A Circuit-Based Approach to Efficient Enumeration

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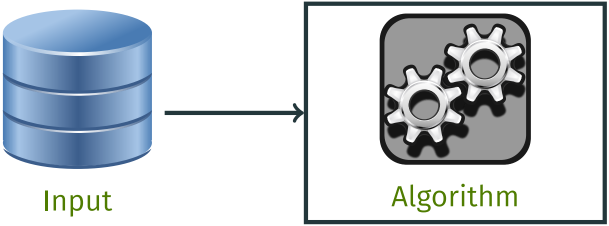
Problem statement

Problem: Enumerating large result sets

Input

Problem: Enumerating large result sets



Problem: Enumerating large result sets

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Algorithm

A	B	C
a	b	c
a’	b	c
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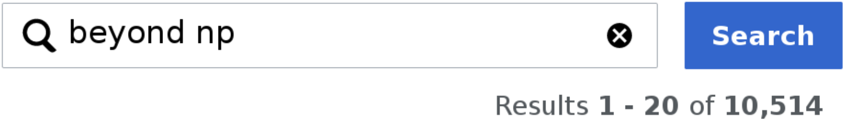

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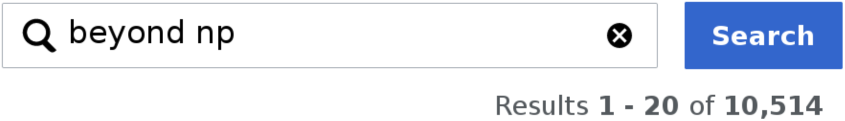

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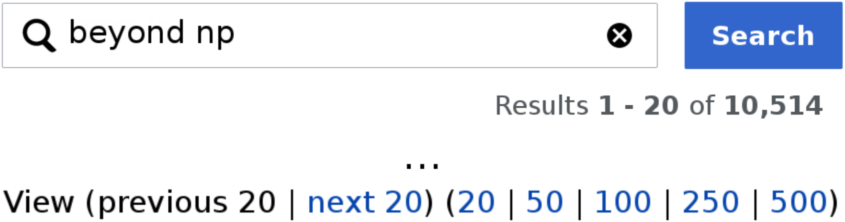

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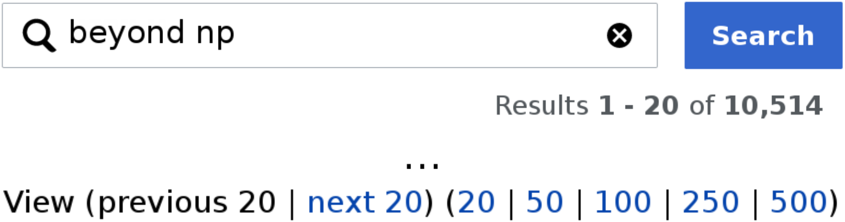

→ Solution: Enumerate solutions one after the other

Enumeration algorithm

Input

Enumeration algorithm

Input → Step 1: Indexing in O(input)

Enumeration algorithm

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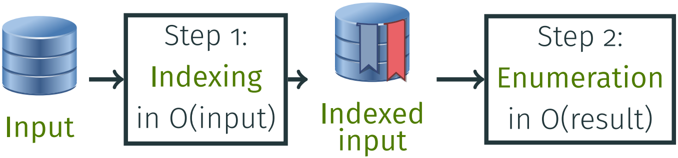

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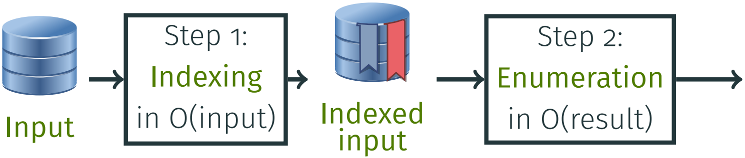

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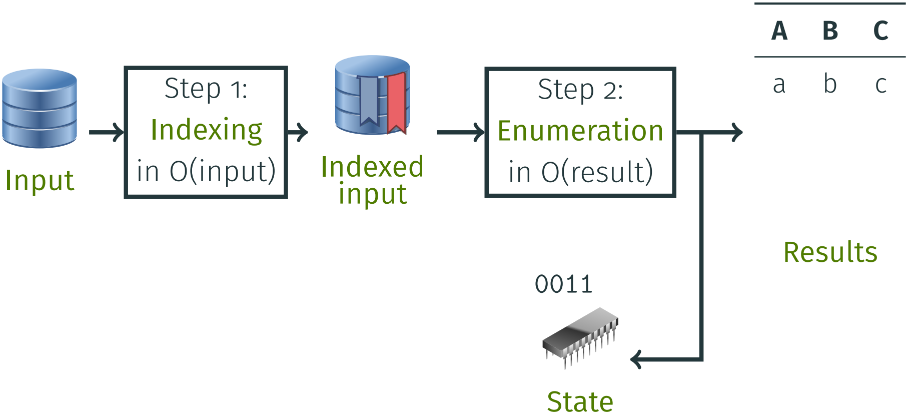
Enumeration algorithm



