Query Evaluation: Enumeration, Maintenance, Reliability

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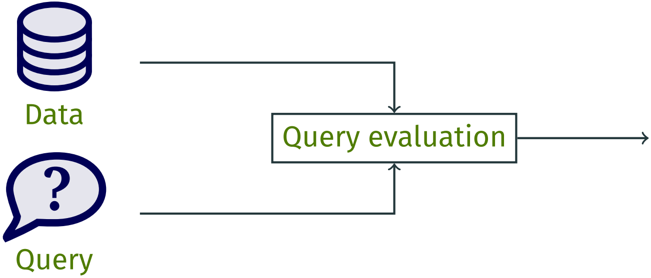
Introduction

Query evaluation

Central question studied in my research: how to efficiently evaluate queries on data?

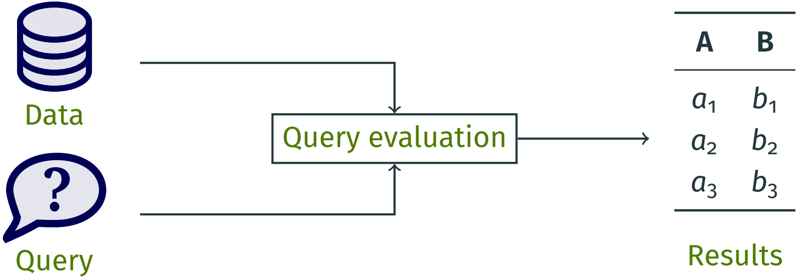


A	B
a_1	b_1
a_2	b_2
a_3	b_3

Results

Query evaluation

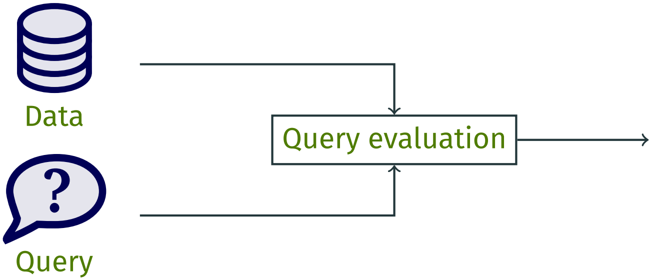
Central question studied in my research: how to efficiently evaluate queries on data?



- Measure the efficiency of this task

Query evaluation

Central question studied in my research: how to efficiently evaluate queries on data?



A	B
a_1	b_1
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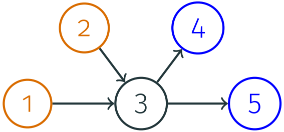
Results

- Measure the efficiency of this task
- Theoretical study (asymptotic complexity, lower bounds) rather than practical

Example: Reachability query



Data: Graph G

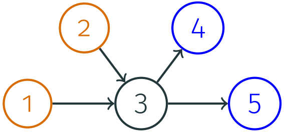
Query $Q(x, y)$: *"Which **orange** nodes **x** have a directed path to which **blue** nodes **y**?"*

Query evaluation

x	y
1	4
1	5
2	4
2	5

Results

Example: Reachability query



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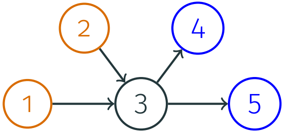
Results

Extend to **three tasks**: enumeration, maintenance, and reliability

Enumeration: Producing results in streaming



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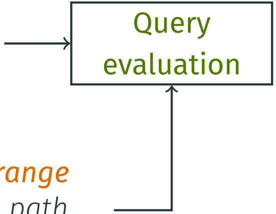

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- **Usual complexity measure:** time to produce the **entire output**

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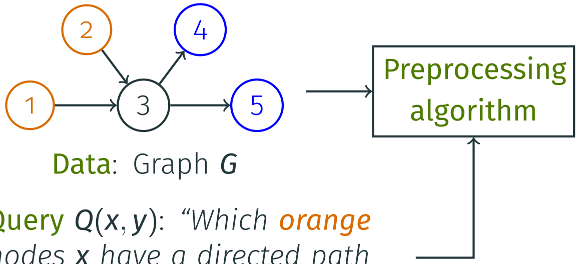

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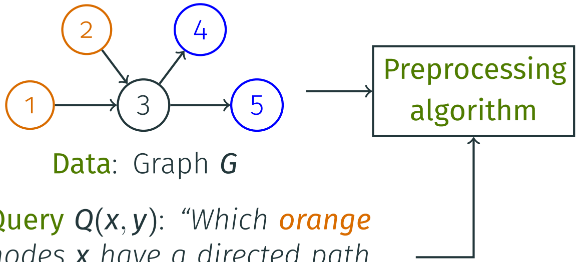

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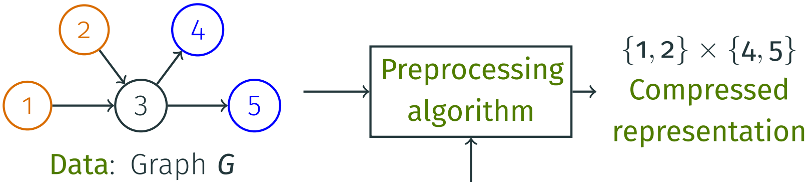

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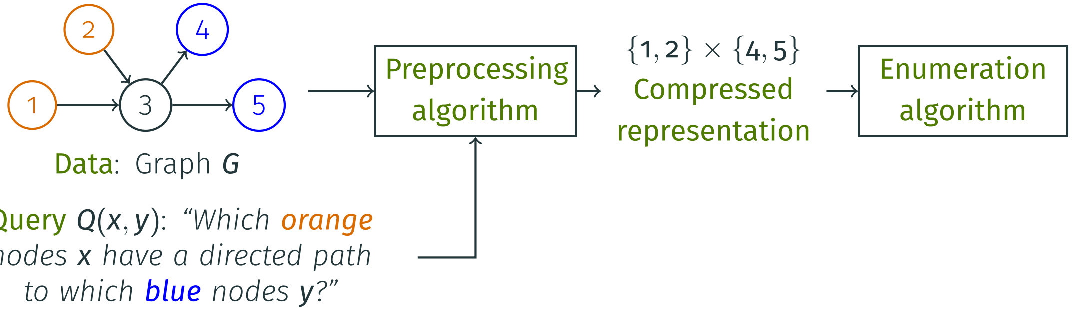

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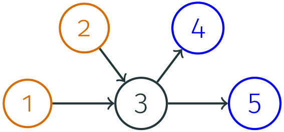

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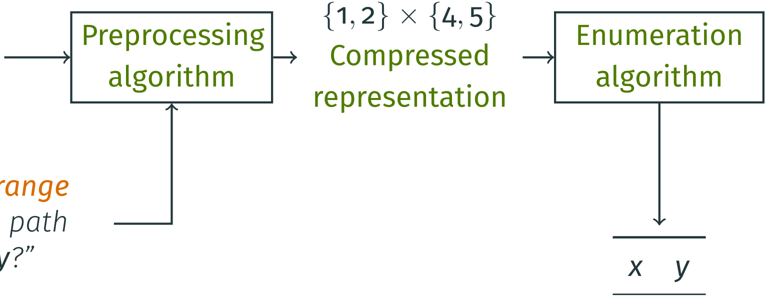

