Provenance

MPRI 2.26.2: Web Data Management

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Provenance Definition

Provenance management

- Data management is **all about query evaluation**
- What if we want **something more** than the query result?
  - **Where** does the result come from?
  - **Why** was this result obtained?
  - **How** was the result produced?
  - What is the **probability** of the result?
  - How many **times** was the result obtained?
  - How would the result **change** if part of the input data was missing?
  - What is the minimal **security clearance** I need to see the result?
  - What is the **most economical way** of obtaining the result?
  - How can a result be **explained** to the user?
- **Provenance management:** along with query evaluation, record **additional bookkeeping information** to answer the questions above

Provenance data model

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name	position	city	classification
John	Director	New York	unclassified
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Provenance data model

- **Relational data model**: data decomposed into relations, with labeled attributes…
- … with an extra **provenance annotation** for each tuple (think of it first as a tuple id)

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Outline

Provenance Definition

Preliminaries

Boolean Provenance

Provenance for Probability Computation

Applications to Enumeration

Semiring Provenance

Implementing Provenance Support

Boolean valuations

- Database D with n tuples
- $\mathcal{X} = \{x_1, x_2, \ldots, x_n\}$ the **Boolean variables** annotating the tuples
- **Valuation** over $\mathcal{X}$: function $\nu : \mathcal{X} \to \{\bot, \top\}$
- **Possible world** $\nu(D)$: the subset of D where we keep precisely the tuples whose annotation evaluates to $\top$

Example of possible worlds

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$$\nu: \quad \begin{array}{ccccccc} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 \\ \top & \top & \top & \top & \top & \top & \top \end{array}$$

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city	prov
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Claim: we can compute this while evaluating the query!

Selection, renaming

Provenance annotations of selected tuples are unchanged

Example ($\rho_{\mathbf{name}\to\mathbf{n}}(\sigma_{\mathbf{city}=\text{“New York”}}(R))$)

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Projection

Take the OR of provenance annotations of identical, merged tuples

Example ($\pi_{\mathbf{city}}(R)$)

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New York	$x_1 \lor x_2$
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Union

Take the OR of provenance annotations of identical, merged tuples

Example

$\pi_{\text{city}}(\sigma_{\textit{ends-with}(\text{position},\text{“agent”})}(R)) \cup \pi_{\text{city}}(\sigma_{\text{position}=\text{“Analyst”}}(R))$

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city	prov
Paris	$x_3 \vee x_5$
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Cross product

Take the AND of provenance annotations of combined tuples

Example

$\pi_{\text{city}}(\sigma_{\textit{ends-with}(\text{position},\text{“agent”})}(R)) \bowtie \pi_{\text{city}}(\sigma_{\text{position}=\text{“Analyst”}}(R))$

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city	prov
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How is provenance actually represented?

Provenance annotations are Boolean functions

- The simplest representation is Boolean formulas
- Formalism used in most of the provenance literature

Example

Is there a city with two different agents?

$$(x_1 \land x_2) \lor (x_3 \land x_6) \lor (x_3 \land x_5) \lor (x_4 \land x_7) \lor (x_5 \land x_6)$$

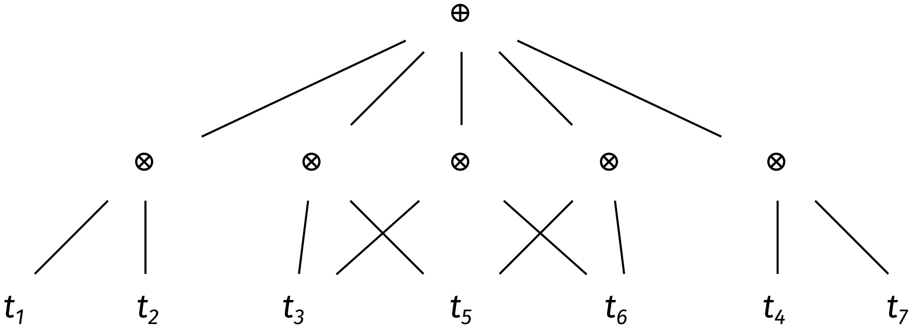
Theorem (PTIME overhead)

For any fixed positive relational algebra expression, given an input database, we can compute in PTIME the provenance annotation of every tuple in the result

Other representation: Provenance circuits
[Deutch et al., 2014]

- Use **Boolean circuits** to represent provenance
- Every time an operation reuses a previously computed result, link to the **previously created circuit gate**
- **Never larger** than provenance formulas
- Sometimes **more concise**

Example provenance circuit



What can we do with Boolean provenance?

$$(x_1 \wedge x_2) \vee (x_3 \wedge x_6) \vee (x_3 \wedge x_5) \vee (x_4 \wedge x_7) \vee (x_5 \wedge x_6)$$

- The provenance describes, for each result tuple, the subsets of the input database for which it appears in the query result

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- #SAT: number of sub-databases where the tuple is a result
  - $\rightarrow$ Useful for probabilistic query evaluation

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- The provenance describes, for each result tuple, the **subsets** of the input database for which it appears in the query result
- **SAT**: test if the tuple can be an answer when we delete some input tuples (trivial for monotone queries)
- **#SAT**: number of sub-databases where the tuple is a result
  - → Useful for **probabilistic query evaluation**
- **Enumerating models:** enumerating sub-databases where the tuple is a result
  - → Useful to **enumerate query results** (see later)

Outline

Reminder: TIDs

- **Tuple-independent database D**: each tuple t in D is annotated with **independent** probability $\Pr(t)$ of existing

name	position	city	classification	prob
John	Director	New York	unclassified	0.5
Paul	Janitor	New York	restricted	0.7
Dave	Analyst	Paris	confidential	0.3
Ellen	Field agent	Berlin	secret	0.2
Magdalen	Double agent	Paris	top secret	1.0
Nancy	HR director	Paris	restricted	0.8
Susan	Analyst	Berlin	secret	0.2

$\rightarrow$ Probability of a possible world $D' \subseteq D$:

$$\Pr(D') = \prod_{t \in D'} \Pr(t) \times \prod_{t \in D' \setminus D} (1 - \Pr(t'))$$

PQE via provenance

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city	prov	prob
New York	$x_1 \vee x_2$	$1 - (1 - 0.5) \times (1 - 0.7) = 0.85$
Paris	$x_3 \vee x_5 \vee x_6$	1.00
Berlin	$x_4 \vee x_7$	$1 - (1 - 0.2) \times (1 - 0.2) = 0.36$

Extensional PQE vs intensional PQE

- Recall that PQE for UCQs is:
    - PTIME in some cases
    - #P-hard in general
    - There is a dichotomy separating tractable and intractable cases

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  - This covers the tractable cases of PQE for select-project-join queries (CQs) without self-joins with an easy algorithm
  - This covers all tractable cases (for UCQs) with a far more complicated algorithm

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    - This covers all tractable cases (for UCQs) with a far more complicated algorithm
- Intensional PQE: compute the provenance of the query as a Boolean circuit (or formula) and compute the probability of the provenance

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Enumerating query results

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we just need to be able to enumerate results quickly

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how to find patterns | **Search**

Results **1 - 20** of **10,514**

...

