Data Path Queries over Embedded Graph Databases

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VardiFest'22, Haifa, Israel

Thank you, Moshe!!

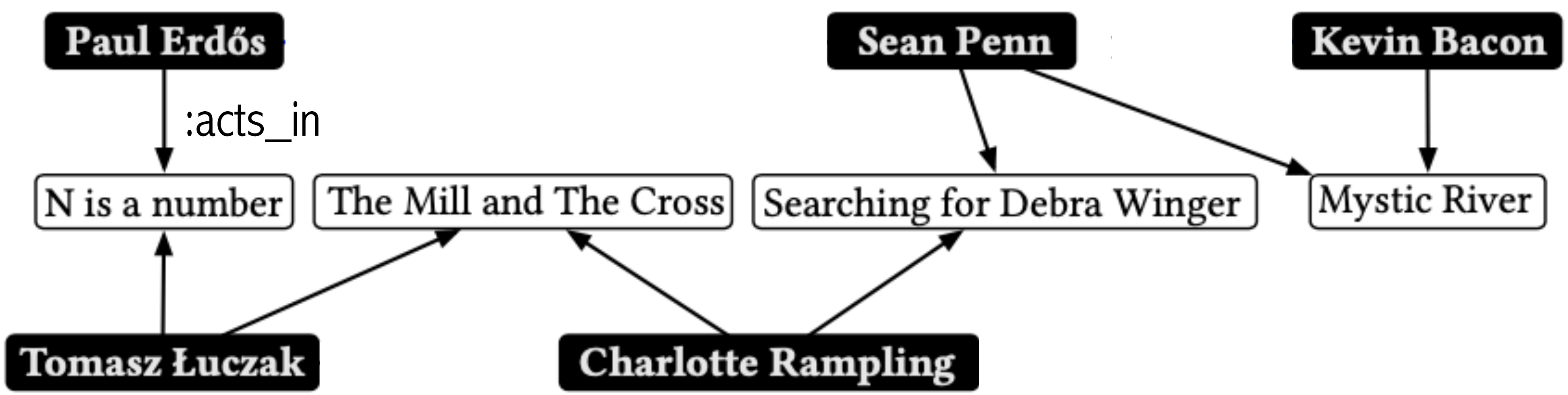
This talk is in honor of Moshe's fundamental contributions in diverse fields especially:

- Database theory (in particular, over graph databases)
- Finite Model Theory
- Automata and Logic
- Boolean satisfiability

The presented result was a modest attempt to learn from Moshe's diversity; it aimed to connect graph databases and SMT

Graph DB: Classic Setting

Output actors that have a finite Bacon number in a movie DB



Regular Path Query (RPQ):

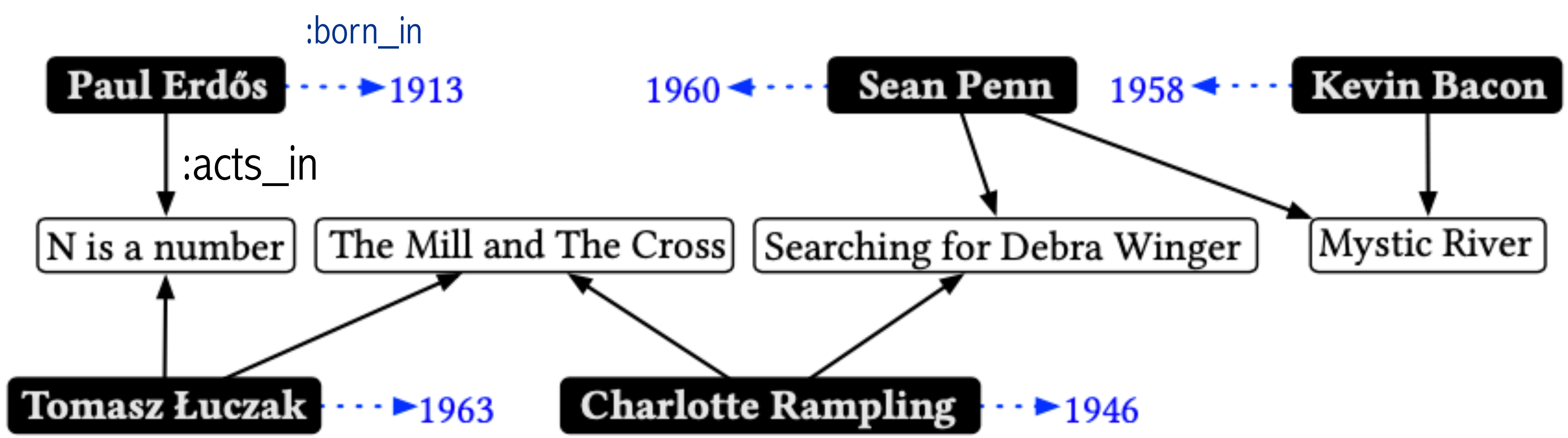
$x \longrightarrow_L$ Bacon, where $L =$ (:acts_in + :acts_in^{-1})*

