Formal semantics of Cypher:
towards a standard language for querying property graphs

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Outline

Representing data as graphs

Most databases use the relational model

- Relational algebra in theory
- The language SQL in practice

Representing data as graphs

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- Relational algebra in theory
- The language SQL in practice

Some data have intrinsically the structure of graphs:

- Semantic web
- Social Networks
- Bioinformatic networks

Native representation of data as graphs allows:

- Efficient algorithms on graphs
- Pattern matching
- Optimisations

More and more ways to manipulate data as graphs

Data model

Property graphs, RDF

Query languages

Cypher, Gremlin, PGQL, SPARQL, G-Core

Engines

JanusGraph, Jena, Neo4j, Virtuoso

Domain

Fraud detection, Investigative journalism

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Cypher

- Language for querying and updating *property graphs*

- Invented by Neo Technology
- Originally, part of engine Neo4j $\longrightarrow$ commercial success
- Now, in multiple datagraph engines (e.g., SAP HANA Graph, Redis Graph, Agens Graph)

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The openCypher project

- Since 2015
- Seeks to standardise Cypher (SQL for property graphs?)
  - Community-led evolution
  - Complete specification

Short term goal

Full denotational semantics for the language Cypher.

- Industrial partnership Neo4j/University of Edinburgh
- Reverse engineering and formalisation from Neo4j
- Done semantics of the "core fragment' [Francis et al'18]
- Soon: semantics of the "update clauses

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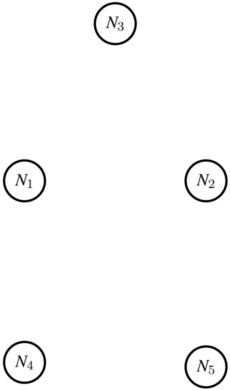
Long term goal

Design a standard language for querying property graphs: GQL.

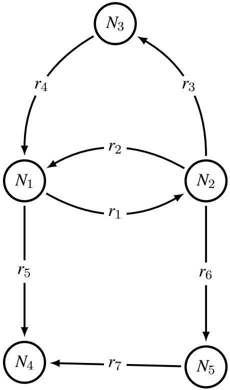
- Merging Cypher, PGQL, G-Core.
- Involvement of Neo Technology, Oracle and LDBC.

Outline



- Nodes : $N_1, N_2, \cdots, N_5$

Property graph



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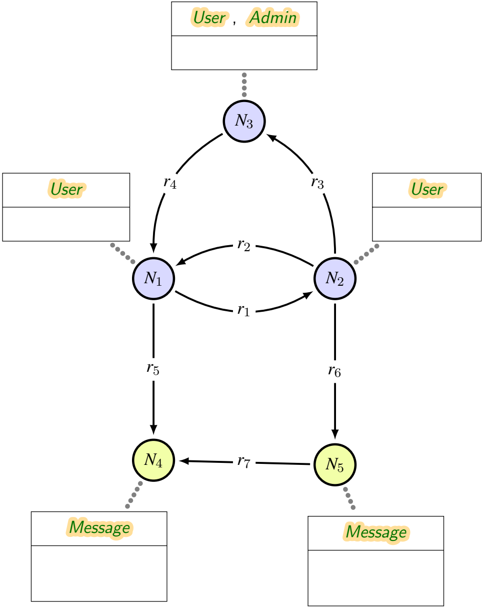
- Relationships : $r_1, r_2, \cdots, r_7$

Property graph



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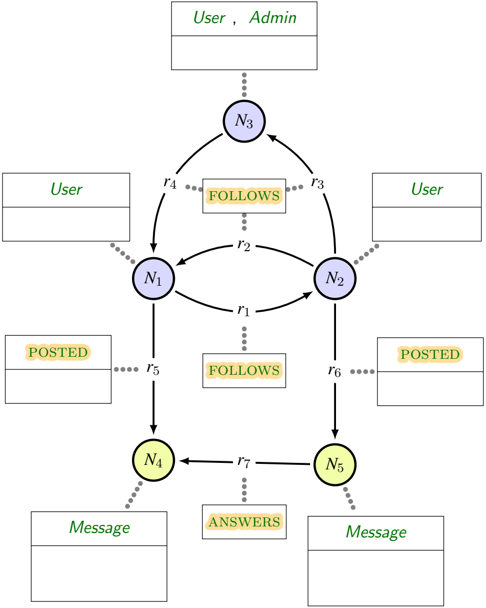
- Labels (de nœuds) :
  - *User*
  - *Message*

Property graph



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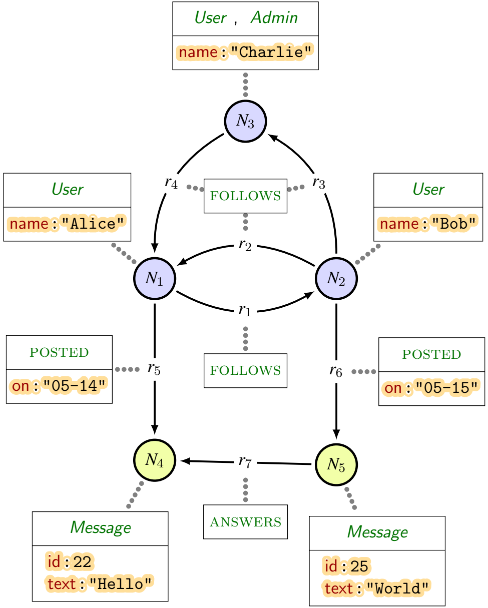
  - FOLLOWS
  - POSTED
  - ANSWERS

Property graph



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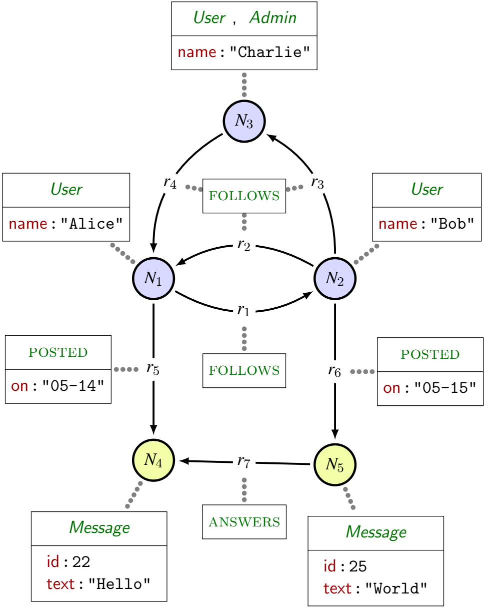
- Labels (de nœuds) :
  - *User*
  - *Message*
- Types (of relationships) :
  - FOLLOWS
  - POSTED
  - ANSWERS
- Properties (*i.e.* Key/Value pairs) :
  - name : "Alice"
  - id : 22
  - text : "Hello"

Outline

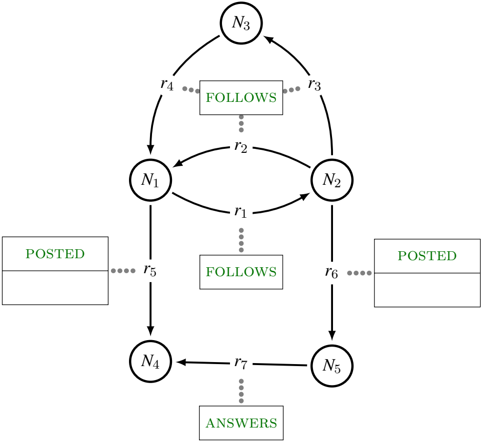
Data model for theoretical query languages



Graph database

- Relation bear types
- Node do not bear types (could be simulated)
- **Neither bears property**

Data model for theoretical query languages



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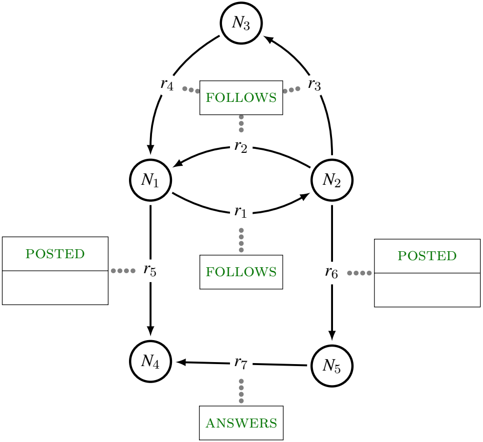

Graph database

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Finite number of relation types (and node types)

→ "Dataless graph"

Regular Path Query (RPQ) – Definition

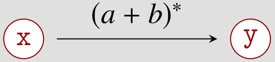
A: finite alphabet (of relation types)
N: nodes in the graph

Definition (RPQ R):

$$R = (x, E, y)$$

$$\begin{cases} E: & \text{regular expr. over } A \\ x, y: & \text{two variables} \end{cases}$$

Example:

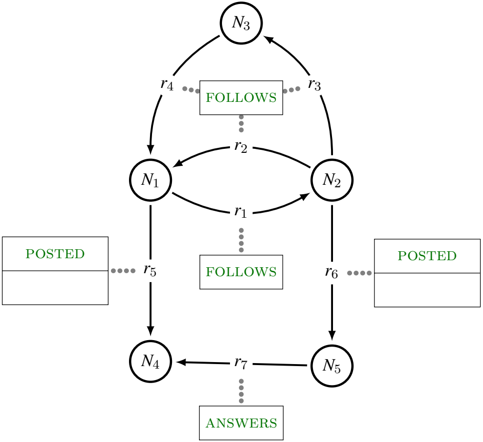


Definition (Answer to R):

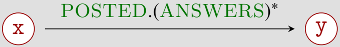
Set of the functions

$$F : \{x, y\} \longrightarrow N \ , \quad \exists u \in E, \ F(x) \xrightarrow{u} F(y)$$

Regular Path Query (RPQ) – Example 1



Query:



Answers:

$$F_1 : \quad x \mapsto N_1 \quad y \mapsto N_4$$
$$F_2 : \quad x \mapsto N_2 \quad y \mapsto N_5$$
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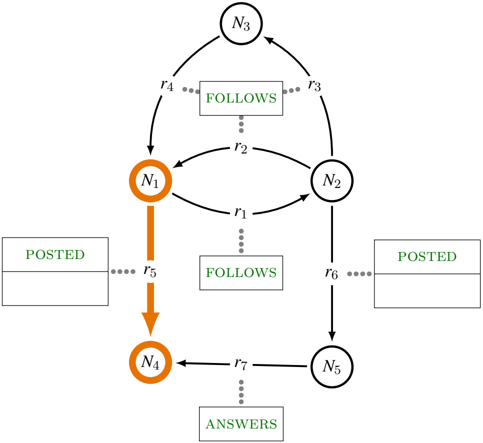

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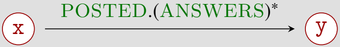

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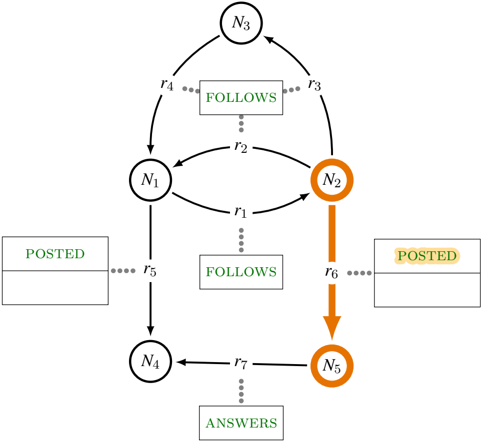

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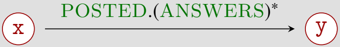

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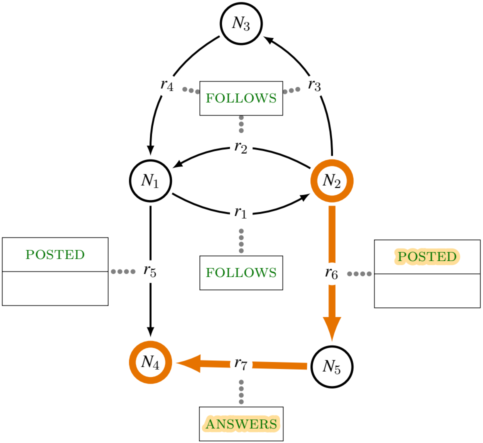

Query:

$x \xrightarrow{\text{POSTED.(ANSWERS)}^*} y$

Answers:

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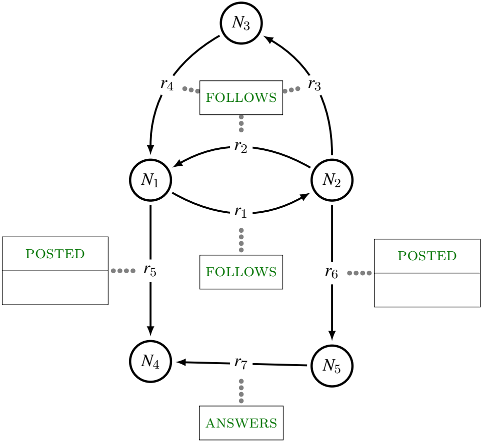

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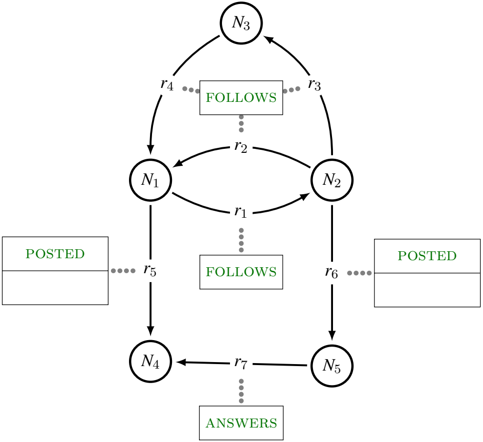

Query:

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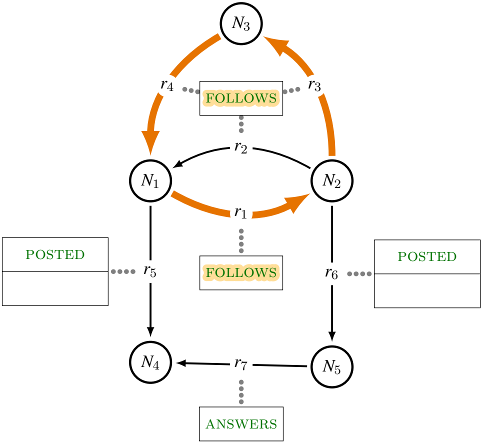

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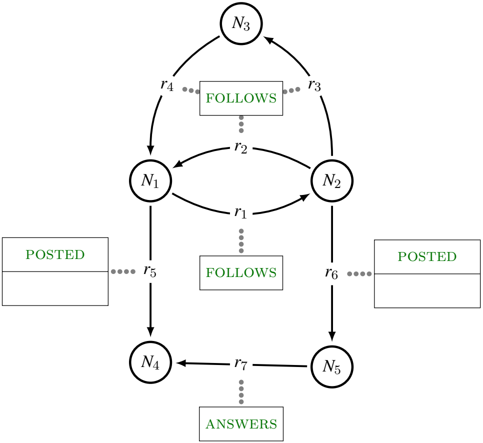

Query:

$x \xrightarrow{(\text{FOLLOWS})^*} y$

Answers:

$$
\begin{array}{llll}
F_1: & x \mapsto N_1 & y \mapsto N_1 \\
F_2: & x \mapsto N_1 & y \mapsto N_2 \\
F_3: & x \mapsto N_1 & y \mapsto N_3 \\
\vdots & \vdots & \vdots \\
F_9: & x \mapsto N_3 & y \mapsto N_3
\end{array}
$$

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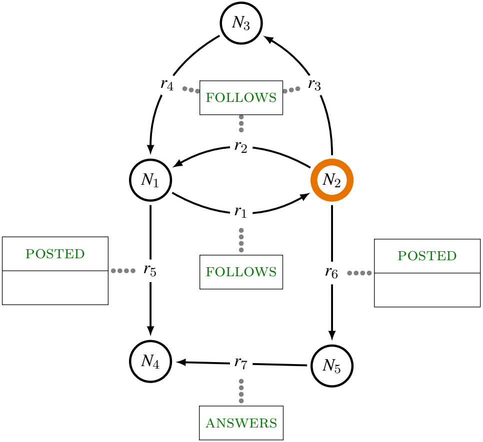

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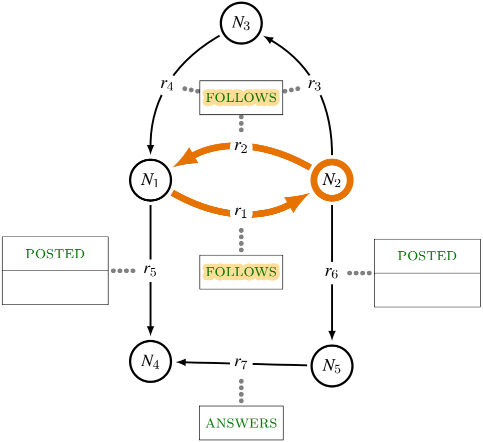

Query:

x —(FOLLOWS)*→ y

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$\vdots \quad \vdots \quad \vdots$

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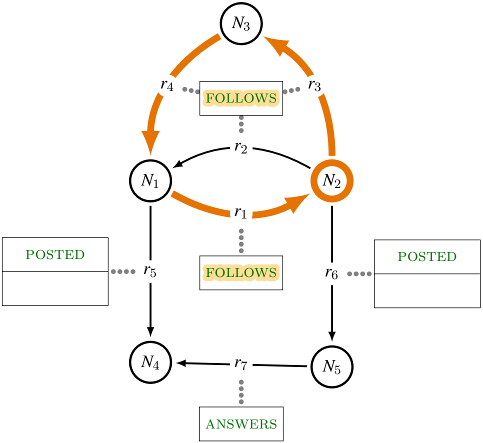

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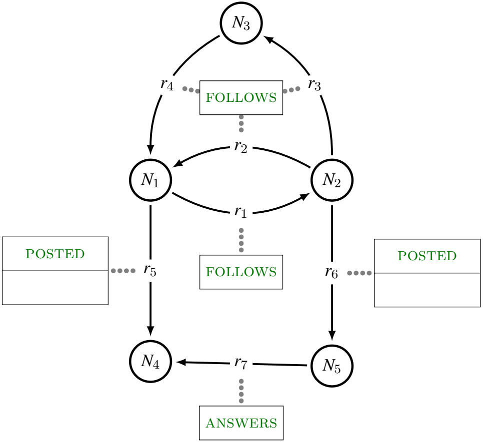

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F_3 :	$x \mapsto N_1$	$y \mapsto N_3$
⋮	⋮	⋮
F_9 :	$x \mapsto N_3$	$y \mapsto N_3$

→ ∞-many path realise F_1

→ RPQ follows set-semantics

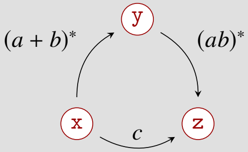
A: alphabet (of relation types)
N: nodes in the graph

Definition (a CRPQ C):

$$C = (R_1 \wedge R_2 \wedge \cdots \wedge R_n)$$

where $R_1,, \ldots, R_n$ are RPQs

Example:

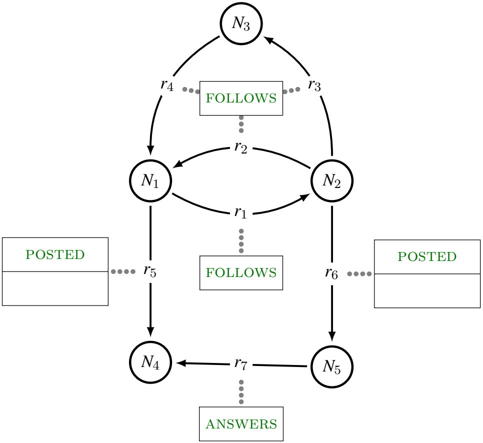


Answer to C:

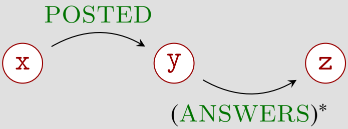
Set of the functions $F : \mathsf{var}(C) \longrightarrow N$

such that $\forall i,\ F_{|\mathsf{var}(R_i)}$ is an answer to R_i

Conjunction of RPQs (CRPQ) – Example



Query:



Answers:

	x	y	z
	$\downarrow$	$\downarrow$	$\downarrow$
F_1 :	N_1	N_4	N_4
F_2 :	N_2	N_5	N_4
F_3 :	N_2	N_5	N_5

Union of CRPQs (UCRPQ) – Defintion

A: alphabet (of relation types)
N: nodes in the graph

Definition (UCRPQ Q)

$$Q = (C_1 \cup C_2 \cup \cdots \cup C_n)$$

where $C_1, C_2, \ldots, C_n$ are CRPQs

Answer to Q:

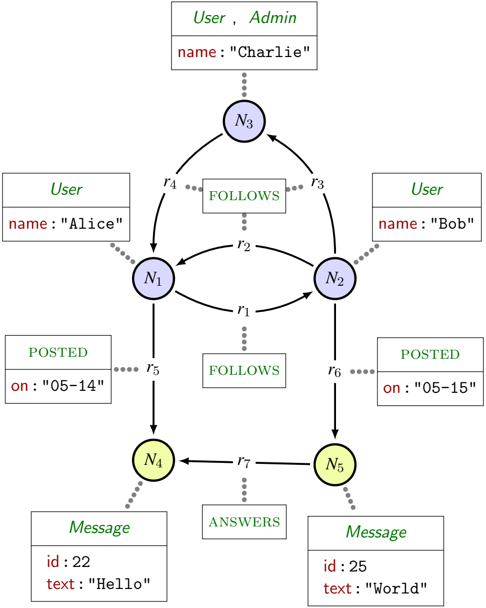
Set of partial functions: $\big(\mathsf{var}(C_1) \cup \cdots \cup \mathsf{var}(C_n)\big) \to N$

$$\bigcup_{i=1}^{n} F_i \ ,$$

where, $\forall i$, F_i is the answer to C_i.

Outline

Evaluating a Cypher query



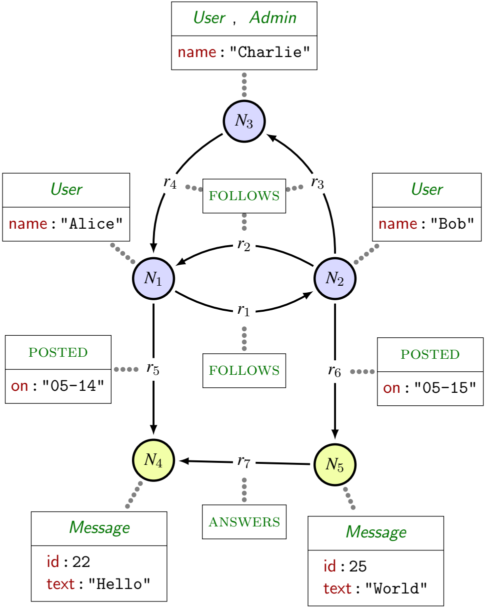
Example of Cypher query:

```
MATCH (u1)-[p1:POSTED]->(m1)
WITH u1, p1, m1.text AS t1
WHERE t1 = "Hello"
```

A Cypher statement

- is a sequence of *clauses*

Evaluating a Cypher query



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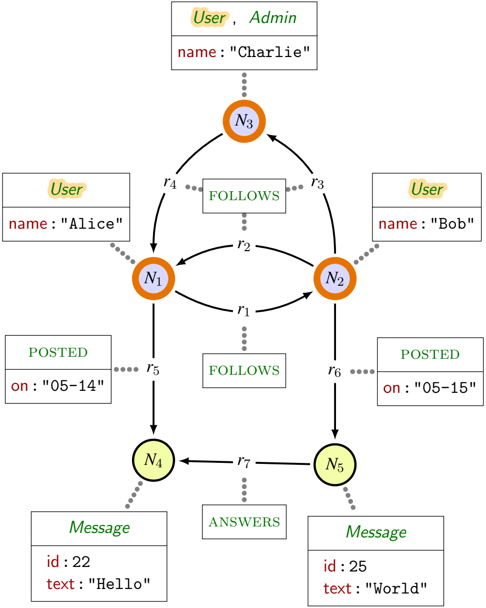
A Cypher statement

