Fully Automated Shape Analysis Based on Forest Automata[†]

Lukáš Holík **Ondřej Lengál** Adam Rogalewicz
Jiří Šimáček Tomáš Vojnar

Brno University of Technology, Czech Republic

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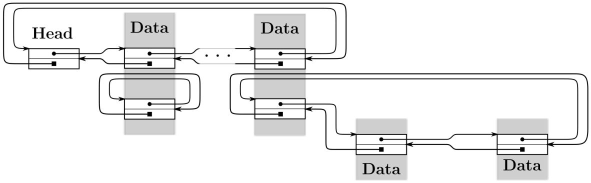
[†]To appear in *Proc. of CAV'13.*

Shape Analysis

- Precise shape analysis:
  - a notoriously difficult problem



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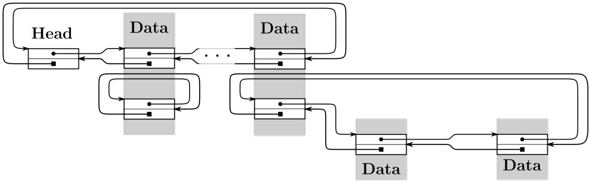

  - specialized solutions (lists)
  - help from the outside (loop invariants, inductive predicates)

- 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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  - ☺ local reasoning, well scalable
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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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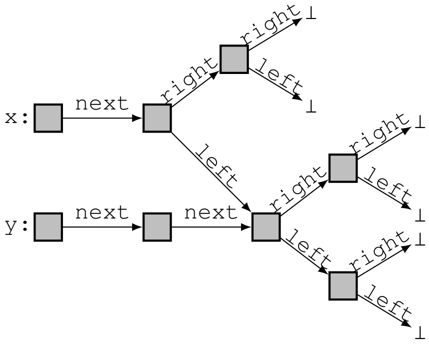
  and
  - ‣ representing sets of heaps using TA

Heap Representation

- Forest decomposition of a heap



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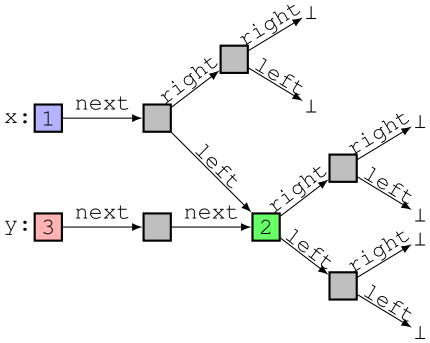

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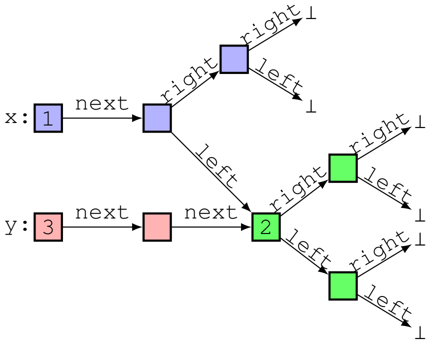

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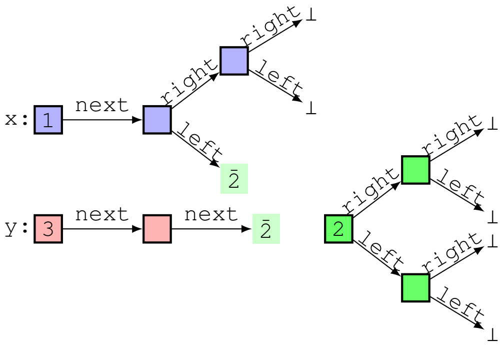

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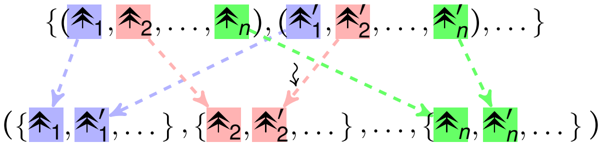

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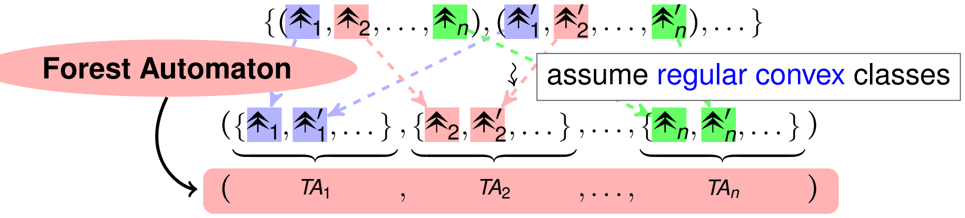

