Efficient Enumeration via Factorized Representations

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Dramatis Personae

Antoine Amarilli

Pierre Bourhis

Louis Jachiet

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Matthias Niewerth

And our recent co-authors: Martín Muñoz, Cristian Riveros

Amarilli, A., Bourhis, P., Jachiet, L., and Mengel, S.
A Circuit-Based Approach to Efficient Enumeration. ICALP 2017.

Amarilli, A., Bourhis, P., and Mengel, S.
Enumeration on Trees under Relabelings. ICDT 2018.

Niewerth, M.
MSO Queries on Trees: Enumerating Answers under Updates Using Forest Algebras. LICS 2018.

Amarilli, A., Bourhis, P., Mengel, S., and Niewerth, M.
Constant-Delay Enumeration for Nondeterministic Document Spanners. ICDT 2019.

Amarilli, A., Bourhis, P., Mengel, S., and Niewerth, M.
Enumeration on Trees with Tractable Combined Complexity and Efficient Updates. PODS 2019

Amarilli, A., Bourhis, P., Mengel, S., and Niewerth, M.
Constant-Delay Enumeration for Nondeterministic Document Spanners. TODS 2020.

Amarilli, A., Jachiet, L., Muñoz, M., and Riveros, C.
Efficient Enumeration for Annotated Grammars. PODS 2022

Problem statement

Enumeration algorithm

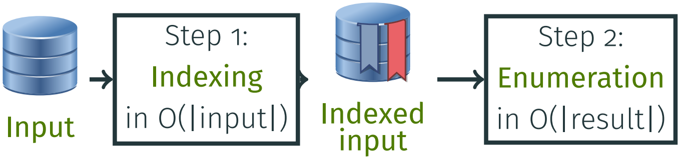
Input

Enumeration algorithm

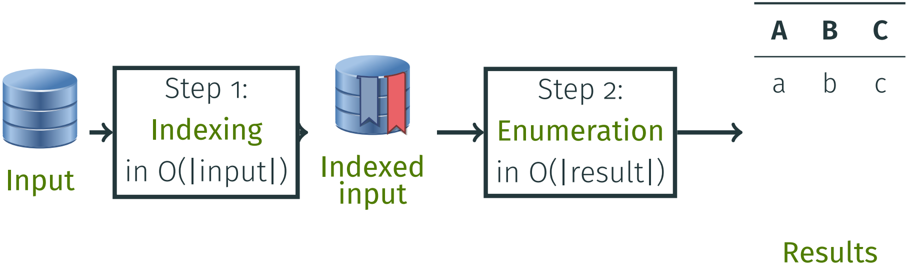
Input → Step 1: **Indexing** in O(|input|)

Enumeration algorithm

Enumeration algorithm



Enumeration algorithm



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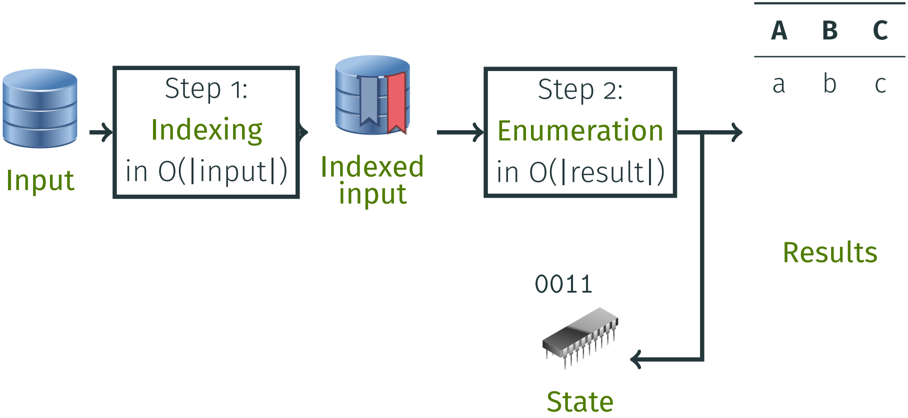

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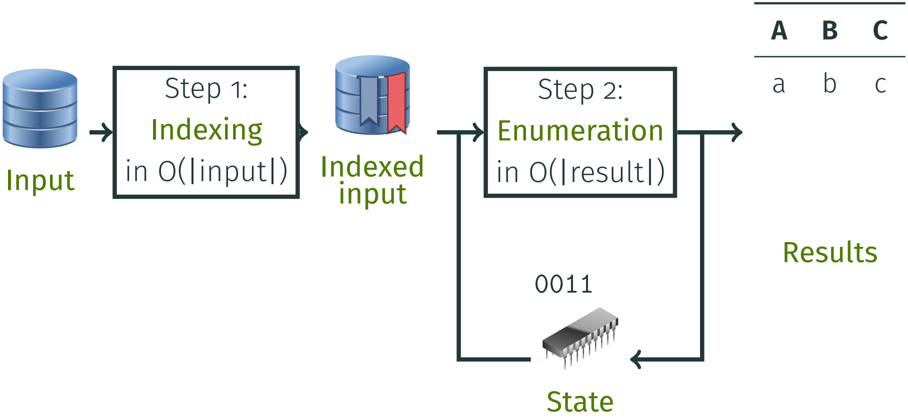

