Compile-Time Verification of Properties of Heap Intensive Programs

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http://www.cs.tau.ac.il/~TVLA
http://www.cs.tau.ac.il/~msagiv/toplas02.pdf

. . . and also

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  - D. Gopan
  - A. Loginov
- IBM Research
  - J. Field
  - H. Kolodner
  - M. Rodeh
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Shape Analysis

- Determine the possible shapes of a dynamically allocated data structure at given program point
- Relevant questions:
  - Does x.next point to a shared element?
  - Does a variable point p to an allocated element every time p is dereferenced
  - Does a variable point to an acyclic list?
  - Does a variable point to a doubly-linked list?
  - ?
  - Can a procedure create a memory-leak

Problem

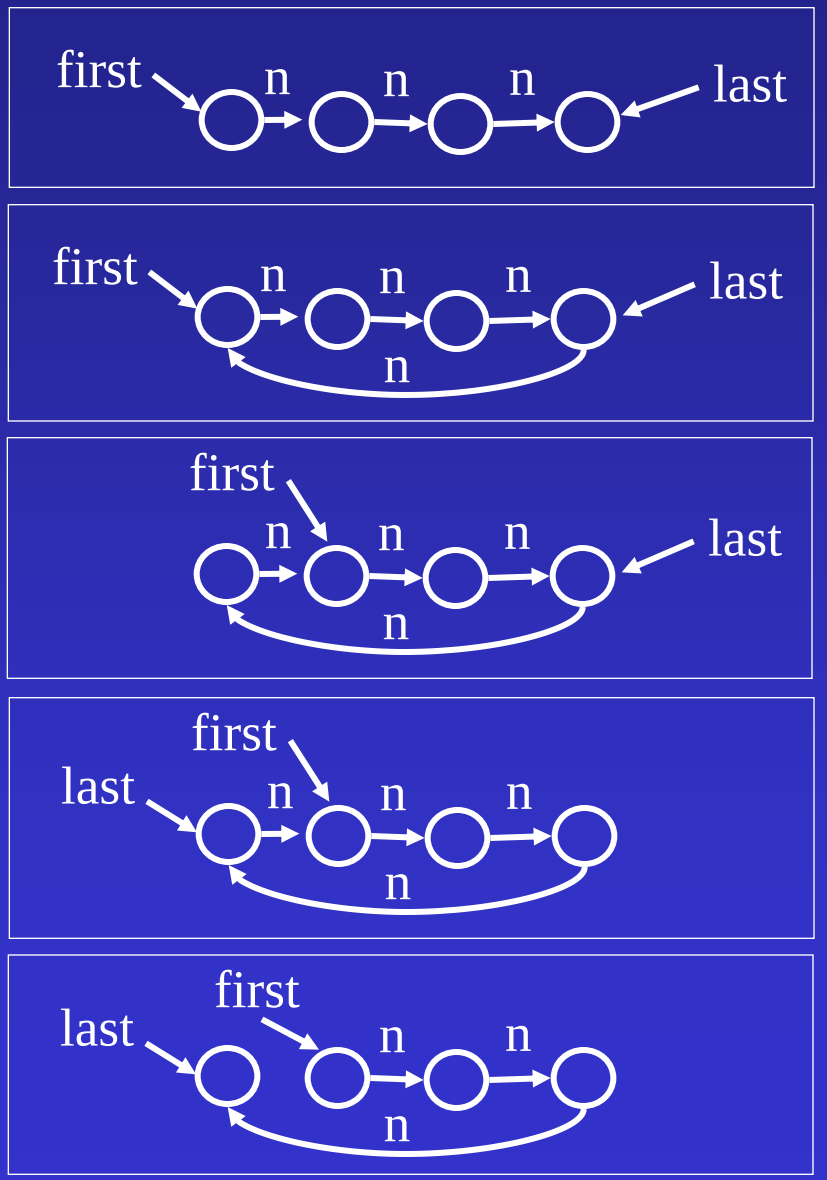
- Programs with pointers and dynamically allocated data structures are error prone
- Automatically prove correctness
- Identify subtle bugs at compile time

Interesting Properties of Heap Manipulating Programs

- No null dereference
- No memory leaks
- Preservation of data structure invariant
- Correct API usage
- Partial correctness
- Total correctness

Example

```
rotate(List first, List last) {
    if ( first != NULL) {
        last → next = first;
        first = first → next;
        last = last → next;
        last → next = NULL;
    }
}
```



Interesting Properties

```
rotate(List first, List last) {
    if ( first != NULL) {
        last → next = first;
        first = first → next;
        last = last → next;
        last → next = NULL;
    }
}
```

✓No null-de references

Interesting Properties

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rotate(List first, List last) {
    if ( first != NULL) {
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        first = first → next;
        last = last → next;
        last → next = NULL;
    }
}
```

- ✓No null-de references
- ✓No memory leaks

Interesting Properties