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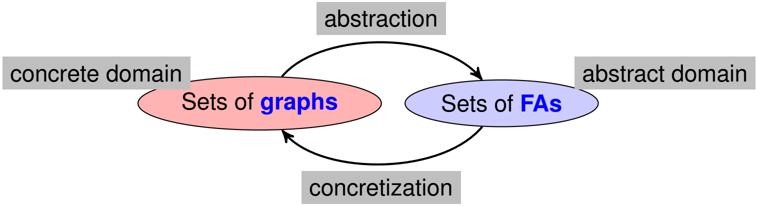
- Abstract Interpretation



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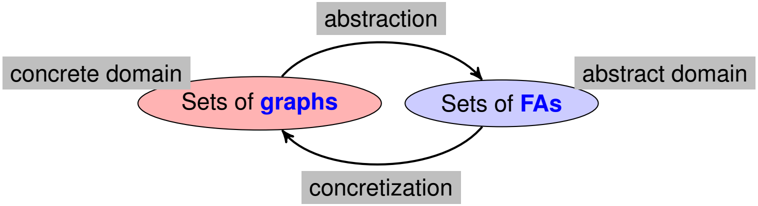

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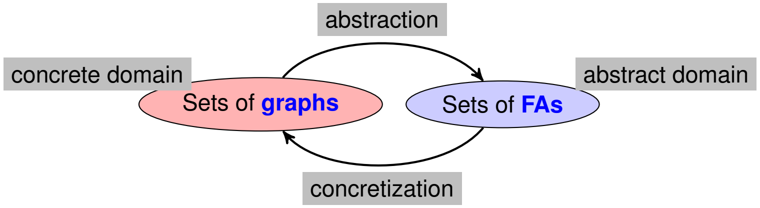

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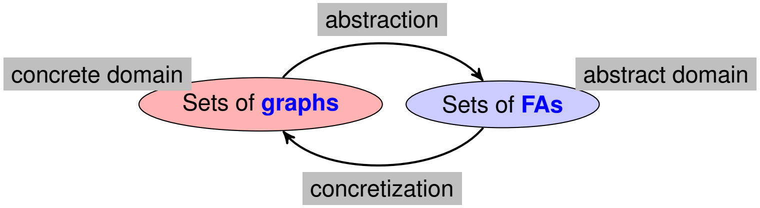

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append a TA

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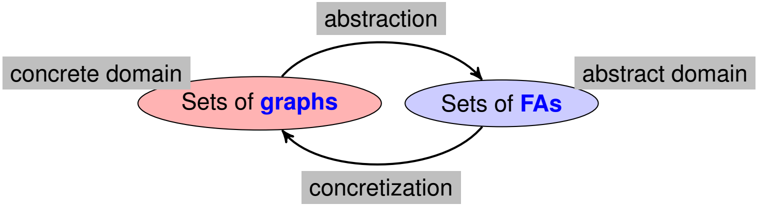

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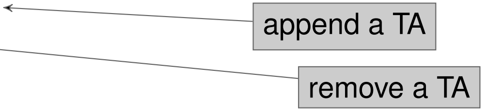

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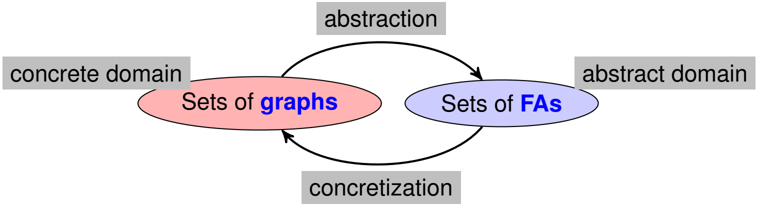

