Fully Automated Shape Analysis Based on Forest Automata[†]

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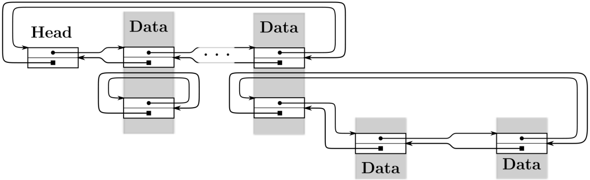
Shape Analysis

- Shape analysis:
  - reasoning about programs with dynamic linked data structures
  - notoriously difficult: infinite sets of complex graphs



  - memory safety: invalid dereferences, double free, memory leakage
  - error line reachability (assertions), shape invariance (testers), ...

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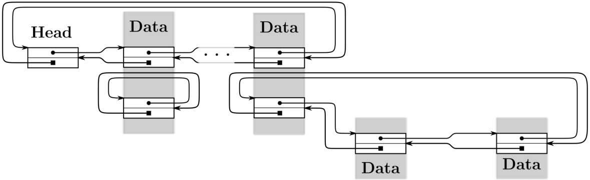

  - memory safety: invalid dereferences, double free, memory leakage
  - error line reachability (assertions), shape invariance (testers), ...

- Existing solutions:
  - often specialized (lists)
  - require human help (loop invariants, inductive predicates)
  - low scalability

Inspiration

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

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  - ☺ local reasoning: well scalable
  - ☹ fixed abstraction
- Abstract Regular Tree Model Checking (ARTMC)
  - ☺ uses tree automata (TA): flexible and refinable abstraction
  - ☹ monolithic encoding of the heap: limited scalability

The Forest Automata-based Approach

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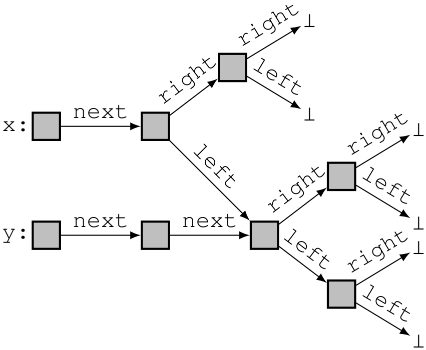
  and
  - using tree automata to represent sets of tree components of heaps

Heap Representation

- Forest decomposition of a heap



Heap Representation

- Forest decomposition of a heap
  - Identify cut-points ← nodes referenced:
    - by variables, or
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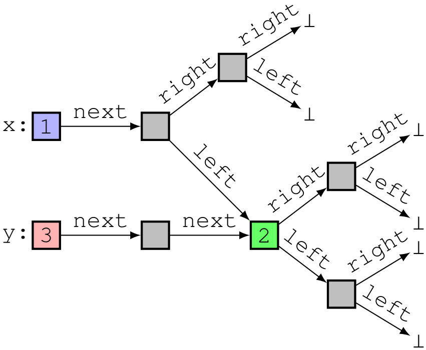

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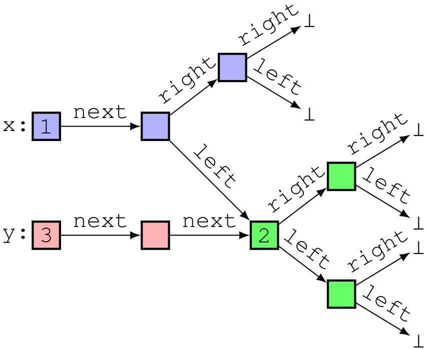

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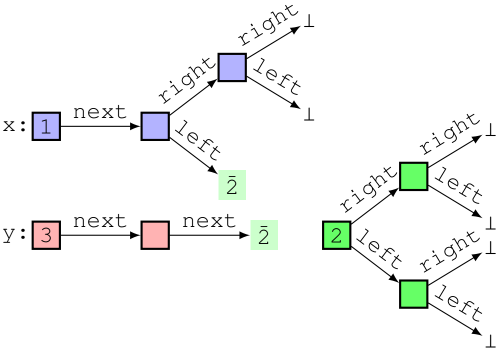
  - Split the heap into tree components
  - References are explicit



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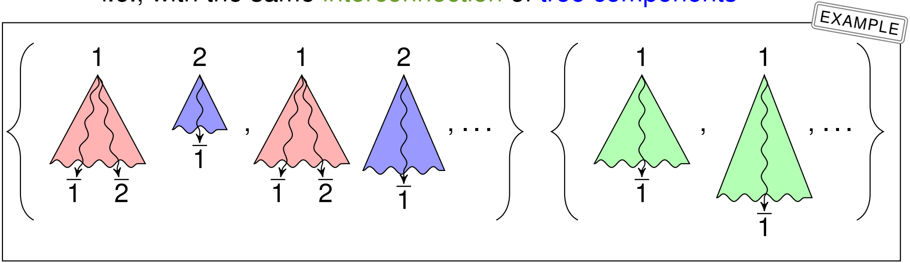

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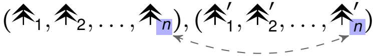

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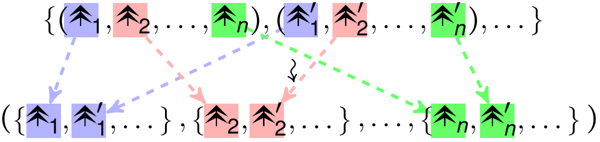

- We assume working with rectangular classes, i.e., for a class C, $(⇞, ⇞), (⇞, ⇞) \in C \Rightarrow (⇞, ⇞), (⇞, ⇞) \in C$, or C is split.

