NAVIGATIONAL QUERIES OVER GRAPHS

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Fundamentos de los datos

THE MESSAGE

- Analysis vs synthesis
  - Push the envelope forward
  - Understand what we have thus far
  - The latter seems to be out of fashion

- What I would like to show:
  - Sometimes it is worth going back to the basics

BREADTH FIRST SEARCH (BFS)

- We all know it, so what will we do?
  - Show that it can evaluate navigational queries efficiently
  - It can return paths as part of the query
  - Allows for "fully compositional" semantics of graph queries
- How do I know these things?
  - Theoreicians have been saying something similar all along
  - Several papers on the topic
  - We built a graph database at IMFD that shows this

GRAPH DATABASES

WHY GRAPH DATABASES?

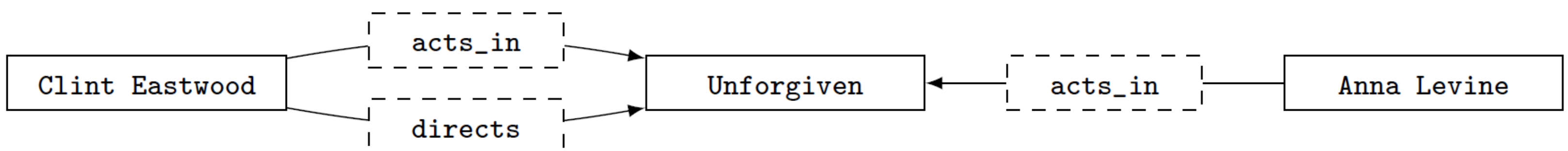
- More intuitive conceptualization:
  - Naturally model relationships (e.g. social networks, bio pathways)

- Potential efficiency gains:
  - Navigation vs. doing a bunch of joins
  - This is where I'm trying to drive the discussion

- Fashion?

GRAPHS IN PRACTICE I

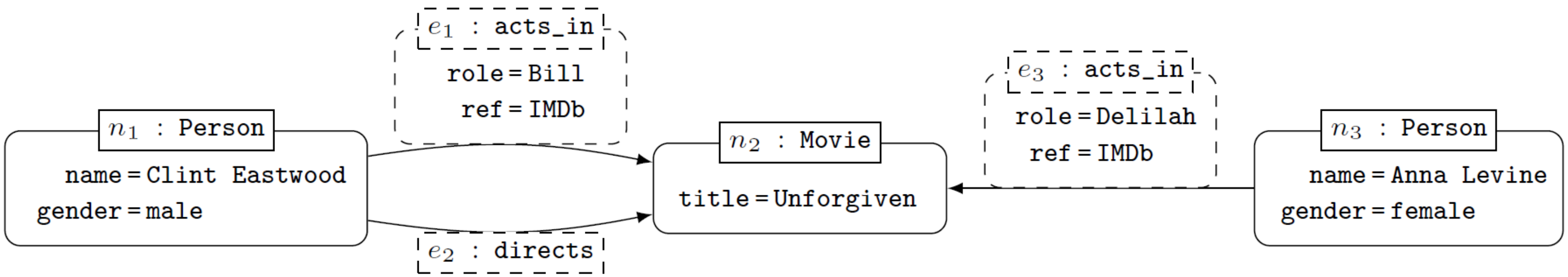
- Edge labeled graphs (RDF)



- Allows recording information in a compact way:
  - Node/edge ***is*** the data
  - The connections can be coded as triples
    - E.g. (Clint Eastwood, acts_in, Unforgiven)

GRAPHS IN PRACTICE II

- Property graphs



- More realistic:
  - Allows recording data using using attribute values
  - Implicit typing through node/edge labels (good for indexing)
  - More robust than RDF
  - Node/Edge IDs are explicit

GRAPH DATABASE SYSTEMS

- Edge labelled graphs
  - RDF systems
  - SPARQL query language (W3C standard)
  - Multiple (reasonable) implementations (Virtuoso, Blaze Graph, Jena)

- Property graphs
  - Neo4j with the Cypher query language
  - Tinkerpop/Gremlin
  - TigerGraph

  - MillenniumDB

QUERYING GRAPHS

GRAPH QUERY FEATURES

- Pattern matching
  - Matching a small graph (pattern/query) onto a bigger one (data)
  - Basically conjunctive queries
  - Different semantics available based on user needs

- Navigational queries
  - Designed to explore connections between points in graph
  - Most common query: path specification
  - Different semantics can have huge impact on evaluation efficiency

See [AABHRV17] for more details

NAVIGATION IN GRAPHS

- Exploring connections
  - Paths whose length is not known in advance
  - Patterns repeated in a "regular" manner

- Examples:
  - Friend-of-a-friend relation in a social network
  - Bacon/Erdos number
  - Shortest routes between two places

PATH QUERIES

- The most basic navigational query class
  - Gives (pairs of) nodes connected by a path conforming to the query
- Usually specified using regular expressions
  - The labels on the edges along a path form a word in the language of the expression
- Present in many languages:
  - SPARQL property paths
  - Neo4J queries
  - Most theoretical literature takes paths as the base for navigation

SPECIFYING PATH QUERIES

- Expressions of the form

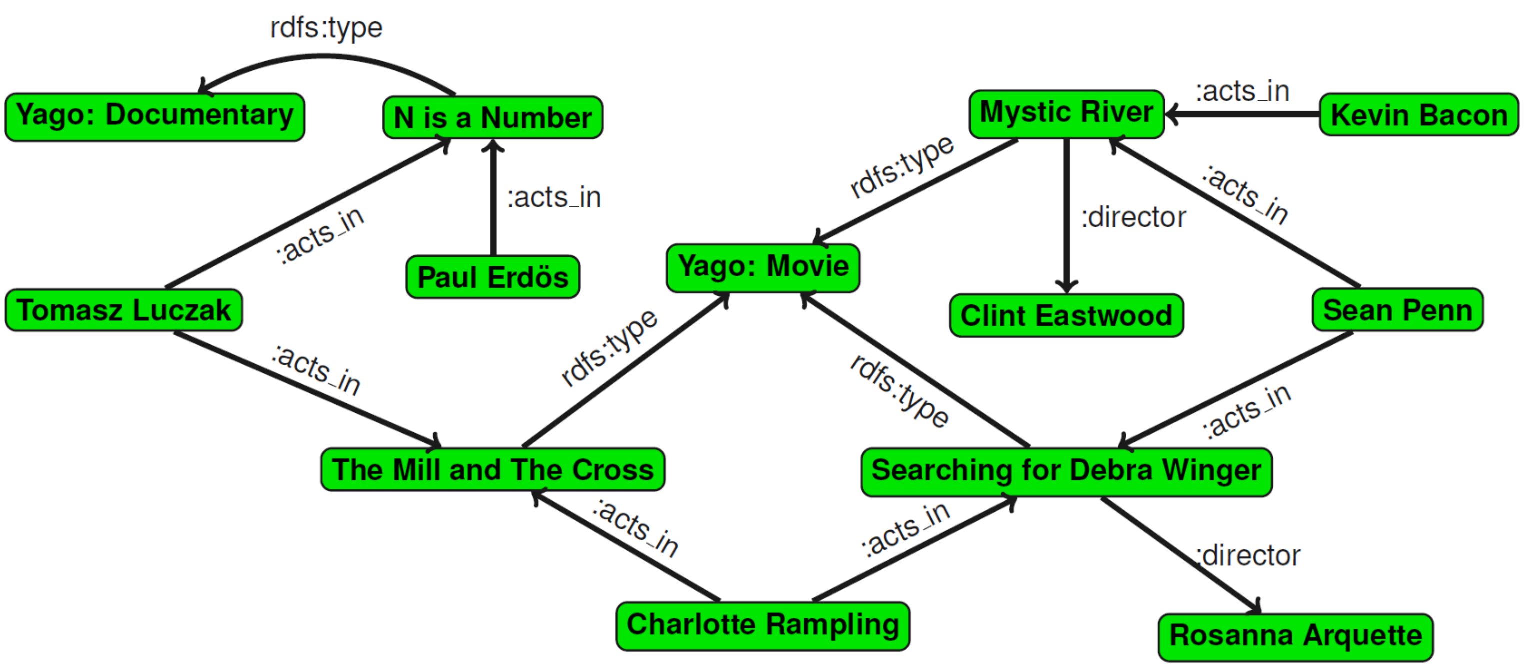
$$x \xrightarrow{regex} y$$

- *x* and *y* are variables or constants (IDs)
- *regex* is a regular expression

- "**Semantics**": All (x,y) connected by a path whose "label" is in the language of *regex*

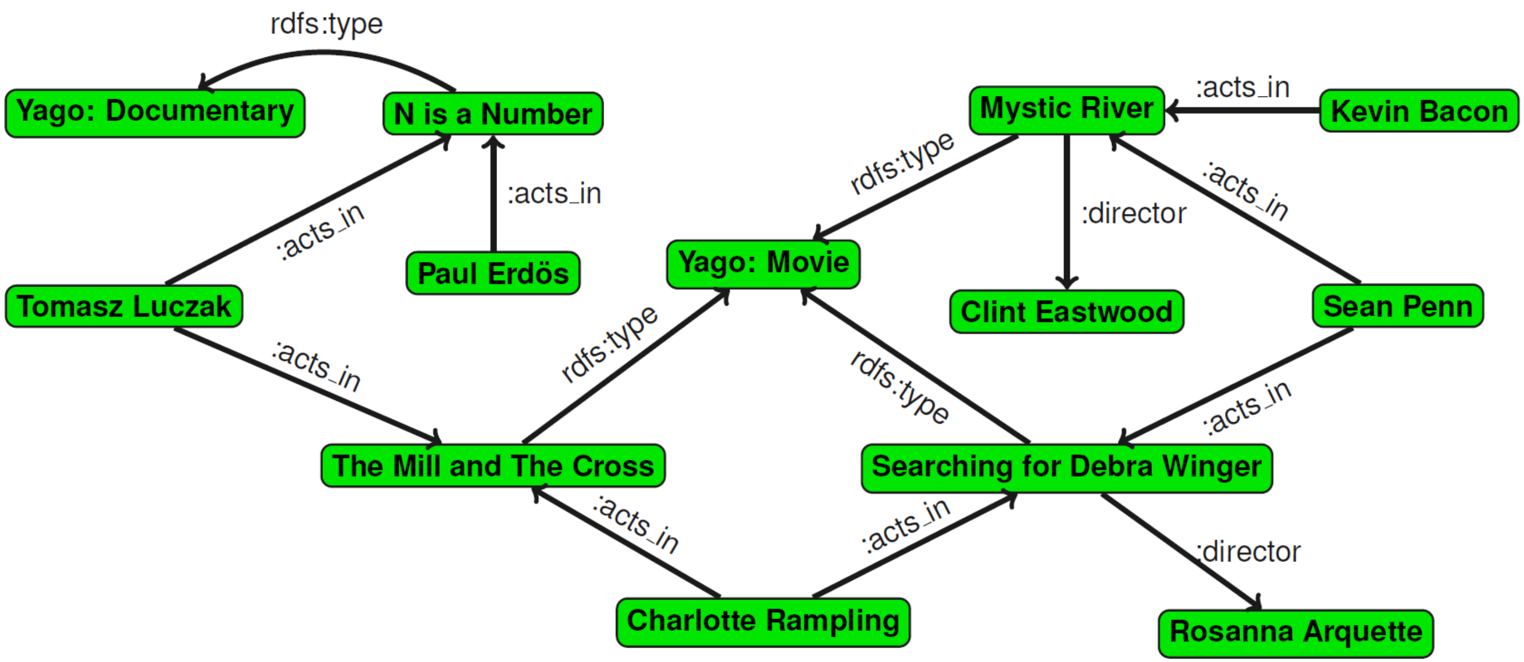
EXAMPLE 1 – BACON NUMBER

- Actors that have a Bacon number in a movie database



EXAMPLE 1 – BACON NUMBER

$$x \xrightarrow{(\mathtt{acts\_in}\cdot\mathtt{acts\_in}^{-})^{*}} \mathtt{Kevin\ Bacon}$$



