Provenance Circuits for Trees and Treelike Instances

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General idea

- We consider a query and a relational instance
- Often it is not sufficient to merely evaluate the query:
  - $\rightarrow$ We need quantitative information
  - $\rightarrow$ We need the link from the output to the input data

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$\rightarrow$ Compute query provenance!

Example 1: security for a conjunctive query

- Consider the conjunctive query: $\exists xyz\ R(x, y) \wedge R(y, z)$
- Consider the relational instance below:

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a	b
b	c
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$\rightarrow$ Result: Confidential

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Example 4: the universal semiring $\mathbb{N}[X]$

- Consider again: $\exists xyz\ R(x, y) \wedge R(y, z)$.
- Annotate input facts with atomic annotations $X = f_1, \ldots, f_n$
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Specialization and homomorphisms

- These examples are captured by commutative semirings:
  - security semiring $(K, \text{min}, \text{max}, \text{Public}, \text{Never available})$
  - bag semiring $(\mathbb{N}, +, \times, 0, 1)$
  - Boolean semiring $(\text{PosBool}[X], \vee, \wedge, \mathfrak{f}, \mathfrak{t})$
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→ Computing $\mathbb{N}[X]$ provenance subsumes all tasks

→ It can be done in PTIME data complexity for CQs

Provenance and probability

- Probabilistic query evaluation:
  - Fixed CQ q, and input TID instance:

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$\rightarrow$ #P-hard in data complexity

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    - k-cliques and k-grids have treewidth $k - 1$
  - Treelike: the treewidth is bounded by a constant

Problem statement

- Many tasks have tractable data complexity on treelike instances:
  - MSO query evaluation is linear [Courcelle, 1990]
  - MSO result counting is linear [Arnborg et al., 1991]
  - Probability evaluation is linear for trees [Cohen et al., 2009]
  - (MSO covers relational algebra, UCQs, monadic Datalog...)

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→ Can we generalize the above results?

Table of contents

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- Bool[X]-provenance on trees and treelike instances
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  - Query: MSO on trees
- The world of treelike instances:
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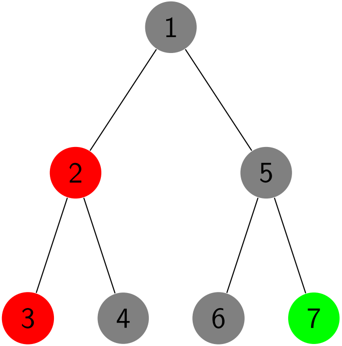
→ Start with $\mathrm{Bool}[X]$-provenance for queries on trees

Uncertain trees



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Example query:
"Is there both a red and a green node?"

Valuation: $\{1, 2, 3, 4, 5, 6, 7\}$

The query is true

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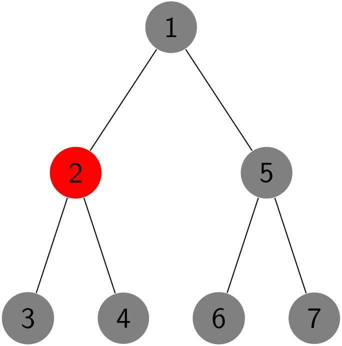

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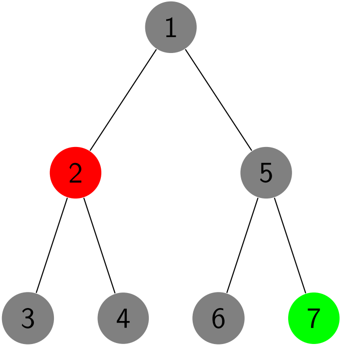

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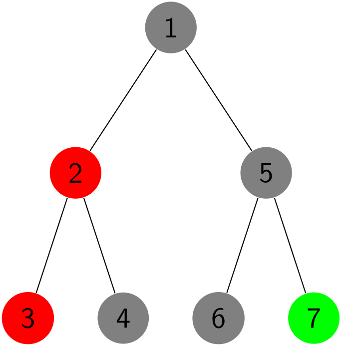
Provenance formulae and circuits



