Introduction to property graphs:
Data model and query languages

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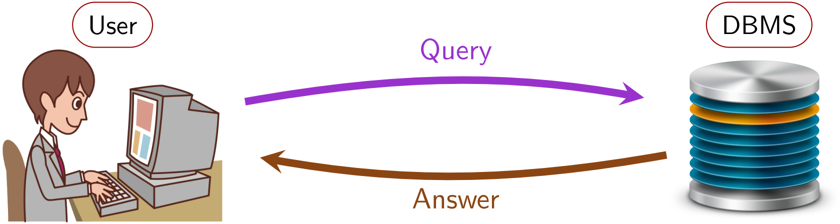
MADICS / DOING

2022-07-11

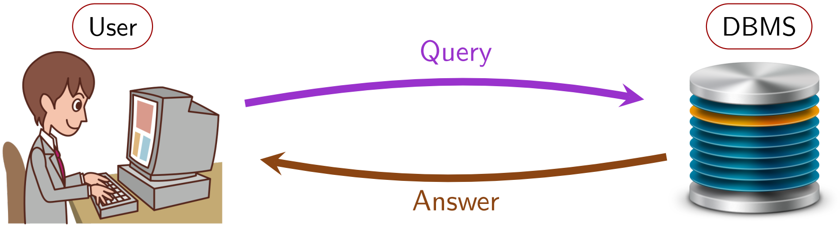
Introduction

General setting



General setting

- DBMS = **D**ata**B**ase **M**anagement **S**ystem



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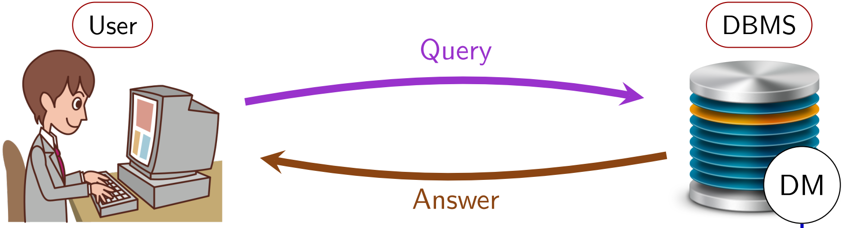
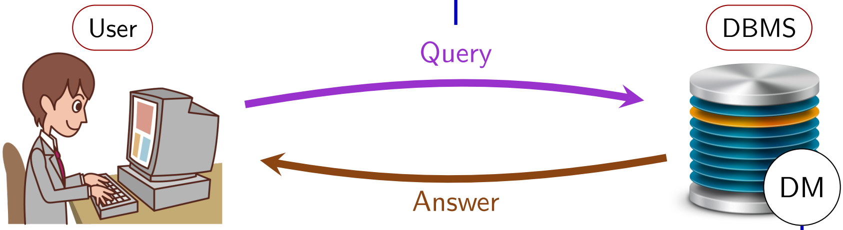


- DM = **D**ata **M**odel = "*The way data is structured*"
  - Relational ? XML ? Property graph ? RDF ? etc.

- DBMS = **D**ata**B**ase **M**anagement **S**ystem
- Query language
  - "*What can users ask for?*"



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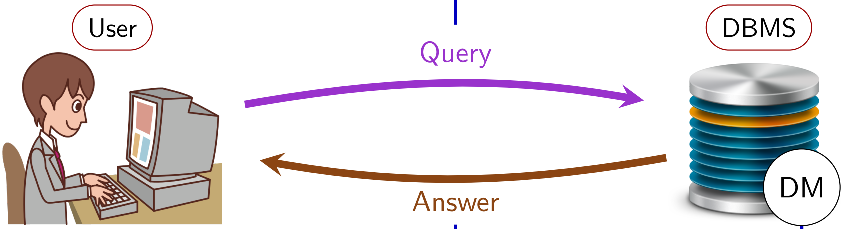

- Semantics of query
  - "*What does the query mean?*"
- DM = **D**ata **M**odel = "*The way data is structured*"
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Relational DBMS = tables with cross-references

Example: DB for a small store

Client table

name	address
Alice	Wonderland
Bob	124 Conch St.
Charlie	1593 Broadway

Product table

name	price
Sponge	1€
Broom	5€
Rabbit	0€
Pocket Watch	100€

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Order table

id	buyer	date
0	Alice	01-11-1865
1	Bob	07-07-2022

Order-content table

order_id	product
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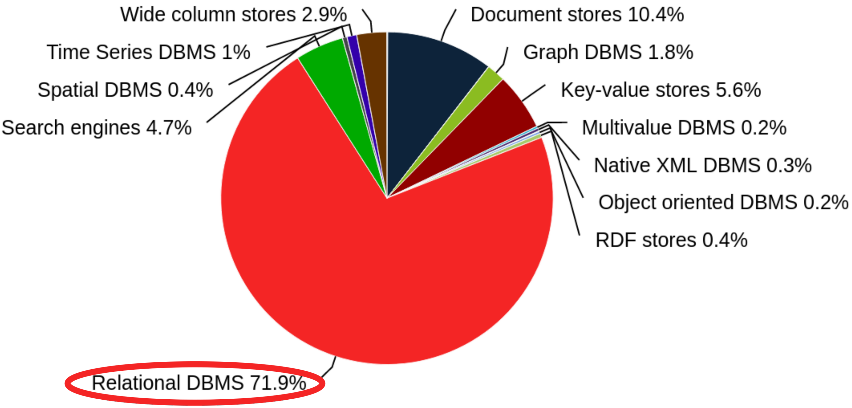
Vast majority of DMBS are relational, not graph



Figure/data from `db-engines.com`, June 2022

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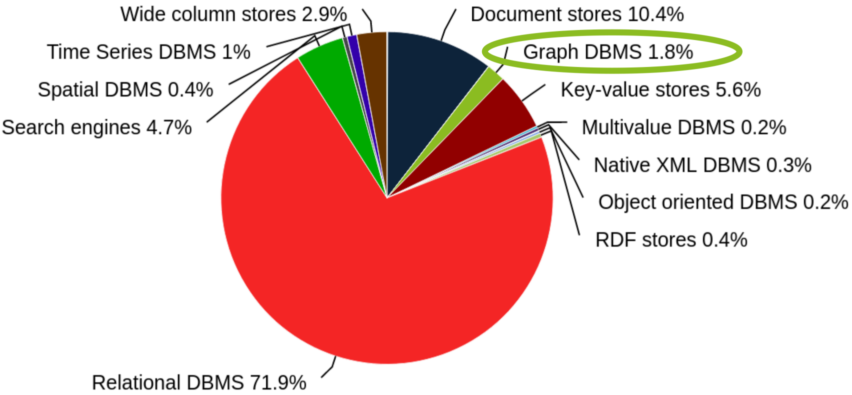

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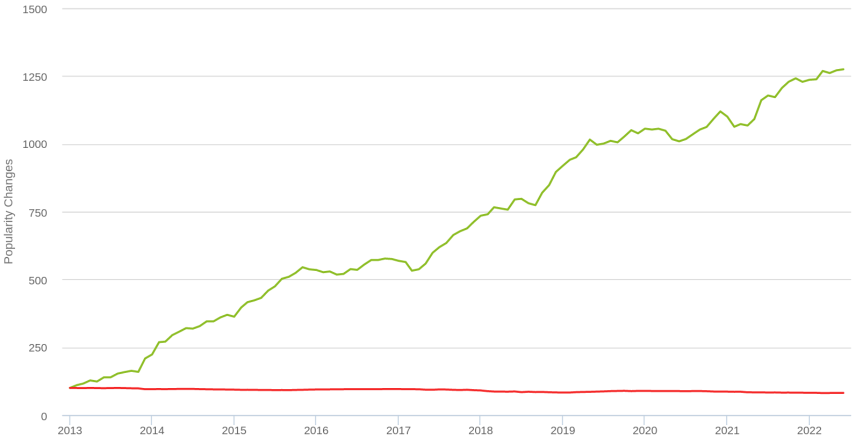
Graph DBMS is growing in popularity

+25% per year since 2013



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Why use graph databases?

Some data have intrinsically the structure of graphs:

- Semantic web
- Network (social, transport, etc.)
- Financial transactions

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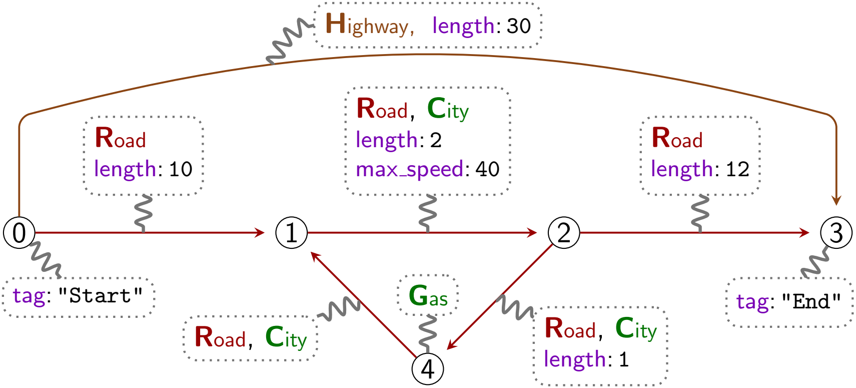
Native representation of data as graphs allows:

- Specific algorithms on graphs
- Pattern matching
- More intuitive understanding/visualisation

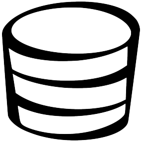
Glimpse at our property graph example



Need for abstraction

Data model
in documentation

DBMS



Property graph
(vendor dependent)

Neo4j,
TigerGraph,
etc.