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```
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MATCH (?x)=[(:acts_in/^:acts_in)*]=>(Kevin Bacon)
```

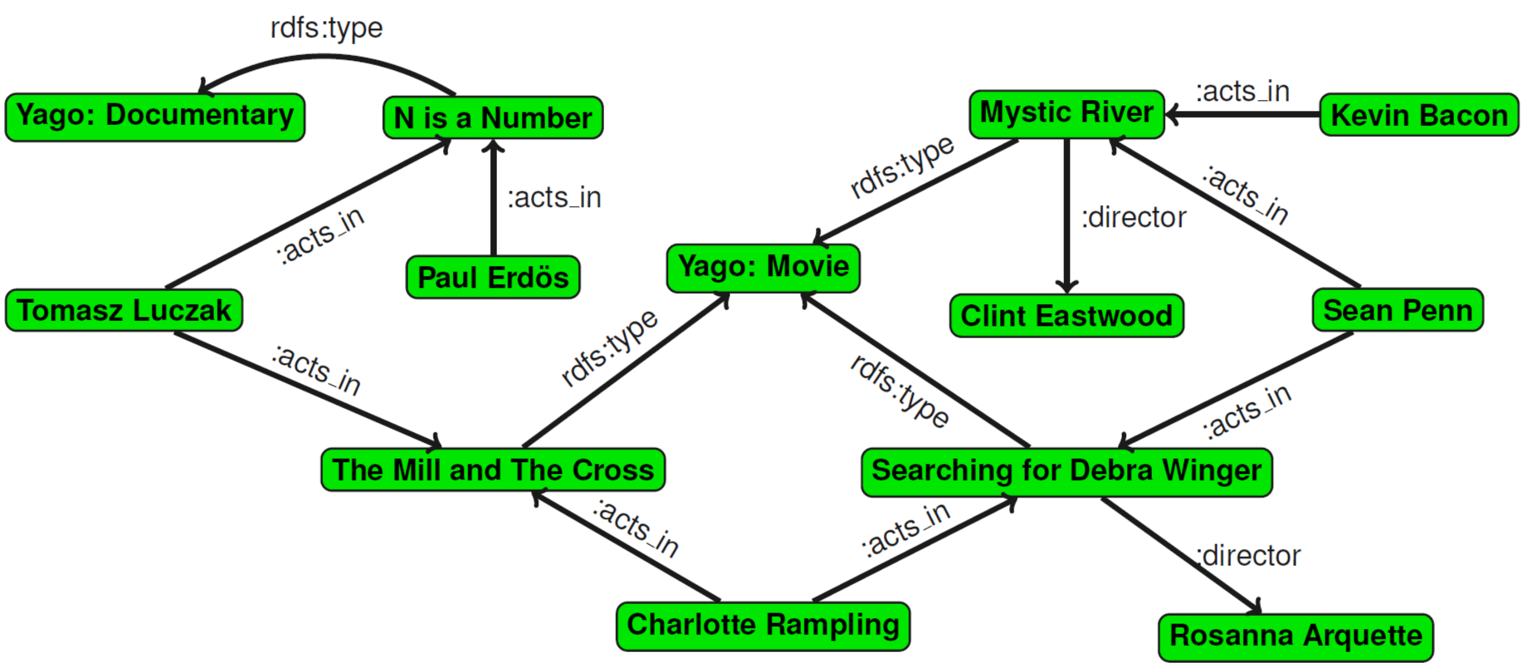

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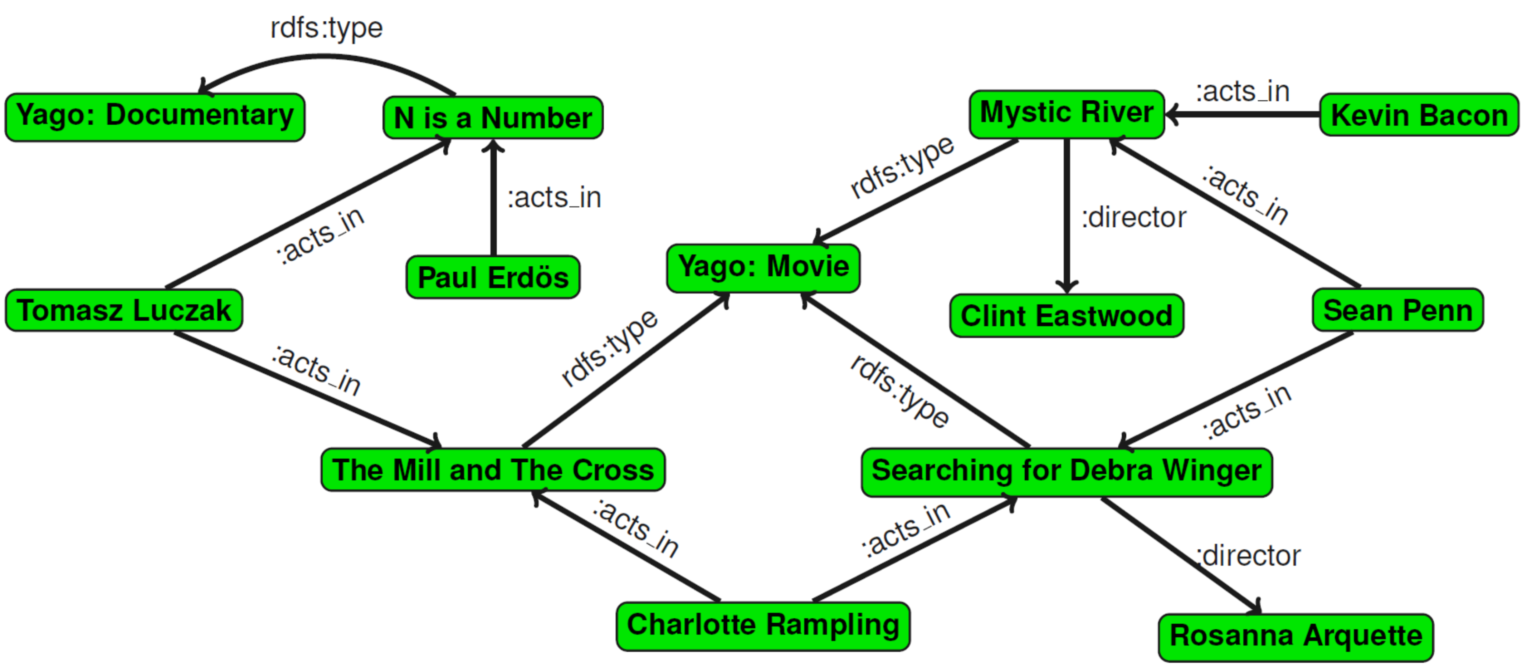

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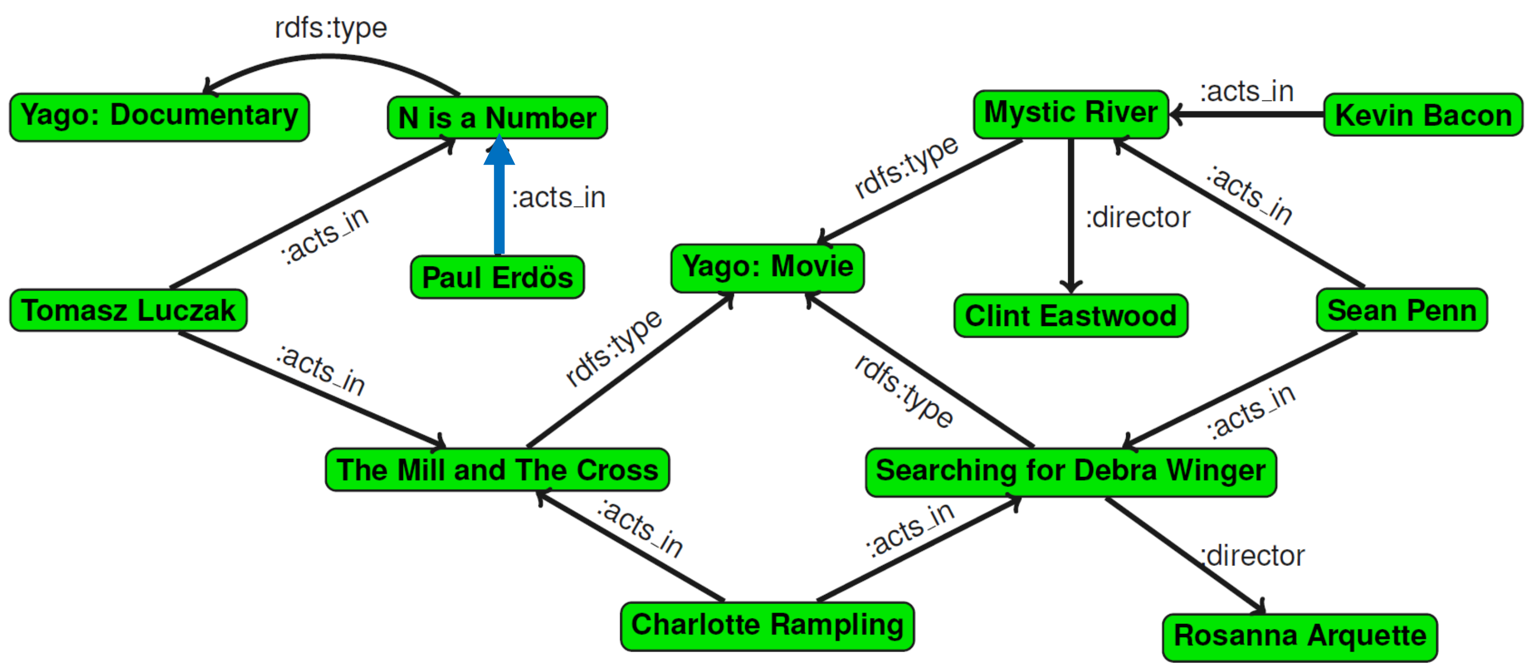

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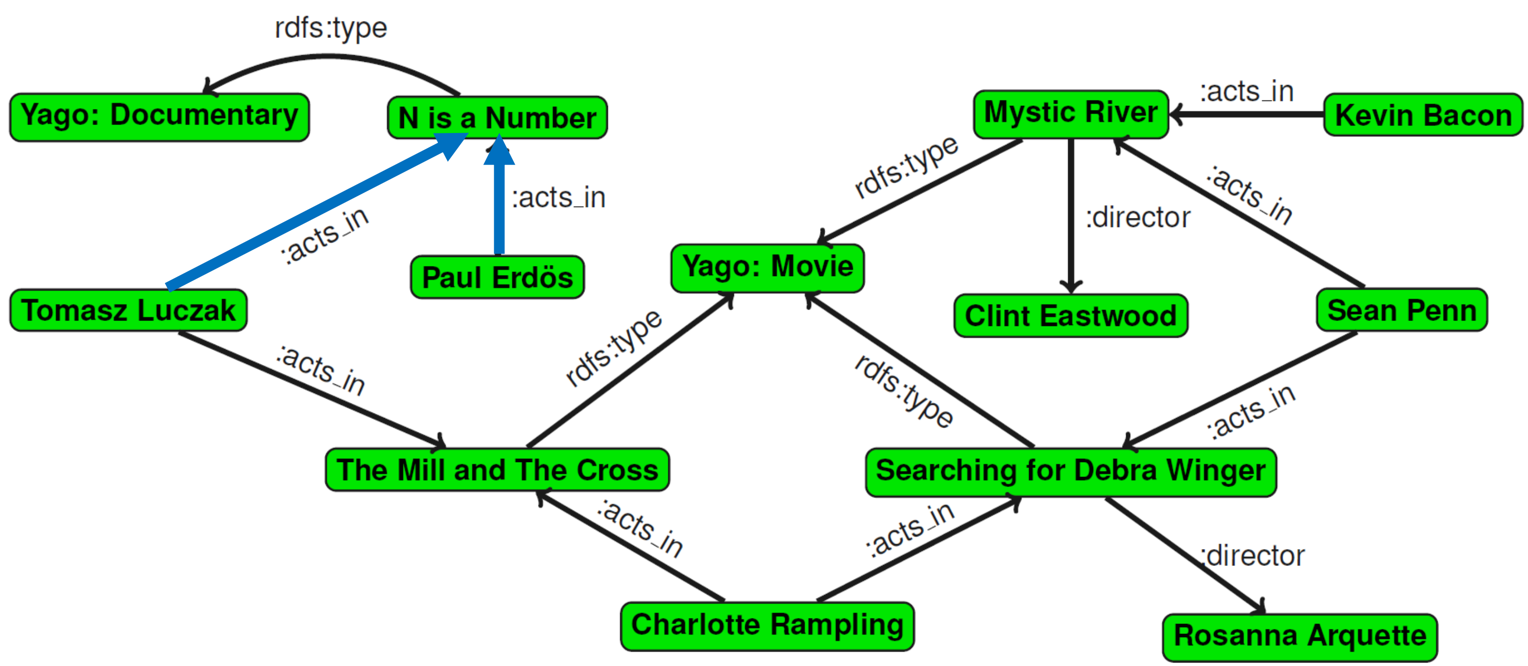

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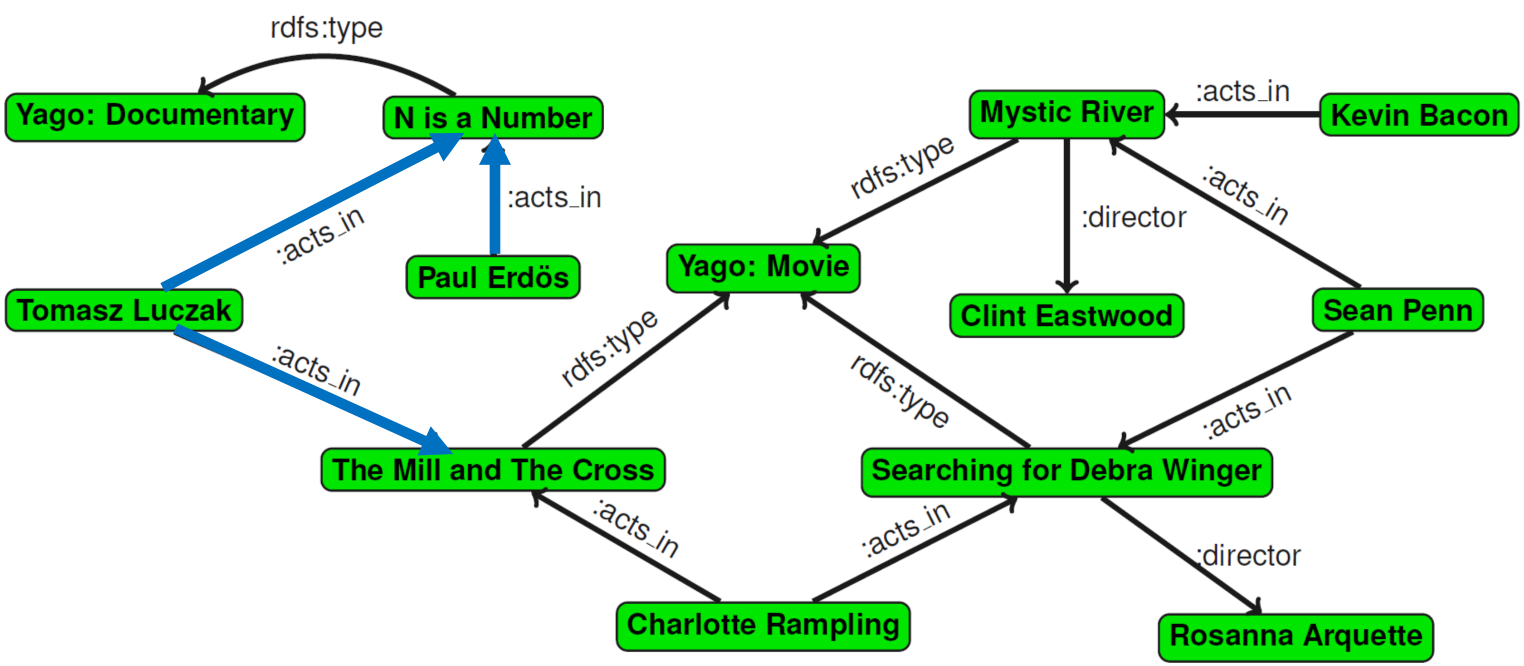

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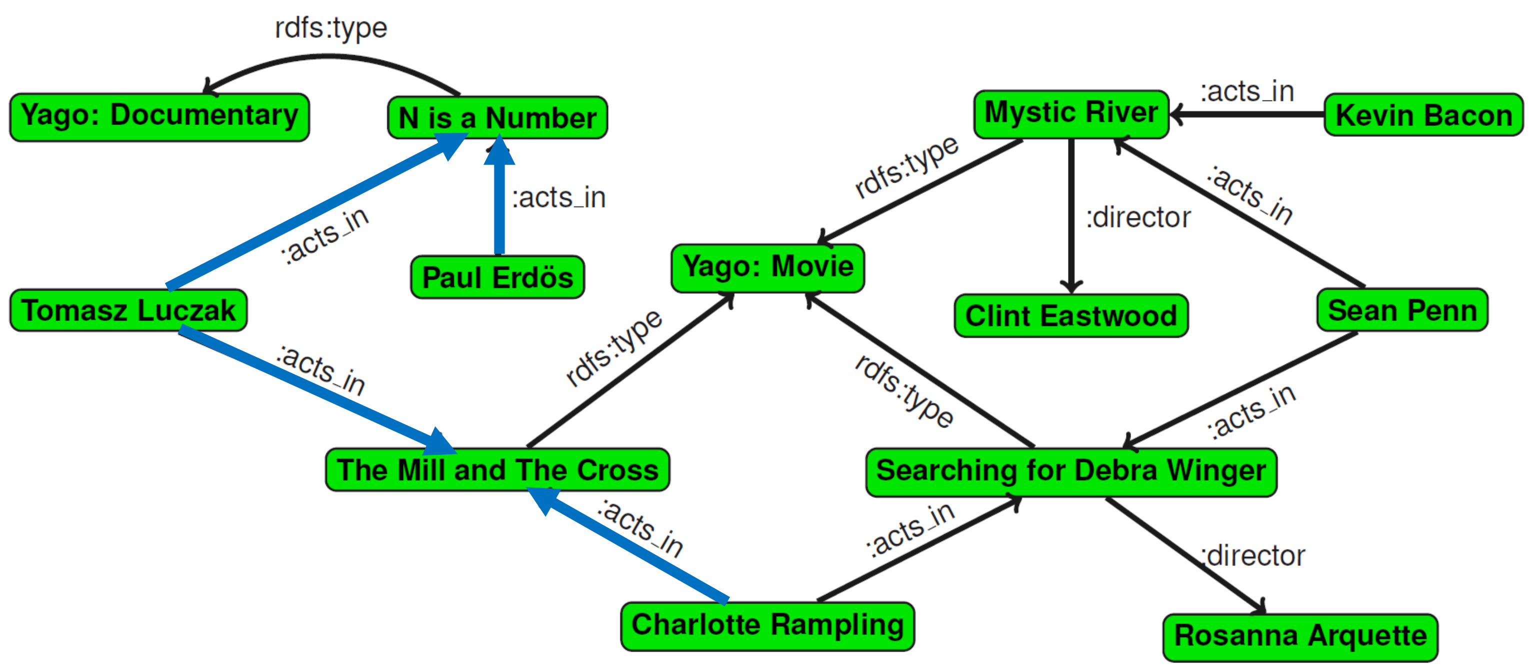

