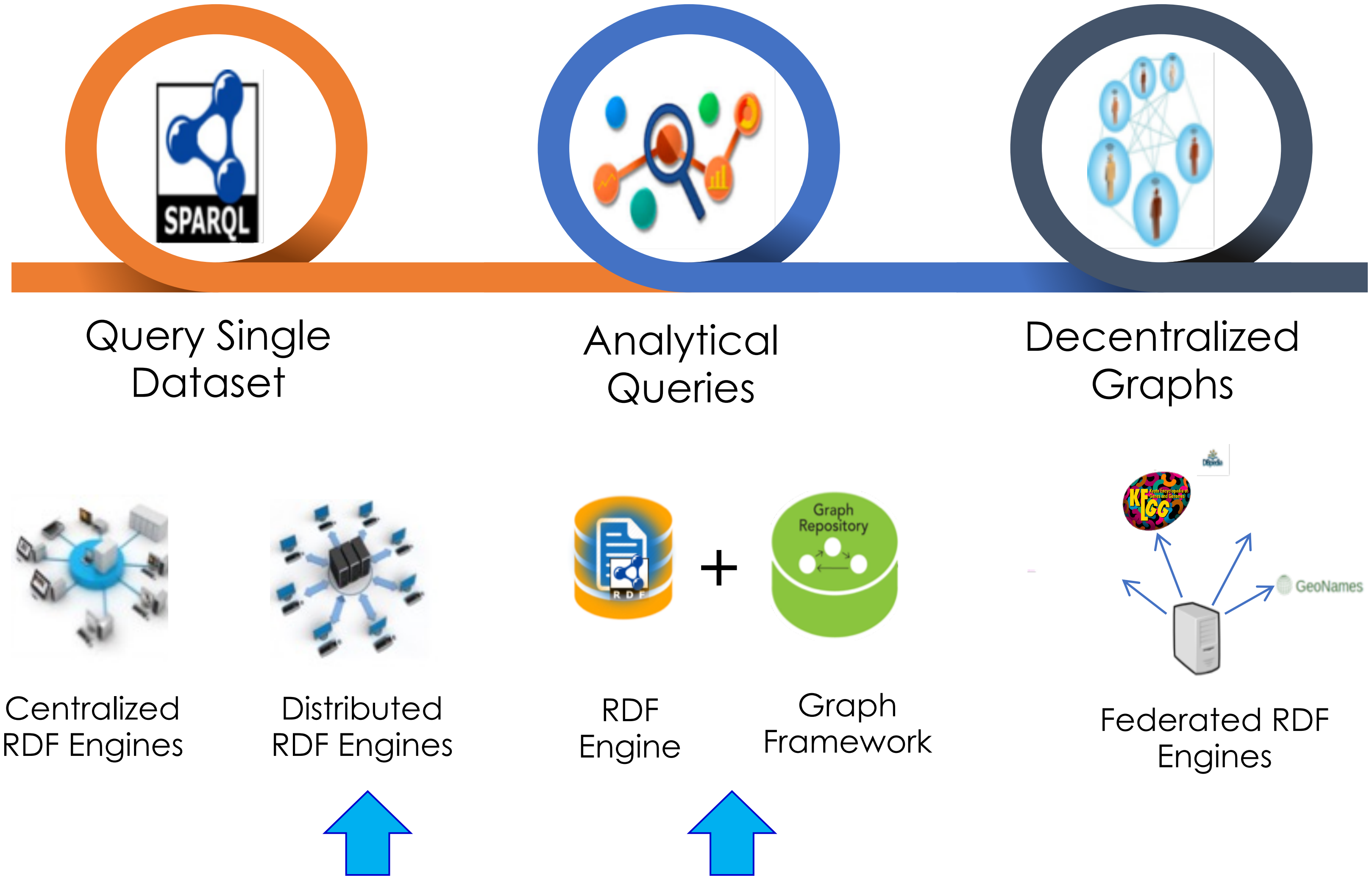


AdPart: Dynamic Partitioning

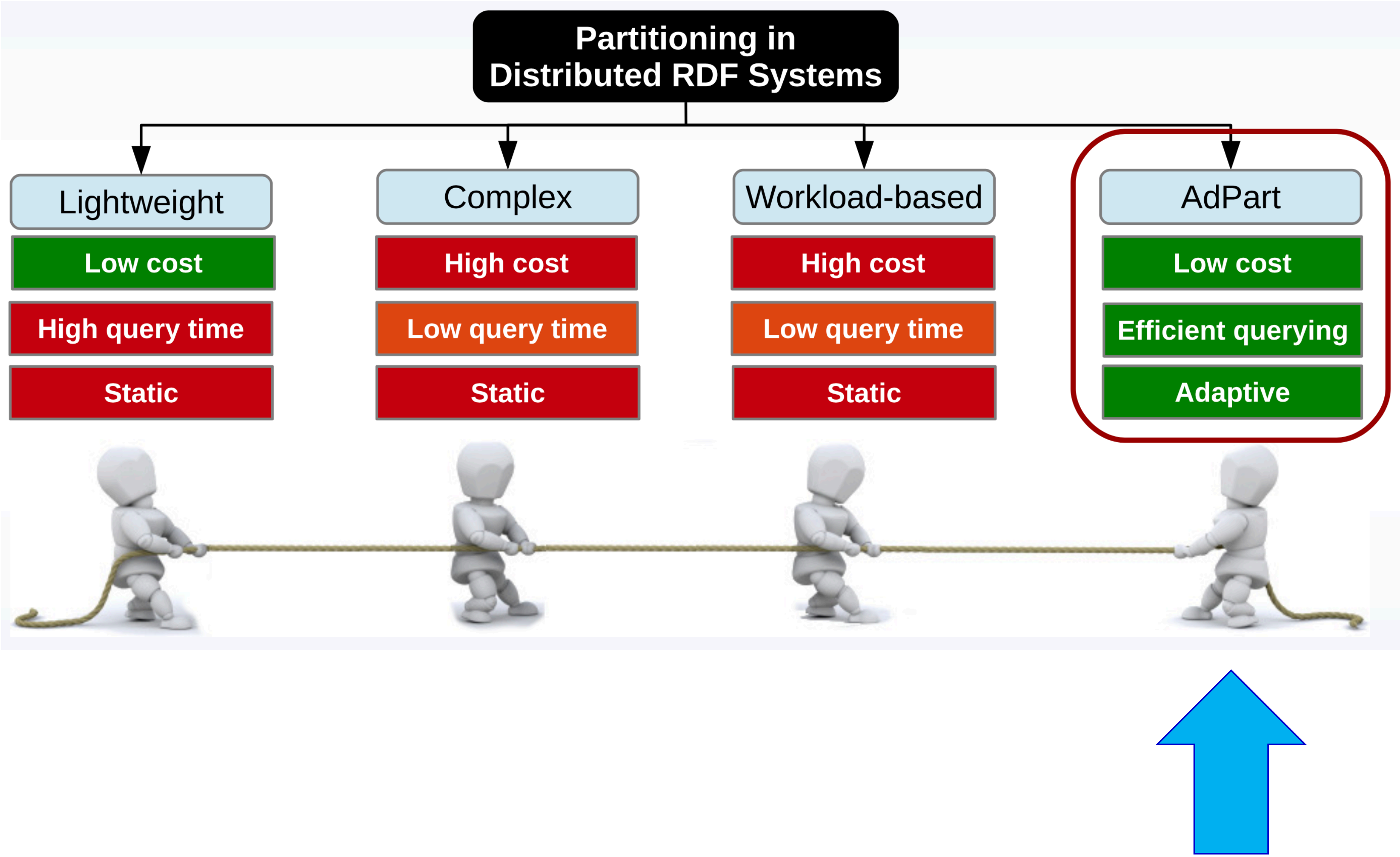
- *In: VLDB Journal, 2016*

- Evaluating SPARQL queries on massive RDF datasets, **PVLDB**, 2015
- Survey & experimental comparison of distributed SPARQL engines for very large RDF data, **PVLDB**, 2017
- Query optimizations over decentralized RDF graphs, **ICDE**, 2017
- Lusail: a system for querying linked data at scale, **PVDLB**, 2017
- A demonstration of Lusail: Querying linked data at scale, **(demo) SIGMOD**, 2017

Classification of RDF systems

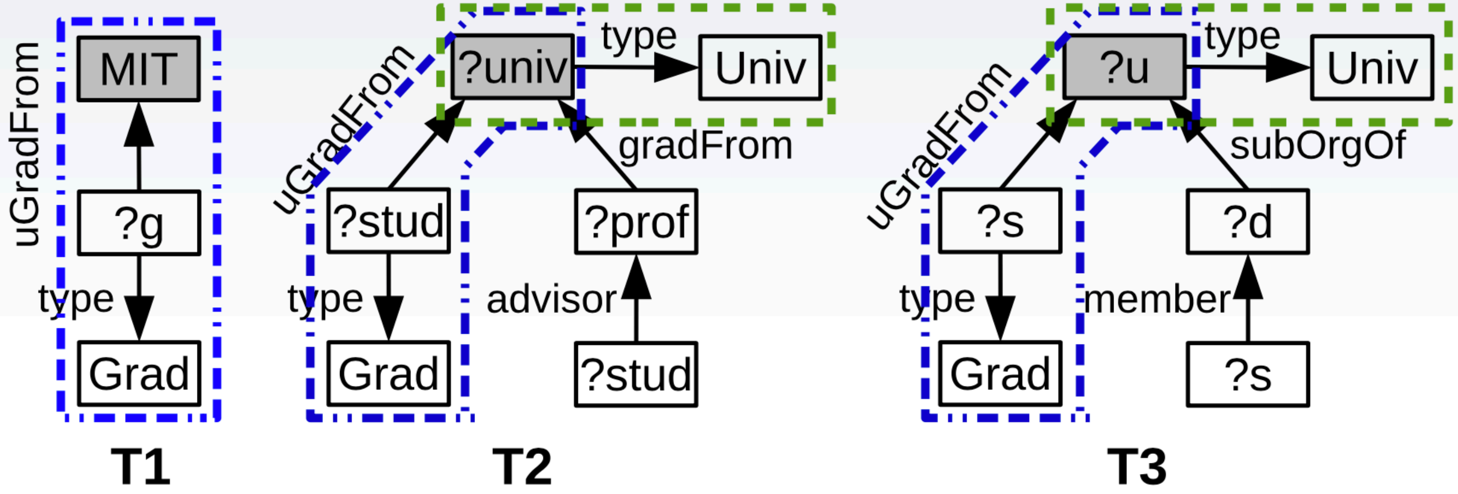


Partitioning for Parallel Processing

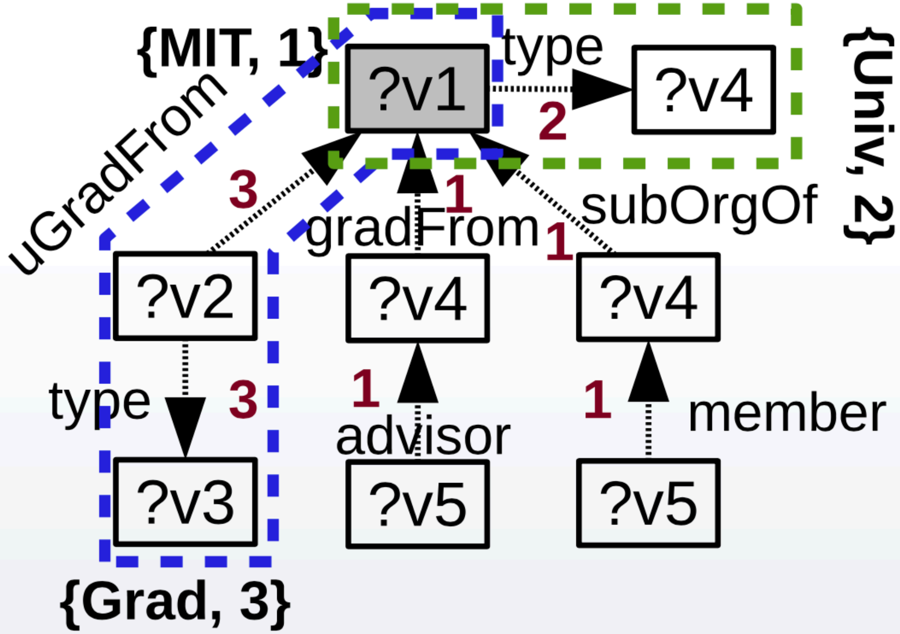


AdPart – Dynamic Partitioning

Queries decomposition



Updated heatmap



AdPart is at least 10x faster

Table 6: Runtime for LUBM-10240 queries (ms). SM: Single Machine, MR: MapReduce, and SS: Specialized systems. S2X failed to execute all queries; gStore and gStoreD could not preprocess the data within 24 hours.

	LUBM-10240	Complex Queries				Simple Queries			Geo-Mean	Query/h
		L1	L2	L3	L7	L4	L5	L6		
SM	RDF-3X	1,812,250	101,750	1,898,500	98,250	38	20	526	10,466	6
MR	SHARD	413,720	187,310	N/A	469,340	358,200	116,620	209,800	261,362	N/A
	H2RDF+	285,430	71,720	264,780	180,320	24,120	4,760	22,910	59,275	30
	CliqueSquare	125,020	71,010	80,010	224,040	90,010	24,000	37,010	74,488	39
	S2RDF-VP	217,537	28,917	145,761	29,965	46,770	5,233	11,308	35,845	52
	S2RDF-ExtVP	46,552	35,802	21,533	47,343	9,222	2,718	4,555	15,275	150
SS	AdPart-NA	2,743	120	320	3,203	1	1	40	75	3,920
	TriAD	6,023	1,519	2,387	17,586	6	4	114	369	912
	TriAD-SG	5,392	1,774	4,636	21,567	9	5	10	333	755
	Urika-GD	5,835	2,396	1,871	6,951	1,442	720	1,588	2,259	1,211
	H-RDF-3X	7,004	2,640	7,957	7,175	1,635	1,586	1,965	3,412	841
	H-RDF-3X (in-memory)	6,841	2,597	7,948	7,551	1,596	1,594	1,926	3,397	839
	SHAPE	25,319	4,387	25,360	15,026	1,603	1,574	1,567	5,575	337
	DREAM	13,031,410	98,263	2,358	4,700,381	18	14	10,755	12,110	1
	DREAM (cached)	1,843,376	98,263	<1	83,053	18	14	468	911	12

- Specialized for Graphs
- 1000x of CPU cores, TBs of RAM
- NUMA architecture
    - Global memory address space
    - Specialized network
    - Transparent to programmer

Spartex: RDF meets Graph Analytics

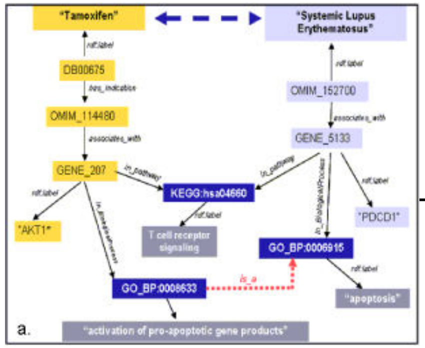
- *In: IEEE Trans. On Parallel and Distributed Systems, 2017*

RDF Analytics: Drug Repositioning

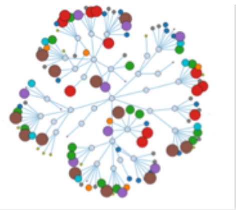
Disease SPARQL Query

RDF data

10g ORACLE DATABASE



Graph Engine



Betweenness, Closeness

Degree Centrality

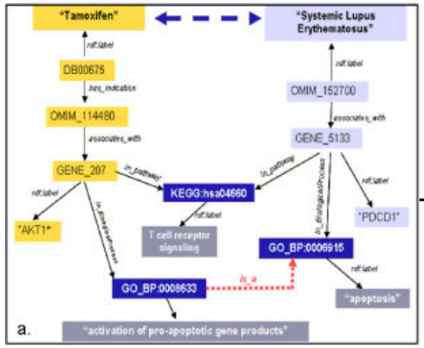
Ranked Drug Candidates

RDF Analytics: Drug Repositioning

RDF data

Disease SPARQL Query

10g ORACLE DATABASE



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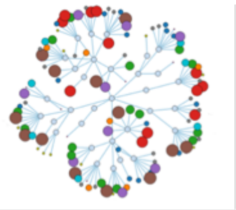