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Abstract
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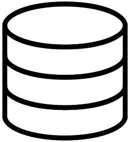

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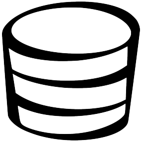

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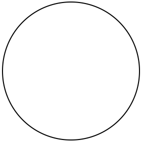

Graph

Abstract
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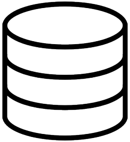

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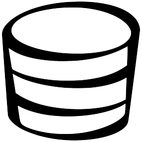

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Outline

Part 1: without data

- Graphs as database
- Foundation of querying graph databases: RPQs
- Ensuring finitess

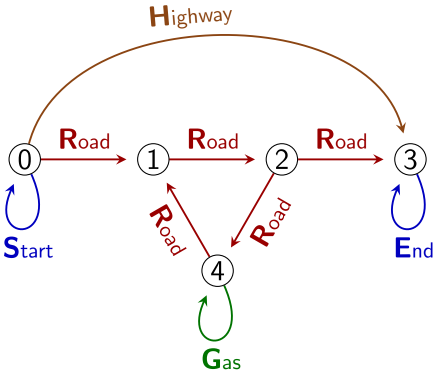
Part 2: with data

- Property graphs
- Cypher
- GQL
- Appendix

Graphs as database

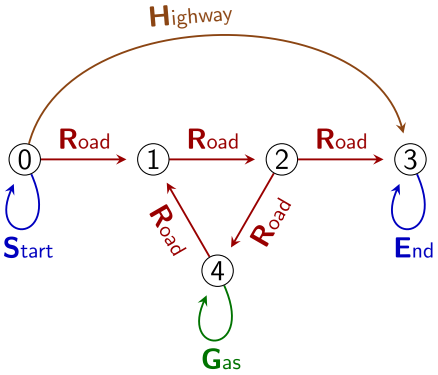
Our example graph

A graph consists of ...



A graph consists of ...

- Vertices (a.k.a. Nodes)
  0, 1, 2, 3, 4



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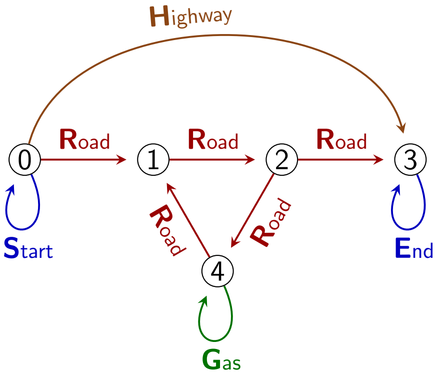

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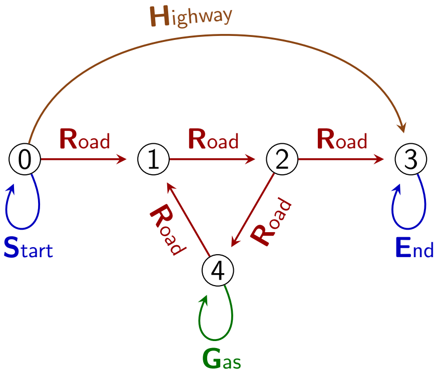

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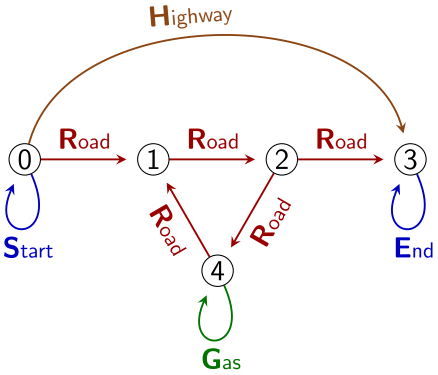
Walk

- a.k.a. Path
- Sequence of edges
- Can reuse vertices and edges



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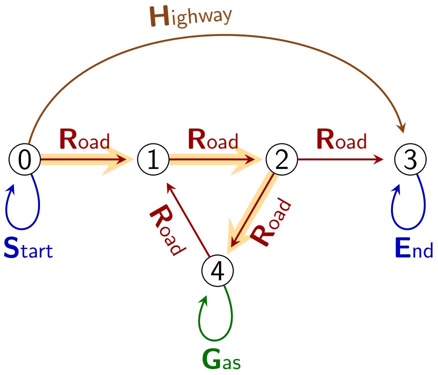

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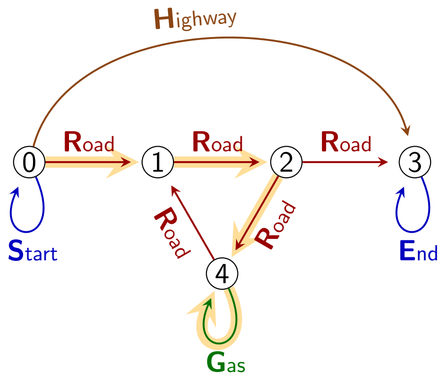

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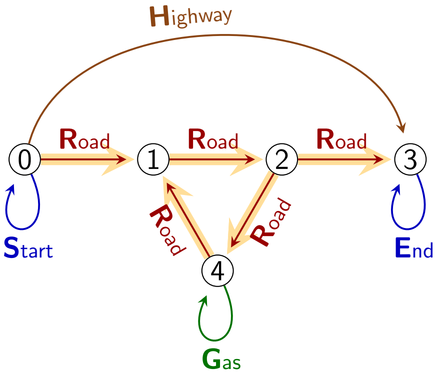


A graph can be stored in tables

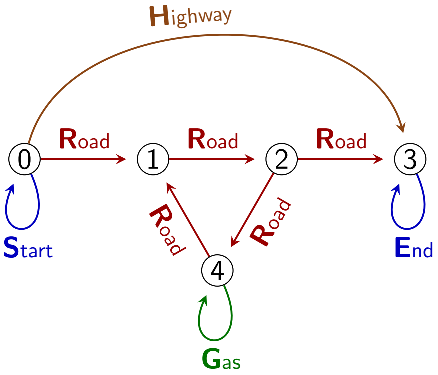
Table for nodes

id
0
1
2
⋮

Table for Road edges

source	target
0	1
1	2
⋮	⋮

One table for Start,
One table for Highway,
etc...



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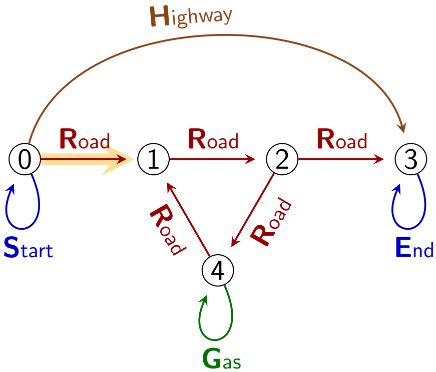
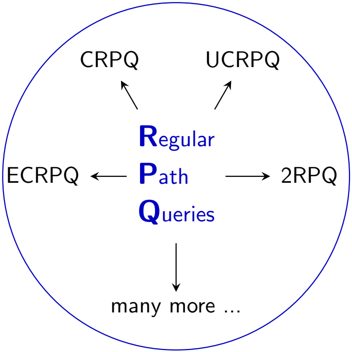


Foundation of querying graph databases: RPQs

Why RPQs are important

Regular
Path
Queries

Why RPQs are important



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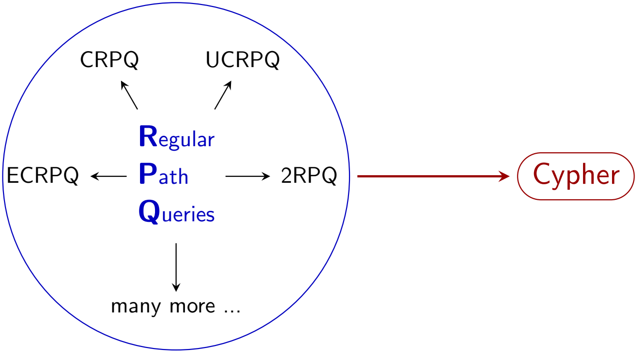

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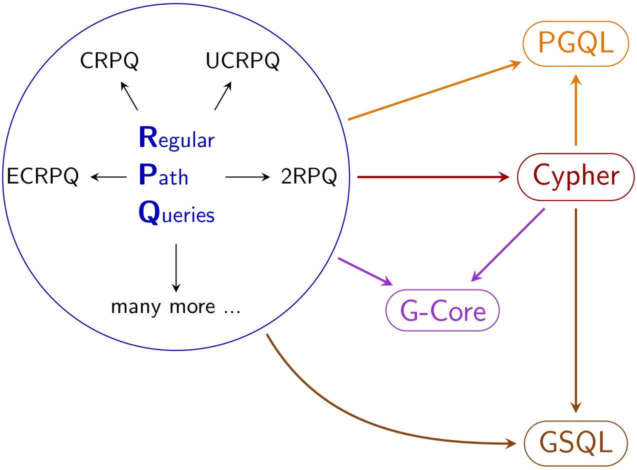

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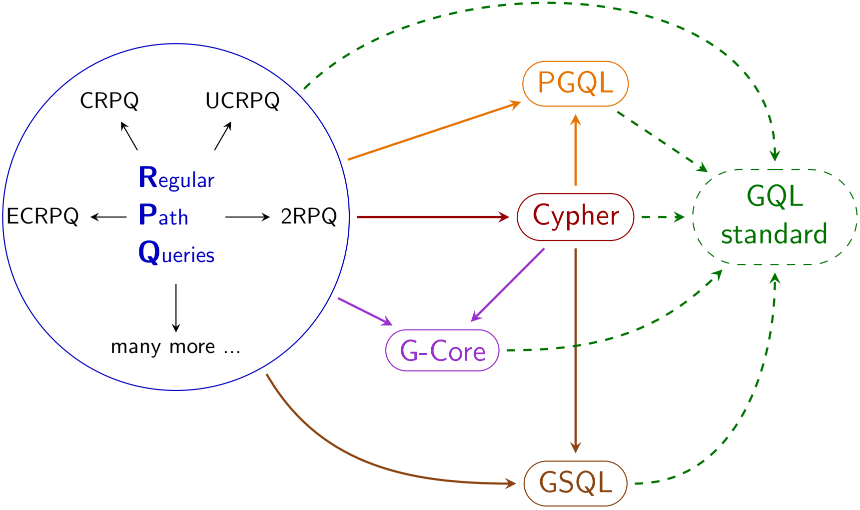

RPQ = Regular expression

$\mathcal{Q} ::=$	**A**	Atoms
	$\mathcal{Q}\mathcal{Q}$	Concatenation
	$\mathcal{Q} + \mathcal{Q}$	Union/Disjunction
	$\mathcal{Q}^*$	Kleene star

where **A** is a label in the graph.