- is a sequence of *clauses*
- queries a graph
- returns a table

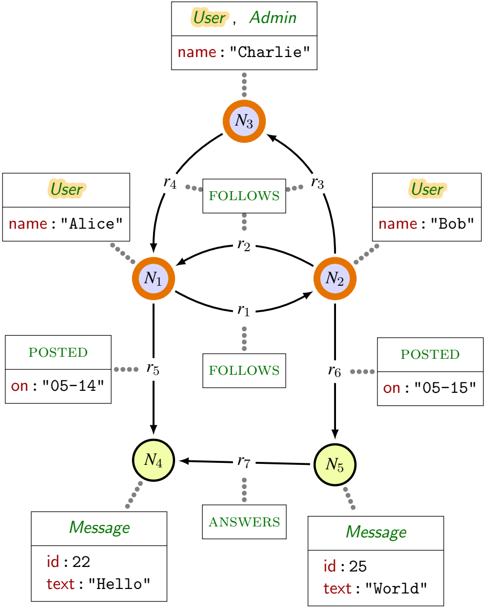
Matching nodes (1)



Query:

```
MATCH (u1:User)
```

Matching nodes (1)



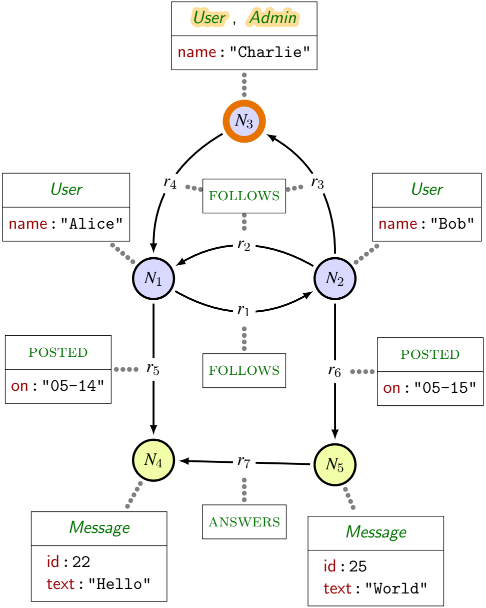
Query:

```
MATCH (u1:User)
```

Result:

u1
N_1
N_2
N_3

Matching nodes (2)



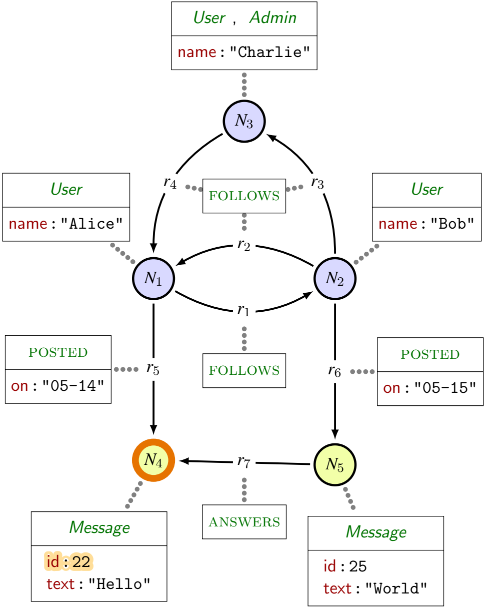
Query:

```
MATCH (u1:User:Admin)
```

Result:

u1
N_3

Matching nodes (3)



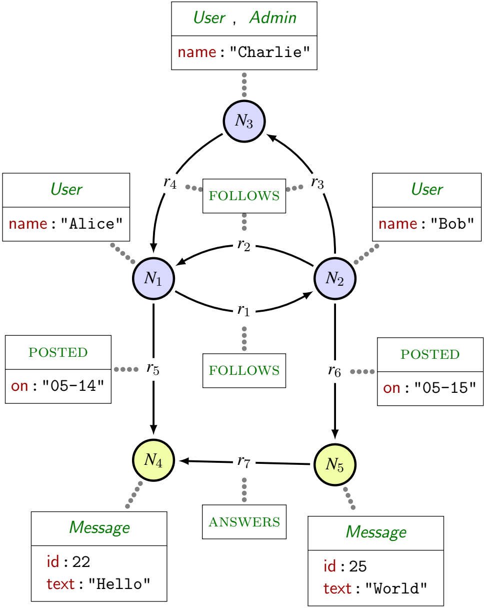
Query:

```
MATCH (u1{id:22})
```

Result:

u1
N_4

Matching relations (1)



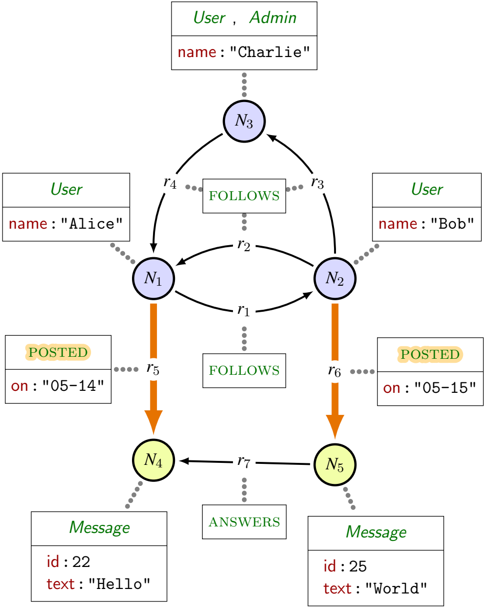
Query:

```
MATCH ()-[p1]->()
```

Result:

p1
r_1
r_2
r_3
r_4
r_5
r_6
r_7

Matching relation (2)



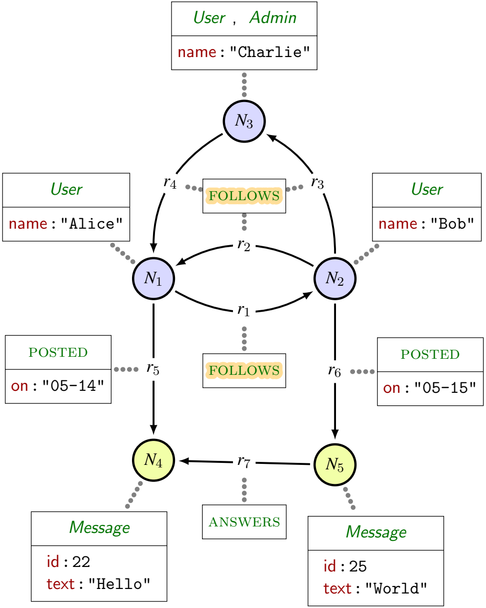
Query:

```
MATCH (u1)-[p1:POSTED]->(m1)
```

Result:

u1	p1	m1
N_1	r_5	N_4
N_2	r_6	N_5

Matching relationships (3)



Query:

```
MATCH (u1)-[:FOLLOWS]->()
```

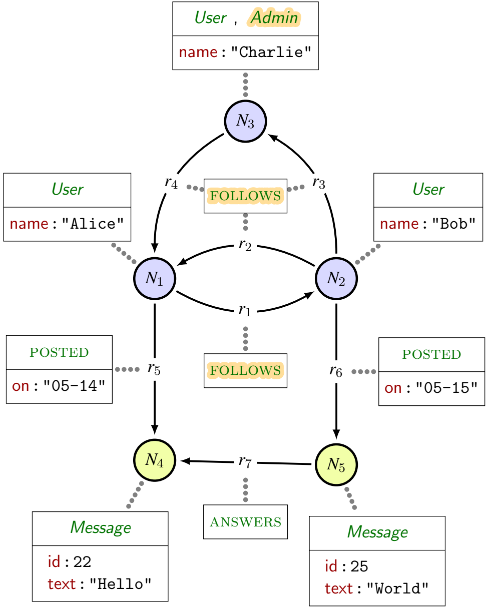
Result:

u1
N_1
N_2
N_2
N_3

Cypher has bag semantics:

N_2 has two outgoing FOLLOWS relations $\Rightarrow$ two lines N_2

Matching paths (1)



Query:

```
MATCH (u1:Admin)
        -[l1:FOLLOWS*]->(m1)
```

Result:

u1	l1	m1
N_3	$[r_4]$	N_1
N_3	$[r_4, r_1]$	N_2
N_3	$[r_4, r_1, r_2]$	N_1
N_3	$[r_4, r_1, r_3]$	N_3

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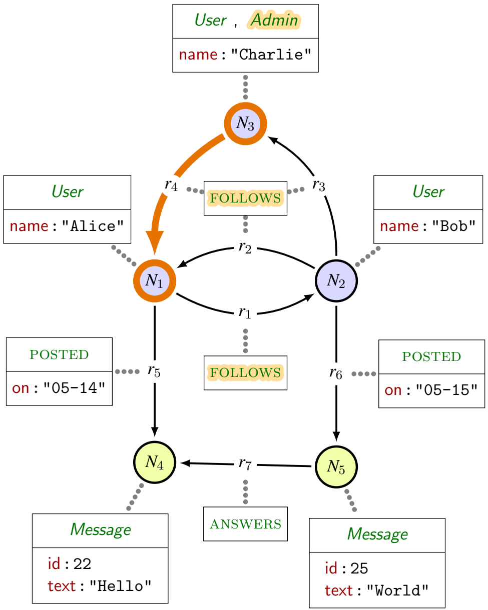

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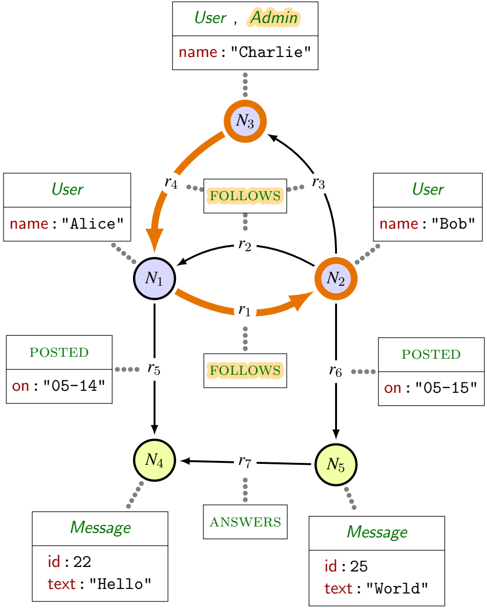

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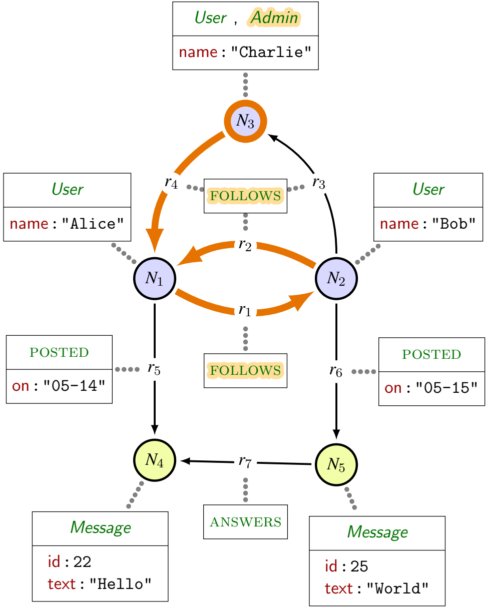
N_3	$[r_4]$	N_1
N_3	$[r_4, r_1]$	N_2
N_3	$[r_4, r_1, r_2]$	N_1
N_3	$[r_4, r_1, r_3]$	N_3

Matching paths (1)



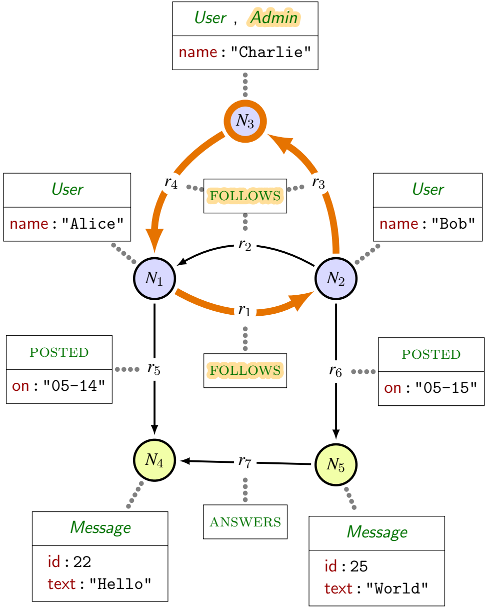
Query:

```
MATCH (u1:Admin)
        -[l1:FOLLOWS*]->(m1)
```

