RDF Stores
and Graph Databases

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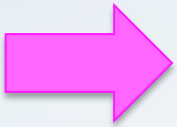
RDF Stores



Part 1: Querying RDF(S P O) tables using SQL

Part 2: Practical Session (RDF graphs)

Part 3: SQL-based RDF Stores

Part 4: MashQL (Graph Query Formulation)

Keywords: RDF, RDF Stores, querying SPO Table, Graph Databases, Querying Graph, self joins, RDF3X, Oracle Semantic Technology, C-Store, vertical patronizing, MashQL, Graph Signature, Semantic Web, Data Web,

RDF as a Data Model

RDF (Resource Description Framework) is the Data Model behind the Semantic/Data Web.

RDF is a graph-based data model.

In RDF, Data is represented as triples: <Subject, Predicate, Object>, or in short: <S,P,O>.

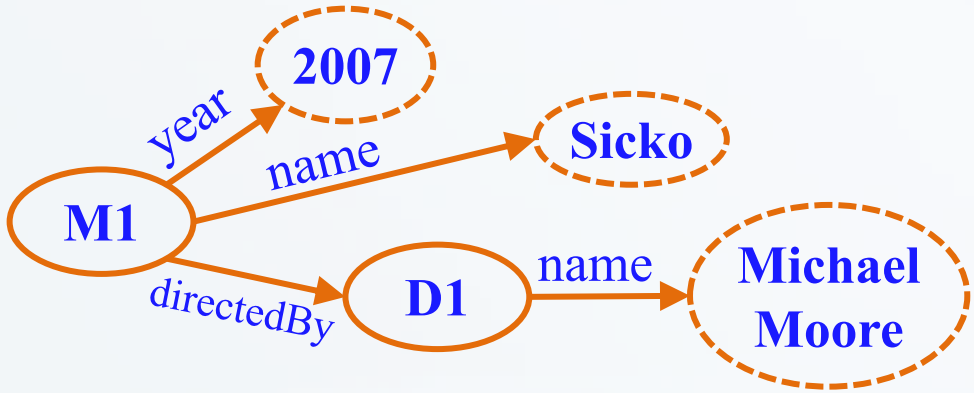
RDF as a Data Model

RDF's way of representing data as triples is more elementary than Databases or XML.

- This enables easy data integration and interoperability between systems (as will be demonstrated later).

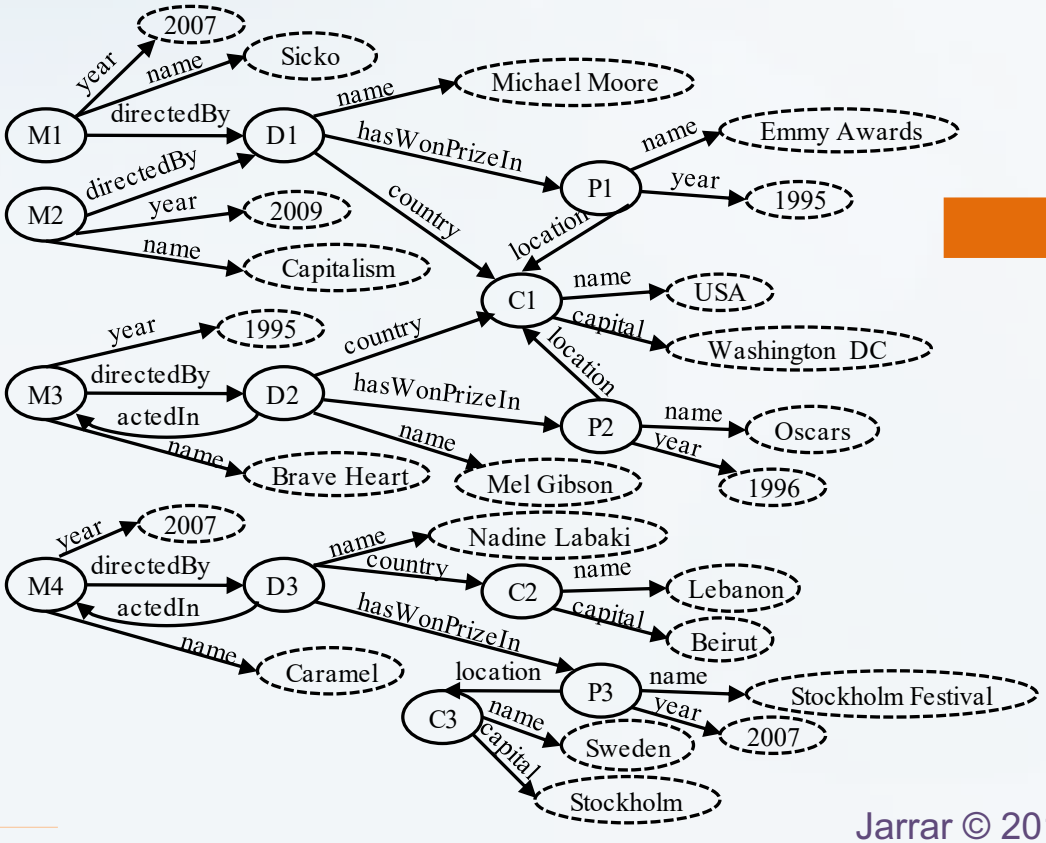
- EXAMPLE: the fact that the movie *Sicko* (2007) is directed by Michael Moore from the USA can be represented by the following triples which form a directed labeled graph:

```
< M1, name, Sicko >
< M1, year, 2007 >
< M1, directedBy, D1 >
< D1, name, Michael Moore >
< D1, country, C1 >
< C1, name, USA>
```



RDF graphs as an SPO table

An RDF Graph can stored in one long and thin <S,P,O> table in RDBMS



S	P	O
M1	year	2007
M1	Name	Sicko
M1	directedBy	D1
M2	directedBy	D1
M2	Year	2009
M2	Name	Capitalism
M3	Year	1995
M3	directedBy	D2
M3	Name	Brave Heart
M4	Year	2007
M4	directedBy	D3
M4	Name	Caramel
D1	Name	Michael Moore
D1	hasWonPrizeIn	P1
D1	Country	C1
D2	Counrty	C1
D2	hasWonPrizeIn	P2
D2	Name	Mel Gibson
D2	actedIn	M3
D3	Name	Nadine Labaki
D3	Country	C2
D3	hasWonPrizeIn	P3
D3	actedIn	M4
…	…	…

RDF graphs as an SPO table

How do we query graph-shaped data stored in one relational table?