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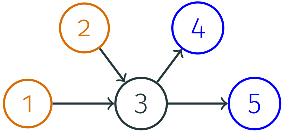

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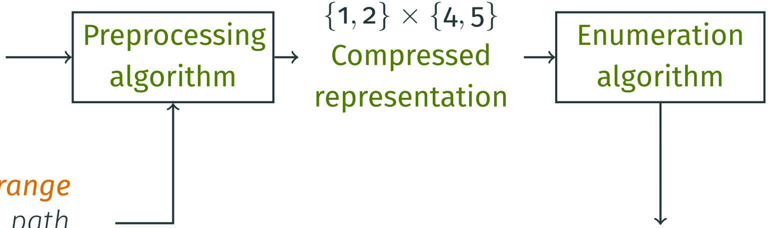

x	y
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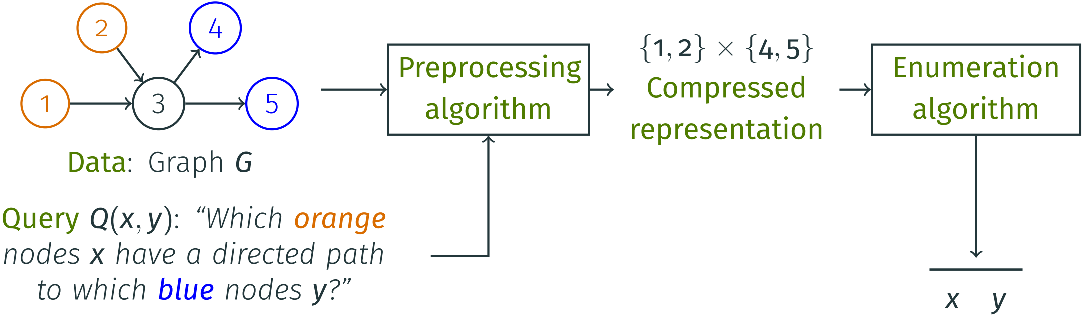

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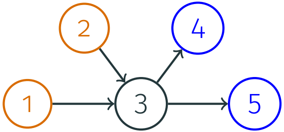

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Query $Q(x, y)$: *"Which orange nodes x have a directed path to which blue nodes y?"*

→ Preprocessing algorithm → $\{1, 2\} \times \{4, 5\}$ Compressed representation → Enumeration algorithm ↓

x	y
1	4
1	5
2	4

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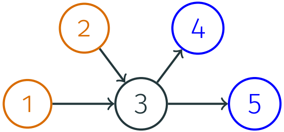

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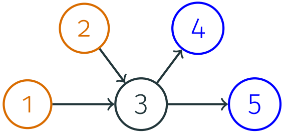

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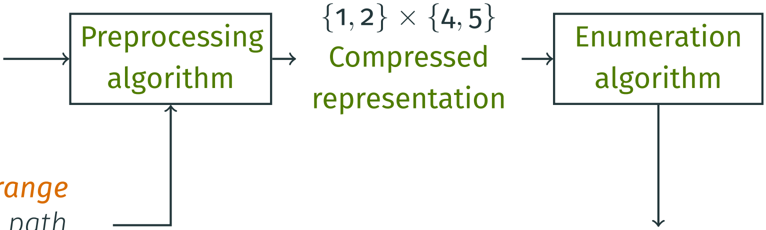

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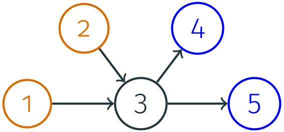
→ Test **existence of a result**, find **some results**, find **all results**...

Maintenance over dynamic data: Adapting to changes



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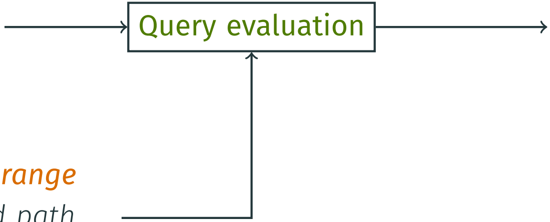

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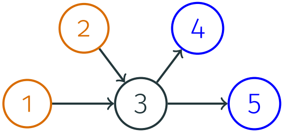

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Incremental query evaluation

x	y
1	4
1	5
2	4
2	4

Results

- Whenever the data is **changed**, do not **recompute** the whole result

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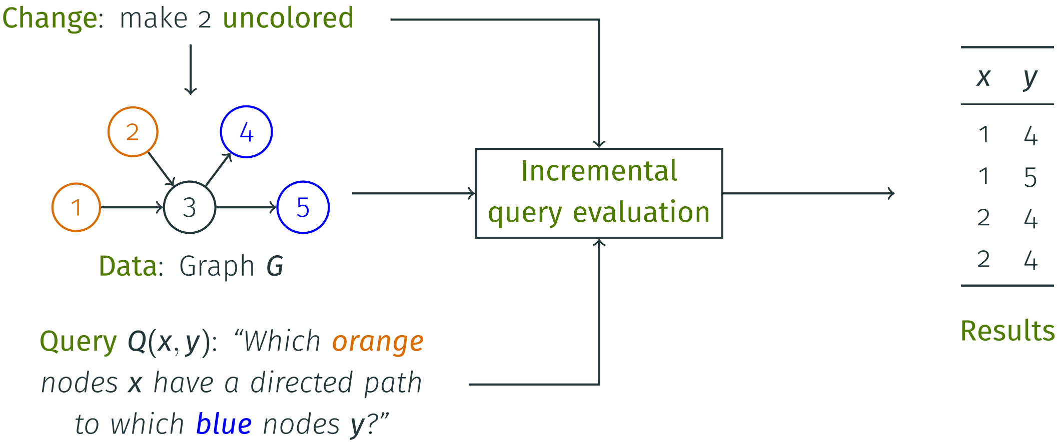

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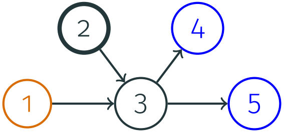
Maintenance over dynamic data: Adapting to changes

Change: make 2 **uncolored**



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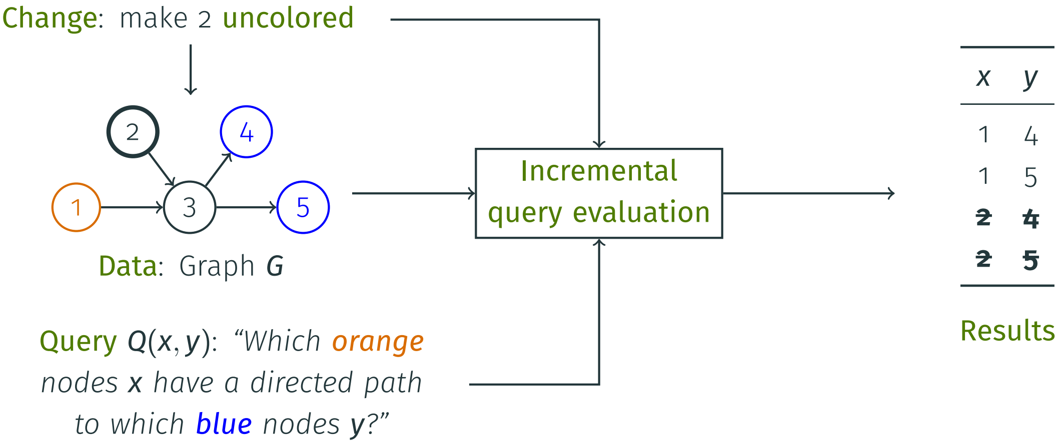