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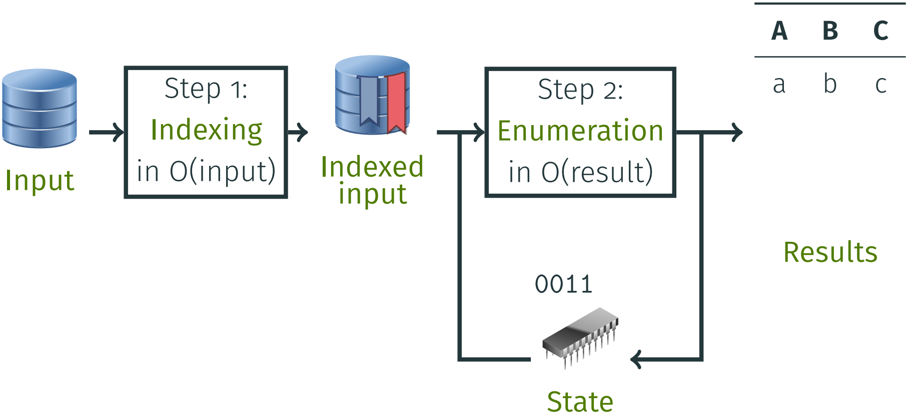

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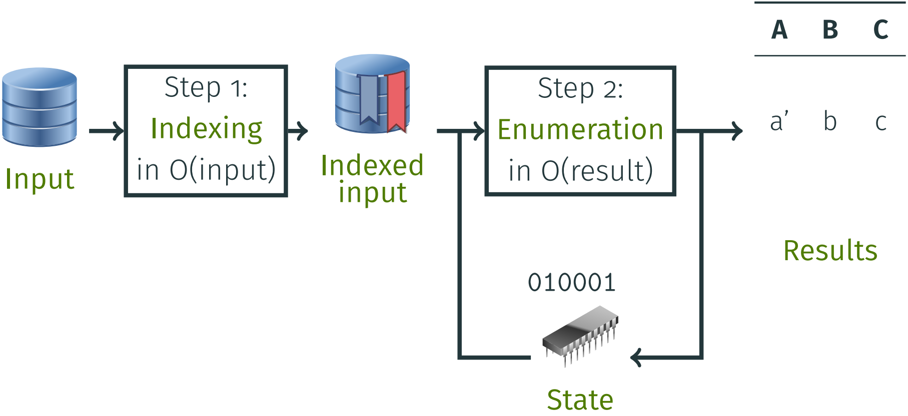

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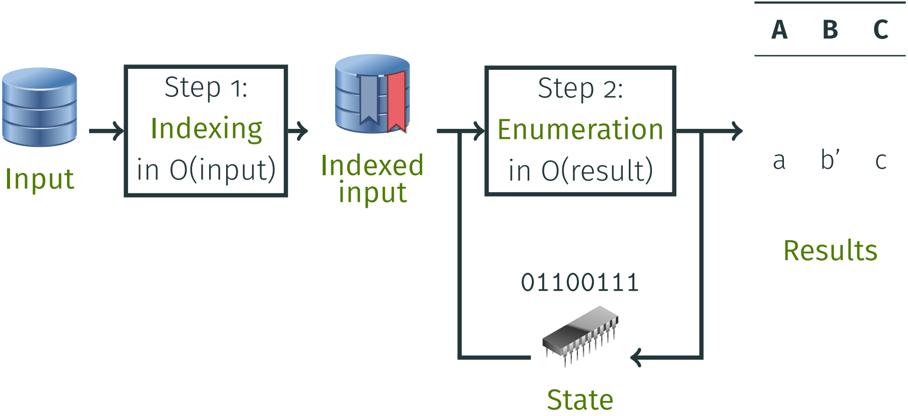

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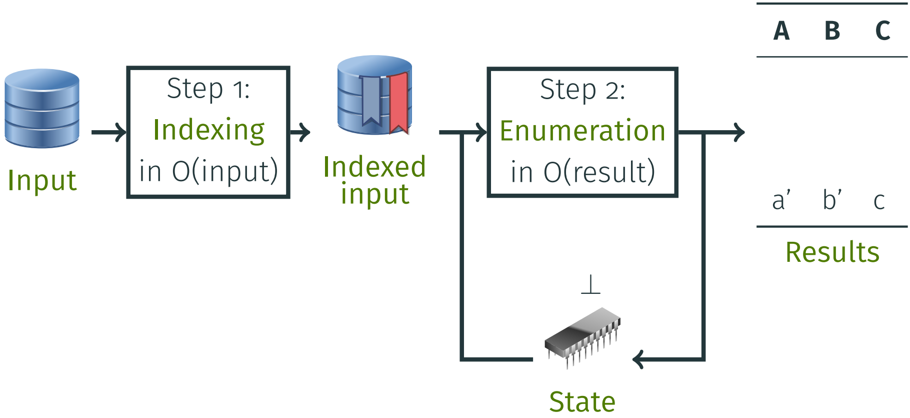

General idea for enumeration

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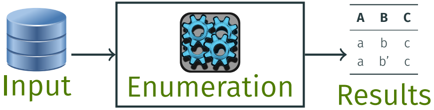

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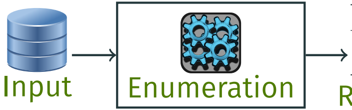

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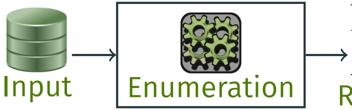