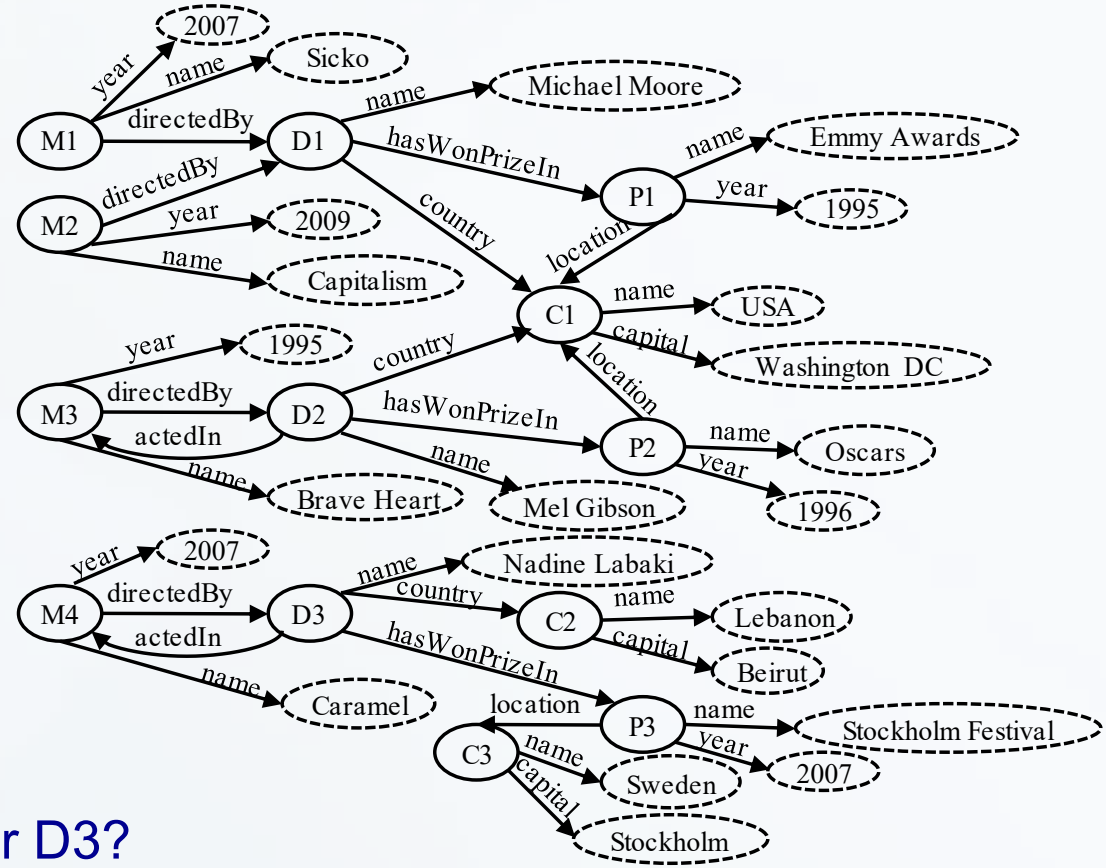
How do we traverse a graph stored in one relational table?

→ Using self joins!

S	P	O
M1	year	2007
M1	Name	Sicko
M1	directedBy	D1
M2	directedBy	D1
M2	Year	2009
M2	Name	Capitalism
M3	Year	1995
M3	directedBy	D2
M3	Name	Brave Heart
M4	Year	2007
M4	directedBy	D3
M4	Name	Caramel
D1	Name	Michael Moore
D1	hasWonPrizeIn	P1
D1	Country	C1
D2	Counrty	C1
D2	hasWonPrizeIn	P2
D2	Name	Mel Gibson
D2	actedIn	M3
D3	Name	Nadine Labaki
D3	Country	C2
D3	hasWonPrizeIn	P3
D3	actedIn	M4
…	…	…

How to Query RDF data stored in SPO table?

S	P	O
M1	year	2007
M1	Name	Sicko
M1	directedBy	D1
M2	directedBy	D1
M2	Year	2009
M2	Name	Capitalism
M3	Year	1995
M3	directedBy	D2
M3	Name	Brave Heart
M4	Year	2007
M4	directedBy	D3
M4	Name	Caramel
D1	Name	Michael Moore
D1	hasWonPrizeIn	P1
…	…	…



Exercises:

(1) What is the name of director D3?

(2) What is the name of the director of the movie M1?

(3) List all the movies who have directors from the USA and their directors.

(4) List all the names of the directors from Lebanon who have won prizes and the prizes they have won.

How to Query RDF data stored in SPO table?

Exercise 1: A simple query.

- What is the name of director D3?
- Consider the table `MoviesTable(s,p,o).`
- SQL:

```
Select o
From MoviesTable T
Where T.s = 'D3' AND T.p = 'Name';
```

Answer: Nadine Labaki

S	P	O
M1	year	2007
M1	Name	Sicko
M1	directedBy	D1
M2	directedBy	D1
M2	Year	2009
M2	Name	Capitalism
M3	Year	1995
M3	directedBy	D2
M3	Name	Brave Heart
M4	Year	2007
M4	directedBy	D3
M4	Name	Caramel
D1	Name	Michael Moore
D1	hasWonPrizeIn	P1
D1	Country	C1
D2	Counrty	C1
D2	hasWonPrizeIn	P2
D2	Name	Mel Gibson
D2	actedIn	M3
D3	Name	Nadine Labaki
D3	Country	C2
D3	hasWonPrizeIn	P3
D3	actedIn	M4
…	…	…

How to Query RDF data stored in SPO table?

Exercise 2: A path query with 1 join.

- What is the name of the director of the movie M1.
- Consider the table `MoviesTable (s,p,o)`.
- SQL:

```
Select T2.o
From MoviesTable T1, MoviesTable T2
Where {T1.s = 'M1' AND
       T1.p = 'directedBy' AND
       T1.o = T2.s AND
       T2.p = 'name'};
```

Answer: Michael Moore

S	P	O
M1	year	2007
M1	Name	Sicko
M1	directedBy	D1
M2	directedBy	D1
M2	Year	2009
M2	Name	Capitalism
M3	Year	1995
M3	directedBy	D2
M3	Name	Brave Heart
M4	Year	2007
M4	directedBy	D3
M4	Name	Caramel
D1	Name	Michael Moore
D1	hasWonPrizeIn	P1
D1	Country	C1
D2	Counrty	C1
D2	hasWonPrizeIn	P2
D2	Name	Mel Gibson
D2	actedIn	M3
D3	Name	Nadine Labaki
D3	Country	C2
D3	hasWonPrizeIn	P3
D3	actedIn	M4
…	…	…

How to Query RDF data stored in SPO table?

Exercise 3: A path query with 2 joins.

- List all the movies who have directors from the USA and their directors.
- Consider the table `MoviesTable(s,p,o)`.
- SQL:

```
Select T1.s, T1.o
From MoviesTable T1, MoviesTable T2,
     MoviesTable T3
Where {T1.o = T2.s AND
       T2.o = T3.s AND
       T1.p = 'directedBy' AND
       T2.p = 'country' AND
       T3.p = 'name' AND
       T3.o = 'USA'};
```

Answer: M1 D1; M2 D1; M3 D2

S	P	O
M1	year	2007
M1	Name	Sicko
M1	directedBy	D1
M2	directedBy	D1
M2	Year	2009
M2	Name	Capitalism
M3	Year	1995
M3	directedBy	D2
M3	Name	Brave Heart
…	…	…
D1	Name	Michael Moore
D1	hasWonPrizeIn	P1
D1	Country	C1
D2	Counrty	C1
D2	hasWonPrizeIn	P2
D2	Name	Mel Gibson
D2	actedIn	M3
…	…	…
C1	Name	USA
C1	Capital	Washington DC
C2	Name	Lebanon
C2	Capital	Beirut
…	…	…

How to Query RDF data stored in SPO table?

