Fully Automated Shape Analysis Based on Forest Automata[†]

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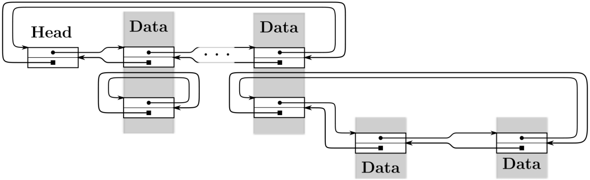
Shape Analysis

- Precise shape analysis:
  - a notoriously difficult problem



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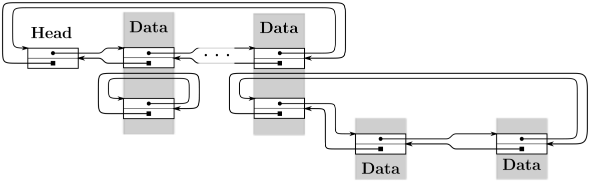

  - specialized solutions (lists)
  - help from the outside (loop invariants, inductive predicates)

- Classes of errors:
  - error line reachability
  - invalid pointer dereference
  - occurrence of garbage

Inspiration

- Separation Logic
  - ☺ local reasoning, well scalable
  - ☹ fixed abstraction

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- Abstract Regular Tree Model Checking (ARTMC)
  - ☺ uses tree automata (TA), flexible and refinable abstraction
  - ☹ monolithic encoding of the heap, not very scalable

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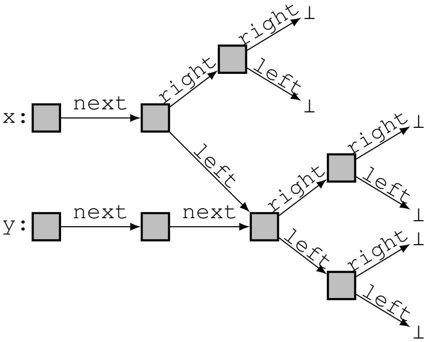
  and
  - TA-based representation of sets of heaps

Heap Representation

- Forest decomposition of a heap



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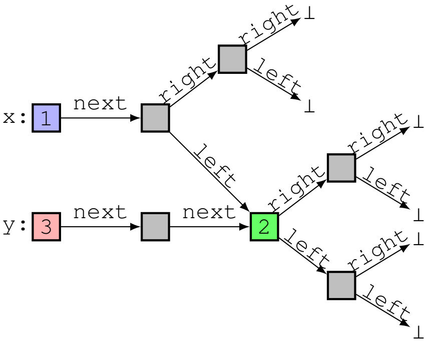

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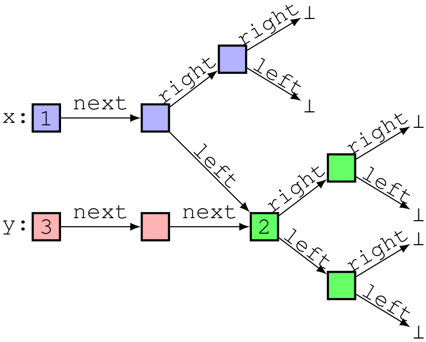

Heap Representation

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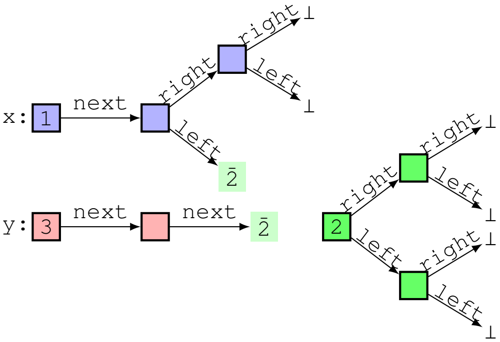

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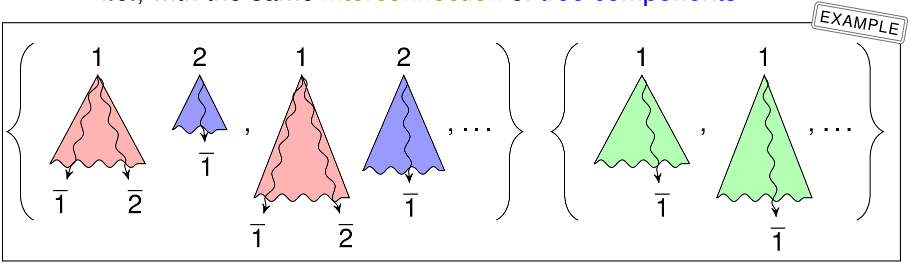

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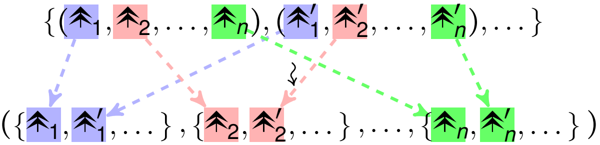

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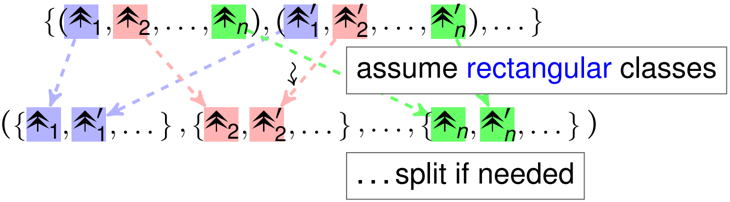

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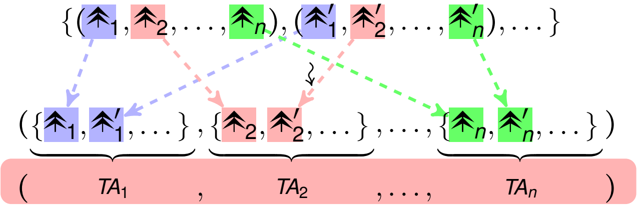