Desirable data complexity (query L fixed):

NLogspace

„Data“ Querying

Output actors that have a finite Bacon number in a movie DB, whose age is at least 30 years apart from Bacon



Data Queries can get complicated:

1. String data type: similar names along path (small edit distance)
2. Non-linear arithmetics: „nearby“ cities along path (Euclidean distance)

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(Libkin, Martens, Vrgoc [early 2010s])

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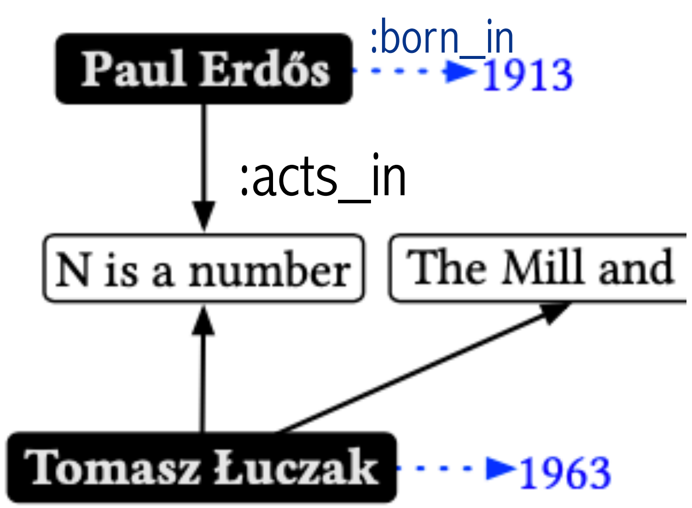

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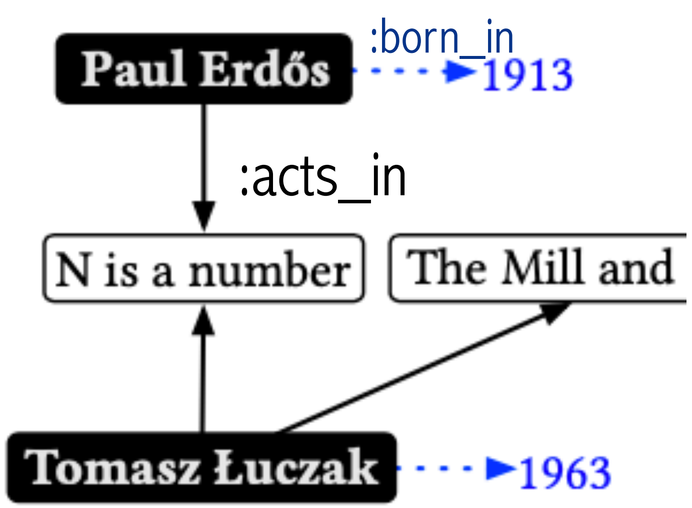

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Gets actors of equal age

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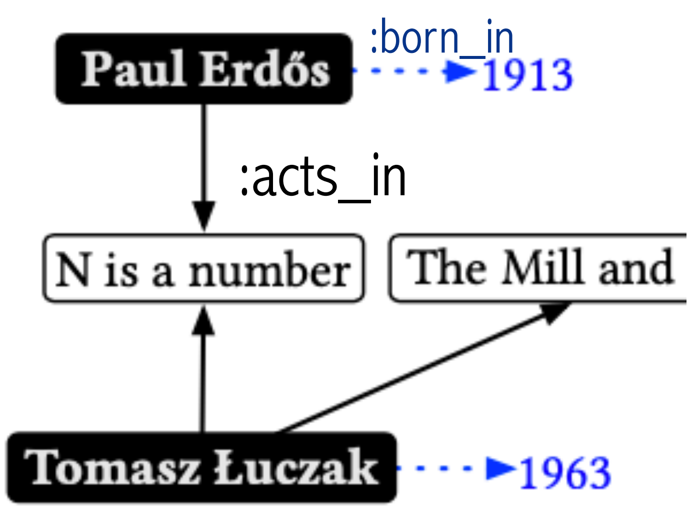