Exercise 4: Star query.

- List all the names of the directors from Lebanon who have won prizes and the prizes they have won.
- Consider the table MoviesTable (S,P,O).

```
Select T1.o, T4.o
From MoviesTable T1, MoviesTable T2,
     MoviesTable T3, MoviesTable T4
Where {T1.p = 'name' AND
       T2.s = T1.s AND
       T2.p = 'country' AND
       T2.o = T3.s AND
       T3.p = 'name' AND
       T3.o = 'Lebanon' AND
       T4.s = T1.s AND
       T4.p = 'hasWonPrizeIn'};
```

S	P	O
D1	Name	Michael Moore
D1	hasWonPrizeIn	P1
D1	Country	C1
D2	Counrty	C1
D2	hasWonPrizeIn	P2
D2	Name	Mel Gibson
D2	actedIn	M3
D3	Name	Nadine Labaki
D3	Country	C2
D3	hasWonPrizeIn	P3
D3	actedIn	M4
…	…	…
C1	Name	USA
C1	Capital	Washington DC
C2	Name	Lebanon
C2	Capital	Beirut
…	…	…

Answer: 'Nadine Labaki' , P3

RDF Stores

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Part 2: Practical Session (RDF graphs)

Part 3: SQL-based RDF Stores

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Practical Session

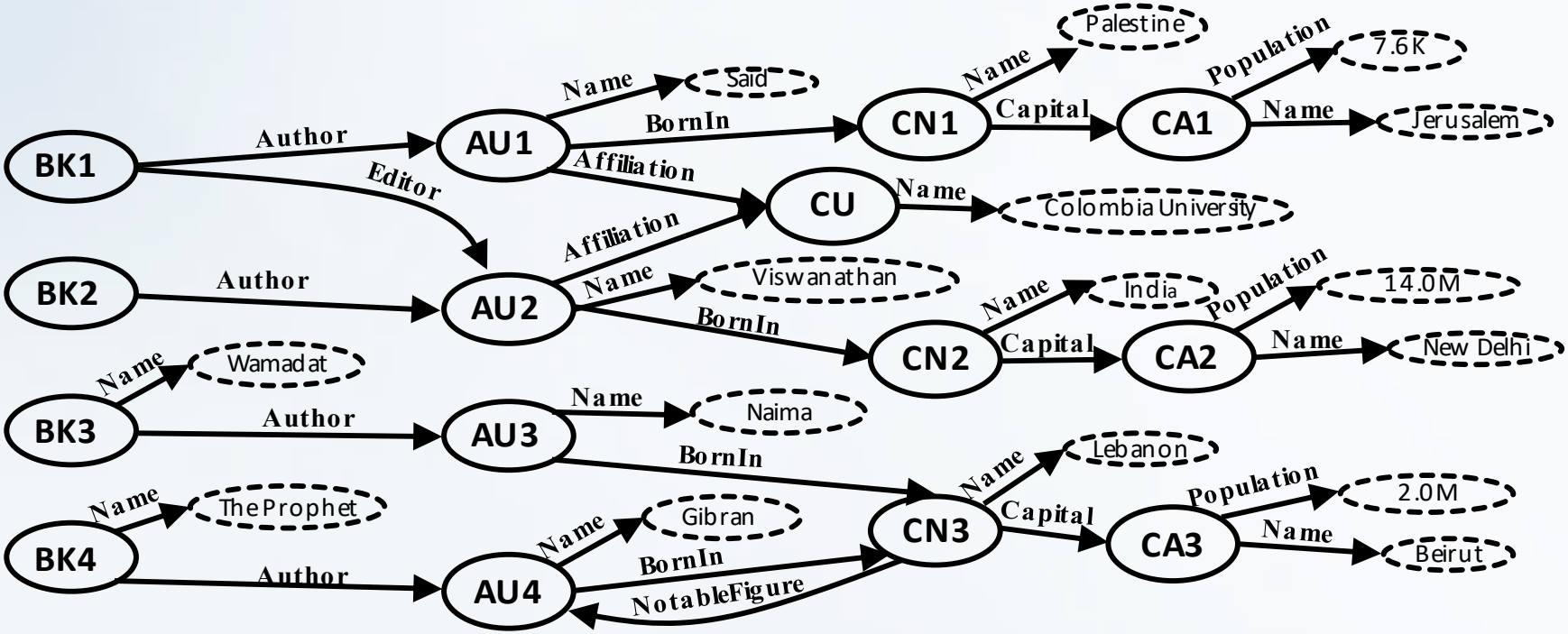
Given the RDF graph in the next slide, do the following:

(1) Insert the data graph as <S,P,O> triples in a 3-column table in any DBMS.

Schema of the table: Books (Subject, Predicate, Object)

(2) Write the following queries in SQL and execute them over the newly created table:

- List all the authors born in a country which has the name Palestine.
- List the names of all authors with the name of their affiliation who are born in a country whose capital's population is 14M. Note that the author must have an affiliation.
- List the names of all books whose authors are born in Lebanon along with the name of the author.



This data graph is about books. It talks about four books (BK1-BK4). Information recorded about a book includes data such as; its author, affiliation, country of birth including its capital and the population of its capital.

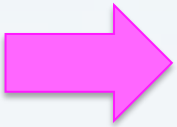
Practical Session

- Each student should work alone.
- The student is encouraged to first answer each query mentally from the graph before writing and executing the SQL query, and to compare the results of the query execution with his/her expected results.
- The student is strongly recommended to write two additional queries, execute them on the data graph, and hand them along with the required queries.
- The student must **highlight problems** and challenges of executing queries on graph-shaped data and propose solutions to the problem.
- Each student must expect to present his/her queries at class and, more importantly, he/she must be ready to discuss the problems of querying graph-shaped data and his/her proposed solutions.
- The final delivery should include **(i)** a snapshot of the built table, **(ii)** the SQL queries, **(iii)** The results of the queries, and **(iv)** a one-page discussion of the problems of querying graph-shaped data and the proposed possible solutions. These must be handed in a report form in PDF Format.

RDF Stores

Part 1: Querying RDF(S P O) tables using SQL

Part 2: Practical Session (RDF graphs)



Part 3: SQL-based RDF Stores

Part 4: MashQL (Graph Query Formulation)

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Complexity of querying graph-shaped data

Where does the complexity of querying graph-shaped data stored in a relational table lie?

The complexity of querying a data graph lies in the many self-joins that are to be performed on the table.