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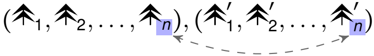

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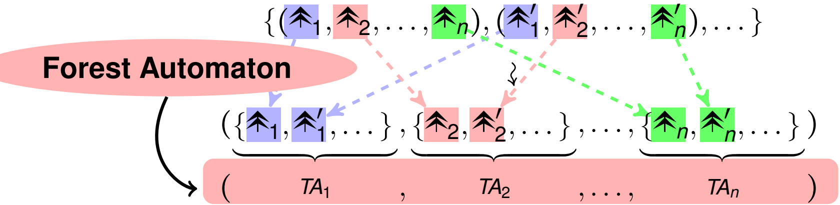
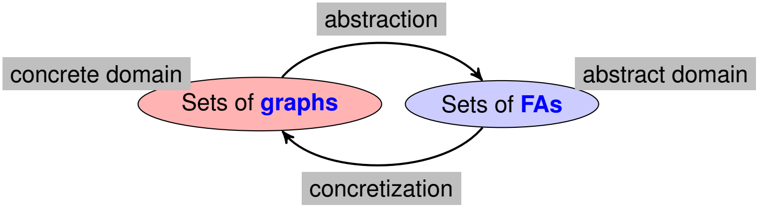


Symbolic Execution

- Abstract Interpretation



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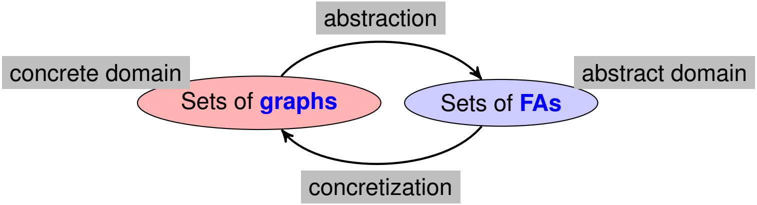

Statements

- `x := new T()`
- `delete(x)`
- `x := null`
- `x := y`
- `x := y.next`
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- `if/while (x == y)`

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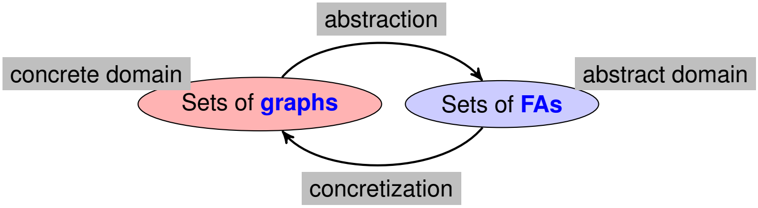

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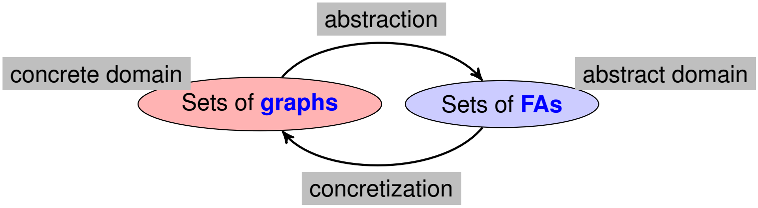

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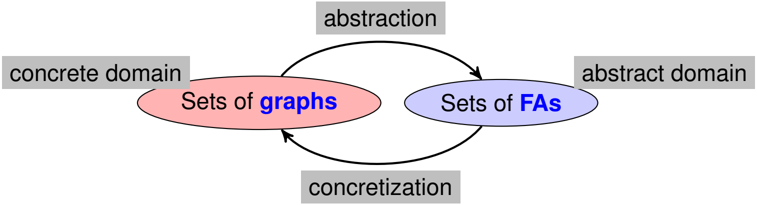

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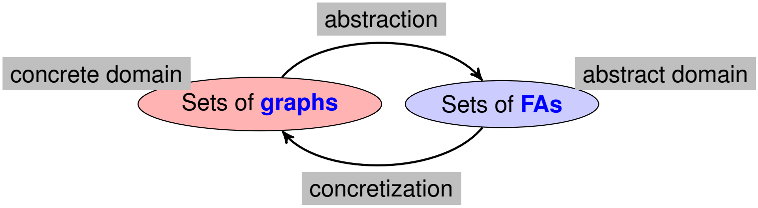

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Abstract Transformers

- append a TA → `x := new T()`
- remove a TA → `delete(x)`
- modify transitions → `x := null`, `x := y`, `x := y.next`, `x.next := y`

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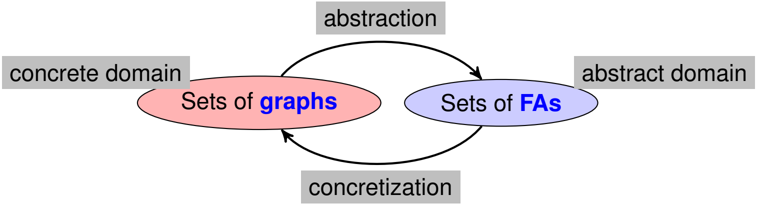

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- `x.next := y` ← modify transitions
- `if/while (x == y)` ← check symbols on transitions

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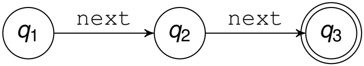
TA



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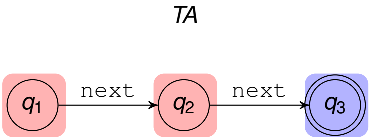

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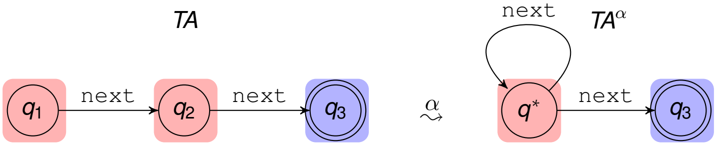