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→ Formalization: **enumeration algorithms**

→ Currently a pretty important topic in database theory

Enumeration algorithm (linear preprocessing, constant delay)

Input

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Input → Step 1: Indexing in O(input)

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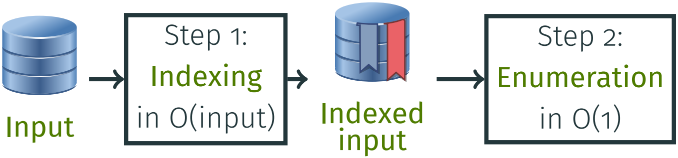

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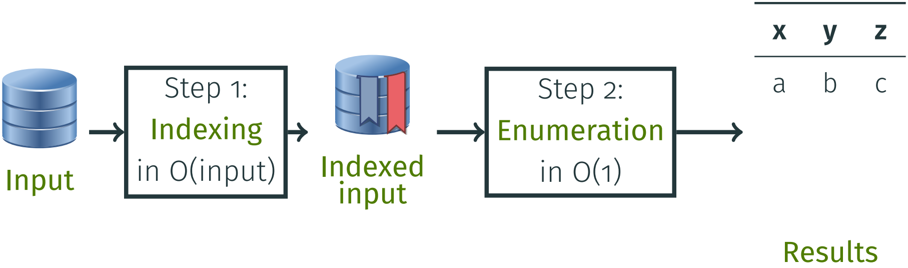

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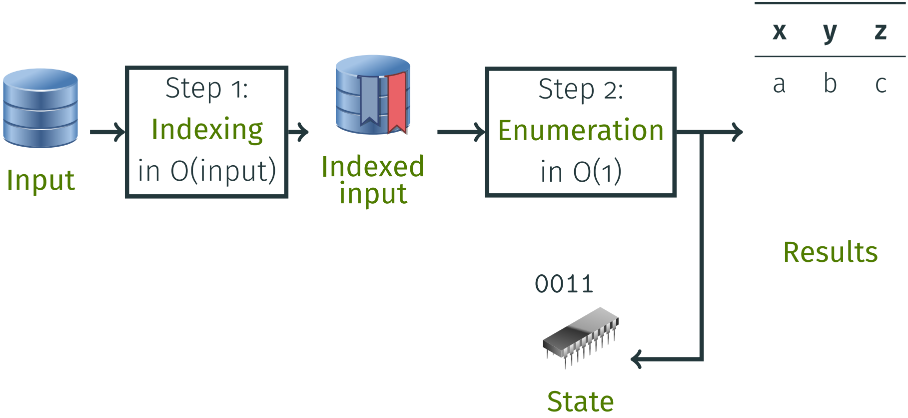

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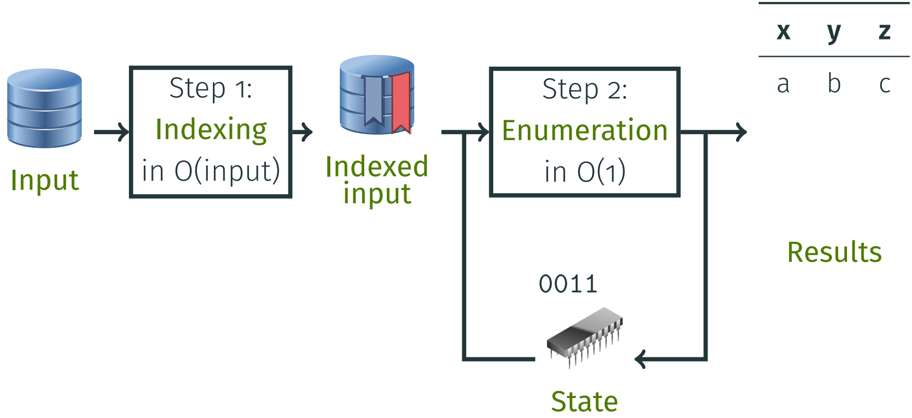

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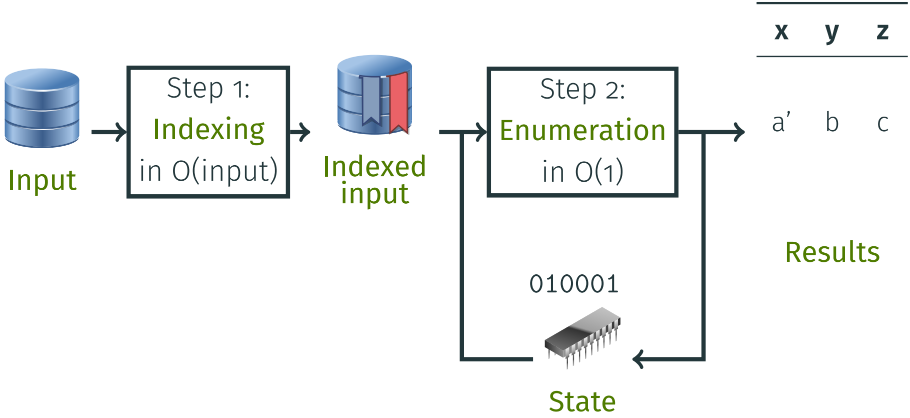

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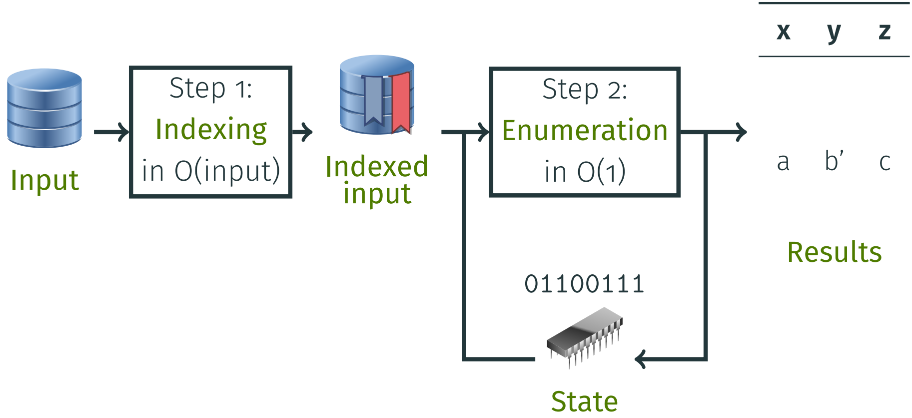