Accessing multiple properties for a resource requires subject-subject joins (Star-shaped queries).

Path expressions require subject-object joins.

In general, **a query with *n* edges on an SPO table requires *n-1* self-joins** of that table.

Solution-1: Indexes and Dictionaries

This solution is called RDF3X, suggested by:

Neumann T, Weikum G: RDF3X: RISC style engine for RDF. VLDB'2008.

Build Indexes.

- On each column: S, P, O
- On Permutations of two columns: SP, SO, PS, PO, …
- On Permutation of three columns: SPO, SOP, PSO, POS, OSP, OPS, …

Dictionary Encoding String Data?

- Replacing all literals by IDs.
- Triple stores are compressed.
- Allows for faster comparison and matching operations.

Solution-2: Vertically Partitioning

This solution is called C-Store, suggested by:

Abadi et al, Scalable Semantic Web Data Management Using Vertical Partitioning. In VLDB 2007.

Subj.	Prop.	Obj.
ID1	type	BookType
ID1	title	"XYZ"
ID1	author	"Fox, Joe"
ID1	copyright	"2001"
ID2	type	CDType
ID2	title	"ABC"
ID2	artist	"Orr, Tim"
ID2	copyright	"1985"
ID2	language	"French"
ID3	type	BookType
ID3	title	"MNO"
ID3	language	"English"
ID4	type	DVDType
ID4	title	"DEF"
ID5	type	CDType
ID5	title	"GHI"
ID5	copyright	"1995"
ID6	type	BookType
ID6	copyright	"2004"

Six Vertically Partitioned Tables:

Type

ID1	BookType
ID2	CDType
ID3	BookType
ID4	DVDType
ID5	CDType
ID6	BookType

Author

ID1	"Fox, Joe"

Title

ID1	"XYZ"
ID2	"ABC"
ID3	"MNO"
ID4	"DEF"
ID5	"GHI"

Artist

ID2	"Orr, Tim"

Copyright

ID1	"2001"
ID2	"1985"
ID5	"1995"
ID6	"2004"

Language

ID2	"French"
ID3	"English"

- Triples table is rewritten into *n* two column tables where *n* is the number of unique properties.
- In each of these tables, the first column contains the subjects that define that property and the second column contains the object values for those subjects.
- An experimental implementation of this approach was performed using an open source column-oriented database system (C-Store).

Solution-3: Subject-Property Matrixes

This solution suggested by Oracle 11g, called **Oracle Semantic Technology:**

Chong E, Das S, Eadon G, Srinivasan J: An efficient SQL-based RDF querying scheme. VLDB'05.

Subj.	Prop.	Obj.
ID1	type	BookType
ID1	title	"XYZ"
ID1	author	"Fox, Joe"
ID1	copyright	"2001"
ID2	type	CDType
ID2	title	"ABC"
ID2	artist	"Orr, Tim"
ID2	copyright	"1985"
ID2	language	"French"
ID3	type	BookType
ID3	title	"MNO"
ID3	language	"English"
ID4	type	DVDType
ID4	title	"DEF"
ID5	type	CDType
ID5	title	"GHI"
ID5	copyright	"1995"
ID6	type	BookType
ID6	copyright	"2004"

Clustered Property Table:

Property Table

Subj.	Type	Title	copyright
ID1	BookType	"XYZ"	"2001"
ID2	CDType	"ABC"	"1985"
ID3	BookType	"MNP"	NULL
ID4	DVDType	"DEF"	NULL
ID5	CDType	"GHI"	"1995"
ID6	BookType	NULL	"2004"

Left-Over Triples

Subj.	Prop.	Obj.
ID1	author	"Fox, Joe"
ID2	artist	"Orr, Tim"
ID2	language	"French"
ID3	language	"English"

- A clustered property table, contains clusters of properties tend to be defined together.
- Multiple property tables with different clusters of properties may be created to optimize queries.
- A key requirement for this property table is that a particular property may only appear in at most one property table.
- Advantage: Some queries can be answered directly from the property table with no joins.
  - Ex: retrieve the title of the book authored in 2001.

Solution-3: Subject-Property Matrixes

This solution suggested by Oracle 11g, called **Oracle Semantic Technology:**

Chong E, Das S, Eadon G, Srinivasan J: An efficient SQL-based RDF querying scheme. VLDB'05.

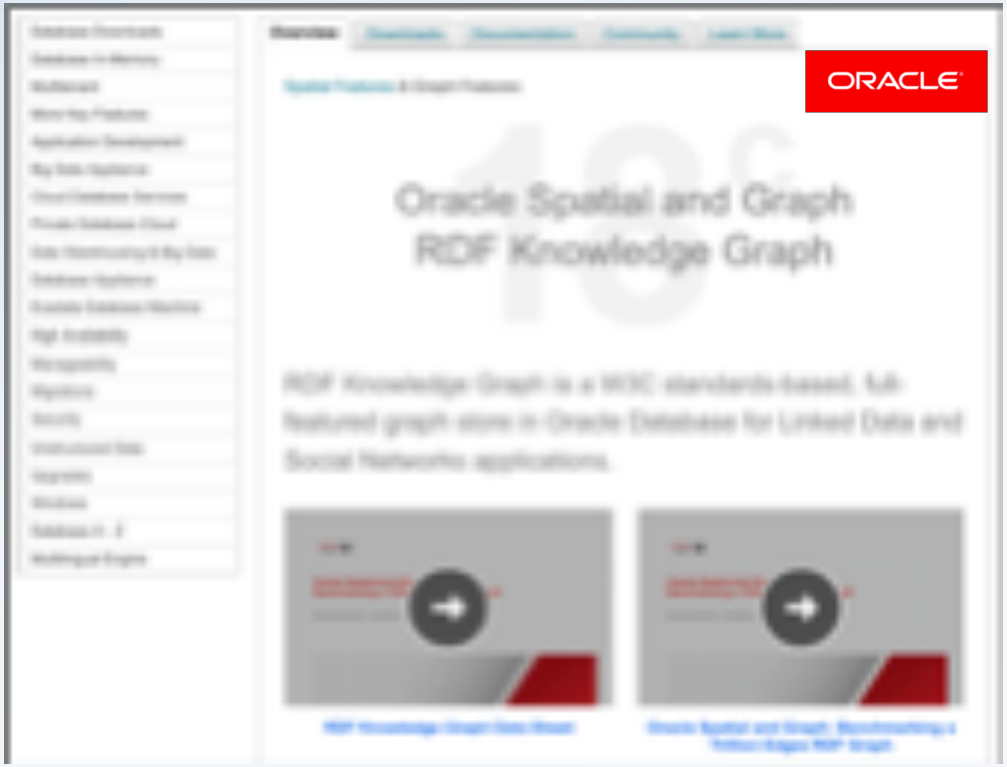
Oracle allows you write graph queries inside SQL using the SEM_Match table function ➔

```
SEM_MATCH(
    query           VARCHAR2,
    models          SEM_MODELS,
    rulebases       SEM_RULEBASES,
    aliases         SEM_ALIASES,
    filter          VARCHAR2,
    index_status    VARCHAR2,
    options         VARCHAR2,
    graphs          SEM_GRAPHS,
    named_graphs    SEM_GRAPHS
) RETURN ANYDATASET;
```