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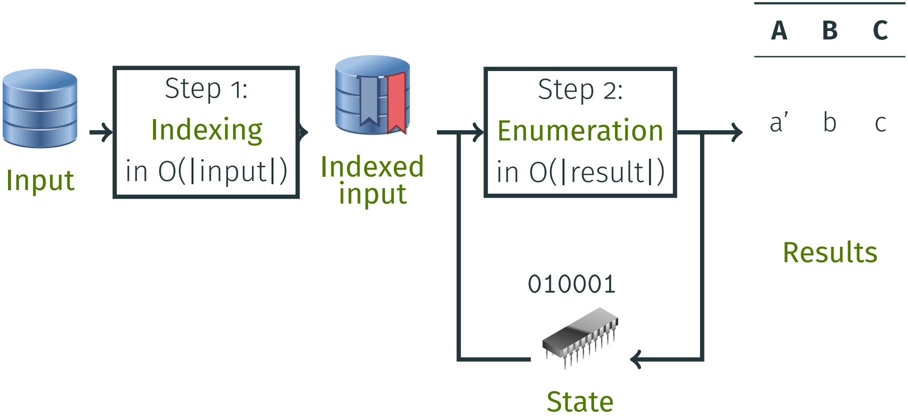

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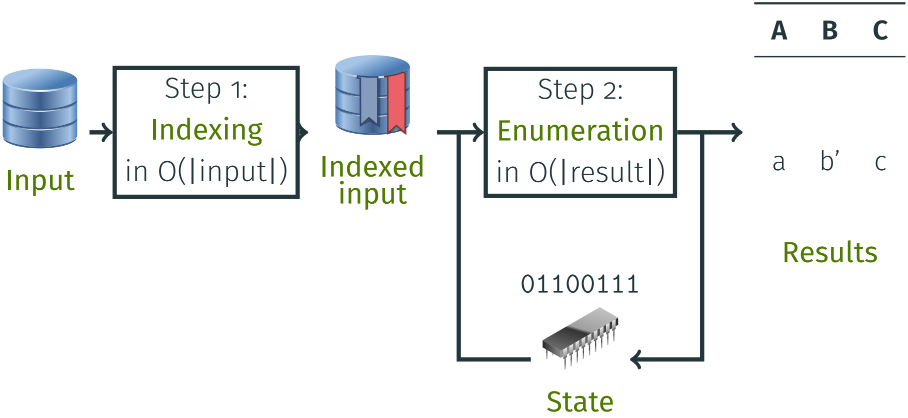

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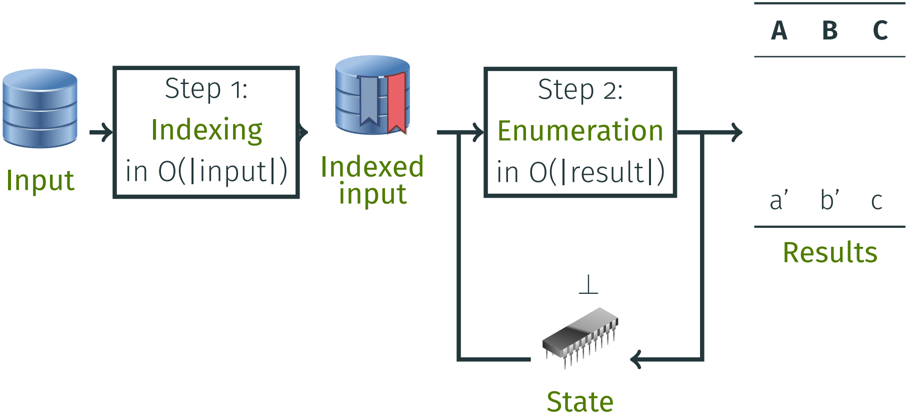
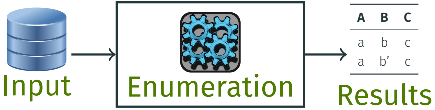


The knowledge compilation approach to enumeration

Currently:



A	B	C
a	b	c
a	b’	c

The knowledge compilation approach to enumeration

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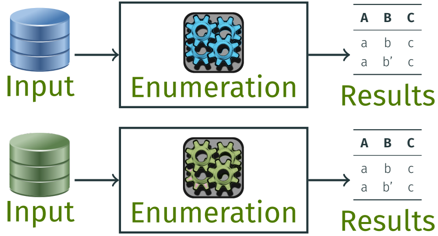