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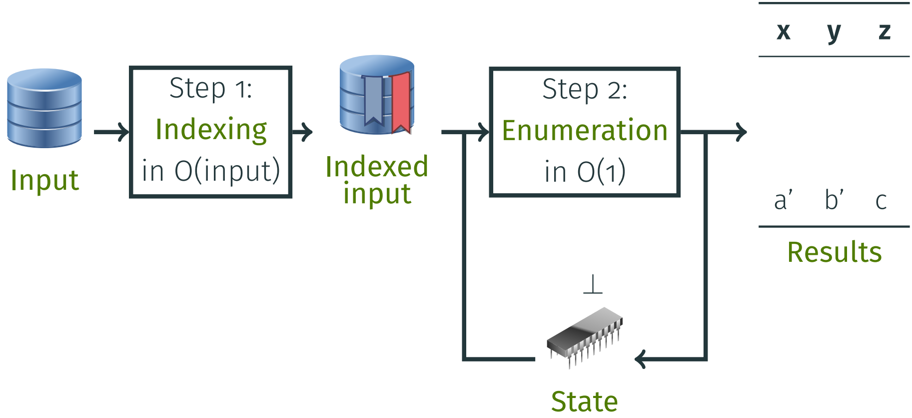

Connection to provenance

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$$D : R(a, b), R(a', b), S(b, c)$$

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- Compute the **provenance** C' of Q' on D plus assignment facts — $(X(a) \land R(a, b) \lor X(a') \land R(a', b)) \land Y(b) \land S(b, c)$
- Define C by replacing all variables by 1 except assignment facts — $(X(a) \lor X(a')) \land Y(b)$

$\rightarrow$ The circuit C represents the **query answers**

Connection to provenance

Provenance can also represent **query answers**!

- Study answers of **non-Boolean query** $Q(x, y)$ on database D — $Q(x,y) : \exists z\ R(x,y) \wedge S(y,z)$; $D : R(a,b), R(a',b), S(b,c)$
- Add **assignment facts** $X(v), Y(v)$ to D for each element v (linear) — $X(a), X(a'), X(b), X(c)$; $Y(a), Y(a'), Y(b), Y(c)$
- Consider the **Boolean query** $Q' : X(x) \wedge Y(y) \wedge Q(x,y)$ — $X(x) \wedge Y(y) \wedge (\exists z\ R(x,y) \wedge S(y,z))$
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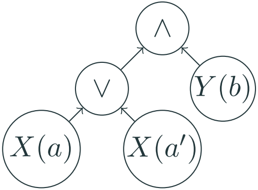
$\rightarrow$ The circuit C represents the **query answers** (a,b) and (a',b)

Enumeration via provenance

- We have a provenance circuit representing the query answers



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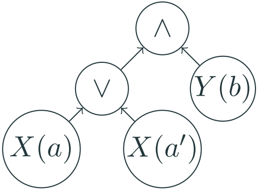

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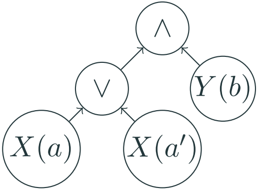


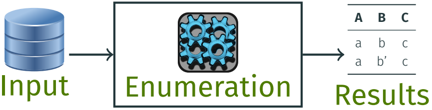
- So to **enumerate query answers** we can:
  - **Compute** this provenance circuit
  - **Enumerate** its satisfying assignments

$\rightarrow$ We want **linear preprocessing** and **constant delay**
so we designed an enumeration algorithm for circuits:

Theorem ([Amarilli et al., 2017])

Given a d-SDNNF circuit, we can preprocess it in linear time and then enumerate its satisfying assignments with constant delay (if the assignments have constant size)

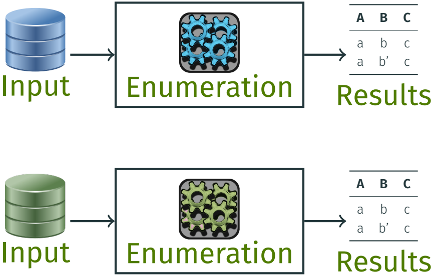
Currently:



A	B	C
a	b	c
a	b’	c

Enumeration via provenance: motivation

Currently:



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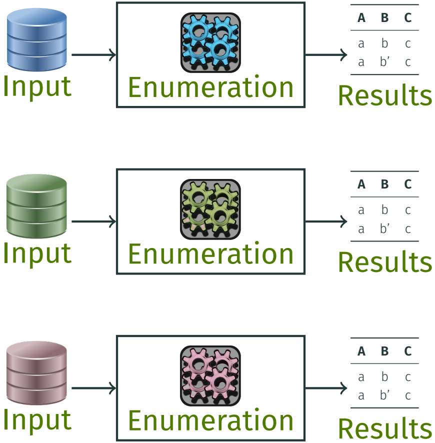

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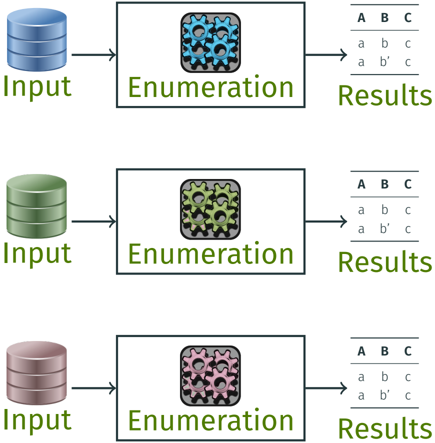

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Enumeration via provenance: motivation

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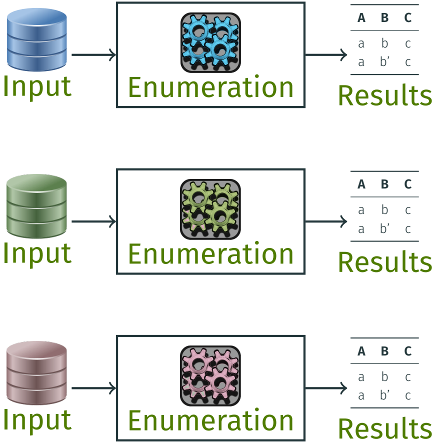