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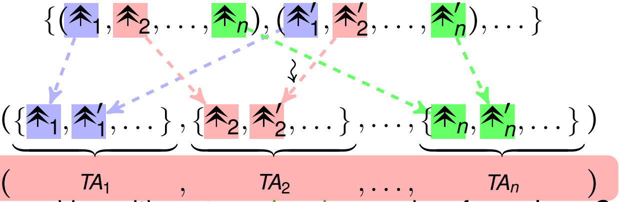

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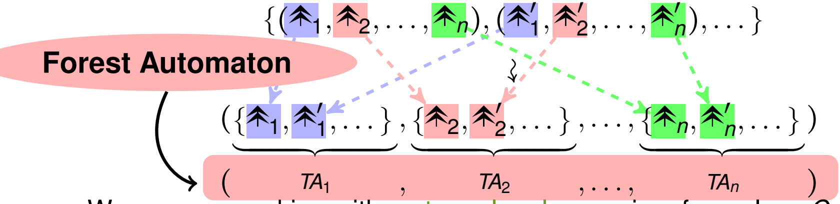

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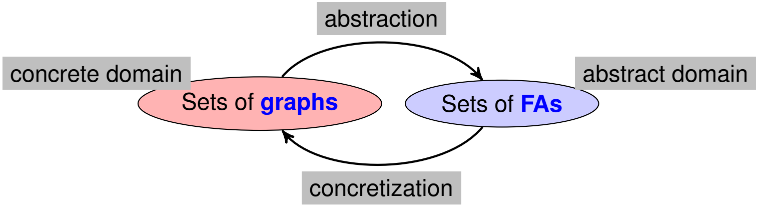

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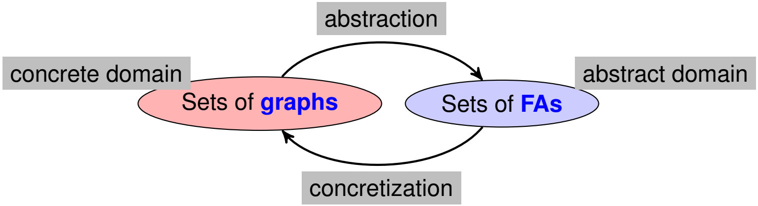

Statements

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

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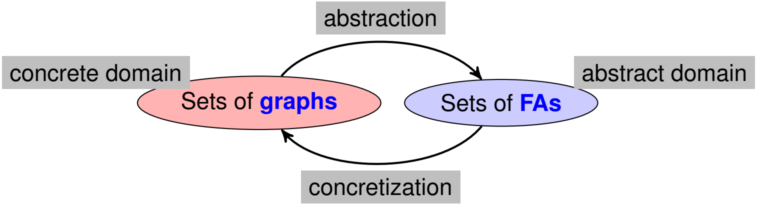

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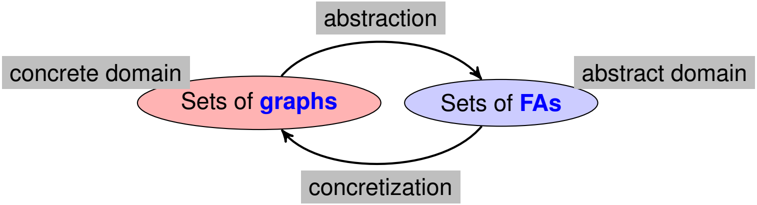

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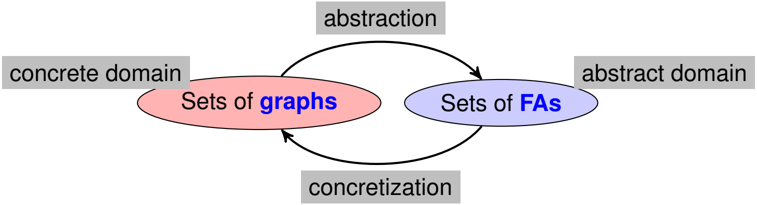

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append a TA (→ `x := new T()`)

remove a TA (→ `delete(x)`)

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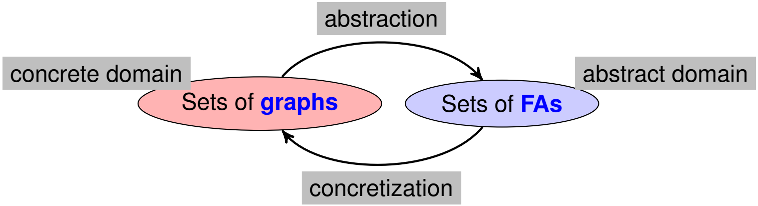

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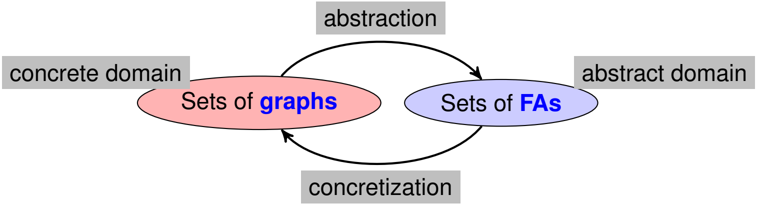