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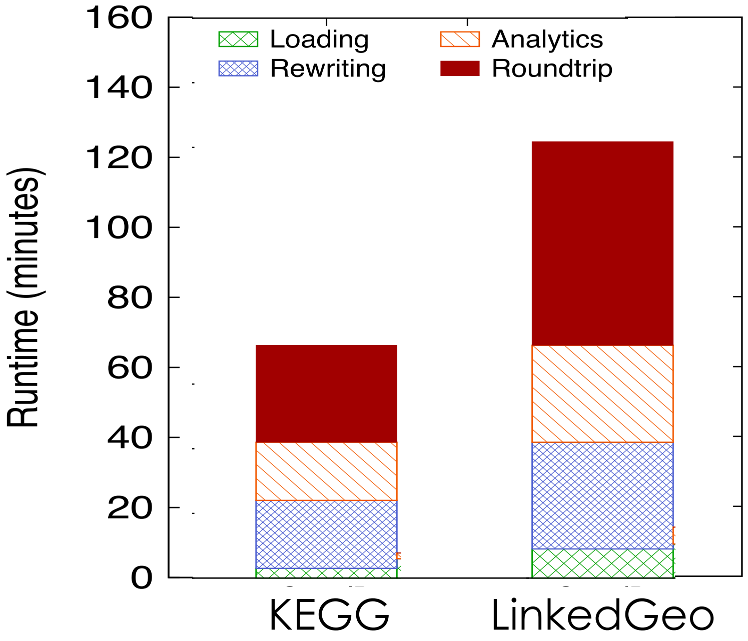
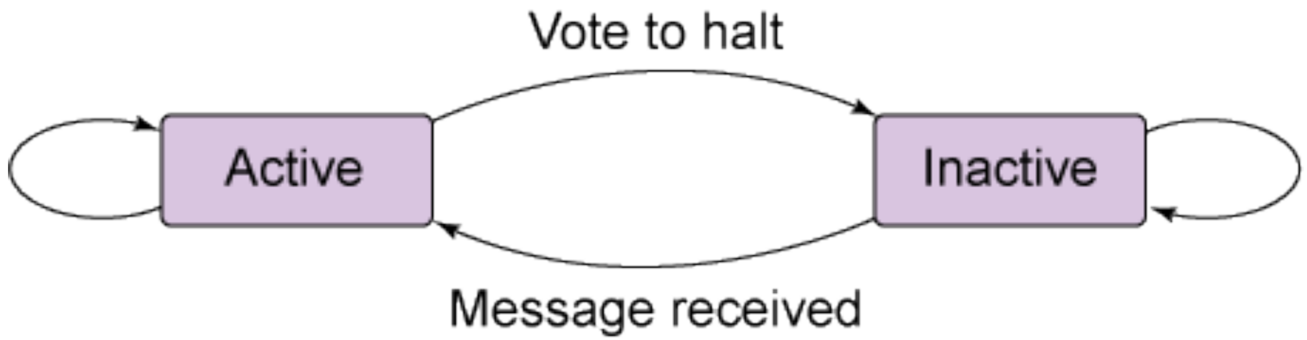
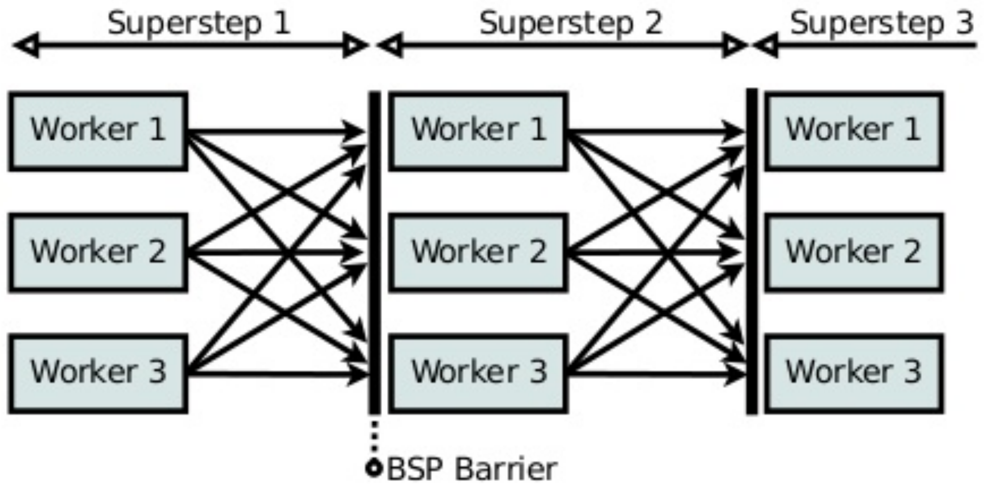
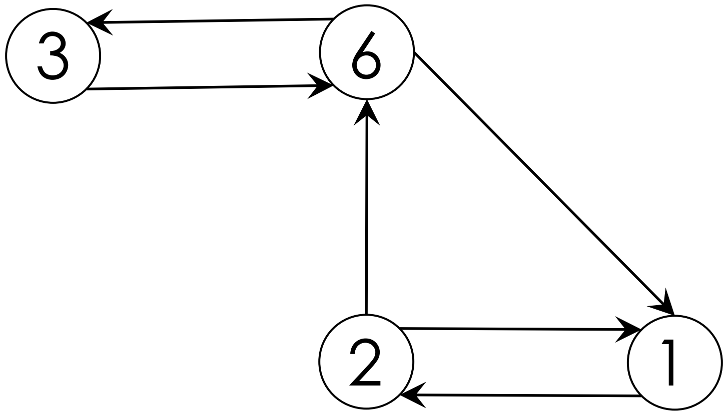


Vertex-Centric Framework: Pregel, …



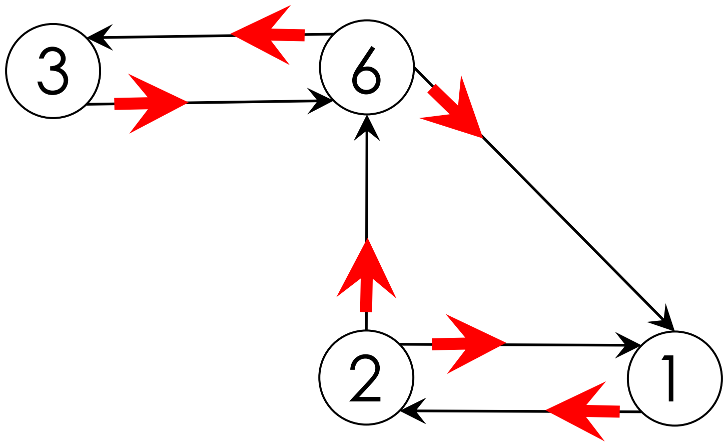


Pregel Example: **MAX**



Example from [Malewich et al., SIGMOD, 2010]

Pregel Example: **MAX**



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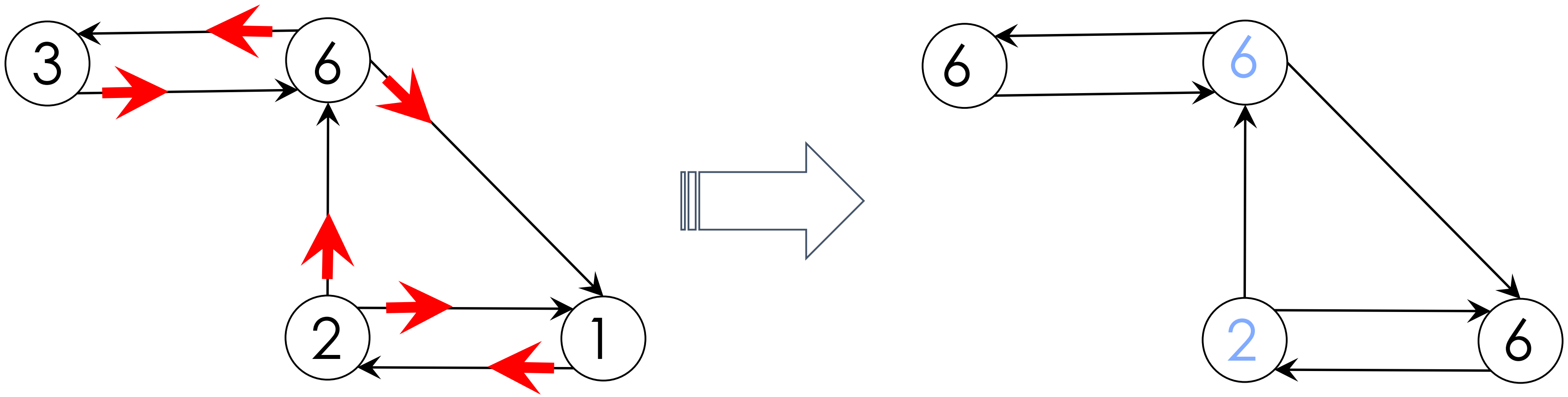

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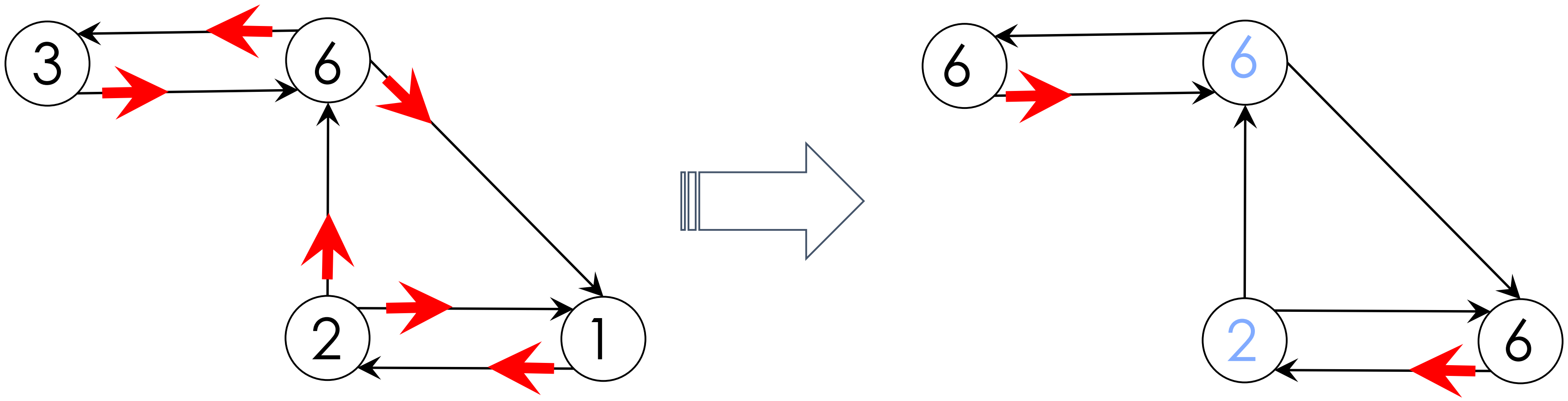

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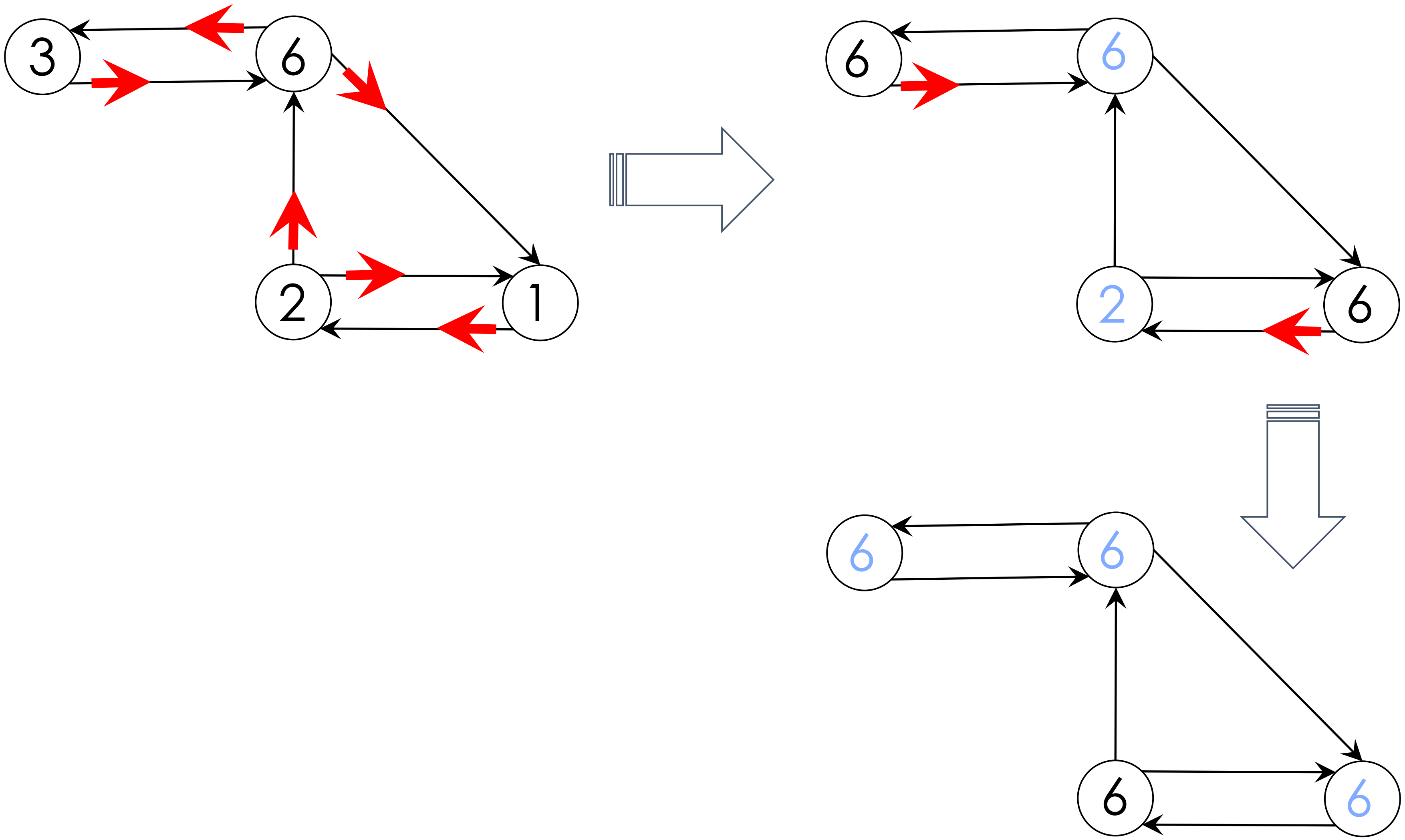

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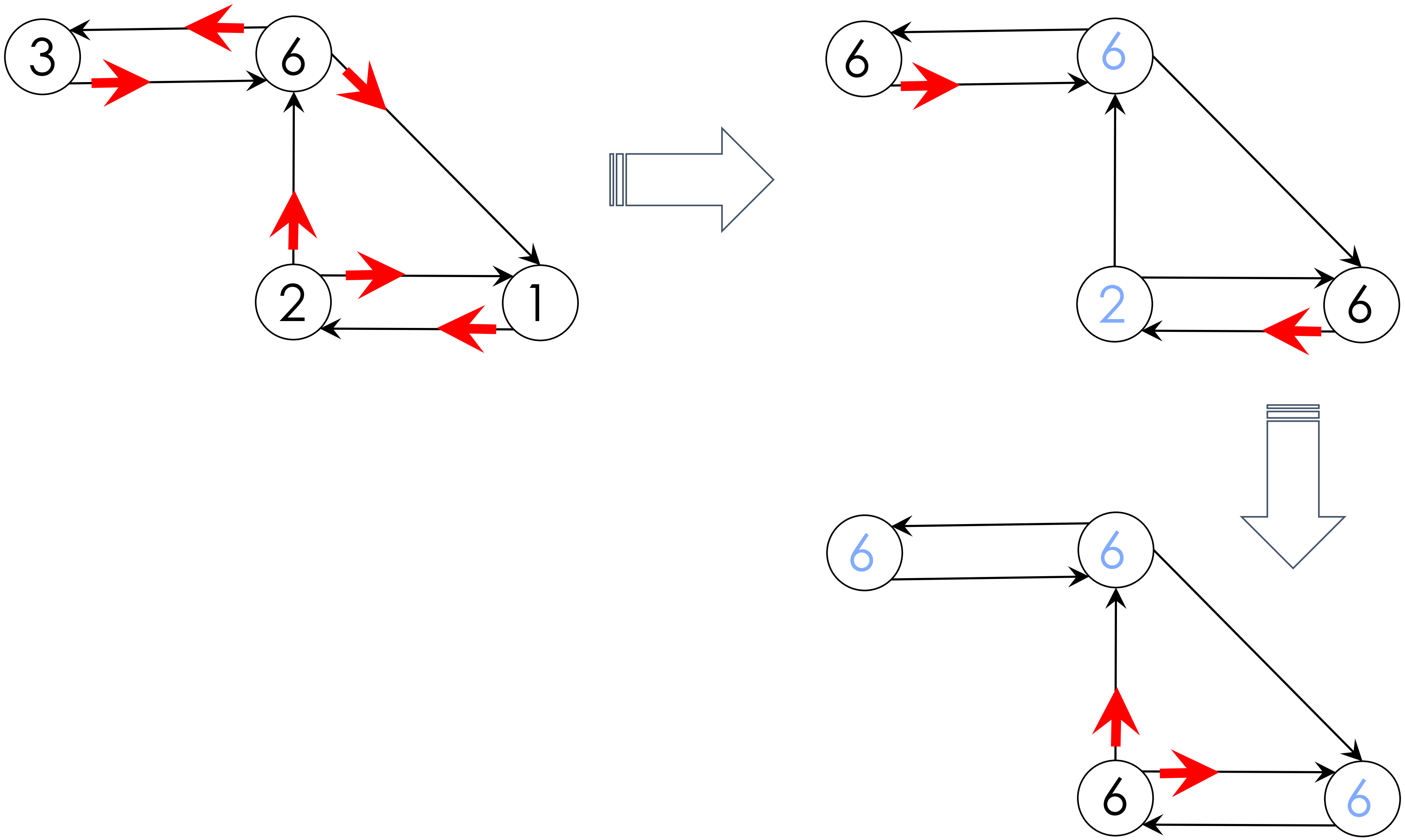