Example

```
Select x, y
FROM TABLE(SEM_MATCH(
'{?x :grandParentOf ?y. ?x rdf:type :Male}',
SEM_Models('family'),
SEM_Rulebases('RDFS','family_rb'),
SEM_ALIASES(SEM_ALIAS('','http://www.example.org/family/')), null));
```

Later: Oracle Spatial and Graph



As part of Oracle Spatial and Graph, Oracle **delivers advanced RDF Knowledge Graph data management and analysis.**

With native support for World Wide Web Consortium (W3C) standards ? RDF and OWL are standards for representing and defining semantic data and SPARQL is a query language designed specifically for graph analysis ? application developers benefit from the industry's leading open, scalable graph data platform on Oracle Database with triple-level security, and high performance and availability. RDF Graphs can create a unified metadata layer for disparate applications that facilitates identification, integration, and discovery. **RDF Graphs are becoming central to linked data and social network applications common in healthcare and life sciences, finance, media and intelligence communities.**

RDF Stores

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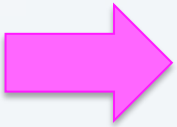

Part 4: MashQL (Graph Query Formulation)

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MashQL (Query Formulation & indexing Graphs)

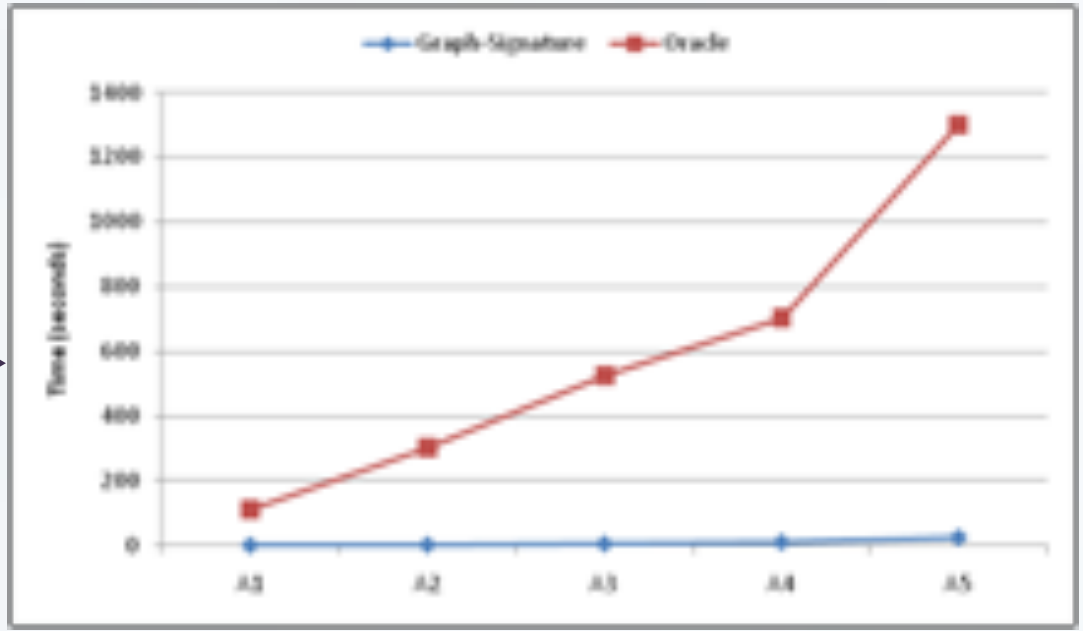
(Research started at the University of Cyprus, then at Birzeit University)

What about summarizing the data graph, and instead of querying the original data, we query the summary and get the same results?

What about summarizing 15M SPO triples into less then 0.5M?

This is called **Graph Signature** Indexing. It is currently in research at Birzeit University.

Initial comparison between GS performance and Oracle's Semantic Technologies

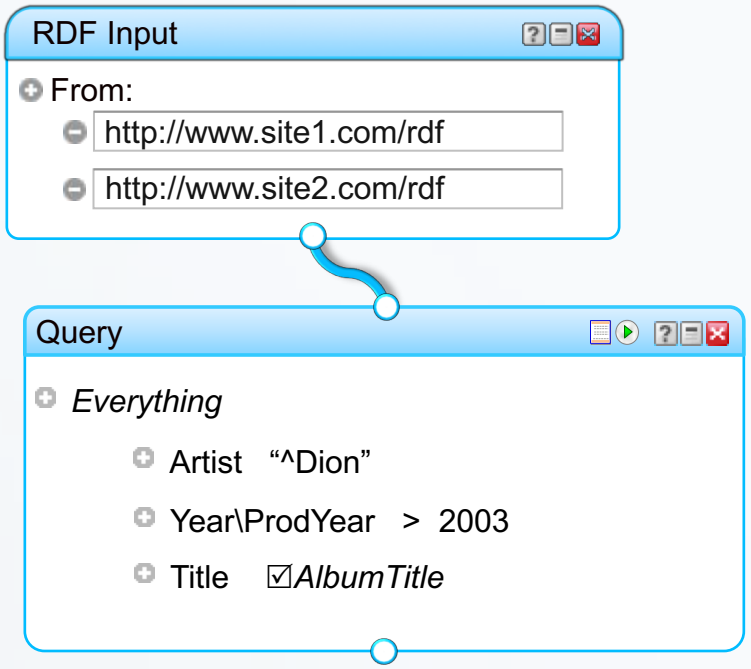


MashQL (Query Formulation & indexing Graphs)

Based on [2]

A graphical query formulation language for the Data Web

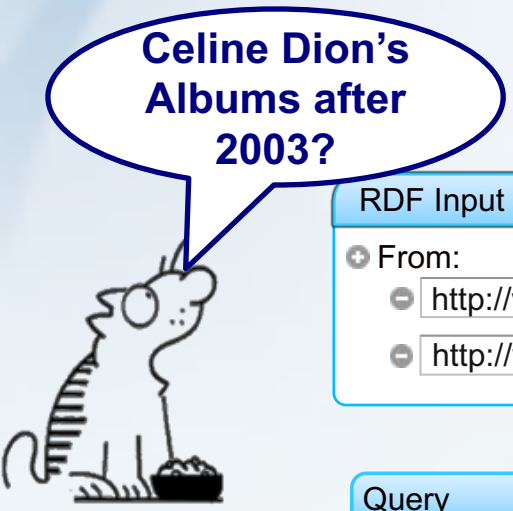
A general structured-data retrieval language (not merely an interface)



Addresses all of the following challenges:

- ✓ *The user does not know the schema.*
- ✓ There is no offline or inline schema\ontology.
- ✓ The query may involve multiple sources.
- ✓ The query language is expressive (not a single-purpose interface)