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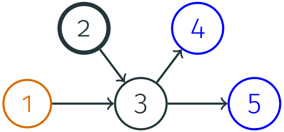


Data: Graph G

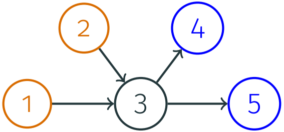
Incremental query evaluation

x	y
1	4
1	5
~~2~~	~~4~~
~~2~~	~~5~~

Results

Query $Q(x, y)$: *"Which **orange** nodes **x** have a directed path to which **blue** nodes **y**?"*

- Whenever the data is **changed**, do not **recompute** the whole result
- **Relabeling updates** vs **more general updates**



Data: Graph G

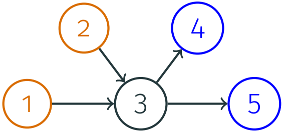
Query $Q(x, y)$: *"Which **orange** nodes x have a directed path to which **blue** nodes y?"*

Query evaluation

x	y
1	4
1	5
2	4
2	5

Results

Reliability: Probabilistic query evaluation



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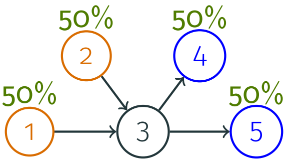

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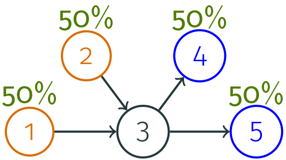
Results

- The color of each node is kept with a given **probability**, assuming **independence**

Reliability: Probabilistic query evaluation



Data: Graph G

Query $Q(x, y)$: *"Which orange nodes* x *have a directed path to which blue nodes* y*?"*

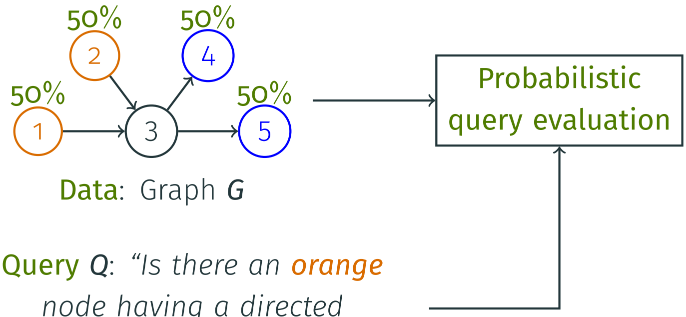
→ Probabilistic query evaluation →

x	y	
1	4	25%
1	5	25%
2	4	25%
2	5	25%

Results

- The color of each node is kept with a given probability, assuming independence
- We want to know the probability of all results

Reliability: Probabilistic query evaluation

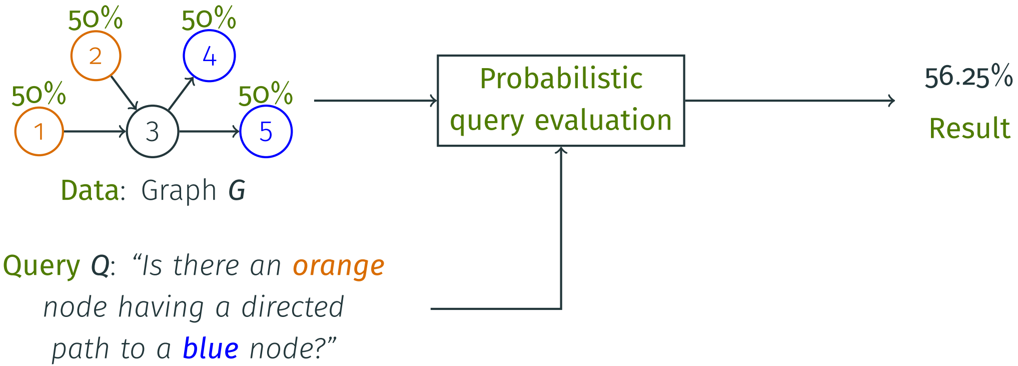


Data: Graph G

Query Q: *"Is there an **orange** node having a directed path to a **blue** node?"*

- The color of each node is kept with a given **probability**, assuming **independence**
- We want to know the **probability** of all results
- Here, more interesting: probability of the **Boolean query**

Reliability: Probabilistic query evaluation



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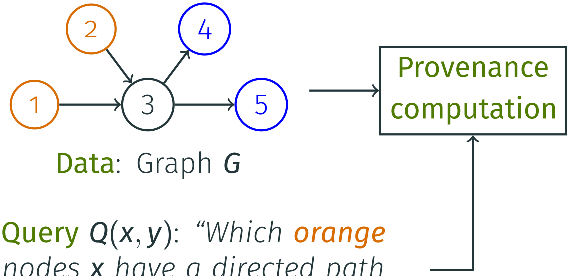
Provenance circuits: A unified approach to these three problems



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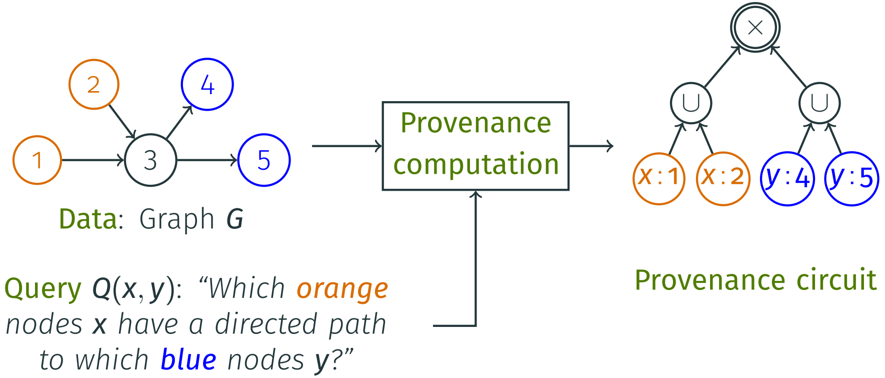

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- Show that it belongs to restricted **circuit classes** from **knowledge compilation**

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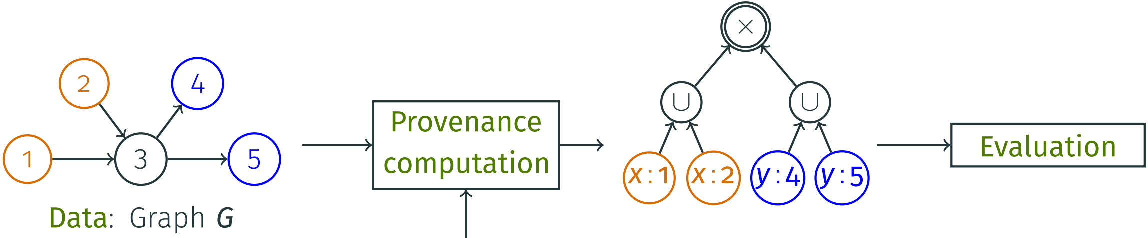