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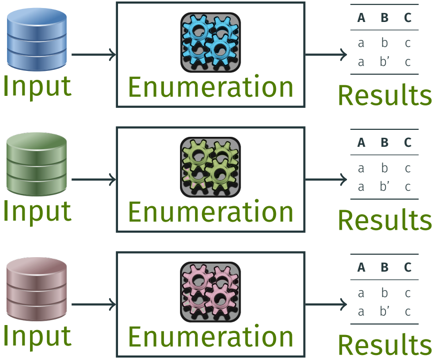
Input
Enumeration
A B C
a b c
a b’ c
Results
Input
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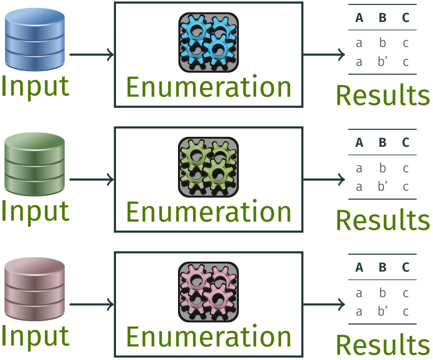

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Our idea:

The knowledge compilation approach to enumeration

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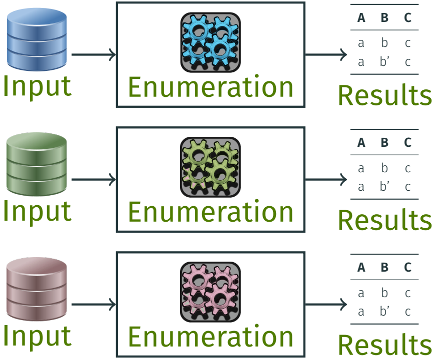

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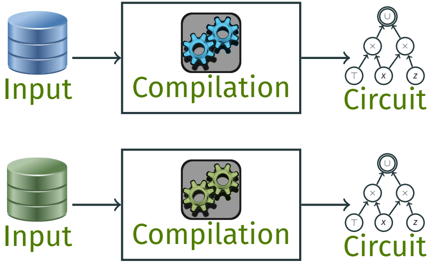

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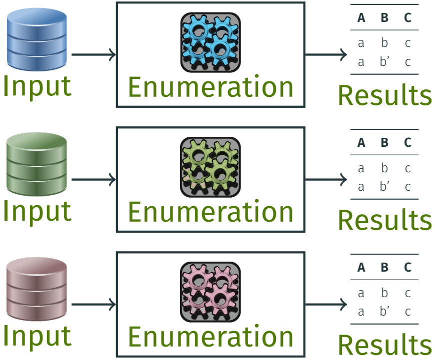

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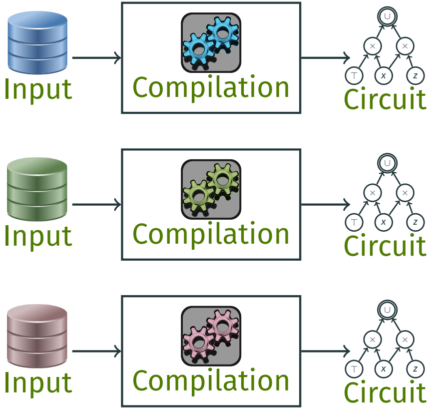

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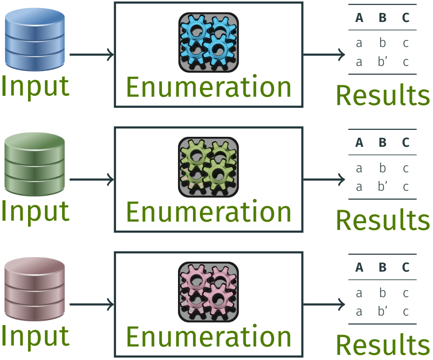

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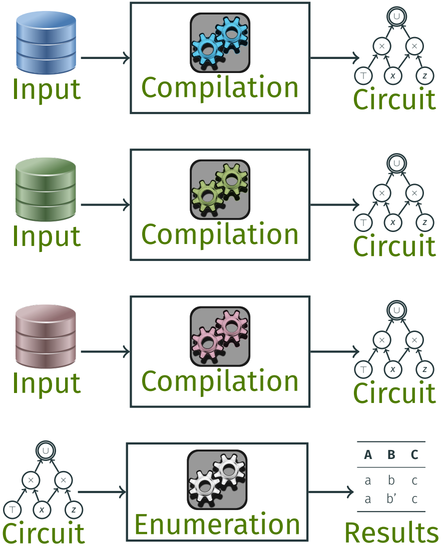
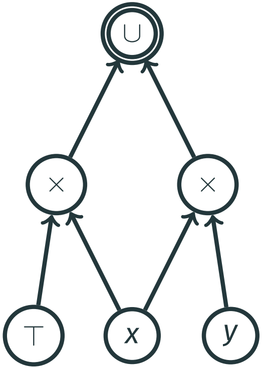
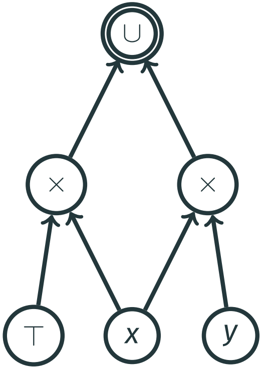