MashQL Example



RDF Input

From:
- http://www.site1.com/rdf
- http://www.site2.com/rdf

Query

Everything
- Artist "^Dion"
- Year\ProdYear > 2003
- Title ☑*AlbumTitle*

www.site1.com/rdf

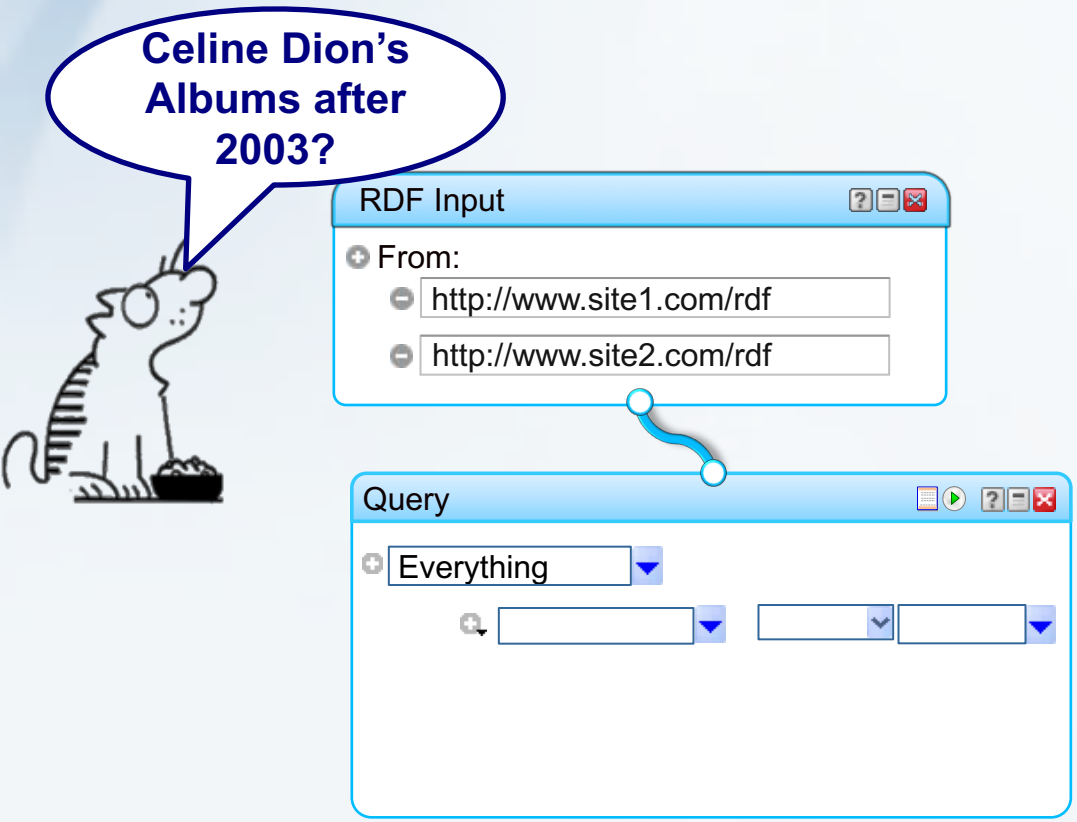
```
:A1 :Title "Taking Chances"
:A1 :Artist "Dion C."
:A1 :ProdYear  2007
:A1 :Producer "Peer Astrom"
:A2 :Title "Monodose"
:A2 :Artist "Ziad Rahbani"
```

www.site2.com/rdf

```
:B1 rdf:Type bibo:Album
:B1 :Title  "The prayer"
:B1 :Artist "Celine Dion"
:B1 :Artist "Josh Groban"
:B1 :Year   2008
:B2 rdf:Type bibo:Album
:B2 :Title "Miracle"
:B2 :Author "Celine Dion"
:B2 :Year   2004
```

- Interactive Query Formulation.
- MashQL queries are translated into and executed as SPARQL.

MashQL Example



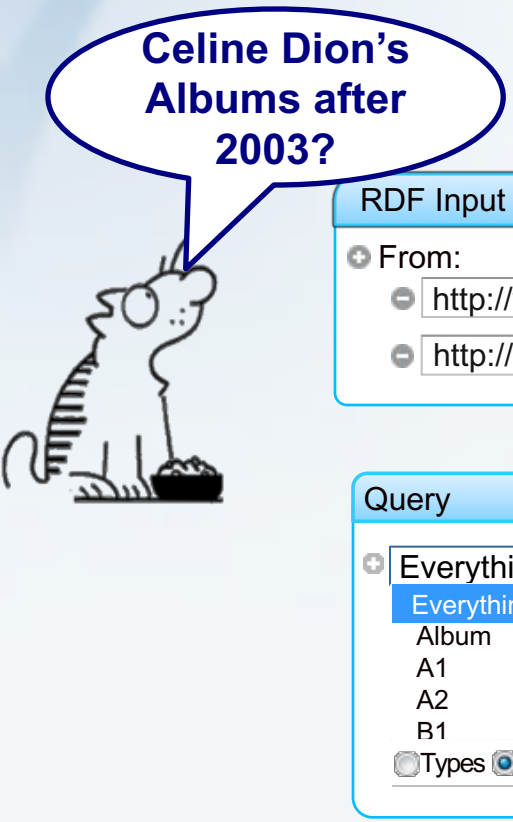
www.site1.com/rdf

```
:A1 :Title "Taking Chances"
:A1 :Artist "Dion C."
:A1 :ProdYear  2007
:A1 :Producer "Peer Astrom"
:A2 :Title "Monodose"
:A2 :Artist "Ziad Rahbani"
```

www.site2.com/rdf

```
:B1 rdf:Type bibo:Album
:B1 :Title  "The prayer"
:B1 :Artist "Celine Dion"
:B1 :Artist "Josh Groban"
:B1 :Year   2008
:B2 rdf:Type bibo:Album
:B2 :Title "Miracle"
:B2 :Author "Celine Dion"
:B2 :Year   2004
```