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Provenance circuit

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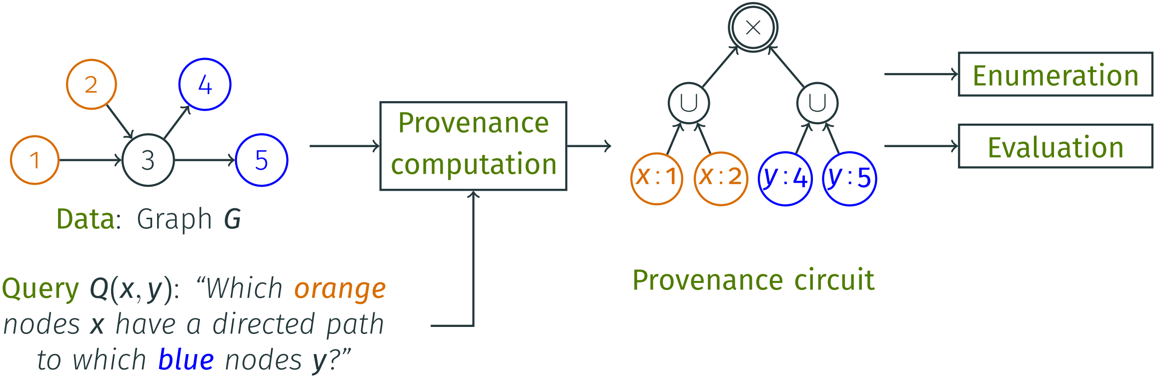

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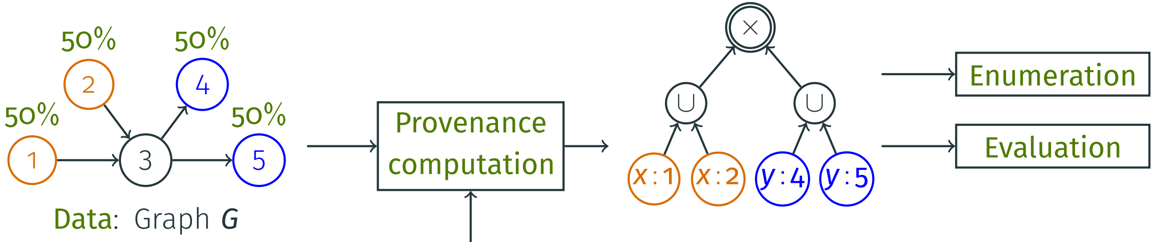

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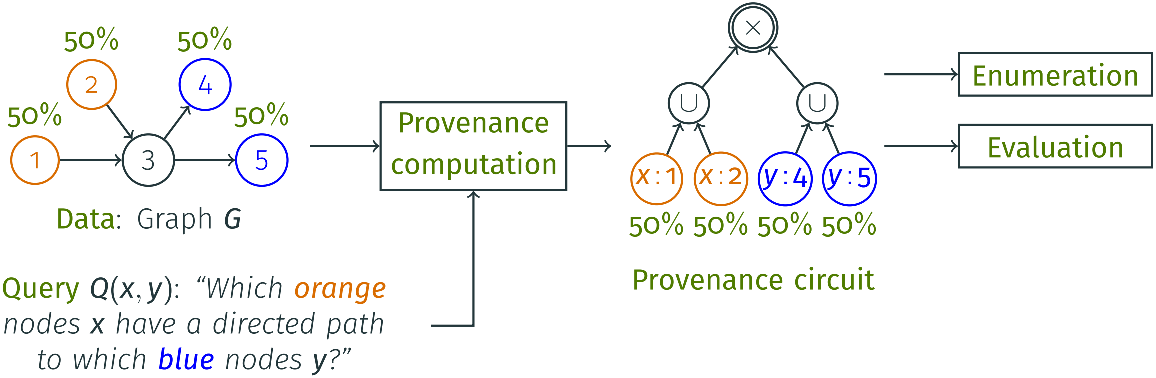

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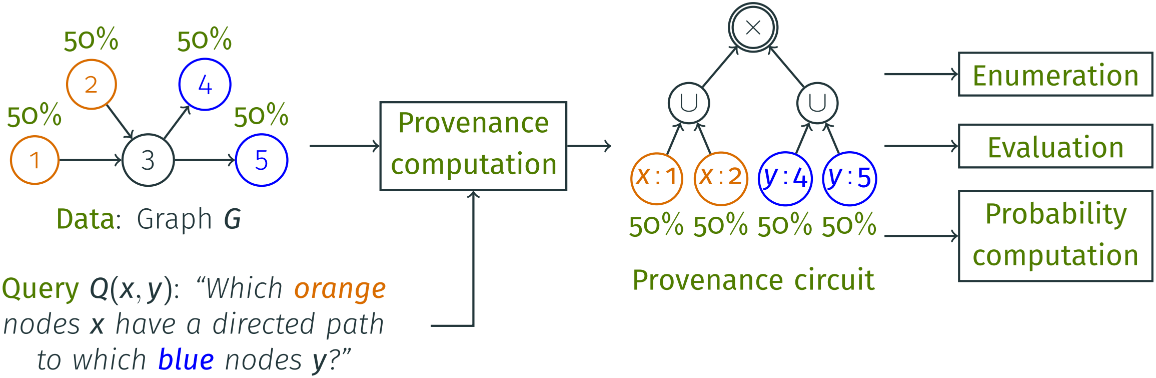

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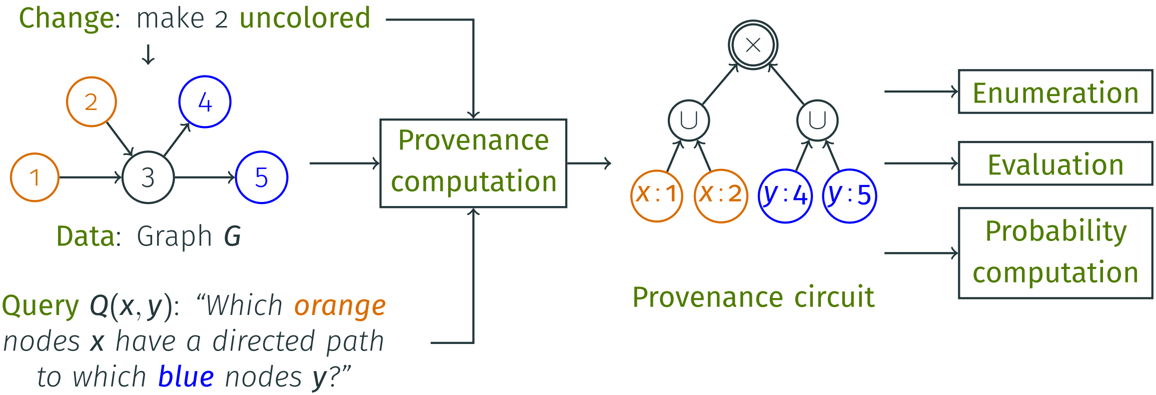

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- Update it if there are **changes** on the data