Set circuits



- Directed acyclic graph of **gates**

Set circuits



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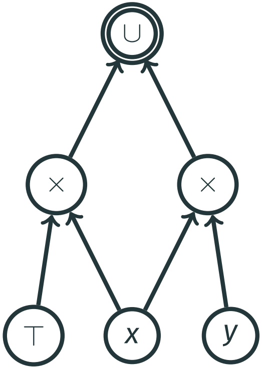

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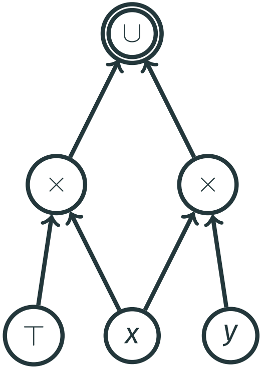
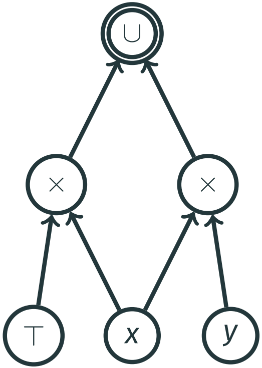
Set circuits



- Directed acyclic graph of **gates**
- **Output** gate: 
- **Variable** gates: 

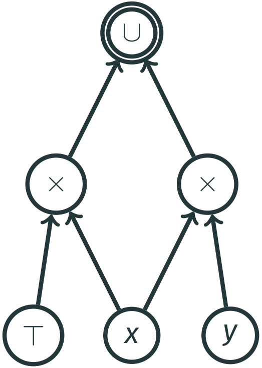
- **Constant** gates: 

Set circuits



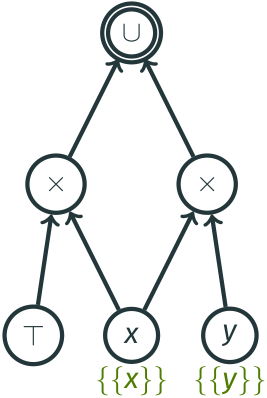
- Directed acyclic graph of **gates**
- **Output** gate:
- **Variable** gates: x
- **Constant** gates: $\top$ $\bot$
- **Internal** gates: $\times$ $\cup$

Semantics of set circuits



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

Semantics of set circuits



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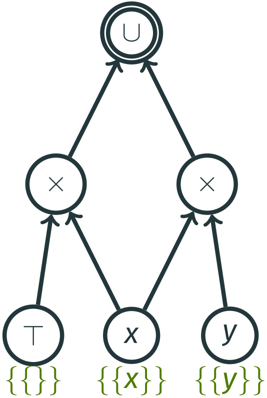

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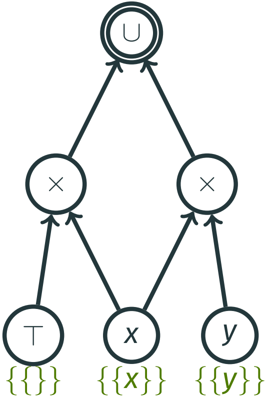

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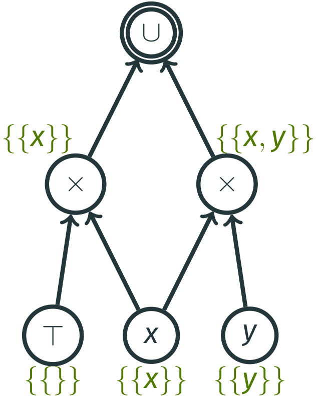

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- $\times$-gate with children g_1, g_2:
  $S(g) := \{s_1 \cup s_2 \mid s_1 \in S(g_1), s_2 \in S(g_2)\}$

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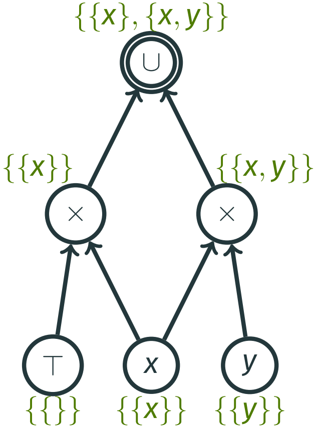

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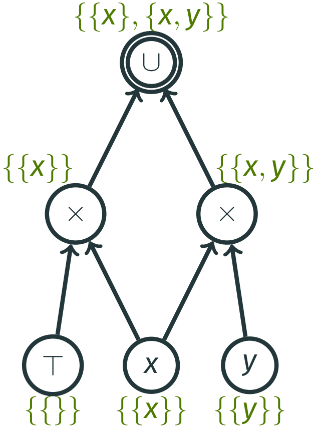

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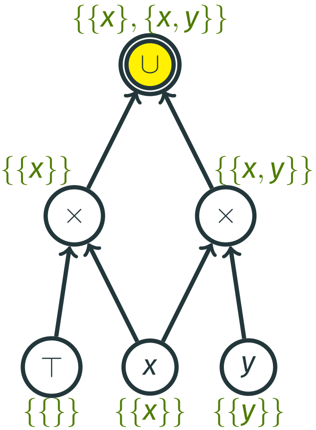
Task: Enumerate the assignments of the set $S(g)$ captured by a gate g
$\rightarrow$E.g., for $S(g) = \{\{x\},\{x,y\}\}$, enumerate $\{x\}$ and then $\{x,y\}$

d-DNNF set circuit:

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

The inputs are **disjoint**

(= no assignment is captured by two inputs)



d-DNNF set circuit:

- 

are all **deterministic**:

The inputs are **disjoint**

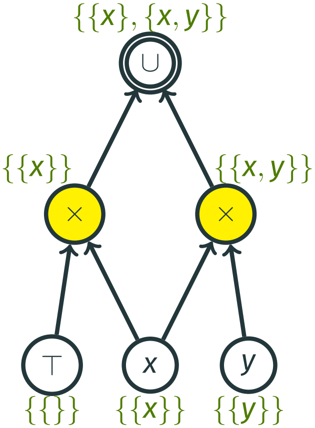
(= no assignment is captured by two inputs)

- 

are all **decomposable**:

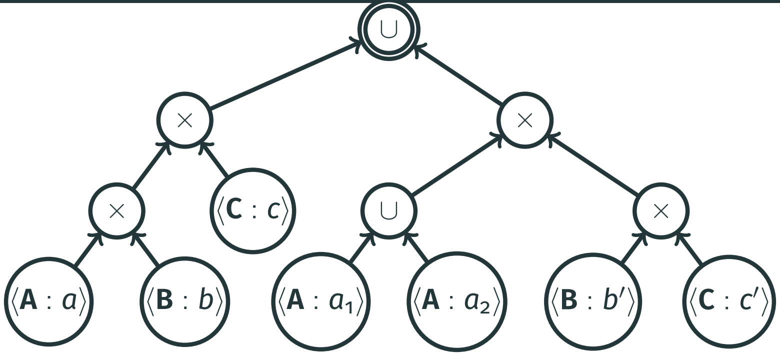
The inputs are **independent**

(= no variable x has a path to two different inputs)



Set circuits vs factorized representations

A	**B**	**C**
a	b	c
a_1	b'	c'
a_2	b'	c'



- Set circuits can be seen as **factorized representations**
  - $\rightarrow$ Not necessarily **well-typed**, height and/or assignment size may be **non-constant**
- **Determinism**: unions are disjoint
- **Decomposability**: no duplicate attribute names in products
- **Structuredness**: always the same decomposition of the attributes

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

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

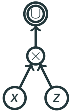
Theorem

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 techniques

Proof overview

Preprocessing phase:



d-DNNF

set circuit

Proof overview

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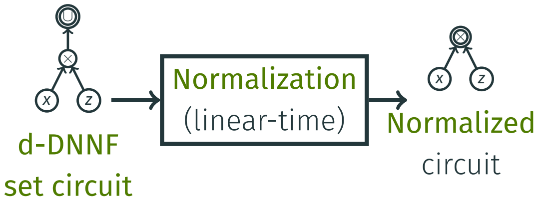

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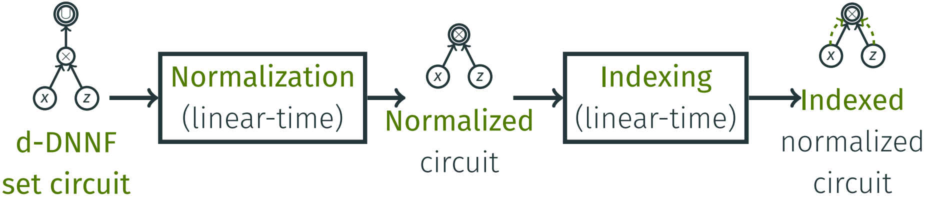

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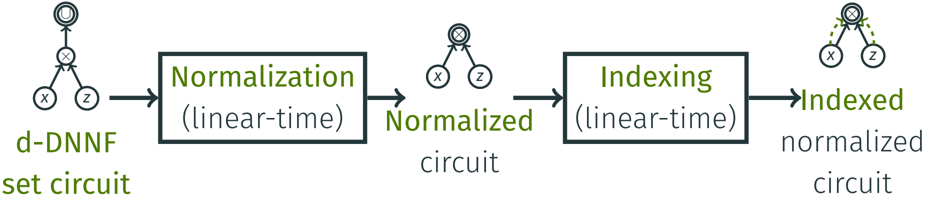
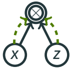


Enumeration phase:



Indexed
normalized
circuit

Proof overview

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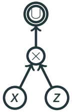
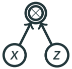
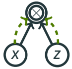


d-DNNF set circuit → **Normalization** (linear-time) →

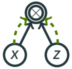


Normalized circuit → **Indexing** (linear-time) →



Indexed normalized circuit

Enumeration phase:



Indexed normalized circuit → **Enumeration** (linear delay in each result) →

A	B	C
a	b	c
a	b’	c

Results

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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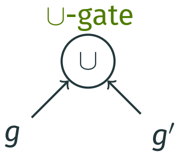