Result:

u1	l1	m1
N_3	$[r_4]$	N_1
N_3	$[r_4, r_1]$	N_2
N_3	$[r_4, r_1, r_2]$	N_1
N_3	$[r_4, r_1, r_3]$	N_3

Matching paths (1)



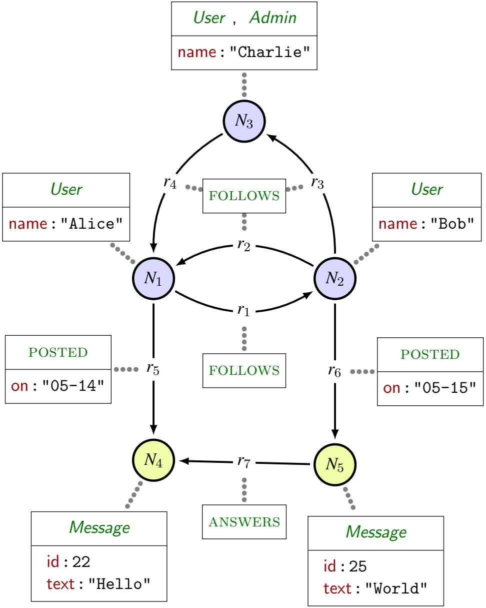
Query:

```
MATCH (u1:Admin)
        -[l1:FOLLOWS*]->(m1)
```

Result:

u1	l1	m1
N_3	$[r_4]$	N_1
N_3	$[r_4, r_1]$	N_2
N_3	$[r_4, r_1, r_2]$	N_1
N_3	$[r_4, r_1, r_3]$	N_3

Matching paths (1)



Query:

```
MATCH (u1:Admin)
        -[l1:FOLLOWS*]->(m1)
```

Result:

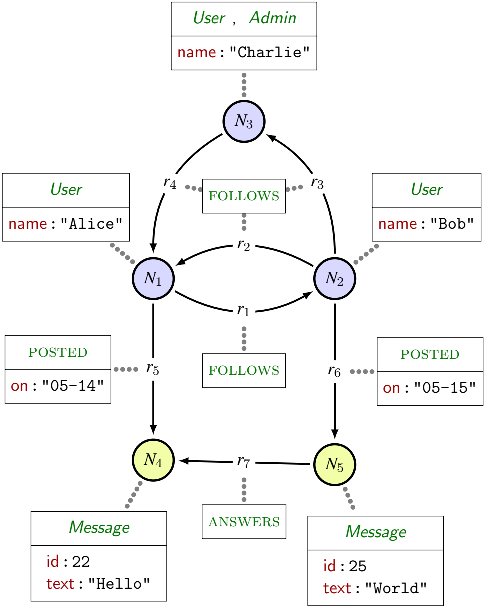
u1	l1	m1
N_3	$[r_4]$	N_1
N_3	$[r_4, r_1]$	N_2
N_3	$[r_4, r_1, r_2]$	N_1
N_3	$[r_4, r_1, r_3]$	N_3

Cypher-Morphism

- Each rel. matched ≤ 1 time

$\Rightarrow$ Finitely many results

Matching paths (2)



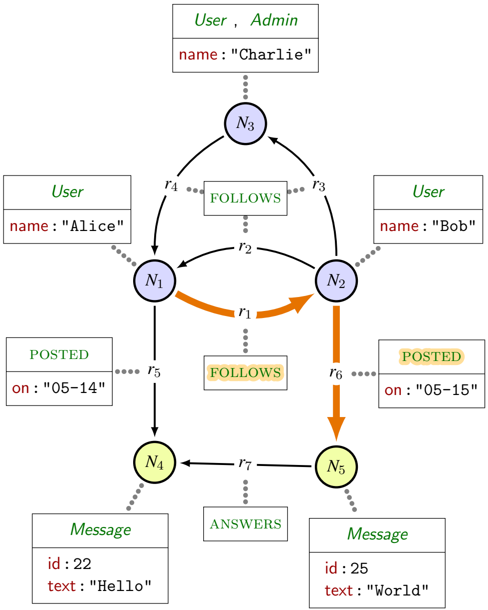
Query:

```
MATCH (u1)-[:FOLLOWS]->()
          -[:POSTED]->(m1)
```

Result:

u1	m1
N_1	N_5
N_2	N_4
N_3	N_5

Matching paths (2)



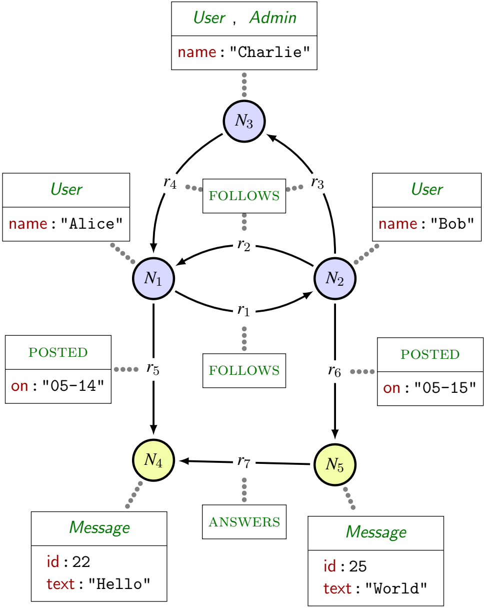
Query:

```
MATCH (u1)-[:FOLLOWS]->()
              -[:POSTED]->(m1)
```

Result:

u1	m1
N_1	N_5
N_2	N_4
N_3	N_5

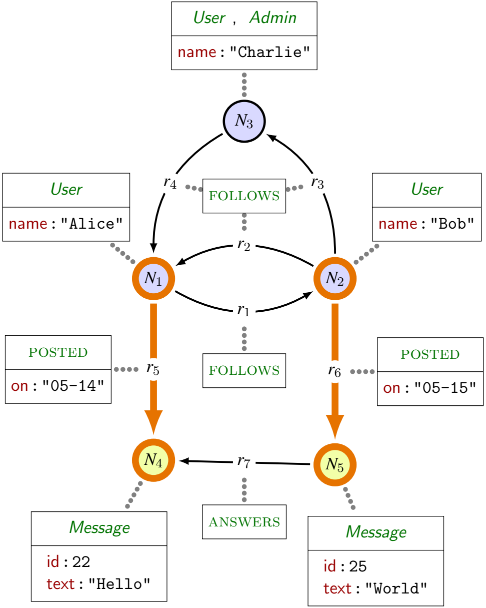
Chaining clauses



Query:

```
MATCH (u1)-[:POSTED]->(m1)
MATCH (u2)<-[:FOLLOWS]-(u1)
                -[:FOLLOWS]->(u3)
```

Chaining clauses



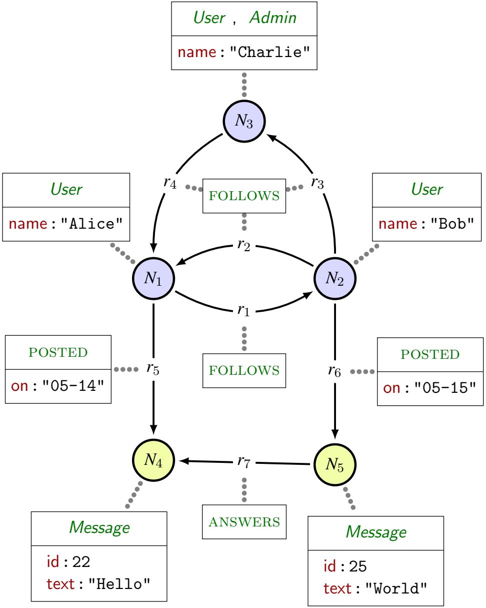
Query:

```
MATCH (u1)-[:POSTED]->(m1)
MATCH (u2)<-[:FOLLOWS]-(u1)
               -[:FOLLOWS]->(u3)
```

Table after first MATCH:

u1	m1
N_1	N_4
N_2	N_5

Chaining clauses



Query:

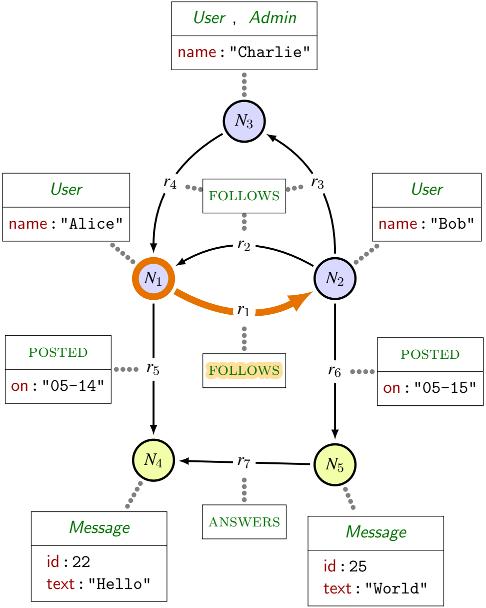
```
MATCH (u1)-[:POSTED]->(m1)
MATCH (u2)<-[:FOLLOWS]-(u1)
                -[:FOLLOWS]->(u3)
```

Table after first MATCH:

u1	m1
N_1	N_4
N_2	N_5

Table after second MATCH:

u1	m1	u2	u3
N_1	N_4	·	·
N_2	N_5	·	·



Query:

```
MATCH (u1)-[:POSTED]->(m1)
MATCH (u2)<-[:FOLLOWS]-(u1)
             -[:FOLLOWS]->(u3)
```

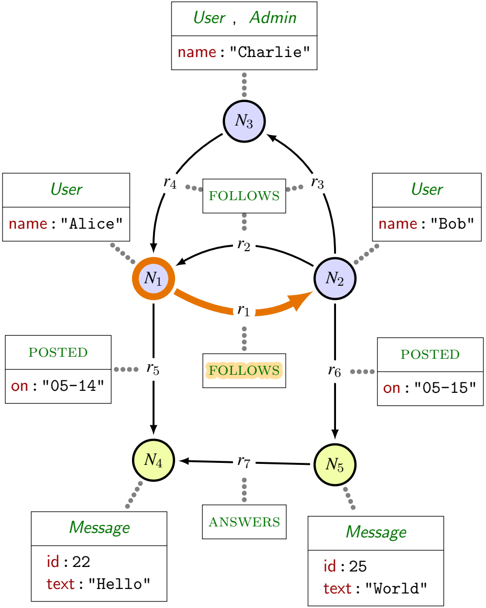
Table after first MATCH:

u1	m1
N_1	N_4
N_2	N_5

Table after second MATCH:

u1	m1	u2	u3
N_1	N_4	·	·
N_2	N_5	·	·

Chaining clauses



Query:

```
MATCH (u1)-[:POSTED]->(m1)
MATCH (u2)<-[:FOLLOWS]-(u1)
               -[:FOLLOWS]->(u3)
```

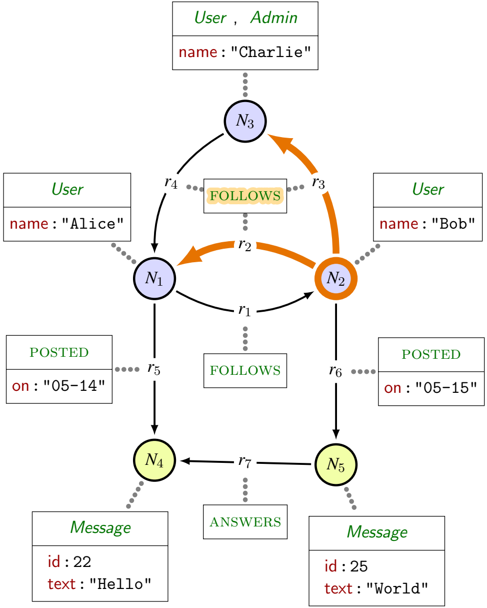
Table after first MATCH:

u1	m1
N_1	N_4
N_2	N_5

Table after second MATCH:

u1	m1	u2	u3
~~N_1~~	~~N_4~~		
N_2	N_5	·	·

Chaining clauses



Query:

```
MATCH (u1)-[:POSTED]->(m1)
MATCH (u2)<-[:FOLLOWS]-(u1)
                  -[:FOLLOWS]->(u3)
```