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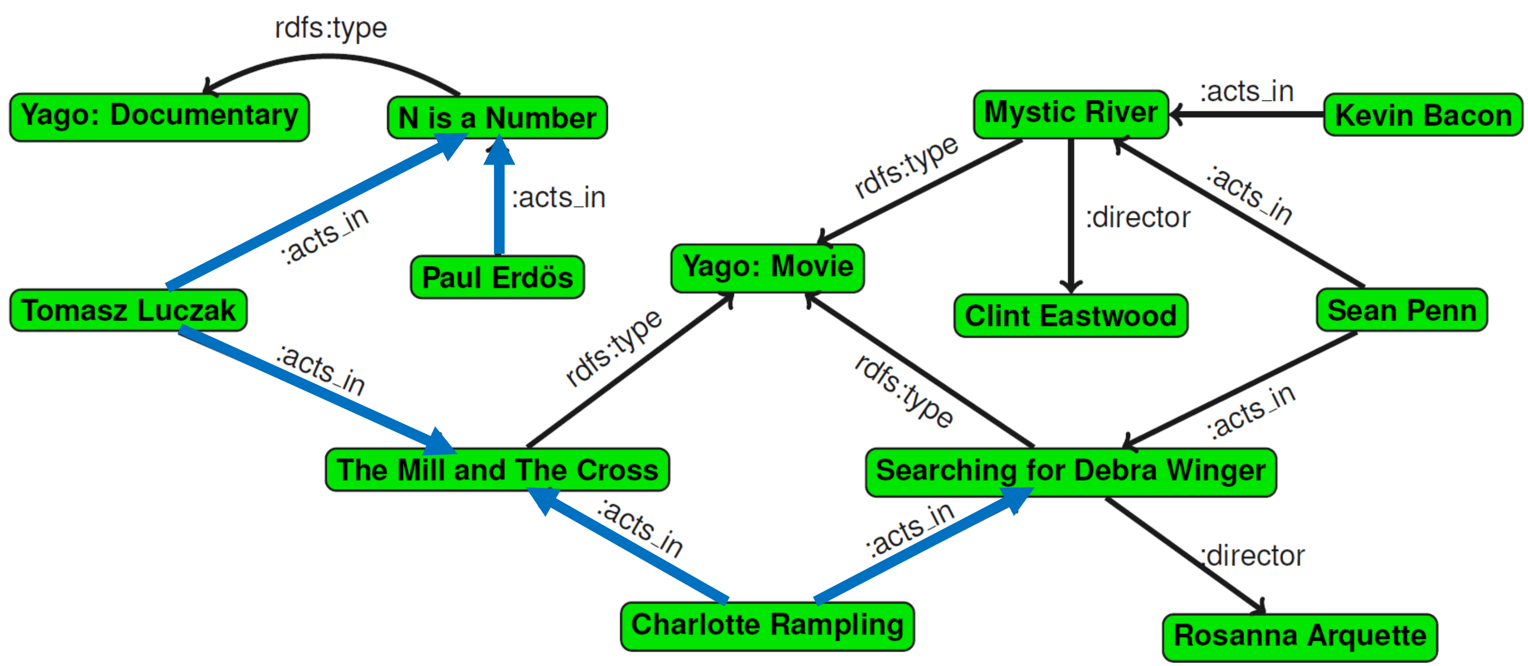

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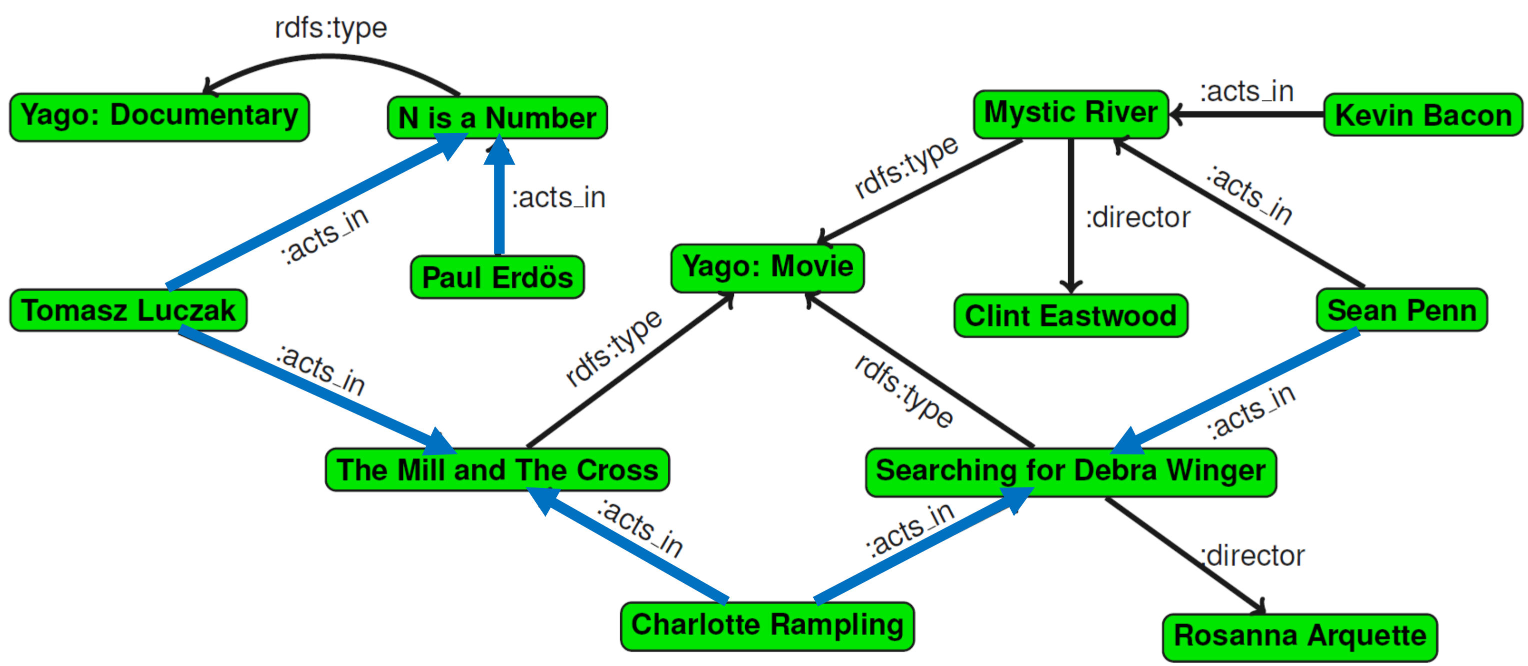

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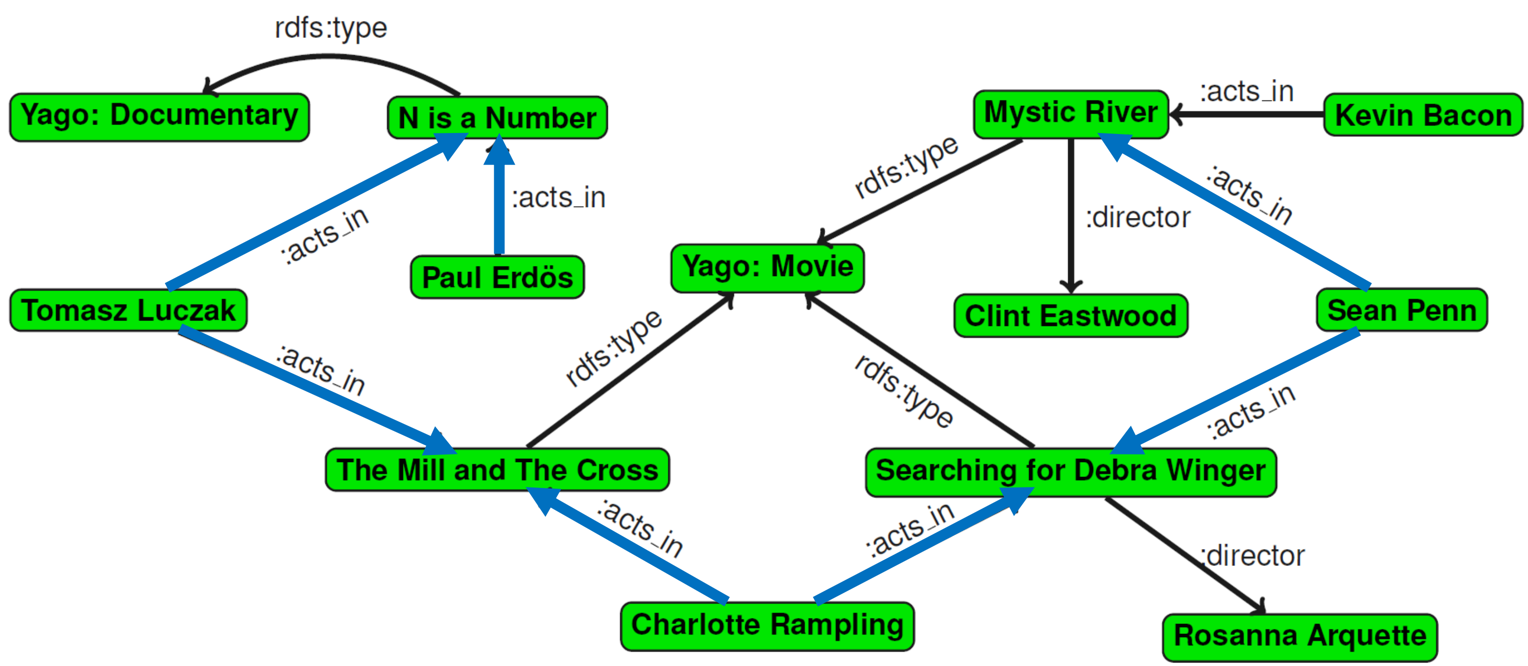

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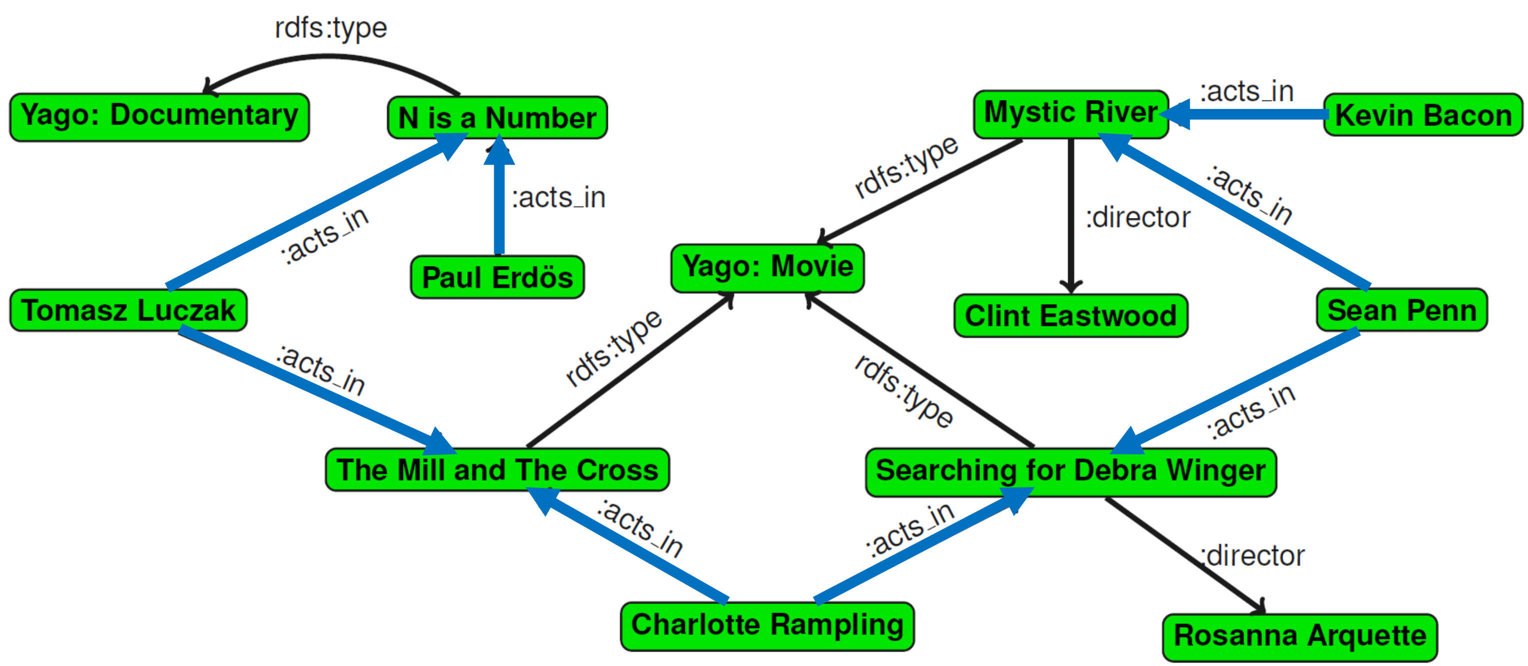
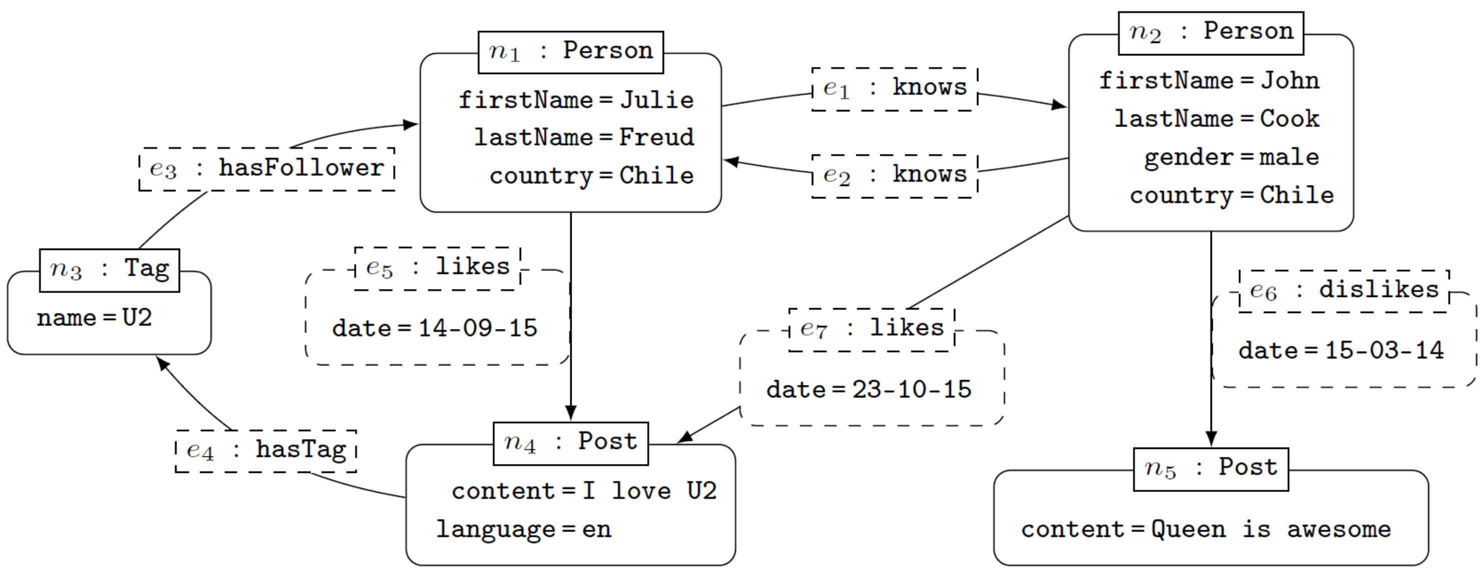


EXAMPLE 2

- Tags of what my friends-of-friends like in a social network

$$x \xrightarrow{\texttt{knows}^{+}\cdot\texttt{likes}\cdot\texttt{hasTag}} y$$



FURTHER EXAMPLES

- Taken from the WikiData dataset user queries

- Bodies of water ending in the Black Sea:

```
SELECT ?watercourse
WHERE { ?watercourse :drains_to* Black_Sea }
```

- Hierarchies/Taxonomies:

```
SELECT ?creature
WHERE { ?creature :instance_of/:subclass_of* Human }
```

QUESTION WE ARE TRYING TO ANSWER

How should one implement path queries in a graph database?

PATH QUERIES - SEMANTICS

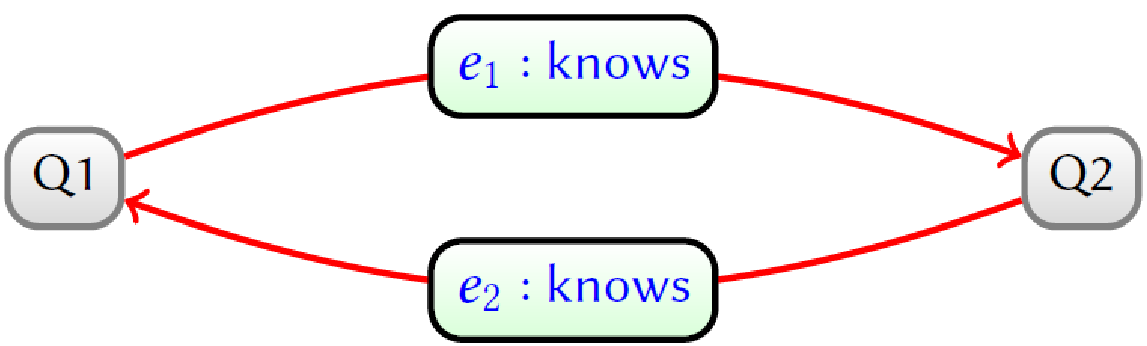
```
SELECT ?x
MATCH (?x)=[(:acts_in/^:acts_in)*]=>(Kevin Bacon)
```

- What is a path?
  - A sequence of nodes/edges: n1 e1 n2 e2 n3 …
- When does a path conform to a regular expressions?
  - When the labels of the edges give a word in its language
- What do we return?
  - Just the endpoints (?x)
  - Paths satisfying the constraint (together with ?x)

PATH QUERIES - SEMANTICS

```
SELECT ?x
MATCH (?x)=[:knows*]=>(Q2)
```

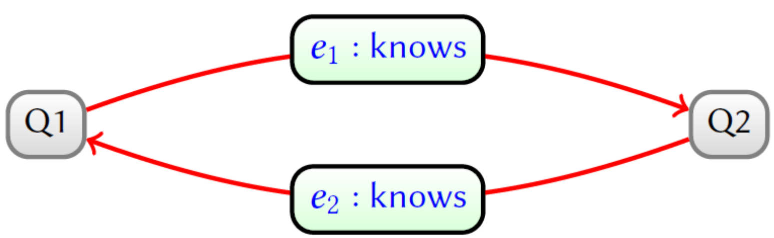
- Returning only endpoints
  - Bag semantics: how many times? Can be infinite!
  - Set semantics: just give me the nodes connected by a "good" path!



PATH QUERIES - SEMANTICS

- Returning paths as well:
  - There can be infinitely many (if a cycle is present)!
  - How would you express this in SPARQL?
  - What does bag semantics mean here?

```
SELECT ?x, ?p
MATCH (?x)=[?p :knows*]=>(Q2)
```



SEMANTICS – AVOIDING INFINITY

- Using simple paths:
  - No repeated nodes – cycles not a problem anymore
  - Immediately leads to intractability [MW95]
  - A reason to exclude them from SPARQL standard [ML12]

- No-repeated-edges:
  - Similarly avoids infinity
  - The semantics of Cypher
  - Equivalent to simple paths
  - If implemented in full (all matches) runs into the same issues

REASONABLE SOLUTIONS

- Shortest paths:
  - No infinity issues
  - Allows bag semantics with endpoints (count all shortest paths)
  - Allows returing paths

- Arbitrary paths:
  - Can be infinite
  - Works when returning endpoints with set semantics
  - SPARQL standard

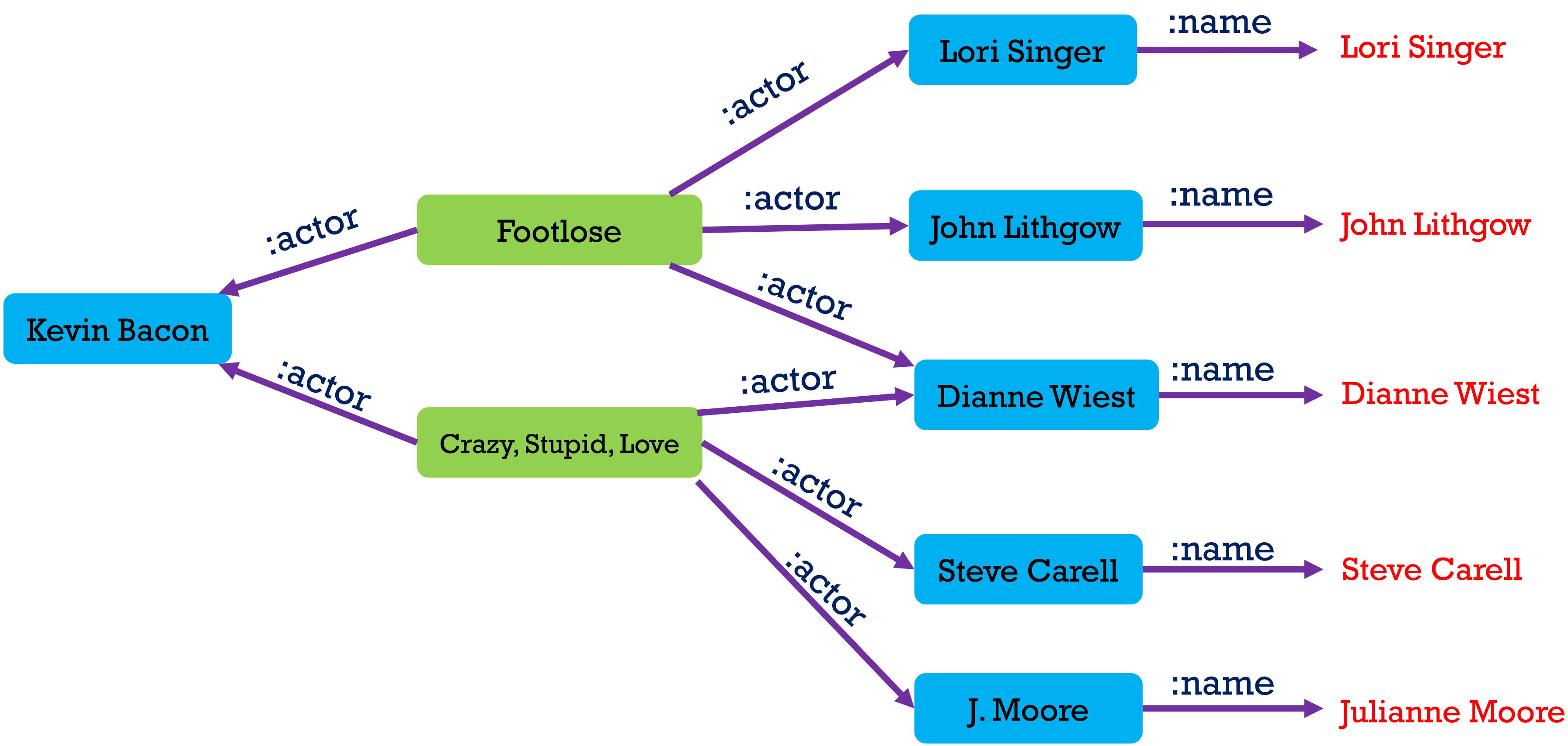
  - Both options have good theoretical properties
  - Many algorithms known for implementing them

HOW DO WE IMPLEMENT PATH QUERIES?

- Theoretician's answer ("This is trivial"): [MW95]
  - Graph is an automaton
  - Regular expression is an automaton
  - Do the cross product (on-the-fly to be "efficient")
  - Do reachability check from start states to end states

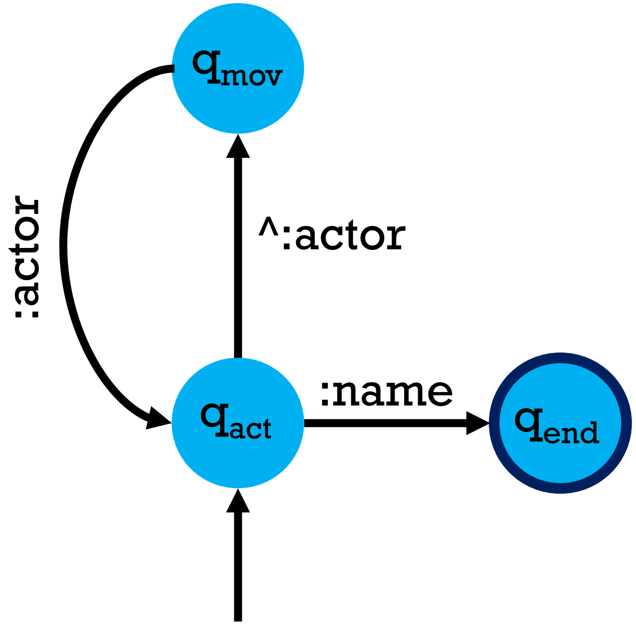
- Which algorithms can do this?
  - BFS
  - DFS
  - A*
  - IDDFS
  - ...

HOW DOES THIS ACTUALLY WORK?

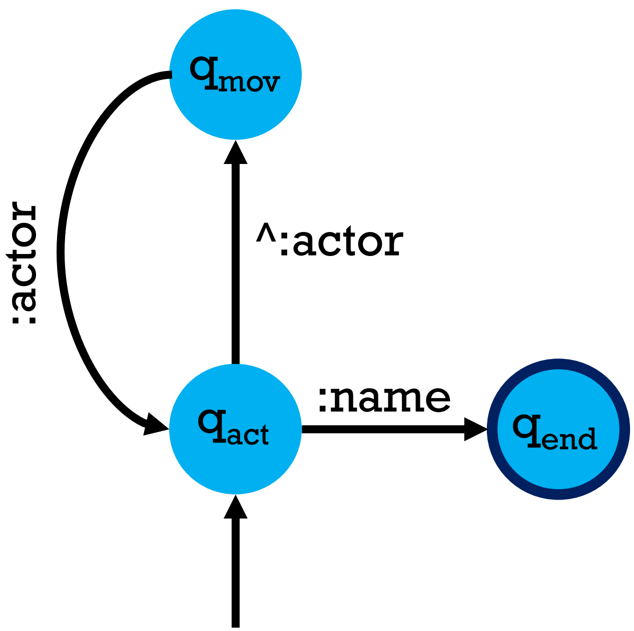


HOW DOES THIS ACTUALLY WORK?