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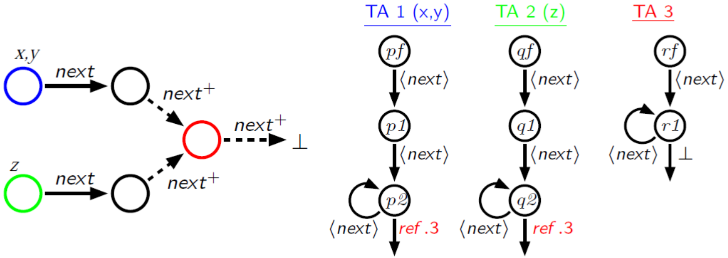
- check symbols on transitions → `if/while (x == y)`

Abstract Transformers for Pointer Updates



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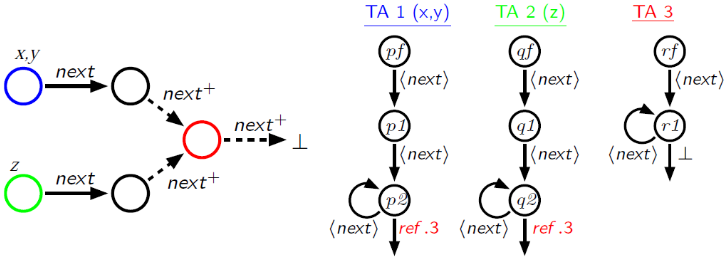

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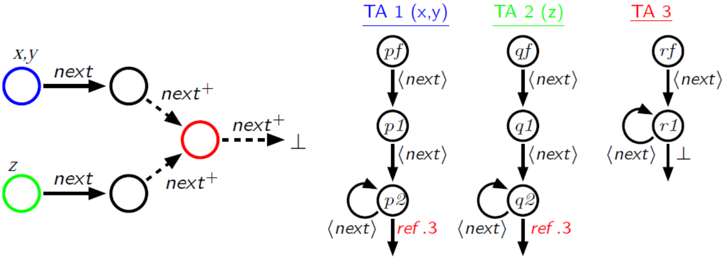

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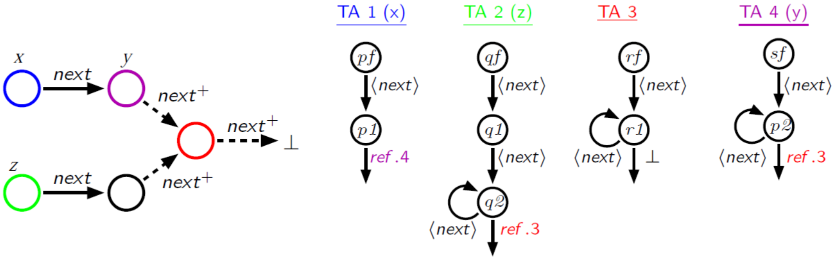

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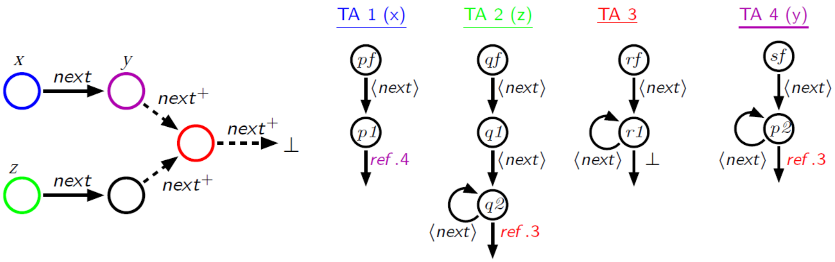

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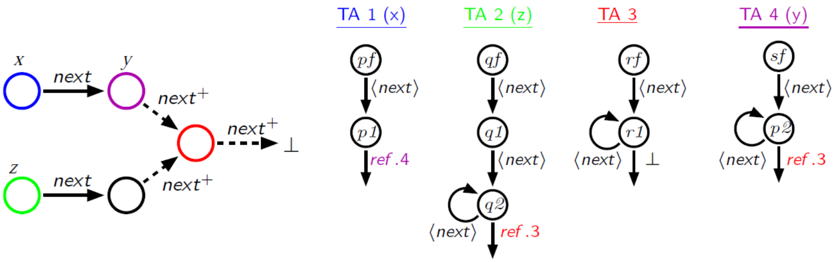

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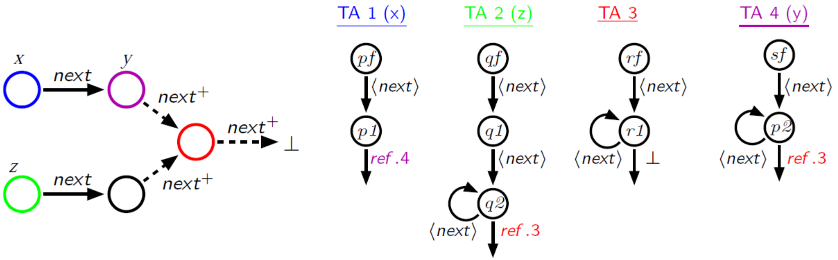

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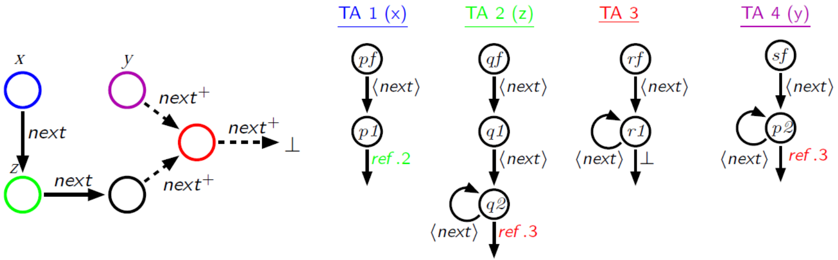