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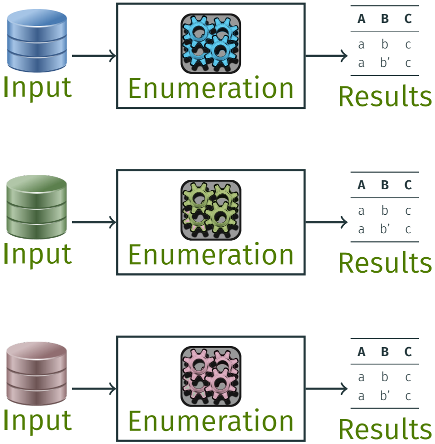

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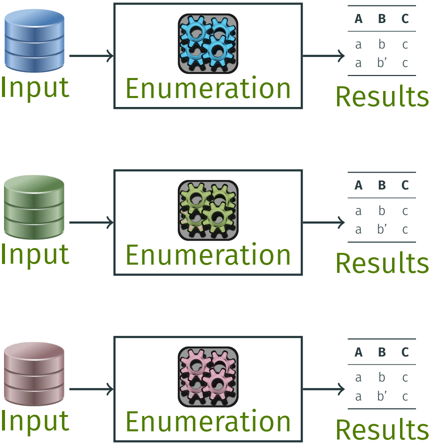

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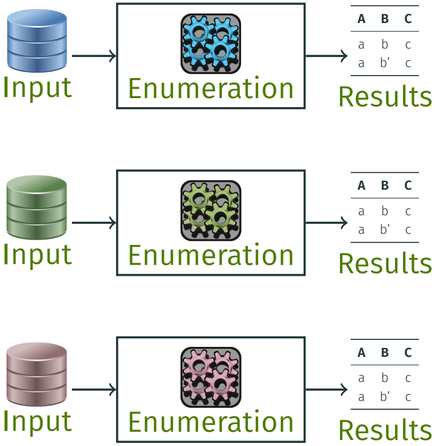

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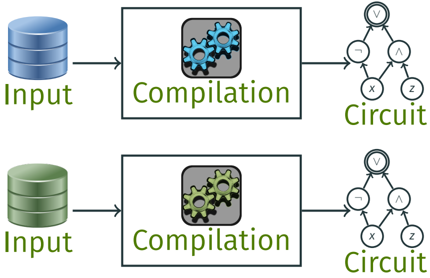

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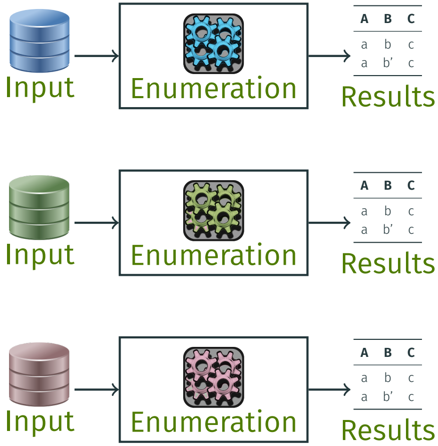

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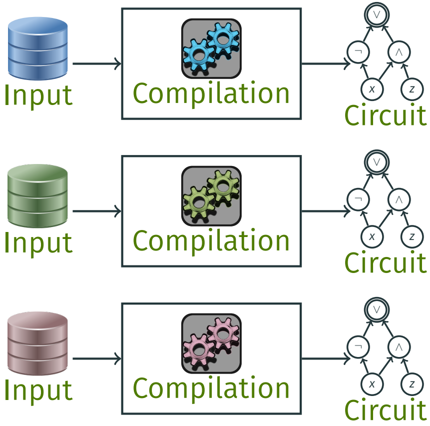

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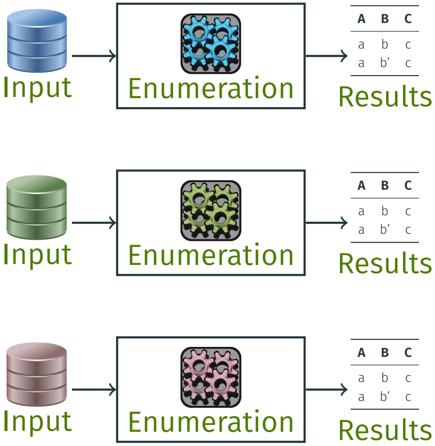

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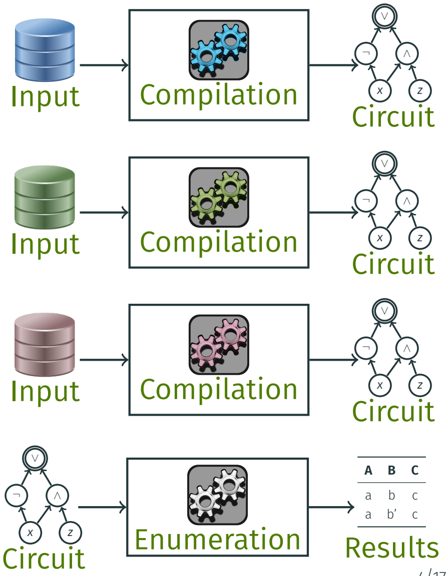
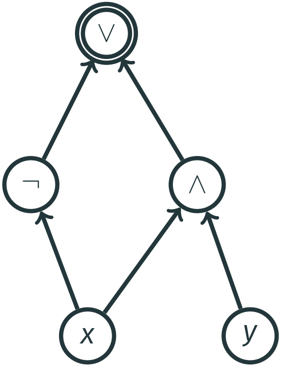