An RPQ denotes a set of words

S (**H**+**R**)* **E** denotes the words of the shape **S**`<something>`**E**

Any number of **H** and **R**, in any order

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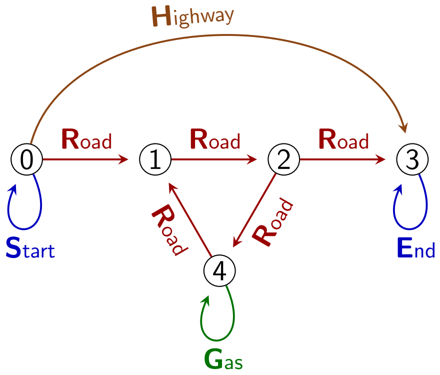
Matches

A match for $\mathcal{Q}$ is any walk w such that $\mathcal{Q}$ denotes the label of w

Query R matches...

...every **R**oad-edge



Edge and concatenation

Query R matches...

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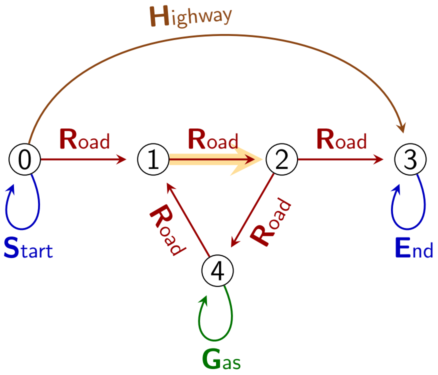
0 → 1	2 → 4
1 → 2	4 → 1
2 → 3	



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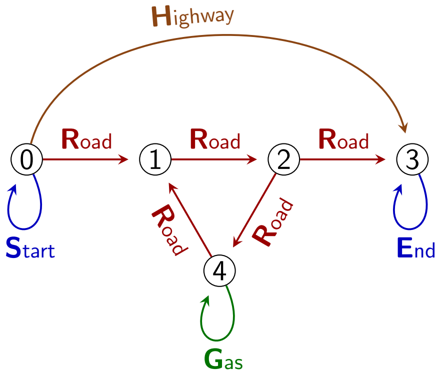
Query **RR** matches...

...walks of two **R**oad-edges



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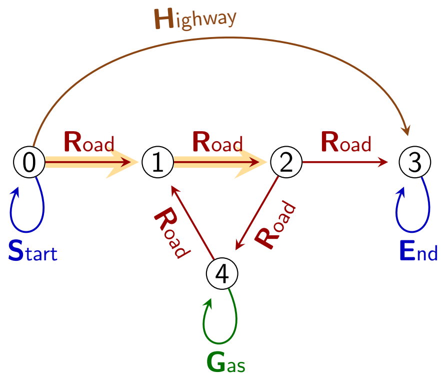

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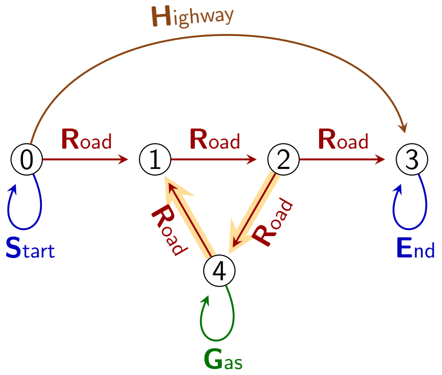
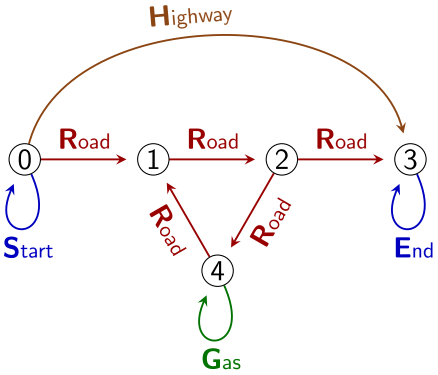


Disjunction

Query R+H matches...

...edges labelled by **R** or by **H**

$0 \to 1$	$2 \to 4$
$1 \to 2$	$4 \to 1$
$2 \to 3$	$0 \to 3$



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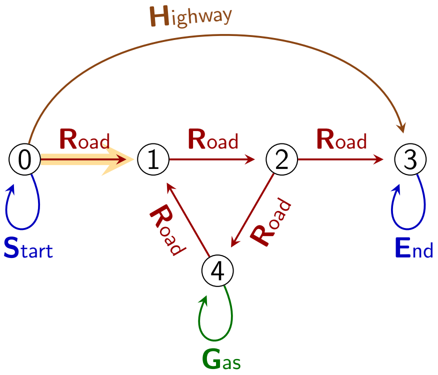

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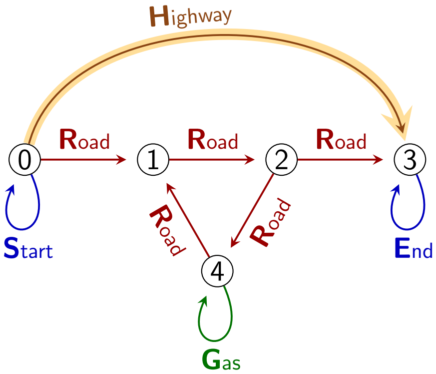

Disjunction

Query **R** + **H** matches…

…edges labelled by **R** or by **H**

0 → 1	2 → 4
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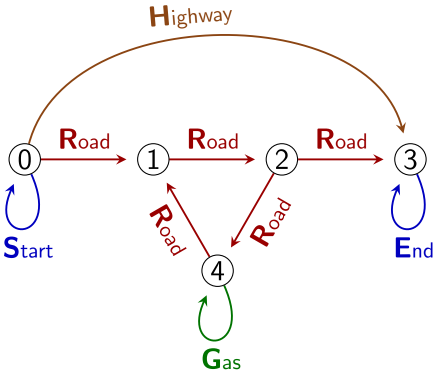
2 → 3	0 → 3

Query **S** (**H** + **R**) matches

0 → 0 → 1
0 → 0 → 3



Disjunction

Query R + H matches...

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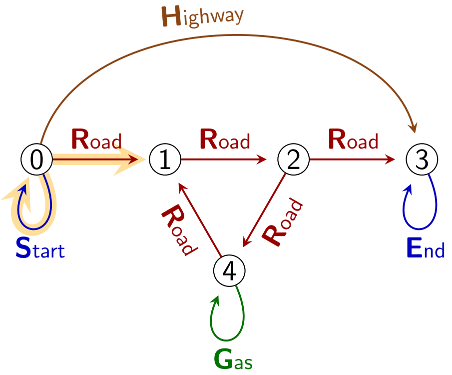

Query S (H + R) matches

$0 \to 0 \to 1$

$0 \to 0 \to 3$

Disjunction

Query R+H matches...

...edges labelled by **R** or by **H**

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1 → 2	4 → 1
2 → 3	0 → 3

Query S (H+R) matches

0 → 0 → 1
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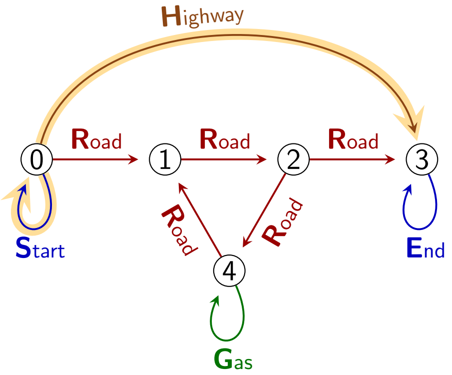


Kleene star

Query **R*** matches...

...walks consisting of **R**oad-edges

$0 \to 1$

$0 \to 1 \to 2$

$0 \to 1 \to 2 \to 3$

$0 \to 1 \to 2 \to 4$

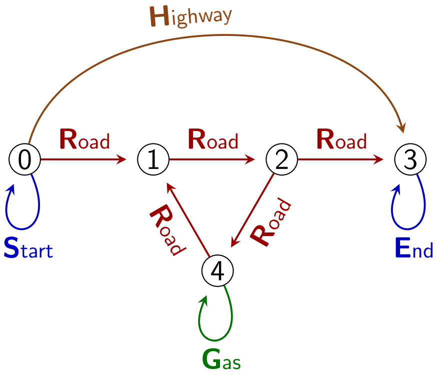
$\vdots$

$1 \to 2 \to 4 \to 1$

$\vdots$

$1 \to 2 \to 4 \to 1 \to 2 \to 4 \to 1$

$\vdots$



Kleene star

Query $\mathbf{R}^*$ matches...