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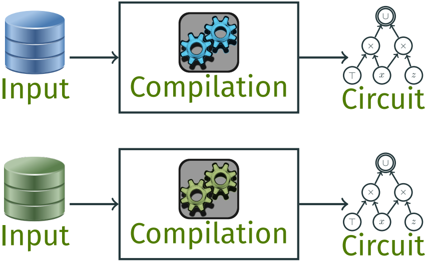

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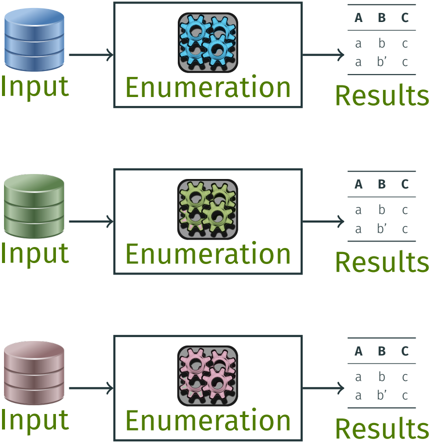

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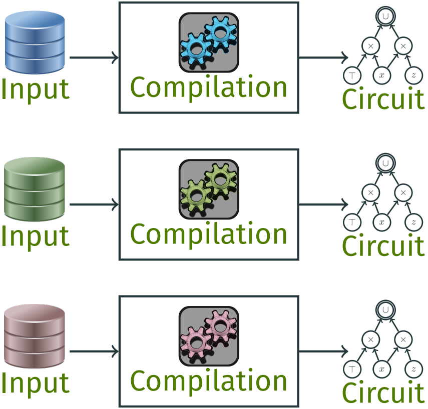

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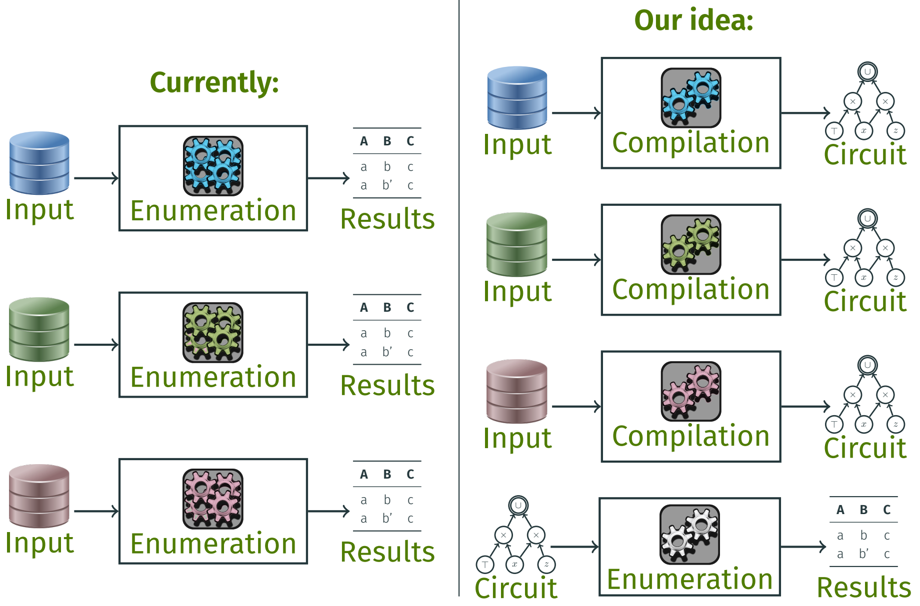
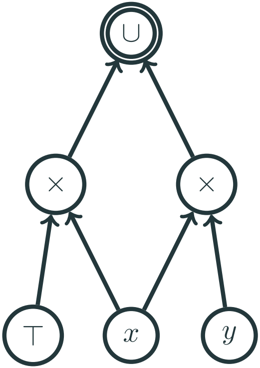
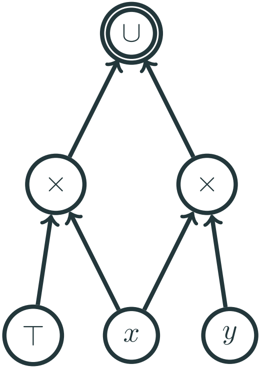


Set circuits



- Directed acyclic graph of **gates**

Set circuits



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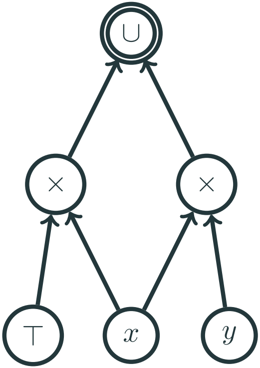

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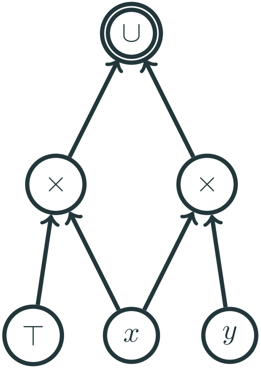

- Directed acyclic graph of **gates**
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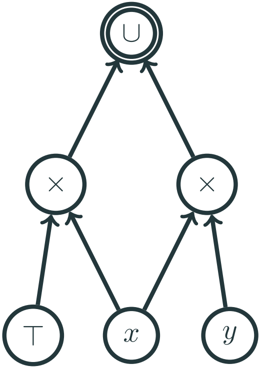
Set circuits



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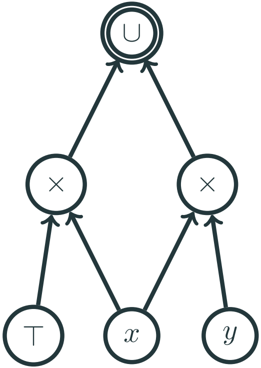
Semantics of set circuits



Every gate g **captures** a set $S(g)$ of sets (called **assignments**)

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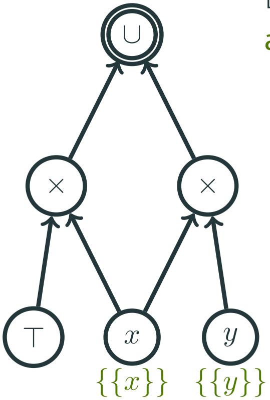