Boolean circuits



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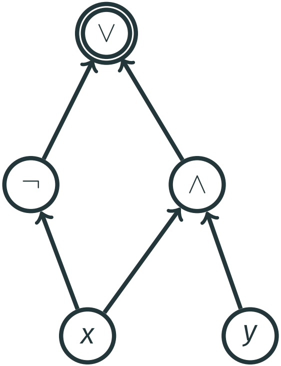
Boolean circuits



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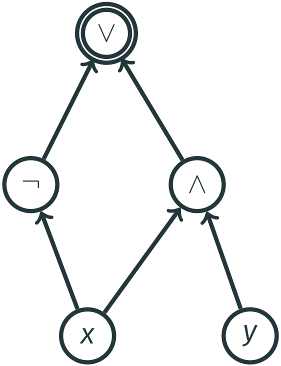

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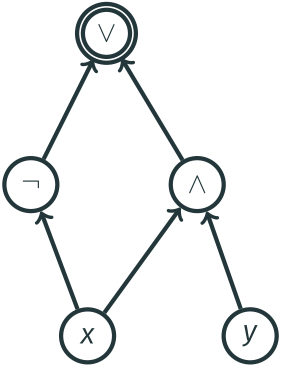

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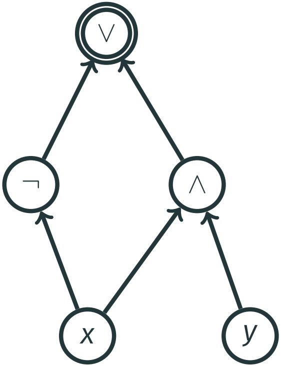

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  Example: $\nu = \{x \mapsto 0,\ y \mapsto 1\}$...

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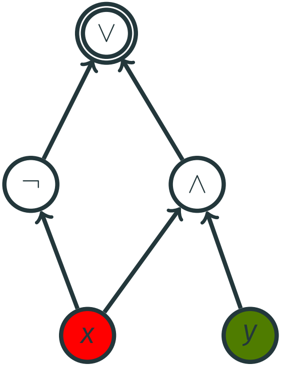

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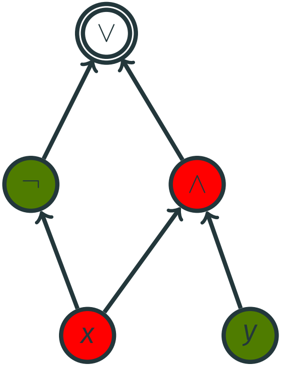

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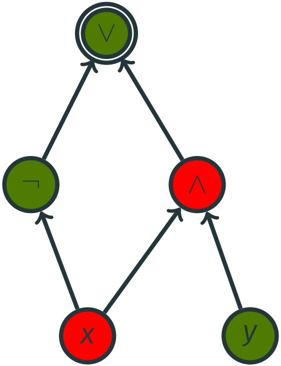

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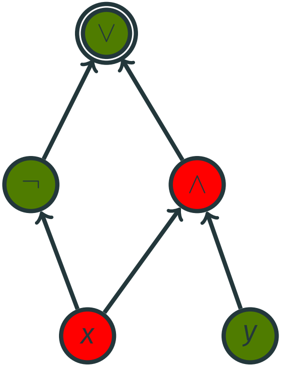

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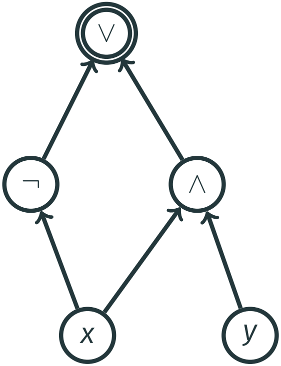

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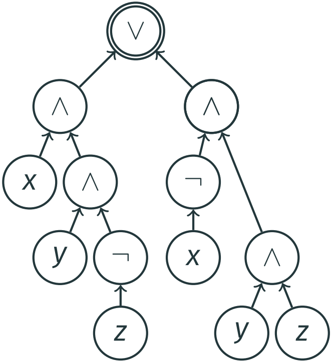
Our task: Enumerate all **satisfying assignments** of an input circuit

Circuit restrictions

d-DNNF:

-  are all deterministic:

The inputs are mutually exclusive (= no valuation ν makes two inputs simultaneously evaluate to 1)



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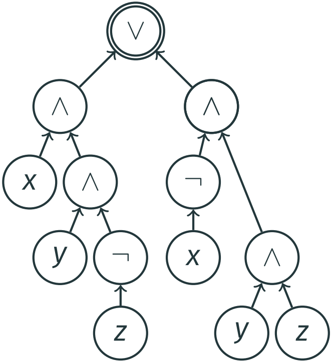

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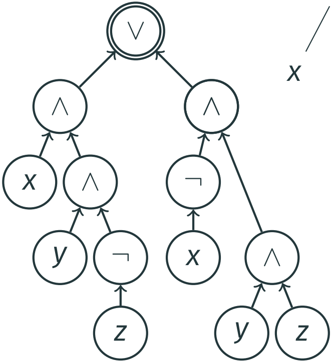
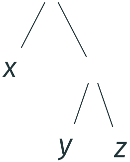
v-tree: ∧-gates follow a tree on the variables