...walks consisting of **R**oad-edges

$0 \rightarrow 1$

$0 \rightarrow 1 \rightarrow 2$

$0 \rightarrow 1 \rightarrow 2 \rightarrow 3$

$0 \rightarrow 1 \rightarrow 2 \rightarrow 4$

$\vdots$

$1 \rightarrow 2 \rightarrow 4 \rightarrow 1$

$\vdots$

$1 \rightarrow 2 \rightarrow 4 \rightarrow 1 \rightarrow 2 \rightarrow 4 \rightarrow 1$

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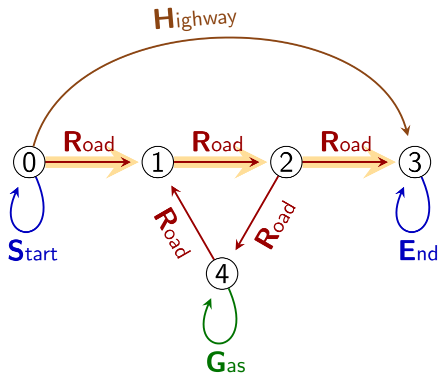

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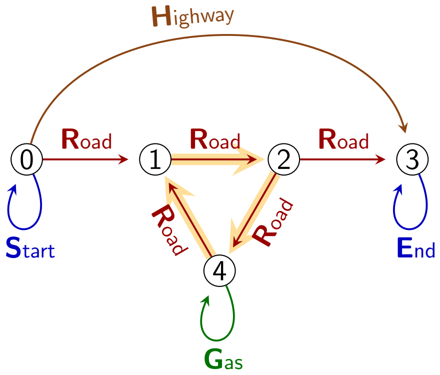

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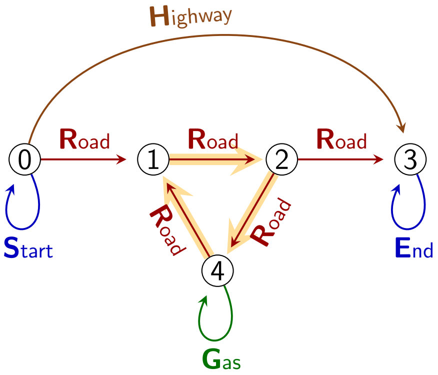
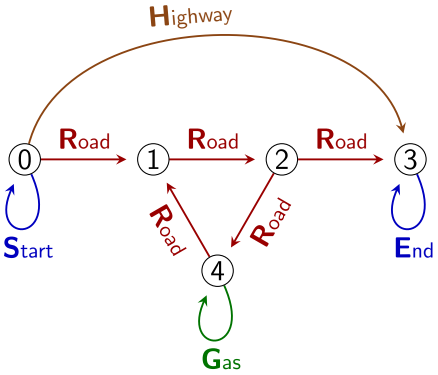


The queries $\mathcal{Q}_1$ and $\mathcal{Q}_2$

$\mathcal{Q}_1 = \mathbf{S}\,(\mathbf{R} + \mathbf{H})^*\,\mathbf{E}$

$\mathcal{Q}_1$ matches...



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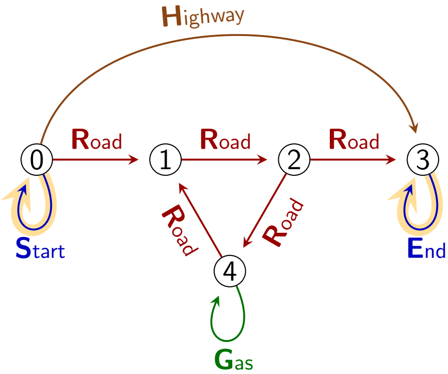

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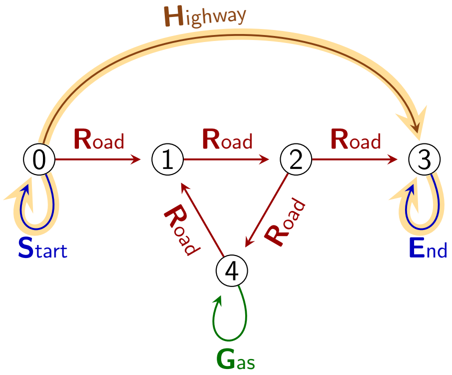
$\mathcal{Q}_1$ matches...

- The highway



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$\mathcal{Q}_1 = \mathbf{S}\,(\mathbf{R}+\mathbf{H})^*\,\mathbf{E}$

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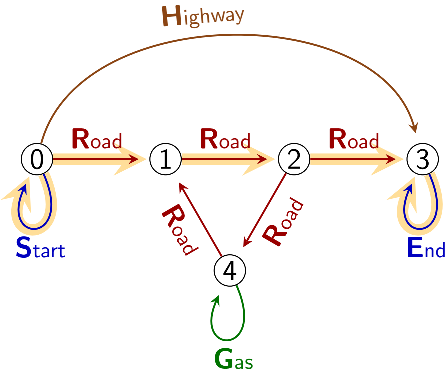
- The highway
- The direct road



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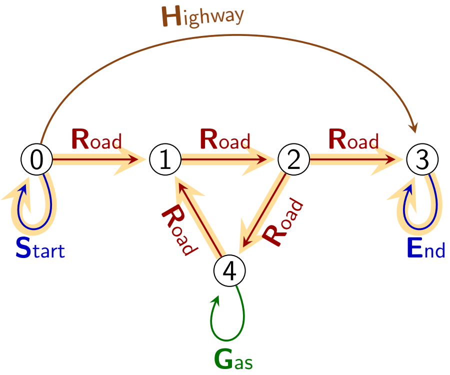
- Road with laps in the circuit



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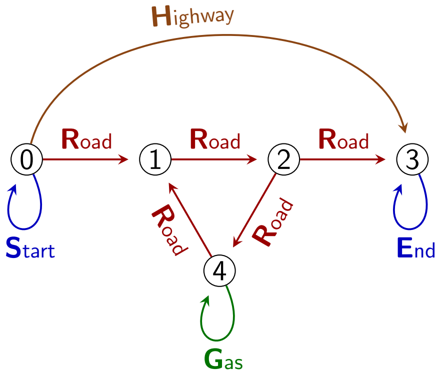

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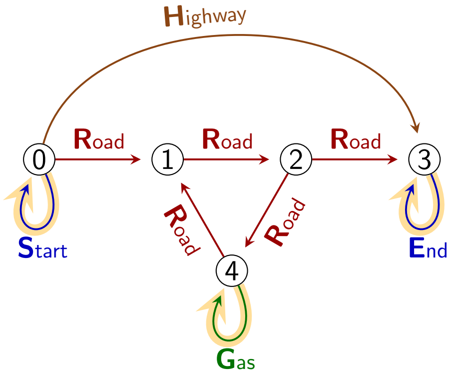

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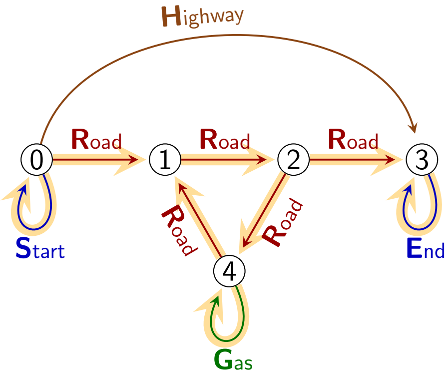
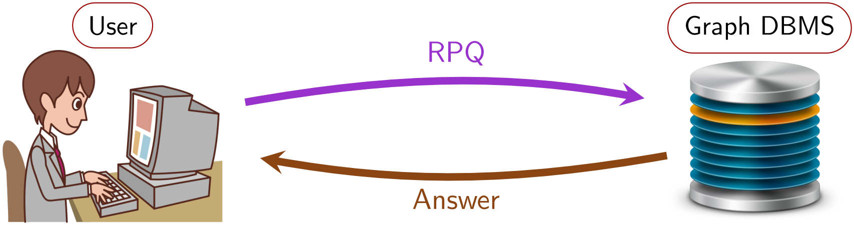


Fundamental challenge with RPQs



⚠ Answer may be infinite ⚠

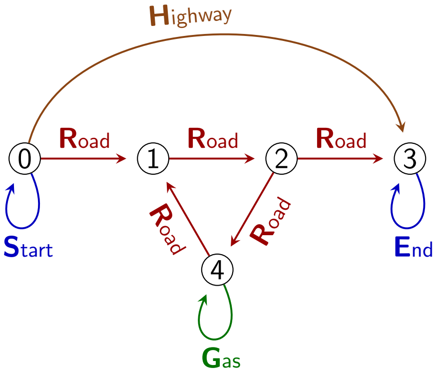
Ensuring finitess

Homomorphism semantics

Main theoretical semantics [Angles et al. 2017]

Definition

- Returns the endpoints of matches



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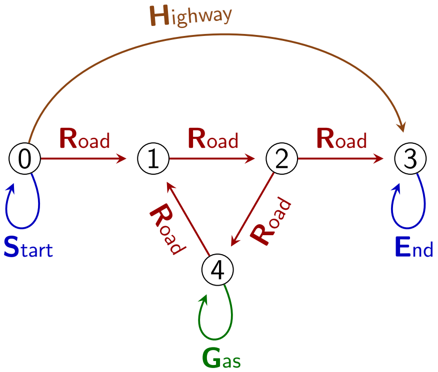
$\mathcal{Q}_1 = \mathbf{S}\ (\mathbf{R}+\mathbf{H})^*\ \mathbf{E}$

$\mathcal{Q}_2 = \mathbf{S}\ (\mathbf{R}+\mathbf{H})^*\ \mathbf{G}\ (\mathbf{R}+\mathbf{H})^*\ \mathbf{E}$

- All matches are: $0 \to \cdots \to 3$

$\Rightarrow \mathcal{Q}_1$ and $\mathcal{Q}_2$ return $\{(0, 3)\}$



Homomorphism semantics (2)

Pros and cons

Pros

- Efficient algorithms
- Well grounded theory

Homomorphism semantics (2)