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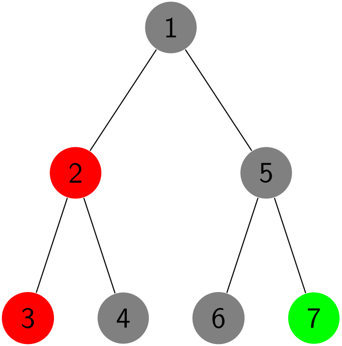

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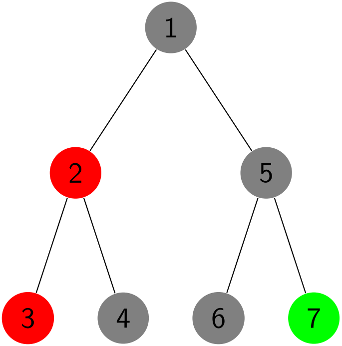

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- Provenance circuit of q on T [Deutch et al., 2014]
  - Boolean circuit C
  - with input gates $g_1 \dots g_7$

  → $\nu(T)$ satisfies q iff $\nu(C)$ is true

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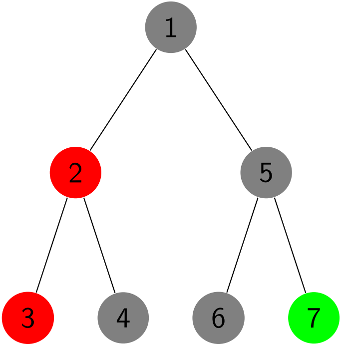

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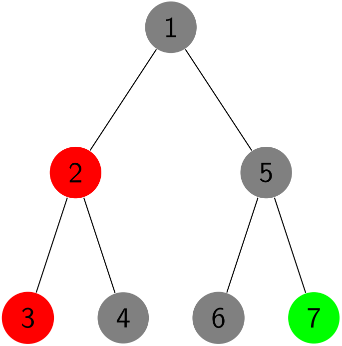

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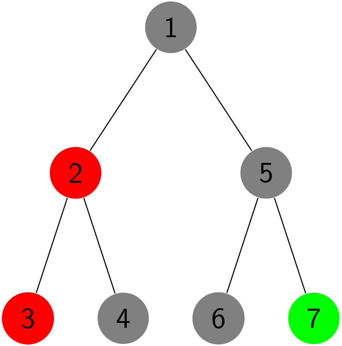

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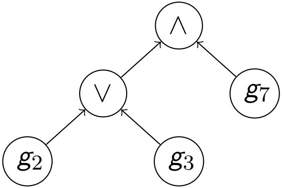

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→ Key ideas:

- Compile q to a tree automaton [Thatcher and Wright, 1968]
- Write the possible transitions of the automaton on T

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→ Key ideas:

- Compile q to a tree automaton [Thatcher and Wright, 1968]
- Write the possible transitions of the automaton on T

Corollary

If tree nodes have a probability of being independently kept, we can compute the query probability in linear time.

Treelike instances

- Tree encodings: represent treelike instances as trees
- MSO query on an instance → MSO query on the tree encoding

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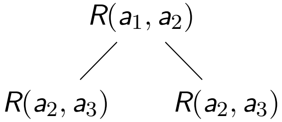
R	
a	b
b	c
b	d



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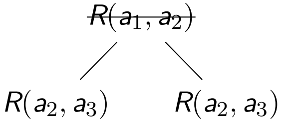

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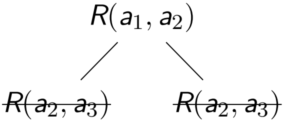

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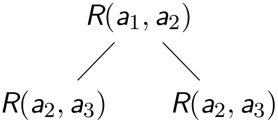

Our result and consequences

Theorem

*For any fixed MSO query q and $k \in \mathbb{N}$,
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we can build in linear time a $\mathrm{Bool}[X]$ provenance circuit of q on I.*

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Corollary

MSO counting has linear time complexity (already known).

Table of contents

First problem: non-monotone queries

- We want to move from $\mathrm{Bool}[X]$ to $\mathbb{N}[X]$
- Semirings and negation don't mix [Amsterdamer et al., 2011]
- Our previous construction builds circuits with NOT-gates

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→ Provenance circuits for monotone queries can be monotone

Second problem: intrinsic definition

- Boolean provenance has an intrinsic definition:
  "Characterize which subinstances satisfy the query"
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$\rightarrow$ We restrict to (Boolean) UCQs from now on

Provenance of a Boolean CQ

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a	a	x_1
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- Query: $q : \exists xy\ R(x, y) \wedge R(y, x)$

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How is $\mathbb{N}[X]$ more expressive than $\mathrm{PosBool}[X]$?