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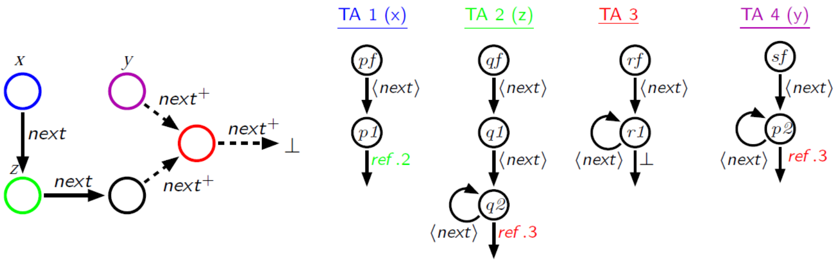

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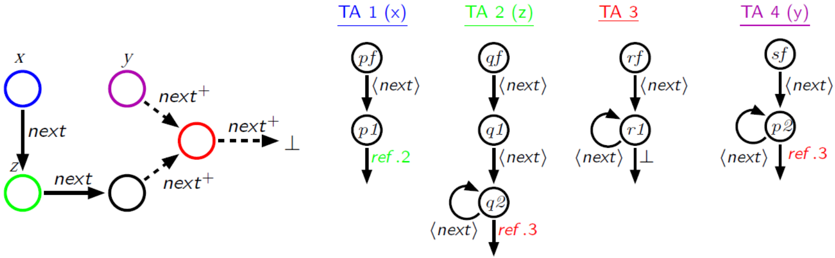

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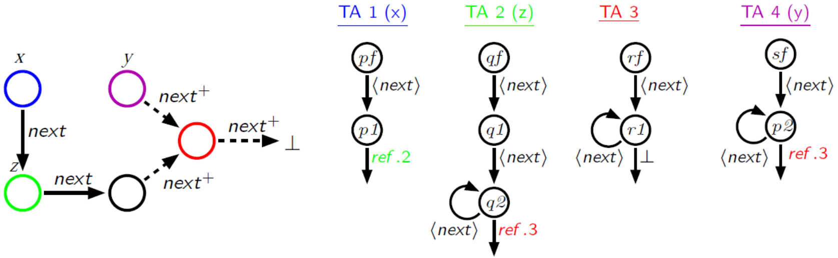

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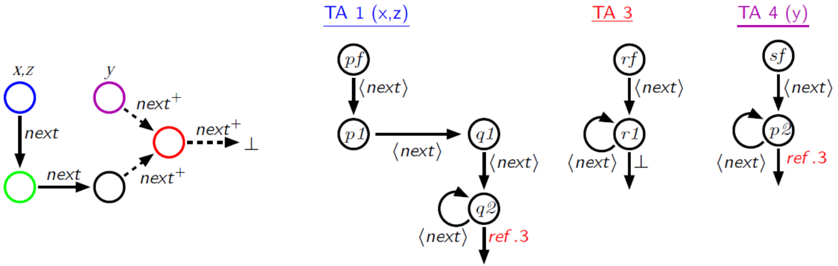

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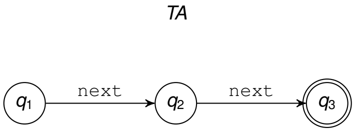

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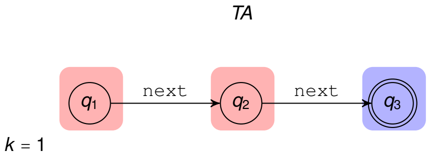

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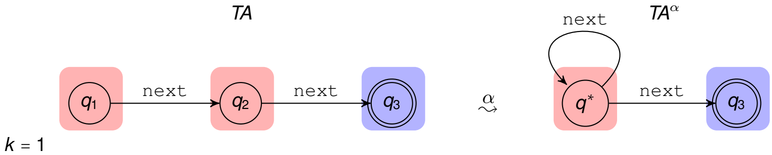

Nondeterministic Tree Automata

- For efficiency reasons, we never determinize TAs.
- All operations done on NTAs, including:
  - inclusion checking: based on antichains and simulations,
    - discarding macro-states during an implicit subset construction,
    - inclusion on (normalized) FA can be checked component-wise —used for detecting the fixpoint
  - size reduction: based on simulation equivalences.
    - collapsing simulation-equivalent states.

Summary

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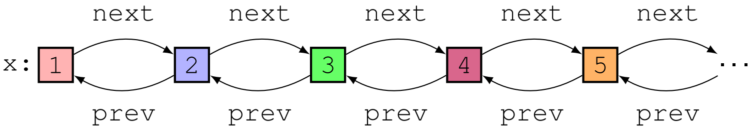
- ☺ works well for singly linked lists (SLLs), trees,
  SLLs with head/tail pointers, trees with root pointers, ...

$$(\Uparrow_1, \Uparrow_2, \ldots, \Uparrow_n) \approx (\Uparrow'_1, \Uparrow'_2, \ldots, \Uparrow'_n)$$

$\ldots$

The so-far-presented:

- ☺ works well for singly linked lists (SLLs), trees, SLLs with head/tail pointers, trees with root pointers, ...
- ☹ fails for more complex data structures
  - unbounded number of cut-points $\rightsquigarrow \infty$ classes of $\mathcal{H}$