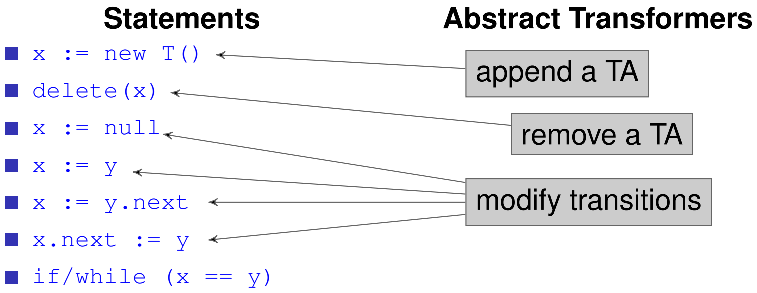

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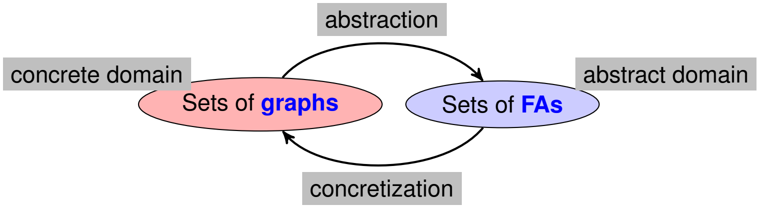

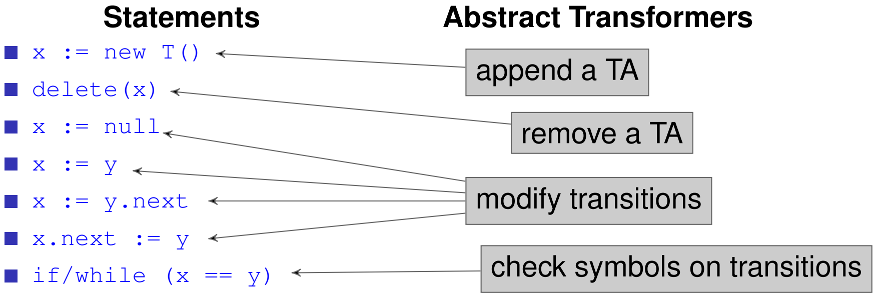

Statements — **Abstract Transformers**

- `x := new T()` ← append a TA
- `delete(x)` ← remove a TA
- `x := null` ← modify transitions
- `x := y` ← modify transitions
- `x := y.next` ← modify transitions
- `x.next := y` ← modify transitions
- `if/while (x == y)` ← check symbols on transitions

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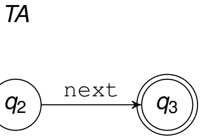

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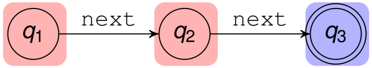

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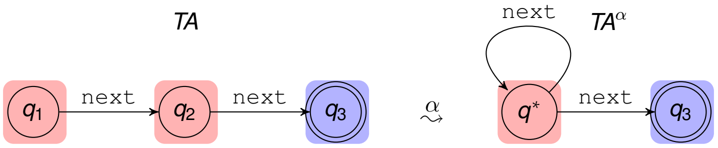

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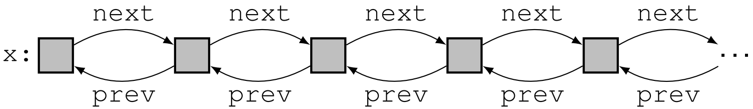

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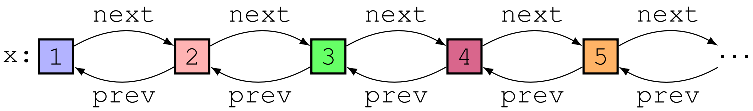

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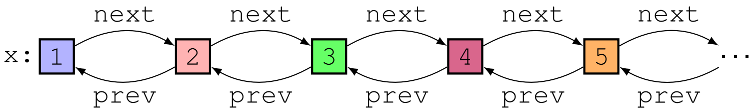

- doubly linked lists (DLLs), circular lists, nested lists,
- trees with parent pointers,
- skip lists

Hierarchical Forest Automata

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doubly linked segment

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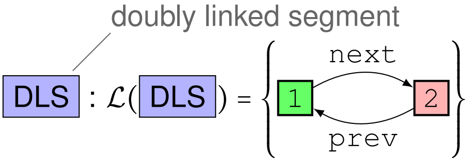

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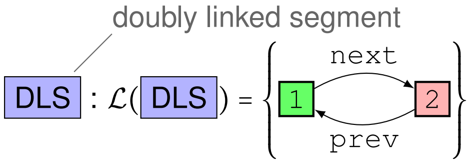
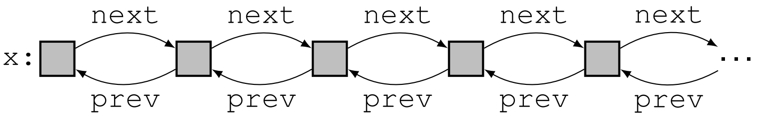
  - FAs are symbols (**boxes**) of FAs of a higher level
  - a hierarchy of FAs
  - Intuition: replace repeated subgraphs with a single symbol

