Fully Automated Shape Analysis Based on Forest Automat

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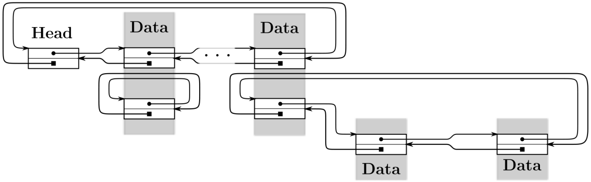
Shape Analysis

- 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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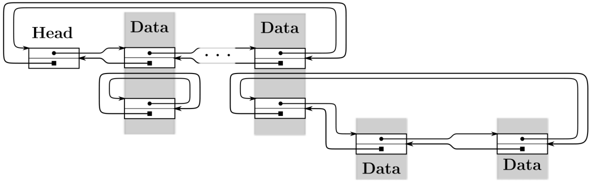

  - memory safety: invalid dereferences, double free, memory leakage
  - error line reachability (assertions), shape invariance (testers), ...

- Existing solutions:
  - often specialized (lists)
  - require human help (loop invariants, inductive predicates)
  - low scalability
  - ⇒ still quite far from a general push-button solution

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: limited scalability

The Forest Automata-based Approach

Forest Automata

- Combine
  - ☺ flexibility of ARTMC

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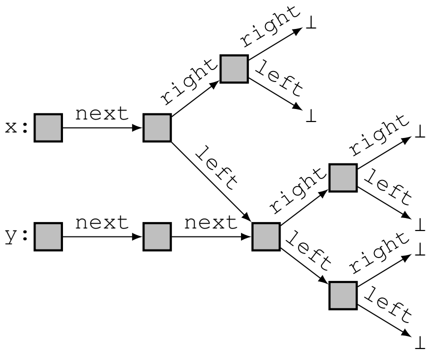
  and
  - using tree automata to represent sets of tree components of heaps

Heap Representation

- Forest decomposition of a heap



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  - Identify cut-points ← nodes referenced:
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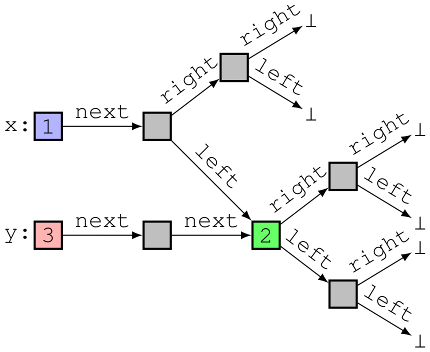

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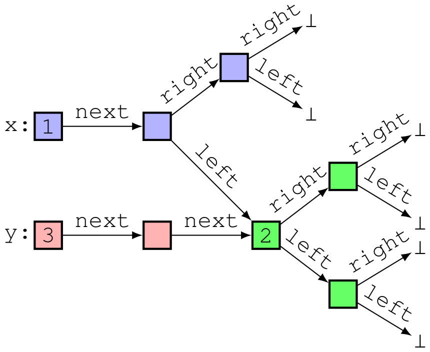

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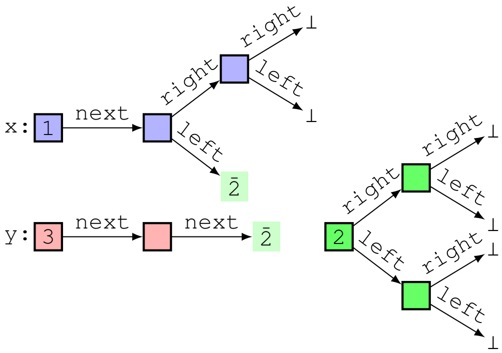

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- Cartesian representation of forests in $\mathcal{H}$:

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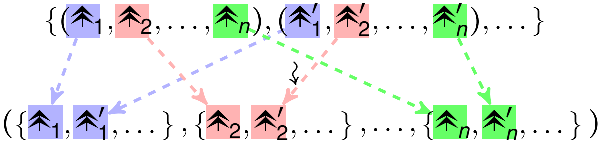

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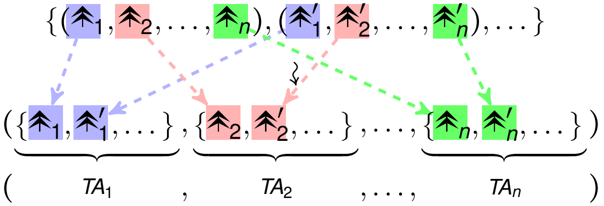

$$\{(⇞_1, ⇞_2, \ldots, ⇞_n), (⇞'_1, ⇞'_2, \ldots, ⇞'_n), \ldots\}$$

$$\wr$$

$$(\underbrace{\{⇞_1, ⇞'_1, \ldots\}}_{TA_1}, \underbrace{\{⇞_2, ⇞'_2, \ldots\}}_{TA_2}, \ldots, \underbrace{\{⇞_n, ⇞'_n, \ldots\}}_{TA_n})$$

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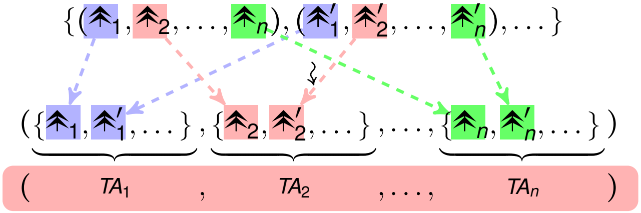