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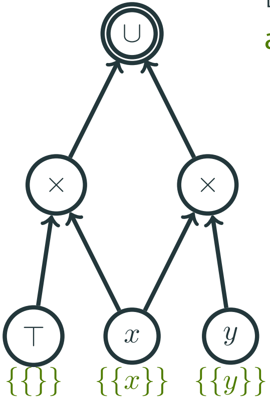

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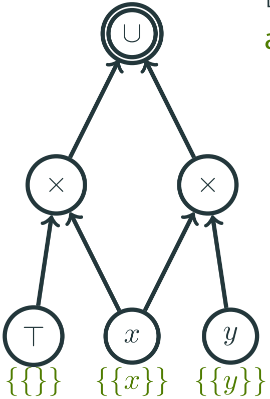

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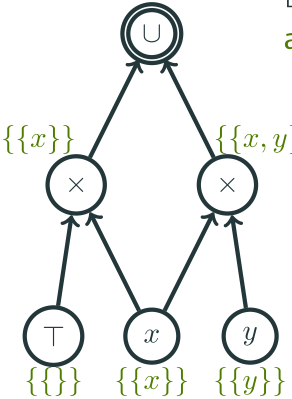

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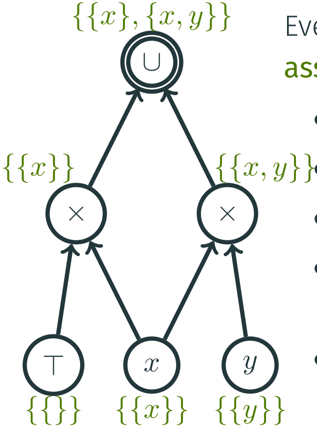

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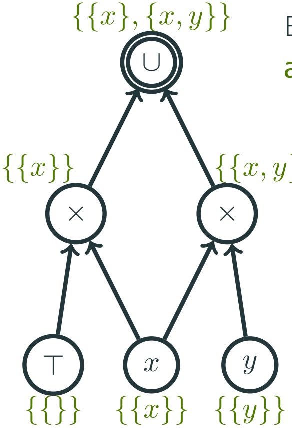

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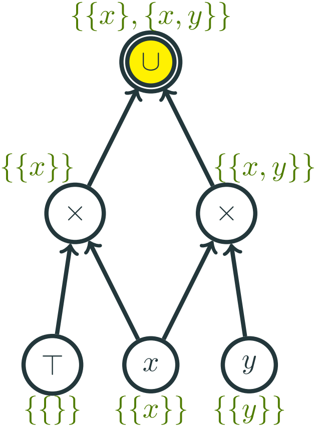
Circuit restrictions

d-DNNF set circuit:

- $\cup$ are all **deterministic**:

The inputs are **disjoint**
(= no assignment is captured by two inputs)



Circuit restrictions

d-DNNF set circuit:

- ∪ are all **deterministic**:

The inputs are **disjoint**
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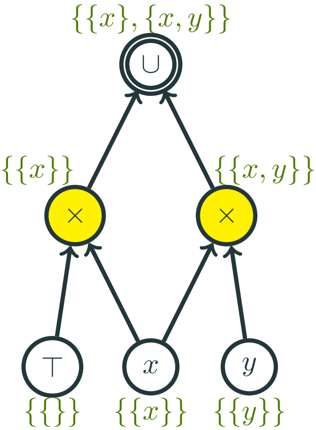
- × are all **decomposable**:

The inputs are **independent**
(= no variable x has a path to two different inputs)



Main results

Theorem

Given a d-DNNF set circuit C, we can enumerate its captured assignments with preprocessing linear in $|C|$ and delay linear in each assignment

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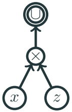
Also: restrict to assignments of **constant size** $k \in \mathbb{N}$

Theorem

Given a d-DNNF set circuit C, we can enumerate its captured assignments of size $\leq k$
with preprocessing linear in $|C|$ and constant delay

Proof overview

Preprocessing phase:



d-DNNF
set circuit

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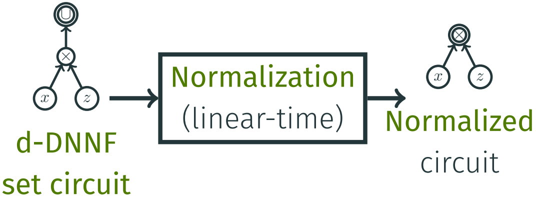

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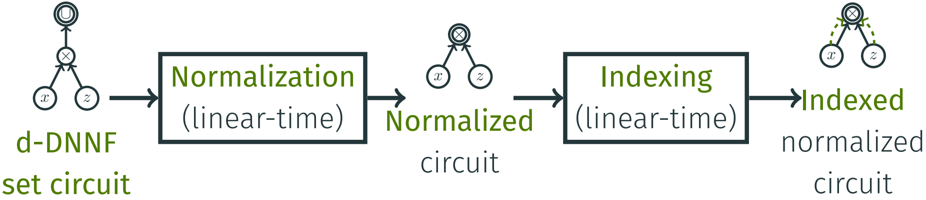

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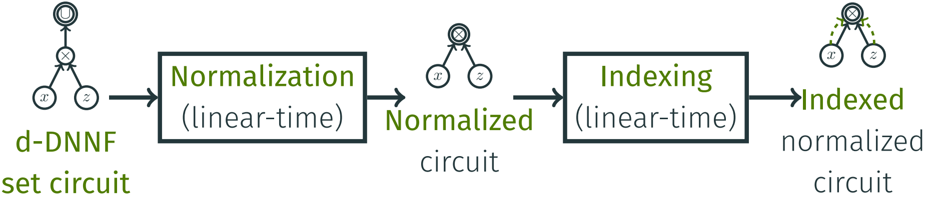
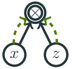


Enumeration phase:



Indexed
normalized
circuit

Proof overview

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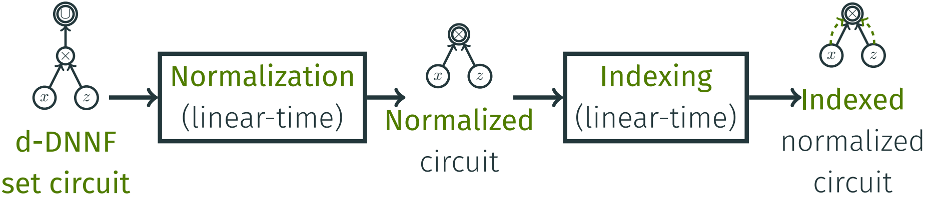