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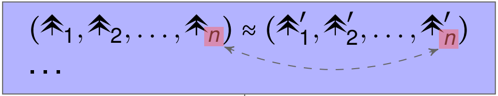

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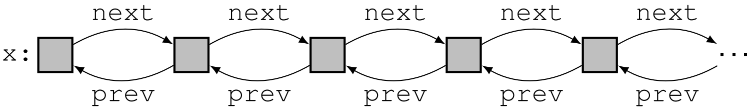

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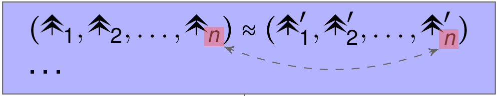

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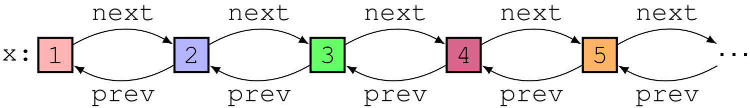

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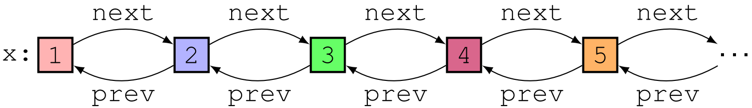

- doubly linked lists (DLLs), circular lists, nested lists,
- trees with parent pointers,
- skip lists

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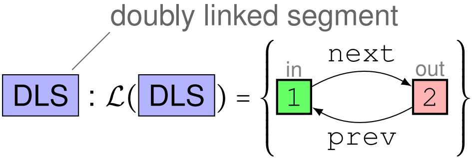

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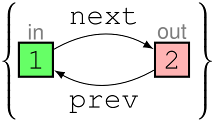
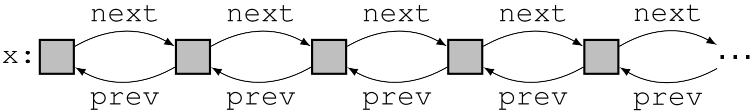
- Example: a box DLS : $\mathcal{L}($DLS$)$ = 



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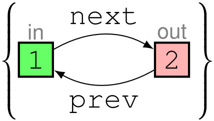
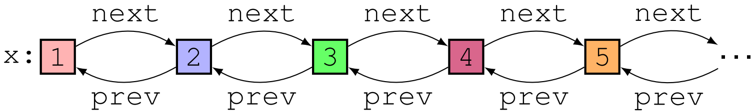
- Example: a box DLS : $\mathcal{L}($DLS$)$ = 



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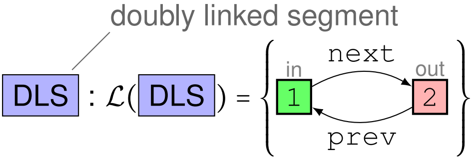
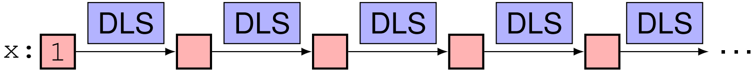
- Hierarchical Forest Automata
  - FAs are symbols (**boxes**) of FAs of a higher level
  - a hierarchy of FAs
  - Intuition: replace repeated subgraphs with a single symbol

- Example: a box DLS : $\mathcal{L}$(DLS) =





Hierarchical Forest Automata

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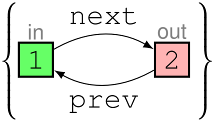
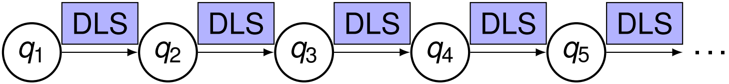
doubly linked segment

- Example: a box DLS : $\mathcal{L}($ DLS $)$ = 



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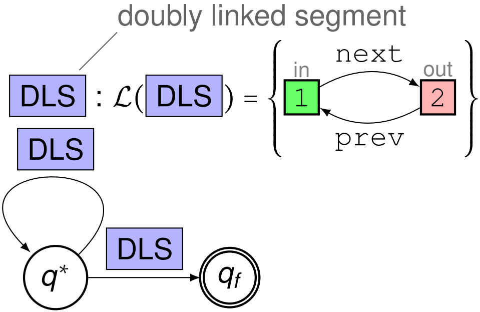
- Example: a box



Learning of Boxes

The Challenge

How to find "the right" boxes?

Learning of Boxes

The Challenge

How to find "the right" boxes?

- CAV'11 — database of boxes
- CAV'13 — automatic discovery

Learning of Boxes

- compromise between

Learning of Boxes

- compromise between
  - reusability

Learning of Boxes

- compromise between
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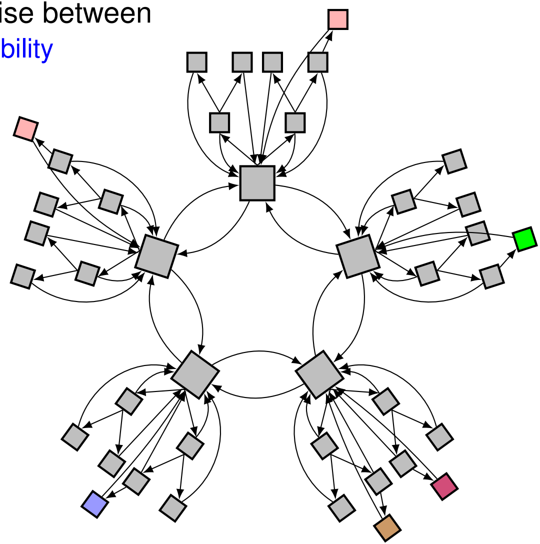