```
SELECT ?x
MATCH (Kevin Bacon)=[(^:actor/:actor)*/:name]=>(?x)
```



HOW DOES THIS ACTUALLY WORK - DFS



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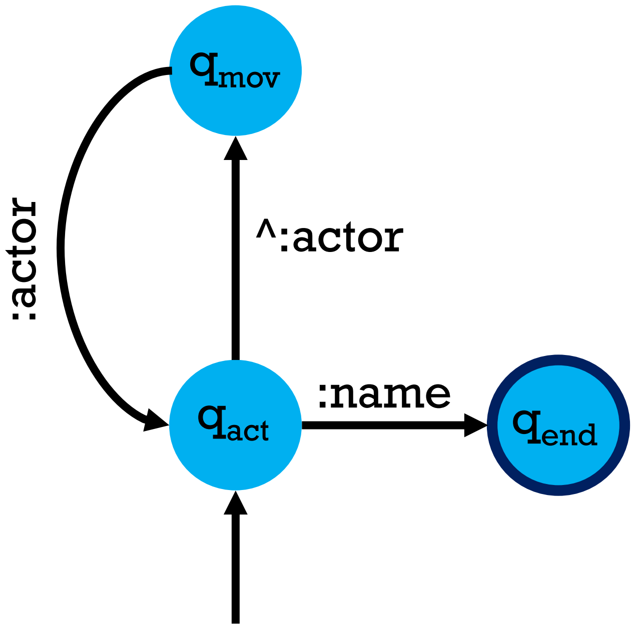

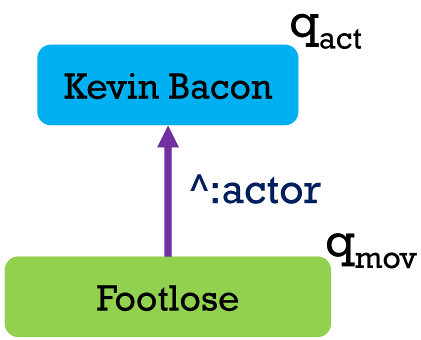

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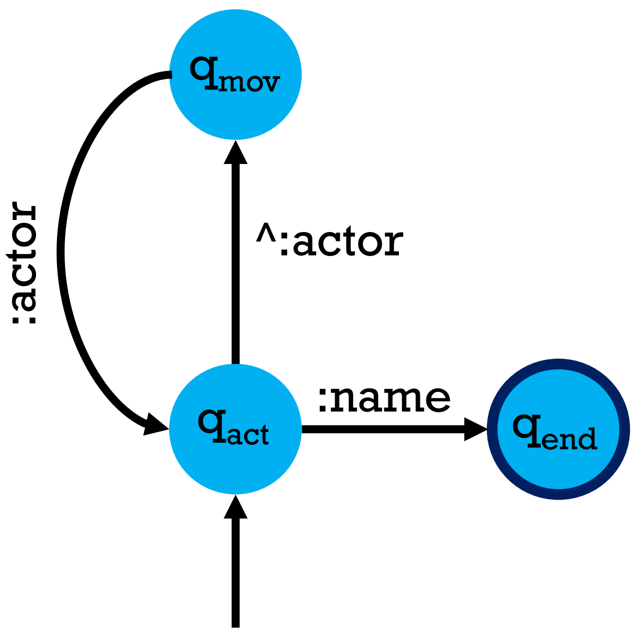

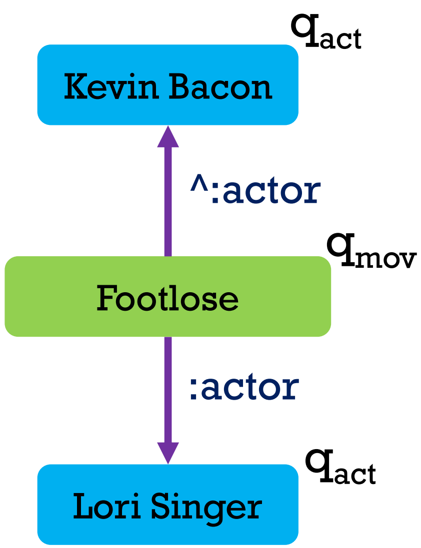

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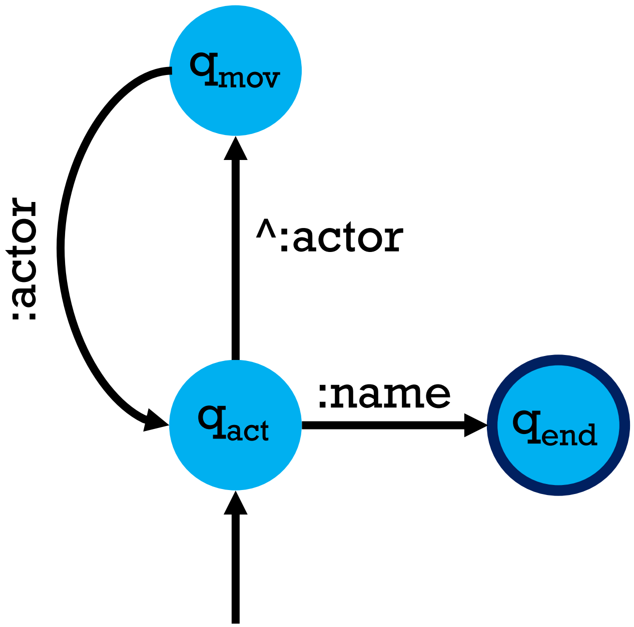

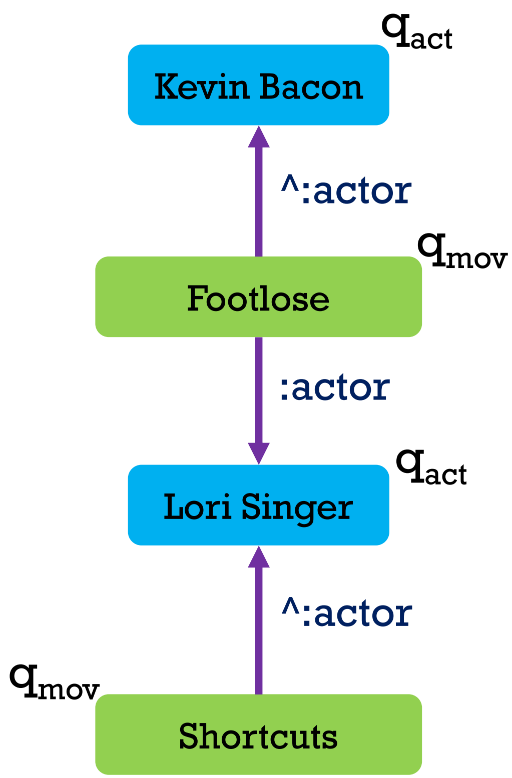

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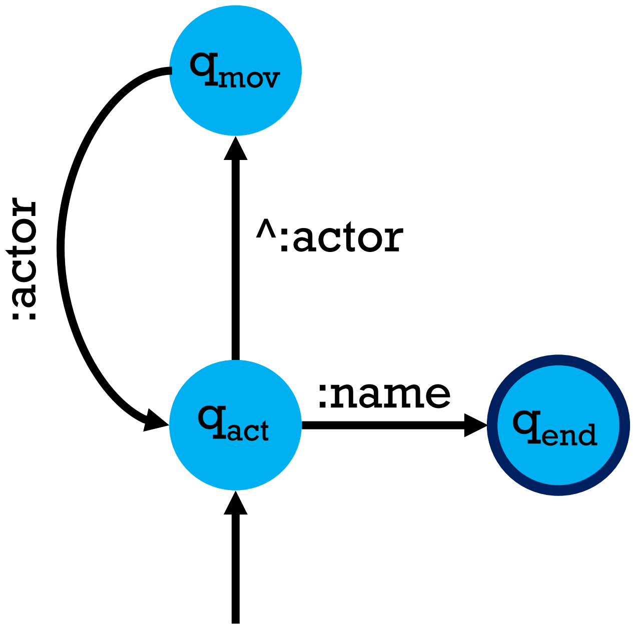

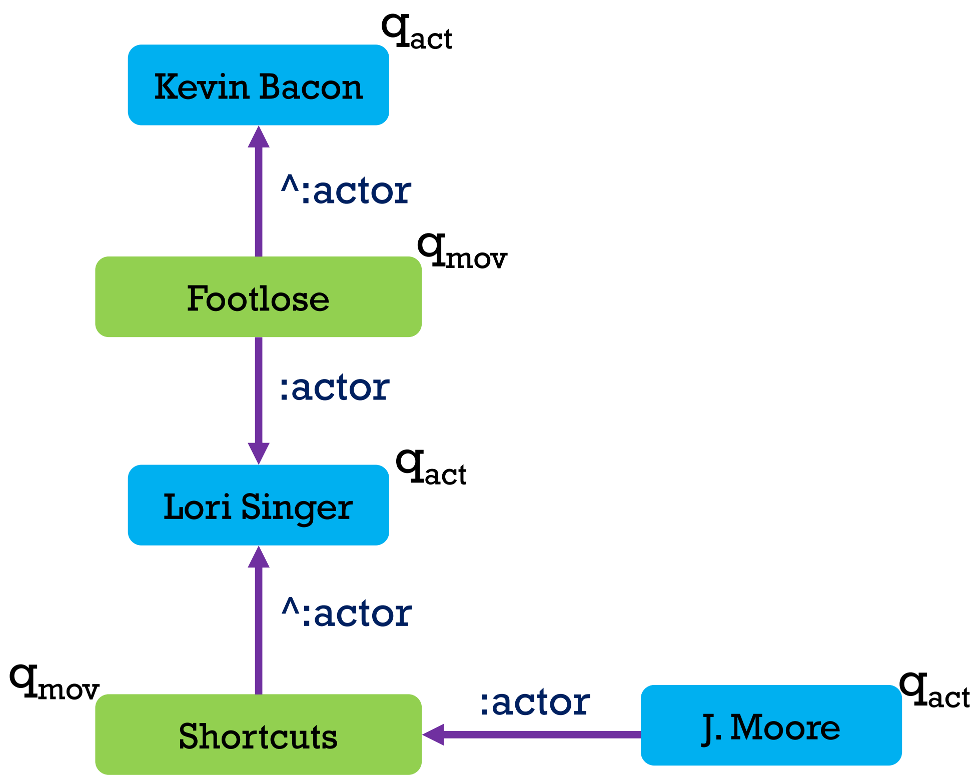

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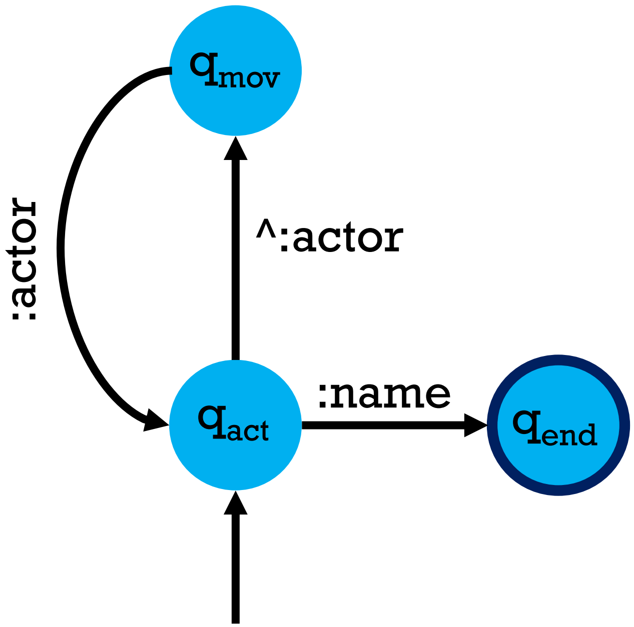

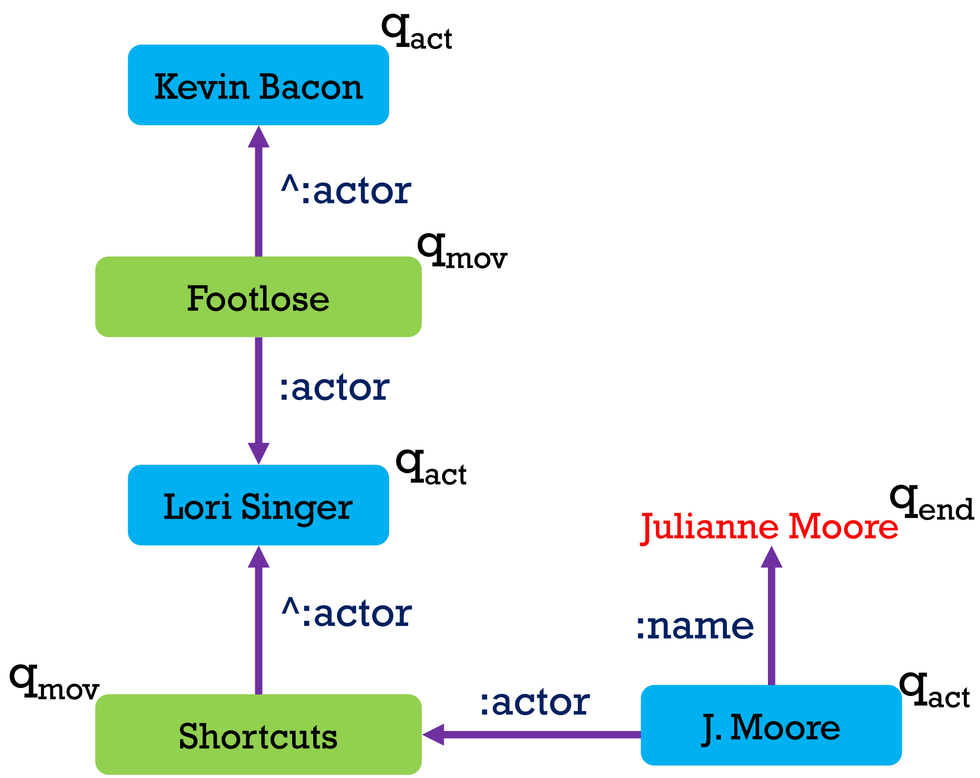

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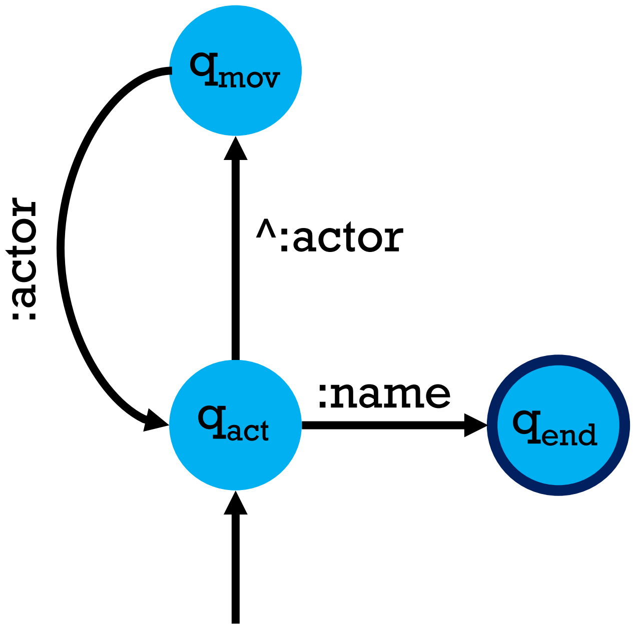
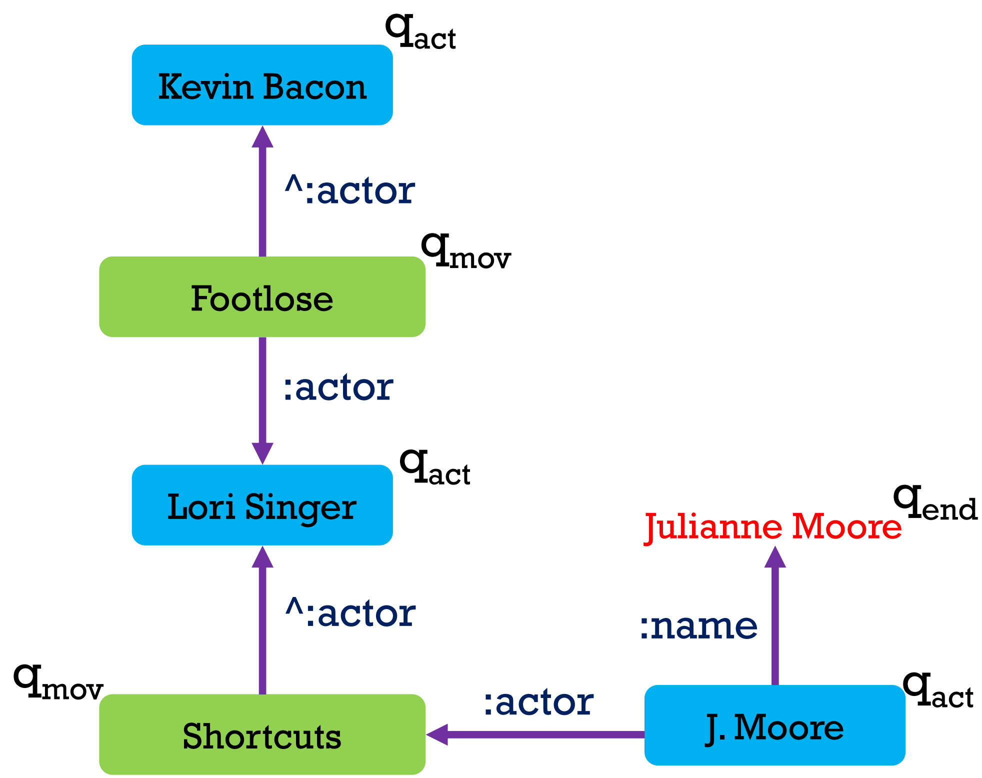
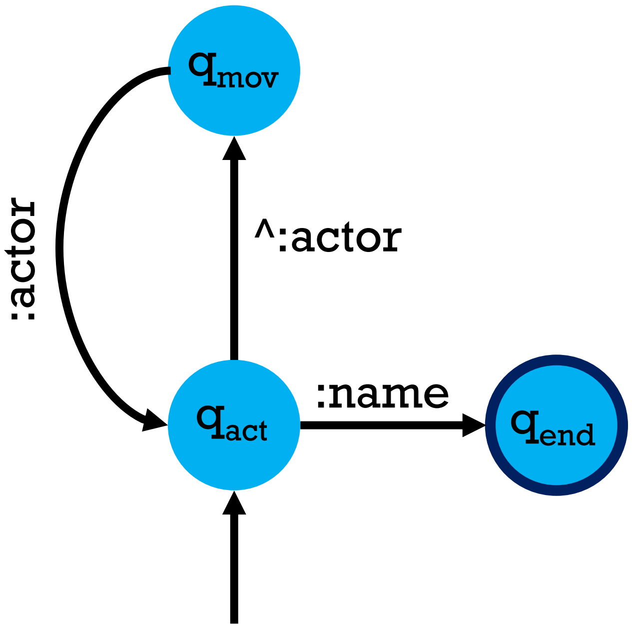




- Can produce long/unintuitive paths

HOW DOES THIS ACTUALLY WORK - BFS



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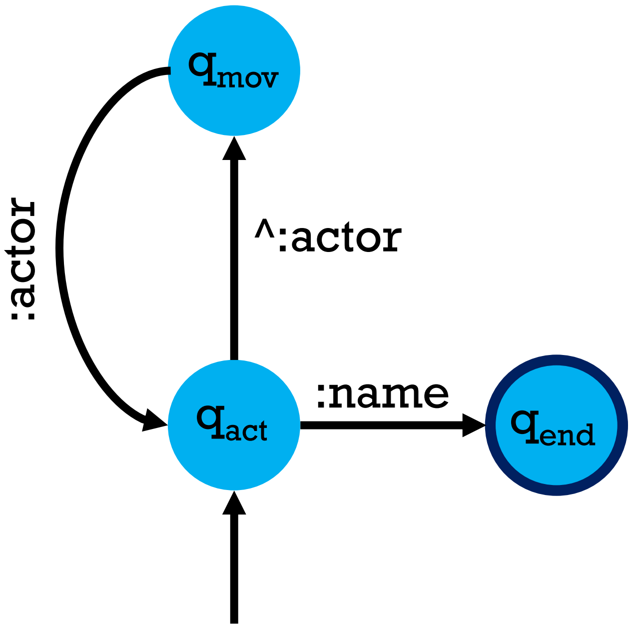

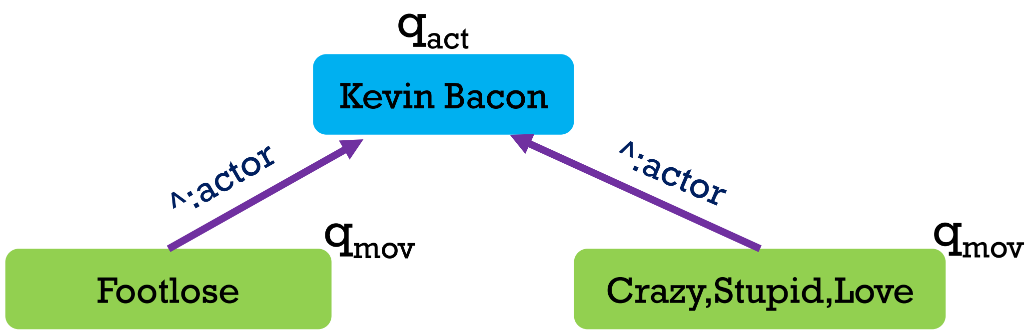

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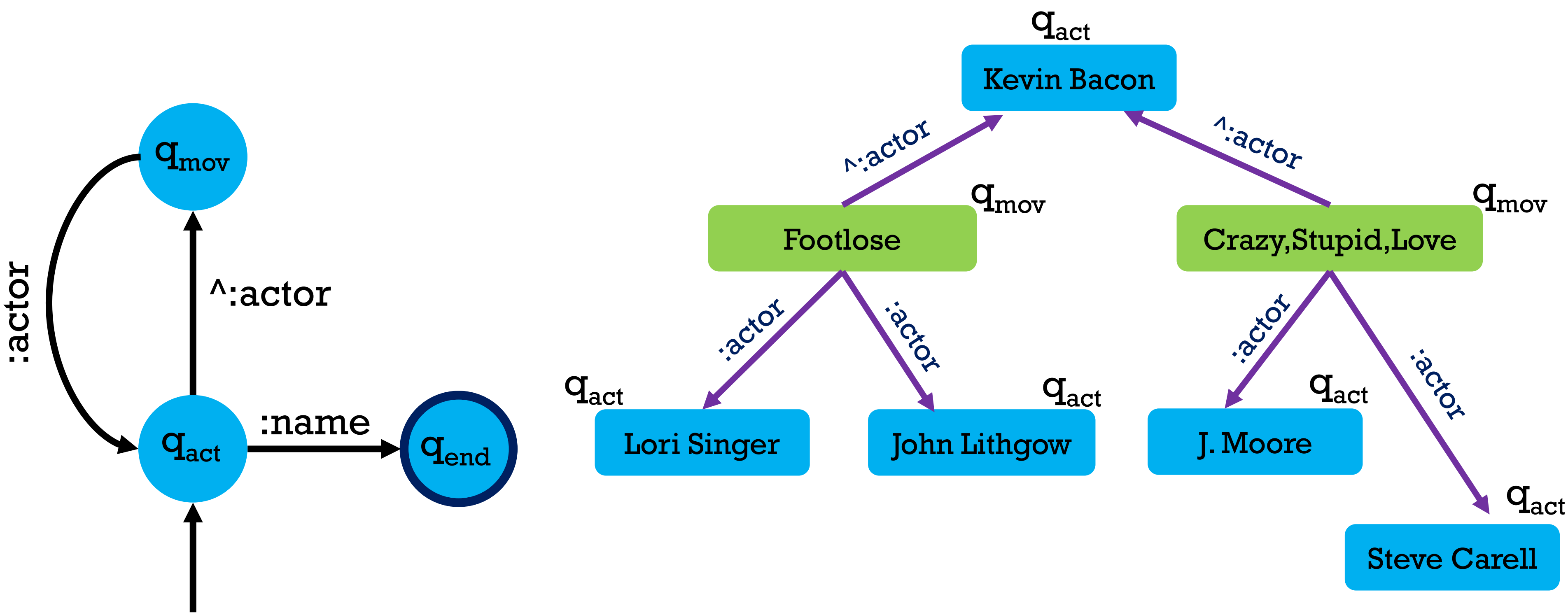

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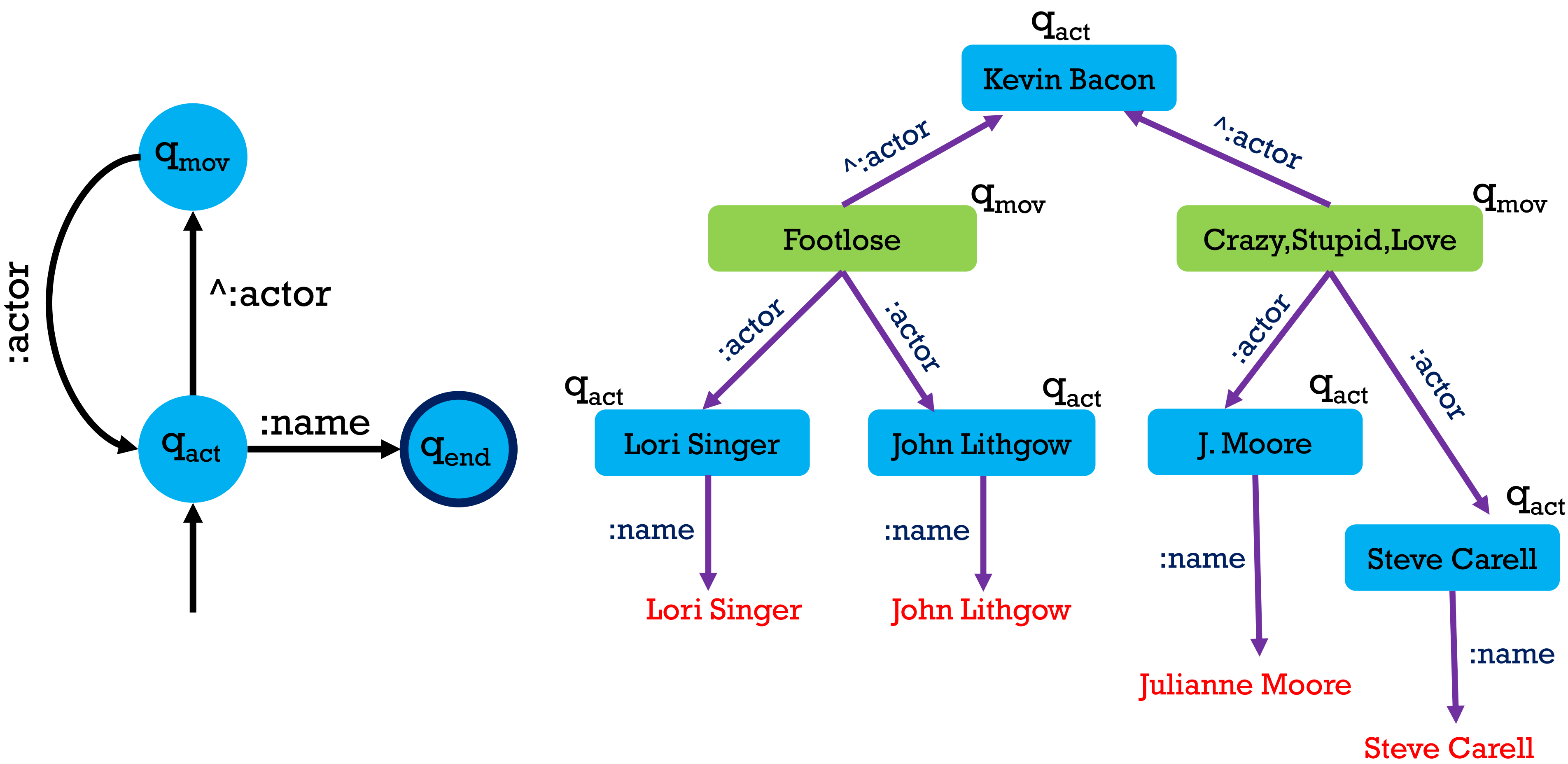

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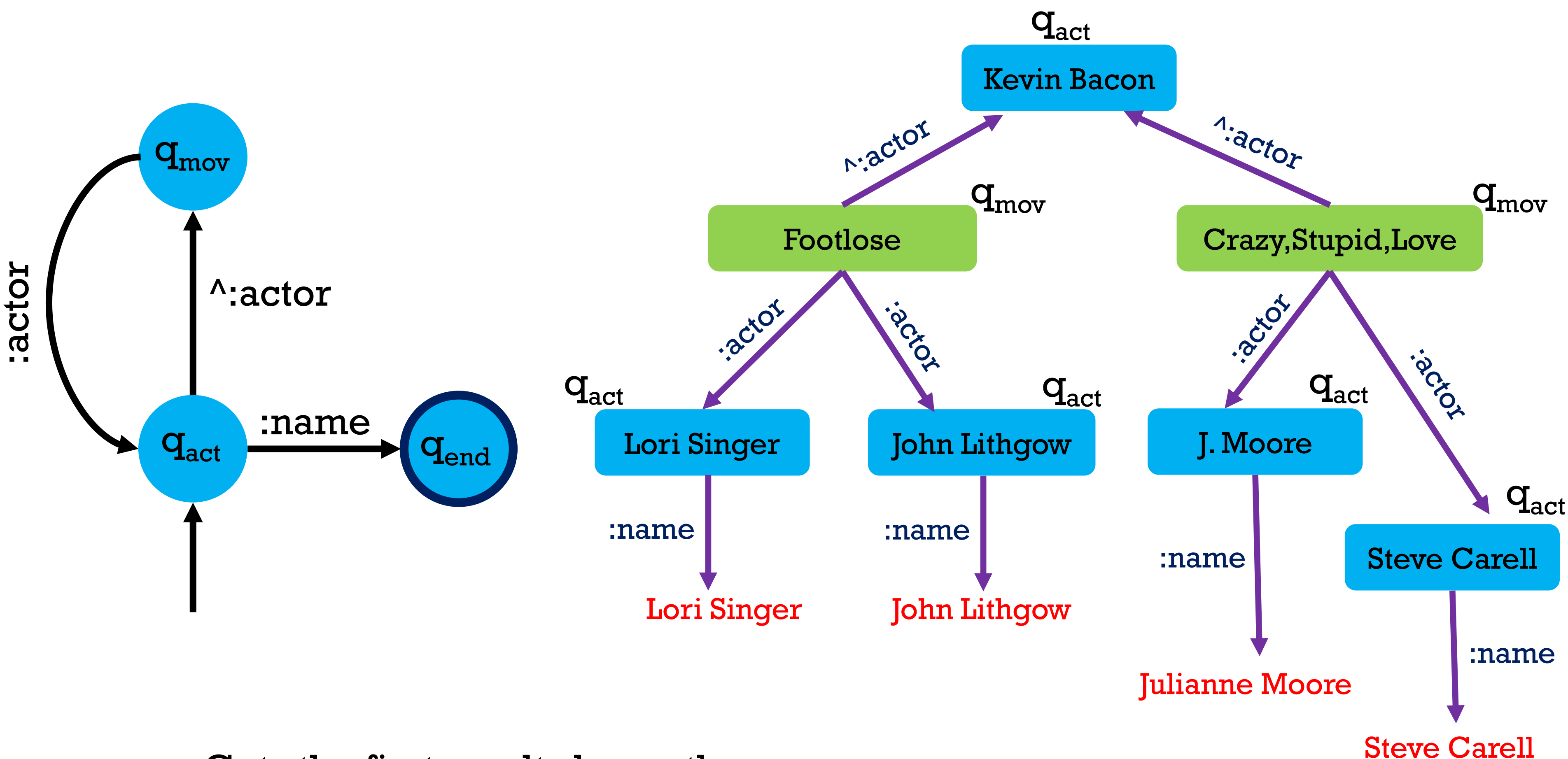
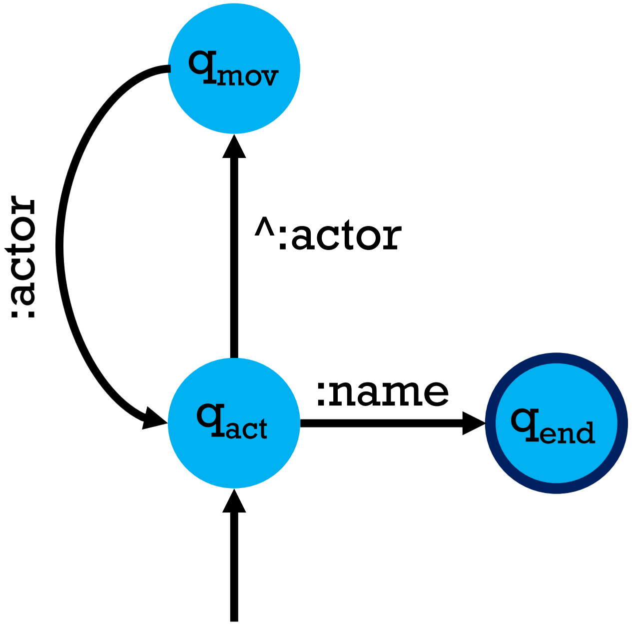


- Gets the first result slower than necessary

HOW DOES THIS ACTUALLY WORK – A*

Heuristic: get close to q_{end}



q_{act}

Kevin Bacon

HOW DOES THIS ACTUALLY WORK – A*

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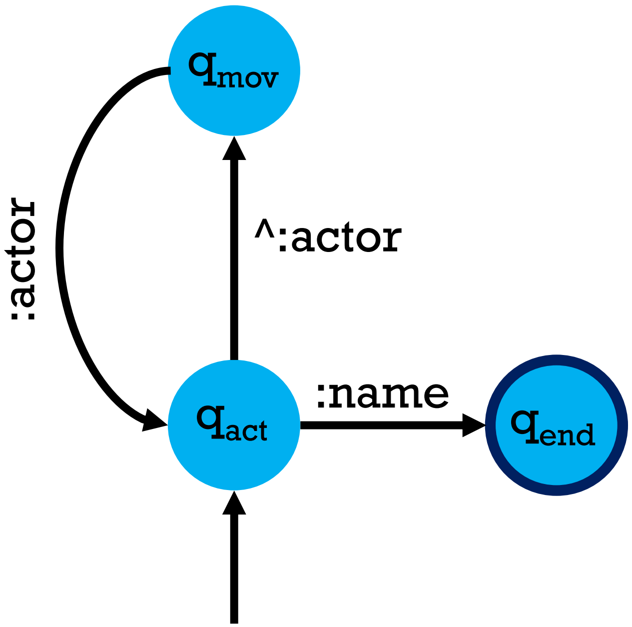

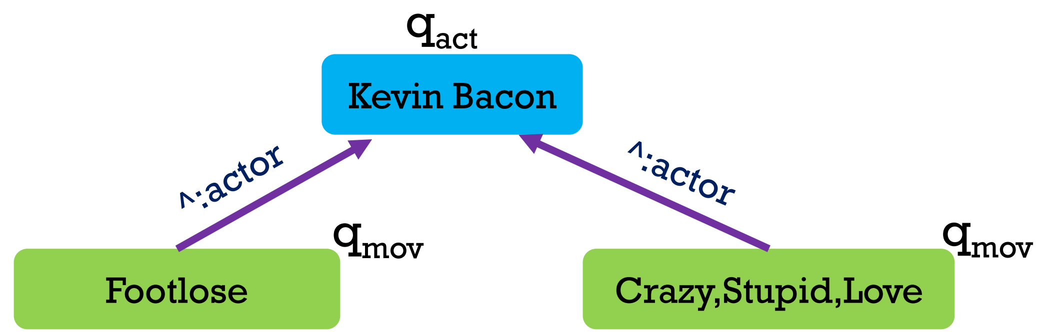

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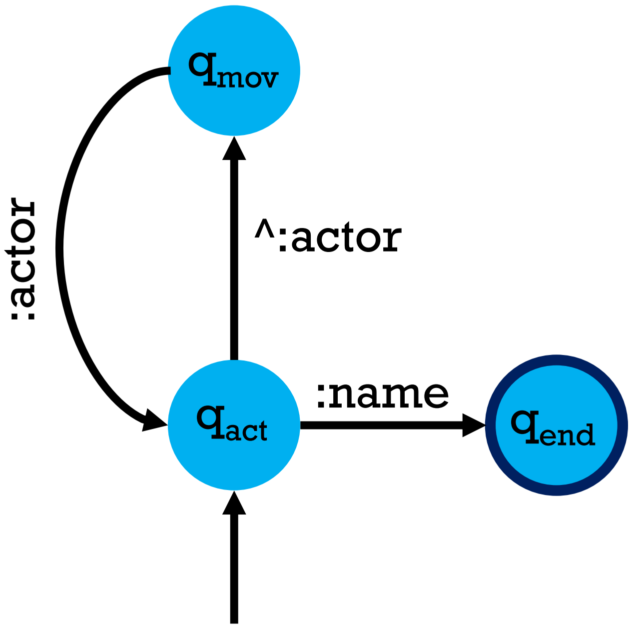

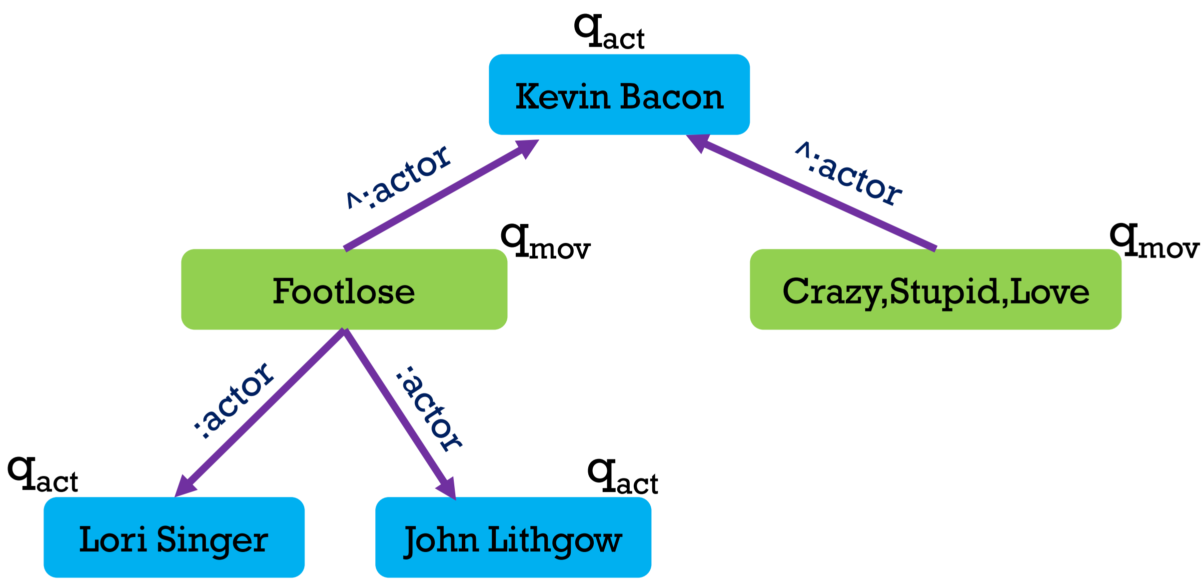