Concatenation: enumerate $S(g)$ and then enumerate $S(g')$

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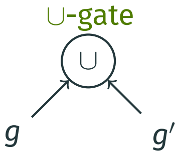

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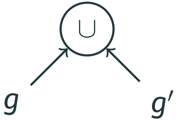
$\cup$-gate



Concatenation: enumerate $S(g)$ and then enumerate $S(g')$

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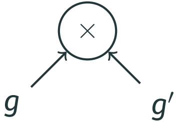
$\times$-gate



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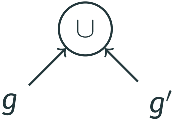

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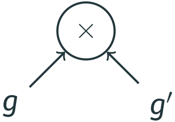

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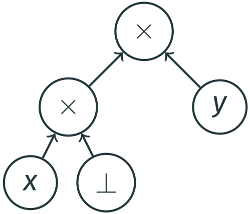
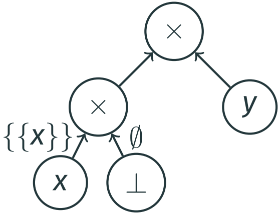
Decomposability: no duplicates

Normalization: handling $\emptyset$



Normalization: handling $\emptyset$



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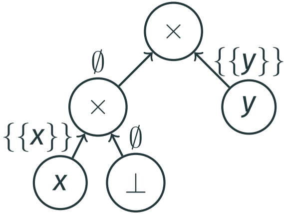

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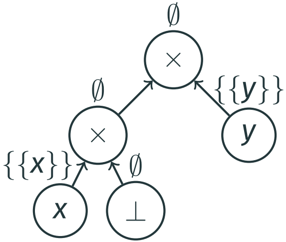

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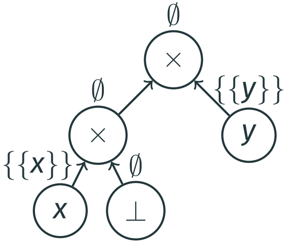

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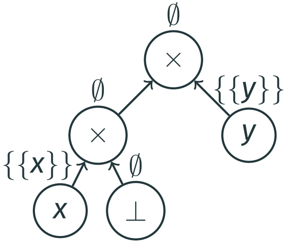

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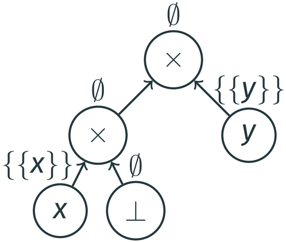

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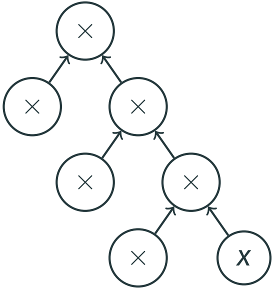
- **Solution:** in preprocessing
  - compute **bottom-up** if $S(g) = \emptyset$
  - then get rid of the gate

Normalization: handling empty assignments



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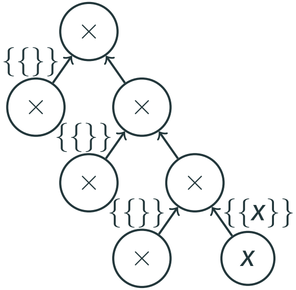

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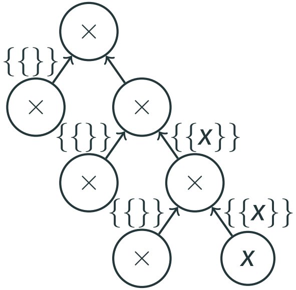

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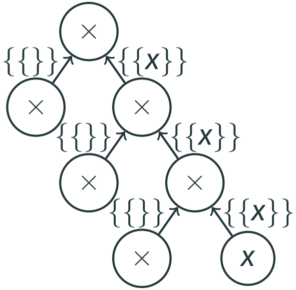

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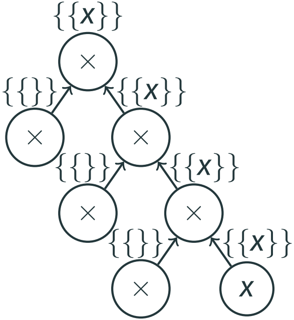

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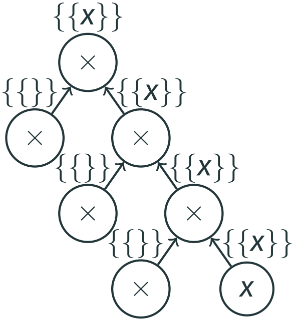

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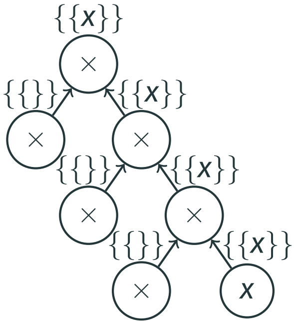