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Also: restrict to assignments of constant size $k \in \mathbb{N}$ (at most k variables are set to 1):

Theorem

Given a d-DNNF circuit C with a v-tree T, we can enumerate its satisfying assignments of size $\leq k$ with preprocessing linear in $|C| + |T|$ and constant delay

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- Factorized databases: implicit representation of database tables

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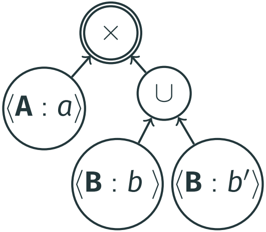

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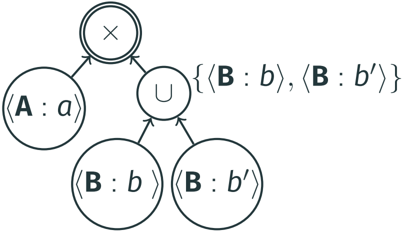

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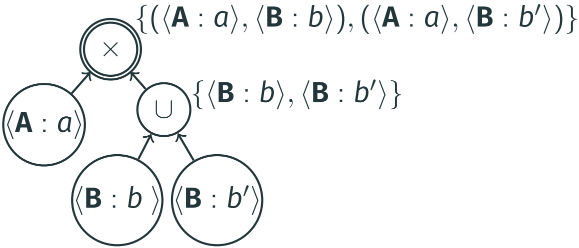

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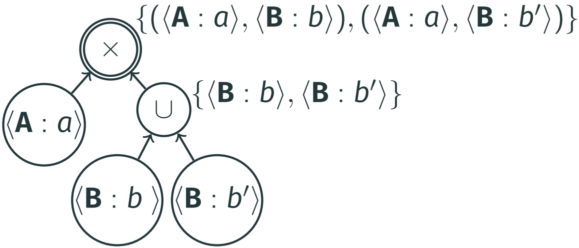

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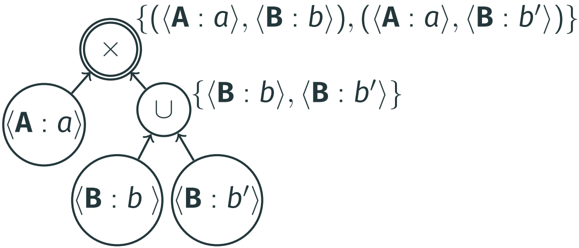

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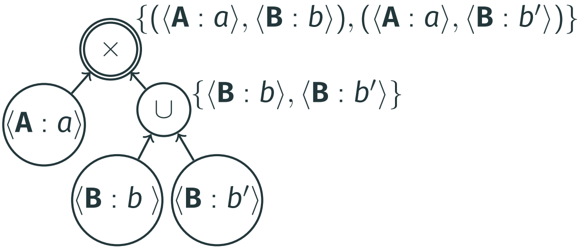

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Theorem (Strenghtens result of [Olteanu and Závodnỳ, 2015])

Given a deterministic factorized representation, we can enumerate its tuples with linear preprocessing and constant delay

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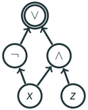
Theorem (Recaptures [Bagan, 2006], [Kazana and Segoufin, 2013])
For any constant $k \in \mathbb{N}$ and fixed MSO query Q,
given a database D of treewidth $\leq k$, the results of Q on D
can be enumerated with linear preprocessing in D and linear delay
in each answer ($\rightarrow$ constant delay for free first-order variables)

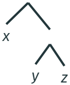
Proof techniques

Proof overview

Preprocessing phase:



Circuit



v-tree

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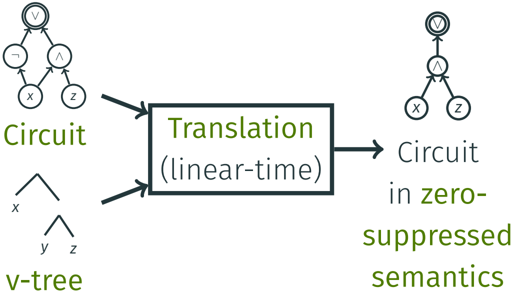

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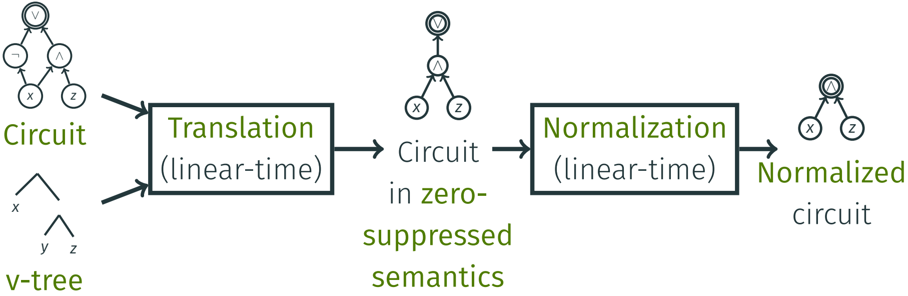