MashQL Example



www.site1.com/rdf

```
:A1 :Title "Taking Chances"
:A1 :Artist "Dion C."
:A1 :ProdYear  2007
:A1 :Producer "Peer Astrom"
:A2 :Title "Monodose"
:A2 :Artist "Ziad Rahbani"
```

www.site2.com/rdf

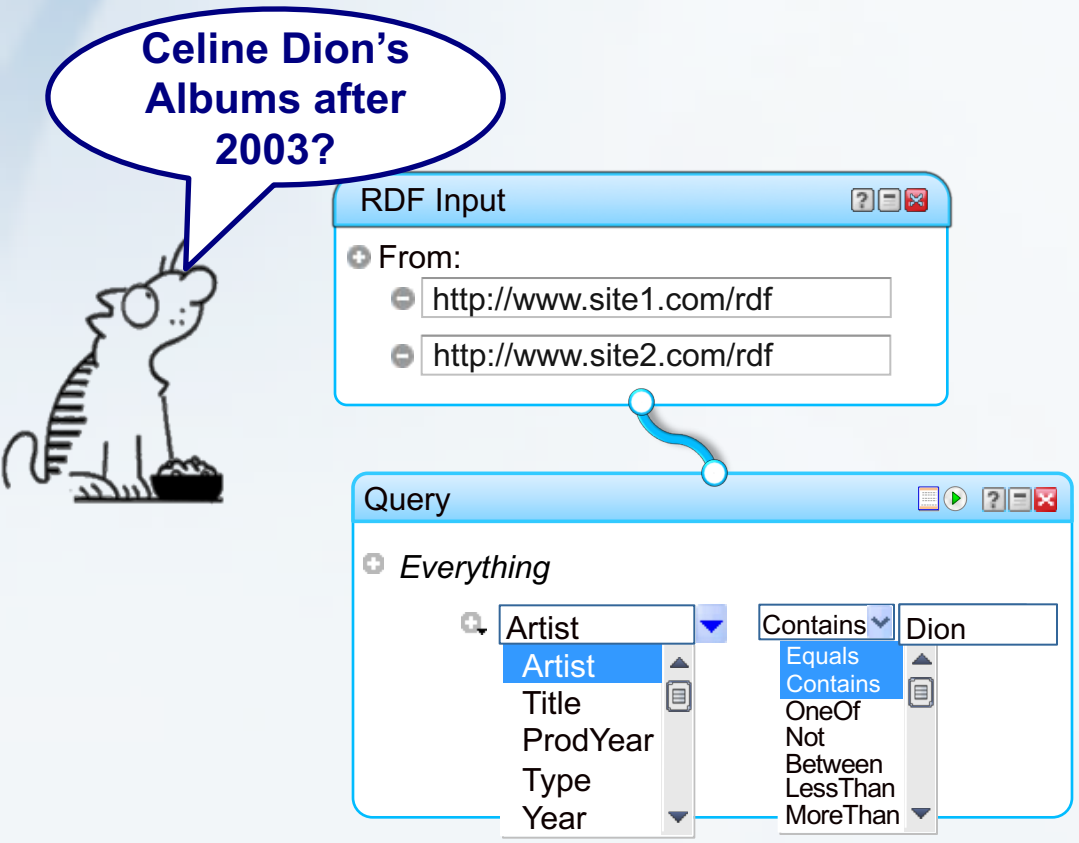
```
:B1 rdf:Type bibo:Album
:B1 :Title  "The prayer"
:B1 :Artist "Celine Dion"
:B1 :Artist "Josh Groban"
:B1 :Year   2008
:B2 rdf:Type bibo:Album
:B2 :Title "Miracle"
:B2 :Author "Celine Dion"
:B2 :Year   2004
```

Background queries

```
SELECT X WHERE {?X ?P ?O}
Union
SELECT X WHERE {?S ?P ?X}
```

```
SELECT X WHERE {?S rdf:Type ?X}
```

MashQL Example



www.site1.com/rdf

```
:A1 :Title "Taking Chances"
:A1 :Artist "Dion C."
:A1 :ProdYear  2007
:A1 :Producer "Peer Astrom"
:A2 :Title "Monodose"
:A2 :Artist "Ziad Rahbani"
```

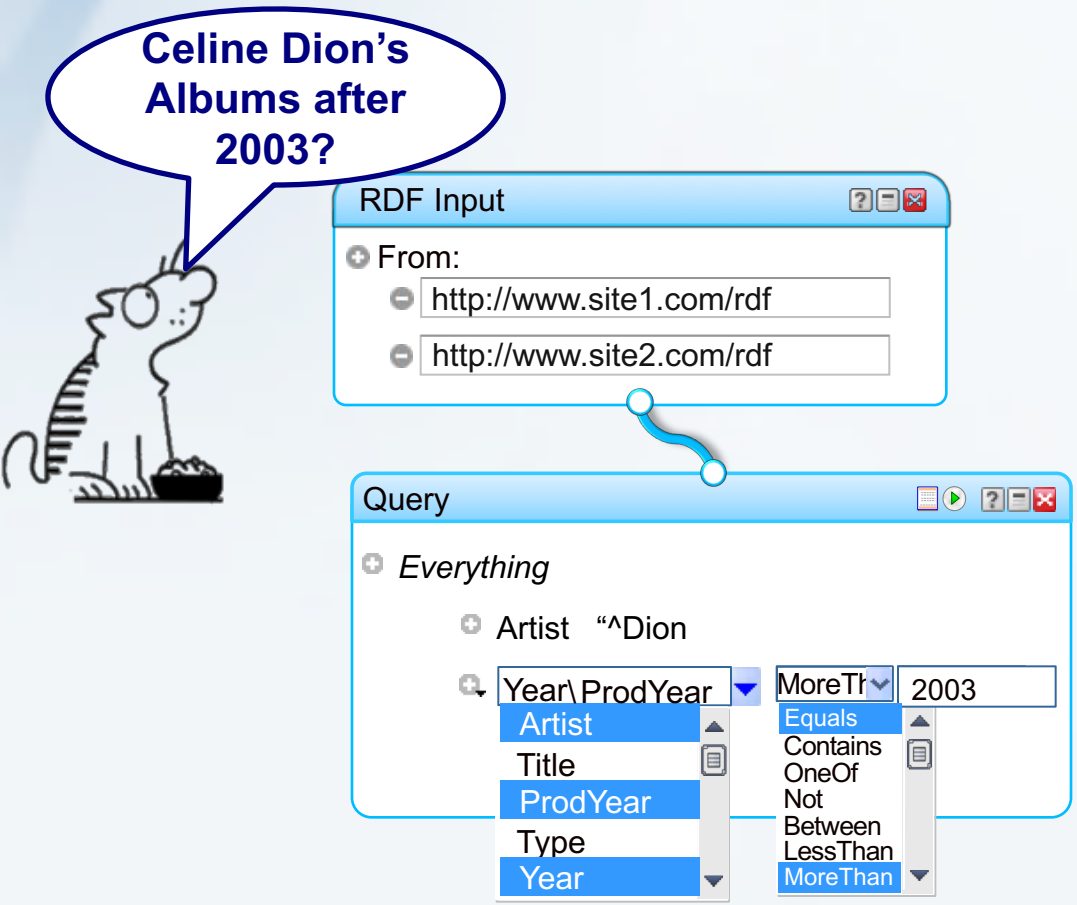
www.site2.com/rdf

```
:B1 rdf:Type bibo:Album
:B1 :Title  "The prayer"
:B1 :Artist "Celine Dion"
:B1 :Artist "Josh Groban"
:B1 :Year   2008
:B2 rdf:Type bibo:Album
:B2 :Title "Miracle"
:B2 :Author "Celine Dion"
:B2 :Year   2004
```