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





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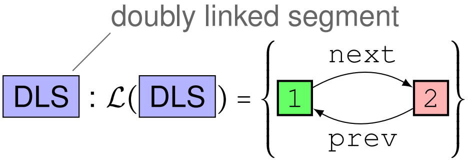

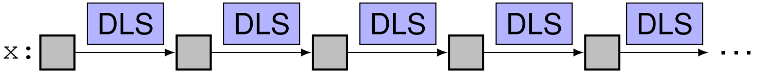

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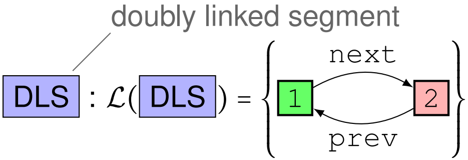

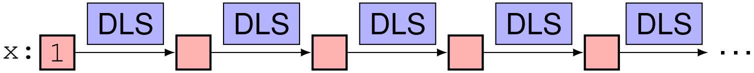

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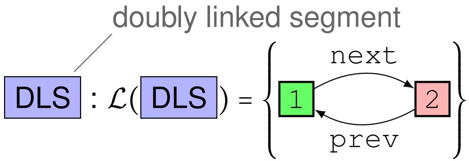

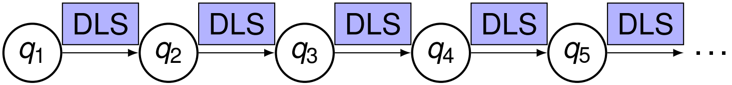

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doubly linked segment

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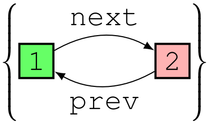

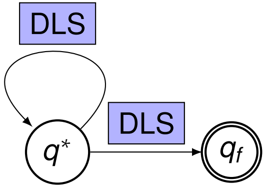

Learning of Boxes

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

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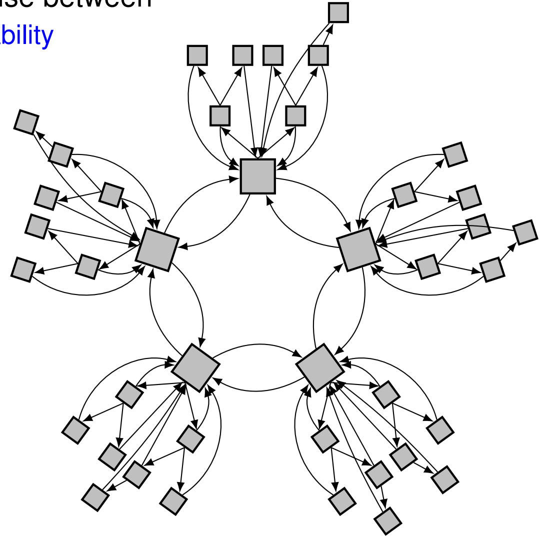

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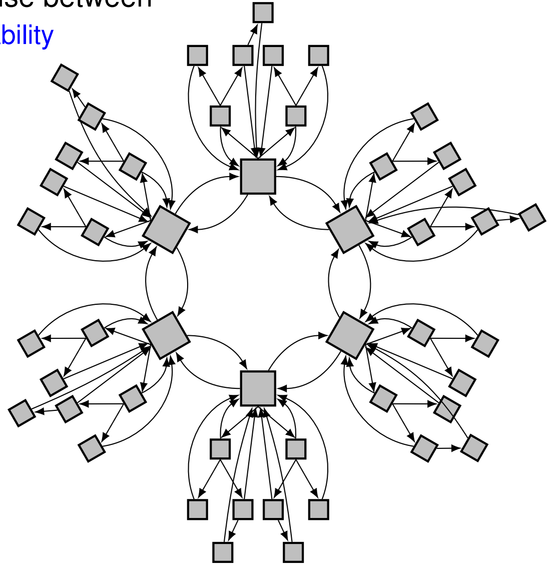