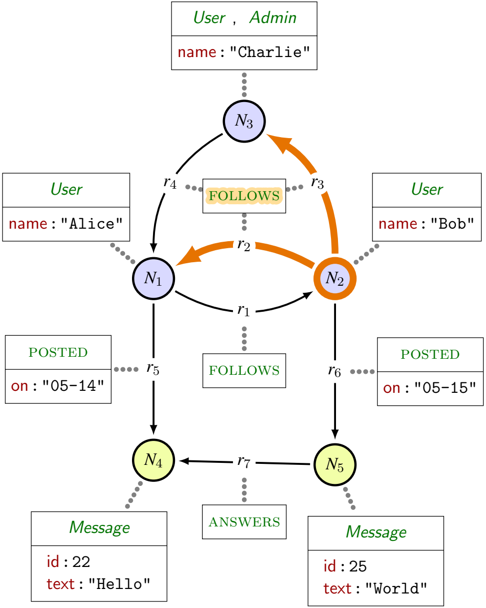
Table after first MATCH:

u1	m1
N_1	N_4
N_2	N_5

Table after second MATCH:

u1	m1	u2	u3
~~N_1~~	~~N_4~~		
N_2	N_5	·	·

Chaining clauses



Query:

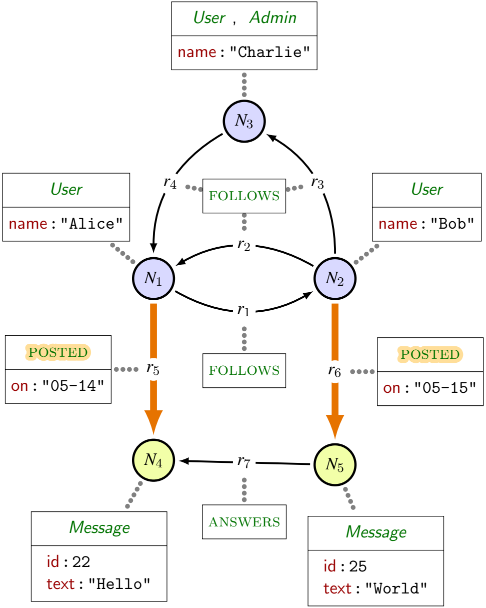
```
MATCH (u1)-[:POSTED]->(m1)
MATCH (u2)<-[:FOLLOWS]-(u1)
            -[:FOLLOWS]->(u3)
```

Table after first MATCH:

u1	m1
N_1	N_4
N_2	N_5

Table after second MATCH:

u1	m1	u2	u3
N_2	N_5	N_1	N_3
N_2	N_5	N_3	N_1



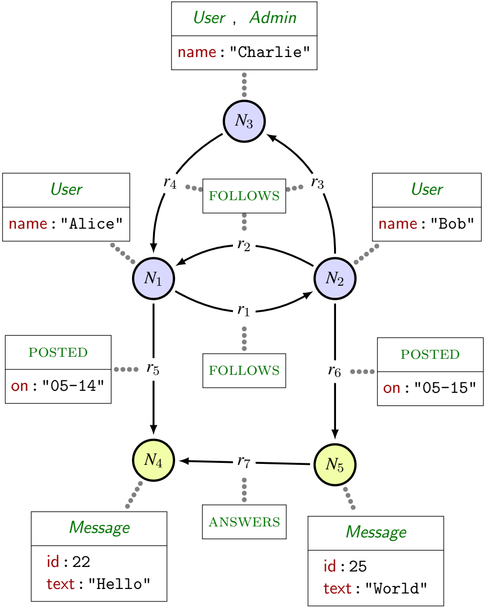
Query:

```
MATCH (u1)-[p1:POSTED]->(m1)
WITH u1, p1, m1.text AS t1
```

After the MATCH clause

u1	p1	m1
N_1	r_5	N_4
N_2	r_6	N_5

Column manipulation (WITH clause)



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MATCH (u1)-[p1:POSTED]->(m1)
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```

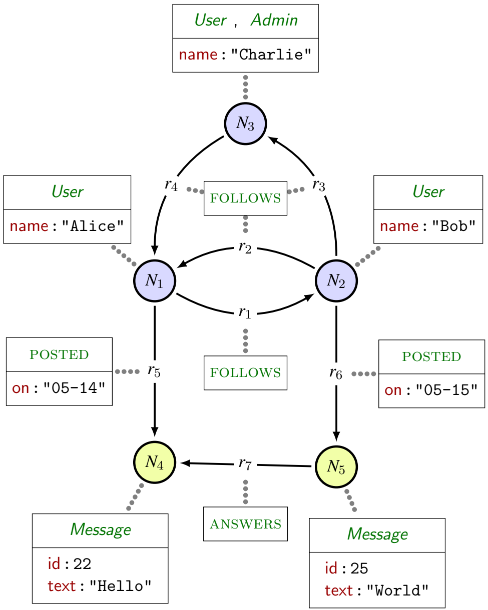
After the MATCH clause

u1	p1	m1
N_1	r_5	N_4
N_2	r_6	N_5

Execution of the WITH clause

u1	p1	t1
N_1	r_5	
N_2	r_6	

Column manipulation (WITH clause)



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u1	p1	t1
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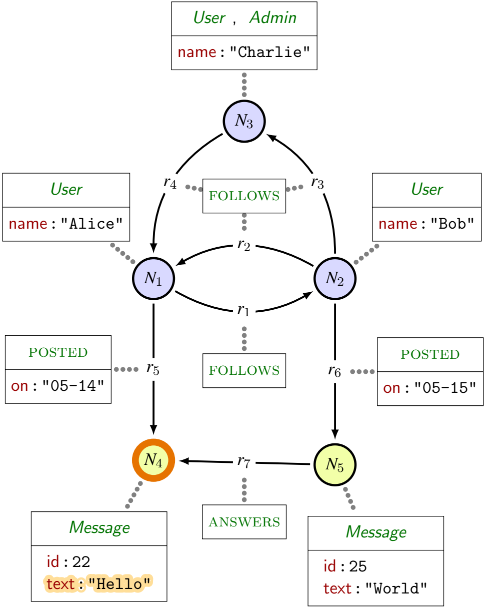

Query:

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WITH u1, p1, m1.text AS t1
```

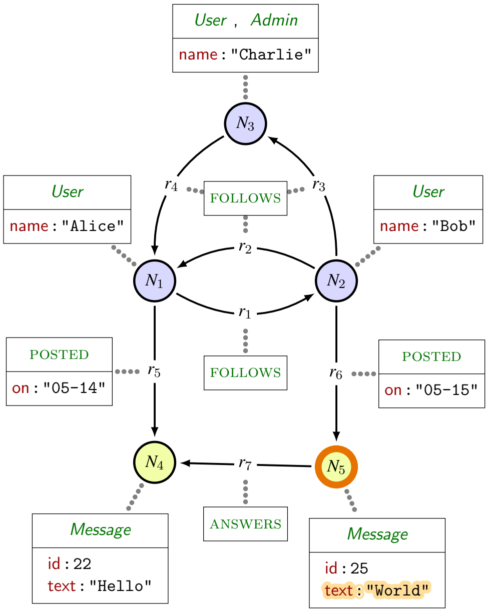
After the MATCH clause

u1	p1	m1
N_1	r_5	N_4
N_2	r_6	N_5

Execution of the WITH clause

u1	p1	t1
N_1	r_5	"Hello"
N_2	r_6	

Column manipulation (WITH clause)



Query:

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MATCH (u1)-[p1:POSTED]->(m1)
WITH u1, p1, m1.text AS t1
```

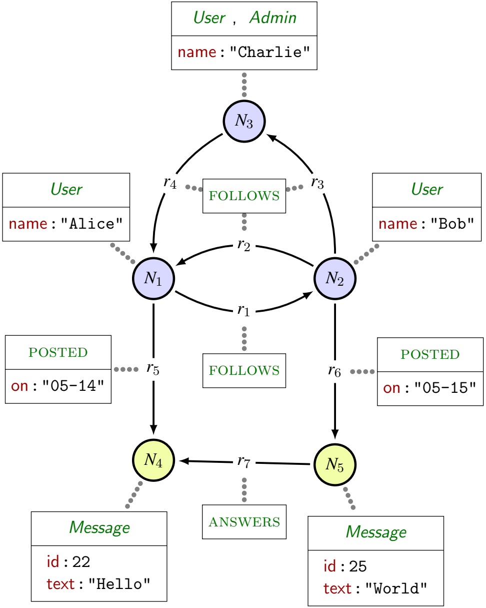
After the MATCH clause

u1	p1	m1
N_1	r_5	N_4
N_2	r_6	N_5

Execution of the WITH clause

u1	p1	t1
N_1	r_5	"Hello"
N_2	r_6	"World"

Column manipulation (WITH clause)



Query:

```
MATCH (u1)-[p1:POSTED]->(m1)
WITH u1, p1, m1.text AS t1
```

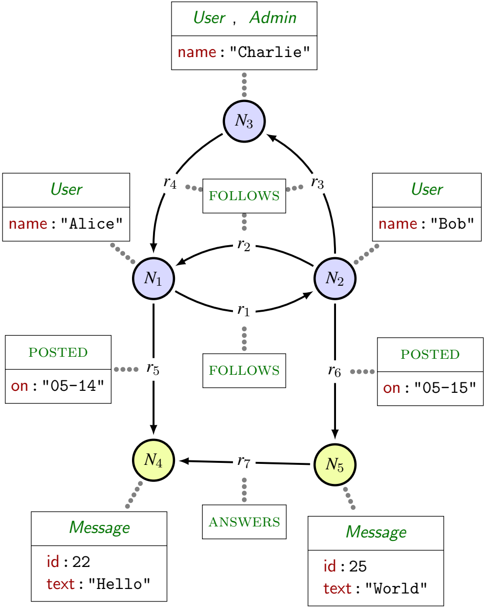
After the MATCH clause

u1	p1	m1
N_1	r_5	N_4
N_2	r_6	N_5

Final result

u1	p1	t1
N_1	r_5	"Hello"
N_2	r_6	"World"

Line filtering (WHERE clause)



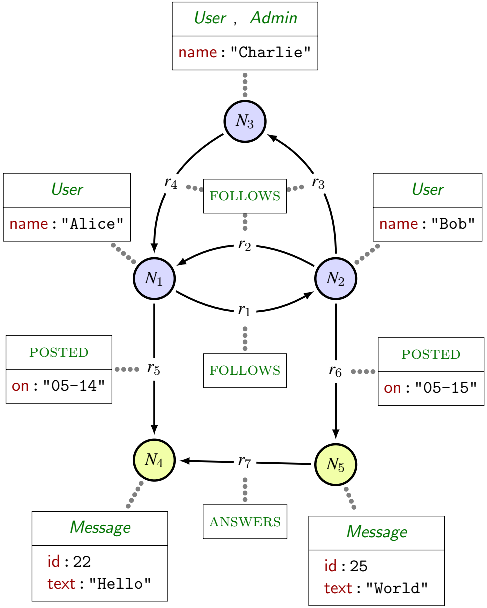
Query:

```
MATCH (u1)-[p1:POSTED]->(m1)
WITH u1, p1, m1.text AS t1
WHERE t1 = "Hello"
```

After the WITH clause

u1	p1	t1
N_1	r_5	"Hello"
N_2	r_6	"World"

Line filtering (WHERE clause)



Query:

```
MATCH (u1)-[p1:POSTED]->(m1)
WITH u1, p1, m1.text AS t1
WHERE t1 = "Hello"
```

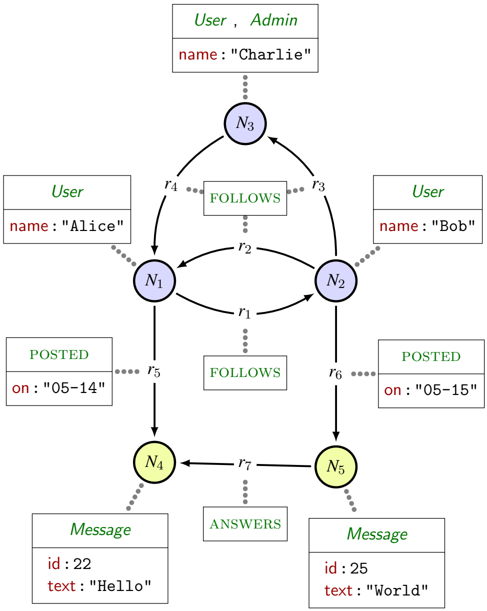
After the WITH clause

u1	p1	t1
N_1	r_5	"Hello"
N_2	r_6	"World"

Execution of the WHERE clause

u1	p1	t1
N_1	r_5	"Hello"
~~N_2~~	~~r_6~~	~~"World"~~

Line filtering (WHERE clause)