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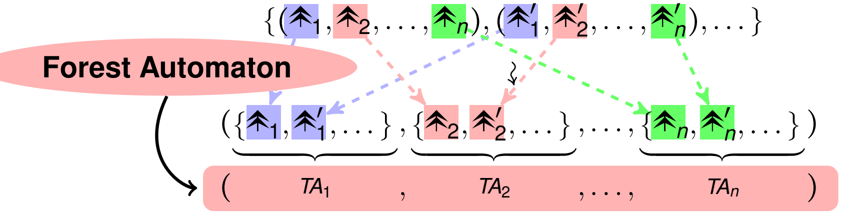

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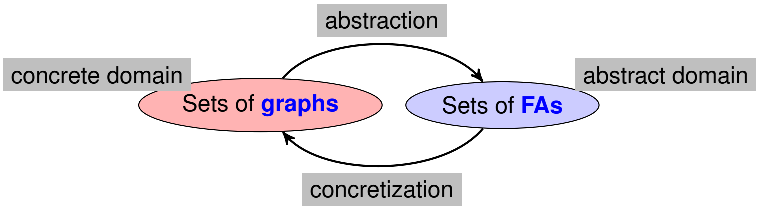

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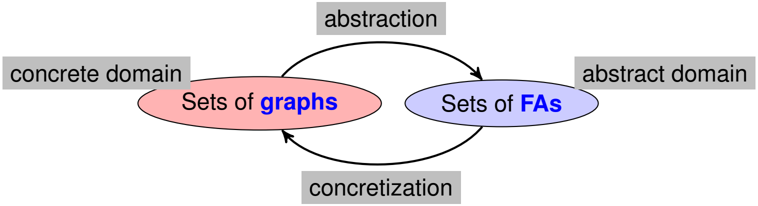

Statements

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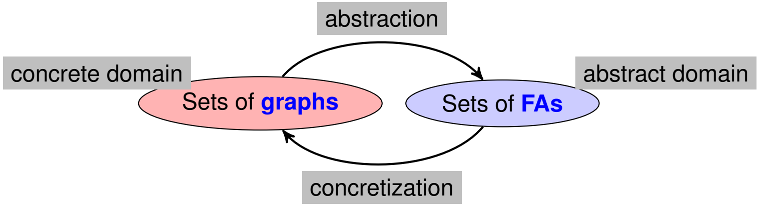

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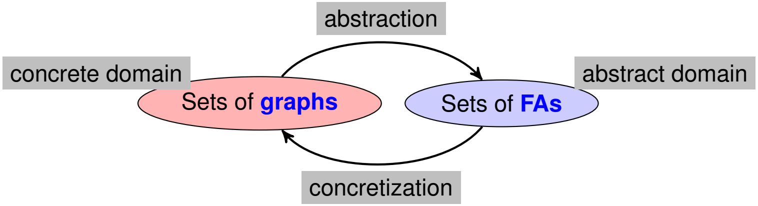

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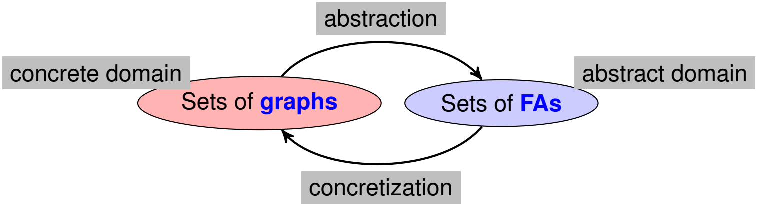

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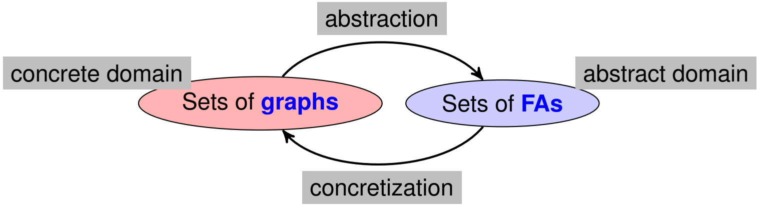

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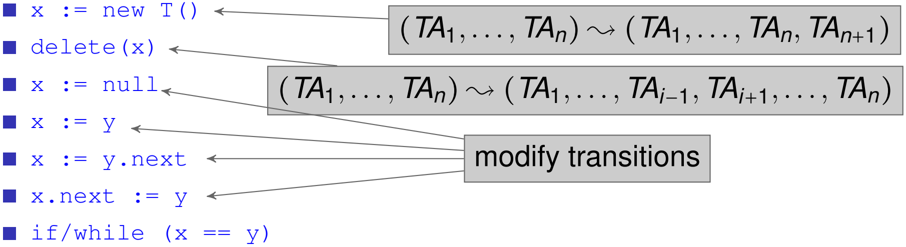

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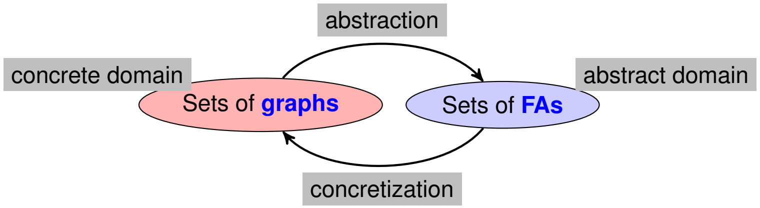
modify transitions

Abstract Interpretation



Statements **Abstract Transformers**

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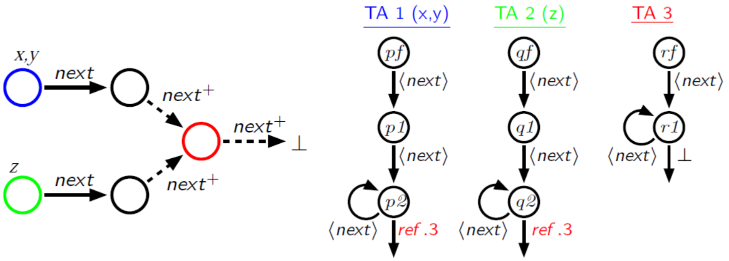
- `delete(x)` ← $(TA_1, \ldots, TA_n) \rightsquigarrow (TA_1, \ldots, TA_{i-1}, TA_{i+1}, \ldots, TA_n)$
- `x := null` ← modify transitions
- `x := y` ← modify transitions
- `x := y.next` ← modify transitions
- `x.next := y` ← modify transitions
- `if/while (x == y)` ← check symbols on transitions