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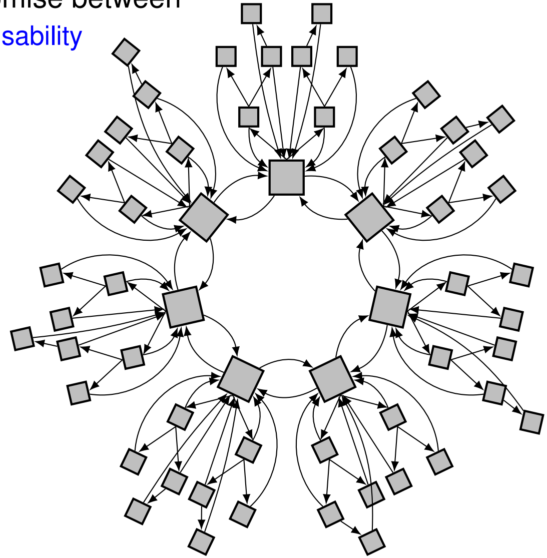

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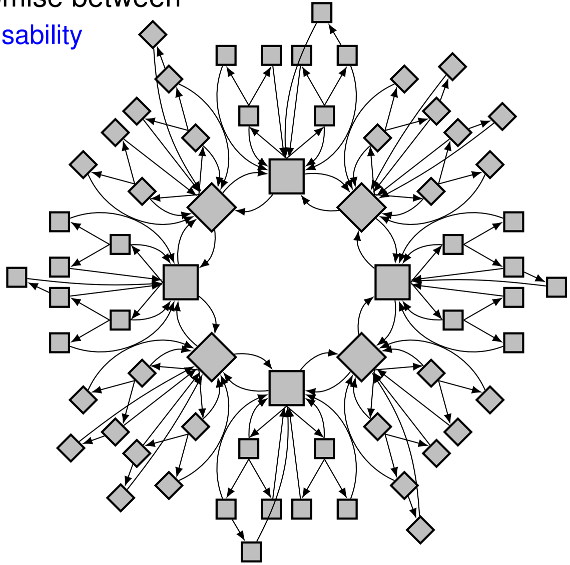

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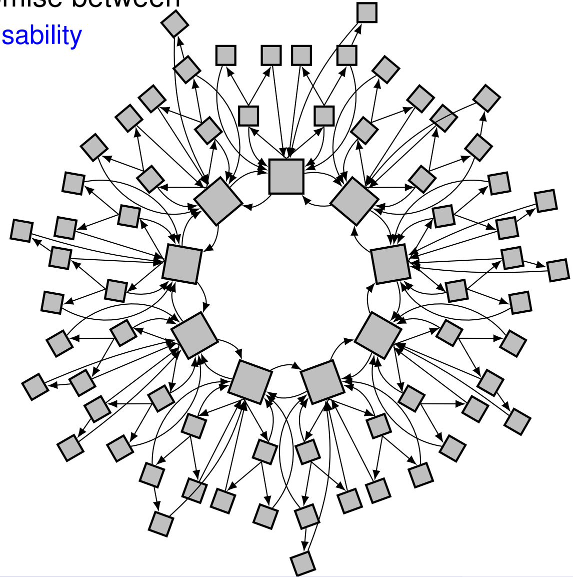

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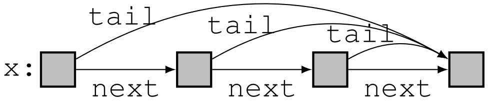

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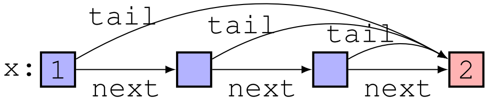

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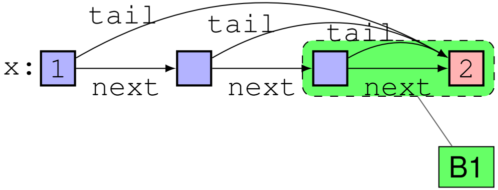

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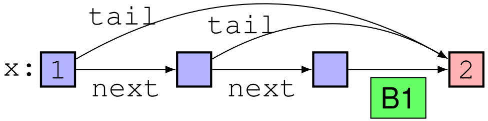

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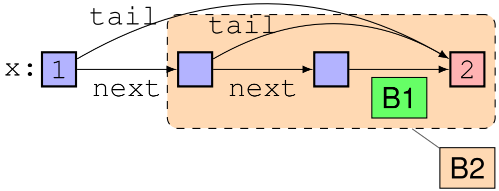

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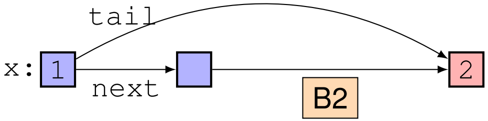