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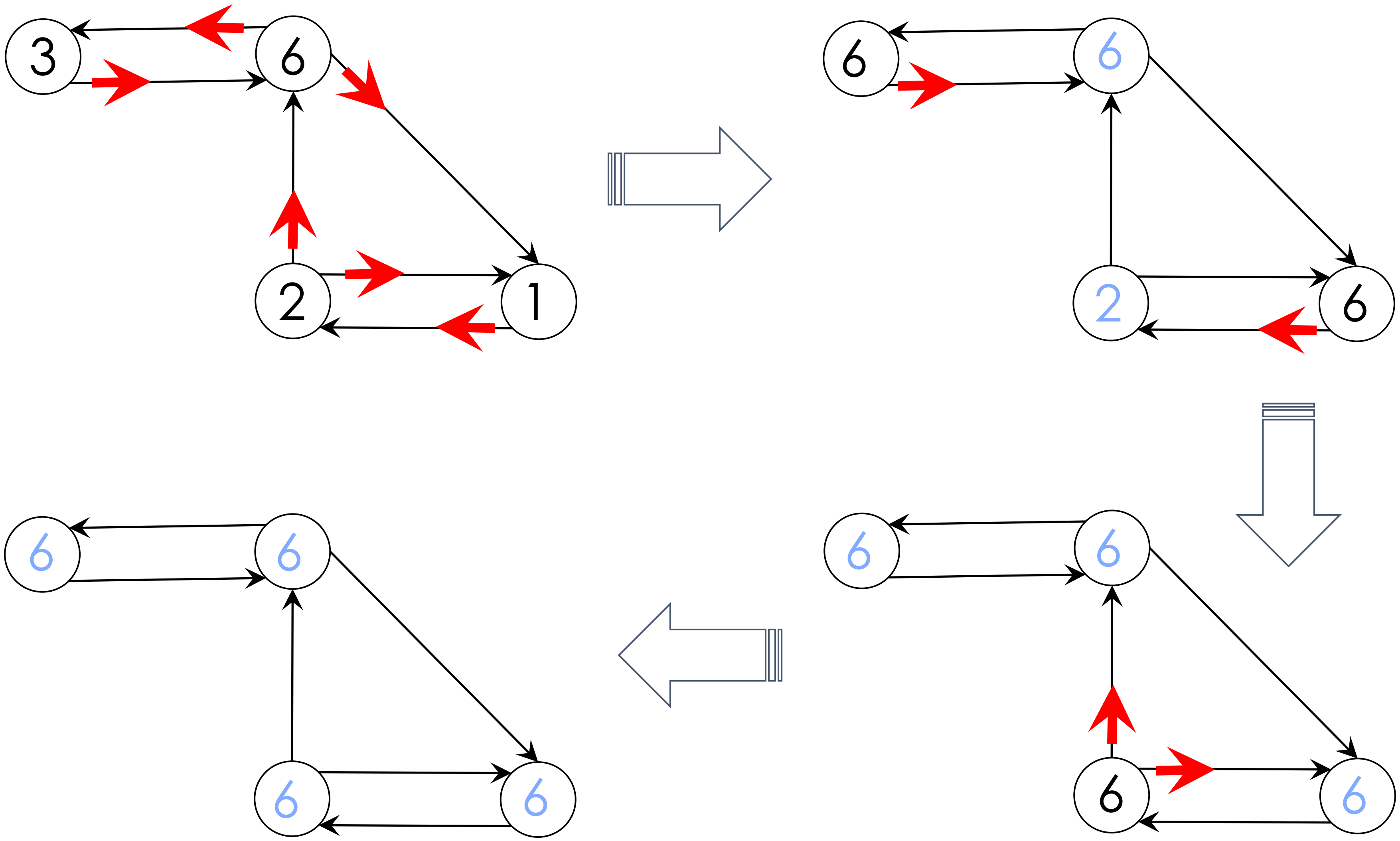
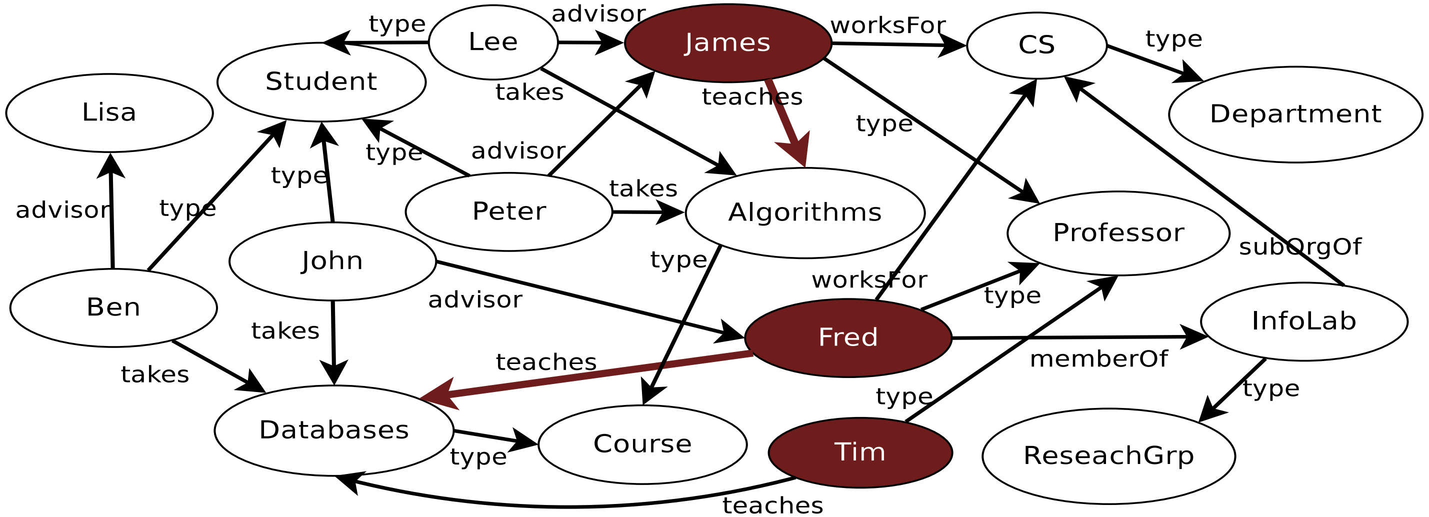
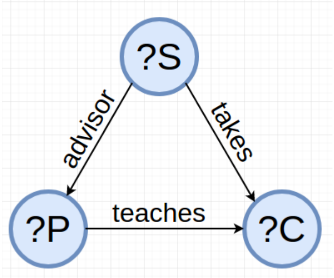
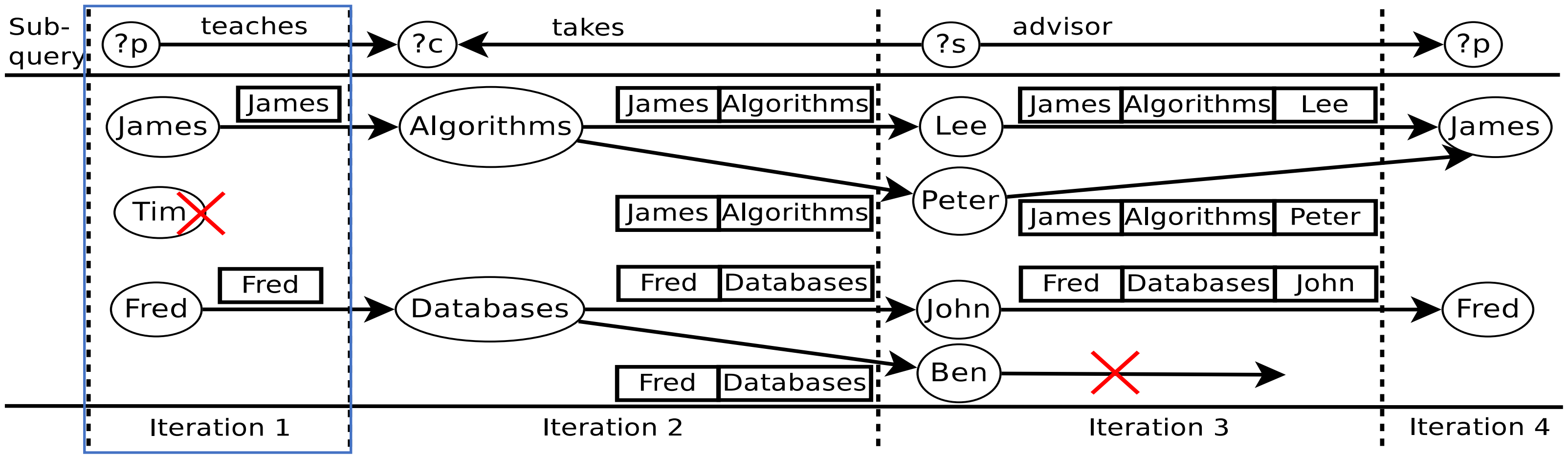


Example from [Malewich et al., SIGMOD, 2010]

SPARTEX: RDF @ Vertex-centric
[Kalnis et al., IEEE-TPDS, 2017]

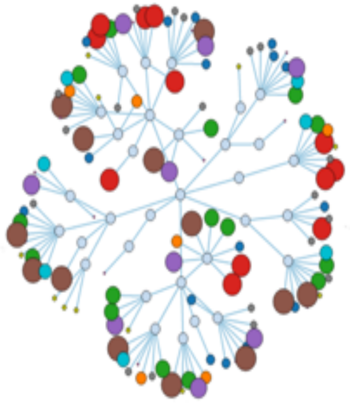






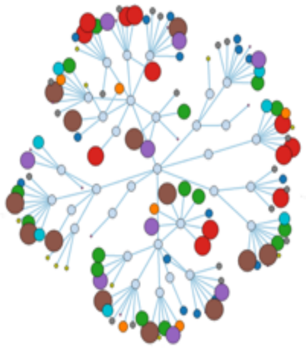
SPARTEX syntax (1)

```
PREFIX sptx: <http://www.spartex.com/analytics/>
CALL com.sptx.algo.centrality() AS sptx:centrality
CALL com.sptx.algo.PageRank(max_iter) AS sptx:pRank
SELECT ?s WHERE {
    ?p   teaches ?c .
    ?s   takes  ?c .
    ?s   advisor ?p .
    ?p   sptx:pRank     ?rank .
    ?c   sptx:centrality ?cent .
    FILTER (?rank > val1 && ?cent > val2)
}
```

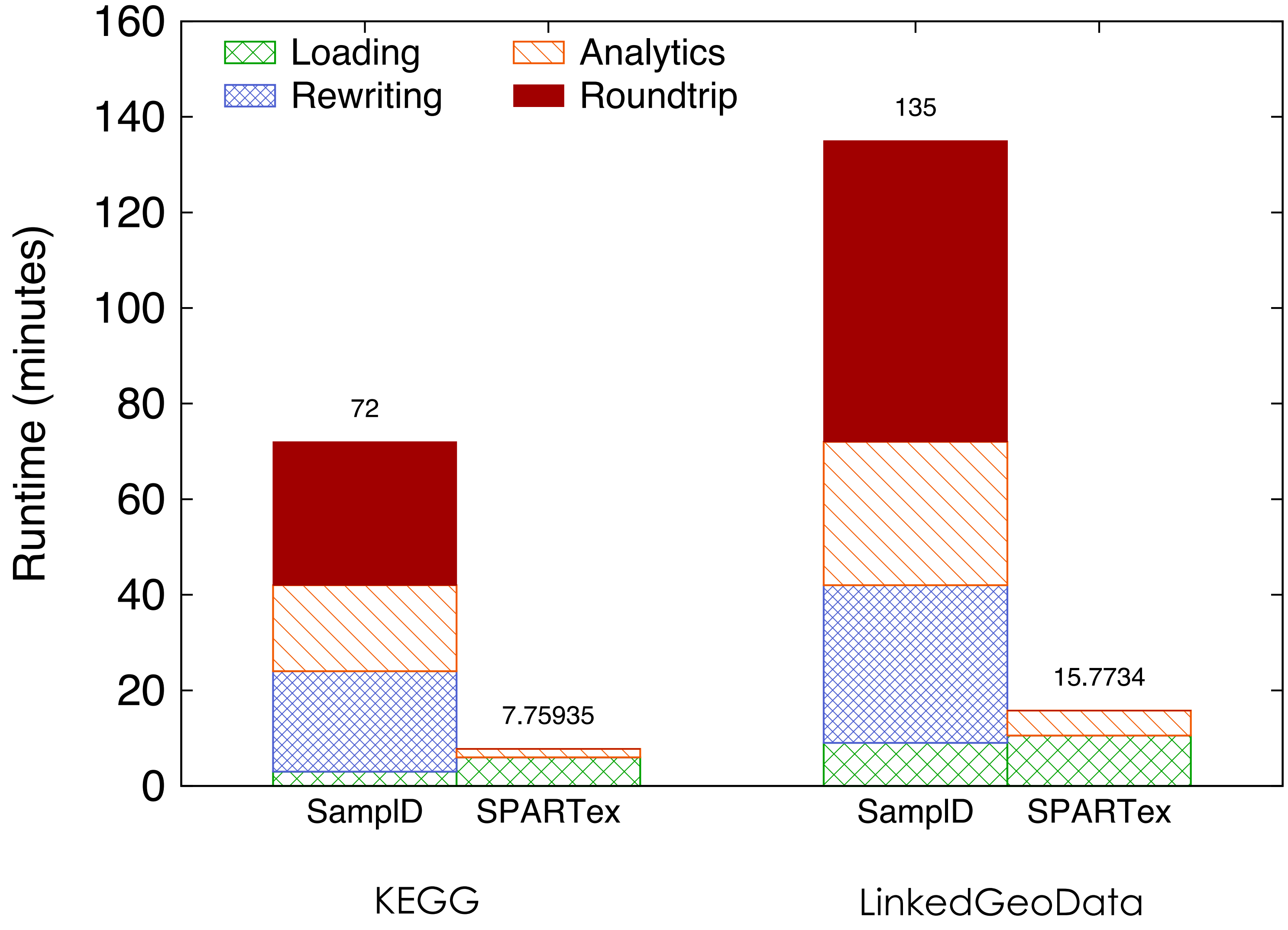


SPARTEX syntax (2)

```
PREFIX sptx: <http://www.spartex.com/analytics/>
CALL com.sptx.algo.centrality() AS sptx:centrality
CALL com.sptx.algo.PageRank(max_iter) AS sptx:pRank
ADD TRIPLE {?p sptx:popular "T" . } WHERE {
    ?p   teaches ?c .
    ?s   takes  ?c .
    ?s   advisor ?p .
    ?p   sptx:pRank    ?rank .
    ?c   sptx:centrality ?cent .
    FILTER (?rank > val1 && ?cent > val2)
}
FILTER_VERTEX AS start WHERE {
  ?p sptx:popular "T" .
}
CALL algo:SSSP() USING start AS sptx:sssp
```