Abstract Transformers for Pointer Updates



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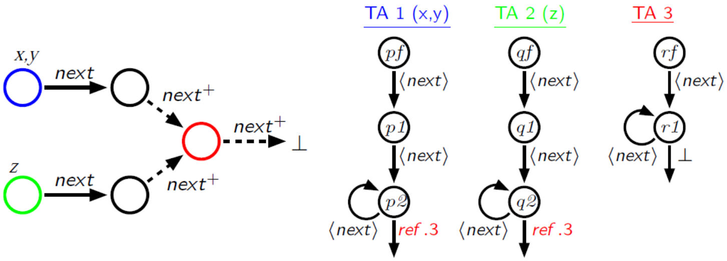

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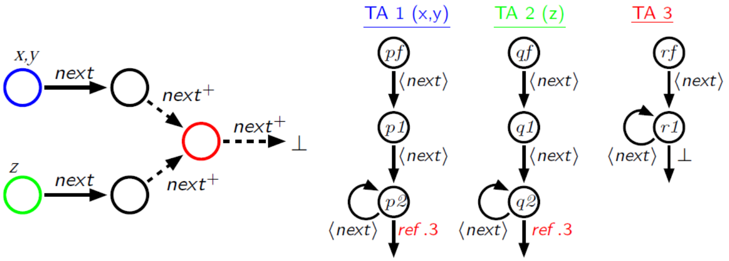

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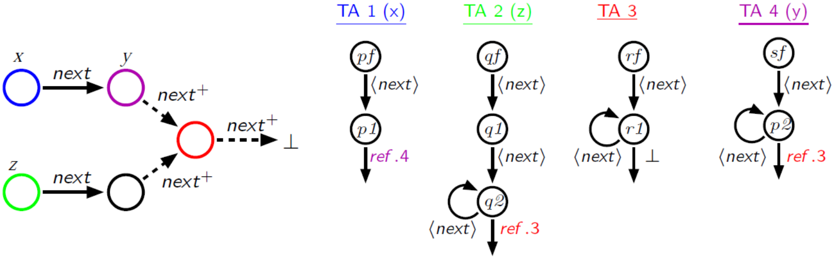

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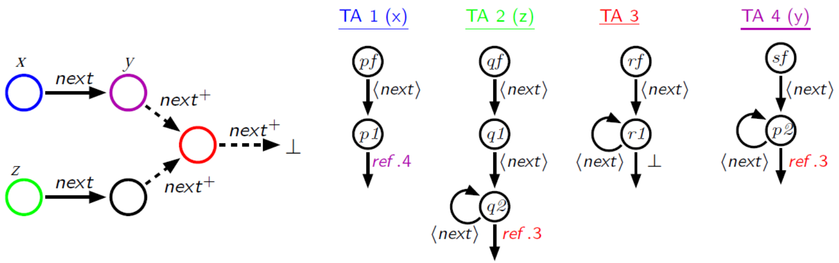

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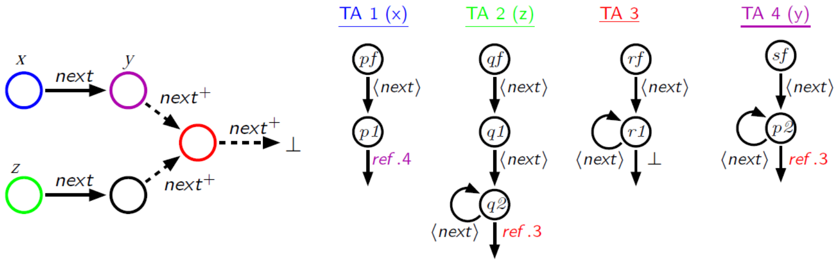

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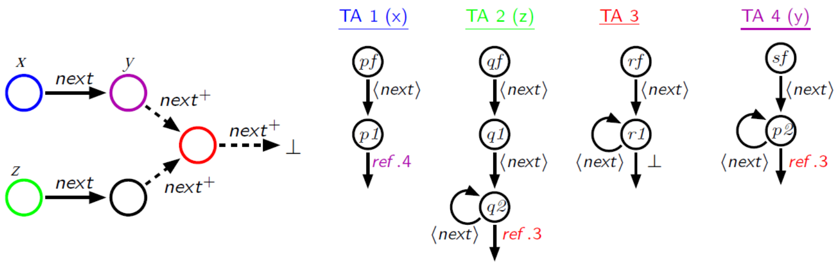

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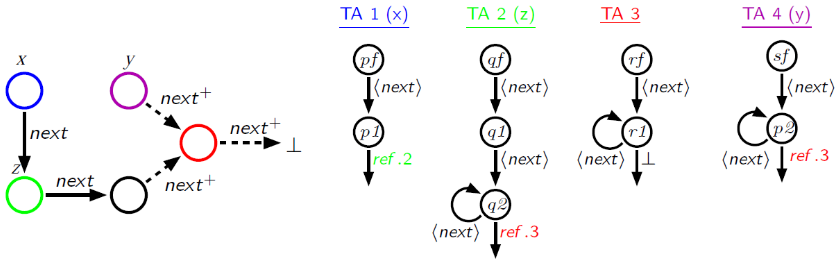