Learning of Boxes

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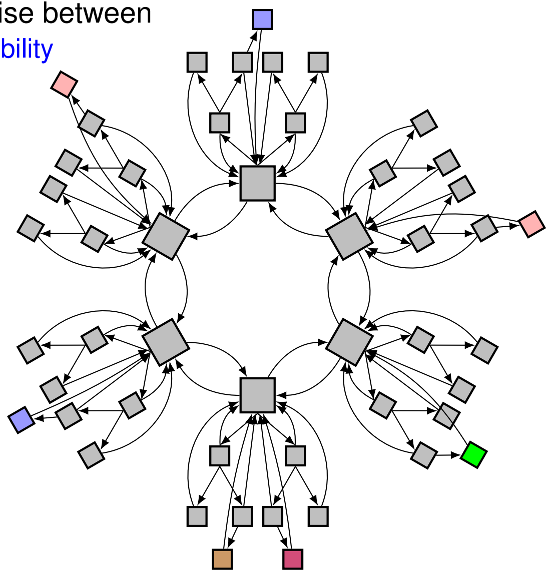

Learning of Boxes

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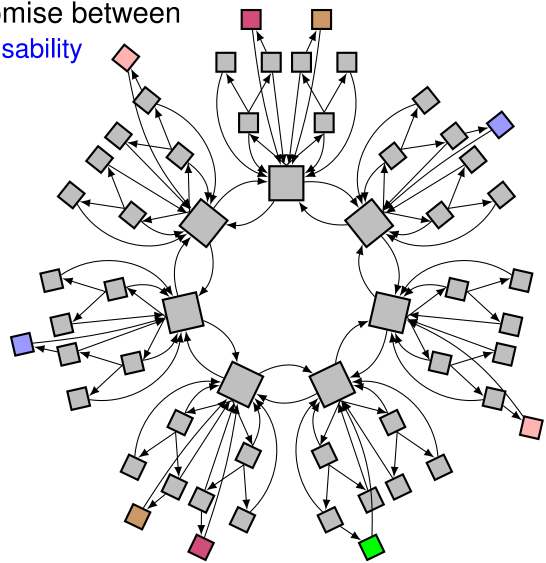

Learning of Boxes

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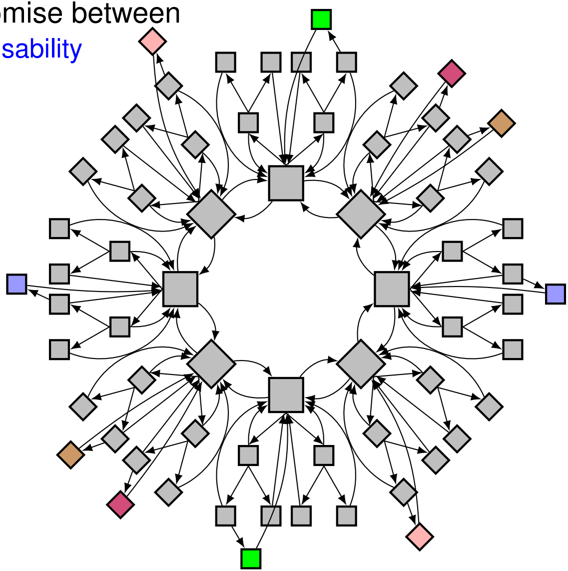

Learning of Boxes

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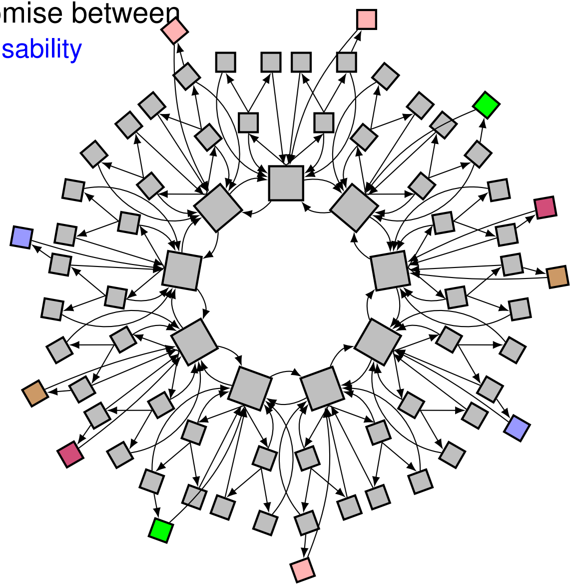

Learning of Boxes

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Learning of Boxes

- compromise between
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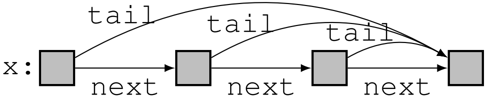

Learning of Boxes

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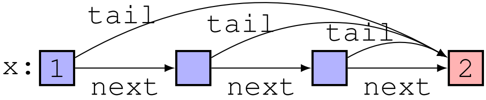

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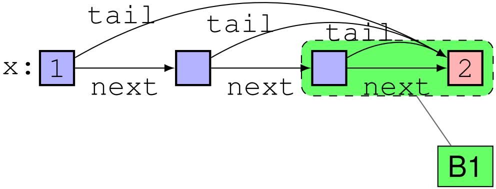

Learning of Boxes

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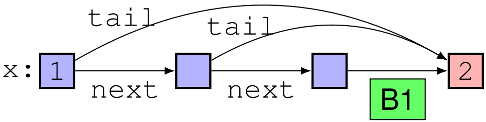

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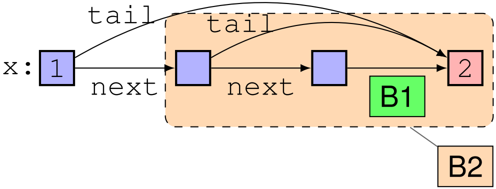

Learning of Boxes

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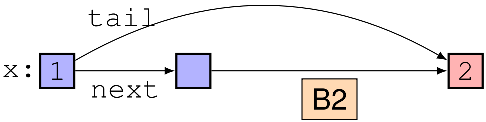