Query:

```
MATCH (u1)-[p1:POSTED]->(m1)
WITH u1, p1, m1.text AS t1
WHERE t1 = "Hello"
```

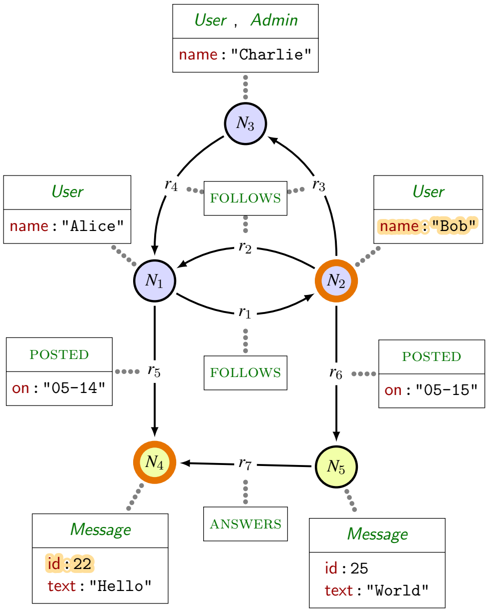
After the WITH clause

u1	p1	t1
N_1	r_5	"Hello"
N_2	r_6	"World"

Final result

u1	p1	t1
N_1	r_5	"Hello"

A last read-only example



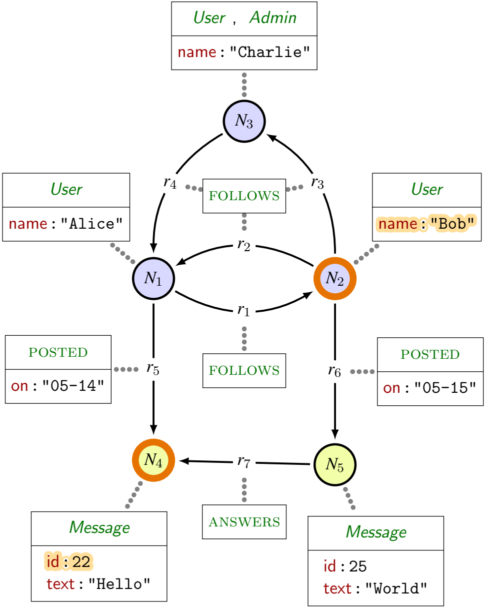
Query:

```
MATCH (a{name:"Bob"})
        -[*]->(b{id:22})
             <-[*]-(a)
```

Question

What does this computes ?

A last read-only example



Query:

```
MATCH (a{name:"Bob"})
        -[*]->(b{id:22})
             <-[*]-(a)
```

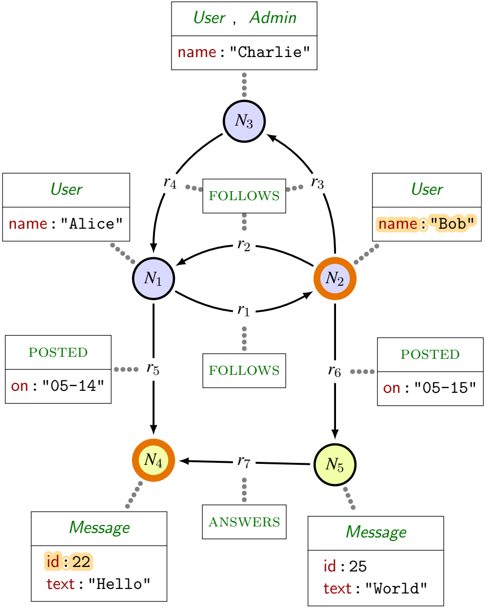
Question

What does this computes ?

Answer

The # of pairs of disjoint paths from N_2 to N_4.

A last read-only example



Query:

```
MATCH (a{name:"Bob"})
        -[*]->(b{id:22})
             <-[*]-(a)
```

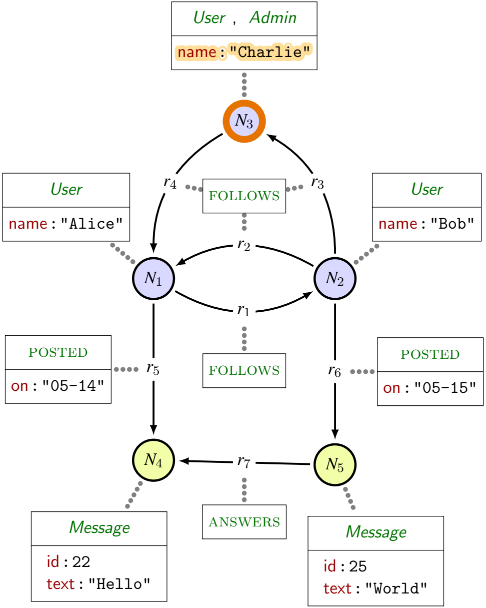
Question

What does this computes ?

Answer

The # of pairs of disjoint paths from N_2 to N_4.

$\Rightarrow$ Evaluation of one constant `MATCH` is NP-HARD



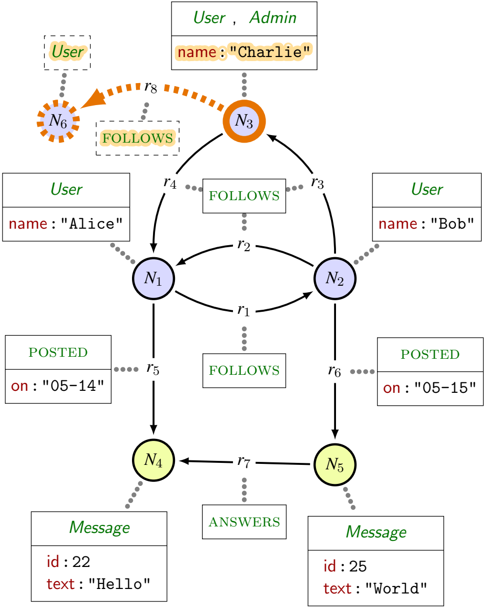
Query:

```
MATCH (a{name:"Charlie"})
CREATE (a)-[:FOLLOWS]->
                    (b:User)
```

Table after MATCH clause:

a
N_3

Node and relation creation (CREATE)



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a
N_3

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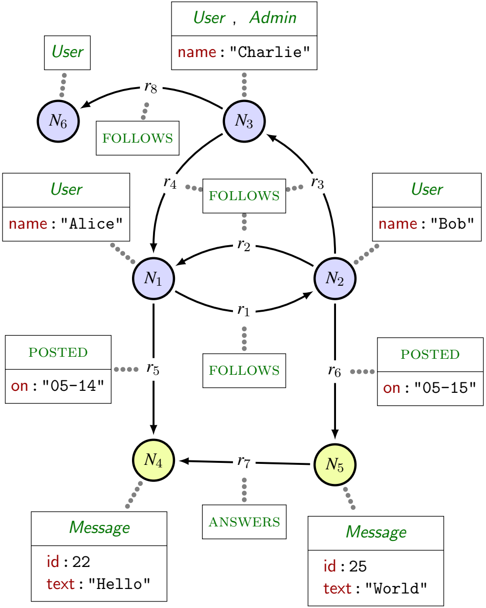


Query:

```
MATCH (a{name:"Charlie"})
CREATE (a)-[:FOLLOWS]->
                    (b:User)
```

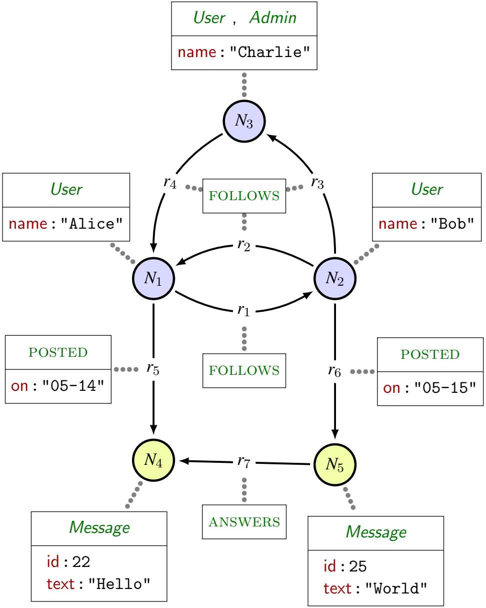
Table after MATCH clause:

a
N_3

Table after CREATE clause:

a	b
N_3	N_6

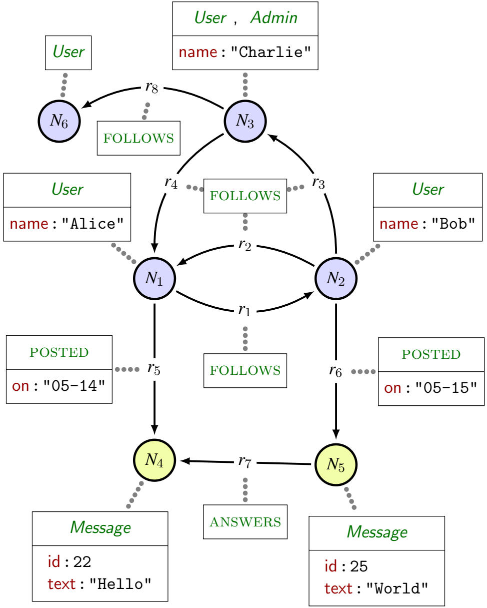
The example graph stored as CREATE clauses



Query:

```
CREATE
  (n1:User{name:"Alice"}),
  (n2:User{name:"Bob"}),
  (n3:User:Admin
            {name:"Charlie"}),
  (n4:Message {id:22,
               text:"Hello"}),
  (n5:Message {id:25,
               text:"World"})
CREATE
  (n1)-[:FOLLOWS]->(n2),
  (n1)-[:POSTED
          {on:"05-04"}]->(n4),
  (n2)-[:FOLLOWS]->(n1),
  (n2)-[:FOLLOWS]->(n3),
  (n2)-[:POSTED
          {on:"05-04"}]->(n5),
  (n3)-[:FOLLOWS]->(n1),
  (n5)-[:ANSWERS]->(n4),
```

Node/Relation modification (SET clause)



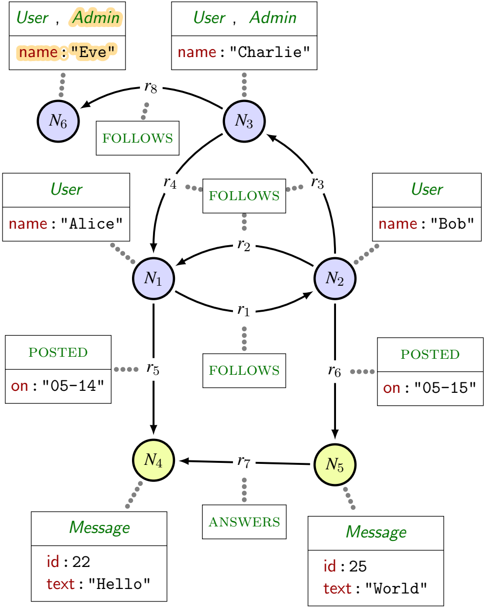
Query:

```
MATCH (a{name:"Charlie"})
CREATE (a)-[:FOLLOWS]->
                        (b:User)
SET b:Admin, b.name="Eve"
```

Table after CREATE clause:

a	b
N_3	N_6

Node/Relation modification (SET clause)



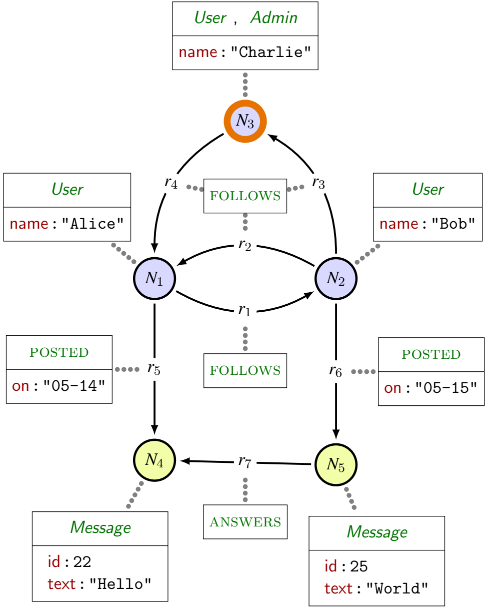
Query:

```
MATCH (a{name:"Charlie"})
CREATE (a)-[:FOLLOWS]->
                    (b:User)
SET b:Admin, b.name="Eve"
```