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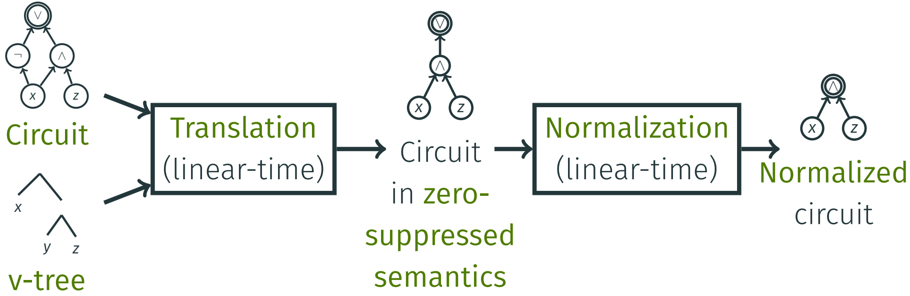

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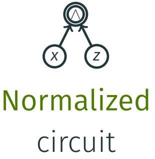

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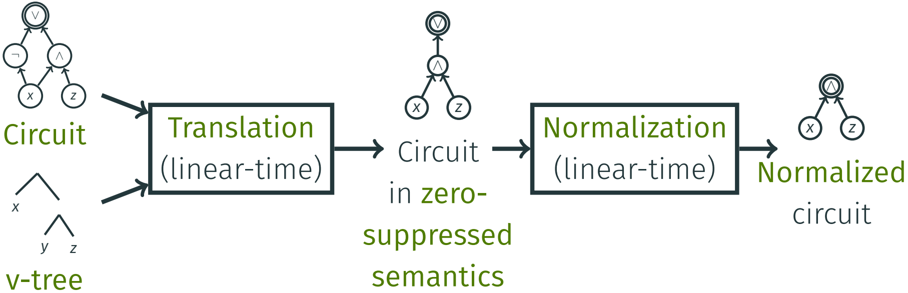
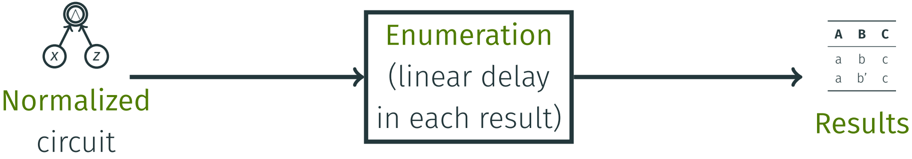
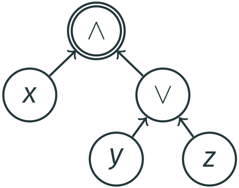


Enumeration phase:



Zero-suppressed semantics



Special zero-suppressed semantics for circuits:

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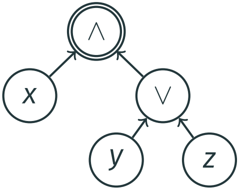
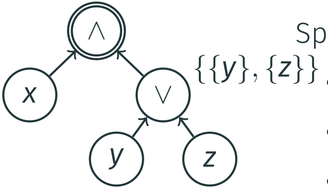


Special zero-suppressed semantics for circuits:

- No NOT-gate
- Each gate captures a set of assignments
- Bottom-up definition with $\times$ and $\cup$

Zero-suppressed semantics



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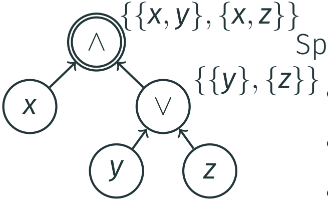

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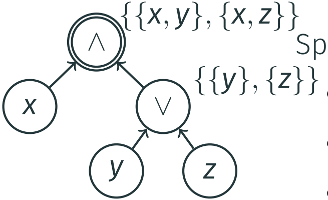

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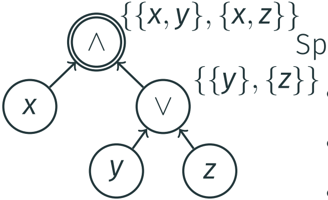

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- Generalization of factorized representations
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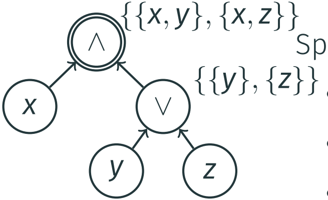
Zero-suppressed semantics



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Simplification: rewrite circuits to arity-two (fan-in ≤ 2)

Enumerating assignments in the zero-suppressed semantics

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

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

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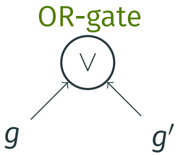

Concatenation: enumerate $S(g)$
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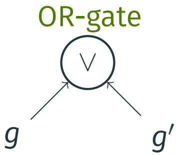

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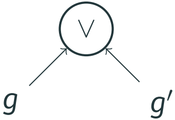
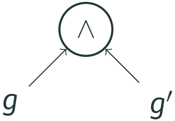
OR-gate



AND-gate



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

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Lexicographic product: enumerate $S(g)$ and for each result t enumerate $S(g')$ and concatenate t with each result

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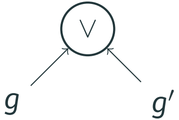
OR-gate



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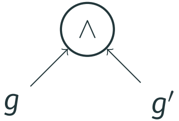

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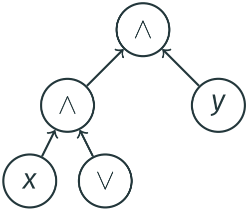
Lexicographic product: enumerate $S(g)$ and for each result t enumerate $S(g')$ and concatenate t with each result