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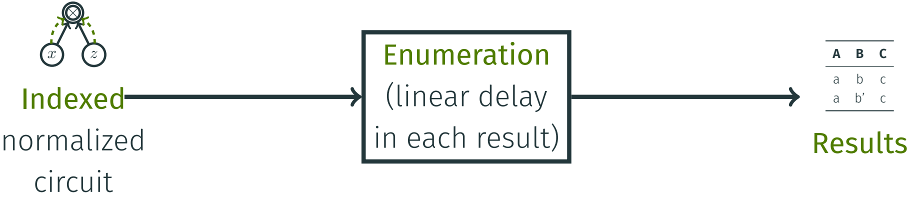

Enumerating captured assignments of d-DNNF set circuits

Task: Enumerate the assignments of the set $S(g)$ captured by a gate g

$\rightarrow$ E.g., for $S(g) = \{\{x\}, \{x, y\}\}$, enumerate $\{x\}$ and then $\{x, y\}$

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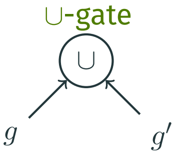

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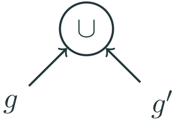
$\cup$-gate



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Determinism: no duplicates

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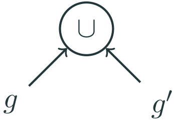

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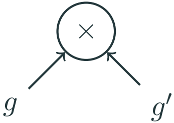

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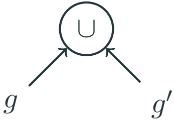

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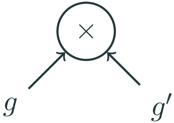

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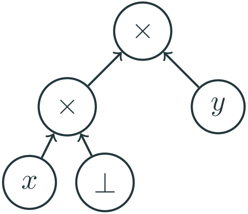
Decomposability: no duplicates

Normalization: handling $\emptyset$



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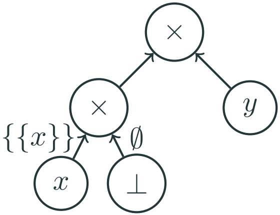

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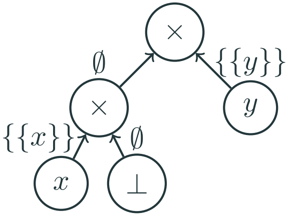

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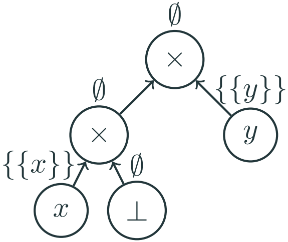

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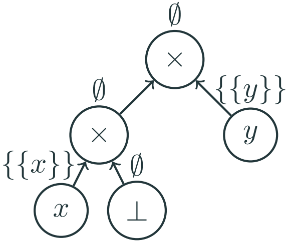

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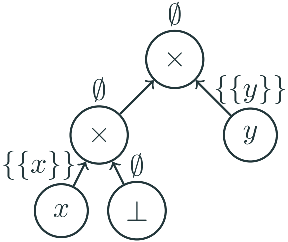

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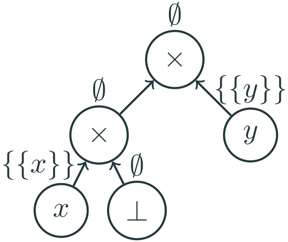

- **Problem:** if $S(g) = \emptyset$ we waste time
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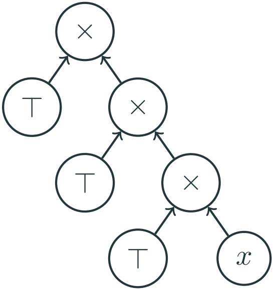
  - then get rid of the gate

Normalization: handling empty assignments



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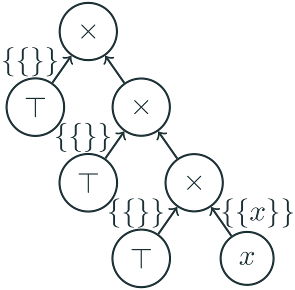
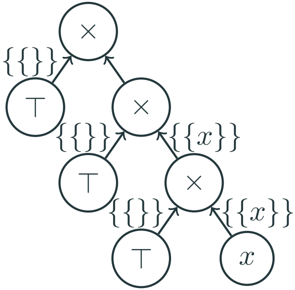


Normalization: handling empty assignments



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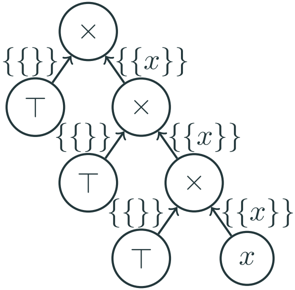

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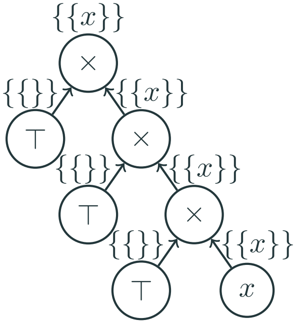

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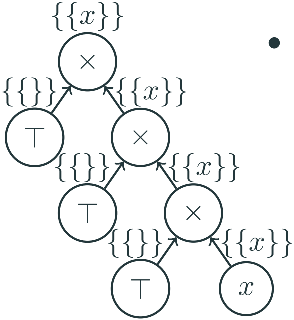

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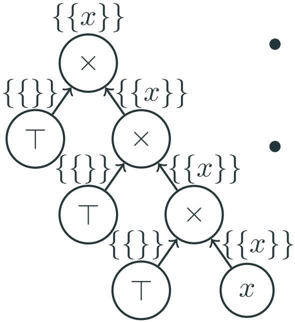

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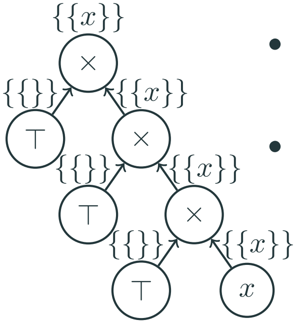

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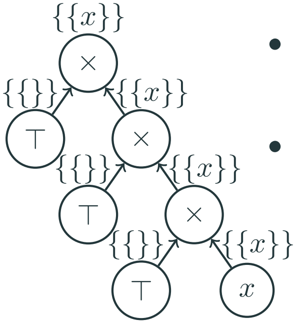