SPARTEX: 10x faster

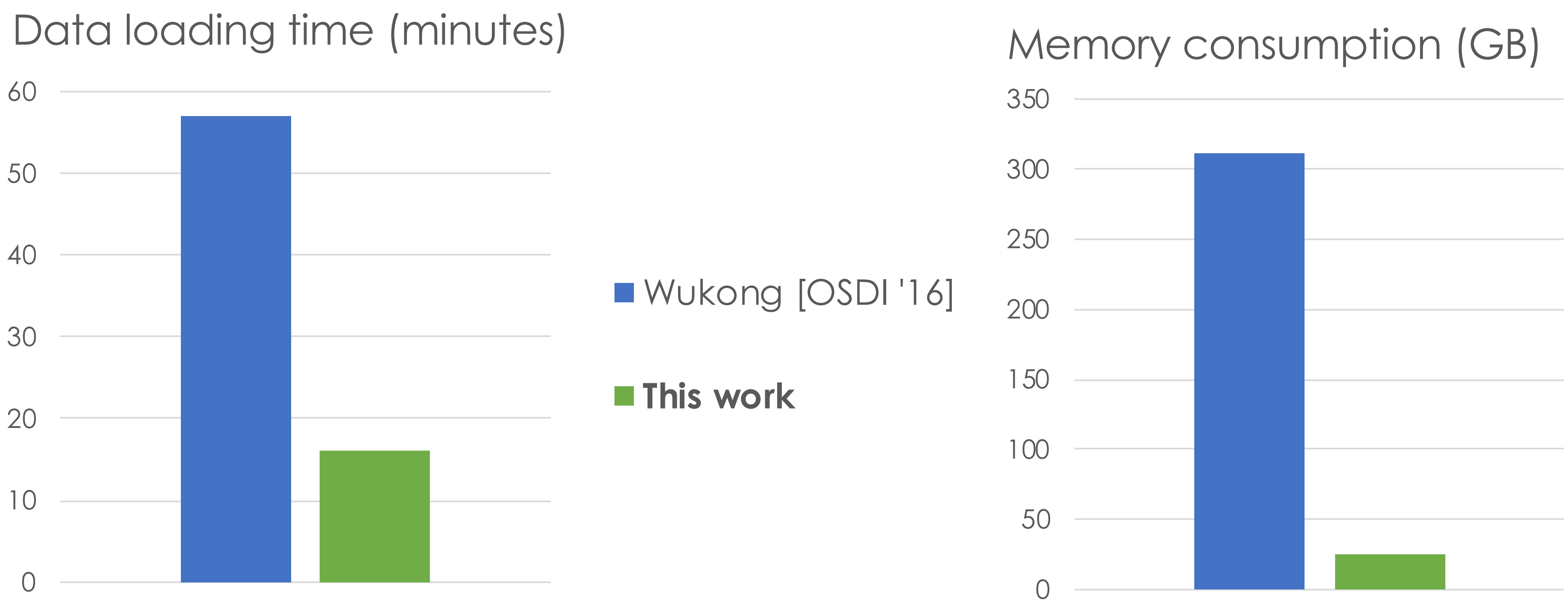


MAGiQ: Portability and Scalability

- *Demo in PVLDB, 2018*
- *In: Proc. of EuroSys, 2019*

Existing Engines and Large Graphs

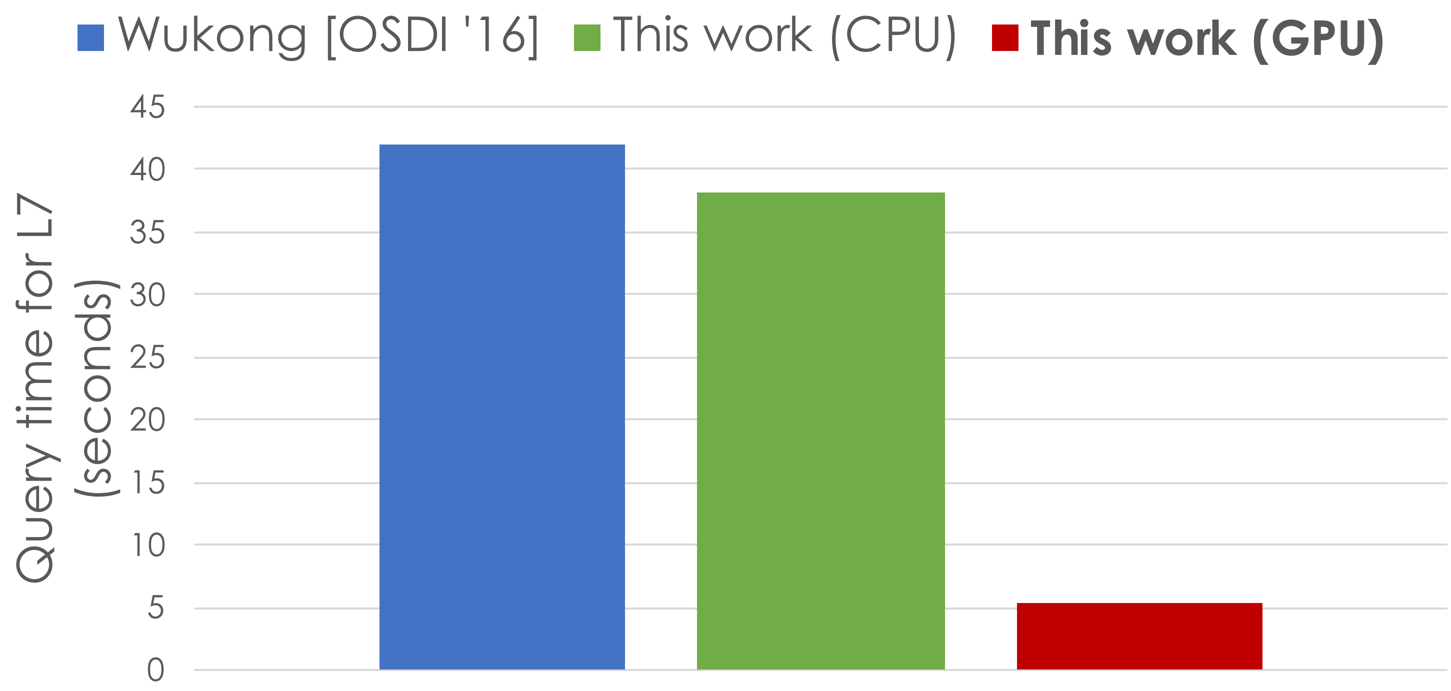
- Expensive indices [almost no indices]



Data: LUBM-1B (1.3B edges); *Hardware*: Linux server, 24 cores@2.4Ghz, 512GB

Existing Engines and Data-intensive Queries

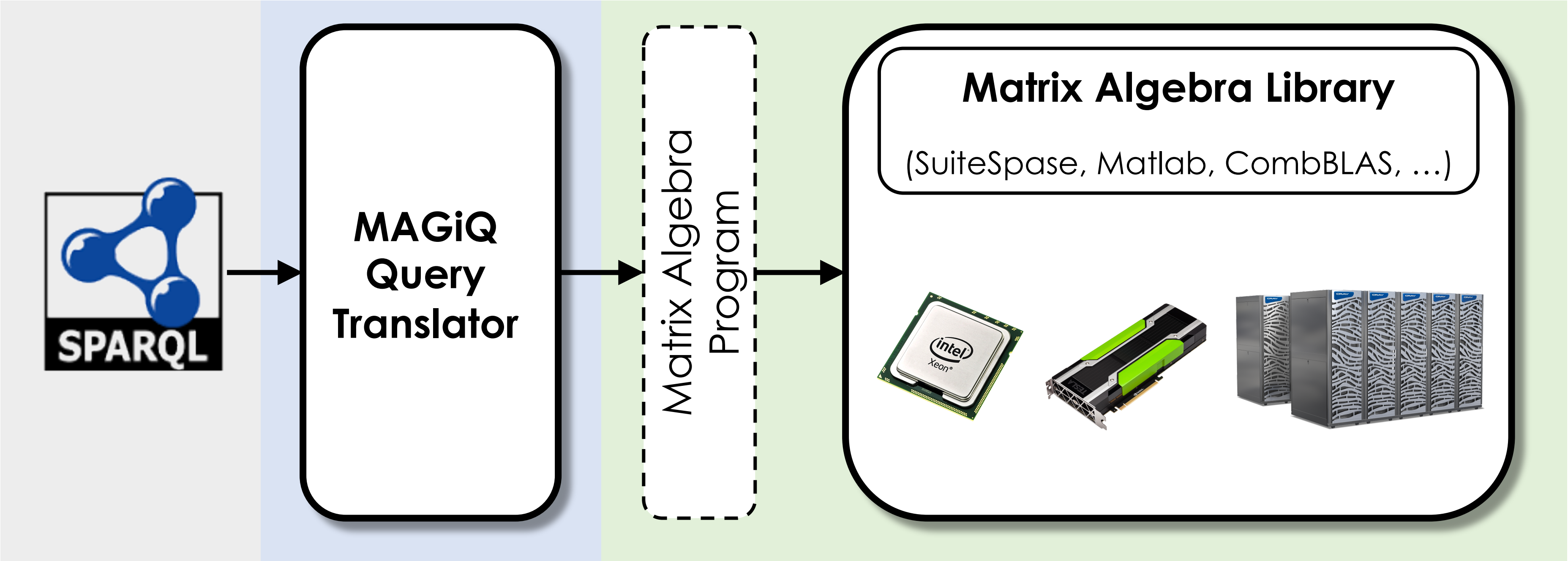
- Slow and difficult to port to different HW [effortlessly portable]
  - Distributed – AdPart [VLDBJ '16]
  - GPU – Wukong+G [ATC '18]



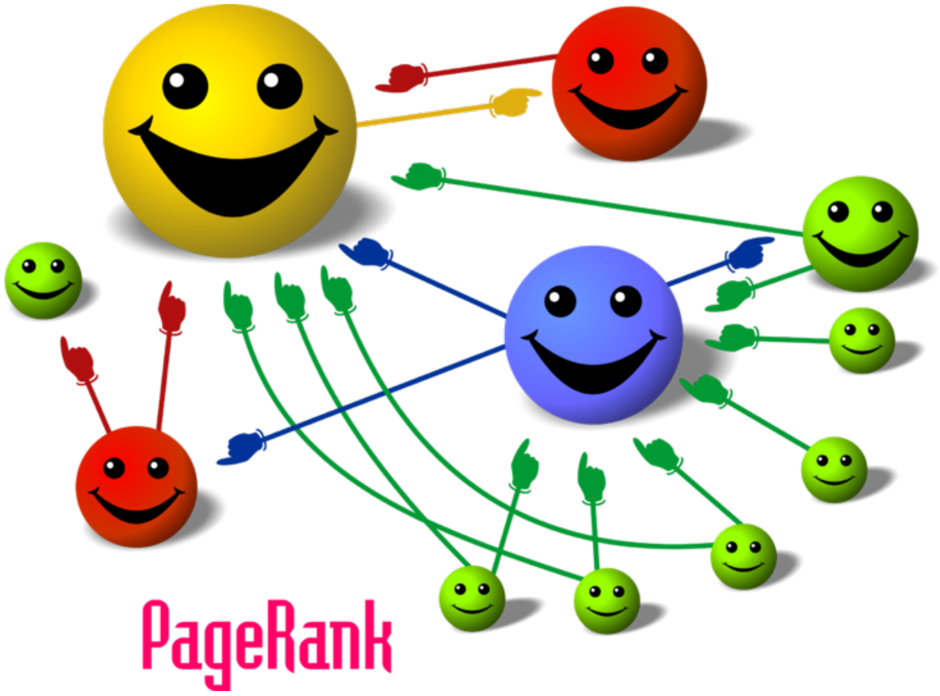
Data: LUBM-1B (1.3B edges); *Hardware*: Linux server, 24 cores@2.4Ghz, 512GB, NVIDIA Quadro P6000

Our Proposal: **MAGiQ**

- **Translate graph queries into matrix algebra programs**:
  - Decouple query evaluation logic from particular HW [**Portability**]
  - Compact sparse matrix representation of input graphs [**Scalability**]
  - Utilize highly efficient existing matrix algebra libraries [**Efficiency**]

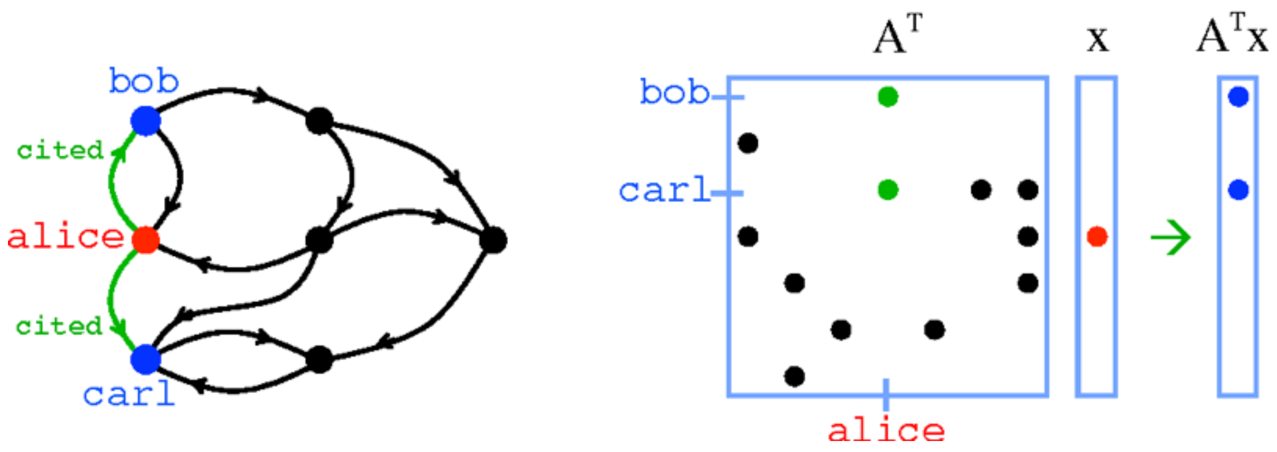


Graphs as Matrices… old news?



$$\mathbf{R} = (\mathbf{I} - d\mathcal{M})^{-1}\frac{1-d}{N}\mathbf{1}$$

GraphBLAS

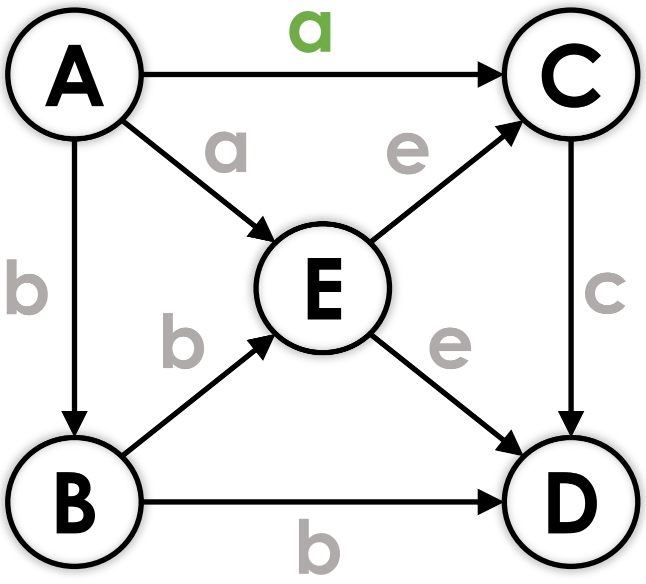


- Represent graphs as sparse matrices
- Define common operations
- Matrix x Vector → BFS

Algorithm (Problem)	Canonical Complexity	LA-Based Complexity
Breadth-first search	$\Theta(m)$	$\Theta(m)$
Betweenness Centrality (unweighted)	$\Theta(mn)$	$\Theta(mn)$
All-pairs shortest-paths (dense)	$\Theta(n^3)$	$\Theta(n^3)$
Prim (MST)	$\Theta(m+n \log n)$	$\Theta(n^2)$
Borůvka (MST)	$\Theta(m \log n)$	$\Theta(m \log n)$
Edmonds-Karp (Max Flow)	$\Theta(m^2 n)$	$\Theta(m^2 n)$
Greedy MIS (MIS)	$\Theta(m+n \log n)$	$\Theta(mn+n^2)$
Luby (MIS)	$\Theta(m+n \log n)$	$\Theta(m \log n)$

MAGiQ – RDF Graph Representation

G



A

	A	B	C	D	E
A		b	a		a
B				b	b
C				c	
D					
E			e	e	

Pre-processing → Matrix operations → Post-processing

MAGiQ – RDF Graph Representation

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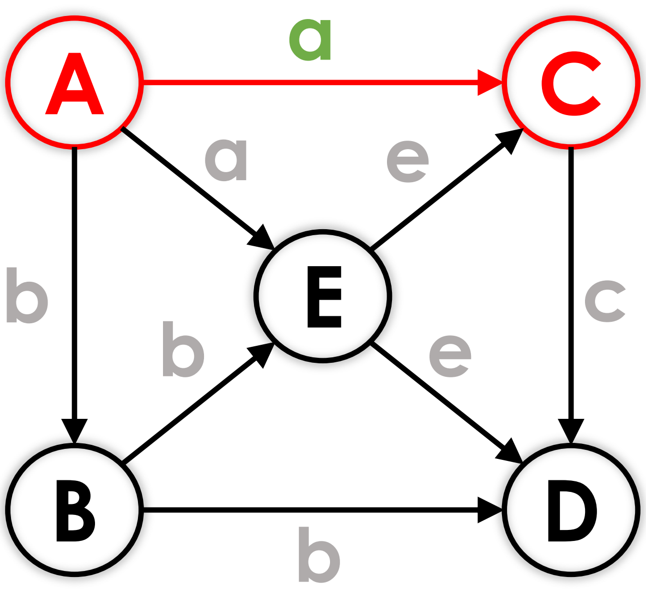


A

	A	B	C	D	E
A		b	a		a
B				b	b
C				c	
D					
E			e	e	

Pre-processing → Matrix operations → Post-processing

Selection as Matrix Multiplication

$$\underbrace{\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{\mathbf{S}} \times \underbrace{\begin{pmatrix} a & b & c \\ a & b & c \\ a & b & c \end{pmatrix}}_{\mathbf{M}} = \underbrace{\begin{pmatrix} 0 & 0 & 0 \\ a & b & c \\ 0 & 0 & 0 \end{pmatrix}}_{\mathbf{C}}$$

- S: 1 at row i → select row i from M

Generalized Matrix Selection

$$\underbrace{\begin{pmatrix} 0 & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{\mathbf{S}*b} \otimes \underbrace{\begin{pmatrix} a & b & c \\ a & b & c \\ a & b & c \end{pmatrix}}_{\mathbf{M}} = \underbrace{\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{C}$$

- Semi-ring with
  - `isEqual` instead of multiplication
  - `OR` instead of addition