Pros and cons

Pros

- Efficient algorithms
- Well grounded theory

Cons

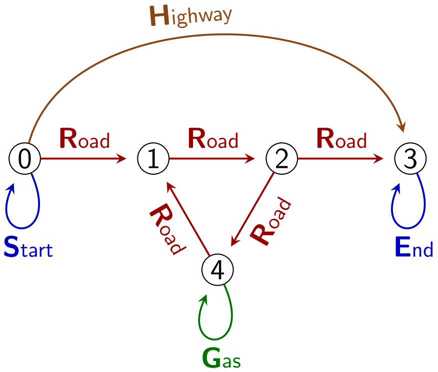
- Limited information in the answer
  - User: *"I want to go from Paris to Lyon by car"*
  - Database: *"Yes you can"*

Shortest-walk semantics

PGQL (Oracle), GSQL (TigerGraph), G-core [Angles et al. 2018]

Definition

- Return the walk with the least number of edges



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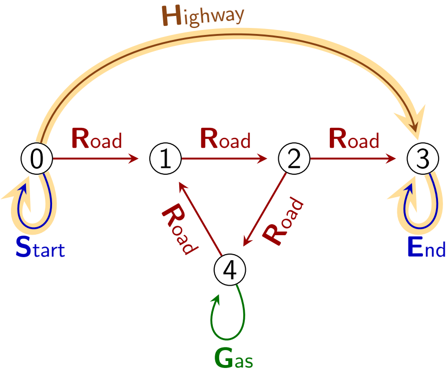
- Return the walk with the least number of edges

$\mathcal{Q}_1 =$ **S** (**R**+**H**)* **E**

- $\mathcal{Q}_1$ returns 1 walks
  - the highway
- Walks taking the road have more edges



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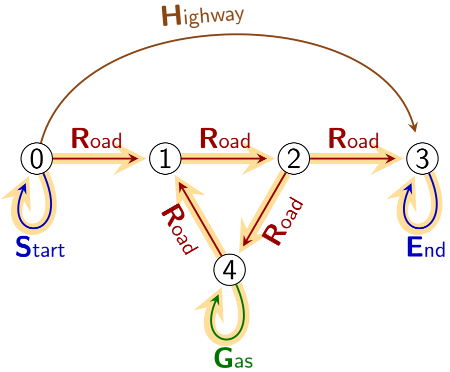
$\mathcal{Q}_2 = \mathbf{S}\ (\mathbf{R}+\mathbf{H})^*\ \mathbf{G}\ (\mathbf{R}+\mathbf{H})^*\ \mathbf{E}$

- $\mathcal{Q}_1$ returns 1 walks
  - the one-lap road



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- Returns walks
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- Horizontal post-processing
  - Horizontal = along the walk
  - *"Is there a gas station on the way?"*
  - *"What is the length of the walk?"*

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- Returns walks
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  - Horizontal = along the walk
  - *"Is there a gas station on the way?"*
  - *"What is the length of the walk?"*

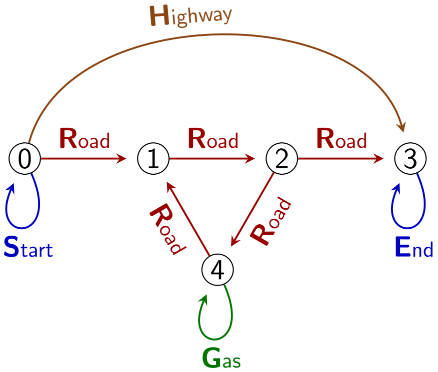
Cons

- No vertical post-processing
  - Vertical = accross the walks with the same endpoints
  - *"What is the shortest walk in time?"*
  - *"What is the connectedness level?"*

Cypher (Neo4j)

Definition

- Return walks
- Forbidden to repeat edges



Definition

- Return walks
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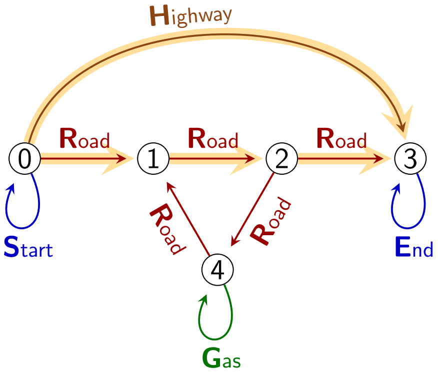
$$\mathcal{Q}_1 = \mathbf{S}\ (\mathbf{R}+\mathbf{H})^*\ \mathbf{E}$$

- $\mathcal{Q}_1$ returns 2 walks
  - the highway
  - the straight road



Trail semantics

Cypher (Neo4j)

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- $\mathcal{Q}_1$ returns 2 walks
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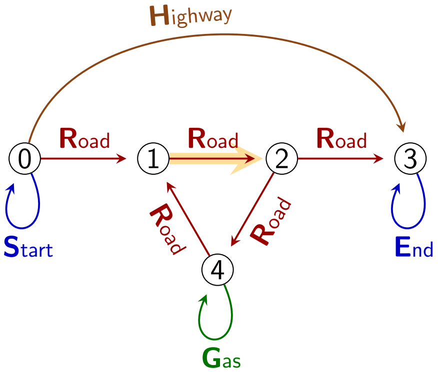
  - the straight road
- Walks with circuit laps
  $\Rightarrow$ repeat the middle edge



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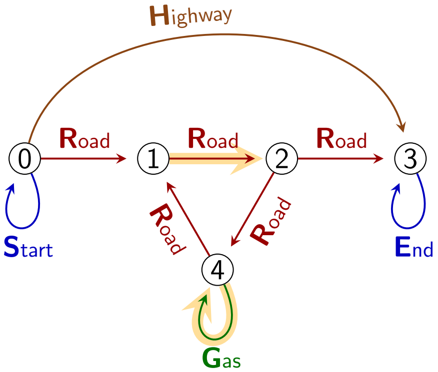
$\mathcal{Q}_2 = \ \mathbf{S}\ (\mathbf{R}+\mathbf{H})^*\ \mathbf{G}\ (\mathbf{R}+\mathbf{H})^*\ \mathbf{E}$

- $\mathcal{Q}_2$ returns nothing



Trail semantics (2)

Pros and cons

Pros

- Returns walks
- Counting matches
- Horizontal and vertical post-processing

Trail semantics (2)

Pros and cons

Pros

- Returns walks
- Counting matches
- Horizontal and vertical post-processing

Cons

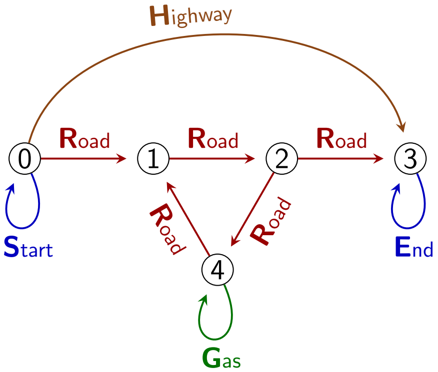
- All problems are computationally hard [Martens et al. 2020]
  - Counting, enumeration, existence
  - Checking whteher Q_2 returns anything $\rightarrow$ Already hard
- No repeated edge $\rightarrow$ not always intuitive

Run-based semantics

New theoretical proposal [David-Francis-Marsault 2023?]

Definition

- Returns walks
- Each edge may match each atom only once



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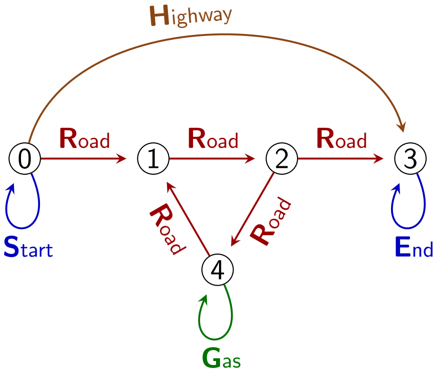

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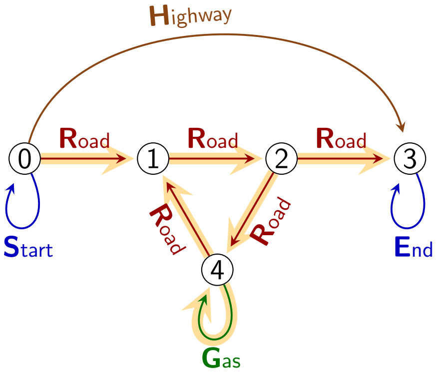

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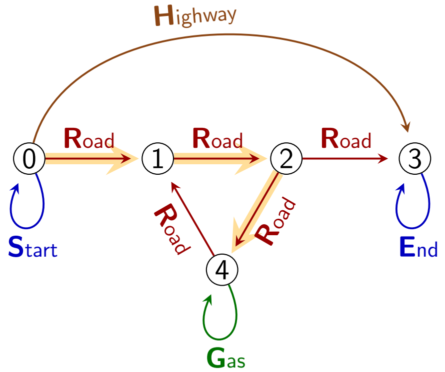
$\mathcal{Q}_2 = \quad \mathbf{S}\ (\mathbf{R}+\mathbf{H})^*\ \mathbf{G}\ (\mathbf{R}+\mathbf{H})^*\ \mathbf{E}$

- Returns the 1-lap road only
  - Before **G** $\rightarrow$ use the left **R**



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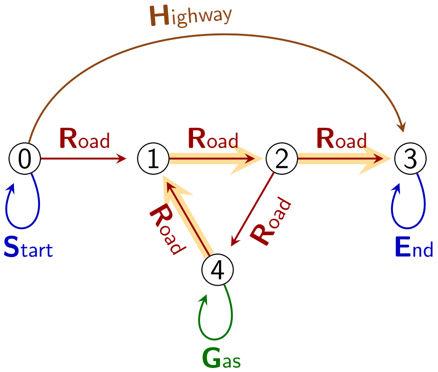