Learning of Boxes

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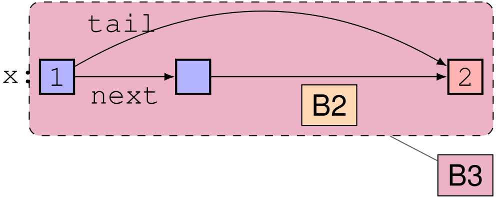

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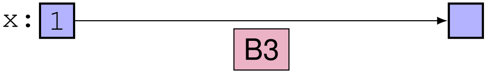

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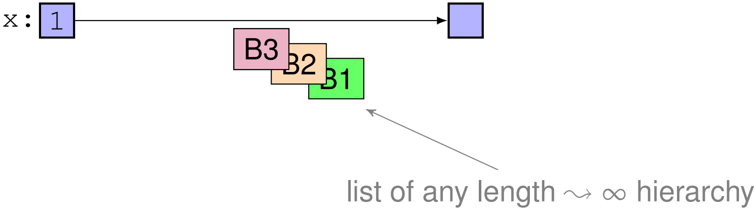


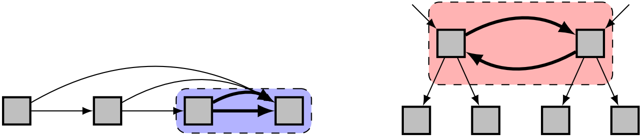
Learning of Boxes: Knots

Knots

Learning of Boxes: Knots

Knots

1. smallest subgraphs meaningful to be folded:



Learning of Boxes: Knots

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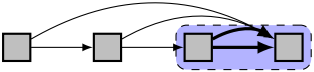

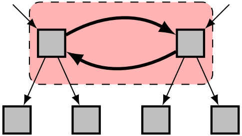

2. handle interface

Learning of Boxes: Knots

Knots

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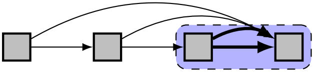
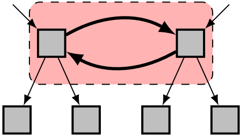
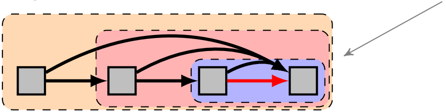




2. handle interface
   - compose intersecting knots

prevent ∞ nesting



Learning of Boxes: Knots

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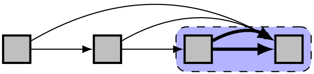

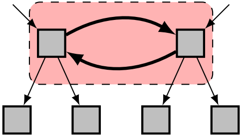

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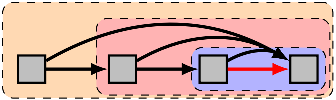
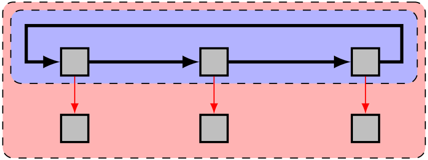


prevent ∞ nesting

   - enclose paths from inner nodes to leaves



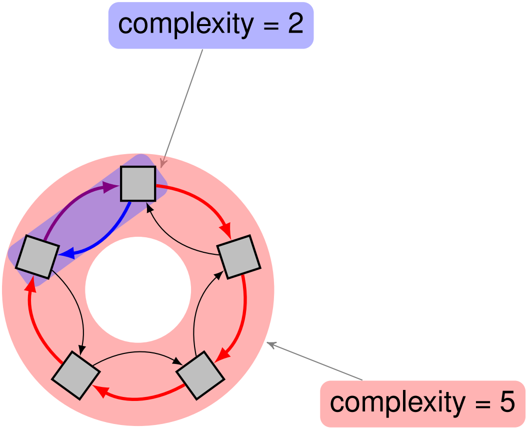
prevent ∞ interface nodes

Learning of Boxes: Knots

3 complexity

Learning of Boxes: Knots

3 complexity



Learning of Boxes: Knots

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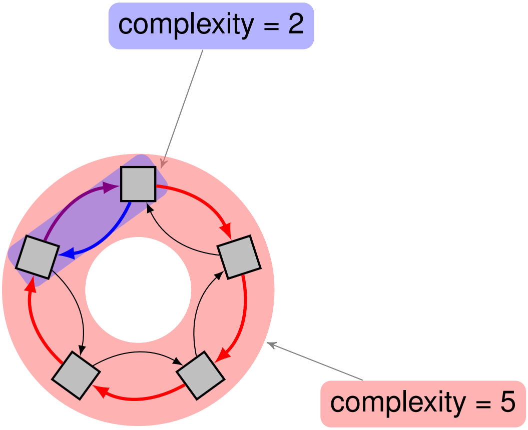

- find basic knots with $1, 2, \ldots$ cut-points

Acceleration Revisited

- learning and folding of boxes in the abstraction loop

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The Goal

Fold boxes that will, after abstraction, appear on cycles of automata.

$\Rightarrow$ hide unboundedly many cut-points

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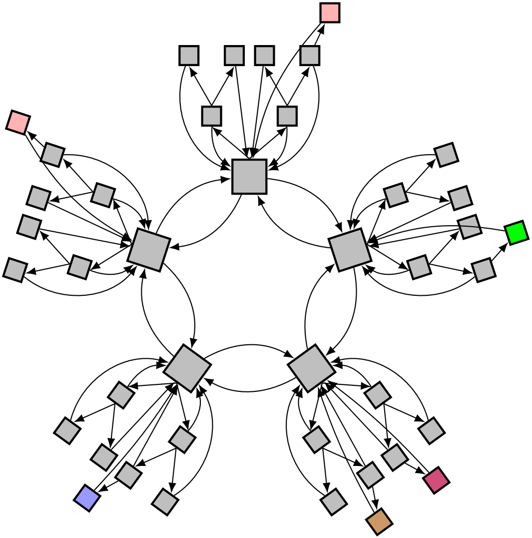
Algorithm: Abstraction Loop