Decomposability: no duplicates

Normalization: handling $\emptyset$



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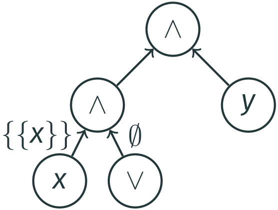

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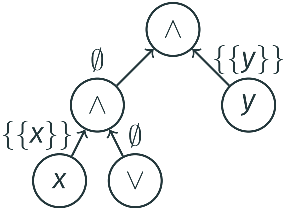

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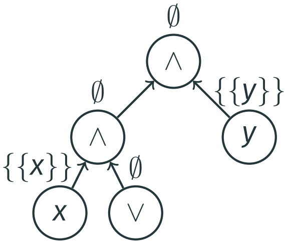

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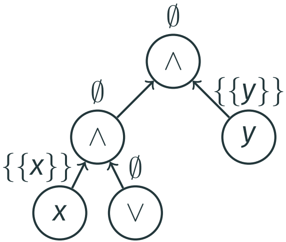

- Problem: if $S(g) = \emptyset$ we waste time

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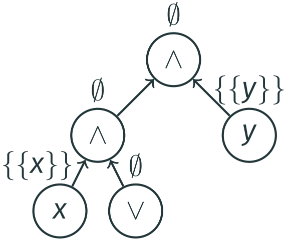
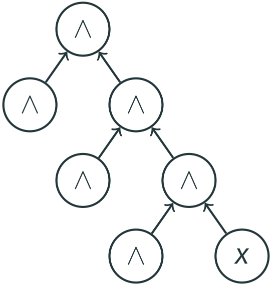


- Problem: if $S(g) = \emptyset$ we waste time
- Solution: compute bottom-up if $S(g) = \emptyset$

Normalization: handling empty assignments



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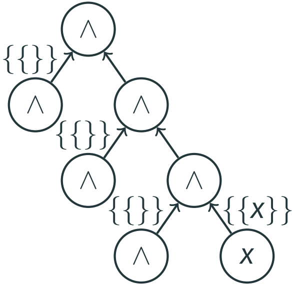

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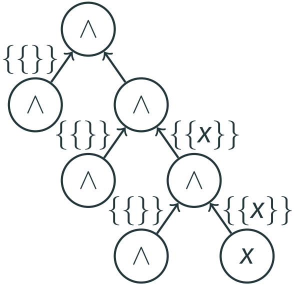

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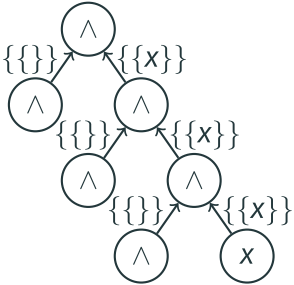

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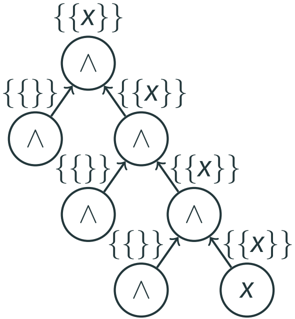

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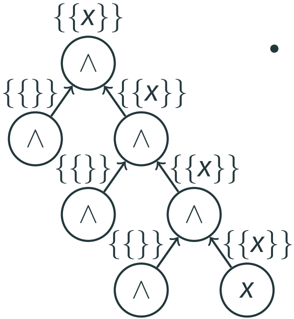
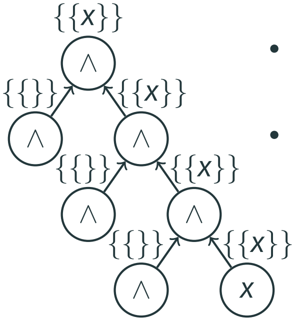


- Problem: if $S(g)$ contains {} we waste time in chains of AND-gates

Normalization: handling empty assignments



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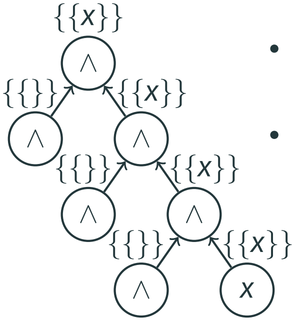
Normalization: handling empty assignments



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  - split g between $S(g) \cap \{\{\}\}$ and $S(g) \setminus \{\{\}\}$ (homogenization)

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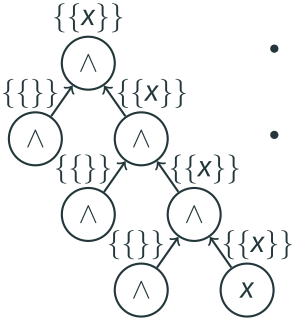

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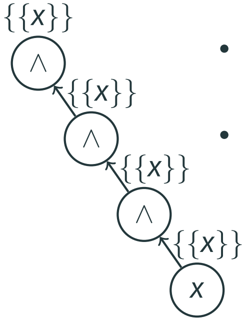

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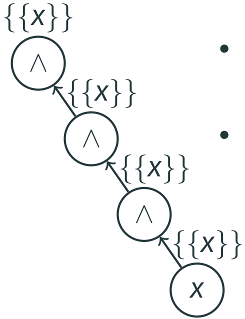