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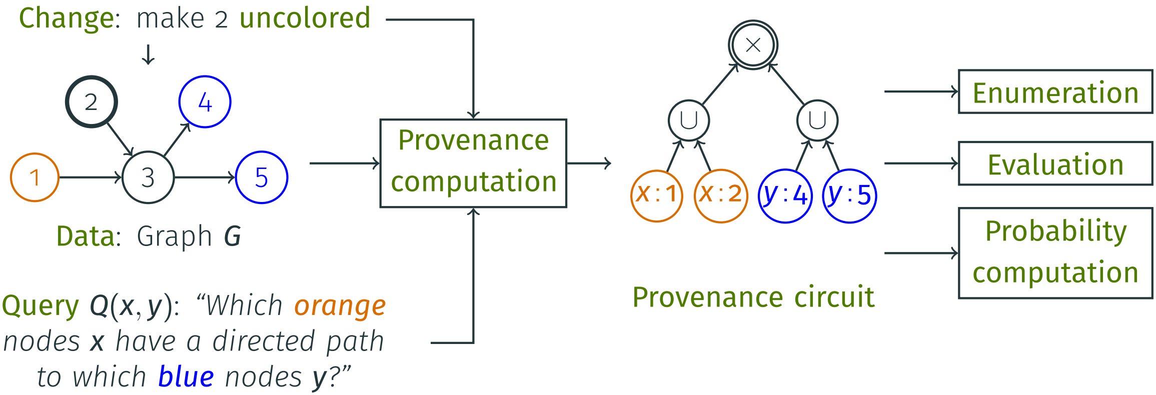

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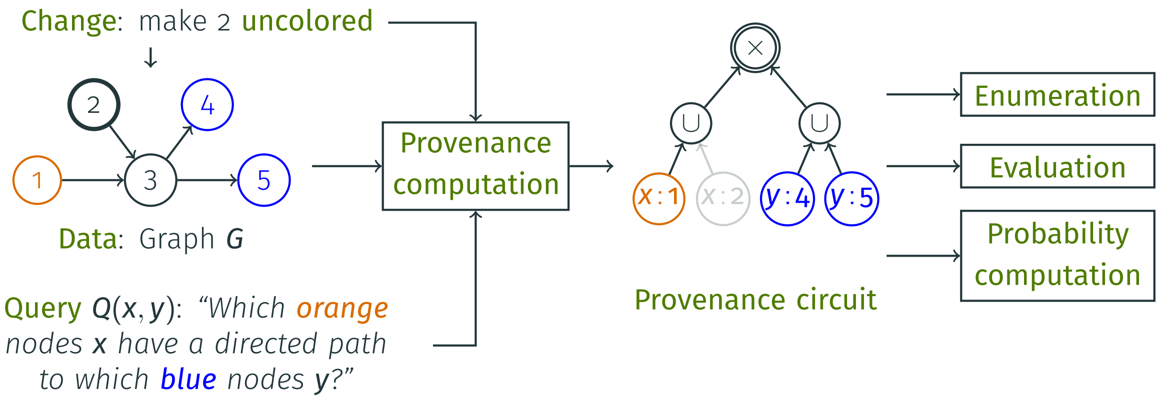

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Roadmap of the presentation

- Present data and query formalisms:
  - $\rightarrow$ Monadic second-order logic (MSO) on words/trees

Roadmap of the presentation

- Present **data** and **query** formalisms:
  $\rightarrow$ **Monadic second-order** logic (MSO) on words/trees

- Results on **enumeration**

Roadmap of the presentation

- Present data and query formalisms:
  $\rightarrow$ Monadic second-order logic (MSO) on words/trees
- Results on enumeration
- Results on incremental maintenance

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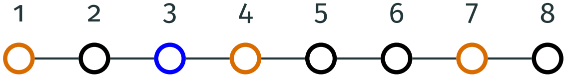
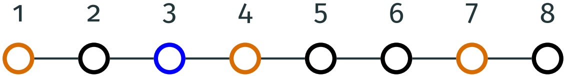
- Results on enumeration
- Results on incremental maintenance
- Results on probabilistic query evaluation

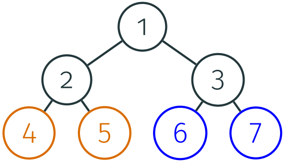
Context

Families of data

- Words: 

Families of data

- Words: 

- Trees: 

less expressive

more expressive

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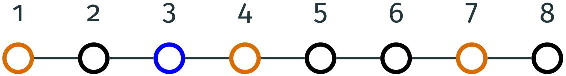
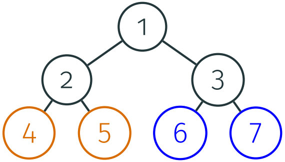
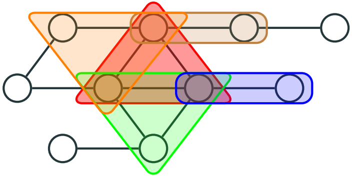
- Words: 

- Trees: 

- Bounded-treewidth graphs: 

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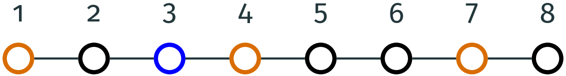
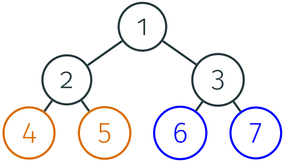
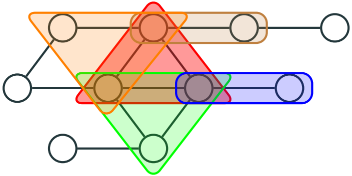
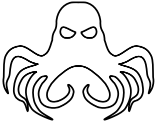
- Words: 

- Trees: 

- Bounded-treewidth graphs: 
- Many other classes of graphs and relational structures: 

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Query languages

From **least** to **most** expressive:

- **Conjunctive queries** (CQs): find a pattern
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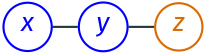
  - $Q(x, y) : \exists z$ 

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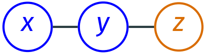
  - $Q(x, y) : \exists z$ 

- Unions of CQs (UCQs): disjunction of CQs
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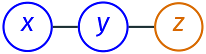
  - $Q(x, y) : \exists z$ 

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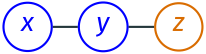
  - $Q(x, y) : \exists z$ 

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- **Monadic second-order logic** (MSO): extend FO with **quantification over sets**
  - Equivalent to **finite automata** on words, trees, tree encodings

Enumeration

Word automata with captures

On words, MSO queries are equivalent to automata

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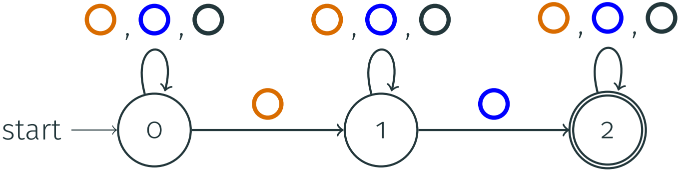

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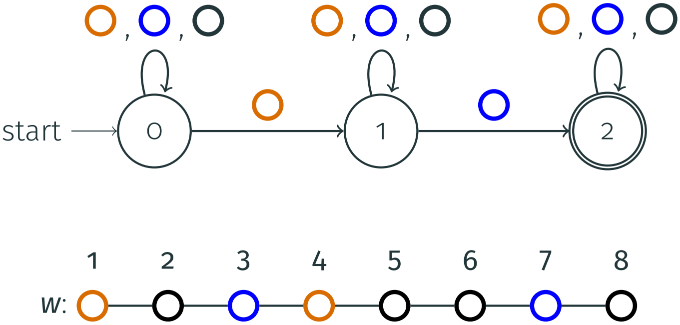