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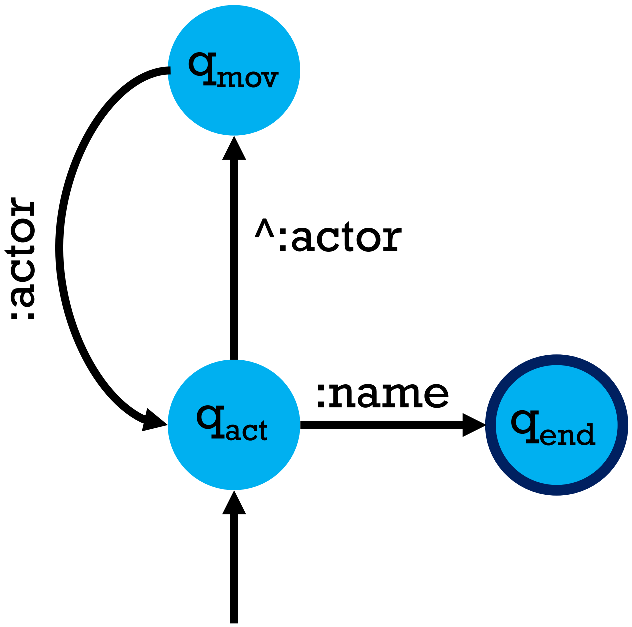

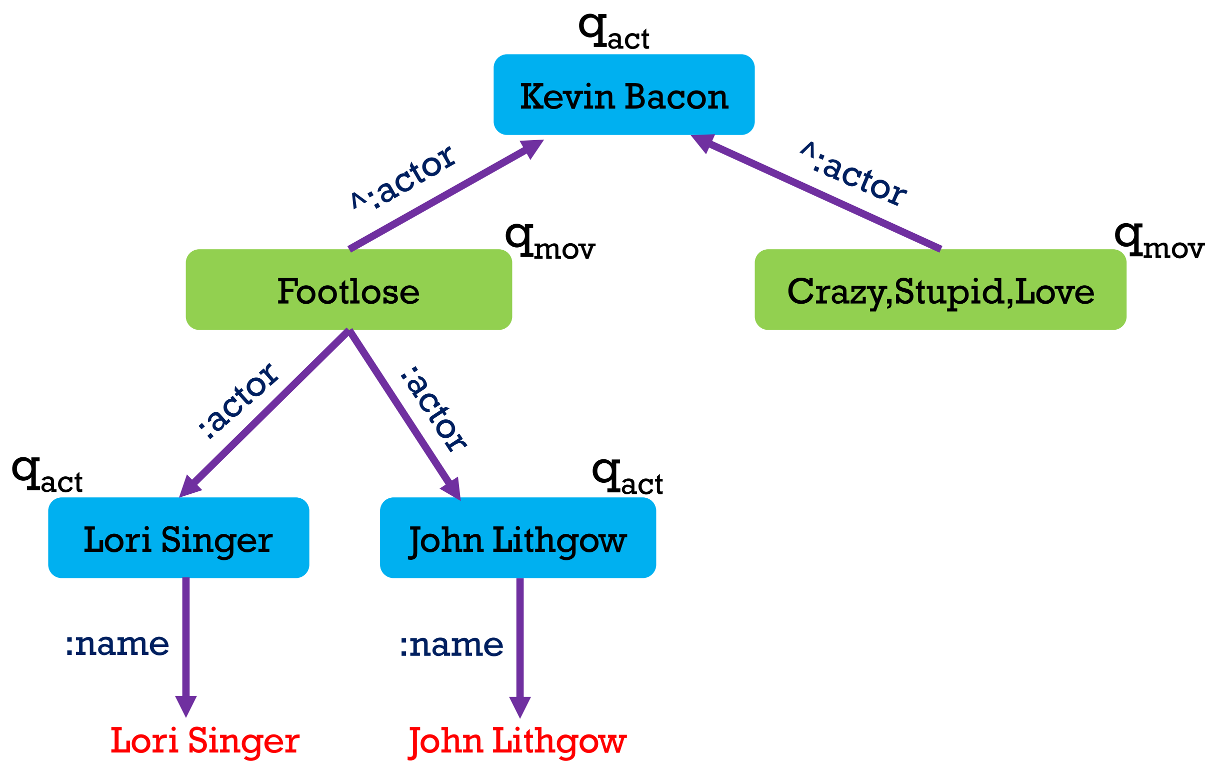

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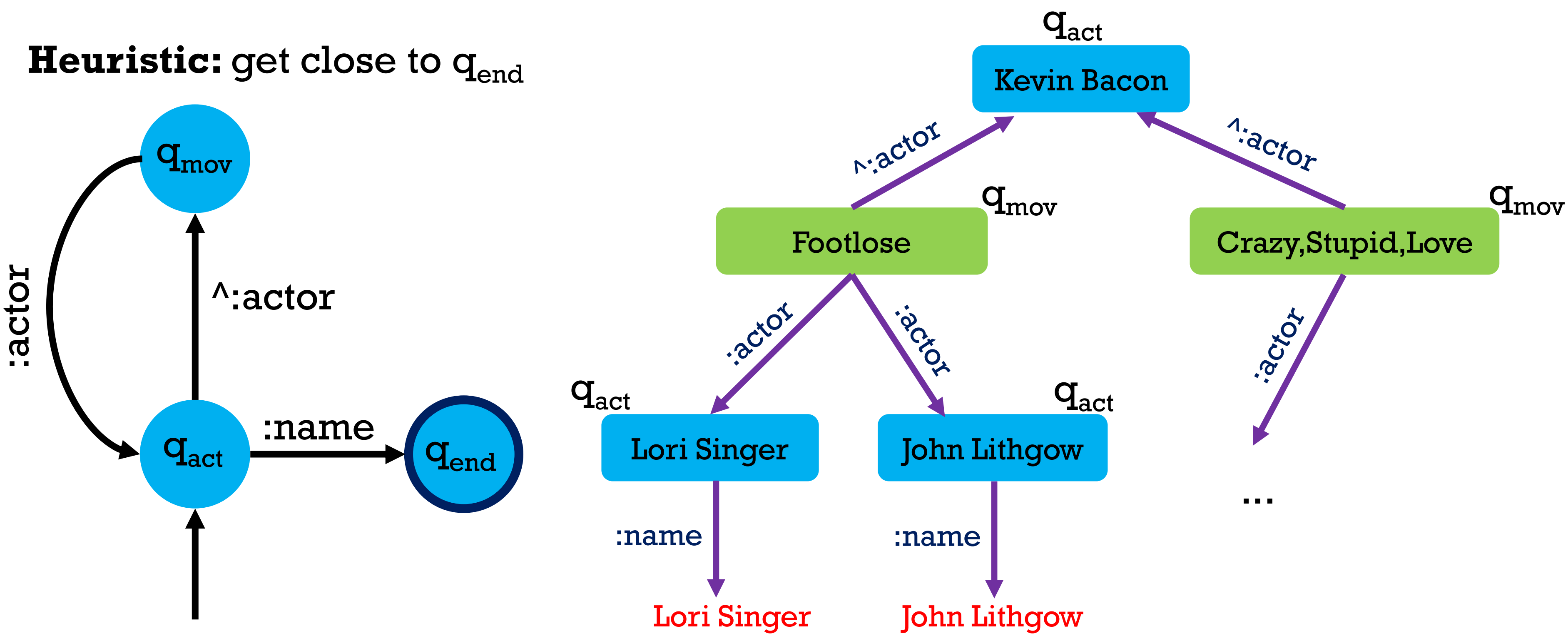
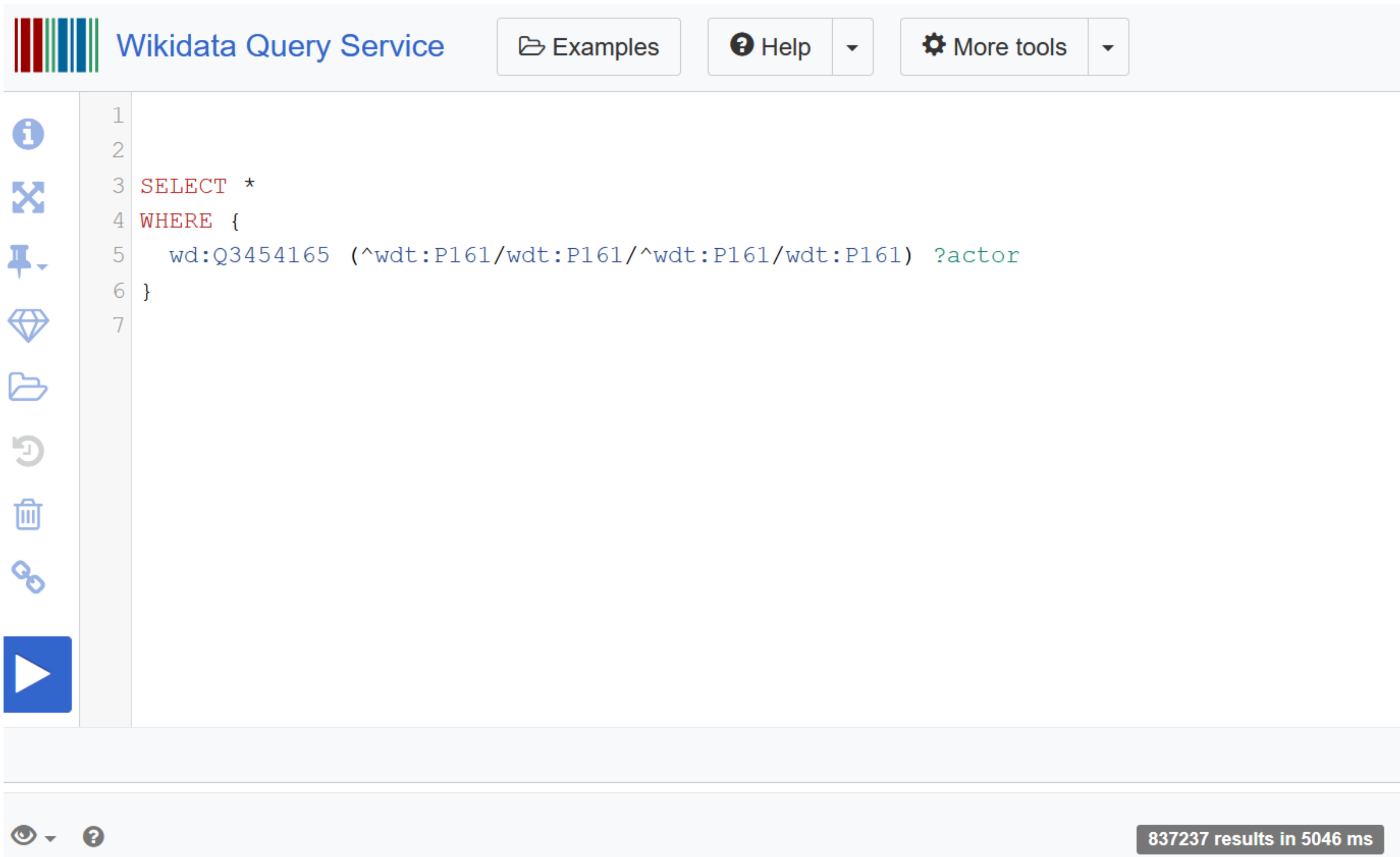


- Seems to bring the best of both worlds

SPARQL

- So you would think this works
  - Endpoints/set semantics
  - No counting paths(standard)

SPARQL'S ODDITIES



SOME APPROACHES

- On top of RDF3X [GBS13]
  - In-memory index used to compress graphs [SABW13]
  - Implements BFS to evaluate property paths
  - Good performance compared to other solutions
  - Endpoint/set semantics

- SQL based approach [RSV15]
  - Seminaive SQL-style recursion in SPARQL
  - Can do decently when evaluating property paths
  - Endpoint/set semantics
  - Controlling recursion depth shown better than manual joins

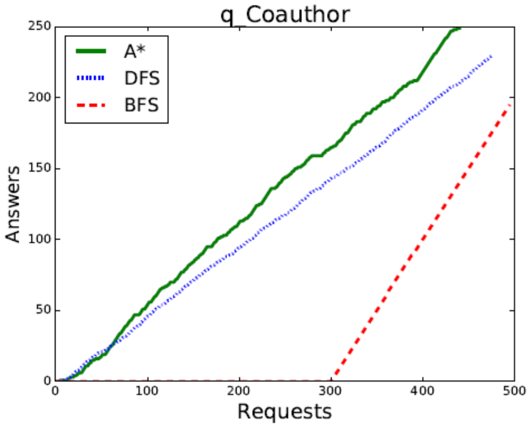
SOME APPROACHES

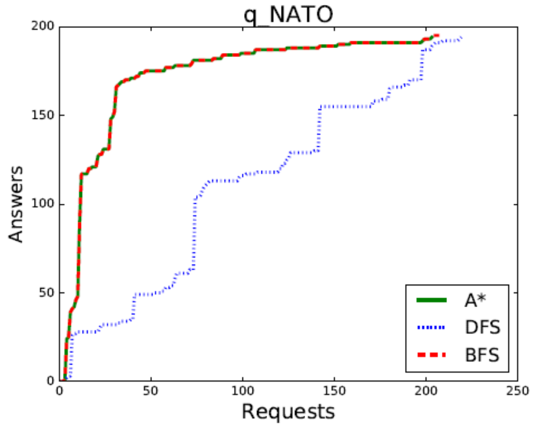
- Query planners for path queries [YGG16]
  - Uses automaton of the regex to plan evaluation
  - Based on Postges
  - Implemented using stored procedures

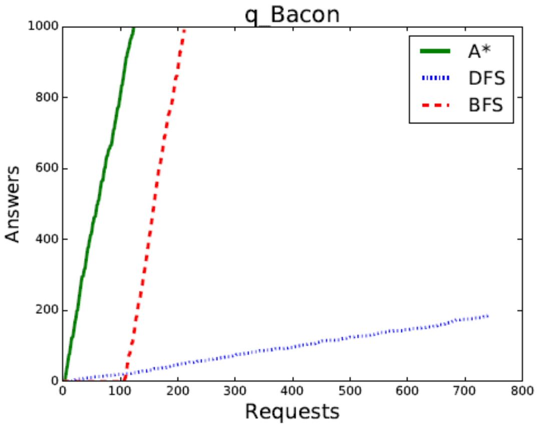
- Path index [FPP16]
  - Assumes bounded repetitions (not Kleene star)
  - Index "popular" path prefixes
  - Rewrite the query and run joins over this

SOME APPROACHES

- On Linked Data [BDRV17]
  - No data available locally (everything is accessed via an IRI)
  - Tests how BFS/DFS/A* perform
  - Allows incremental solutions and returning paths
  - For a small amount of solutions runs better than existing engines





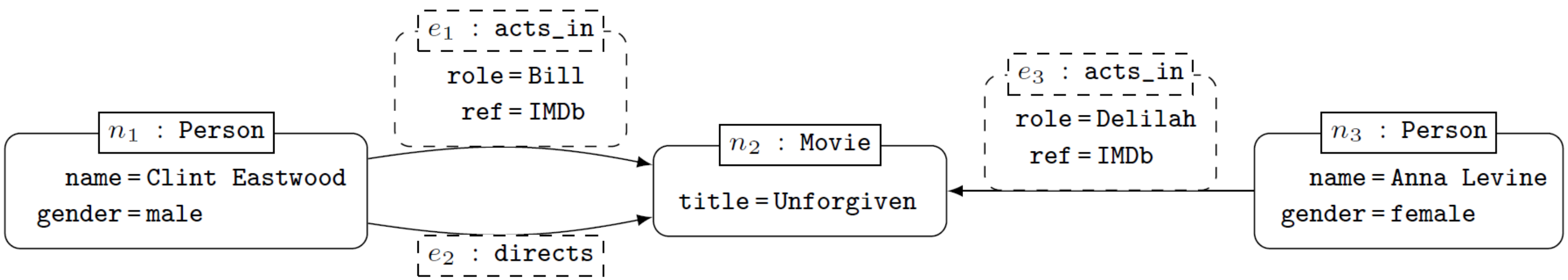


WHAT ARE WE DOING NOW

- MillenniumDB
  - A persistend graph database engine
  - Based on standard relational techniques tweaked for graphs
  - Pipelined query evaluation
  - WCO query planner (in conjunction with Selinger) [HRRS19]
  - Full support for navigational queries [BDRV17]:
    - Endpoints/set semantics
    - Returning paths
    - Bag semantics with shortest paths

MILLENNIUM DB

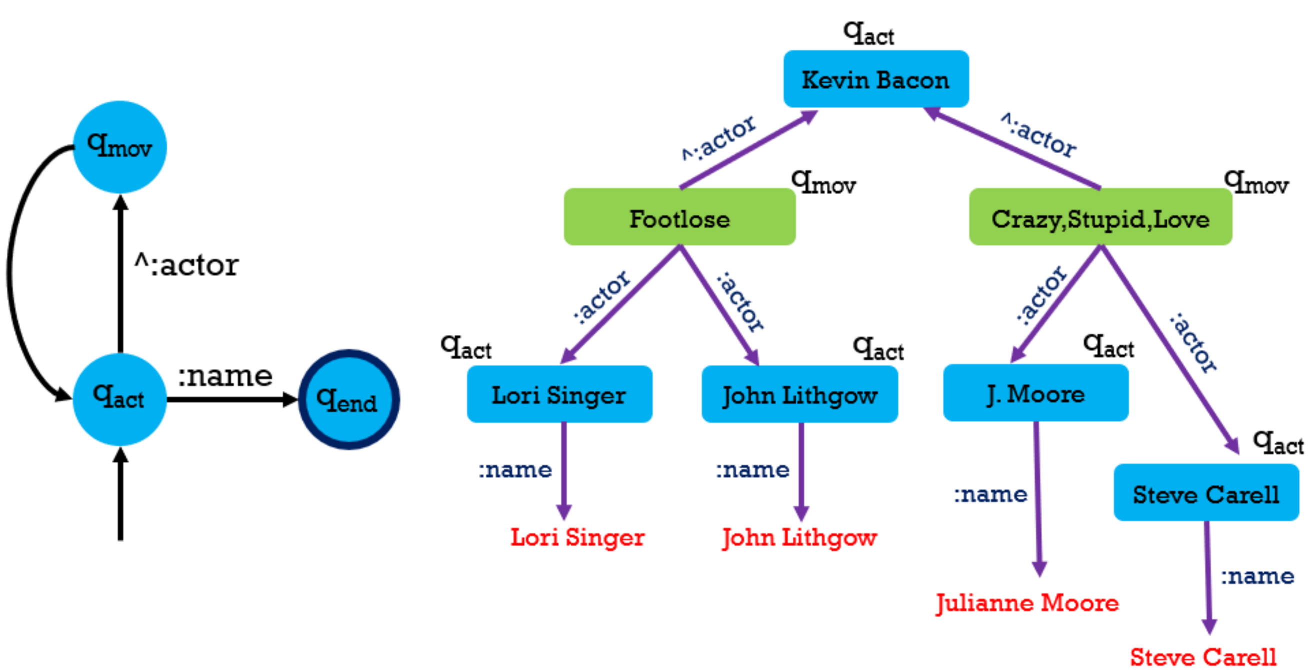