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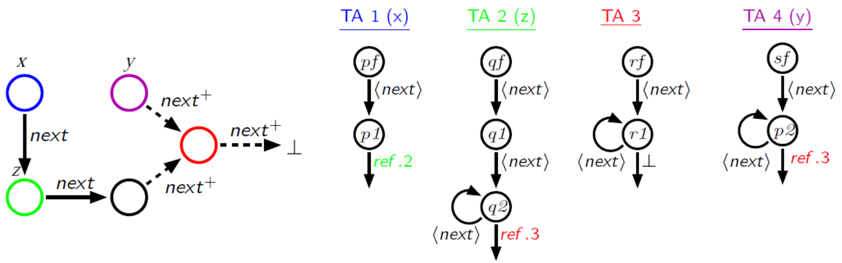

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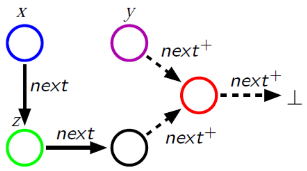

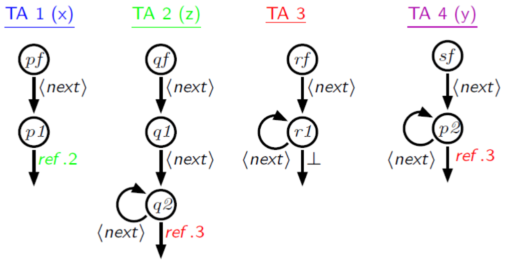

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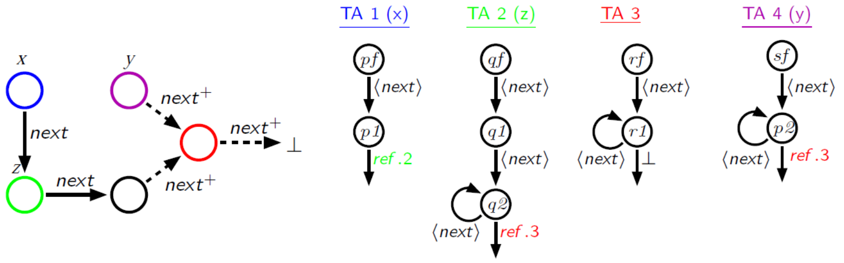

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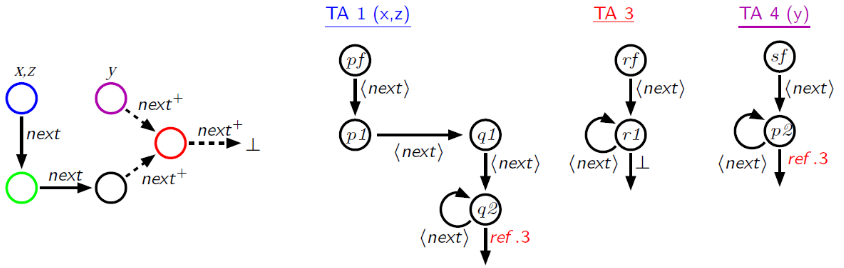

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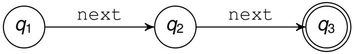
TA



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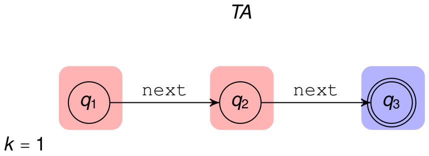

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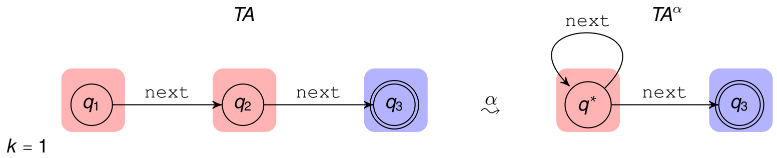

Nondeterministic Tree Automata

- 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,
  - size reduction: based on simulation equivalences.
    - collapsing simulation-equivalent states.

Summary

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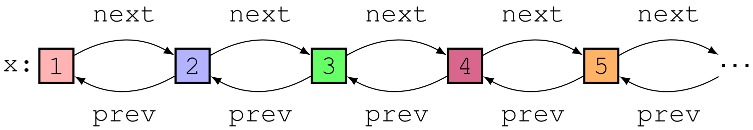
- ☺ works well for singly linked lists (SLLs), circular lists, trees, SLLs with head/tail pointers, trees with root pointers, ...
- ☹ fails for more complex data structures
  - unbounded number of cut-points $\rightsquigarrow$
    heaps with different numbers of cut-points need to be treated separately



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

Hierarchical Forest Automata

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doubly linked segment

- Example: a box $\boxed{\text{DLS}}$

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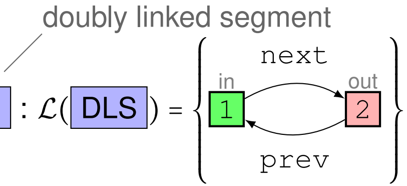
- Example: a box $\boxed{\text{DLS}}$: $\mathcal{L}(\boxed{\text{DLS}}) =$



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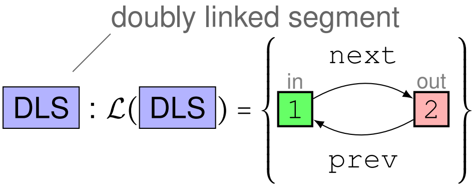

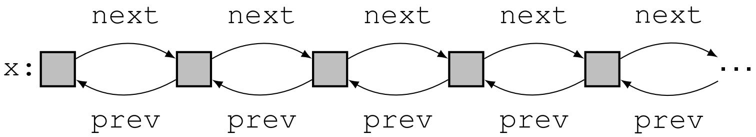

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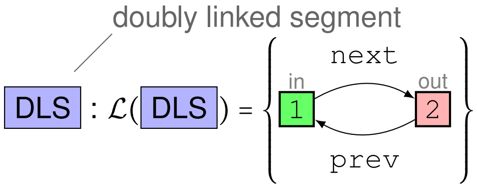