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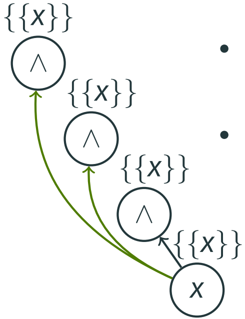

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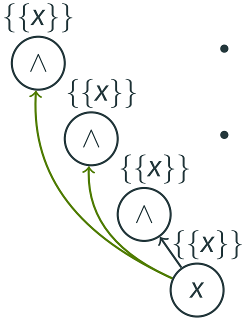

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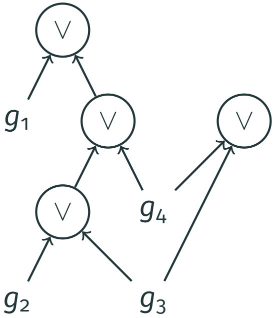
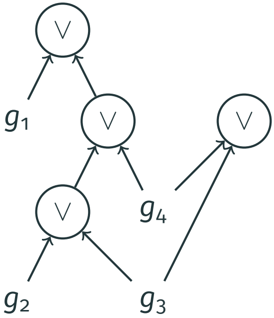
→ Now, traversing an AND-gate ensures that we make progress: it splits the assignments non-trivially

Normalization: handling OR-hierarchies



- Problem: we waste time in OR-hierarchies to find a reachable exit (non-OR gate)

Normalization: handling OR-hierarchies



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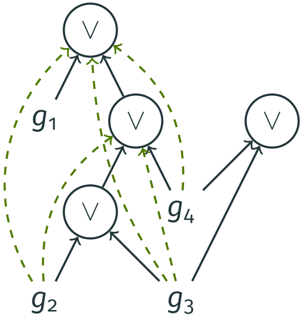

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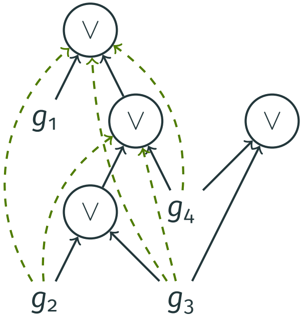

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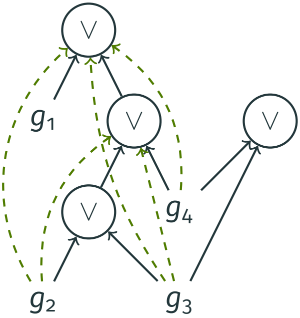

- **Problem:** we waste time in OR-hierarchies to find a **reachable exit** (non-OR gate)
- **Solution:** compute **reachability index**
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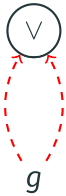
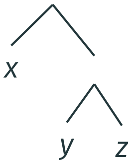
Solution:

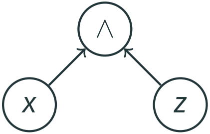
- **Determinism** ensures we have a **multitree** (we cannot have the pattern at the right)
- **Custom** constant-delay reachability index for multitrees



Translating to zero-suppressed semantics

- This is where we use the v-tree





Translating to zero-suppressed semantics

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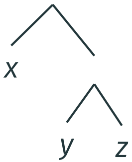
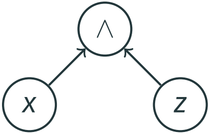
- Add explicitly untested variables





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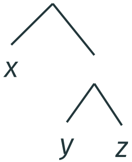

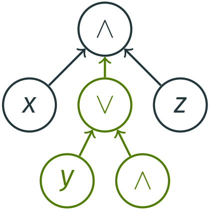

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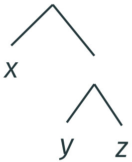

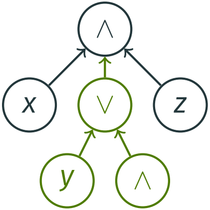

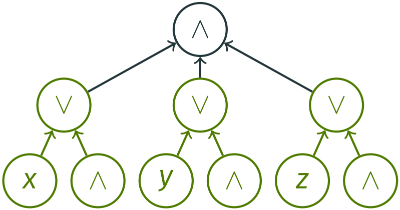

- Problem: quadratic blowup

Translating to zero-suppressed semantics

- This is where we use the **v-tree**
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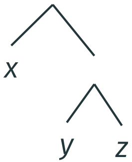

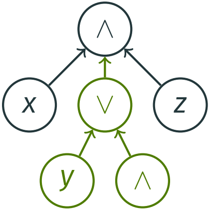

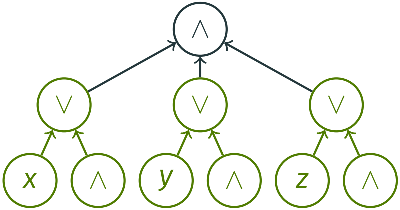

- **Problem:** quadratic blowup
- **Solution:**
  - **Order** $<$ on variables in the v-tree ($x < y < z$)
  - **Interval** $[x, z]$
  - **Range gates** to denote $\bigvee[x, z]$ in constant space

Conclusion

Summary and conclusion

Summary:

- Usual approach: develop enumeration algorithms by hand

Summary and conclusion

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- Proposed approach:

Summary and conclusion

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  - Develop linear-time compilation algorithm to circuits

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Thanks for your attention!

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