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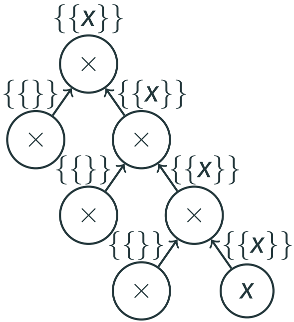

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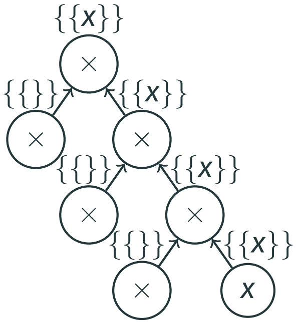

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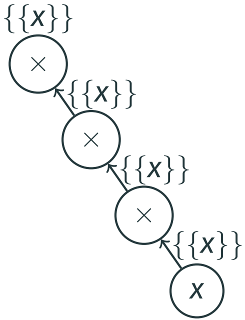

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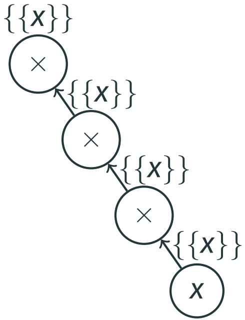

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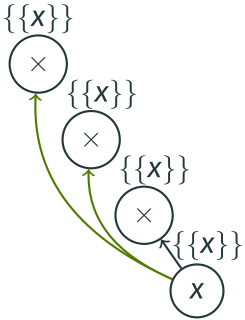

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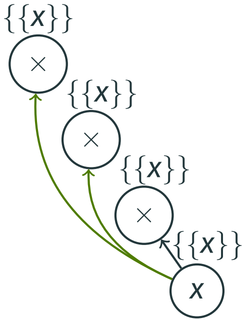

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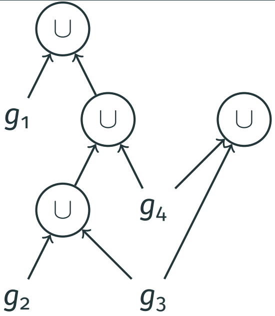
$\rightarrow$ Now, when traversing a $\times$**-gate** we make progress: **non-trivial split** of each set

Indexing: handling ∪-hierarchies



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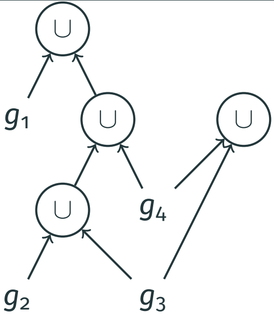

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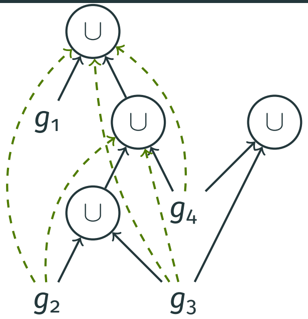

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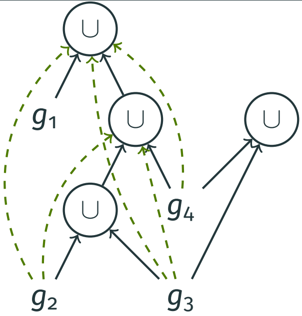

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- **Problem:** must be done in **linear time**

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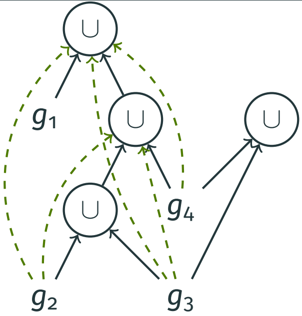

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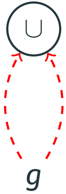

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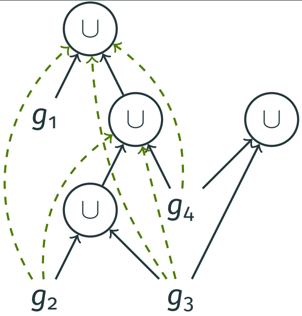

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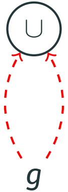
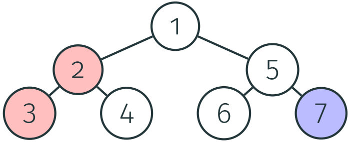


- **Solution:** Determinism ensures we have a **multitree** (we cannot have the pattern at the right)
- **Custom** constant-delay reachability index for multitrees

Applications

Application 1: MSO query evaluation on trees

Data: a **tree** T where nodes have a color from an alphabet ○ ○ ○



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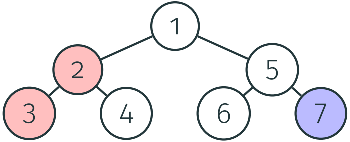

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Query Q in monadic second-order logic (MSO)

- $P_{\bigcirc}(x)$ means "x is blue"
- $x \rightarrow y$ means "x is the parent of y"

"Find the pairs of a pink node and a blue node?"