Table after CREATE clause:

a	b
N_3	N_6

The MERGE clause : MATCH else CREATE



Input table:

a	n
N_3	"Alice"
N_3	"Eve"

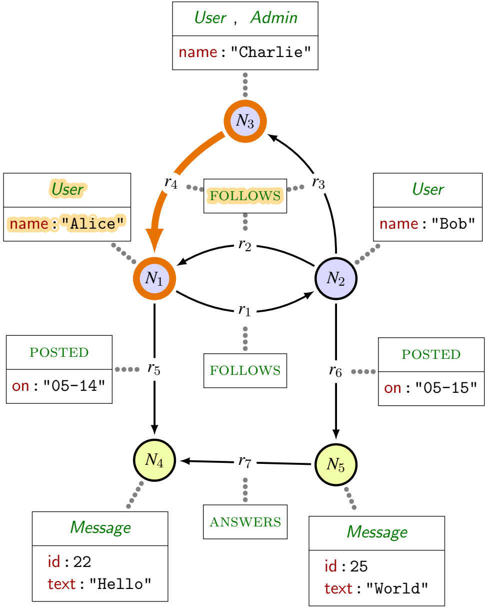
Query:

```
MERGE (a)-[:FOLLOWS]->
            (b:User {name:n})
```

Output table:

a	n	c
N_3	"Alice"	
N_3	"Eve"	

The MERGE clause : MATCH else CREATE



Input table:

a	n
N_3	"Alice"
N_3	"Eve"

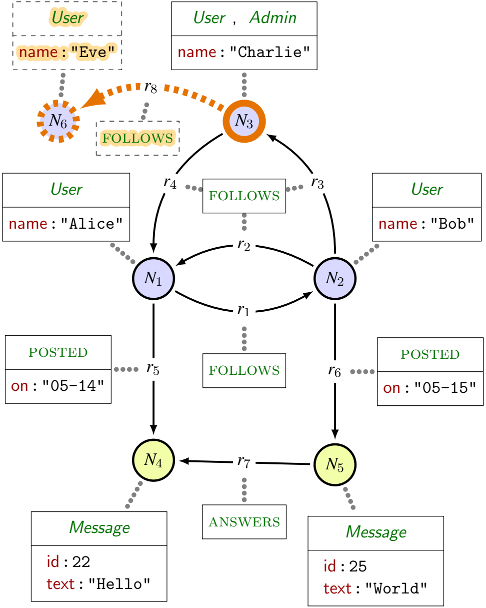
Query:

```
MERGE (a)-[:FOLLOWS]->
          (b:User {name:n})
```

Output table:

a	n	c
N_3	"Alice"	N_1
N_3	"Eve"	

The MERGE clause : MATCH else CREATE



Input table:

a	n
N_3	"Alice"
N_3	"Eve"

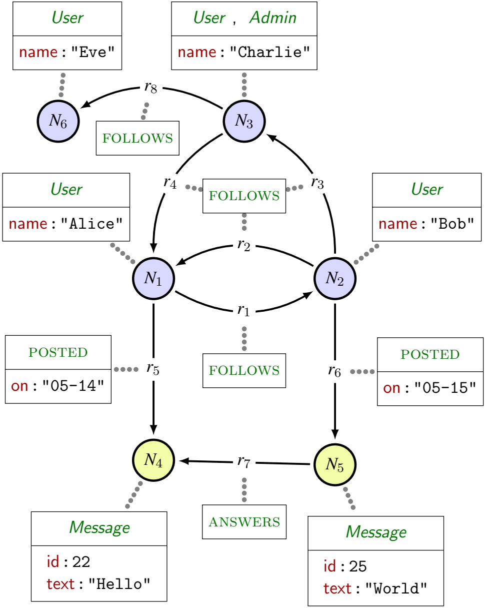
Query:

```
MERGE (a)-[:FOLLOWS]->
          (b:User {name:n})
```

Output table:

a	n	c
N_3	"Alice"	N_1
N_3	"Eve"	N_6

The MERGE clause : MATCH else CREATE



Input table:

a	n
N_3	"Alice"
N_3	"Eve"

Query:

```
MERGE (a)-[:FOLLOWS]->
          (b:User {name:n})
```

Output table:

a	n	c
N_3	"Alice"	N_1
N_3	"Eve"	N_6

Other constructs

- `DELETE` deletes node and relations.

Ex: `MATCH (a{name:"Eve"}) DELETE a`

- `REMOVE` removes labels or properties.

Ex: `MATCH (a{name:"Charlie"}) REMOVE a:Admin,a.name`

- `WITH` allows to perform aggregations.

Ex: `MATCH (a)-[:FOLLOWS]->(b) WITH a, count(b) as c`

- `ORDER BY` limits size of table.

Ex: `MATCH (a:User) ORDER BY a.name LIMIT 1`

Outline

Record (table row)

A *record* is a partial function from variables to values.

Example: $(x \mapsto$ `"Bob"` ; $y \mapsto$ `1`$)$

Modelling Tables

Record (table row)

A *record* is a partial function from variables to values.

Example: $(x \mapsto$ `"Bob"` $;\ y \mapsto 1)$

Table

A *table* is a multi-set (or bag) of records with the same domain.

Example:

x	y
"Bob"	1
"Alice"	999
"Bob"	1

Modelling Tables

Record (table row)

A *record* is a partial function from variables to values.

Example: $(x \mapsto$ `"Bob"` ; $y \mapsto$ `1`$)$

Table

A *table* is a multi-set (or bag) of records with the same domain.

Example:

x	y
"Bob"	1
"Alice"	999
"Bob"	1

=

y	x
999	"Alice"
1	"Bob"
1	"Bob"

Semantics brackets – Read-Only

G: a graph

Semantics of expressions

$\llbracket \cdot \rrbracket_{u,G}$: expression $\longmapsto$ value (where u is a record)

Semantics of clauses

$\llbracket \cdot \rrbracket_{G}$: clause $\longmapsto$ (function: Tables $\to$ Tables)

Semantics of queries

$\llbracket \cdot \rrbracket_{G}$: query $\longmapsto$ (function: Tables $\to$ Tables)

output : (Graphs $\times$ Queries) $\longmapsto$ Tables

Principle of Read-Only Semantics

G: a graph
Q: a query

To compute the output of Q

- Q is a sequence of clauses $Q = C_1\, C_2\, \cdots\, C_n$

Principle of Read-Only Semantics

G: a graph
Q: a query

To compute the output of Q

- Q is a sequence of clauses $Q = C_1\, C_2 \cdots C_n$
- Compute $\left[\!\left[C_1\right]\!\right]_G, \ \left[\!\left[C_2\right]\!\right]_G, \ \ldots, \ \left[\!\left[C_n\right]\!\right]_G$

Principle of Read-Only Semantics

G: a graph
Q: a query

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- Let $[\![Q]\!]_G = [\![C_n]\!]_G \circ \cdots \circ [\![C_2]\!]_G \circ [\![C_1]\!]_G$
- output$(G, Q) = [\![Q]\!]_G\left(T_{\text{unit}}\right)$

where T_{unit} is the 1-line 0-column table.

Excerpt of Read-Only semantics (2)

- $\left[\!\left[\texttt{WHERE}\ e\right]\!\right]_G(T) = \left\{ u \in T \;\middle|\; \left[\!\left[e\right]\!\right]_{G,u} = \texttt{true} \right\}$

- $\left[\!\left[\texttt{MATCH}\ \bar{\pi}\right]\!\right]_G(T) = \biguplus_{u \in T} \{u \cdot u' \mid u' \in \mathsf{match}(\bar{\pi}, G, u)\}$
- $\left[\!\left[\texttt{MATCH}\ \bar{\pi}\ \texttt{WHERE}\ e\right]\!\right]_G(T) = \left[\!\left[\texttt{WHERE}\ e\right]\!\right]\left(\left[\!\left[\texttt{MATCH}\ \bar{\pi}\right]\!\right]_G(T)\right)$
- $\left[\!\left[\texttt{OPTIONAL MATCH}\ \bar{\pi}\ \texttt{WHERE}\ e\right]\!\right]_G(T)$
  $$= \biguplus_{u \in T} \begin{cases} \left[\!\left[\texttt{MATCH}\ \bar{\pi}\ \texttt{WHERE}\ e\right]\!\right]_G(\{u\}) & \text{if } \left[\!\left[\texttt{MATCH}\ \bar{\pi}\ \texttt{WHERE}\ e\right]\!\right]_G(\{u\}) \neq \emptyset \\ (u, (\mathsf{free}(u, \bar{\pi}) : \texttt{null})) & \text{otherwise} \end{cases}$$
- $\left[\!\left[\texttt{OPTIONAL MATCH}\ \bar{\pi}\right]\!\right]_G(T) = \left[\!\left[\texttt{OPTIONAL MATCH}\ \bar{\pi}\ \texttt{WHERE true}\right]\!\right]_G(T)$

Excerpt of Read-Only semantics (2)

- $[\![\texttt{WITH } *]\!]_G(T) = T$ if T has at least one column
- $[\![\texttt{WITH } *, e_1 \ [\texttt{AS } a_1], \ldots, e_m \ [\texttt{AS } a_m]]\!]_G(T) =$
  $$[\![\texttt{WITH } b_1 \texttt{ AS } b_1, \ldots, b_q \texttt{ AS } b_q, e_1 \ [\texttt{AS } a_1], \ldots, e_m \ [\texttt{AS } a_m]]\!]_G(T)$$
- $[\![\texttt{WITH } e_1 \ [\texttt{AS } a_1], \ldots, e_m \ [\texttt{AS } a_m]]\!]_G(T) =$
  $$\biguplus_{u \in T} \left\{ (a'_1 : [\![e_1]\!]_{G,u}, \ldots, a'_m : [\![e_m]\!]_{G,u}) \right\}$$

- $[\![\texttt{UNWIND } e \texttt{ AS } a]\!]_G(T) = \biguplus_{u \in T} \biguplus_{v \in E_u} \{(u, a : v)\},$
  $$\text{with } \ E_u = \begin{cases} \biguplus_{0 \leq i < m} \{v_i\} & \text{if } [\![e]\!]_{G,u} = \text{list}(v_0, \ldots, v_{m-1}) \\ \{\} & \text{if } [\![e]\!]_{G,u} = \text{list}() \\ \left\{ [\![e]\!]_{G,u} \right\} & \text{otherwise} \end{cases}$$

Semantics brackets – Read-Write

Semantics of expressions: (Nothing changes)

$[\![\cdot]\!]_{u,G}$: expression $\longmapsto$ value (where u is a record)

Semantics of clauses:

$[\![\cdot]\!]$: clause $\longmapsto$ (function: (Graphs $\times$ Tables) $\rightarrow$ (Graphs $\times$ Tables))

Semantics of queries:

$[\![\cdot]\!]$: query $\longmapsto$ (function: (Graphs $\times$ Tables) $\rightarrow$ (Graphs $\times$ Tables))

output : (Graphs $\times$ Queries) $\longmapsto$ (Graphs $\times$ Tables)

(Computed just like RO $\rightarrow$ composition of clause semantics)

Desirable properties of the semantics at Clause-level

Atomicity:
Each clause is executed as a single unit

Consistency:
Each clause should on valid Graph/Table pair

General scheme of the semantics if a clause is:

1. Ensure that the input Graph/Table is valid w.r.t. clause
2. Compute output Table and all changes to graph
3. Apply all changes to Graph
4. Ensure validity of output Graph/Table

If any fails, semantics is undefined.

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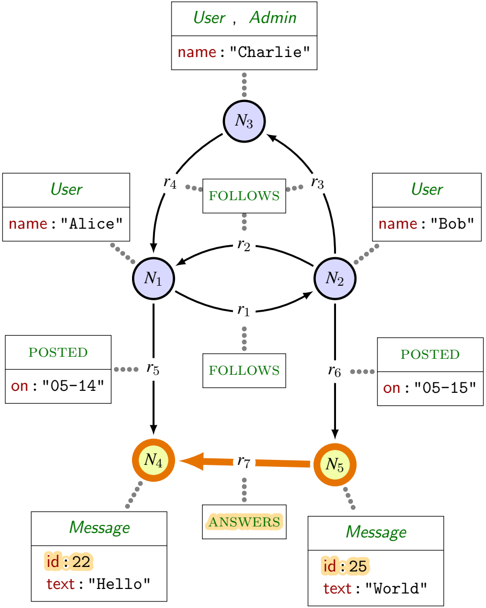
In Neo4j, Atomicity and Consistency are verified at query level only.