- We use good old B+ trees



- Relations required:
  - NodeLabel … e.g. (n1, Person)
  - NodeKeyValue … e.g. (n1,gender,male), (e1,role,Bill)
  - FromTypeToEdge … e.g. (n1, :acts_in, n2, e1)
  - and several of their permutations

MILLENNIUM DB – PATH QUERIES

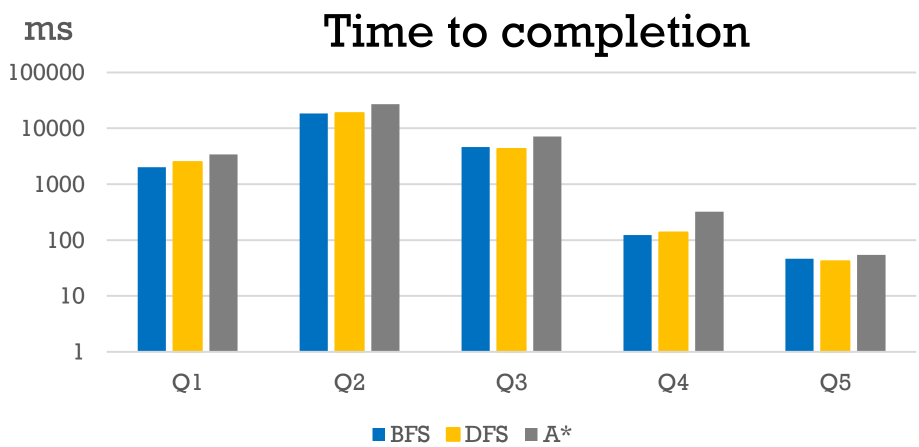
- FromTypeToEdge ... e.g. (n1, :acts_in, n2, e1)
  - Support for BFS/DFS/A*
  - All implemented in a pipelined fashion (via a linear iterator)
  - How to return a result as soon as it is encountered: B+tree iter stays live



MILLENNIUM DB – PATH QUERIES

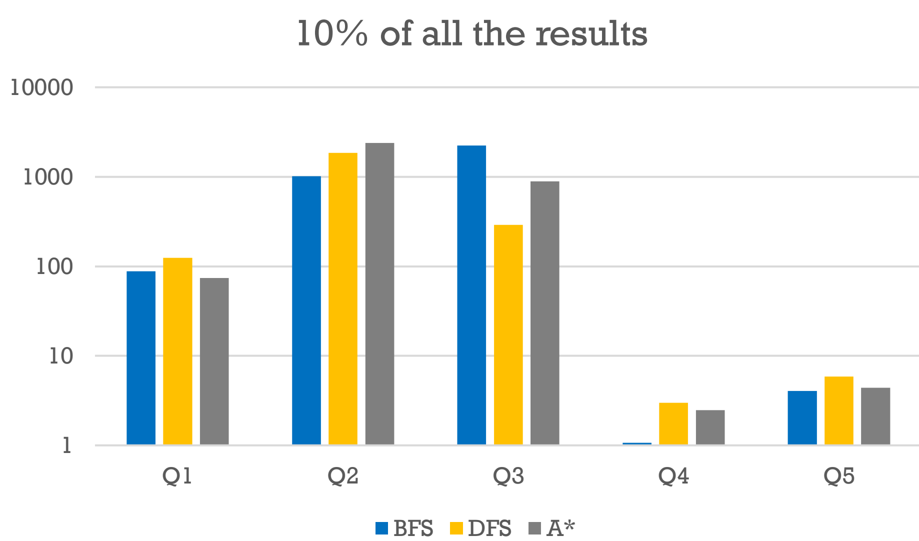
- Some results on full WikiData (cca 1TB on disk)
  - Q1 … Bacon Number … 160K results
  - Q2 … Places located in a Nato state … 4.8M results
  - Q3 … Organizations dealing with EU capitals … 17K results
  - Q4 … Where can I get to from the Netherlands … 4K results
  - Q5 … Spouses of people born in a place in the US … 35K results
- What do you think the best algorithm is?
  - Recall, you are now reading data from disk
  - You have pages pinned in the buffer
  - You have auxiliary data structures to keep track of visited nodes

MILLENNIUM DB – PATH QUERIES



- Basically, BFS wins in every experiment

MILLENNIUM DB – PATH QUERIES



- Still holding strong, but DFS/A* do well
- Identical graph with only 1% of all the results required

MILLENNIUM DB – PATH QUERIES

- Why would BFS run so well?
  - If we are also returning paths, it is orders of magnitude faster

- How many pages need to be pinned in the buffer?
  - DFS: length of the current path (stack height)
  - A*: all top elements on the priority queue
  - BFS: just one (the item on the top of the queue)

- Also means parrallel executions are feasible for BFS

BFS – OTHER ADVANTAGES

- We can return a single shortest path by default
- With a bit of tweaking can return all shortest paths

- Allows compositionality:
  - What does a graph query return?
  - Let's say a graph
  - But which one?

COMPOSITIONALITY