$Q(x, y) := P_{\bigcirc}(x) \wedge P_{\bigcirc}(y)$

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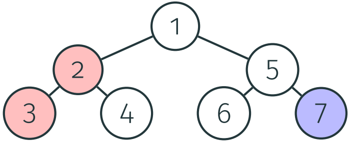

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Result: **Enumerate** all pairs (a, b) of nodes of T such that $Q(a, b)$ holds

results: $(2, 7), (3, 7)$

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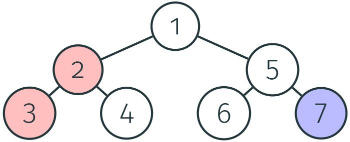

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Data complexity: Measure efficiency as a function of T (the query Q is **fixed**)

Application 1: Results

Theorem [Bagan, 2006, Kazana and Segoufin, 2013]

We can enumerate the answers of MSO queries on trees with linear-time preprocessing and constant delay.

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We can prove this with our methods:

Theorem (A., Bourhis, Jachiet, Mengel, ICALP'15, ICALP'17)

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- Same result for leaf **insertion/deletion** (A., Bourhis, Mengel, Niewerth, PODS'19) up to **fixing a buggy result** [Niewerth, 2018]

Application 2: Enumerating matches of nondeterministic document spanners

Data: a text T

```
Antoine Amarilli Description Name Antoine Amarilli.  Handle:  a3nm.  Identity Born 1990-02-07.  French national.  Appearance as
of 2017.  Auth OpenPGP. OpenId.  Bitcoin.  Contact Email and XMPP a3nm@a3nm.net Affiliation Associate professor of computer
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test@example.com More Résumé Location Other sites Blogging:  a3nm.net/blog Git:  a3nm.net/git ...
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$P :=$ `␣ [a-z0-9.]* @ [a-z0-9.]* ␣`

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$$[186, 200\rangle, \quad [483, 500\rangle, \quad \dots$$

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Goal:

- be **very efficient** in T (constant-delay)
- be **reasonably efficient** in P (polynomial-time)

Application 2: Results

Theorem (A., Bourhis, Mengel, Niewerth, ICDT'19)

*We can enumerate all matches of an input **nondeterministic automaton with captures** on an input **text** with*

- *Preprocessing **linear** in the text and **polynomial** in the automaton*
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$\rightarrow$ Generalizes earlier result on **deterministic automata** [Florenzano et al., 2018]

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→ Actually equivalent to **MSO evaluation** on **text**; generalizes to **trees**

Application 3: Enumerating matches of annotated grammars

Data: a text *T*, e.g., source code

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long elt, prev, elt2, prev2=-1;
int ret = fscanf(fi, "%ld%ld", &elt, &prev);
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Theorem (A., Jachiet, Muñoz, Riveros, PODS'22)

*Given an **unambiguous annotation grammar** $\mathcal{G}$ and input text w, we can enumerate the **matches** with preprocessing $O(|\mathcal{G}| \times |w|^3)$ and delay **linear in each assignment***

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 exit(1);
}
```

Query: a pattern P given as a context-free grammar with annotated terminals

$$P := \text{“\textit{find all quoted strings in the program}”}$$

Theorem (A., Jachiet, Muñoz, Riveros, PODS'22)

Given an unambiguous annotation grammar $\mathcal{G}$ and input text w, we can enumerate the matches with preprocessing $O(|\mathcal{G}| \times |w|^3)$ and delay linear in each assignment

- Improves on a quintic preprocessing result [Peterfreund, 2021]

Application 3: Enumerating matches of annotated grammars

Data: a text T, e.g., **source code**

```
long elt, prev, elt2, prev2=-1;
int ret = fscanf(fi, "%ld%ld", &elt, &prev);
if (ret != 2) {
 fprintf(stderr, "Bad offsets after position %ld in index!\n", pi);
 exit(1);
}
```

Query: a **pattern** P given as a **context-free grammar with annotated terminals**

$$P := \text{“\textit{find all quoted strings in the program}”}$$

Theorem (A., Jachiet, Muñoz, Riveros, PODS'22)

*Given an **unambiguous annotation grammar** $\mathcal{G}$ and input text w, we can enumerate the **matches** with preprocessing $O(|\mathcal{G}| \times |w|^3)$ and delay **linear in each assignment***

- Improves on a **quintic** preprocessing result [Peterfreund, 2021]
- **Quadratic** and **linear** preprocessing for **subclasses** (rigid grammars, deterministic pushdown annotators)

Conclusion

Summary and conclusion

- Enumerate the captured assignments of d-DNNF set circuits
  - $\rightarrow$ with preprocessing linear in the d-DNNF
  - $\rightarrow$ in delay linear in each assignment
  - $\rightarrow$ in constant delay for constant size

$\rightarrow$ Applies to MSO enumeration on words and trees

$\rightarrow$ Applies to enumeration of the matches of annotated context-free grammars (with more expensive preprocessing)

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Future work:

- **In-order** enumeration
- Linear-time preprocessing on **more general context-free grammar classes**
- Connect results on **updates** to **incremental maintenance for regular languages** (A., Jachiet, Paperman, ICALP'21)

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Thanks for your attention!

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