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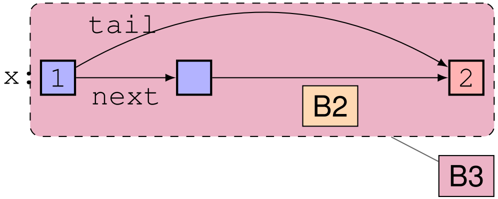

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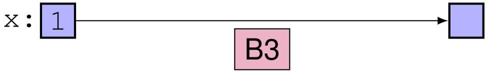

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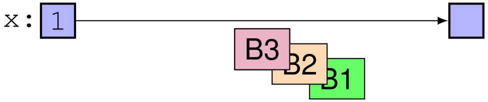

Learning of Boxes: Knots

Knots

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Knots

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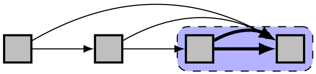

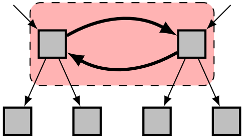

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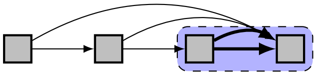

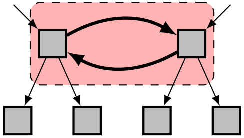

2. handle inputs/outputs

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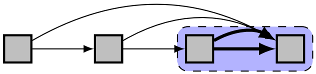

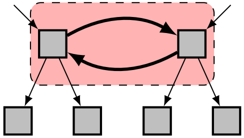

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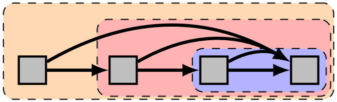

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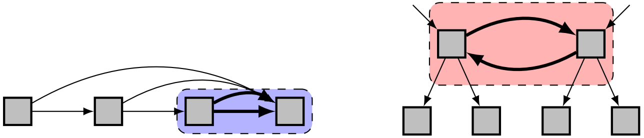

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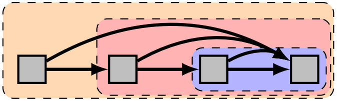
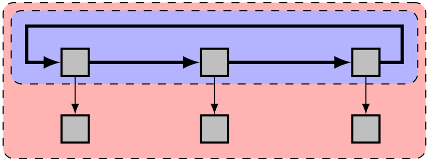


   - enclose paths from inner nodes to leaves



Learning of Boxes: Knots

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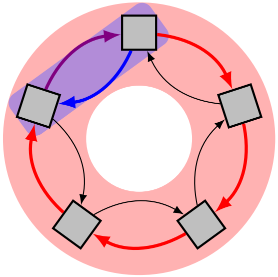

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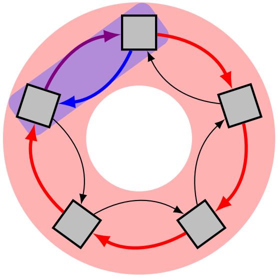

- find basic knots with $1, 2, \ldots$ cut-points

Widening Revisited

- learning and folding of boxes in the abstraction loop

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The Goal

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$\Rightarrow$ hide unboundedly many cut-points

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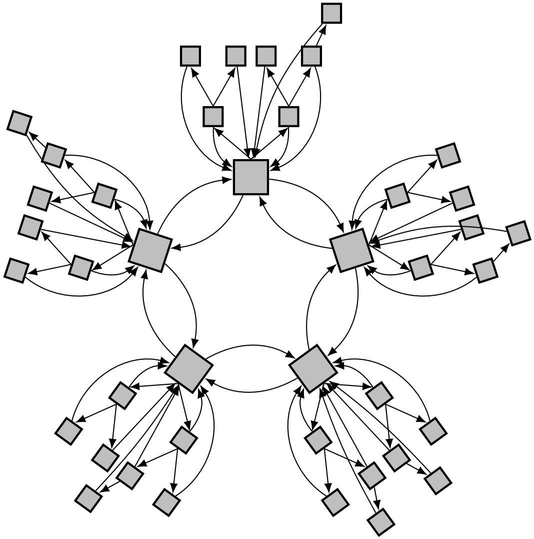
```
1 Algorithm: Abstraction Loop
2 Unfold solo boxes
3 repeat
4     Abstract
5     Fold
6 until fixpoint
```