→ Coefficients: counting multiple derivations

→ Exponents: using facts multiple times

Our result for $\mathbb{N}[X]$-provenance circuits

Theorem

For any fixed UCQ q and $k \in \mathbb{N}$,
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$\rightarrow$ What fails for MSO/Datalog?

- Unbounded maximal multiplicity
- Logical definition of fact multiplicity?

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Summary

- Result:
  - → Linear time provenance circuit computation on trees and treelike instances:
    - for MSO, $\mathrm{Bool}[X]$
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  - → Capture existing results (decouple symbolic and numerical computation)
  - → Extend to new applications (probabilities)

Future work

- Extend $\mathbb{N}[X]$ beyond UCQs (e.g., formal series, multiplicities)
- Monadic Datalog? [Gottlob et al., 2010]
- Other applications? aggregation, enumeration?
- Experiments for efficient probabilistic query evaluation
- Query-specific tree decompositions?

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Thanks for your attention!

References I

Amsterdamer, Y., Deutch, D., and Tannen, V. (2011).
On the limitations of provenance for queries with difference.
In *TaPP*.

Arnborg, S., Lagergren, J., and Seese, D. (1991).
Easy problems for tree-decomposable graphs.
J. Algorithms, 12(2):308–340.

Chaudhuri, S. and Vardi, M. Y. (1992).
On the equivalence of recursive and nonrecursive Datalog programs.
In *PODS*.

Cohen, S., Kimelfeld, B., and Sagiv, Y. (2009).
Running tree automata on probabilistic XML.
In *PODS*.

References II

- Courcelle, B. (1990).
  The monadic second-order logic of graphs. I. Recognizable sets of finite graphs.
  Inf. Comput., 85(1).

- Deutch, D., Milo, T., Roy, S., and Tannen, V. (2014).
  Circuits for datalog provenance.
  In *ICDT*.

- Gottlob, G., Pichler, R., and Wei, F. (2010).
  Monadic datalog over finite structures of bounded treewidth.
  TOCL, 12(1):3.

- Green, T. J., Karvounarakis, G., and Tannen, V. (2007).
  Provenance semirings.
  In *PODS*.

References III

Thatcher, J. W. and Wright, J. B. (1968).
Generalized finite automata theory with an application to a decision problem of second-order logic.
Mathematical systems theory, 2(1):57–81.

Semiring provenance [Green et al., 2007]

- Semiring $(K, \oplus, \otimes, 0, 1)$
  - $(K, \oplus)$ commutative monoid with identity 0
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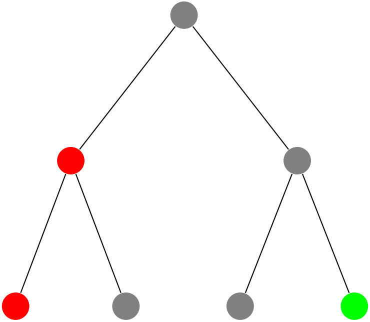
- Idea: Maintain annotations on tuples while evaluating:
  - Union: annotation is the sum of union tuples
  - Select: select as usual
  - Project: annotation is the sum of projected tuples
  - Product: annotation is the product

Tree automata

Tree alphabet:



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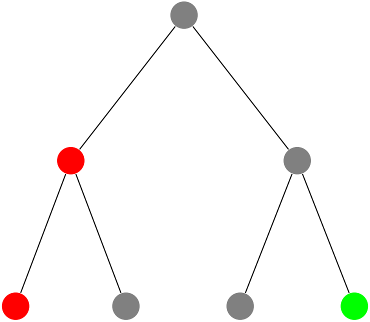