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

Hierarchical Forest Automata

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  - FAs are symbols (**boxes**) of FAs of a higher level
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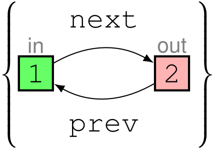

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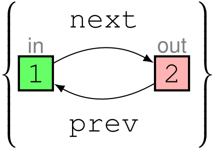

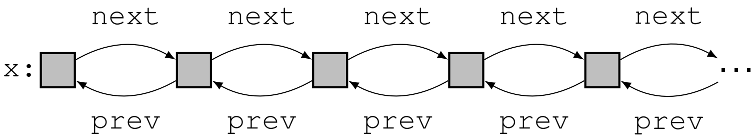

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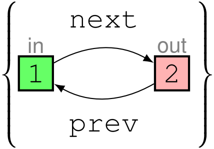

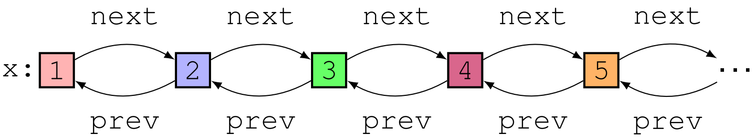

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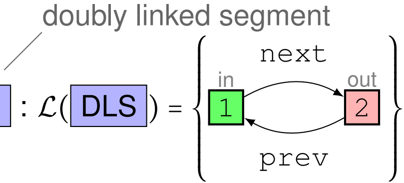

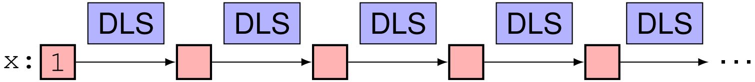

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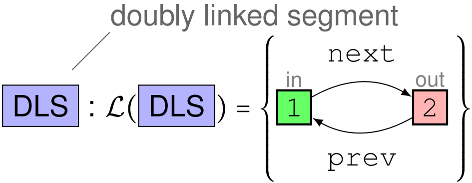

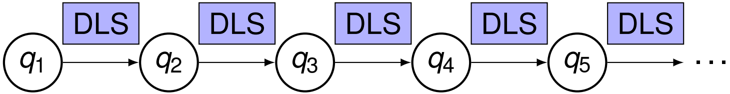

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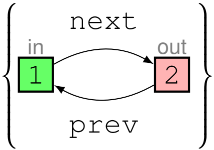

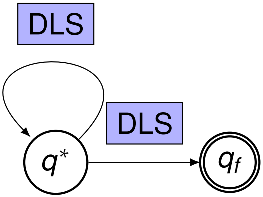

Learning of Boxes

The Challenge

How to find the “right” boxes?

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How to find the "right" boxes?

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

Learning of Boxes

- compromise between

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  - reusability: use on different heaps of the same kind

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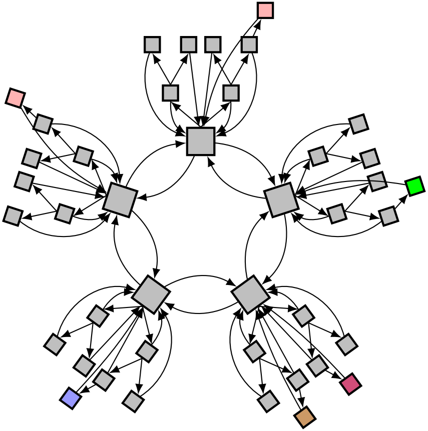

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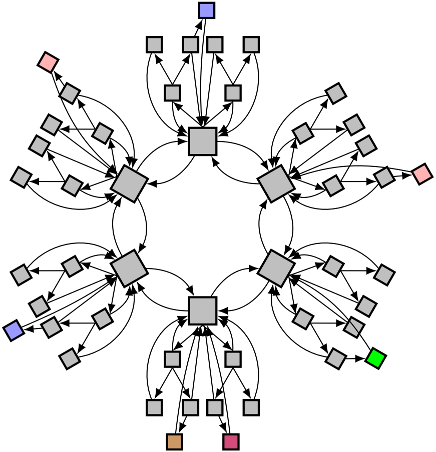

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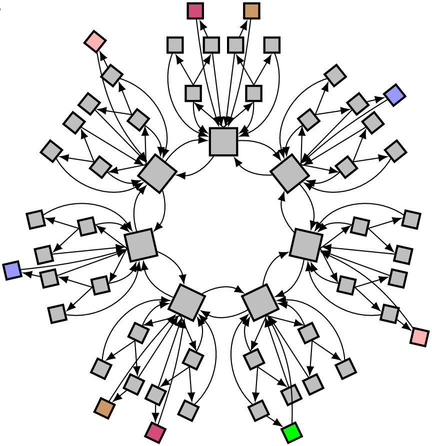

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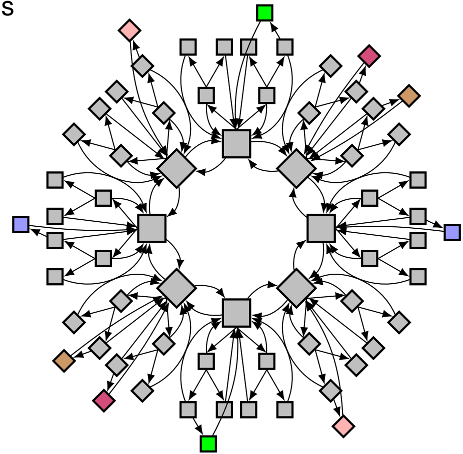