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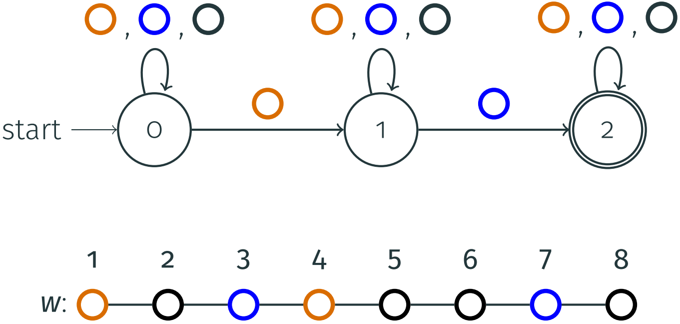

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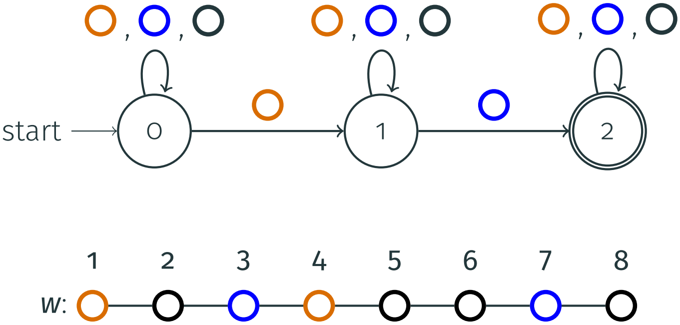

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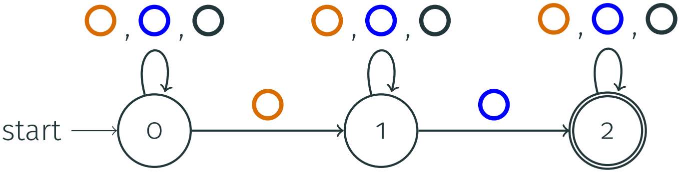

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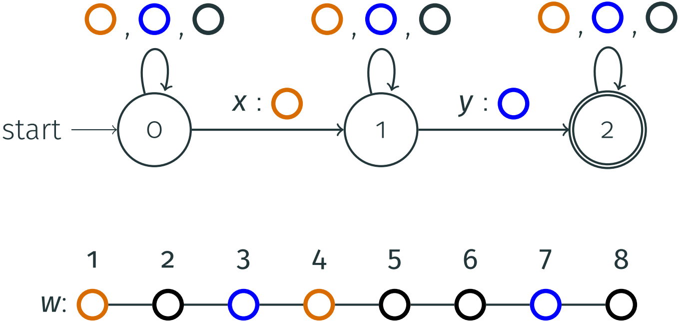

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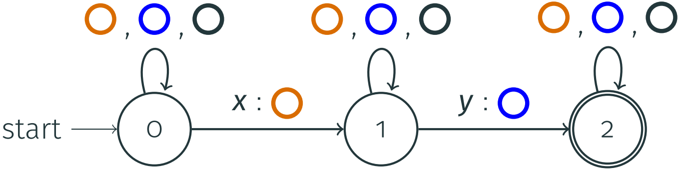
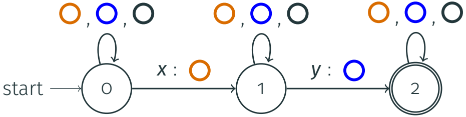


Results: $(x\!:\!1, y\!:\!3), (x\!:\!1, y\!:\!7), (x\!:\!4, y\!:\!7)$

Provenance circuit computation: Product construction



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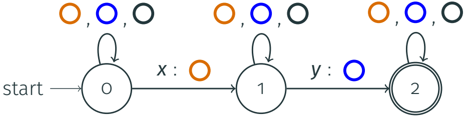

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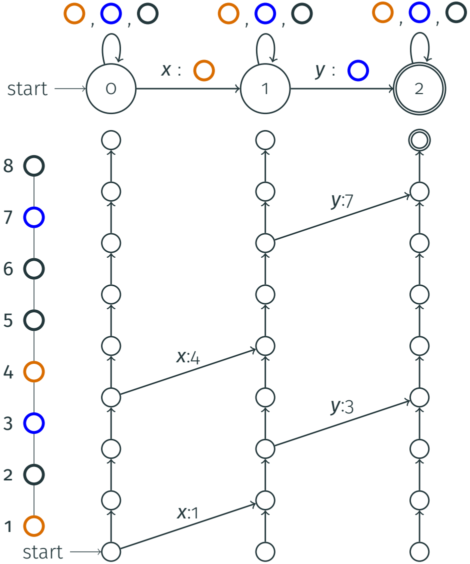

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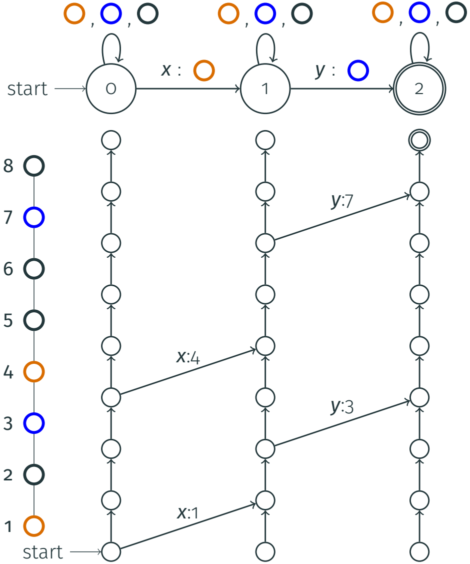

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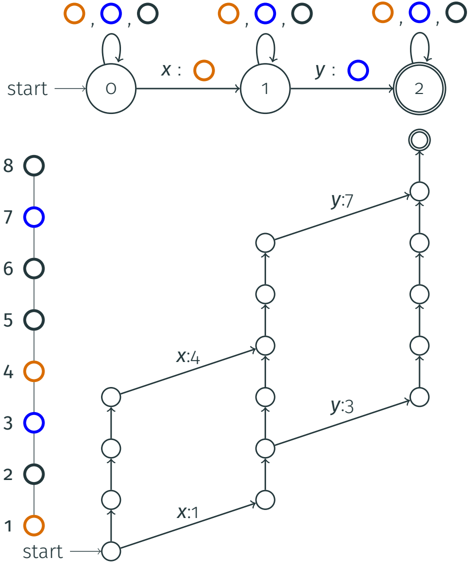

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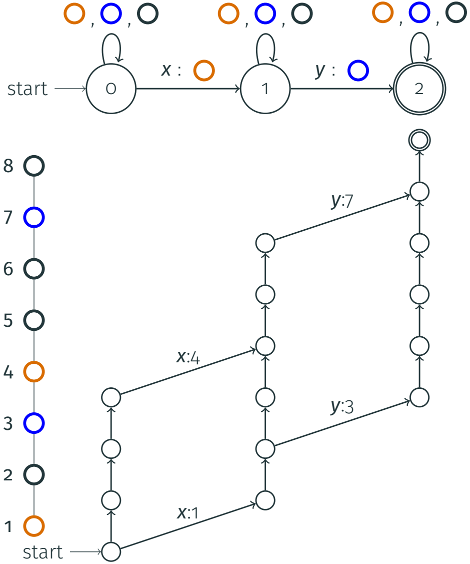