not on a cycle

Learning of Boxes: Example



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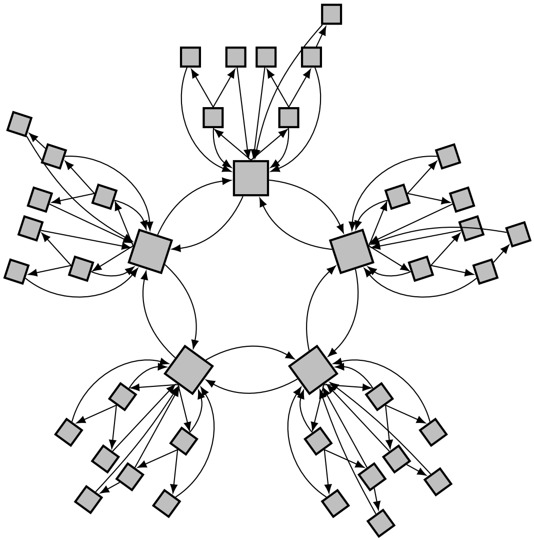

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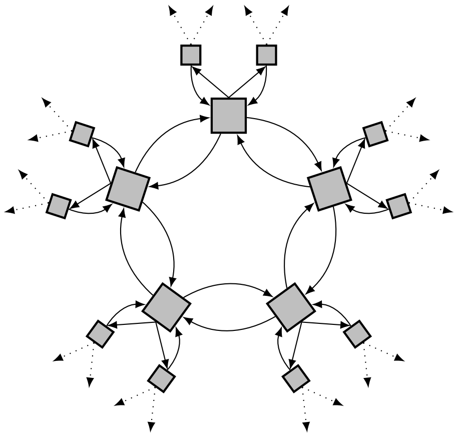

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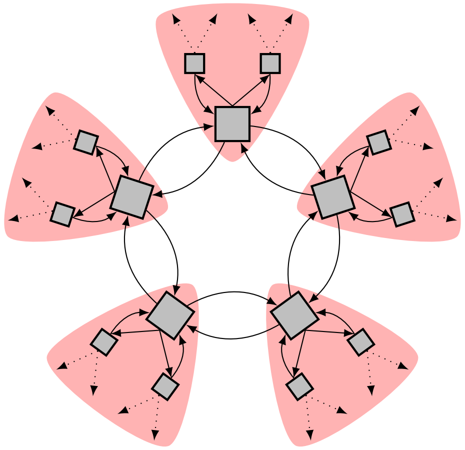

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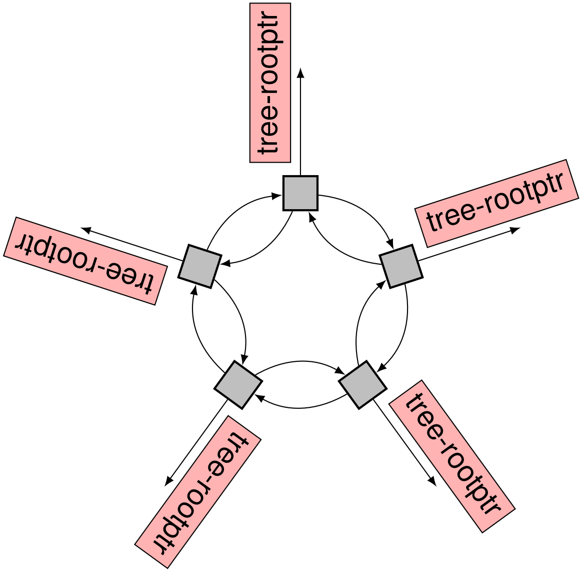

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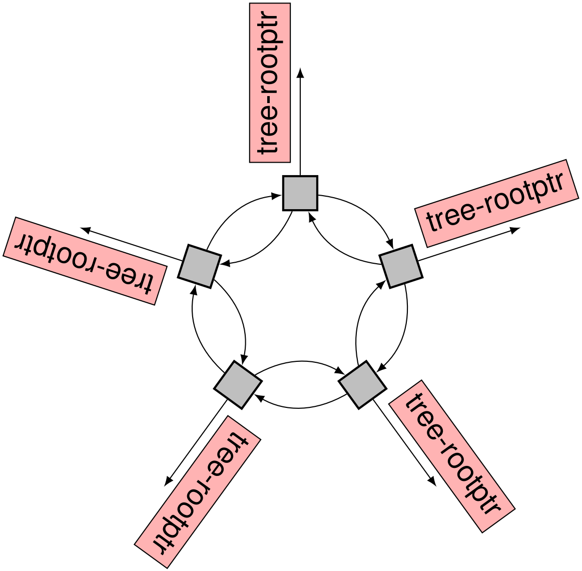