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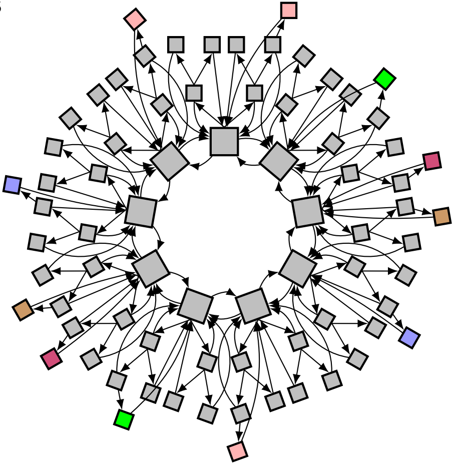

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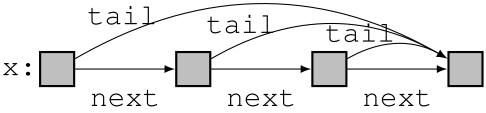

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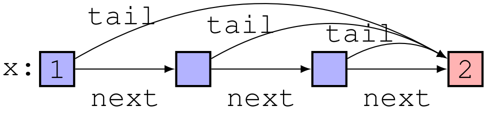

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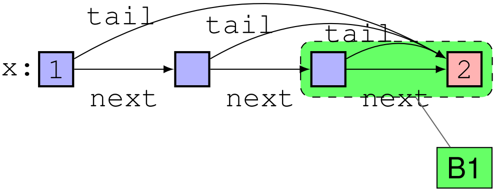

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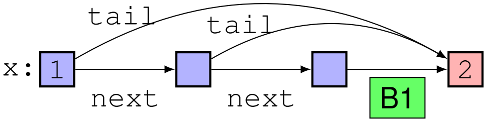

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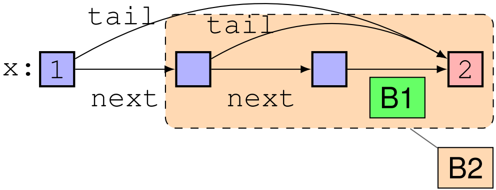

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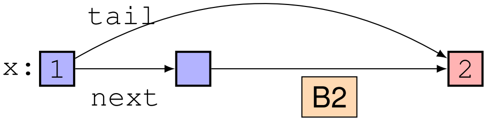

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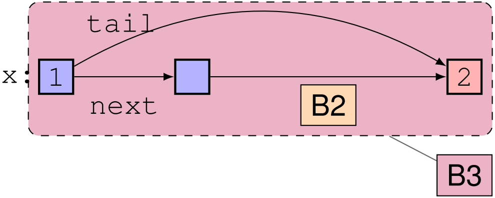

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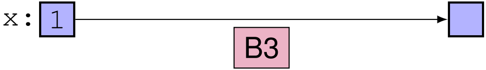

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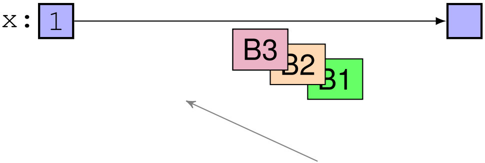
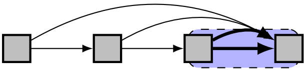
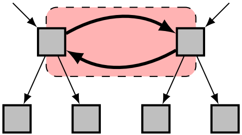


list of any length $\leadsto$ ∞ hierarchy

Learning of Boxes: Knots

1. Smallest subgraphs meaningful to be folded:





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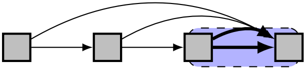

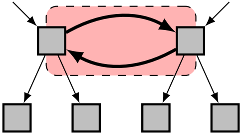

2. Handle interface

Learning of Boxes: Knots

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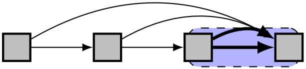
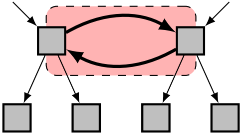
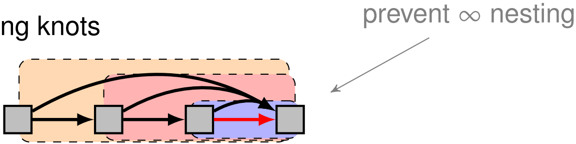




2. Handle interface
   - compose intersecting knots



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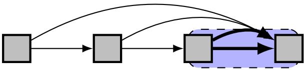

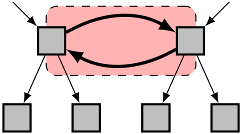

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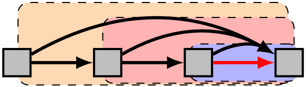
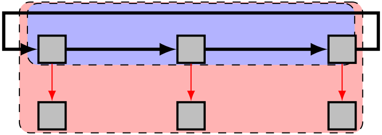


prevent ∞ nesting

   - enclose paths from inner nodes to leaves



prevent ∞ interface nodes

Learning of Boxes: Knots

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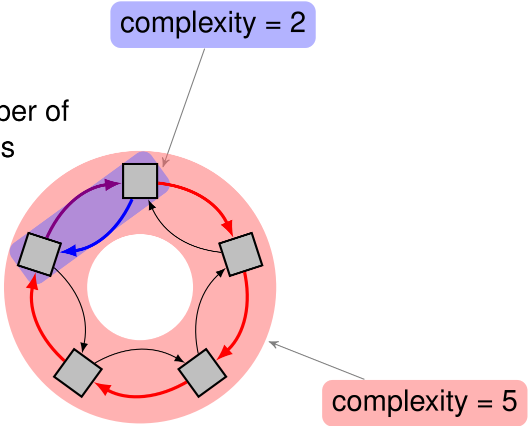