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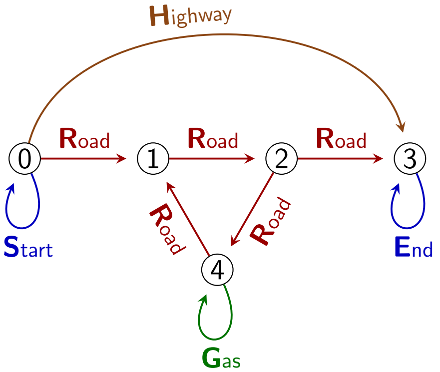

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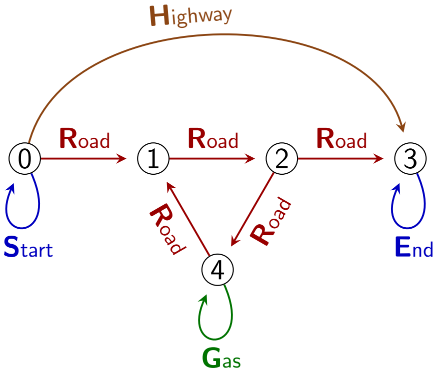

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$\mathcal{Q}_1 = \; \mathbf{S}\ (\mathbf{R}+\mathbf{H})^*\ \mathbf{E}$

- Returns the highway and the straight road

Run-based semantics (2)

Pros and cons

Pros

- Returns walks
- Horizontal and vertical post-processing
- Enumerating matches is efficient
- Counting matches

Run-based semantics (2)

Pros and cons

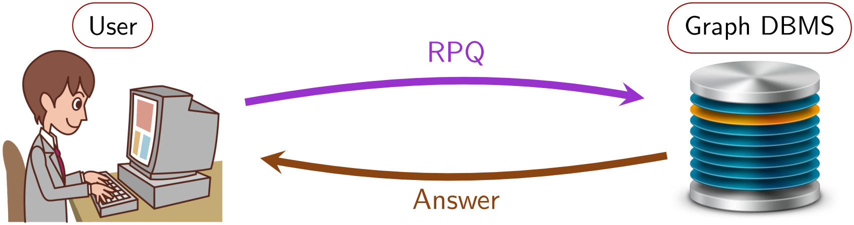
Pros

- Returns walks
- Horizontal and vertical post-processing
- Enumerating matches is efficient
- Counting matches

Cons

- Counting matches is computationally hard
- Answer depends on the way the query is written
  - $\mathbf{R}^*$ allows no lap in the circuit
  - $\mathbf{R}^*\mathbf{R}^*$ allows 1 lap in the circuit
  - $\mathbf{R}^*\mathbf{R}^*\mathbf{R}^*$ allows 2 lap in the circuit
  - etc.

Fundamental challenge with RPQs

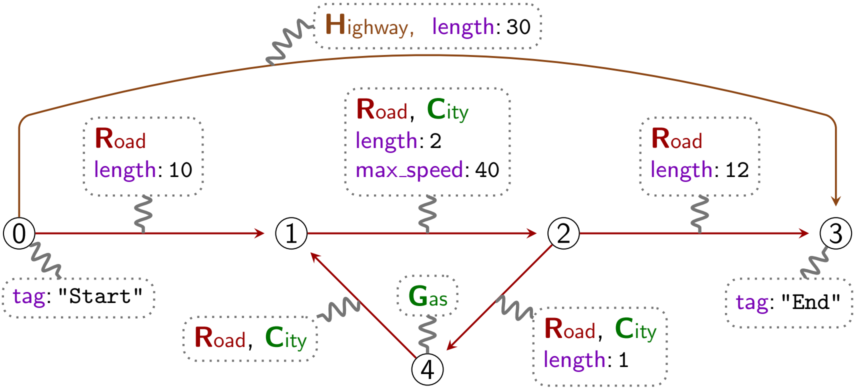


⚠ Answer may be infinite ⚠

- Several way to ensure finiteness
  - Homomorphism semantics → Returns litte information
  - Shortest-walk semantics → No vertical post-processing
  - Trail semantics → Not efficient in bad cases
  - etc.
- No solution is clearly superior

Property graphs

Example property graph

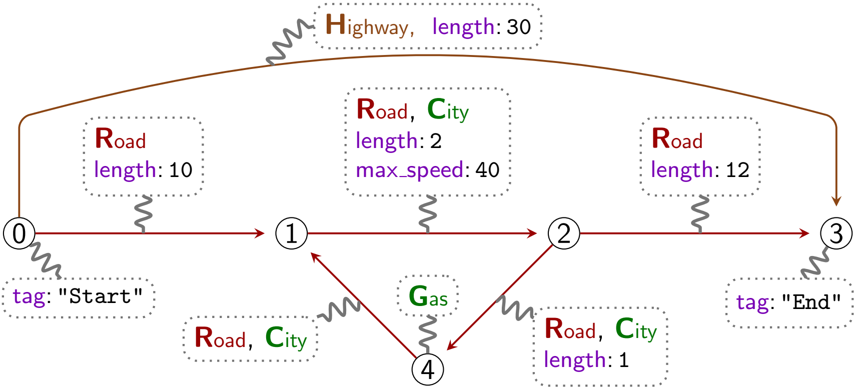


Vertices and edges may bear:

- zero or more labels
- zero or more properties

- Property = key-value pair
- Key = string
- Value = `bool`, `int`, `str`, ...

Storing our property graph into tables



id	source_id	target_id	Road	Highway	City	length	max_speed
e_{01}	0	1	true	false	false	10	
e_{12}	1	2	true	false	true	10	40
e_{41}	4	1	true	false	true		
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Graph | Labels | Properties

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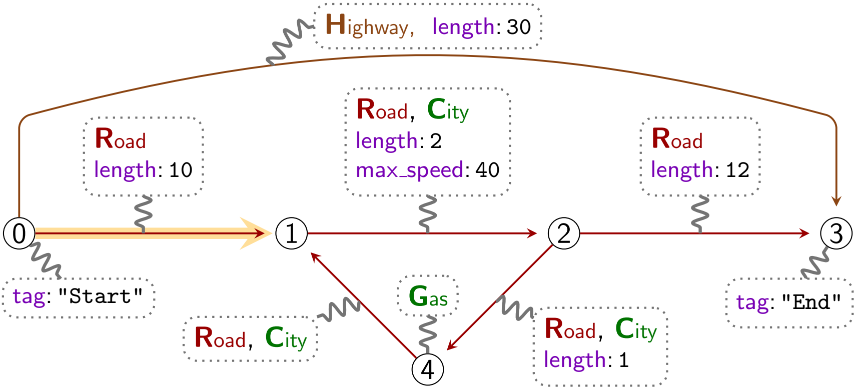

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▶	e_{01}	0	1	true	false	false	10		◀
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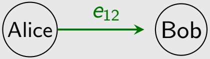
	e_{41}	4	1	true	false	true			
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	

Graph — Labels — Properties

What property graphs can't do

Wedding is edgy...

id	person1	person2
e_{12}	Alice	Bob
⋮	⋮	⋮



..but trouple is trouble

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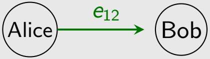
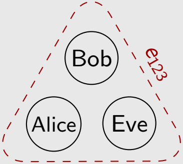


..but trouple is trouble

id	person1	person2	person3
e_{123}	Alice	Bob	Eve
⋮	⋮	⋮	⋮



Cypher

History

- Created for Neo4j DBMS in 2011
- Neo4j and Cypher become popular
- Project openCypher since 2015
  - Goal: standardize Cypher
  - Evolution led by community (oCIM)
  - Formal semantics [Francis et al. 2018] [Green et al. 2019]
  - Replaced by GQL
- Implemented in SAP HANA, Redis graph, etc.

ASCII-art syntax for RPQs

- Vertices: `MATCH (:Gas)`

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- Concatenation: `MATCH ()-[:Road]->(:Gas)-[:Road]->()`

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- Kleene star: `MATCH ()-[:Road*]->()`

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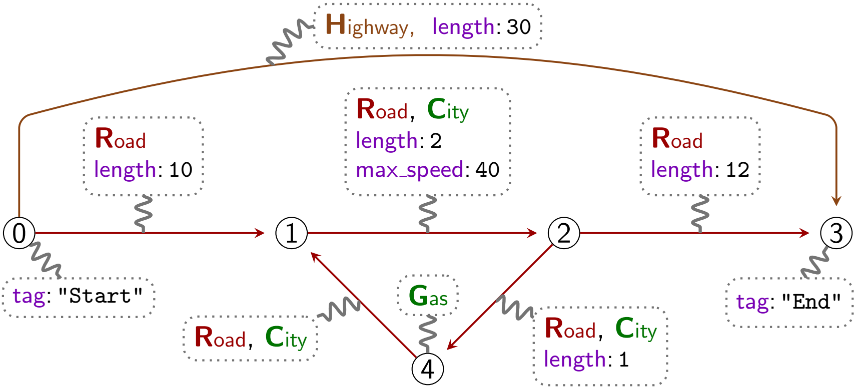
- Concatenation: `MATCH ()-[:Road]->(:Gas)-[:Road]->()`
- Kleene star: `MATCH ()-[:Road*]->()`
- $\mathcal{Q}_1$:
  `MATCH ({tag:"Start"})-[:Road|Highway*]->({tag:"End"})`

Cypher returns a table...