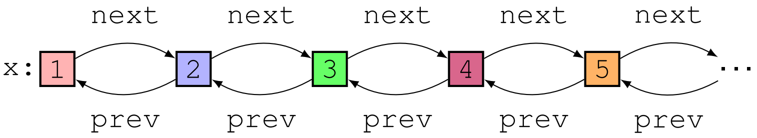

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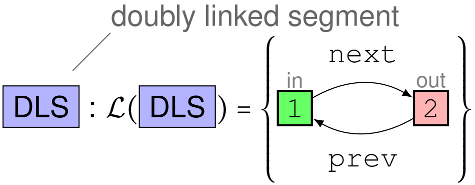

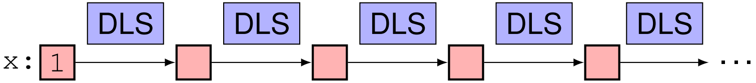

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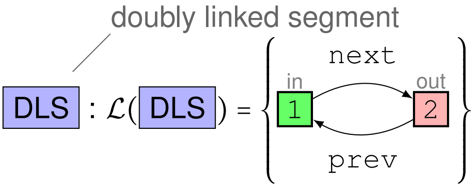

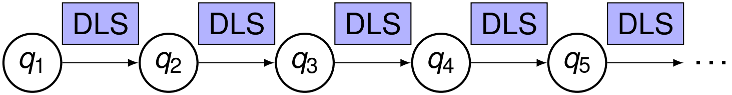

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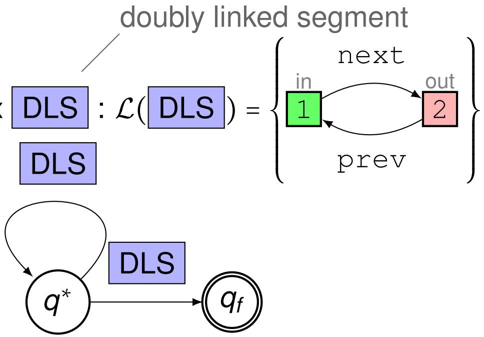

Learning of Boxes

The Challenge

How to find the "right" boxes?

Learning of Boxes

The Challenge

How to find the “right” boxes?

- database of boxes
- automatic discovery

Learning of Boxes

- compromise between

Learning of Boxes

- compromise between
  - reusability: use on different heaps of the same kind
    $\leadsto$ use small boxes

Learning of Boxes

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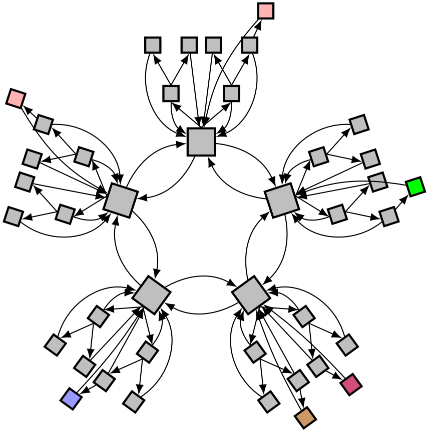

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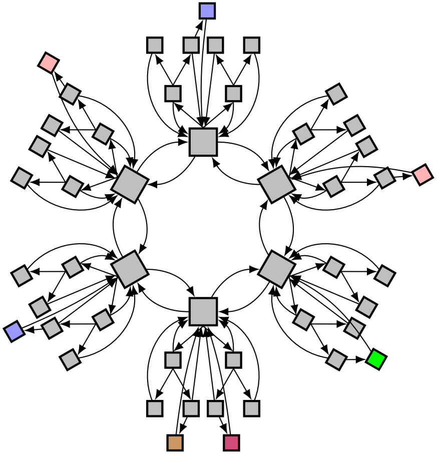

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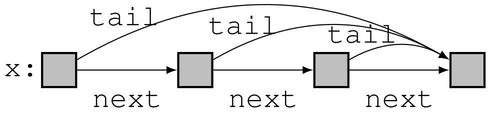

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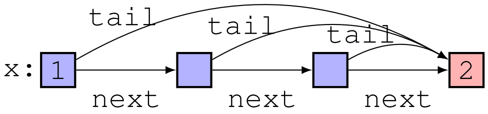

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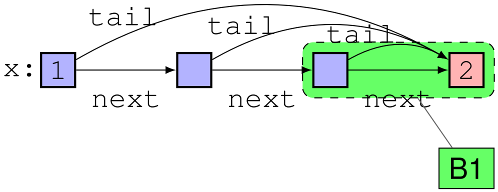

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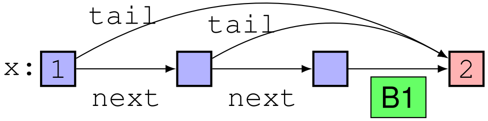

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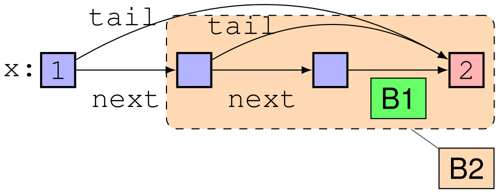

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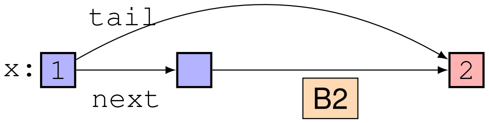