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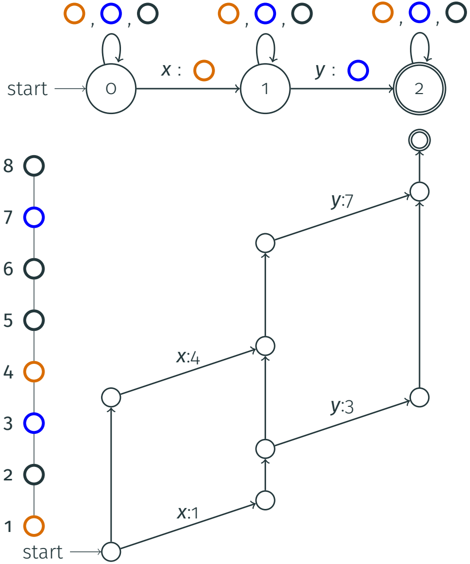

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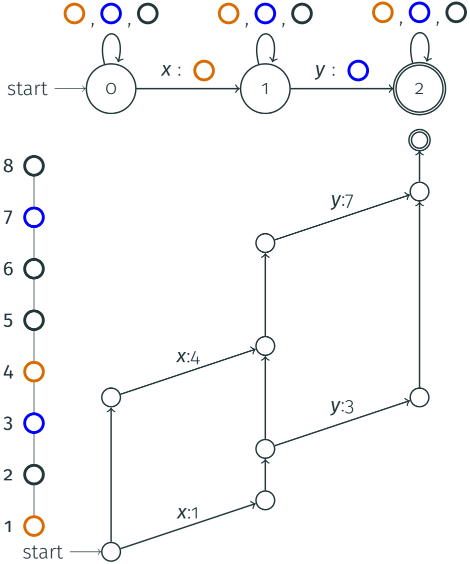

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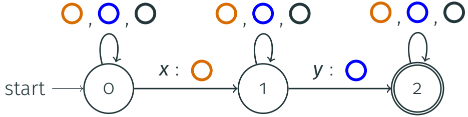

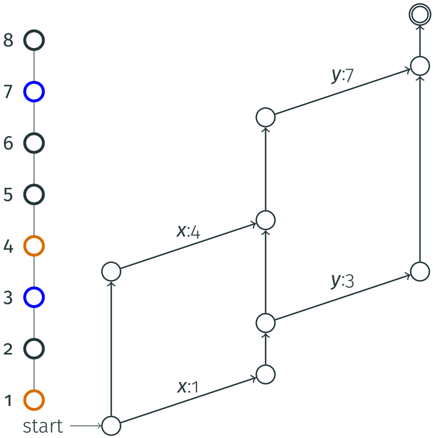

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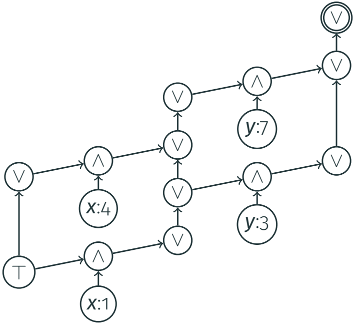

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We can enumerate query results (= satisfying assignments) using the provenance circuit

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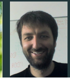


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Given an automaton with captures A with constant number of variables, given a word w, we can enumerate the results of A on w with preprocessing $O(Poly(|A|) \times |w|)$ and delay $O(Poly(|A|))$.

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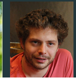
Known result [Bagan, 2006, Kazana and Segoufin, 2013] but polynomial dependency in A

Enumeration for general circuits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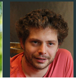

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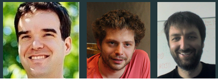

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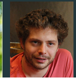


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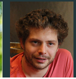


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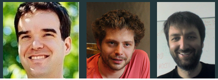

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Theorem (ICALP'17; with Bourhis, Jachiet, Mengel)

Given a d-SDNNF **C** *and a v-tree that structures* **C**, *we can enumerate the satisfying assignments of* **C** *with* ***linear preprocessing*** *and* ***output-linear delay***.

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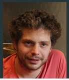


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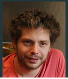
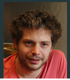
Also works for **ranked enumeration** (according to an order) if the circuit is **smooth**, with **logarithmic** delay (ICDT'24; with Bourhis, Capelli, Monet)

Beyond regular languages



Generalize automata with captures into annotation context-free grammars

Beyond regular languages



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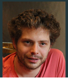

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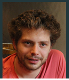
Annotation grammar must be **input-output-unambiguous**: no result is captured twice



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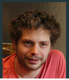

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Given an unambiguous annotation grammar $\mathbf{G}$ *and word* $\mathbf{w}$*, we can enumerate the results of* $\mathbf{G}$ *on* $\mathbf{w}$ *with preprocessing* $O(|G| \times |w|^3)$ *and **output-linear** delay*

Better preprocessing time for restricted grammar classes

Maintenance

Maintenance for MSO enumeration on trees

We use provenance circuits for automata on words and trees

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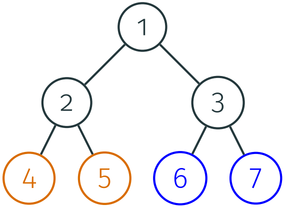

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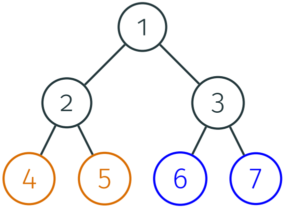

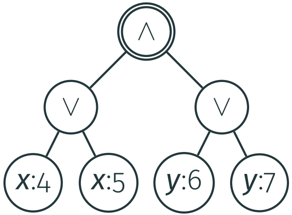

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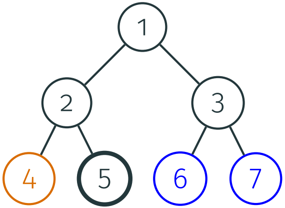

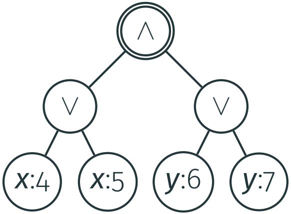

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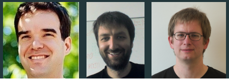
Maintaining MSO enumeration structures under relabelings



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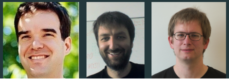

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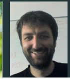


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Same for updates that **change the tree structure** (PODS'19; with Bourhis, Mengel, Niewerth) assuming we have an algorithm to **keep the tree balanced**

Improving the logarithmic complexity

- The update time is $O(\log n)$ and there is a lower bound of $\Omega(\log n / \log \log n)$
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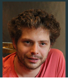
→ For a fixed language L, given a word w of length n, what is the **best update time** to maintain membership of w to L under relabelings?

Incremental maintenance for regular word languages



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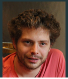

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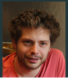


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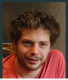


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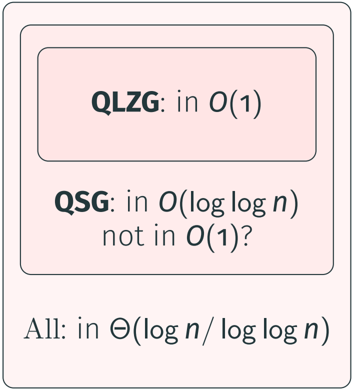

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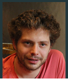

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QLZG: in $O(1)$

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not in $O(1)$?