Query

```
MATCH (s)-[:City]->(t)
```

Result

s	t
1	2
2	4
4	1

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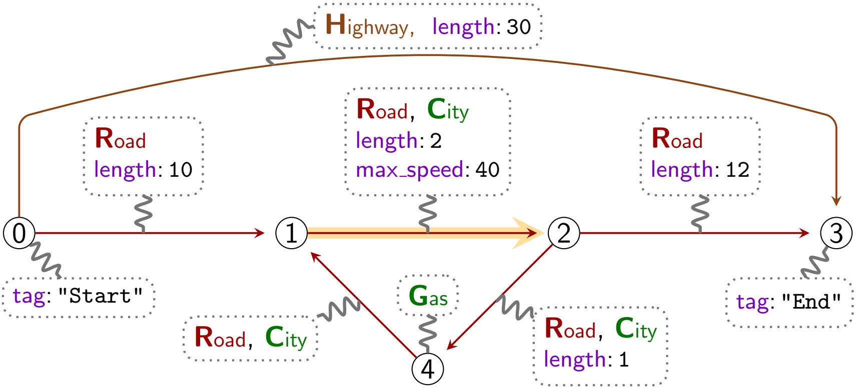

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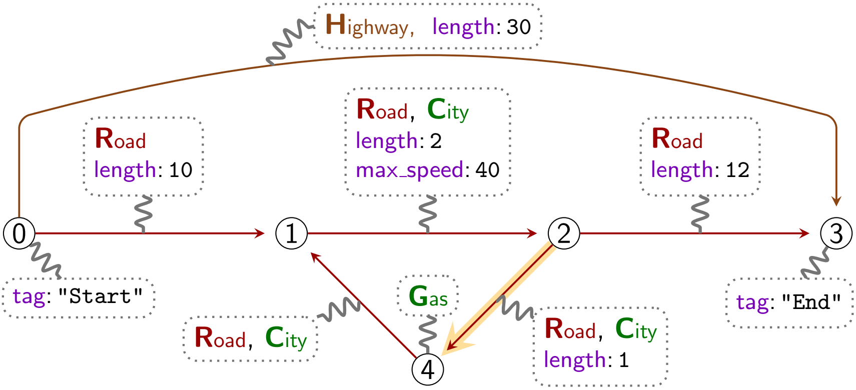

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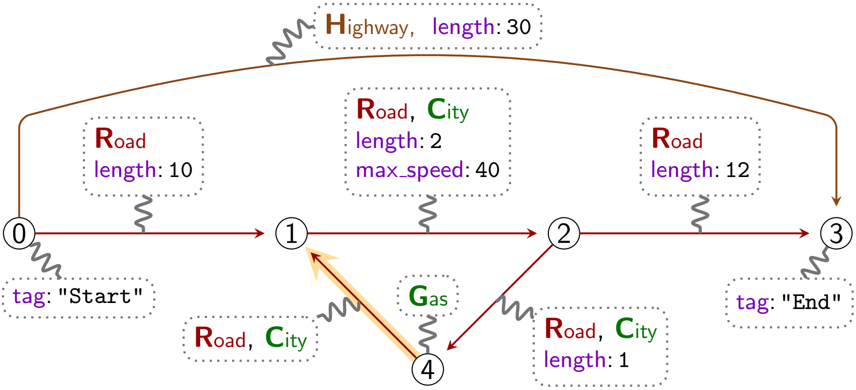

Query

```
MATCH (s)-[:City]->(t)
```

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1	2
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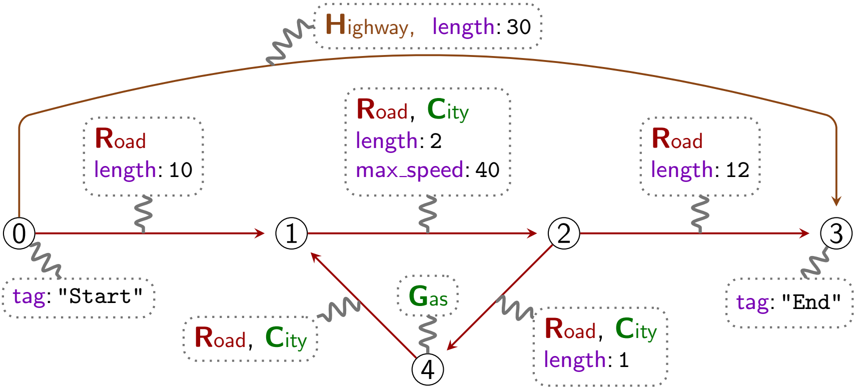


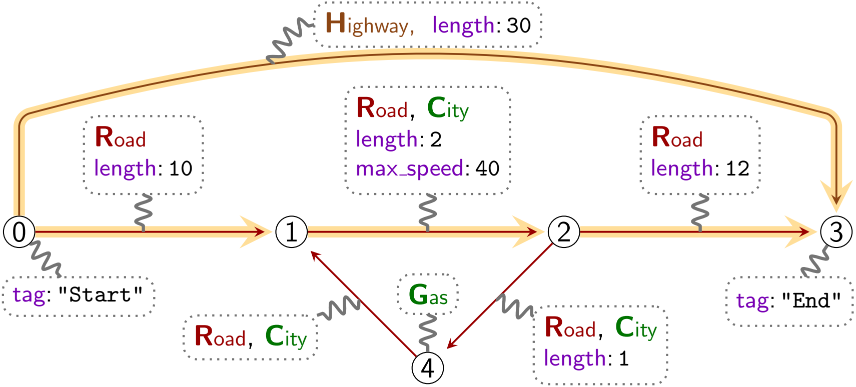
Query

```
MATCH
    (s {name:"Start"})
        -[:Road|Highway*]->
            (t {name:"End"})
```

Result

s	t
0	3
0	3

Cypher returns a table… but computes walks



Query

```
MATCH
    (s {name:"Start"})
        -[:Road|Highway*]->
            (t {name:"End"})
```

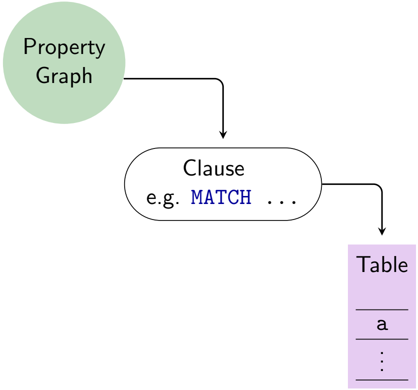
Result

s	t	
0	3	← The highway
0	3	← The direct road

Other Cypher features

- `ORDER BY`: orders row
- `WHERE`: filters row
- `WITH` or `RETURN`:
  - adds/renames columns
  - horizontal aggregation: e.g. `reduce`
  - vertical aggregation: e.g. `count`
- `CREATE`/`DELETE`/`SET`: updates the property graph

A Cypher query actually chain clauses



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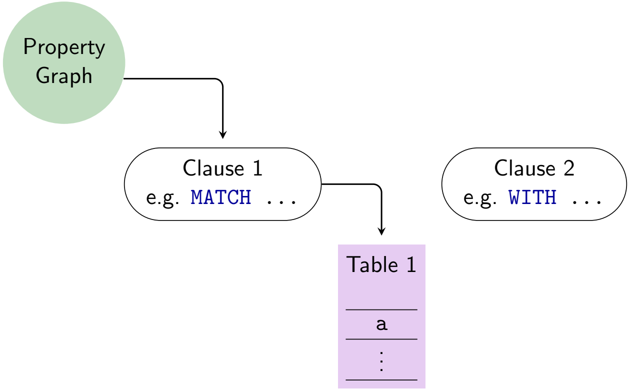

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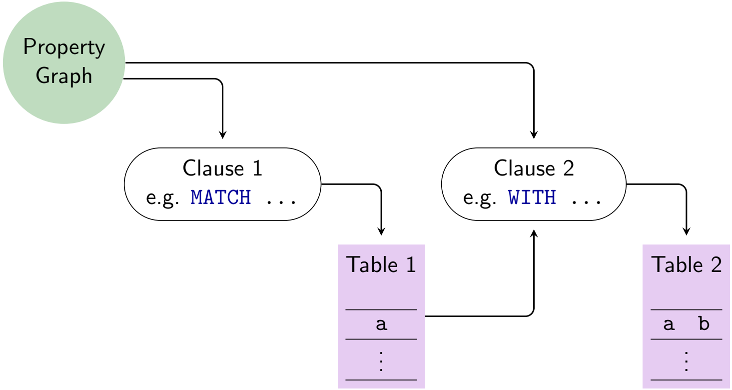

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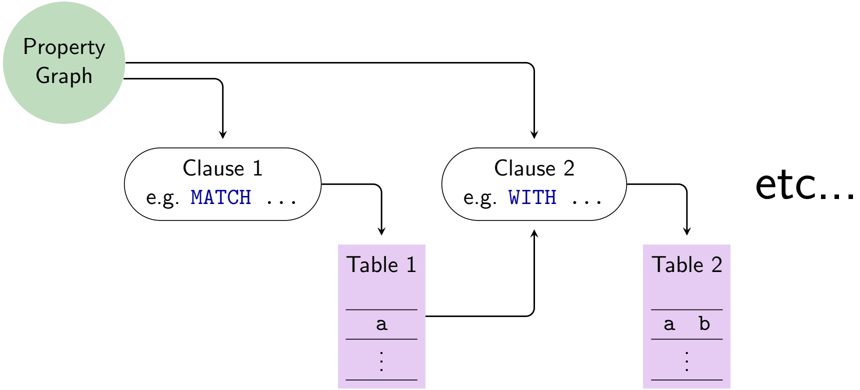