MAGiQ – Algebraic Operations

Matrix-matrix multiplication over `isEqual , OR` **semi-ring**

$$
\begin{array}{c}
\textbf{S} \\
\begin{array}{c|ccccc|}
 & A & B & C & D & E \\
\hline
A & & & & & \\
B & & & & & \\
C & & & e & & \\
D & & & & & \\
E & & & & & e \\
\hline
\end{array}
\end{array}
\otimes
\begin{array}{c}
\textbf{A} \\
\begin{array}{c|ccccc|}
 & A & B & C & D & E \\
\hline
A & & b & a & & a \\
B & & & & b & b \\
C & & & & c & \\
D & & & & & \\
E & & & e & e & \\
\hline
\end{array}
\end{array}
=
\begin{array}{c}
\\
\begin{array}{c|ccccc|}
 & A & B & C & D & E \\
\hline
A & & & & & \\
B & & & & & \\
C & & & & & \\
D & & & & & \\
E & & & 1 & 1 & \\
\hline
\end{array}
\end{array}
$$

MAGiQ – Algebraic Operations

Matrix-matrix multiplication over **`isEqual , OR`** **semi-ring**

S

	A	B	C	D	E
A					
B					
C			e		
D					
E					e

$\otimes$

A

	A	B	C	D	E
A		b	a		a
B				b	b
C				c	
D					
E			e	e	

$=$

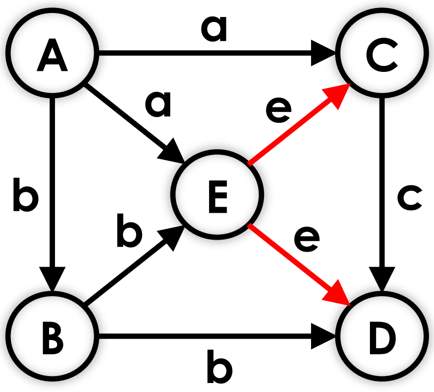
	A	B	C	D	E
A					
B					
C					
D					
E			1	1	

MAGiQ – Algebraic Operations

Matrix-matrix multiplication over `isEqual , OR` **semi-ring**

Row selection with predicate:

neighbors connected to **C** and **E** with **e** outgoing edges



S

	A	B	C	D	E
A					
B					
C			e		
D					
E					e

$\otimes$

A

	A	B	C	D	E
A		b	a		a
B				b	b
C				c	
D					
E			e	e	

=

	A	B	C	D	E
A					
B					
C					
D					
E			1	1	

MAGiQ – Algebraic Operations

`any`(**M**): reduction with **`OR`**

$$\texttt{any}\left(\begin{array}{|c:c:c:c:c|}\hline & 1 & & & 1 \\ \hdashline & & & & \\ \hdashline & & & & \\ \hdashline & 1 & & & \\ \hdashline & & & & \\ \hline\end{array}\right) = \begin{array}{|c|}\hline 1 \\ \hdashline \\ \hdashline \\ \hdashline 1 \\ \hdashline \\ \hline\end{array}$$

MAGiQ – Algebraic Operations

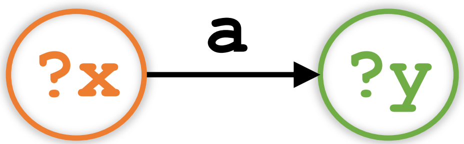
`diag(v)`: construct diagonal selection matrix

$$\mathtt{diag}\left(\begin{bmatrix} 1 \\ \ \\ \ \\ 1 \\ \ \end{bmatrix}\right) = \begin{bmatrix} 1 & & & & \\ & & & & \\ & & & & \\ & & & 1 & \\ & & & & \end{bmatrix}$$

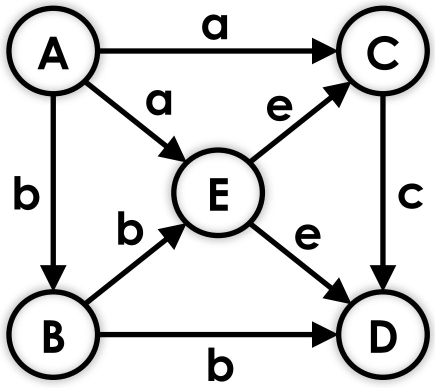
MAGiQ – Query Translation

Single edge translation

```
SELECT ?x ?y WHERE {
   ?x    <a>   ?y  .
}
```



$$\mathbf{M}_{xy} = \mathbf{I} * a \otimes \mathbf{A}$$



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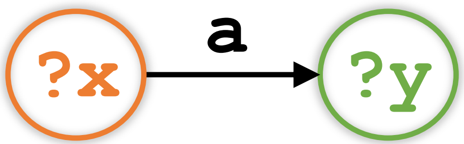

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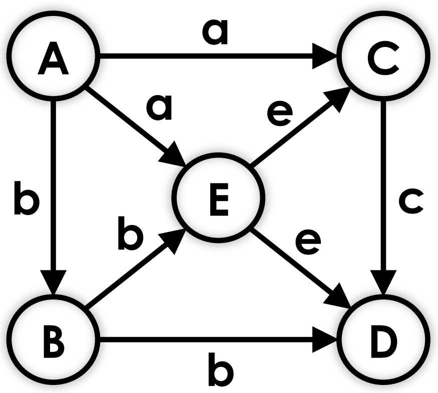

$\mathbf{I} * a$

	A	B	C	D	E
A	a				
B		a			
C			a		
D				a	
E					a

$\otimes$

$\mathbf{A}$

	A	B	C	D	E
A		b	a		a
B				b	b
C				c	
D					
E			e	e	

$=$

$\mathbf{M}_{xy}$

	A	B	C	D	E
A			1		1
B					
C					
D					
E					

MAGiQ – Query Translation

Single edge translation

```
SELECT ?x ?y WHERE {
   ?x   <a>   ?y .
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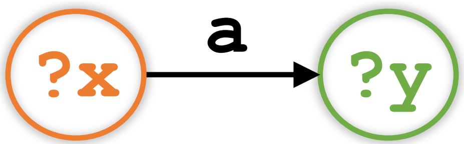
```



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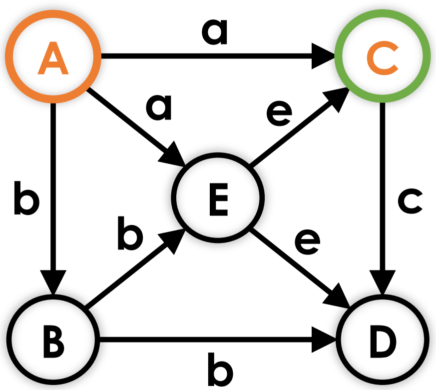