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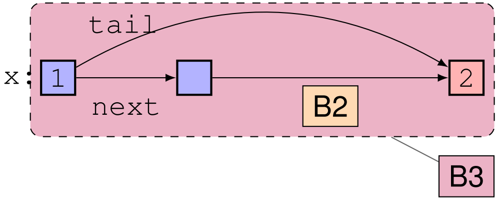

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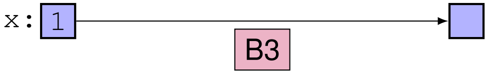

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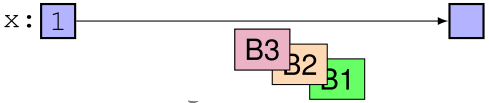
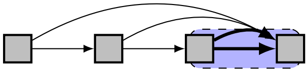
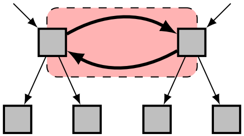


list of any length $\leadsto$ ∞ hierarchy

Learning of Boxes: Knots

1. Smallest subgraphs meaningful to be folded:





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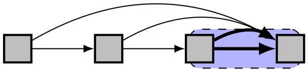
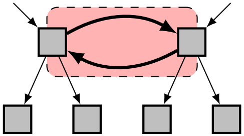

2. Handle interface

Learning of Boxes: Knots

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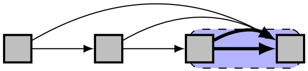
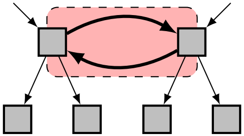

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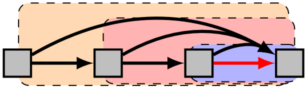
    - compose intersecting knots



prevent ∞ nesting

Learning of Boxes: Knots

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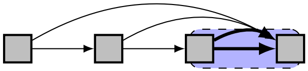

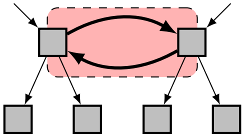

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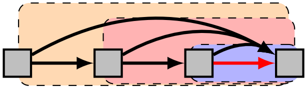
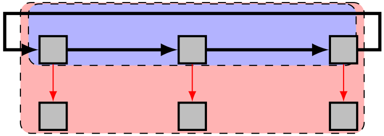


   - enclose paths from inner nodes to leaves



prevent ∞ nesting

prevent ∞ interface nodes

Learning of Boxes: Knots

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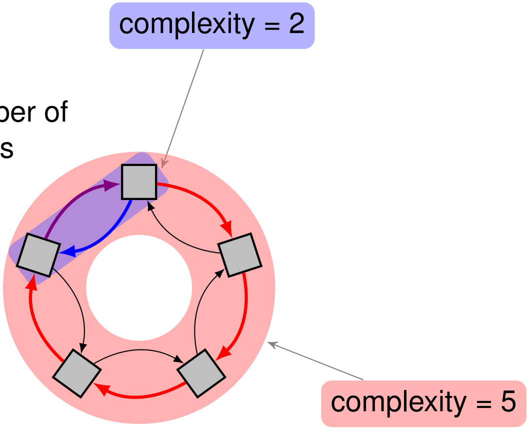

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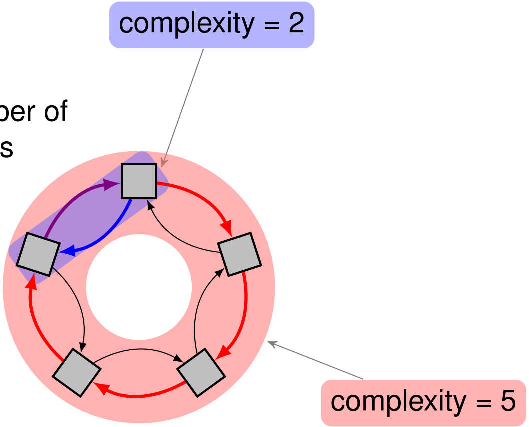

- find basic knots with $1, 2, \ldots$ cut-points

Widening Revisited

- learning and folding of boxes in the abstraction loop

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The Goal

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$\Rightarrow$ hide unboundedly many cut-points

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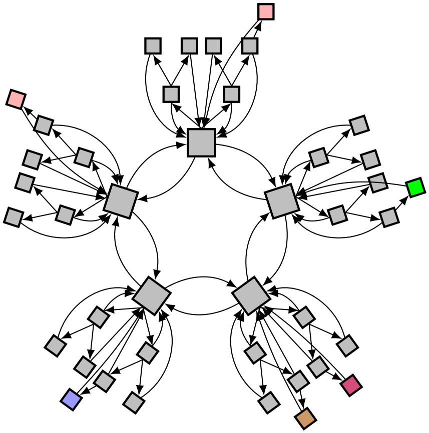
```
1 Algorithm: Abstraction Loop
2 Unfold solo boxes
3 repeat
4     Abstract
5     Fold
6 until fixpoint
```

not on a cycle

Learning of Boxes: Example



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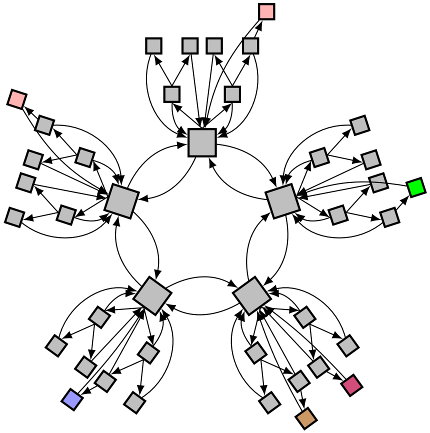