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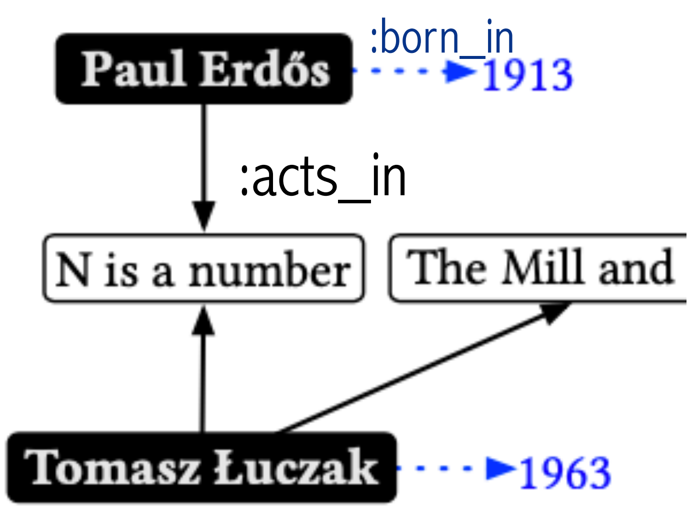

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Theorem: RDPQ with register automata has NL data complexity.

No domain-specific reasoning (e.g. no arithmetics)

Our Main Result

NLogspace data complexity for RDPQ with:

1. Domain-Specific Reasoning (over integer linear arithmetic, theory real closed fields, and various string theories)
2. Generic data graph model

Key ideas:

1. Embedded Finite Model Theory

2. Theory-Aware Register Automata

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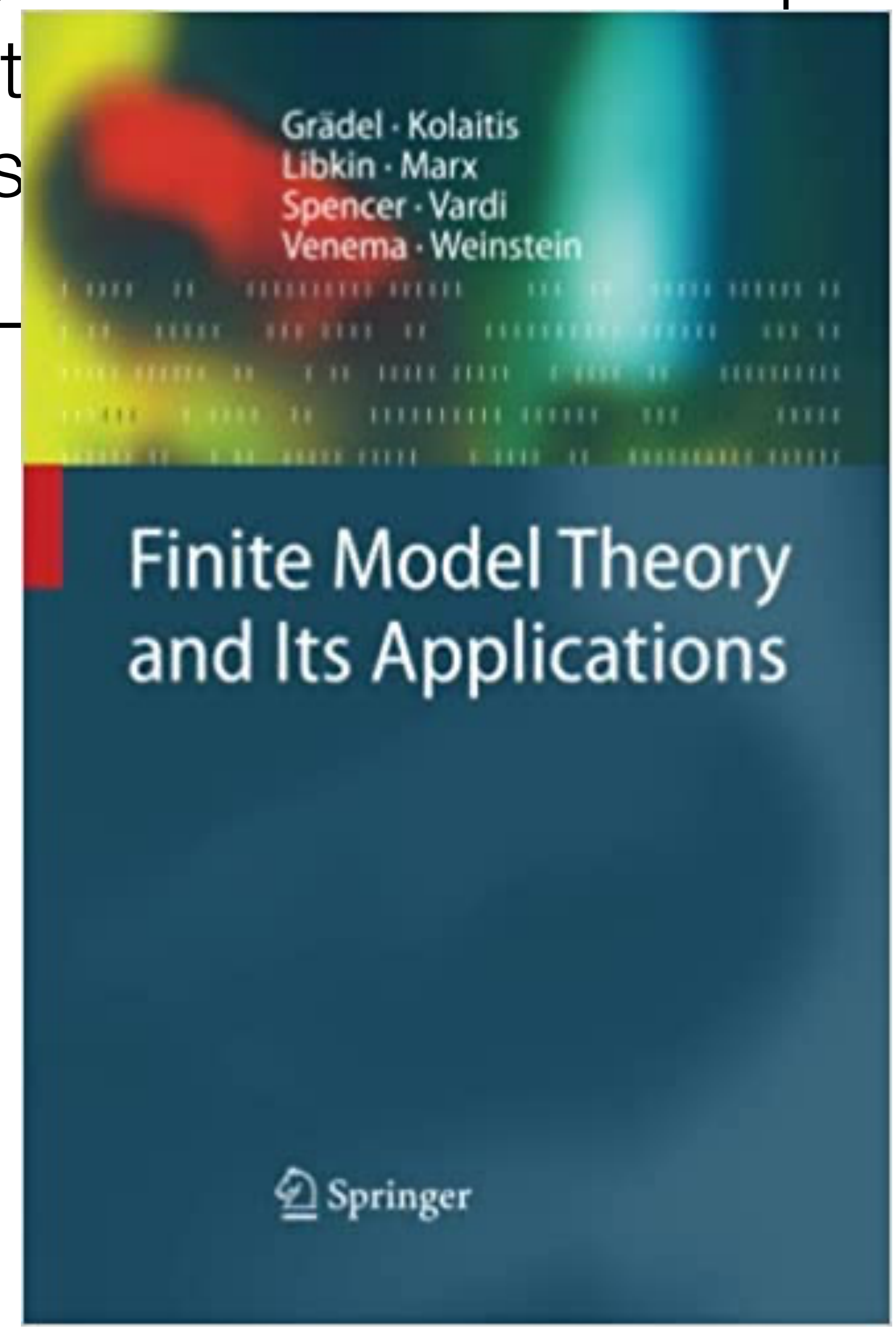