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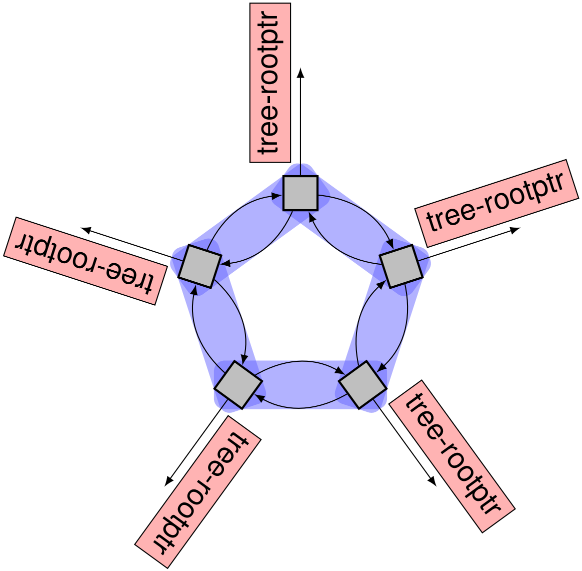

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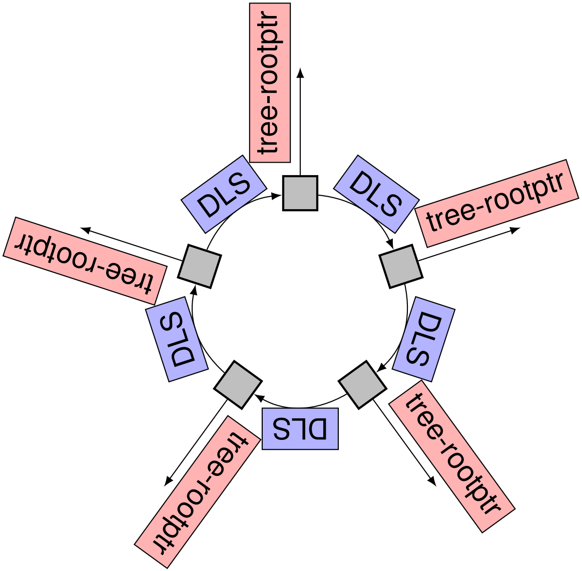

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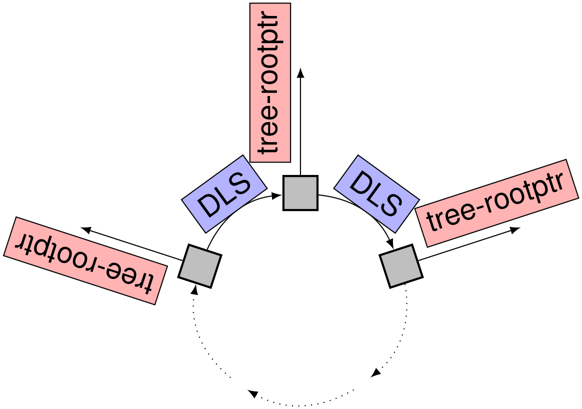

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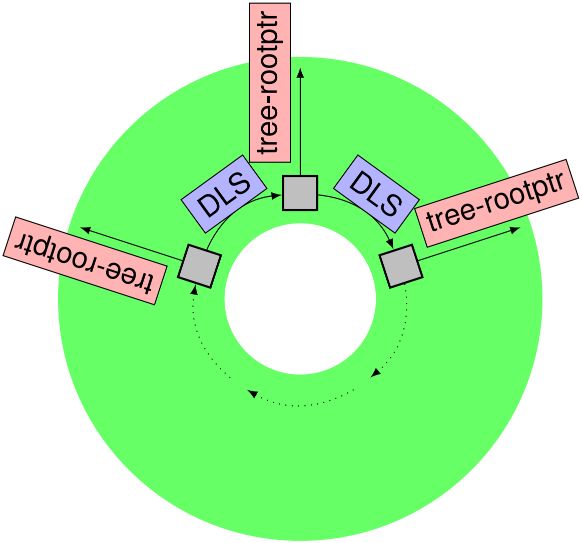

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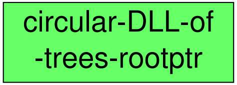

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Table : Results of the experiments [s]

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
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 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:

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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

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- recursive boxes
  - B+ trees, . . .