Unfold solo boxes
repeat
    Abstract
    Fold
until *fixpoint*

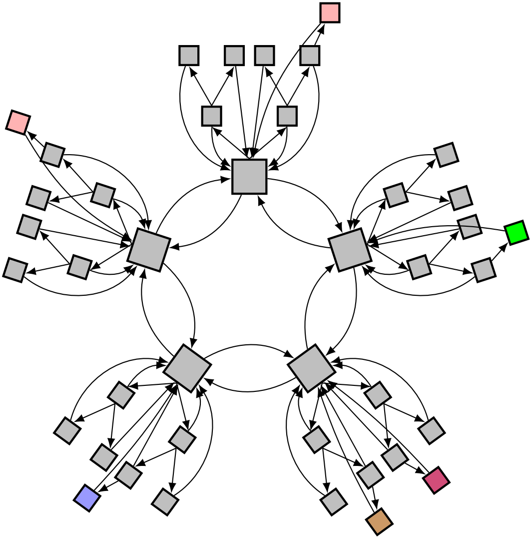
not on a cycle

Learning of Boxes: Example



1 *Unfold solo boxes*
2 **repeat**
3 *Abstract*
4 *Fold*
5 **until** *fixpoint*

Learning of Boxes: Example



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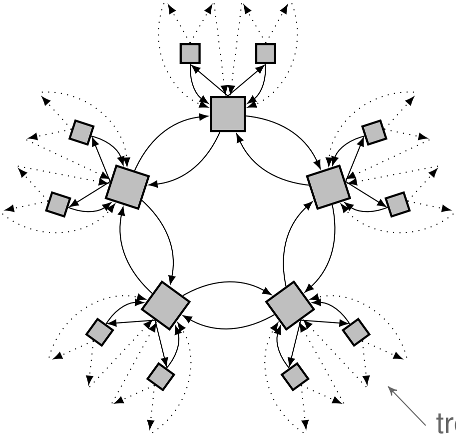

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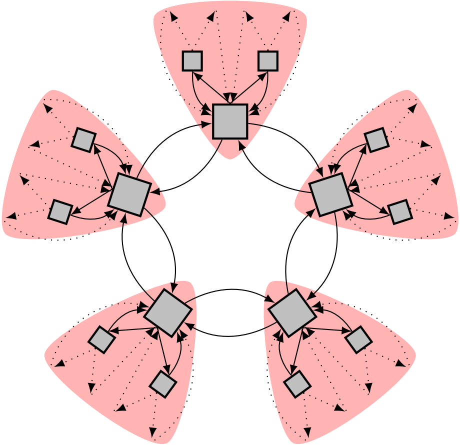
tree with root ptrs of any height

Learning of Boxes: Example



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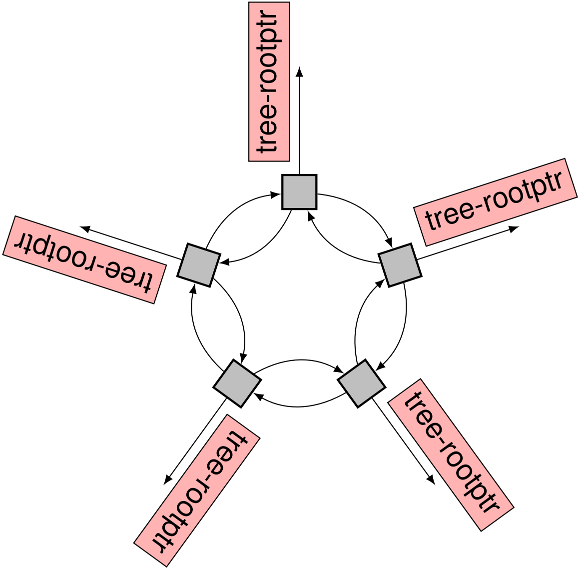
Learning of Boxes: Example



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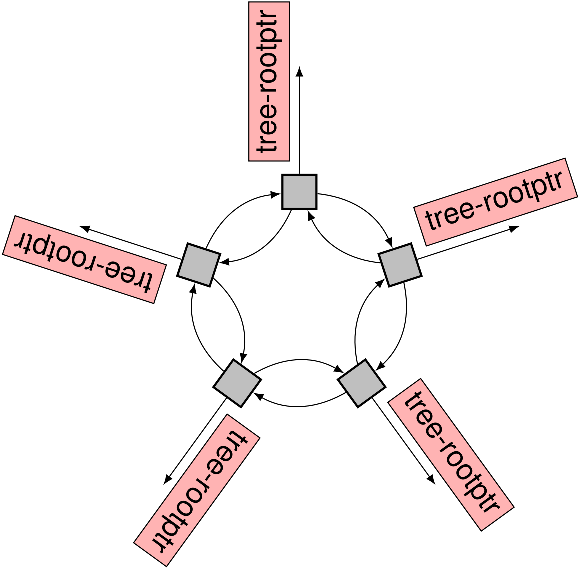
Learning of Boxes: Example



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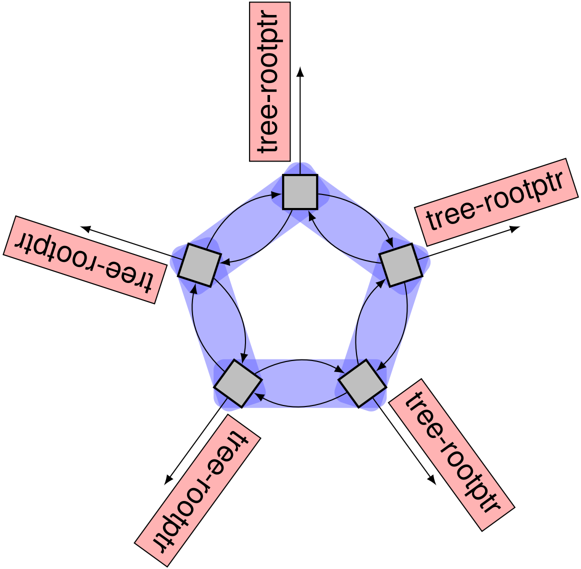
Learning of Boxes: Example