$\mathbf{I} * a$

	A	B	C	D	E
A	a				
B		a			
C			a		
D				a	
E					a

$\otimes$

$\mathbf{A}$

	A	B	C	D	E
A		b	a		a
B				b	b
C				c	
D					
E			e	e	

=

$\mathbf{M}_{xy}$

	A	B	C	D	E
A			$\boxed{1}$		1
B					
C					
D					
E					

MAGiQ – Query Translation

Single edge translation

```
SELECT ?x ?y WHERE {
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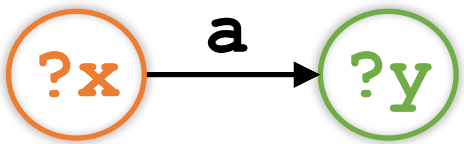

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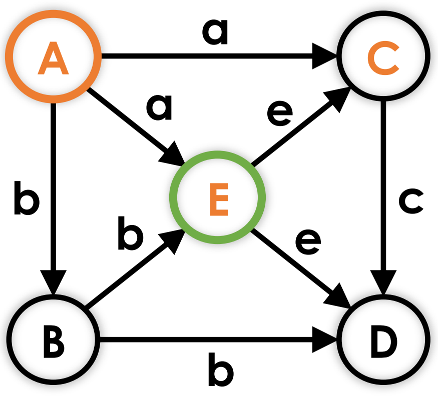


$\mathbf{I} * a$

	A	B	C	D	E
A	a				
B		a			
C			a		
D				a	
E					a

$\otimes$

$\mathbf{A}$

	A	B	C	D	E
A		b	a		a
B				b	b
C				c	
D					
E			e	e	

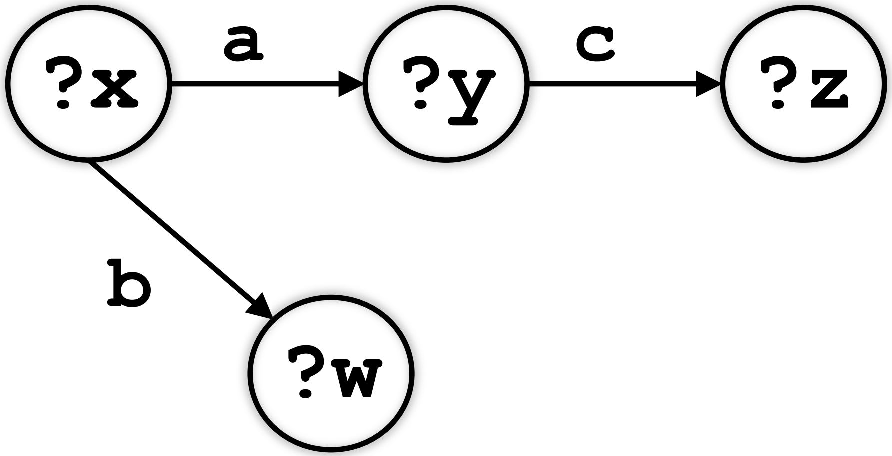
=

$\mathbf{M}_{xy}$

	A	B	C	D	E
A			1		$\boxed{1}$
B					
C					
D					
E					

MAGiQ – Query Translation

Graph query translation



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$$\mathbf{M}_{xy} = \mathbf{M}_{xy} \times \mathtt{diag}(\mathtt{any}(\mathbf{M}_{yz}))$$

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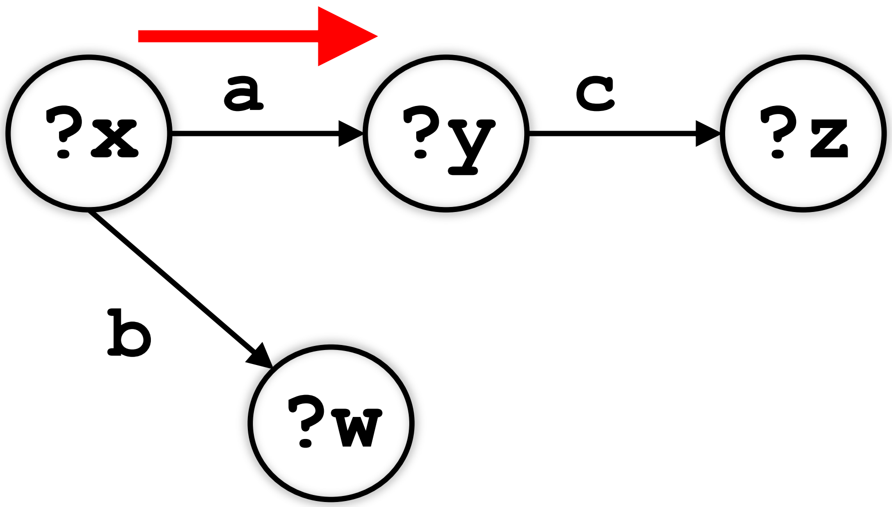

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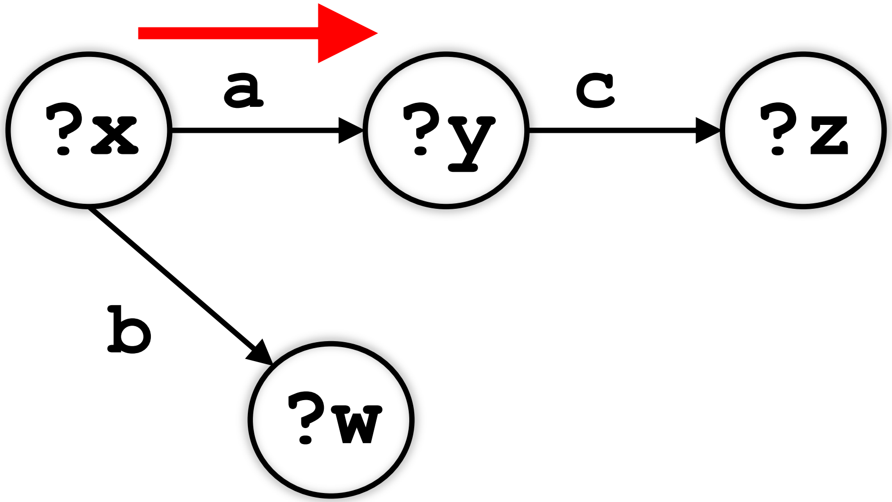

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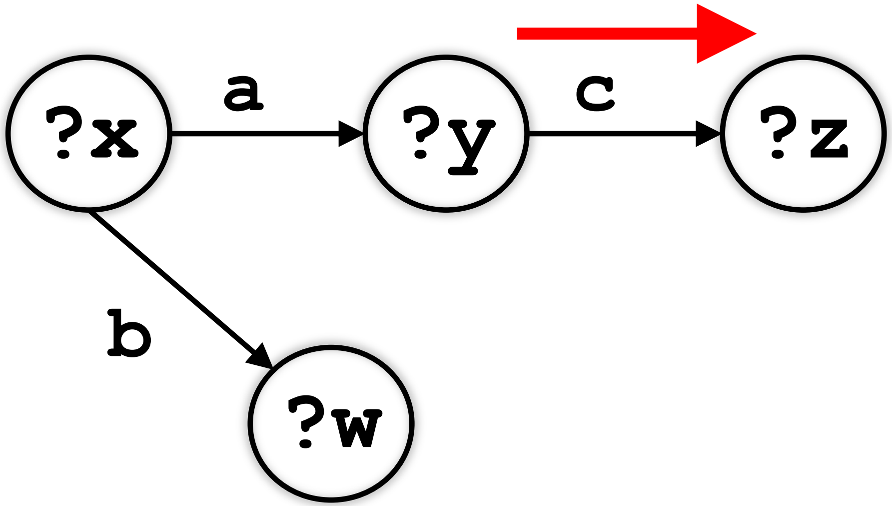

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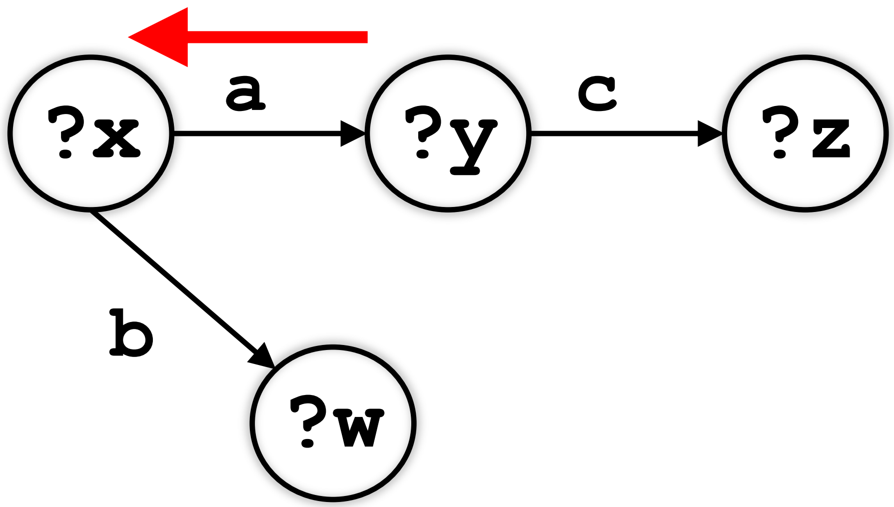

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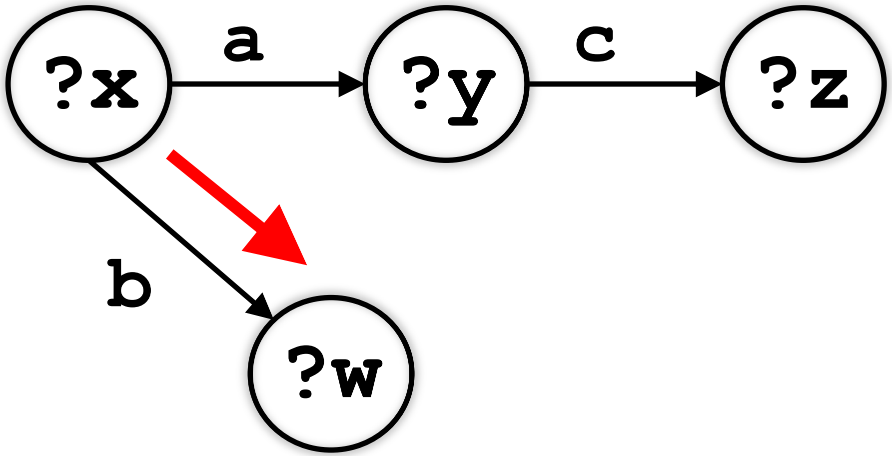

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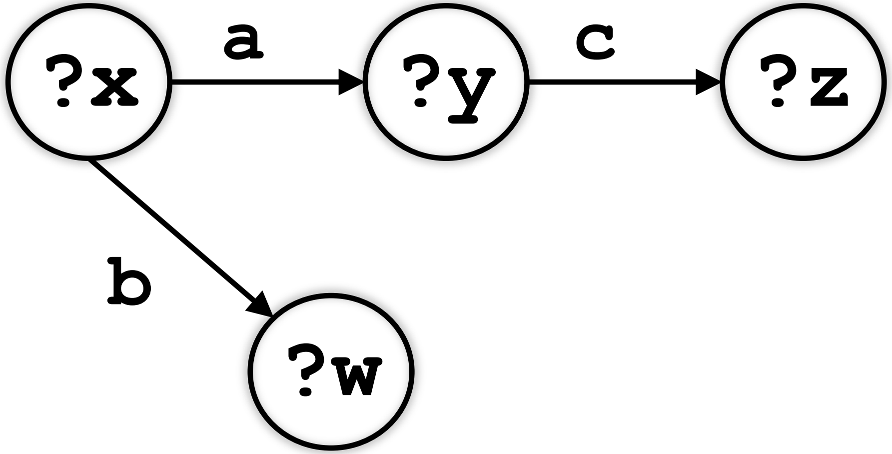

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MAGiQ – Architecture

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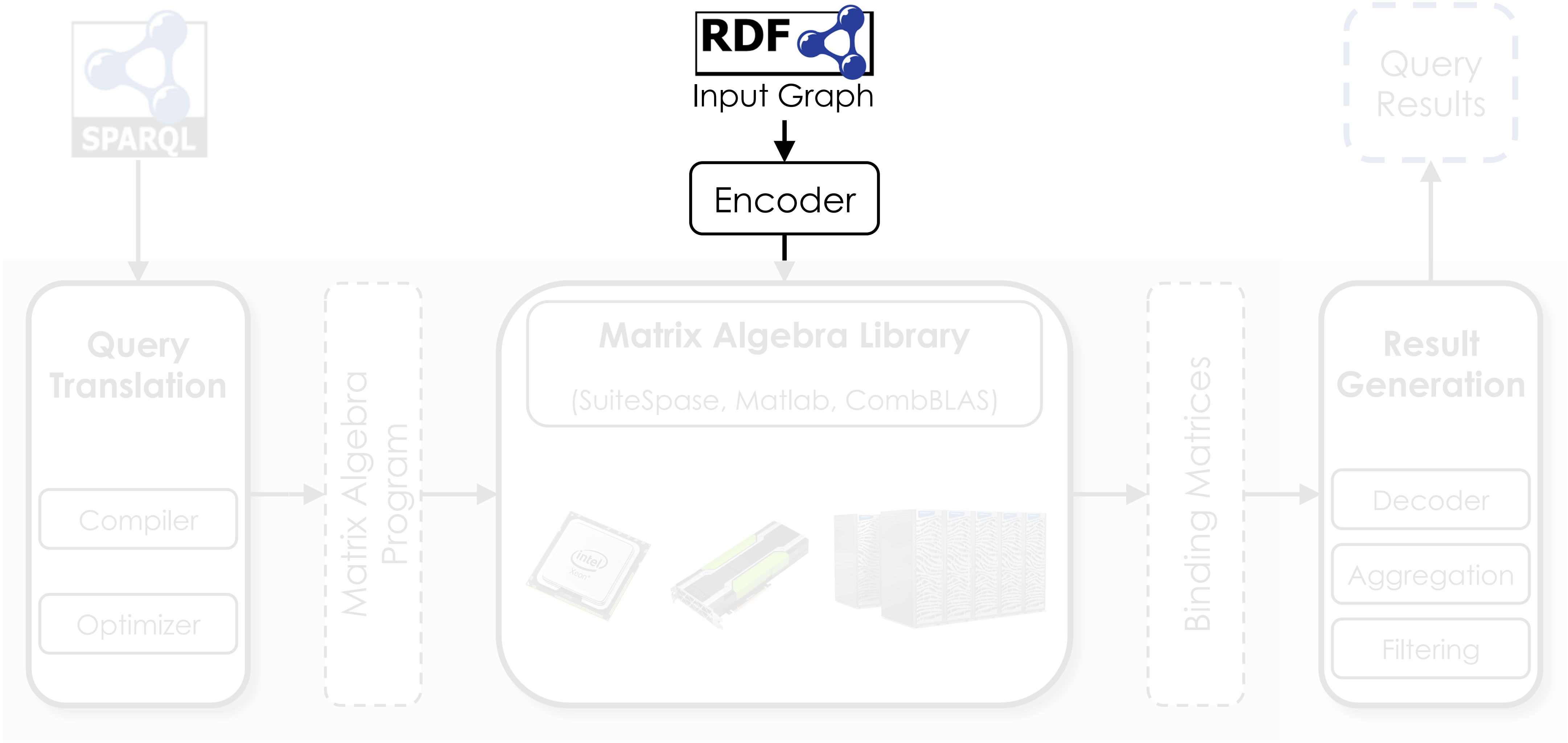

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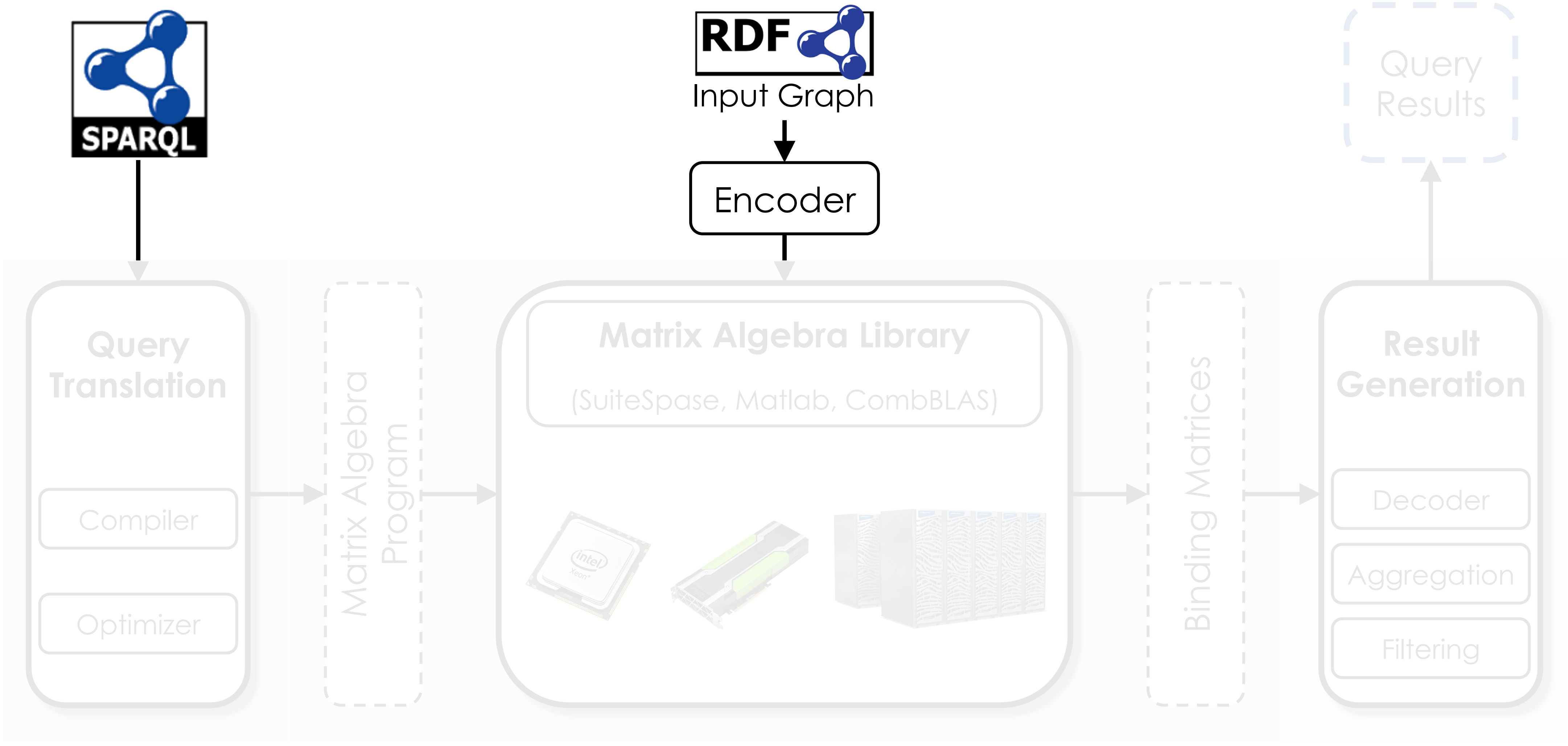

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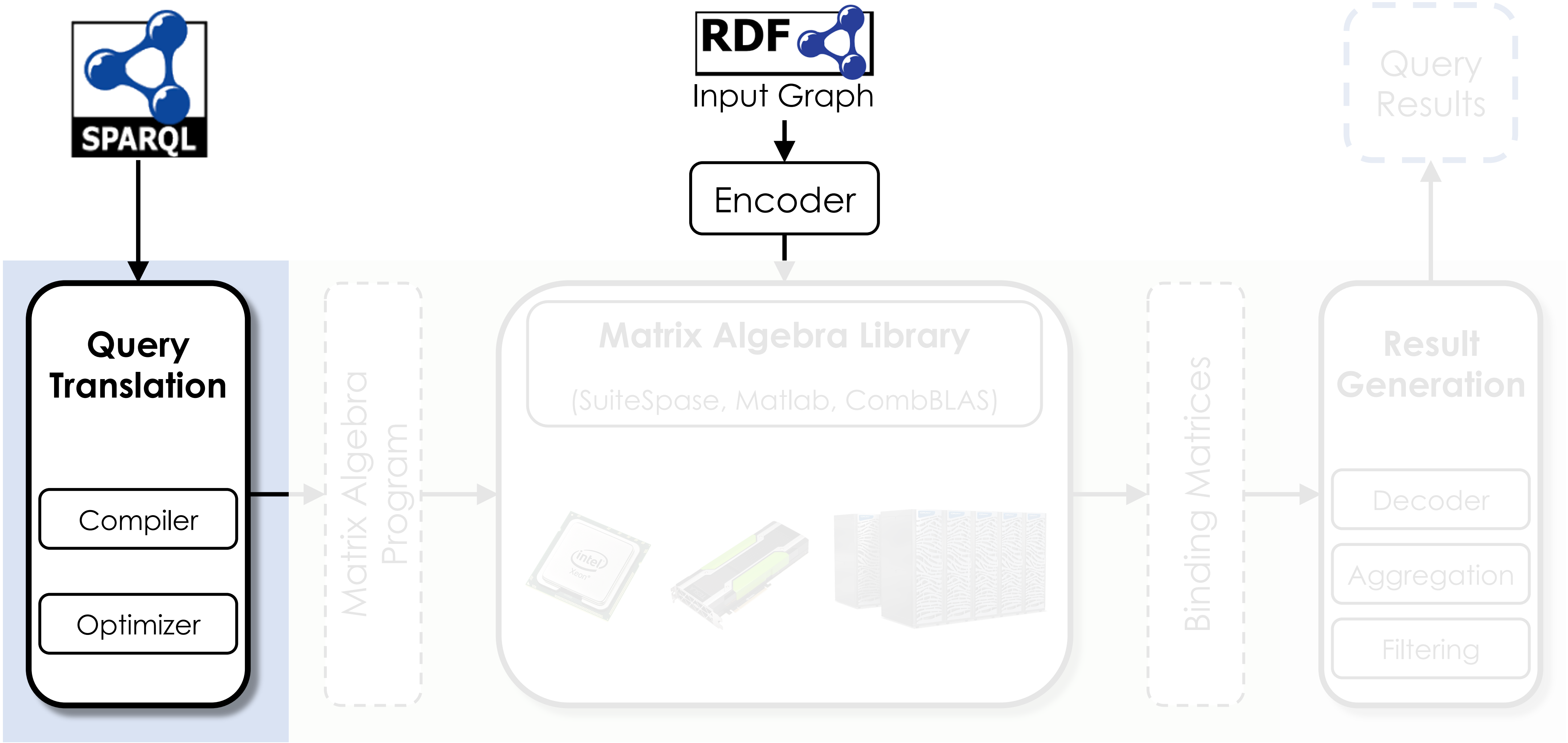

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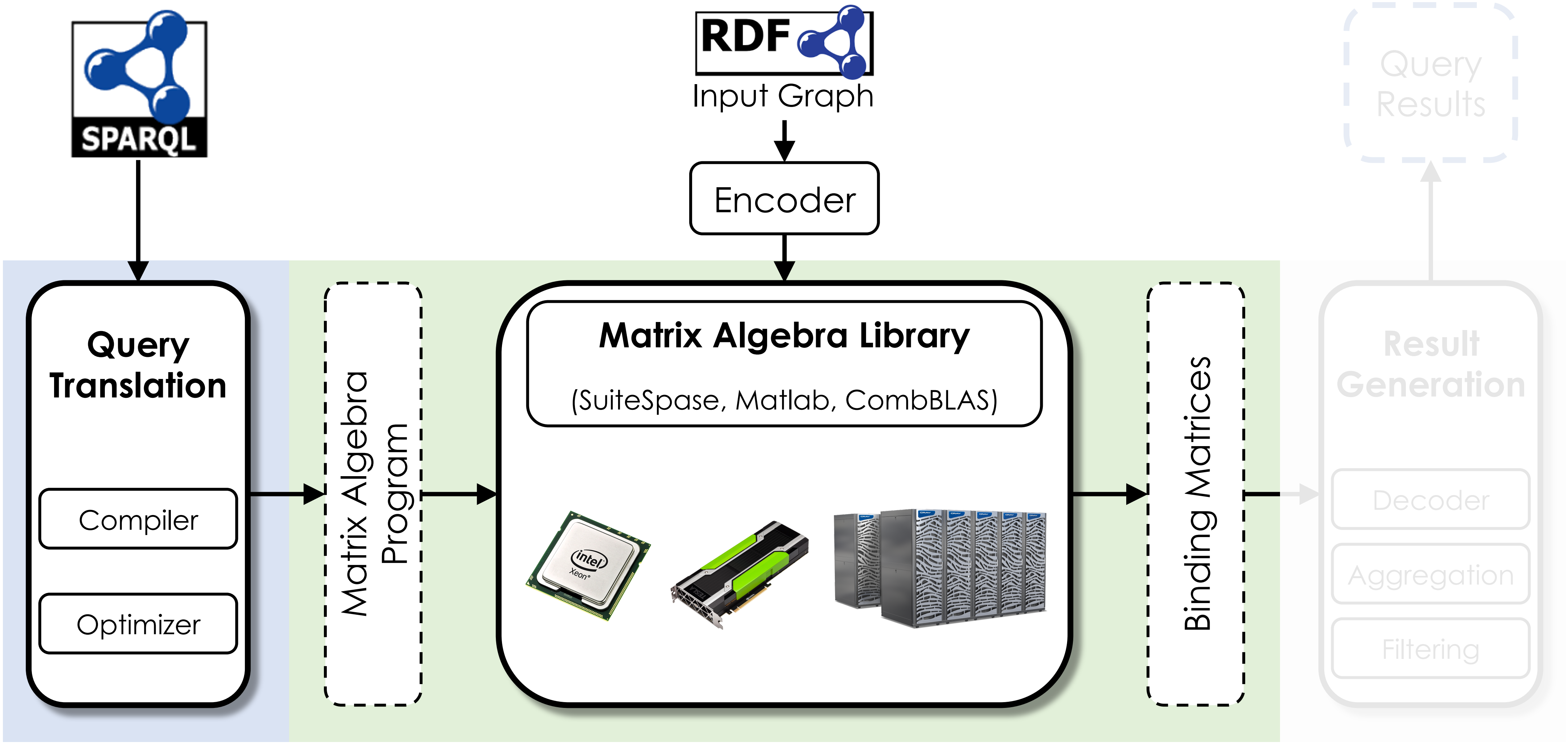

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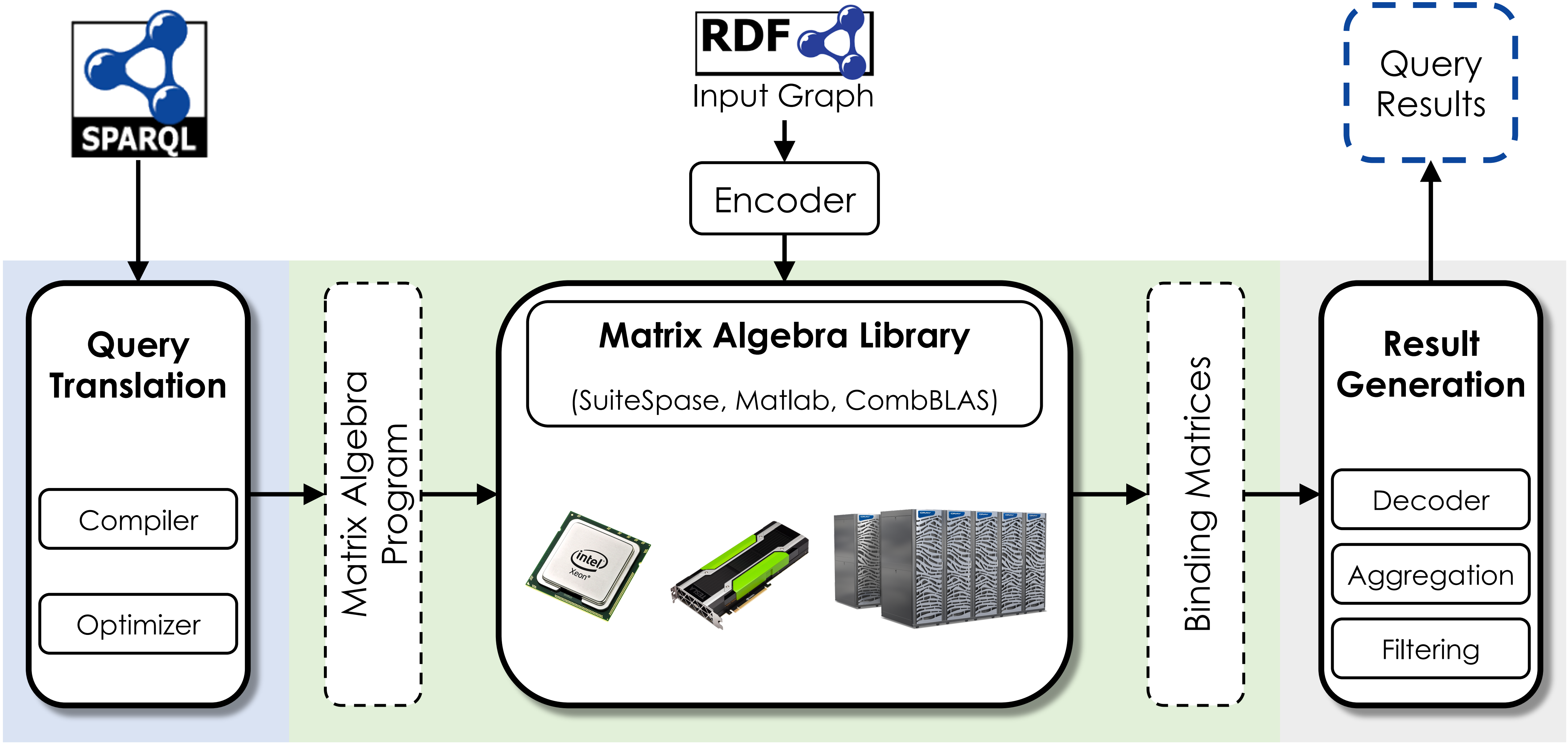

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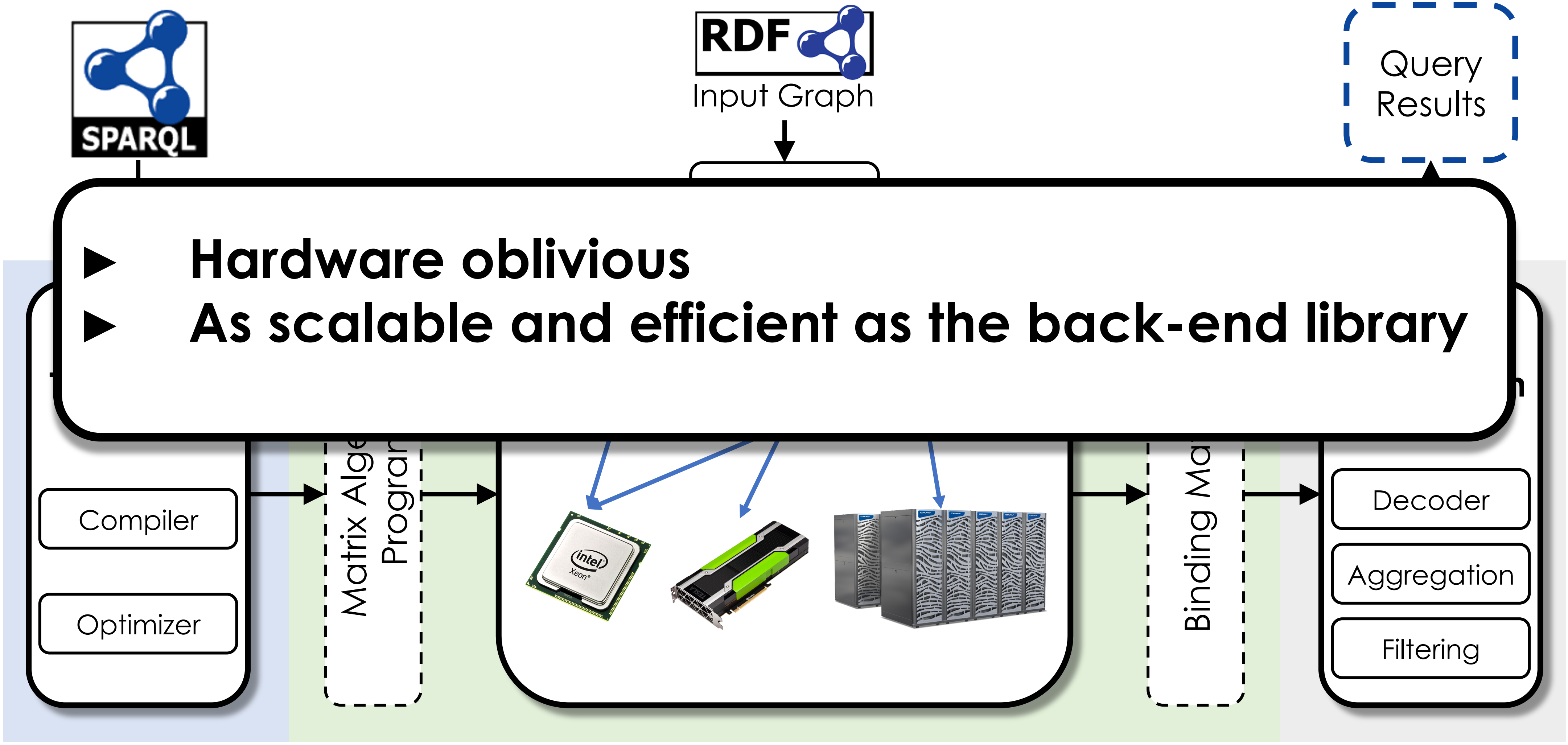