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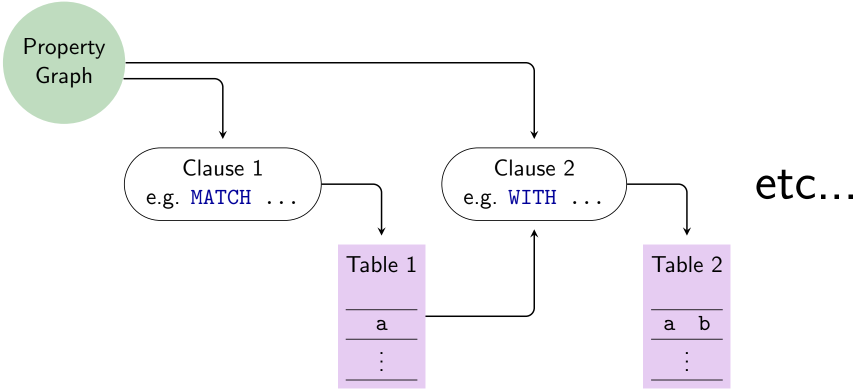
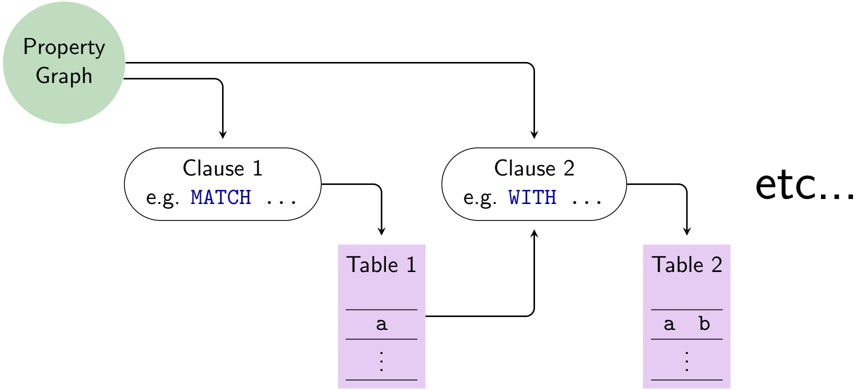


Example

- Clause 1 makes some pattern matching
- Clause 2 aggregates over the result of Clause 1

A Cypher query actually chain clauses



Example

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- Clause 2 aggregates over the result of Clause 1

$\Rightarrow$ Trail semantics (rich post-processing at the cost of efficiency)

GQL

Since 2015: openCypher aims at making Cypher a standard

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2017:

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- Merge existing languages instead ?

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2023 (expected): Publication of version 1 of GQL Standard

GQL and the fundamental challenge with RPQs

An RPQ may have infinitely many matches

- GQL has to ensure finiteness of answer
- No solution is clearly superior

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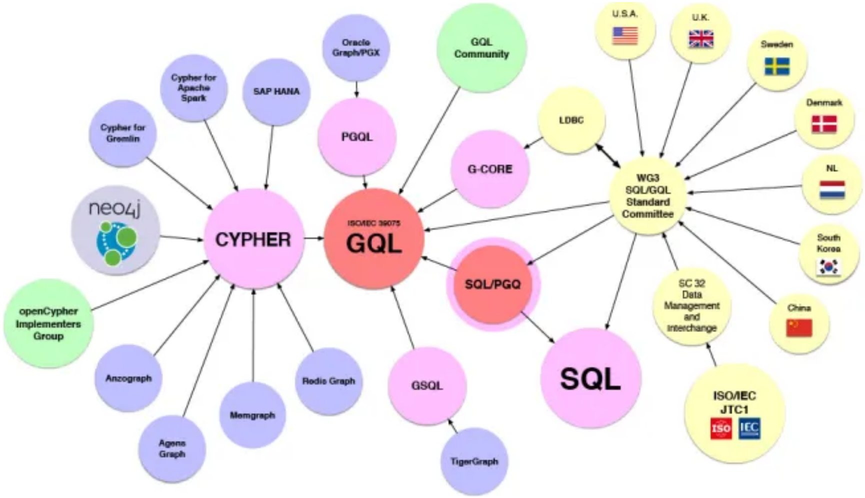
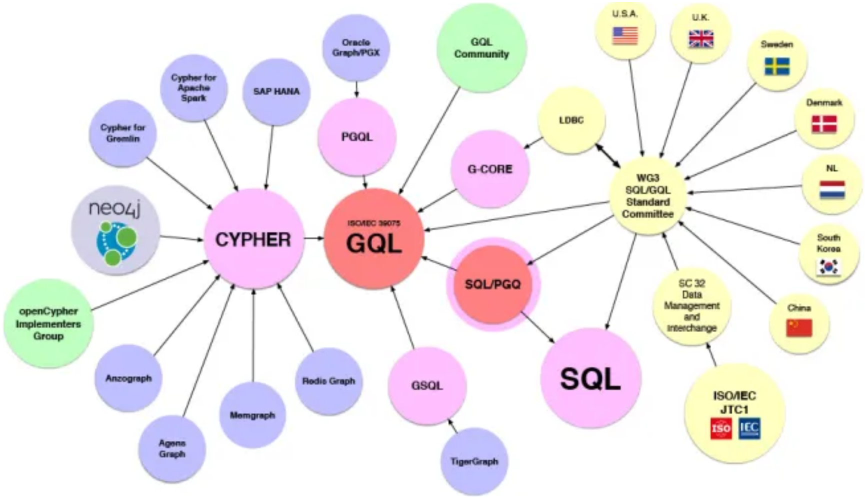
GQL does not choose

- Trail semantics $\rightarrow$ `TRAIL`
- Shortest-walk semantics $\rightarrow$ `SHORTEST`
- Syntax restriction $\rightarrow$ `WALK`
- $\cdots$



Oracle Graph/PGX
GQL Community
U.S.A.
U.K.
Sweden
Denmark
NL
South Korea
China
Cypher for Apache Spark
SAP HANA
PGQL
Cypher for Gremlin
LDBC
G-CORE
WG3 SQL/GQL Standard Committee
neo4j
CYPHER
ISO/IEC 39075
GQL
SQL/PGQ
openCypher Implementers Group
SC 32 Data Management and Interchange
Anzograph
Redis Graph
GSQL
SQL
Memgraph
Agens Graph
TigerGraph
ISO/IEC JTC1
ISO
IEC



Thank you for your attention !

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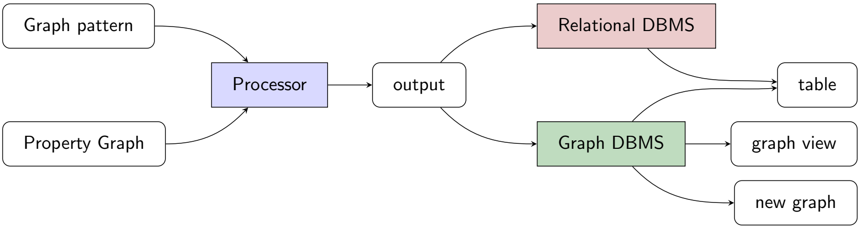
GQL will be usable from SQL



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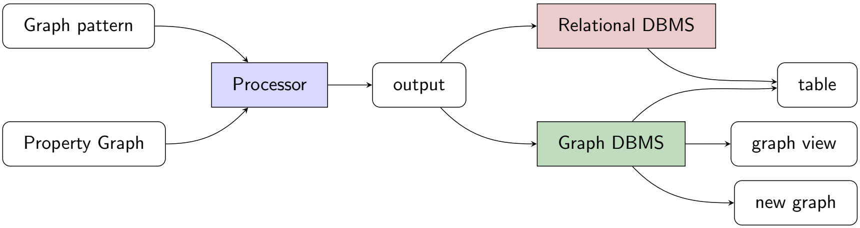
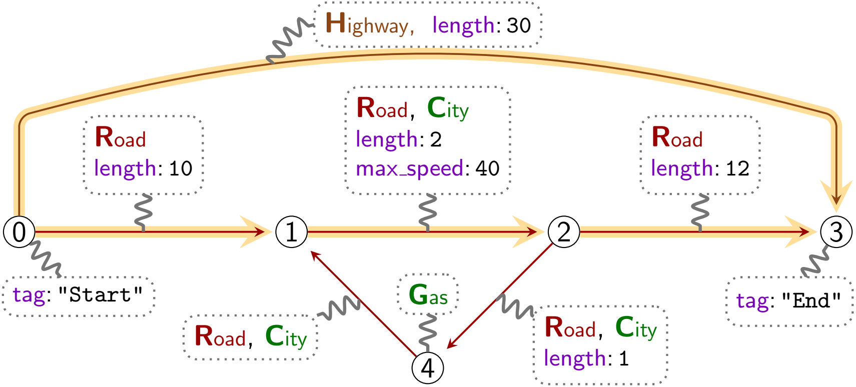


Output of GQL: set of path bindings
Path binding = walk annotated with variables

GQL path-bindings in one slide




```
MATCH TRAIL (a WHERE a.tag="Start")
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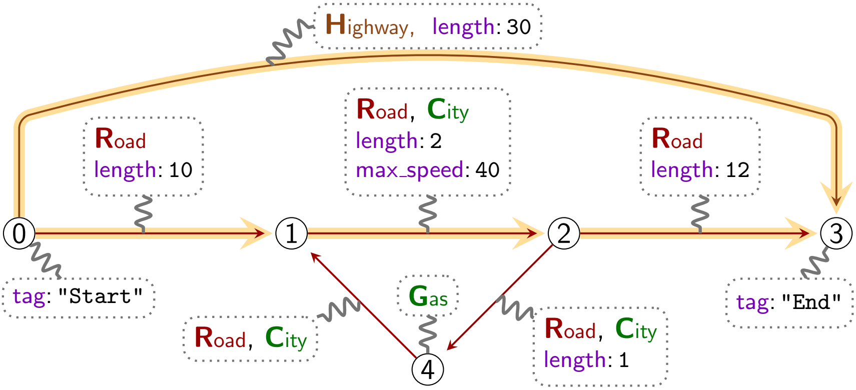


```
MATCH TRAIL (a WHERE a.tag="Start")
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```

0	→	1	→	2	→	3	
a	r		r		r	b	

0	→	1	→	2	→	3	
a	r		c		r	b	