```
rotate(List first, List last) {
    if ( first != NULL) {
        last → next = first;
        first = first → next;
        last = last → next;
        last → next = NULL;
    }
}
```

- ✓No null-de references
- ✓No memory leaks
- ✓Returns an acyclic linked list
- ✓Partially correct

Partial Correctness

```
typedef struct list_cell {
    int data;
    struct list_cell *n;
} *List;
```

```
List InsertSort(List x) {
List r, pr, rn, l, pl; r = x; pr = NULL;
   while  (r != NULL) {
      l = x; rn = r → n; pl = NULL;
      while  (l != r) {
         if  (l → data > r → data) {
            pr → n = rn; r → n = l;
            if  (pl == NULL) x = r;
            else pl → n = r;
            r = pr;
            break;
         }
         pl = l; l = l → n;
      }
      pr = r; r = rn;
   }
   return x;
}
```

Partial Correctness

```
List quickSort(List p, List q) {
        if(p==q || q == NULL)
         return p;
    List h = partition(p,q);
    List x = p→n;
    p →n = NULL;
    List low = quickSort(h, p);
    List high = quickSort(x, NULL);
    p→n = high;
    return low;
}
```

Challenges

- Specification
  - Desired properties
  - Program Semantics
- Automatic Verification
  - Program Semantics $\Rightarrow$ Desired properties
  - Undecidable even for simple programs and prooperties

Plan

- Concrete Interpretation of Heap
- Canonical Heap Abstraction
- Abstract Interpretation using Canonical Abstraction
- The TVLA system
- Applications
- Techniques for scaling

Logical Structures (Labeled Graphs)