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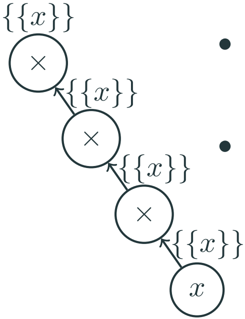

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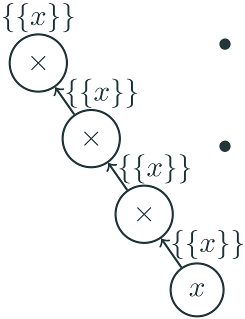

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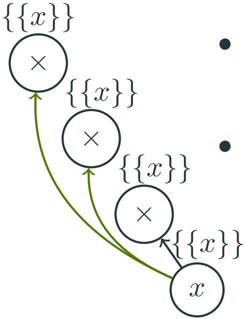

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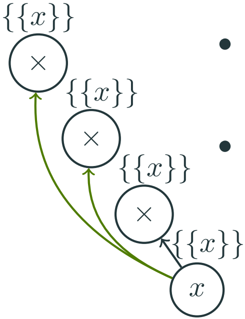

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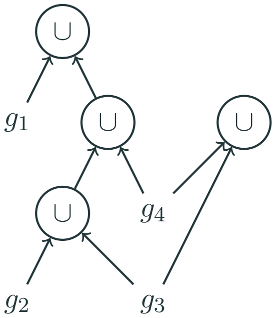
$\rightarrow$ Now, when traversing a **$\times$-gate** we make progress: **non-trivial split** of each set

Indexing: handling ∪-hierarchies



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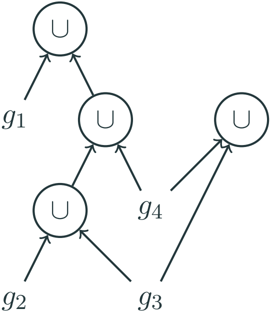

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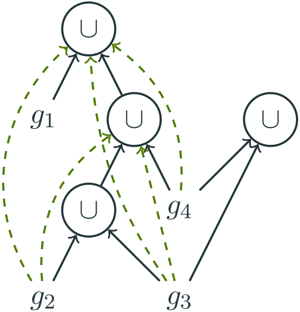

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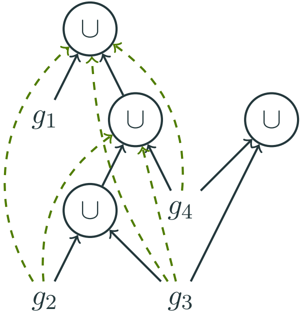

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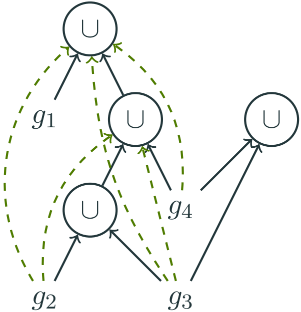

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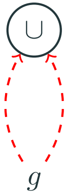

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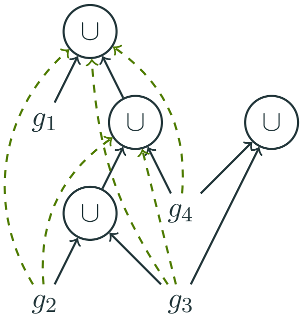

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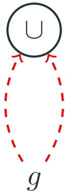


- **Solution:** Determinism ensures we have a **multitree** (we cannot have the pattern at the right)
- **Custom** constant-delay reachability index for multitrees

Outline

Commutative semiring $(K, \mathbb{0}, \mathbb{1}, \oplus, \otimes)$

- Set K with distinguished elements $\mathbb{0}$, $\mathbb{1}$
- $\oplus$ associative, commutative operator, with identity $\mathbb{0}_K$:
  - $a \oplus (b \oplus c) = (a \oplus b) \oplus c$
  - $a \oplus b = b \oplus a$
  - $a \oplus \mathbb{0} = \mathbb{0} \oplus a = a$
- $\otimes$ associative, commutative operator, with identity $\mathbb{1}_K$:
  - $a \otimes (b \otimes c) = (a \otimes b) \otimes c$
  - $a \otimes b = b \otimes a$
  - $a \otimes \mathbb{1} = \mathbb{1} \otimes a = a$
- $\otimes$ distributes over $\oplus$:

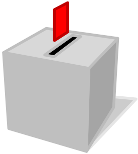
$$a \otimes (b \oplus c) = (a \otimes b) \oplus (a \otimes c)$$

- $\mathbb{0}$ is annihilating for $\otimes$:

$$a \otimes \mathbb{0} = \mathbb{0} \otimes a = \mathbb{0}$$

Commutative semiring examples

Which commutative semirings do you know about?



Example semirings

- $(\mathbb{N}, 0, 1, +, \times)$: **counting** semiring
- $(\{\bot, \top\}, \bot, \top, \vee, \wedge)$: **Boolean** semiring
- $(\{\textit{unclassified}, \textit{restricted}, \textit{confidential}, \textit{secret}, \textit{top secret}\},$ $\textit{top secret}, \textit{unclassified}, \min, \max)$: **security** semiring
- $(\mathbb{N} \cup \{\infty\}, \infty, 0, \min, +)$: **tropical** semiring
- $(\{\text{Boolean functions over } \mathcal{X}\}, \bot, \top, \vee, \wedge)$: semiring of **Boolean functions** over $\mathcal{X}$
- $(\mathbb{N}[\mathcal{X}], 0, 1, +, \times)$: semiring of integer-valued **polynomials** with variables in $\mathcal{X}$ (also called **How**-semiring or **universal** semiring)

Semiring provenance [Green et al., 2007]

- We **fix** a semiring $(K, \mathbb{0}, \mathbb{1}, \oplus, \otimes)$
- We assume provenance annotations are **in K**
- We consider a query Q from the **positive relational algebra** (selection, projection, renaming, product, union)
- We define a semantics for the provenance of a tuple $t \in Q(D)$ **inductively** on the structure of Q just like before

Selection, renaming

Provenance annotations of selected tuples are **unchanged**

Example $(\rho_{\mathbf{name}\to\mathbf{n}}(\sigma_{\mathbf{city}=\text{“New York”}}(R)))$

name	position	city	classification	prov
John	Director	New York	unclassified	x_1
Paul	Janitor	New York	restricted	x_2
Dave	Analyst	Paris	confidential	x_3
Ellen	Field agent	Berlin	secret	x_4
Magdalen	Double agent	Paris	top secret	x_5
Nancy	HR director	Paris	restricted	x_6
Susan	Analyst	Berlin	secret	x_7