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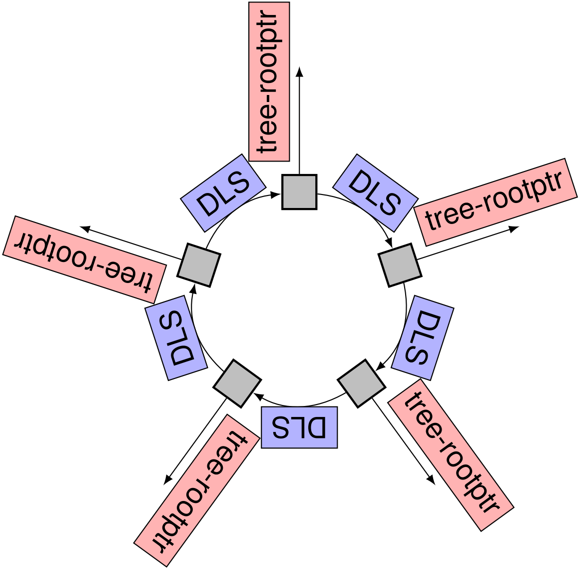

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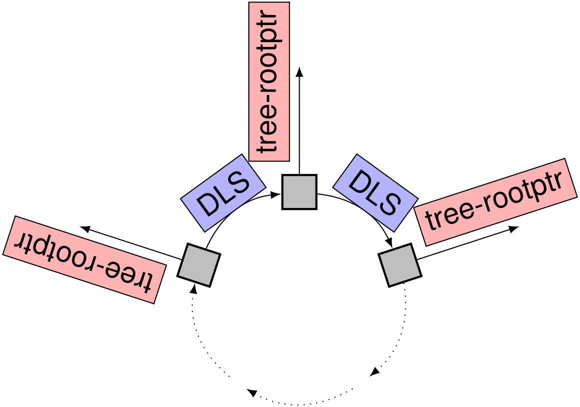

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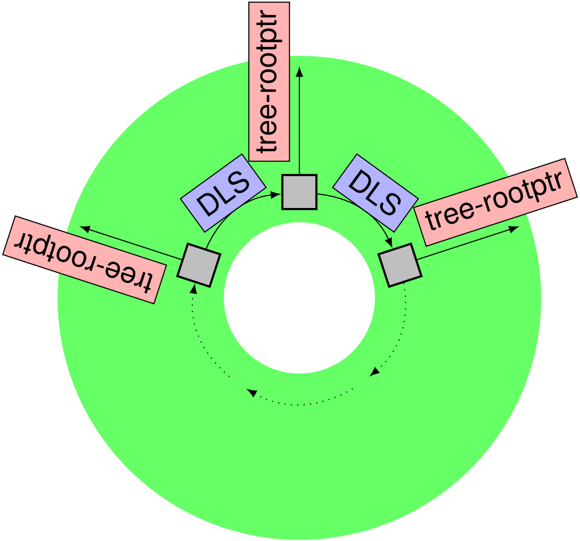