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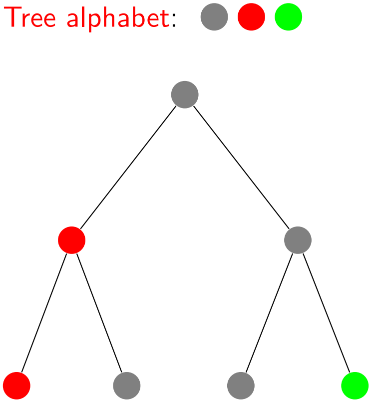

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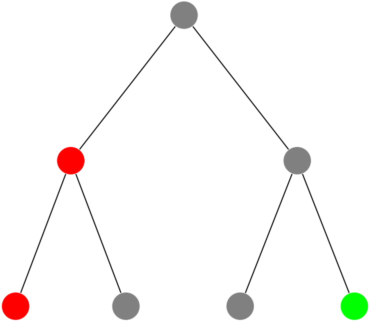

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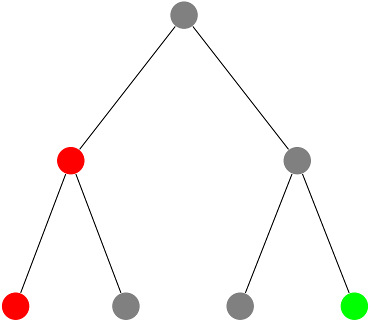

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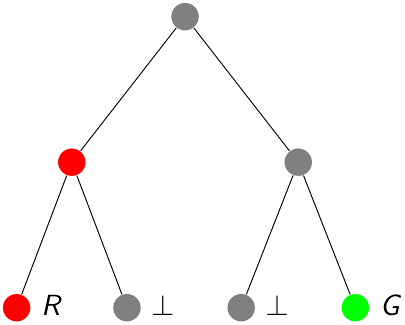

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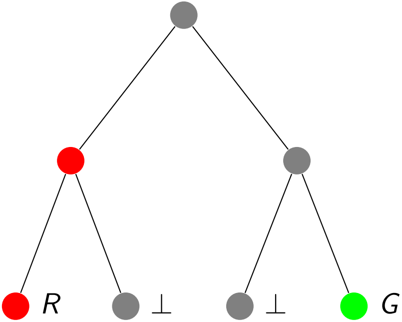

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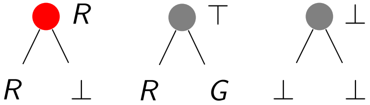

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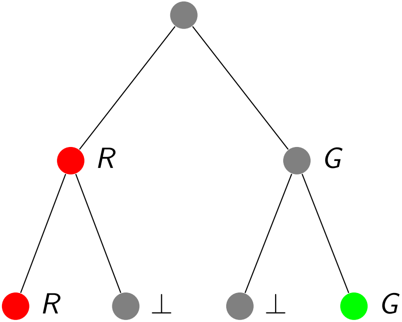

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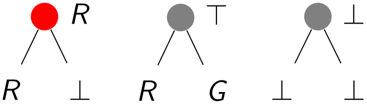

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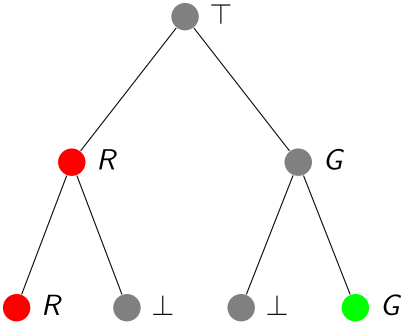

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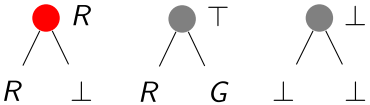
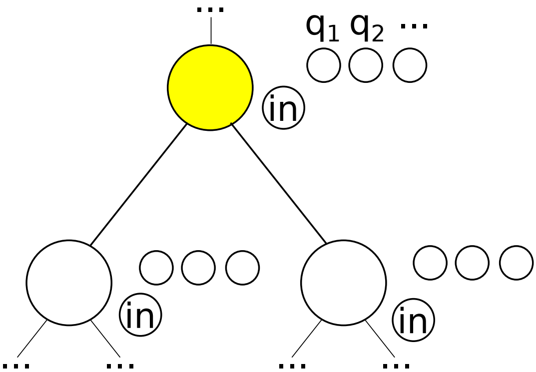