Background query

```
SELECT P WHERE {?Everything ?P ?O}
```

MashQL Example



www.site1.com/rdf

```
:A1 :Title "Taking Chances"
:A1 :Artist "Dion C."
:A1 :ProdYear  2007
:A1 :Producer "Peer Astrom"
:A2 :Title "Monodose"
:A2 :Artist "Ziad Rahbani"
```

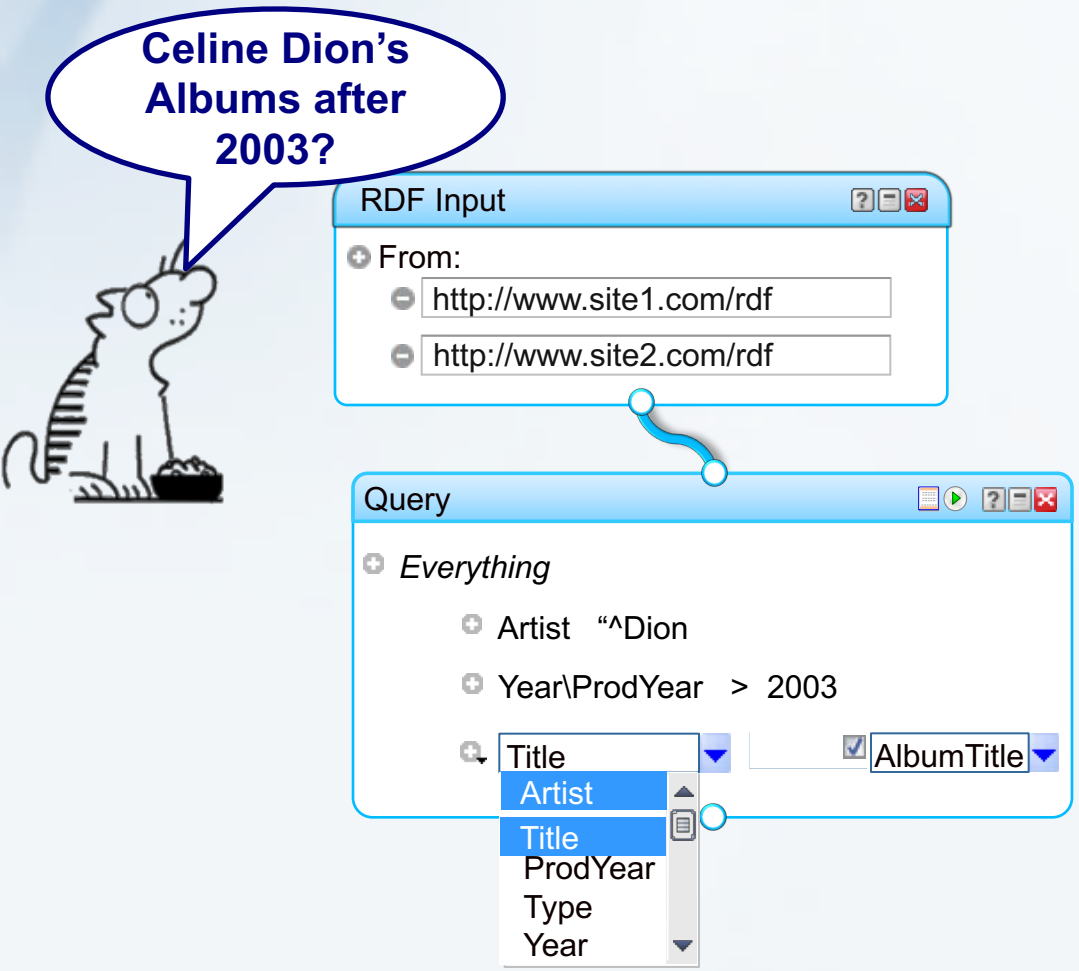
www.site2.com/rdf

```
:B1 rdf:Type bibo:Album
:B1 :Title  "The prayer"
:B1 :Artist "Celine Dion"
:B1 :Artist "Josh Groban"
:B1 :Year   2008
:B2 rdf:Type bibo:Album
:B2 :Title "Miracle"
:B2 :Author "Celine Dion"
:B2 :Year   2004
```

Background query

```
SELECT P WHERE {?Everything ?P ?O}
```

MashQL Example



www.site1.com/rdf

```
:A1 :Title "Taking Chances"
:A1 :Artist "Dion C."
:A1 :ProdYear  2007
:A1 :Producer "Peer Astrom"
:A2 :Title "Monodose"
:A2 :Artist "Ziad Rahbani"
```

www.site2.com/rdf

```
:B1 rdf:Type bibo:Album
:B1 :Title  "The prayer"
:B1 :Artist "Celine Dion"
:B1 :Artist "Josh Groban"
:B1 :Year   2008
:B2 rdf:Type bibo:Album
:B2 :Title "Miracle"
:B2 :Author "Celine Dion"
:B2 :Year   2004
```

Background query

```
SELECT P WHERE {?Everything ?P ?O}
```

MashQL Example

RDF Input

From:

http://www.site1.com/rdf

http://www.site2.com/rdf

Query

Everything

Artist "^Dion"

Year\ProdYear > 2003

Title ☑*AlbumTitle*

```
PREFIX S1: <http://site1.com/rdf>
PREFIX S2: <http://site1.com/rdf>
SELECT ?AlbumTitle
FROM <http://site1.com/rdf>
FROM <http://site2.com/rdf>
WHERE {
 {?X S1:Artist ?X1} UNION {?X S2:Artist ?X1}
 {?X S1:ProdYear ?X2} UNION {?X S2:Year ?X2}
 {{?X S1:Title ?AlbumTitle} UNION {?X
S2:Title ?AlbumTitle}}
 FILTER regex(?X1, "^Dion")
 FILTER (?X2 > 2003)}
```

MashQL Query Optimization

- The major challenge in MashQL is **interactivity**!
- User interaction must be within **100ms**.
- However, querying RDF is typically slow.
- How about dealing with huge datasets!?
- Implemented Solutions (i.e., Oracle) proved to perform weakly specially in MashQL background queries.

➡ **A query optimization solution was developed., called Graph Signature Index.**

MashQL Query Optimization: Graph Signature

‘Graph Signature’ optimizes RDF queries by :

Summarizing the RDF dataset
(Algorithms were developed)

Then, executing the queries on the summary instead of the original dataset
(A new execution plan was developed)

Experiments

- Experiments performed on 15M SPO triples (rows) of the Yago Dataset.
- Graph Signature Index of less than 500K was built on the data.
- Two sets of queries were performed, and the results were as follows:

Extreme-case linear queries of depth 1-5:

Query	A1	A2	A3	A4	A5
GS	0.344	1.953	5.250	10.234	24.672
Oracle	110.390	302.672	525.844	702.969	>20min

Queries that cover all MashQL Background queries some queries that might occur as the final queries generated in MashQL:

Query	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
GS	0.441	0.578	0.587	0.556	0.290	0.291	0.587	0.785	2.469
Oracle	25.640	29.875	29.593	29.641	19.922	21.922	62.734	64.813	32.703

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