Key ideas:
1. Embedded Finite Model Theory

2. Theory-Aware Register Automata

Key Idea #2: „Theory-Aware“ Register Automata

First approach:

(1) fix an infinite structure $\mathcal{S}$ with a decidable theory

(2) Registers take values and permit operations from $\mathcal{S}$

Problem: undecidable emptiness already for $\mathcal{S} = \langle \mathbb{N}; +1, = \rangle$

Our solution:

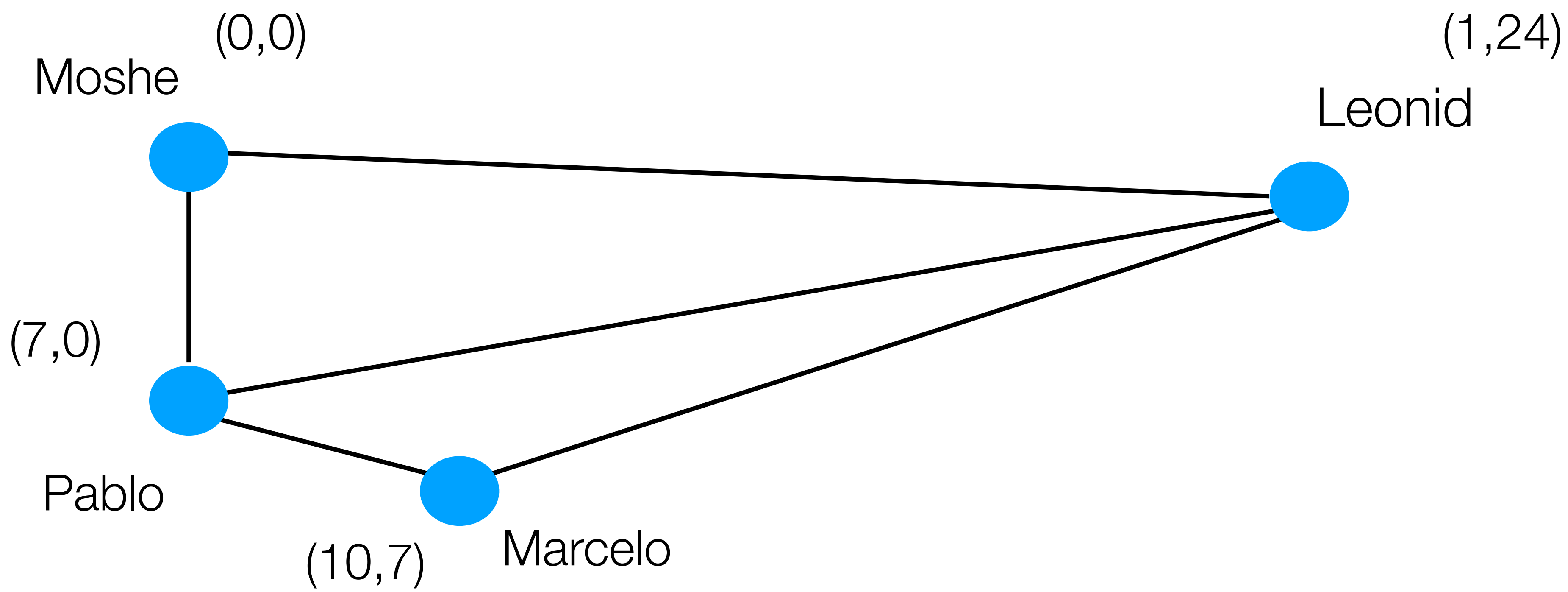
(1) Distinguish between <u>active-domain</u> and <u>general-valued</u> registers

(2) General-valued registers are <u>bounded-rewrite</u>

(3) <u>First-order</u> guards

For important theories T (over integers, reals, and strings), we show that T-RDPQ querying still has NL data complexity!