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John	Director	New York	unclassified	x_1
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Projection

Provenance annotations of identical, merged, tuples are $\oplus$-ed

Example ($\pi_{\textbf{city}}(R)$)

name	position	city	classification	prov
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city	prov
New York	$x_1 \oplus x_2$
Paris	$x_3 \oplus x_5 \oplus x_6$
Berlin	$x_4 \oplus x_7$

Union

Provenance annotations of identical, merged, tuples are $\oplus$-ed

Example

$\pi_{\text{city}}(\sigma_{\textit{ends-with}(\text{position},\text{“agent”})}(R)) \cup \pi_{\text{city}}(\sigma_{\text{position}=\text{“Analyst”}}(R))$

name	position	city	classification	prov
John	Director	New York	unclassified	x_1
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city	prov
Paris	$x_3 \oplus x_5$
Berlin	$x_4 \oplus x_7$

Cross product

Provenance annotations of combined tuples are $\otimes$-ed

Example

$\pi_{\text{city}}(\sigma_{\textit{ends-with}(\text{position},\text{“agent”})}(R)) \bowtie \pi_{\text{city}}(\sigma_{\text{position}=\text{“Analyst”}}(R))$

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city	prov
Paris	$x_3 \otimes x_5$
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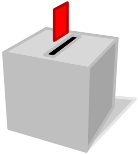
Poll: counting semiring

Say we annotate each tuple of the input database by 1 and evaluate a query with provenance in $(\mathbb{N}, 0, 1, +, \times)$. What will the provenance of every result mean?

- **A**: The number of possible worlds giving the result
- **B**: The minimum number of tuples required to obtain the result
- **C**: The number of times the result is obtained
- **D**: The number of subqueries giving the result



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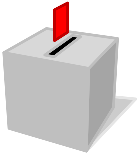
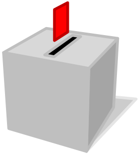


Poll: universal provenance

There is a semiring for which the provenance that we obtain is the most informative, i.e., we can recover provenance for any other semiring from it. Which one is it?

- **A**: The tropical semiring
- **B**: The semiring $\mathbb{N}[X]$
- **C**: The semiring of Boolean functions
- **D**: The security semiring



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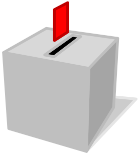

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What can we do with semiring provenance?

counting semiring: count the number of times a tuple can be derived, multiset semantics

Boolean semiring: determines if a tuple exists when a subdatabase is selected

security semiring: determines the minimum clearance level required to get a tuple as a result

tropical semiring: minimum-weight way of deriving a tuple (think shortest path in a graph)

Boolean functions: Boolean provenance, as previously defined

integer polynomials: $\mathbb{N}[X]$, universal provenance, see further

Example of security provenance

$$\pi_{\text{city}}(\sigma_{\text{name}<\text{name2}}(\pi_{\text{name,city}}(R) \bowtie \rho_{\text{name}\to\text{name2}}(\pi_{\text{name,city}}(R))))$$

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- This means **all computations can be performed in the universal semiring**, and homomorphisms applied next
- Two **equivalent queries** can have two **different provenance annotations** on the same database, in some semirings

Outline

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Desiderata for a provenance-aware DBMS

- Extends a **widely used** database management system
- **Easy to deploy**
- **Easy to use**, transparent for the user
- Provenance **automatically maintained** as the user interacts with the database management system
- Provenance computation **benefits from query optimization** within the DBMS
- Allow **probability computation** based on provenance
- **Any form of provenance** can be computed: Boolean provenance, semiring provenance in any semiring (possibly, with monus), aggregate provenance, **on demand**

ProvSQL: Provenance within PostgreSQL (1/2) [Senellart et al., 2018]

- Lightweight extension/plugin for PostgreSQL ≥ 9.5
- Provenance annotations stored as UUIDs, in an extra attribute of each provenance-aware relation
- A provenance circuit relating UUIDs of elementary provenance annotations and arithmetic gates stored as tables
- All computations done in the universal semiring (more precisely, with monus, in the free semiring with monus)

ProvSQL: Provenance within PostgreSQL (2/2) [Senellart et al., 2018]

- **Query rewriting** to automatically compute output provenance attributes in terms of the query and input provenance attributes:
  - Duplicate elimination (DISTINCT, set union) results in aggregation of provenance values with $\oplus$
  - Cross products, joins results in combination of provenance values with $\otimes$
  - Difference results in combination of provenance values with $\ominus$
- **Probability computation** from the provenance circuits, via various methods (naive, sampling, compilation to d-DNNFs)

Challenges

- **Low-level** access to PostgreSQL data structures in extensions
- No simple **query rewriting** mechanism
- SQL is much **less clean** than the relational algebra
- **Multiset semantics** by default in SQL
- SQL is a very **rich language**, with many different ways of expressing the same thing
- Inherent **limitations**: e.g., no aggregation within recursive queries
- Implementing provenance computation should **not slow down** the computation
- User-defined functions, updates, etc.: **unclear** how provenance should work

ProvSQL: Current status

- **Supported** SQL language features:
  - Regular SELECT-FROM-WHERE queries (aka conjunctive queries with multiset semantics)
  - JOIN queries (regular joins and outer joins; semijoins and antijoins are not currently supported)
  - SELECT queries with nested SELECT subqueries in the FROM clause
  - GROUP BY queries (without aggregation)
  - SELECT DISTINCT queries (i.e., set semantics)
  - UNION's or UNION ALL's of SELECT queries
  - EXCEPT queries
- Longer term project: aggregate computation
- Homepage: `https://github.com/PierreSenellart/provsql`

Provenance applications in practice

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Provenance applications in practice

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- How can we do enumeration via provenance?
  - Prototype: `https://github.com/PoDMR/enum-spanner-rs`
- Remark: missing studies of provenance notions used in the real world, e.g., “data lineage” used by Pachyderm

Provenance in theory

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    - We have seen two examples : probabilities and enumeration
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  - Showing bounds on provenance representations
    - Connects to knowledge compilation work on circuit classes
    - Can be easier than computational complexity lower bounds

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  - Using provenance for computational tasks
    - We have seen two examples : probabilities and enumeration
    - In both cases, provenance competes against other approaches
    - Sometimes, provenance provides new insights
  - Showing bounds on provenance representations
    - Connects to knowledge compilation work on circuit classes
    - Can be easier than computational complexity lower bounds

Thanks for your attention!

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Credits

Original class material by Pierre Senellart