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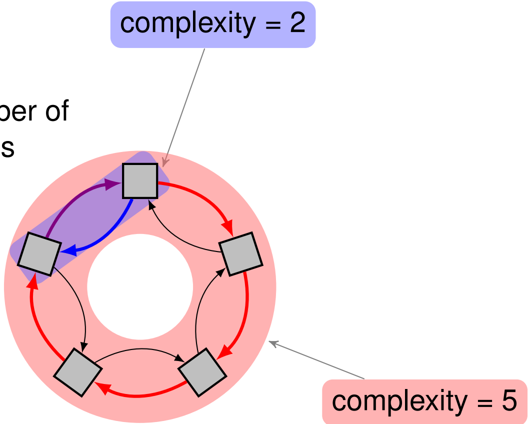

- find basic knots with $1, 2, \ldots$ cut-points

Widening 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.

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

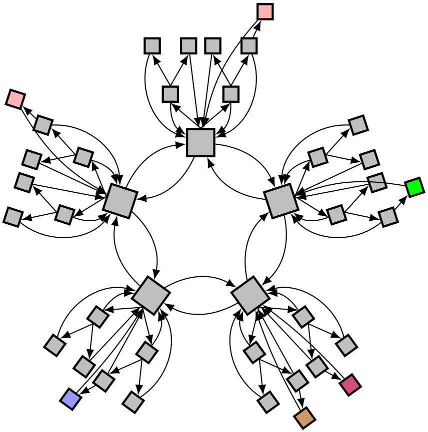
⇒ hide unboundedly many cut-points

Algorithm: Abstraction Loop

Unfold solo boxes
repeat
    Abstract
    Fold
until *fixpoint*

not on a cycle

Learning of Boxes: Example



1. *Unfold solo boxes*
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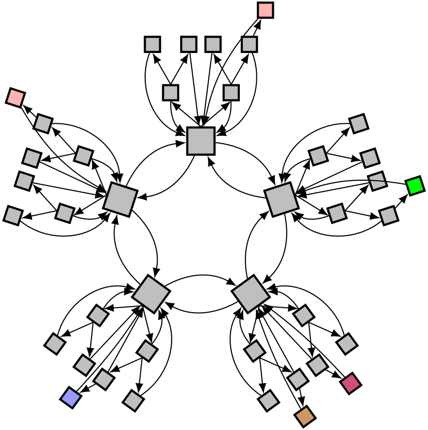
5. **until** *fixpoint*

Learning of Boxes: Example



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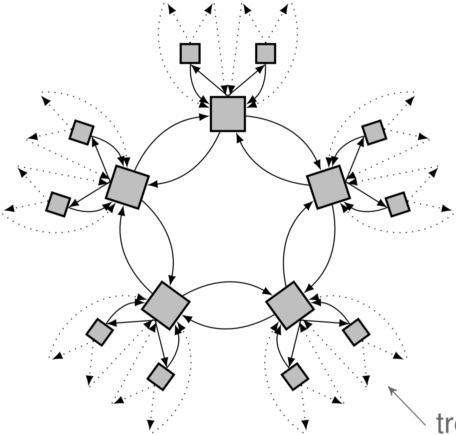

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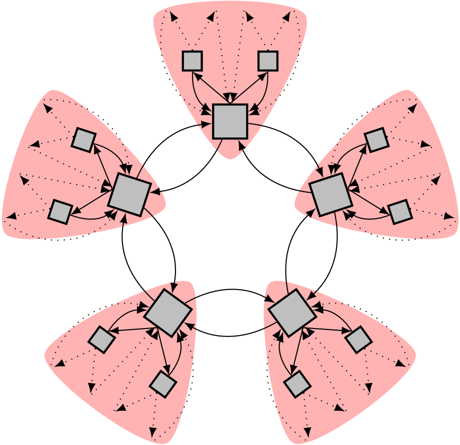
tree with root ptrs of any height

Learning of Boxes: Example



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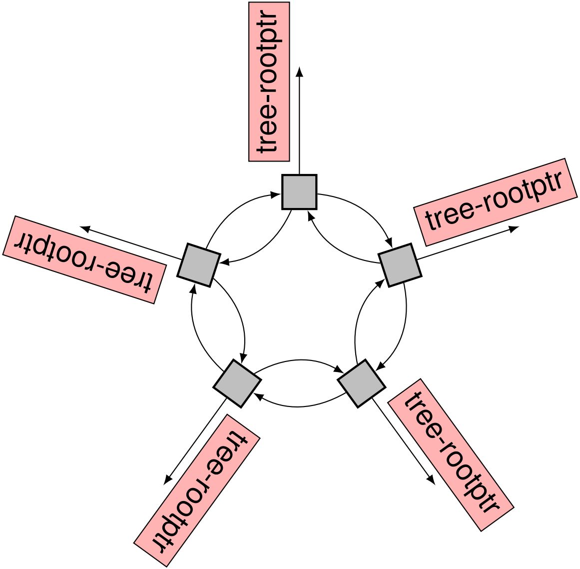