All: in $\Theta(\log n / \log \log n)$

- **QLZG**: "in all submonoids of the stable semigroup, all subgroup elements are central"
  - → Commutative languages, finite languages, disjoint shuffles, modulo, nearby positions...
- **QSG**: "the stable semigroup satisfies the equation $x^{\omega+1}yx^{\omega} = x^{\omega}yx^{\omega+1}$"
  - → Aperiodic languages, tame combinations of aperiodic and commutative languages...

Reliability

Probabilistic query evaluation (PQE)

Tuple-independent probabilistic data (TID): facts carry independent probabilities

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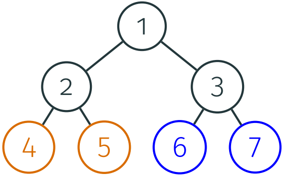

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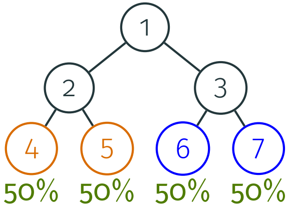

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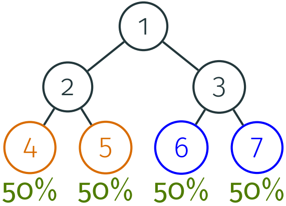

PQE(*Q*): compute the **total probability** that *Q* is satisfied, here:

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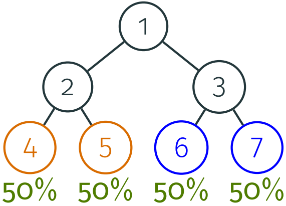

PQE(Q): compute the **total probability** that Q is satisfied, here: 56.25%

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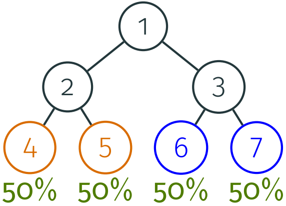

PQE(Q): compute the **total probability** that Q is satisfied, here: **56.25%**

- Known dichotomy for PQE on **unions of conjunctive queries** (on arbitrary data) [Dalvi and Suciu, 2013]: the problem is either **#P-hard** or **in PTIME**

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For MSO queries on trees, we can solve PQE using d-SDNNF provenance circuits!

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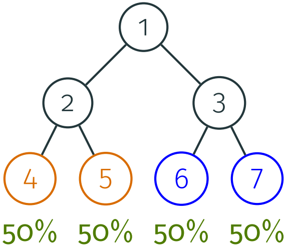

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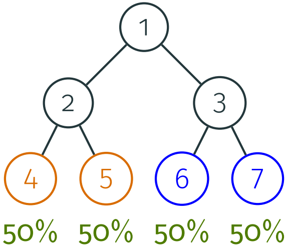

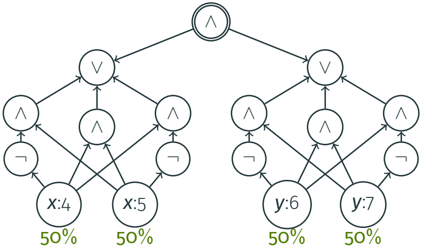

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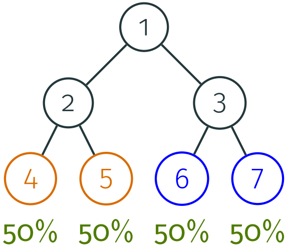

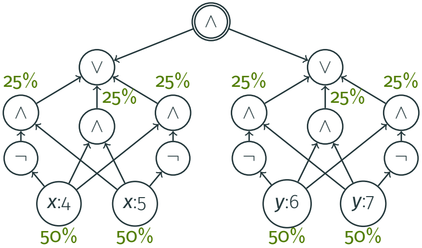

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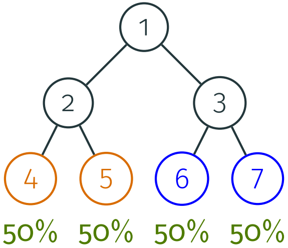

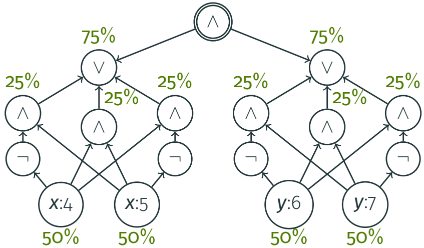

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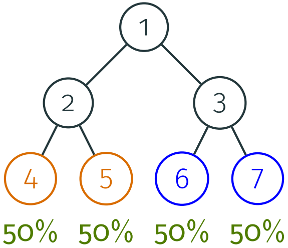

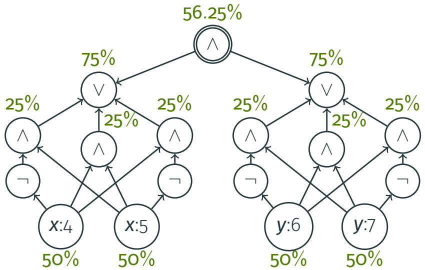

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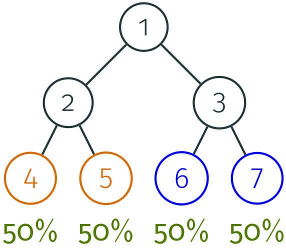

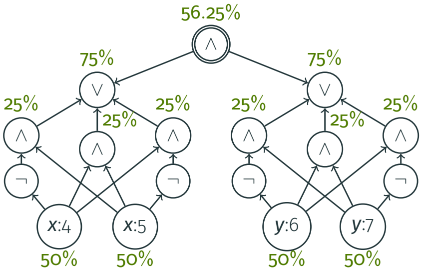

- Probability of ∧ is the **product** of the probabilities (uses decomposability)
- Probability of ∨ is the **sum** of the probabilities (uses determinism)

Intractability of probabilistic query evaluation in the general case

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  - We show the same for all **unbounded homomorphism-closed queries** on graphs

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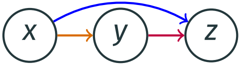
Uses polynomial bounds on the grid minor theorem [Chekuri and Chuzhoy, 2016]

Intractability in the uniform setting

A conjunctive query is **self-join-free** if all **edge colors** are different

E.g.,



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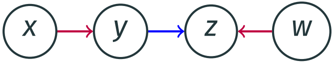

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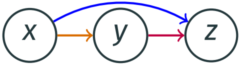
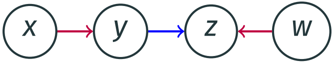
E.g., 

but not 

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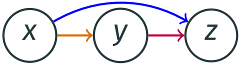
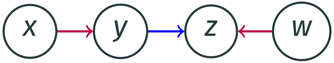
E.g., 

but not 

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Theorem (ICDT'21, LMCS; with Kimelfeld)

For any non-hierarchical self-join-free conjunctive query Q*, computing probabilistic query evaluation problem for* Q *input TID databases is #P-hard* ***even if all input probabilities are*** $1/2$.

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A query Q is homomorphism-closed if whenever G satisfies Q and G has a homomorphism to G' then G' satisfies Q

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(with Antonin Delpeuch)

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