Constructing the provenance circuit

→ Construct a Boolean provenance circuit bottom-up



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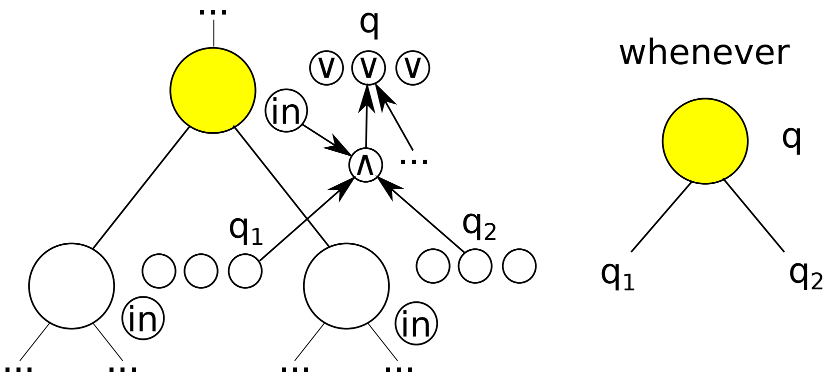

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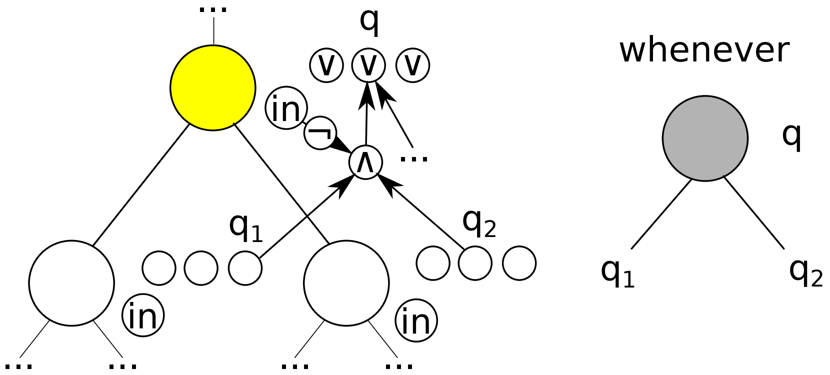

Encoding treelike instances [Chaudhuri and Vardi, 1992]

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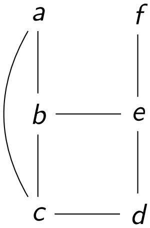

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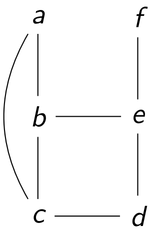

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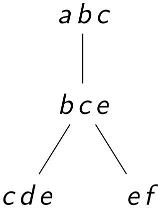

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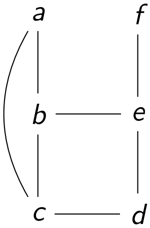

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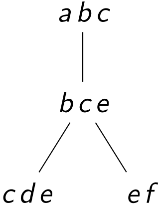
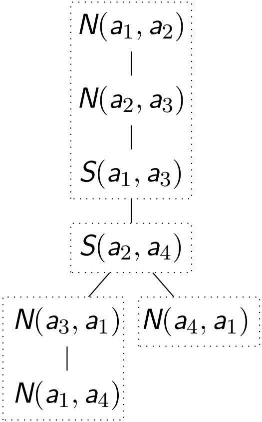


Tree encoding:



Example: block-independent disjoint (BID) instances

name	**city**	**iso**	*p*
pods	melbourne	au	0.8
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→ For a treelike instance, linear time!

Supporting coefficients

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  - The same valuation can be accepted multiple times
  - $\rightarrow$ Number of accepting runs of the bNTA
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→ Add assignment facts to represent possible assignments

→ Encode to a bNTA that guesses them

Supporting exponents

- In the world of trees
  - The same fact can be used multiple times
  - Annotate nodes with a multiplicity
  - The bNTA is monotone for that multiplicity
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→ Encodes CQs to bNTAs that read multiplicities

  - Consider all possible CQ self-homomorphisms
  - Count the multiplicities of identical atoms
  - Rewrite relations to add multiplicities
  - Usual compilation on the modified signature