```
SELECT ?x, ?y, ?z
MATCH (?x :Person)-[:knows]->(?y :Person),
      (?y)-[:lives_in]->(?z : City),
      (Kevin Bacon)=[(^:actor/:actor)*/:name]=>(?x)
```

- Construct the graph:
  - All nodes/edges in fixed size pattern
  - All shortest paths in path queries
  - Assume that SELECT variables are your view of this graph
  - [G-CORE] tried something along these lines

LOOKING FORWARD

- GPU transitive closure
  - Seems to be much faster that the classical one

- Shrinking the graph:
  - Remove the noise, work with the paths alone
  - Preliminary results promising, but no paths [AHNRRS21]

- Learning the relevant parts of the graph:
  - Try to learn which part of the graph will be accessed by the query

LOOKING FORWARD

- Understanding indexing schemes:
  - With good guarantees/estimates
  - Which scheme goes with which algorithm/approach
- Query plans based on automata, and not SQL-like plans:
  - Transitive closure approach a good option, but maybe missing the point
  - Compiling query into automata (what is the optimal one?)
  - This line of work was started in [YGG16]

BOTTOM LINE

- Do we know how to implement a graph database?
  - Does any existing system support path queries?
  - Do classical algorithms suffice?

- Do we know what we want to implement?
  - What types of queries
  - Which semantics
  - Ongoing standardization efforts

- Seems like there is work to be done ☺

Thank you!

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