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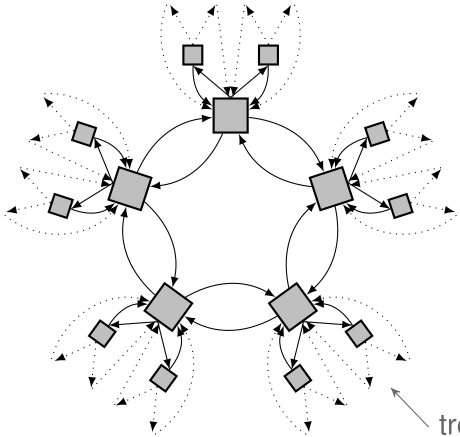

1 *Unfold solo boxes*
2 **repeat**
3 *Abstract*
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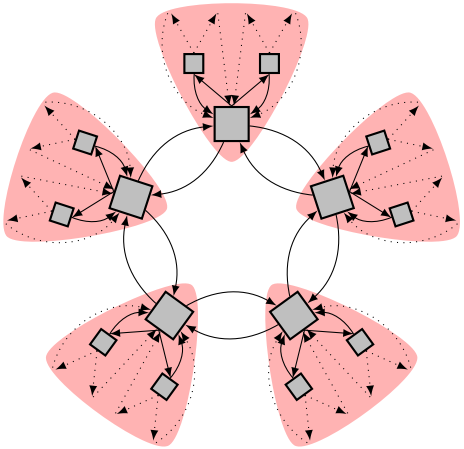
5 **until** *fixpoint*

tree with root ptrs of any height

Learning of Boxes: Example



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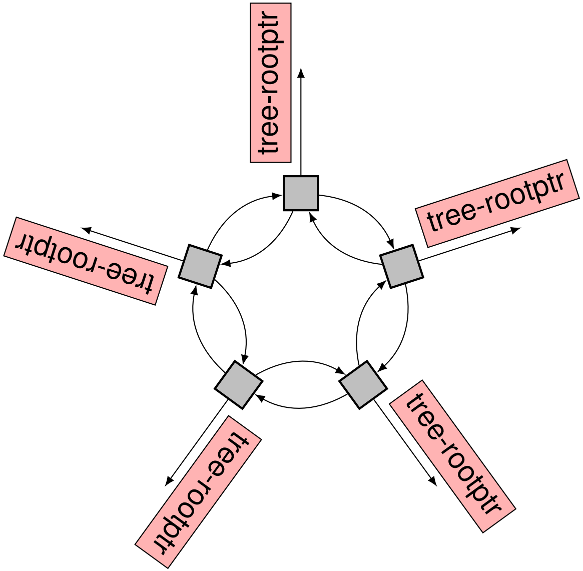

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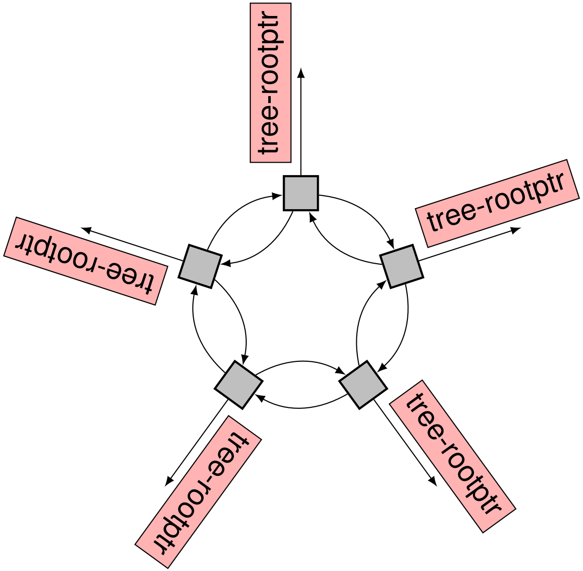

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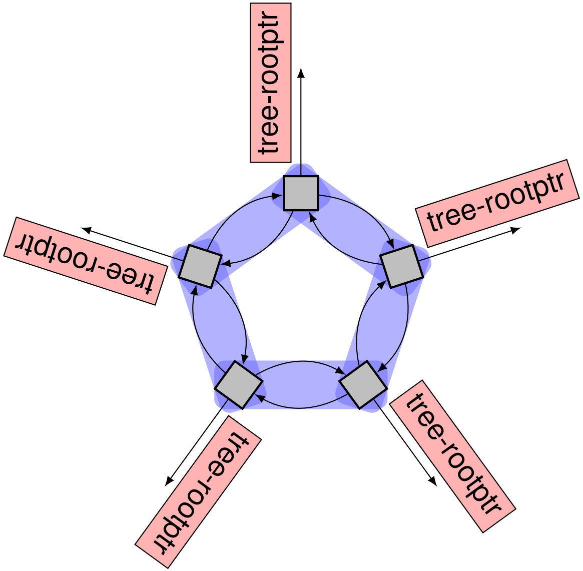

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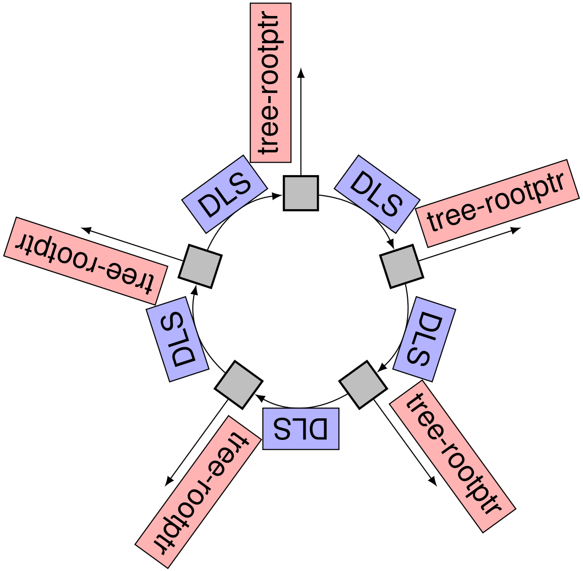