- ▶ **Hardware oblivious**
- ▶ **As scalable and efficient as the back-end library**

MAGiQ – Evaluation Setup

- Single machine: 2 x 14-core Intel Xeon E5-2680 @ 2.4Gh
  512GB
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- Distributed-memory: Cray XC40

[6,174 Compute Nodes: 12,348 CPUs]
2 x 16-core Intel Xeon E5-2698 @ 2.3 GHz
128GB per Compute Node

MAGiQ – Datasets

Dataset	#Triples (M)	#Nodes (M)	#P
WatDiv-100M	109.23	10.28	85
YAGO2	284.30	60.70	98
WatDiv-1B	1,092.16	97.39	86
LUBM-1B	1,366.71	336,51	18
Bio2RDF	4,287.59	1,135.93	1,714
LUBM-10B	10,677.83	2,628.99	18
LUBM-512B	512,527.41	126,188.23	18

MAGiQ – Competing Engines

- Research:
  - **RDF-3X** [VLDB'08] – Relational, single machine, serial
  - **gStore** [VLDB'11] – Graph-based, single machine, serial
  - **AdPart** [VLDBJ'16]– Relational, distributed
  - **Wukong**[OSDI'16] – Graph-based, distributed, multithreaded
- Commercial:
  - **UrikaGD** – Specialized hardware appliance
  - **Virtuoso** – Relational, single machine, multithreaded

MAGiQ – Data-intensive Queries*

LUBM-1B (1.3B edges)

	Loading time (minutes)	Data-intensive query time (seconds)				Query time GeoMean (seconds)
		L1	L2	L3	L7	
RDF-3X [VLDB'08]	447	901	116	898	426	308
Wukong [OSDI'16]	57	11	10	11	42	15
MAGiQ(SuiteSparse)	16	173	38	108	155	102
MAGiQ(Matlab-CPU)	16	25	14	6	38	17
MAGiQ(Matlab-GPU)	16	**3**	**2**	**2**	**5**	**3**

*MAGiQ is slower for selective queries

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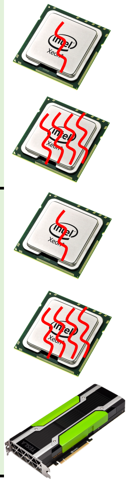

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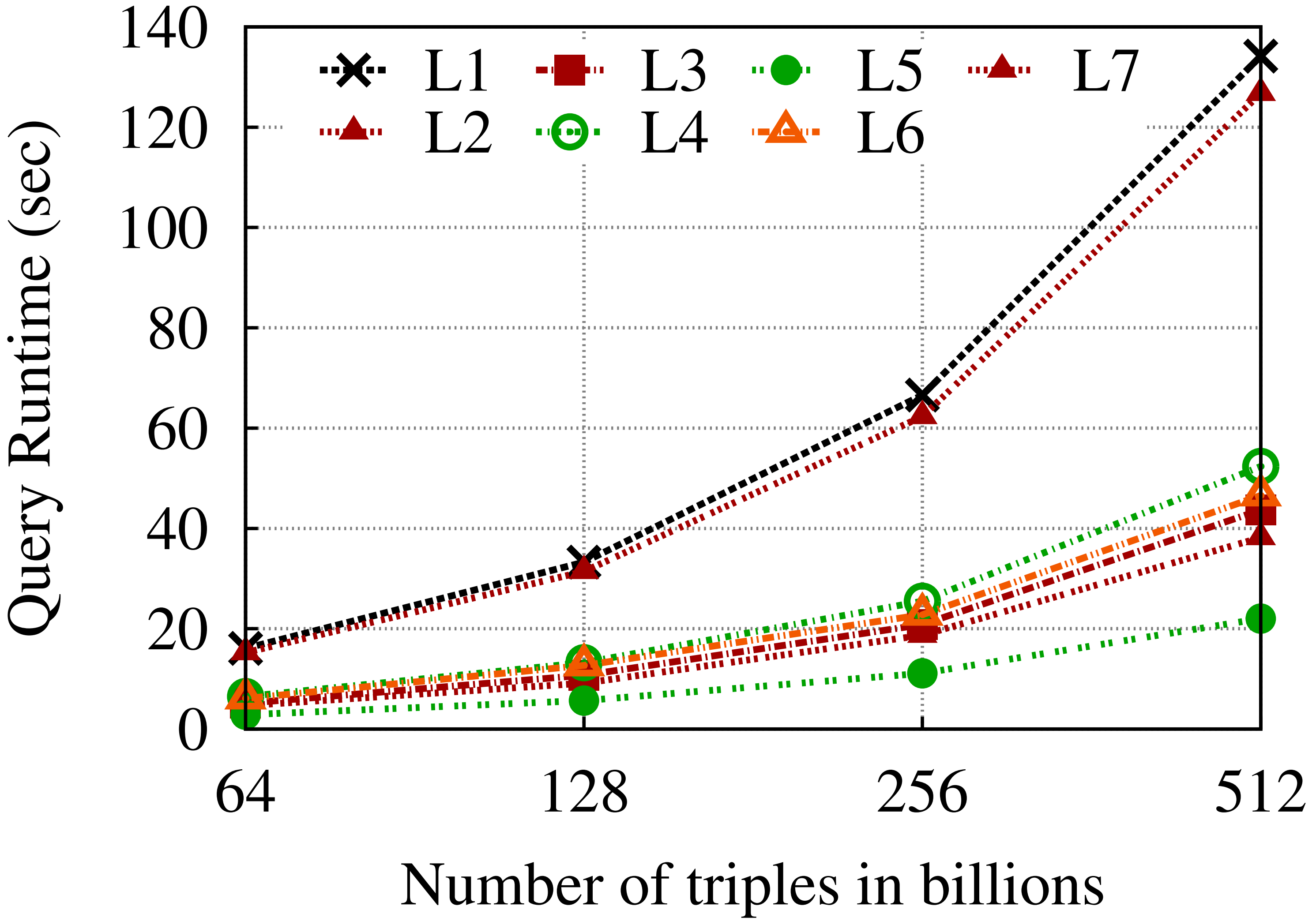
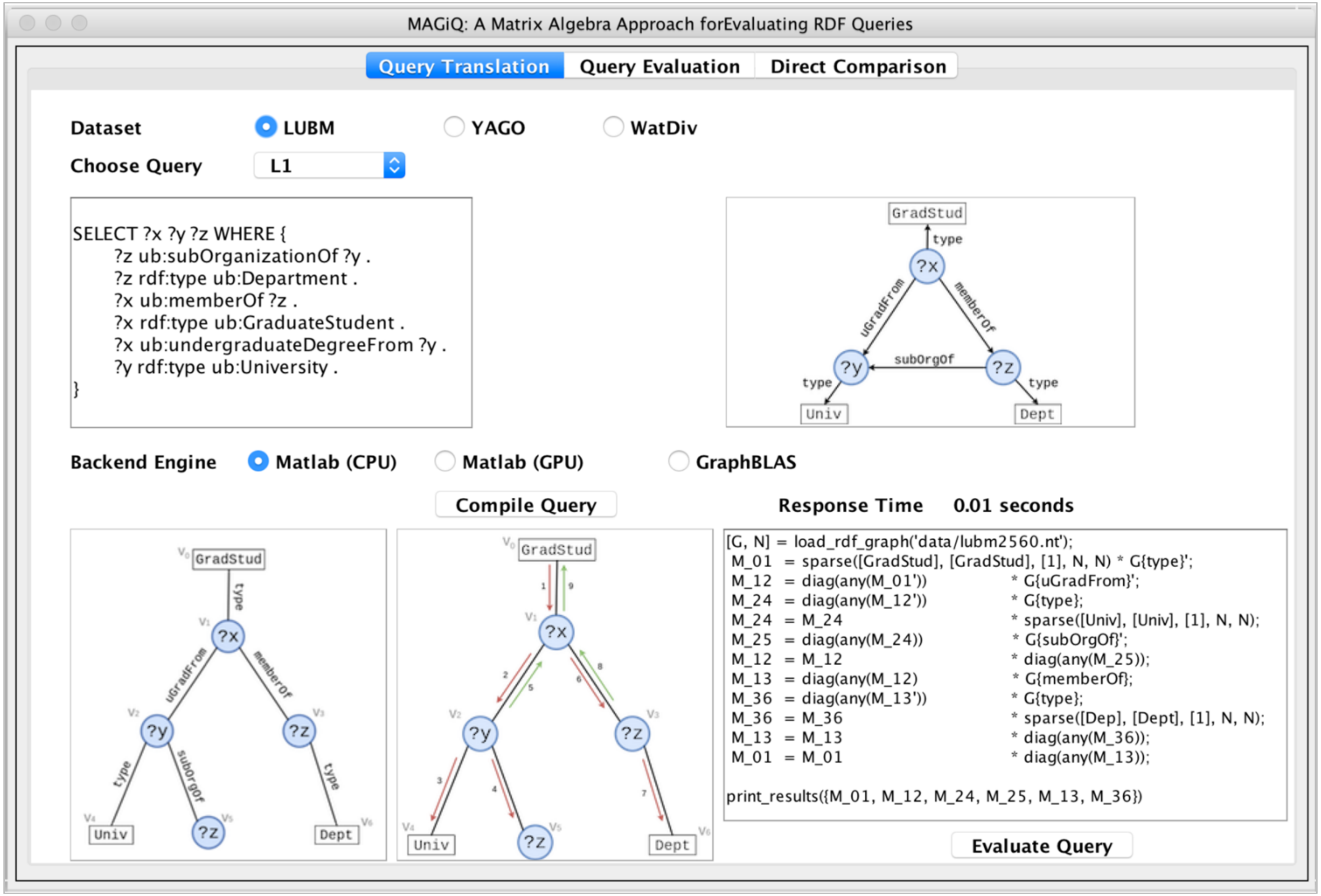
MAGiQ – Scalability on Cray XC40 Supercomputer

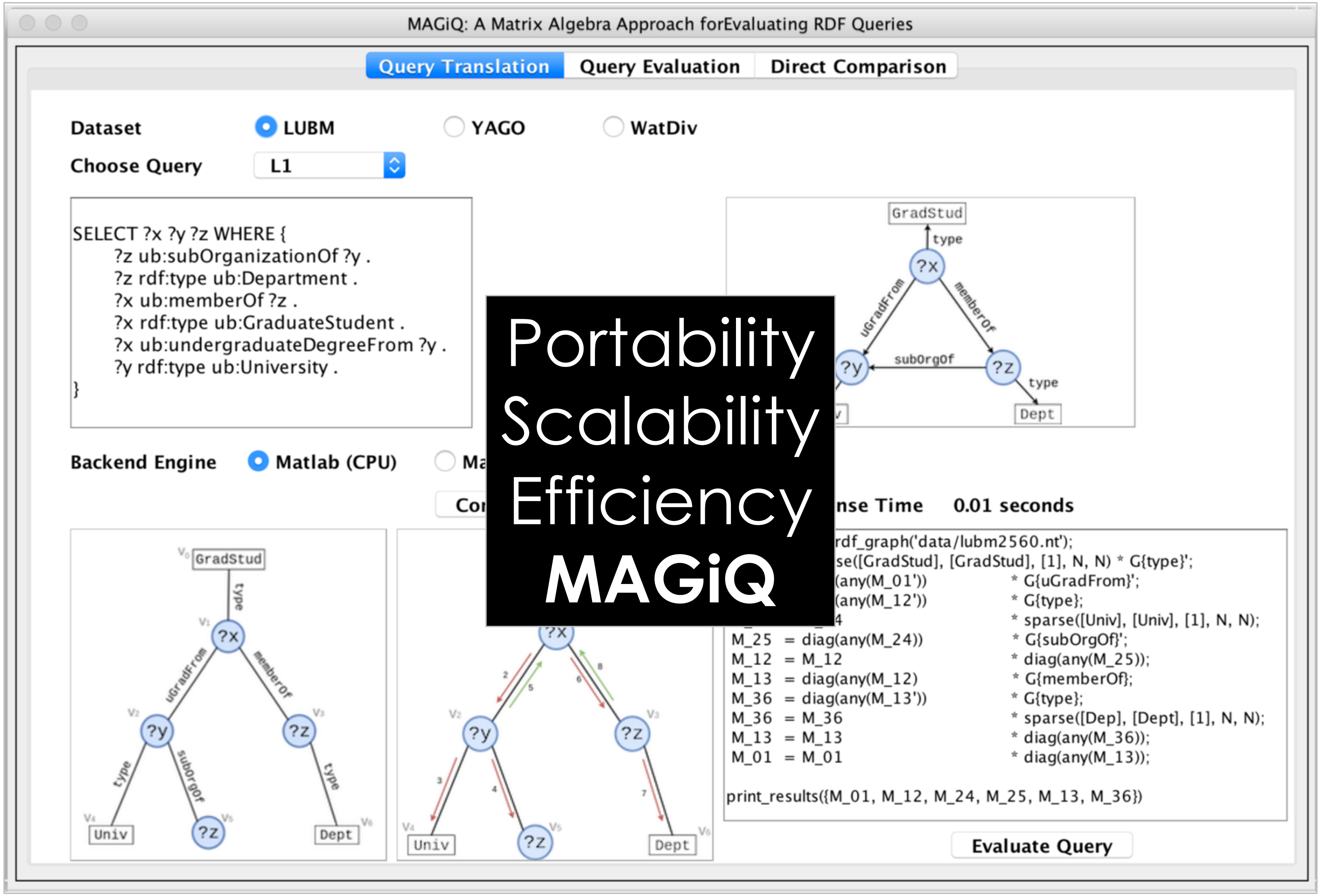


Data Scalability

2,048 compute nodes



MAGiQ: A Matrix Algebra Approach forEvaluating RDF Queries
Query Translation
Query Evaluation
Direct Comparison
Dataset
LUBM
YAGO
WatDiv
Choose Query
L1
SELECT ?x ?y ?z WHERE {
?z ub:subOrganizationOf ?y .
?z rdf:type ub:Department .
?x ub:memberOf ?z .
?x rdf:type ub:GraduateStudent .
?x ub:undergraduateDegreeFrom ?y .
?y rdf:type ub:University .
}
GradStud
type
?x
uGradFrom
memberOf
?y
subOrgOf