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Learning of Boxes: Example

circular-DLL-of
-trees-rootptr

```
Unfold solo boxes
repeat
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```

Experimental Results

- implemented in **Forester** tool

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    - winner of HeapManipulation and MemorySafety of SV-COMP'13

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  - winner of HeapManipulation and MemorySafety of SV-COMP'13

Table : Results of the experiments [s]

Example	**FA**	Predator	Example	**FA**	Predator
SLL (delete)	0.04	0.04	DLL (reverse)	0.06	0.03
SLL (bubblesort)	0.04	0.03	DLL (insert)	0.07	0.05
SLL (mergesort)	0.15	0.10	DLL (insertsort_1)	0.40	0.11
SLL (insertsort)	0.05	0.04	DLL (insertsort_2)	0.12	0.05
SLL (reverse)	0.03	0.03	DLL of CDLLs	1.25	0.22
SLL+head	0.05	0.03	DLL+subdata	0.09	T
SLL of 0/1 SLLs	0.03	0.11	CDLL	0.03	0.03
$\text{SLL}_{\text{Linux}}$	0.03	0.03	tree	0.14	Err
SLL of CSLLs	0.73	0.12	tree+parents	0.21	T
SLL of $\text{2CDLLs}_{\text{Linux}}$	0.17	0.25	tree+stack	0.08	Err
skip list_2	0.42	T	tree (DSW) Deutsch-Schorr-Waite	0.40	Err
skip list_3	9.14	T	tree of CSLLs	0.42	Err

timeout (T) — false positive (Err)

Conclusion

Shape analysis with forest automata:

Conclusion

Shape analysis with forest automata:

- fully automated

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- very flexible framework

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- successfully verified:
  - (singly/doubly linked (circular)) lists (of (. . .) lists)
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Shape analysis with forest automata:

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- **Forester** tool
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  - trees
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- not covered here:
  - support for pointer arithmetic
  - tracking ordering relations
    - P. Abdulla, L. Holík, B. Jonsson, O. Lengál, C.Q. Tring, and T. Vojnar. **Verification of Heap Manipulating Programs with Ordered Data by Extended Forest Automata.** To appear in *Proc. of ATVA'13*.

Future work

- CEGAR loop
  - **red**-**black** trees, ...

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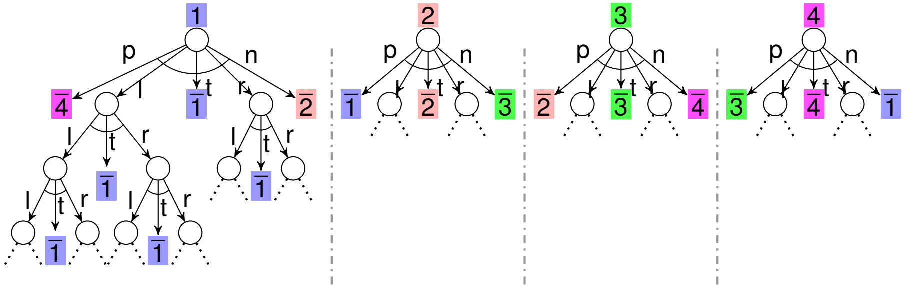
  - lockless skip lists, . . .

Future work

- CEGAR loop
  - **red**-**black** trees, . . .
- concurrent data structures
  - lockless skip lists, . . .
- recursive boxes
  - B+ trees, . . .

Appendix



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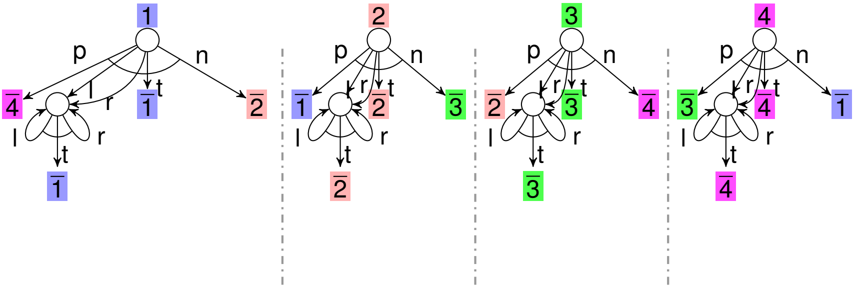

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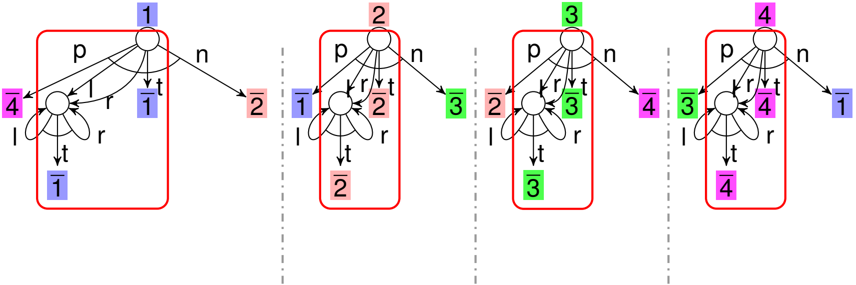
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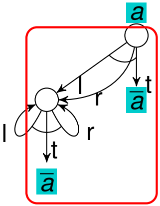
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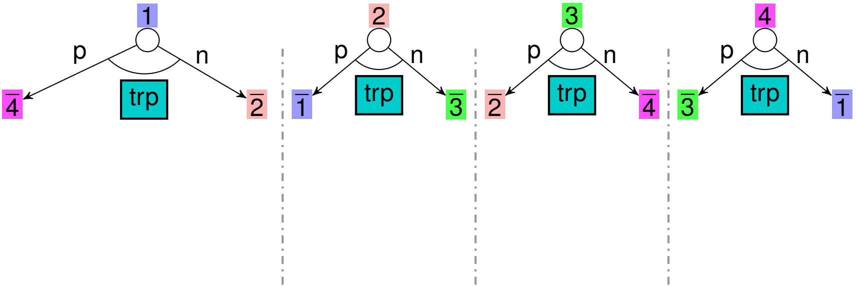

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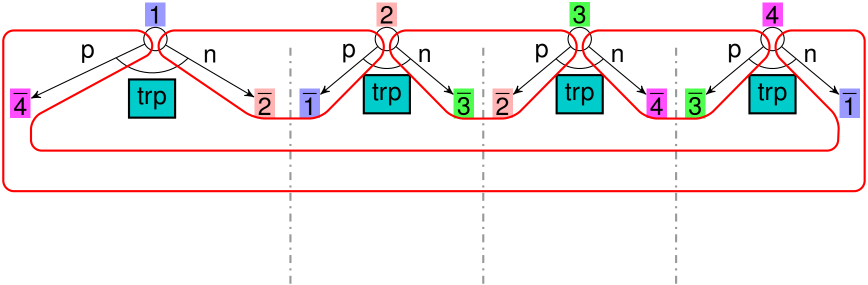

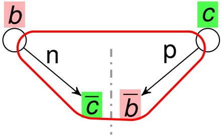

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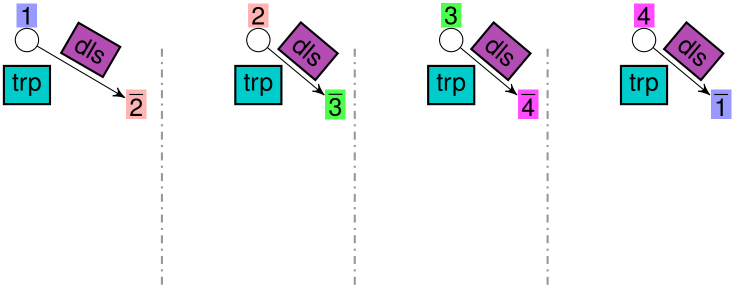

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2
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$\overline{3}$
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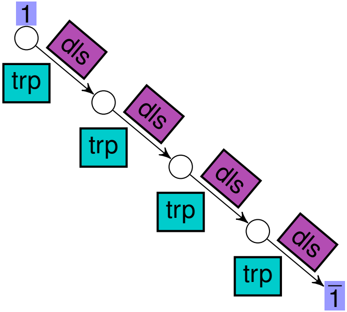
$\overline{1}$

Appendix



Appendix