Ex: Path of Coauthors whose „center“ is of distance <= 6



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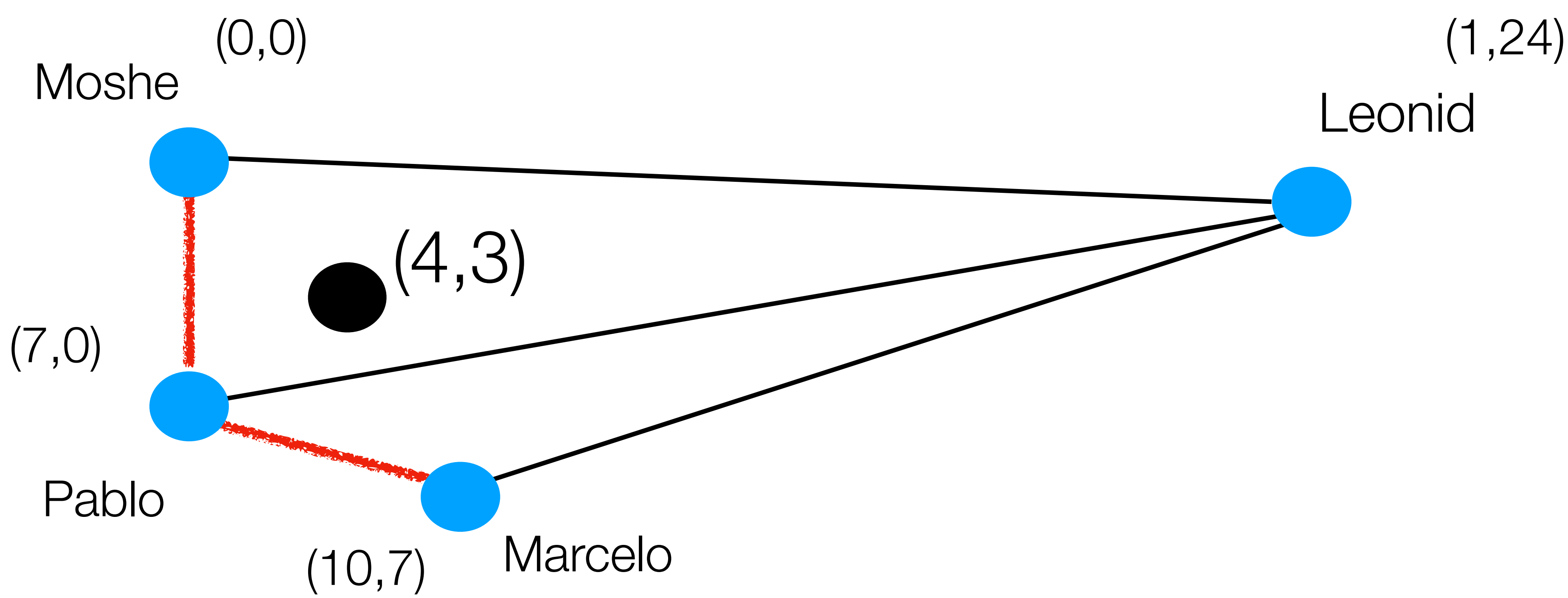