In Neo4j, SET violate Atomicity



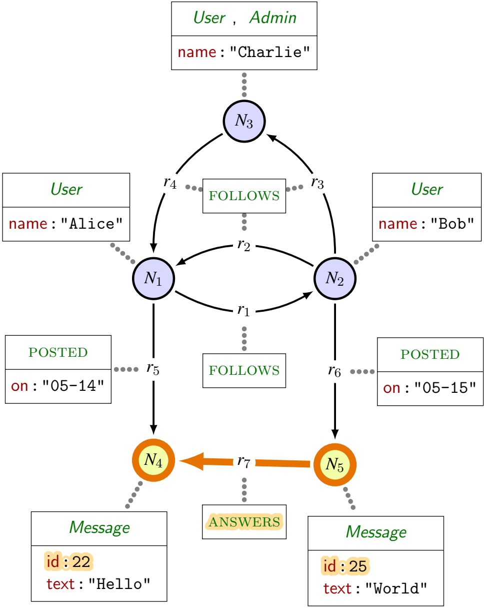
Query:

```
MATCH (m1)-[:ANSWERS]->(m2)
SET m1.id = m2.id,
    m2.id = m1.id
```

Table before SET clause:

m1	m2
N_5	N_4

In Neo4j, SET violate Atomicity



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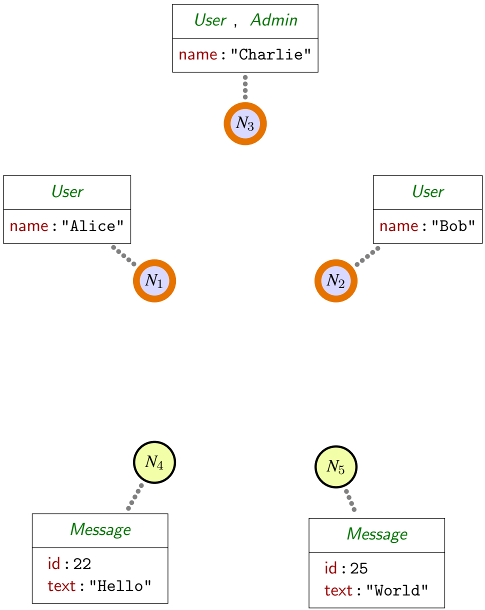
Neo4j sets both id to 25.

Semantics exchange id values

In Neo4j, MERGE is highly non-deterministic



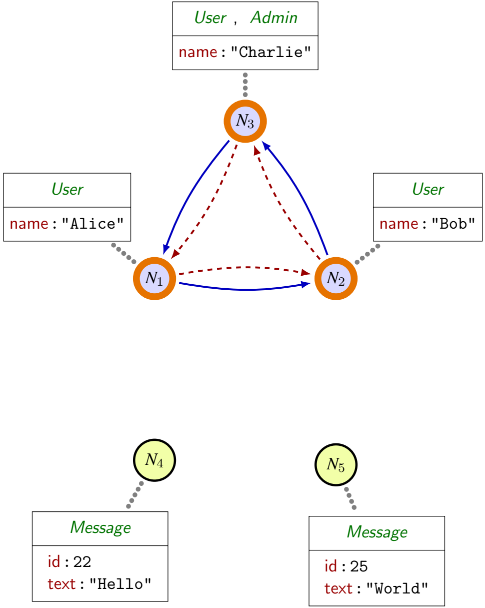
Input Table:

a	b	c
N_1	N_2	N_3
N_2	N_3	N_1
N_3	N_1	N_2

Query:

```
MERGE (a)-[:FOLLOWS]->(b)
         -[:FOLLOWS]->(c)
```

In Neo4j, MERGE is highly non-deterministic



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Neo4j creates 4 edges

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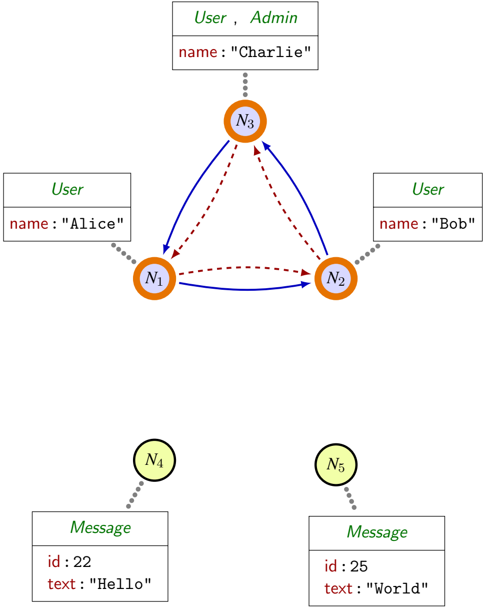

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```
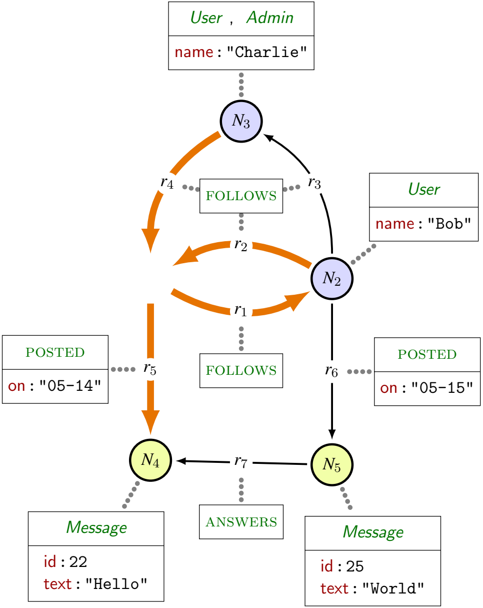

Neo4j creates 4 edges

Semantics propose different semantics creating either 3 or 6.

In Neo4j, DELETE violates clause-level consistency

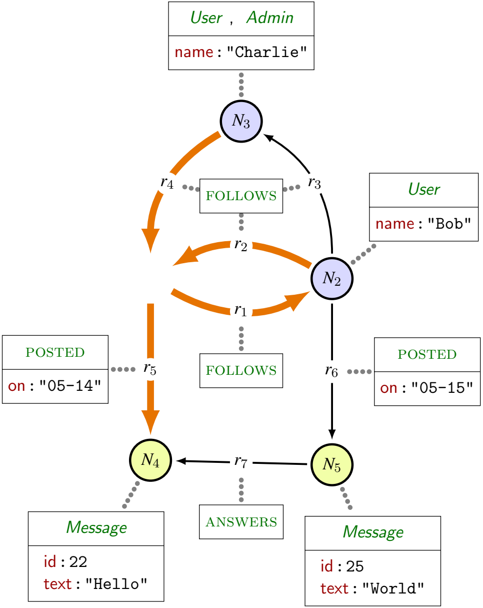


Query:

```
MATCH (a {name:"Alice"})
MATCH (a)-[r]-()
DELETE a
  [...]   // Arbitrary clauses
DELETE r
RETURN a.name AS n
```

- Execution of arbitrary code on invalid graph
- Access to deleted-entity

In Neo4j, DELETE violates clause-level consistency



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- Execution of arbitrary code on invalid graph
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Semantics

- is undefined if it should produce invalid graphs
- replaces deleted entities by null in the table

Outline

Cypher vs RPQ

Cypher queries vs UCRPQs

- Cypher has bag + cypher-morphism semantics
  (Set+ standard morphism semantics may be emulated...)
- Cypher has relationship/path variables
- (Data model is different)

RPQs not expressible in Cypher

- $(ab)^*$: no concatenation under star in Cypher
- $(a^*)^*$: no nested stars in Cypher
- $(a+b^{-1})^*$: some unions are not allowed under star in Cypher

- $(ab+cd)^3$: nested alternations of concatenations and unions require multi-exponential blow-up of the query
  $\longrightarrow (ab)^3+(ab)^2cd+ab(cd)^2+(cd)^3$

PGQL (Property Graph Query Language)

- Designed by Oracle Inc.
- Support full UCRPQ
- ASCII-art representation of patterns (similar to Cypher)
- Syntax close to SQL

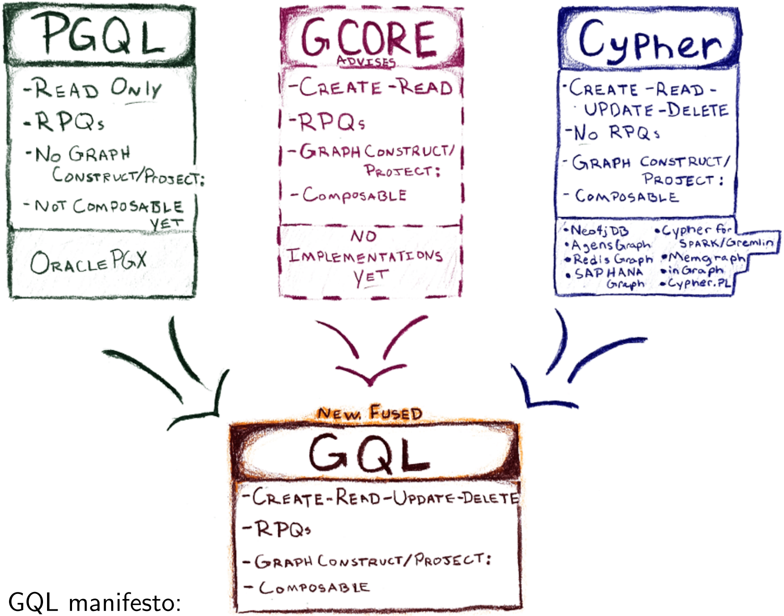
Example: (from http://pgql-lang.org/)

```
SELECT p1.name
FROM facebook_graph          /* In the Facebook graph,..   */
MATCH (p1:Person)            /* ..find persons such that.. */
WHERE NOT EXISTS (           /* ..there does not exist..   */
  SELECT p2
    FROM twitter_graph         /* ..in the Twitter graph.. */
    MATCH (p2:Person)          /* ..a person..             */
    WHERE p1.name = p2.name /* ..with the same name.       */
)
```

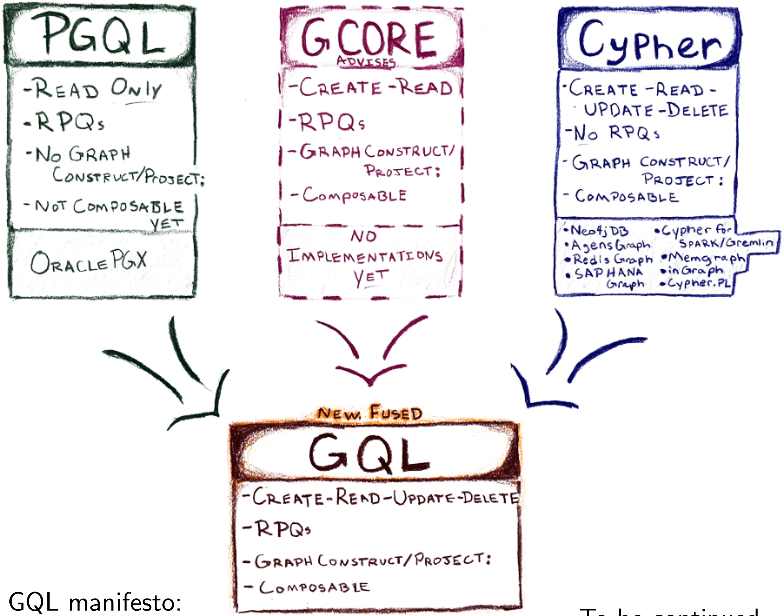
- Designed by LDBC
- Experimental
- Support full UCRPQ
- ASCII-art representation of patterns (similar to Cypher)
- Support Multiple graphs, graph views, and paths cost
- Multiple semantics

Example:

```
CONSTRUCT (n)-[:To{distance:=c}]->(m)
  MATCH (n) -/SHORTEST p<:KNOWS*> COST c/->(m)
    ON facebook_graph
  MATCH (n),(m) ON upem_graph
```



cf. GQL manifesto:
`http://gql.today`



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To be continued...