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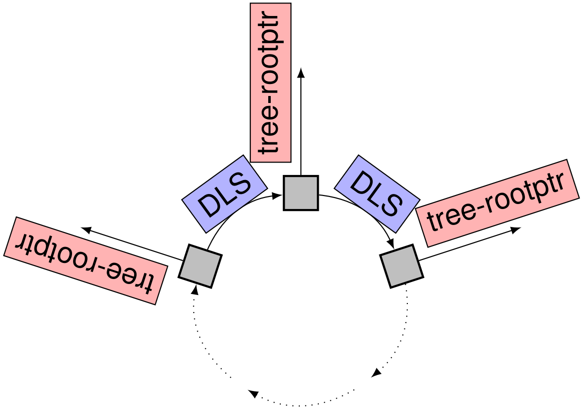

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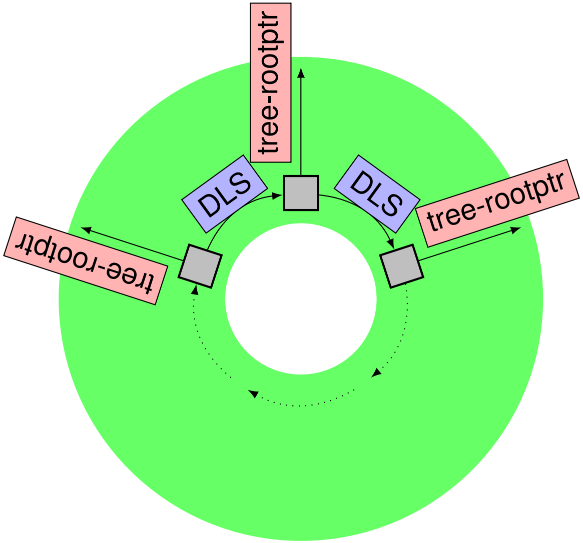

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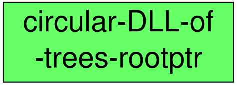

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Table: Results of the experiments [s]

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

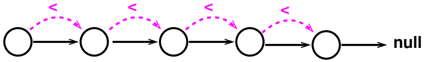
Extension to data

Extension to data

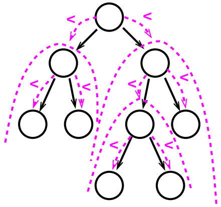
Tracking Relations over Data Values

- Verify data-related properties such as sortedness.

Sorted list



Search tree



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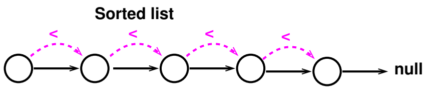
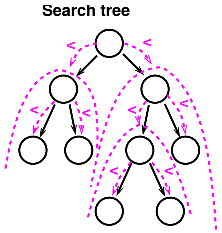
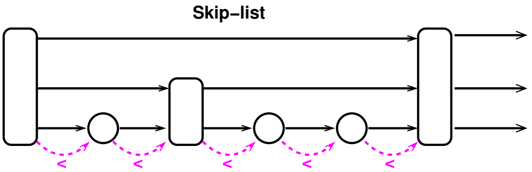




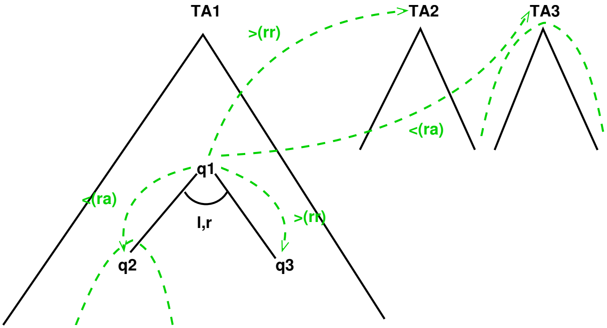
- Verify data-dependent memory safety/shape invariance.



Forest Automata with Data Constraints

- TA rules extended with constraints
  - local: between states of a single rule,
  - global: between a state and a whole TA
- comparing:
  - two nodes: root-root (rr),
  - a node and all nodes of a tree: root-all (ra).

$$q1 \xrightarrow{l,r} (q2, q3) : \{0 >_{ra} 1, 0 <_{rr} 2\} \text{ vs } G = \{q1 >_{rr} TA2, q1 <_{ra} TA3\}$$



Experimental Results

Support for ordering relations implemented in an extension of Forester.

Example	time [s]
SLL insert	0.06
SLL delete	0.08
SLL reverse	0.07
SLL bubblesort	0.13
SLL insertsort	0.10
DLL insert	0.14
DLL delete	0.38
DLL reverse	0.16
DLL bubblesort	0.39
DLL insertsort	0.43

Example	time [s]
BST insert	6.87
BST delete	114.00
BST left rotate	7.35
BST right rotate	6.25
SL_2 insert	9.65
SL_2 delete	10.14
SL_3 insert	56.99
SL_3 delete	57.35

Conclusion

Shape analysis with forest automata:

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Conclusion

Shape analysis with forest automata:

- fully automated, very flexible
- the **Forester** tool
  - `http://www.fit.vutbr.cz/research/groups/verifit/tools/forester`
- successfully verified:
  - (singly/doubly linked (circular)) lists (of (. . .) lists)
  - trees (with additional pointers)
  - skip lists
  - tracking ordering relations
- not covered here:
  - support for pointer arithmetic
    - needed for lists used e.g. in the Linux kernel

Future Work

- CEGAR loop
  - **red-black** trees, . . .
  - already some preliminary results for lists
- concurrent data structures
  - lockless skip lists, . . .
- recursive boxes
  - B+ trees, . . .
- support for incomplete code