?z
type
type
Univ
Dept
Backend Engine
Matlab (CPU)
Matlab (GPU)
GraphBLAS
Compile Query
Response Time
0.01 seconds
[G, N] = load_rdf_graph('data/lubm2560.nt');
M_01 = sparse([GradStud], [GradStud], [1], N, N) * G{type}';
M_12 = diag(any(M_01')) * G{uGradFrom}';
M_24 = diag(any(M_12')) * G{type};
M_24 = M_24 * sparse([Univ], [Univ], [1], N, N);
M_25 = diag(any(M_24)) * G{subOrgOf}';
M_12 = M_12 * diag(any(M_25));
M_13 = diag(any(M_12)) * G{memberOf};
M_36 = diag(any(M_13')) * G{type};
M_36 = M_36 * sparse([Dep], [Dept], [1], N, N);
M_13 = M_13 * diag(any(M_36));
M_01 = M_01 * diag(any(M_13));
print_results({M_01, M_12, M_24, M_25, M_13, M_36})
Evaluate Query



Portability

Scalability

Efficiency

MAGiQ

Matrix algebra for RDF: it's MAGIQ

Panos.Kalnis @ KAUST.edu.sa

Extra slides

Extra:

- Main limitations:
  - No support for queries with variable predicates.
  - No support property path queries.
  - Slow performance for selective queries compared to index-based engines.

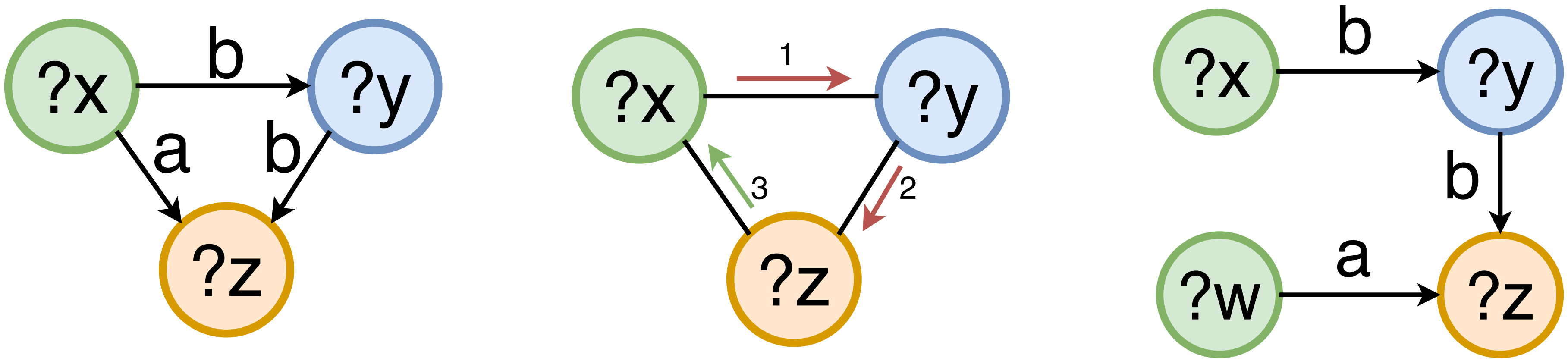
Extra: Slow for selective queries

LUBM-1B [data-intensive] query times (seconds)

	L1	**L2**	**L3**	**L7**	**GeoMean**
RDF-3X	901.4	115.6	898.2	426.2	307.6
Virtuoso	25.0	1,268.2	11.7	308.1	103.3
UrikaGD	5.8	2.4	1.9	7.0	3.7
Wukong	11.1	10.3	10.5	42.0	15.0
MAGiQ (SuiteSparse)	173.2	38.0	107.7	155.0	102.4
MAGiQ (Matlab-CPU)	24.9	14.3	6.1	38.2	17.0
MAGiQ (Matlab-GPU)	**3.2**	**2.1**	**1.5**	**5.4**	**2.7**

Extra: Cycles

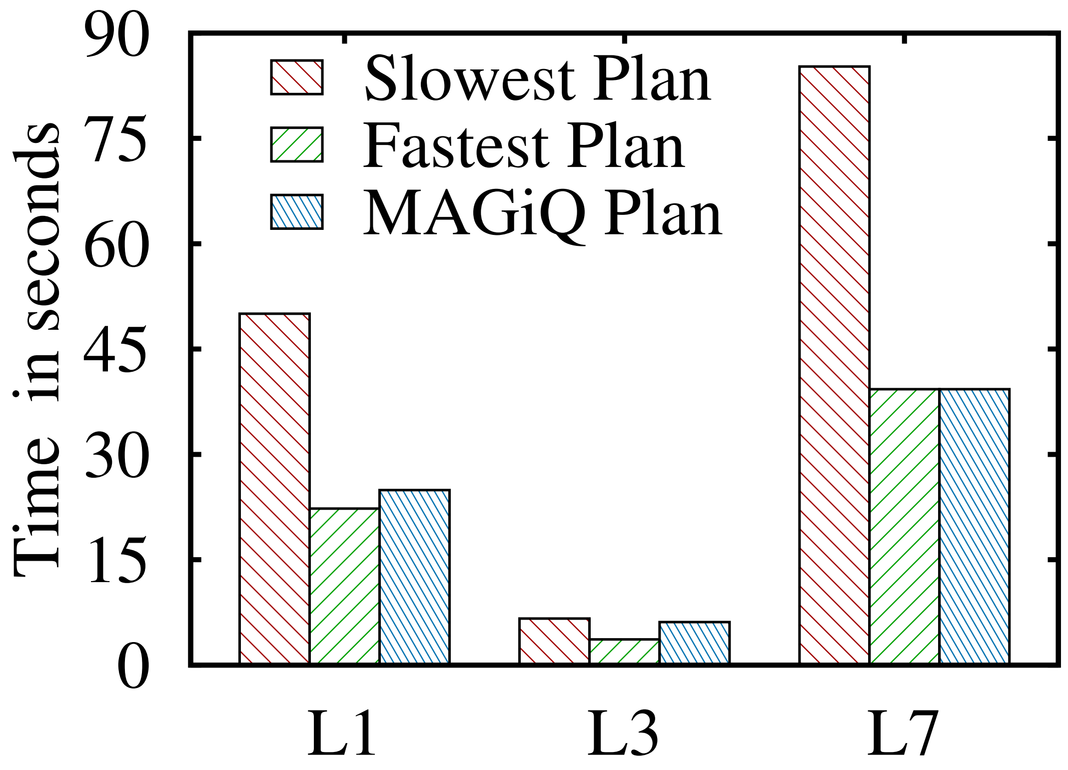
Cyclic queries



(a) (b) (c)

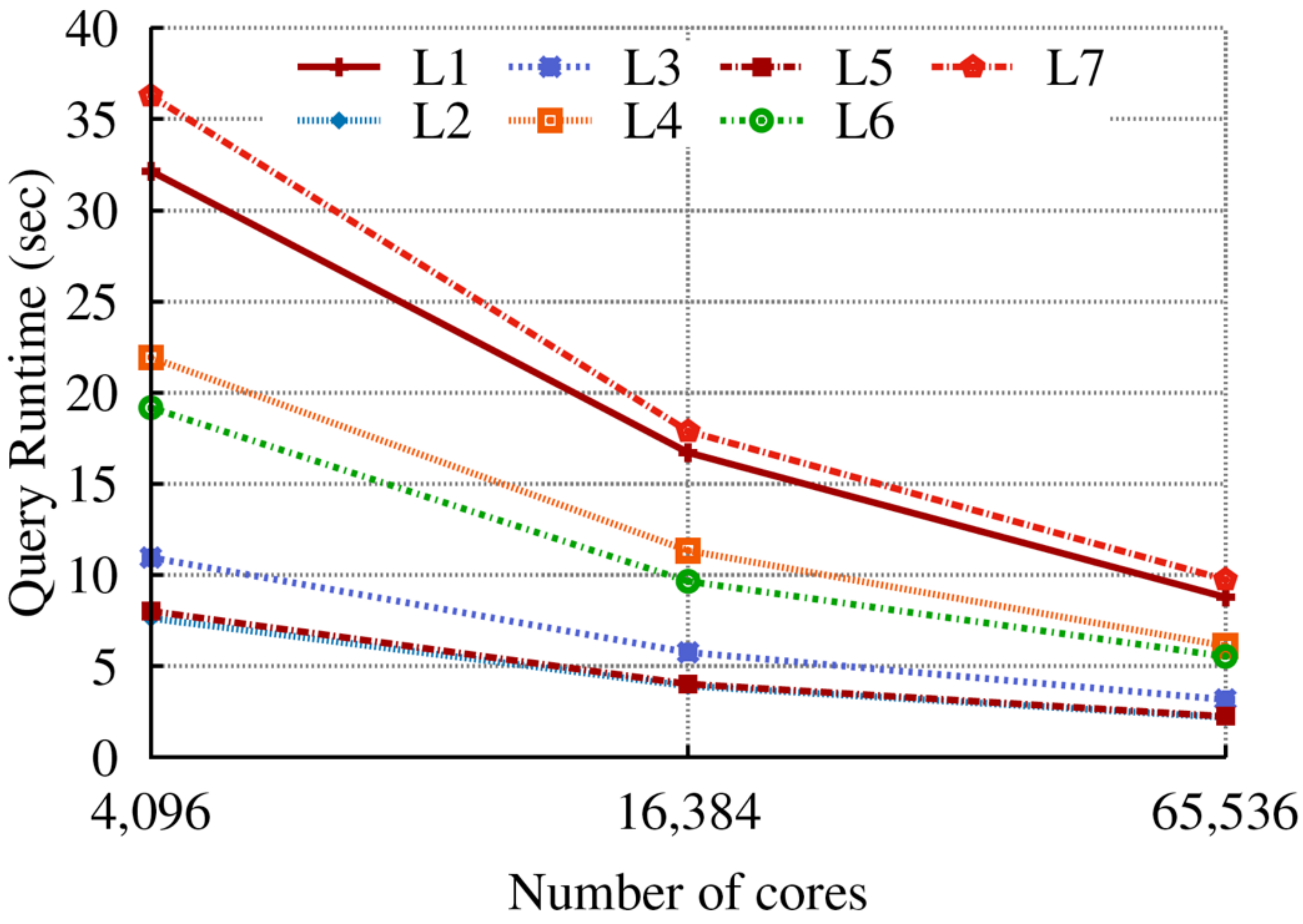
Extra:

Query planning



(a) MAGiQ (MATLAB-CPU)

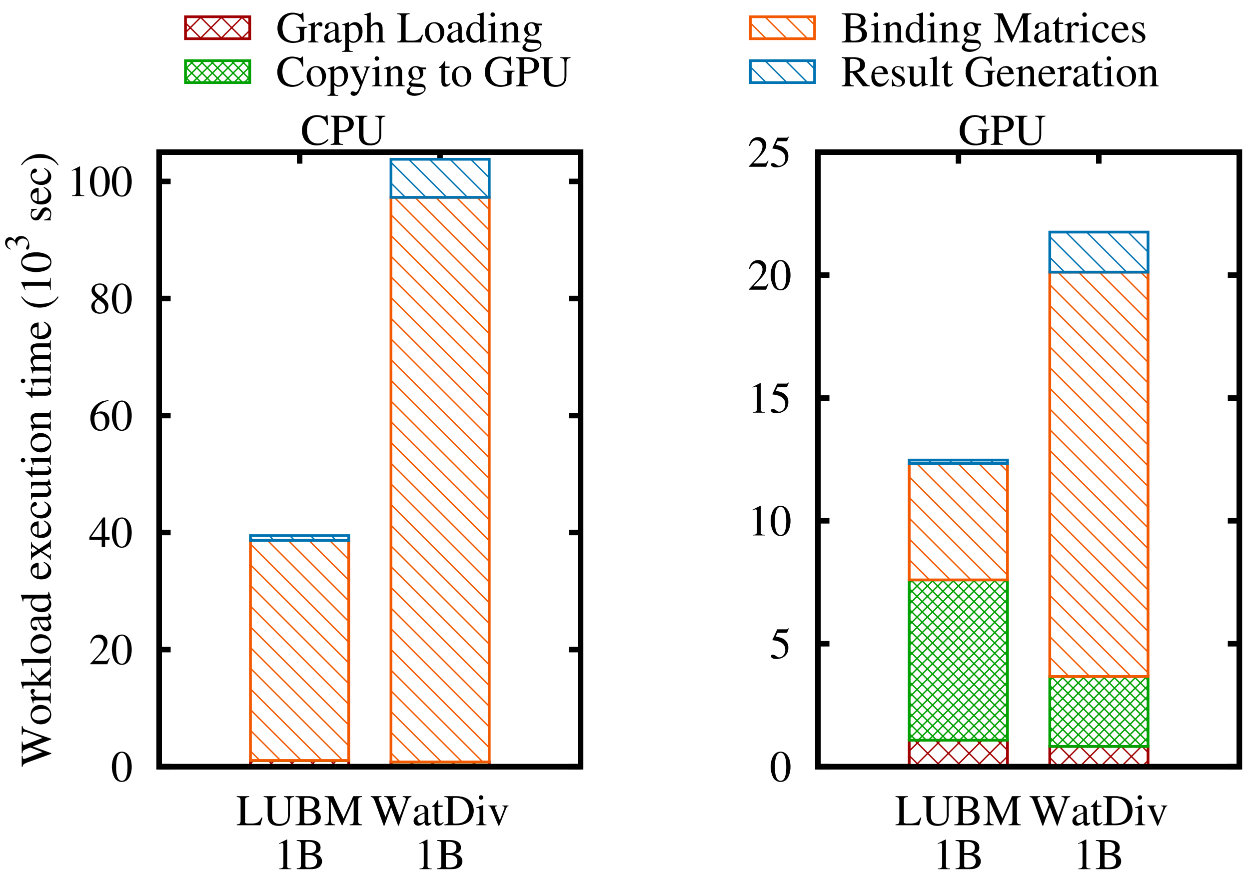
13B Triples - Shaheen



- CombBLAS
  - Scales with *sqrt*(p), where p: number of cores

Extra:

Workload evaluation



Extra:

LUBM-10B query times (seconds)

	L1	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**
AdPart	5.12	**0.12**	**0.24**	**0.07**	**0.08**	3.51	4.84
MAGiQ (CombBLAS)	**3.08**	0.93	0.67	1.66	0.61	**1.36**	**3.79**

Extra:

Loading time (minutes)

Dataset	RDF-3X	gStore	Virtuoso	Wukong	MAGiQ
WatDiv-100M	18	40	9	4	**1**
YAGO2	78	63	50	9	**3**
LUBM-1B	447	n/a	191	57	**16**
Bio2RDF	n/a	n/a	331	n/a	**92**