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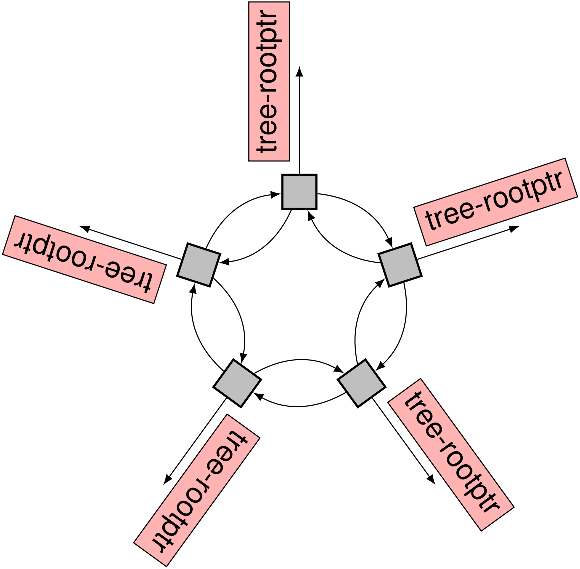

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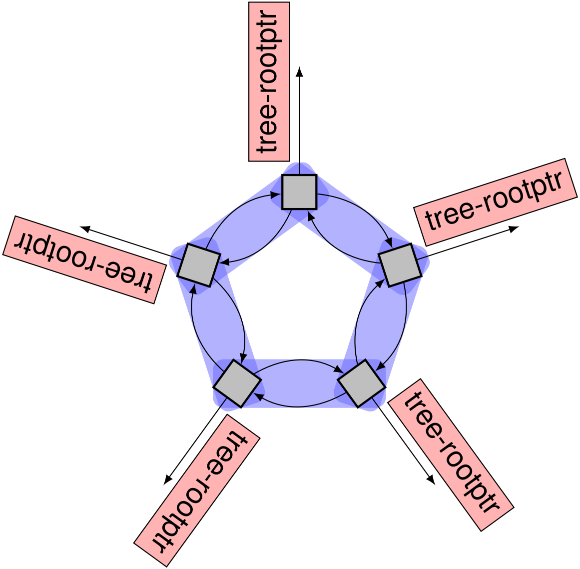

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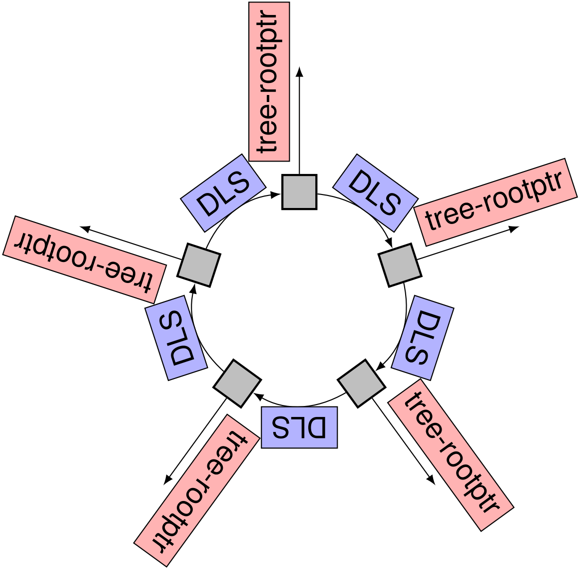

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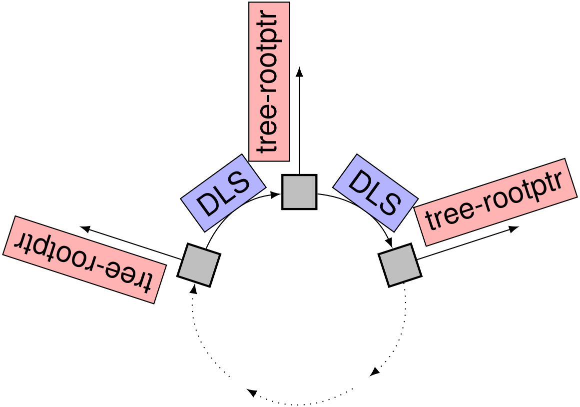

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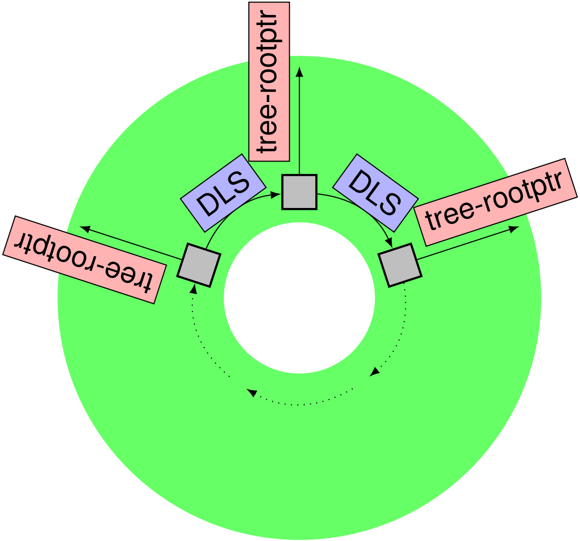

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Learning of Boxes: Example

circular-DLL-of
-trees-rootptr

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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

false positive

Conclusion

Shape analysis with forest automata:

- fully automated
- very flexible framework
- **Forester** tool
- successfully verified:
  - (singly/doubly linked (circular)) lists (of (. . .) lists)
  - trees
  - skip lists
- 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.** In *Proc. of ATVA'13*.

Future work

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