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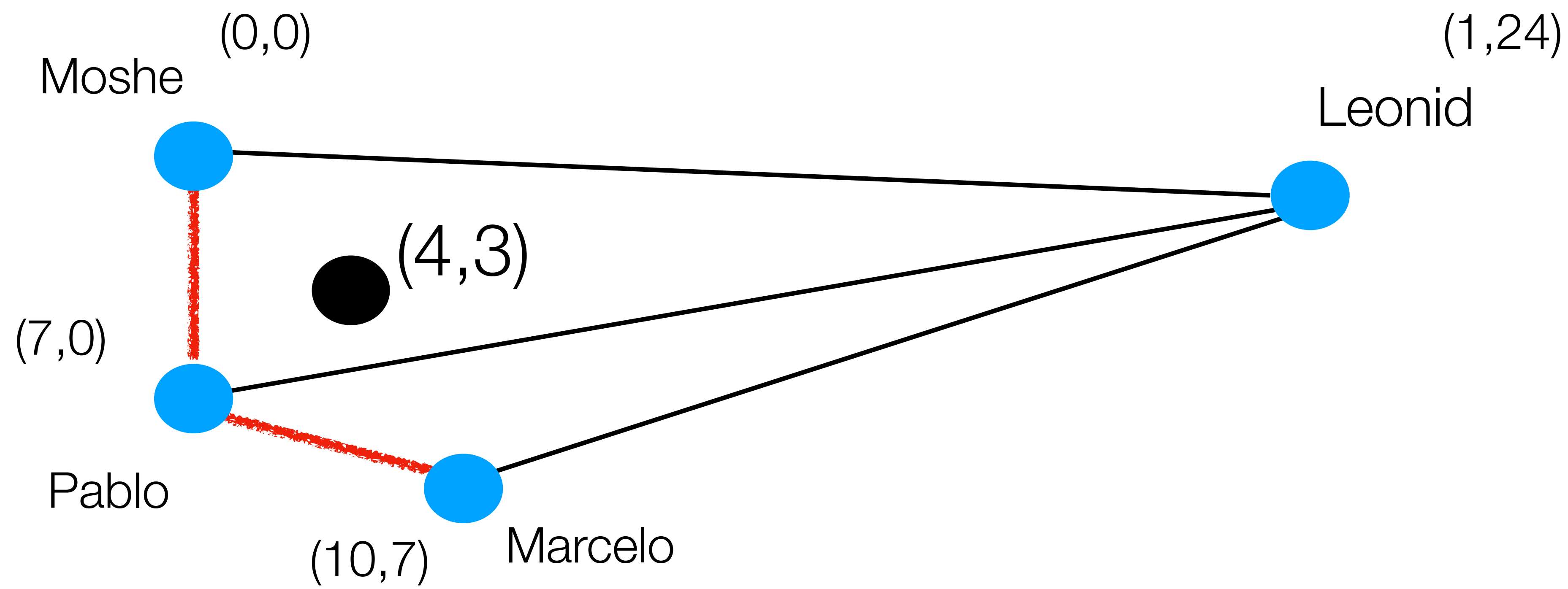
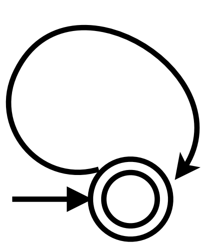


<u>Two unrestricted registers</u>: r_1, r_2



$$\text{coauthors}(curr, next) \wedge$$
$$\exists x, y \in adom \left(\text{xval}(curr, x) \wedge \text{yval}(curr, y) \wedge \sqrt{(x - r_1)^2 + (y - r_2)^2} \leq 6 \right)$$

Theorem (formally)

Theorem:

- RDPQ with $\langle \mathbb{Z}; +, <, 1, 0 \rangle$-RA is NL-complete
- RDPQ with $\langle \mathbb{R}; +, \times, <, 1, 0 \rangle$-RA is NL-complete
- RDPQ with RA over existential positive string equation is NL-complete
- RDPQ with RA over existential automatic structures is NP-hard, but is NL-complete under log-size hypothesis.

Key Technique

Restricted Register Collapse: linear arithmetic, real closed fields

- Each unrestricted register could be effectively replaced by active-domain registers
- Extends the classic notion of Restricted Quantifier Collapse from EFMT

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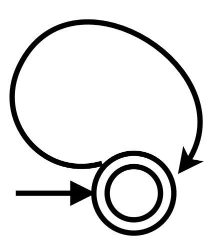

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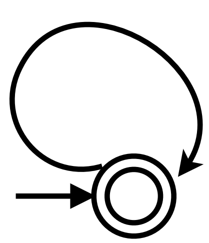

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To remove r_2, we can rewrite this to an expression in terms of roots of $(x - r_1)^2 + (y - r_2)^2 \leq 36$ treated as univariate r_2-polynomial, for some active-domain values x, y

Future Work

- Query containment for RDPQ and extensions
- NL data complexity for a more expressive query language, e.g., Regular Data Queries (RDQ)?

Thanks!