- Nullary relation symbols
- Unary relation symbols
- Binary relation symbols
- FO^{TC} over $TC, \forall \exists \neg \wedge \vee$ express logical structure properties
- Logical Structures provide meaning for relations
  - A set of individuals (nodes) U
  - Interpretation of relation symbols in P
    $p^0() \rightarrow \{0,1\}$
    $p^1(v) \rightarrow \{0,1\}$
    $p^2(u,v) \rightarrow \{0,1\}$

Fixed

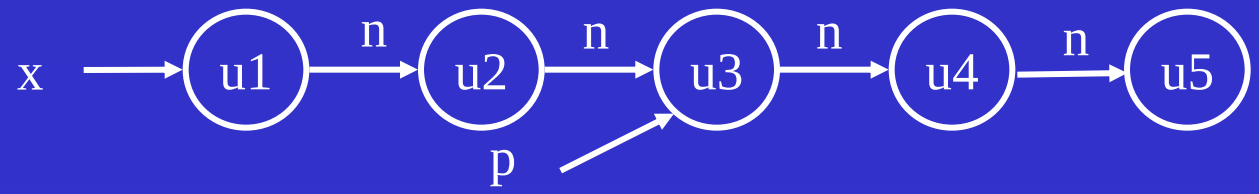
Representing Stores as Logical Structures

- Locations ≈ Individuals
- Program variables ≈ Unary relations
- Fields ≈ Binary relations
- Example
  - U = {u1, u2, u3, u4, u5}
  - x = {u1}, p = {u3} n = {<u1, u2>, <u2, u3>, <u3, u4>, <u4, u5>}

	x
u1	1
u2	0
u3	0
u4	0
u5	0

	p
u1	0
u2	0
u3	1
u4	0
u5	0

n	u1	u2	u3	u4	u5
u1	0	1	0	0	0
u2	0	0	1	0	0
u3	0	0	0	1	0
u4	0	0	0	0	1
u5	0	0	0	0	0



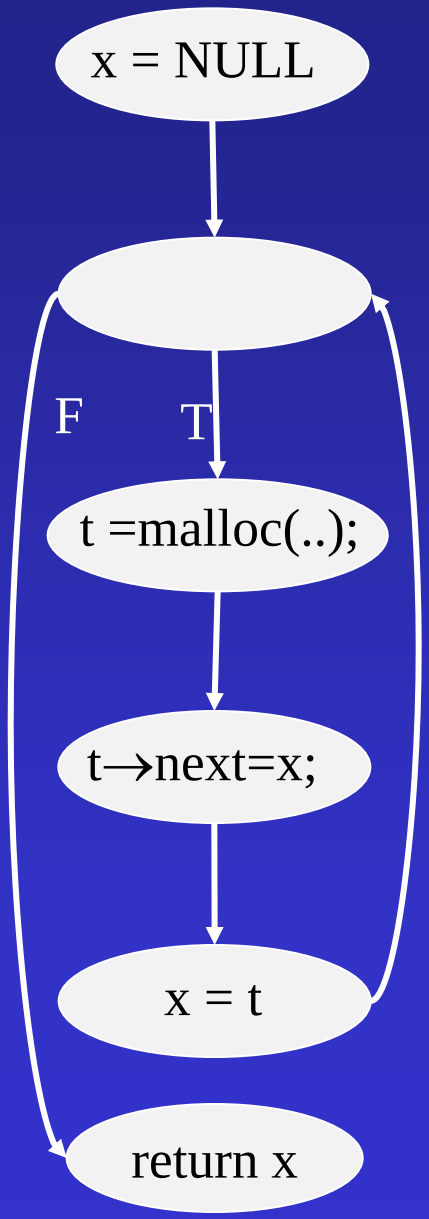
Example: List Creation

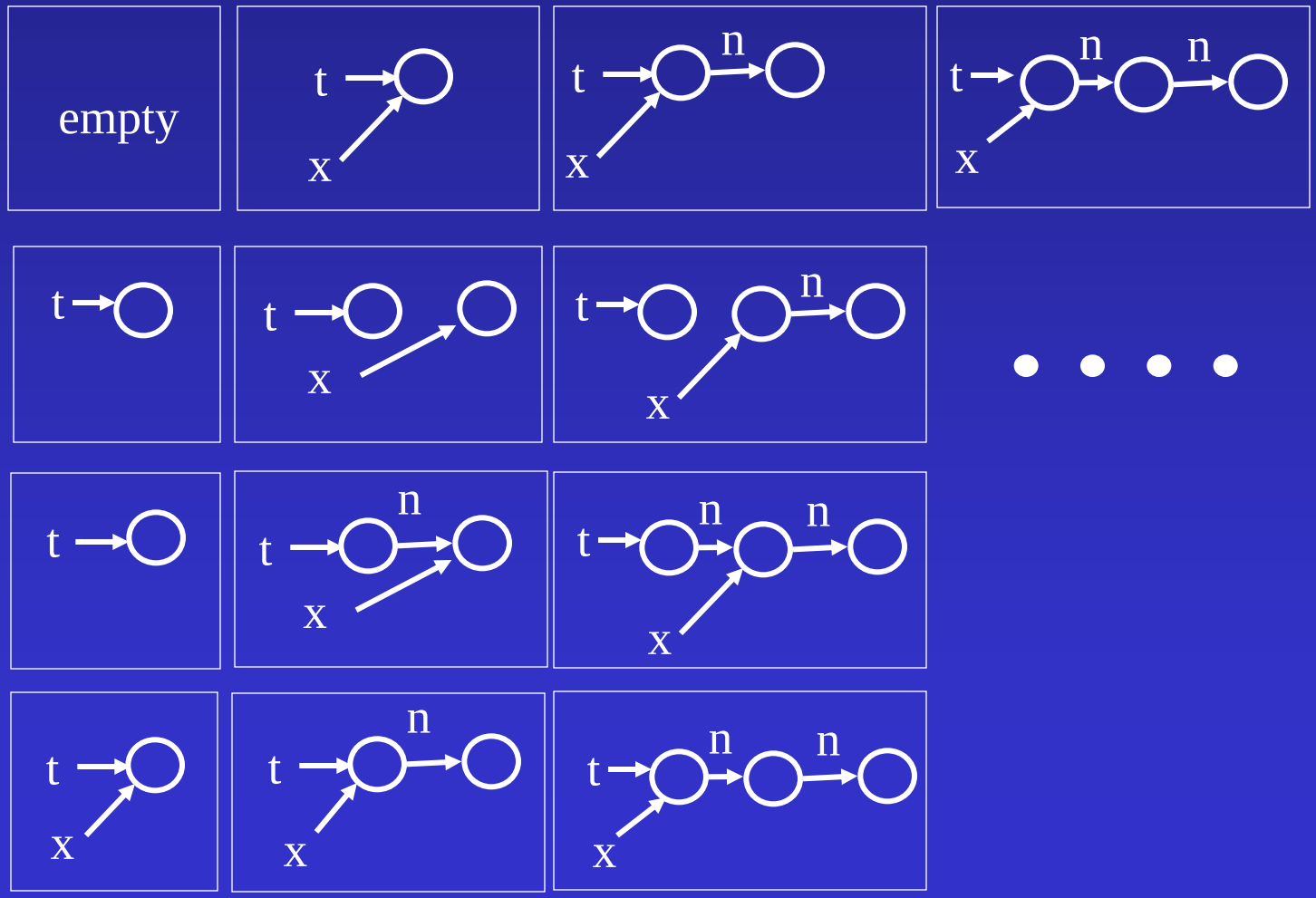
```
typedef struct node {
    int val;
    struct node *next;
} *List;
```

```
List create (…)
{
List x, t;
x = NULL;
while (…) do {
      t = malloc();
      t →next=x;
     x = t ;}
return x;
}
```

- ✓ No null dereferences
- ✓ No memory leaks
- ✓ Returns acyclic list

Example: Concrete Interpretation





Concrete Interpretation Rules

Statement	Update formula
x =NULL	$x'(v) = 0$
x= malloc()	$x'(v) = IsNew(v)$
x=y	$x'(v) = y(v)$
x=y →next	$x'(v) = \exists w: y(w) \wedge n(w, v)$
x →next=y	$n'(v, w) = (x(v) ?\ y(w) : n(v, w))$

Invariants

- No garbage

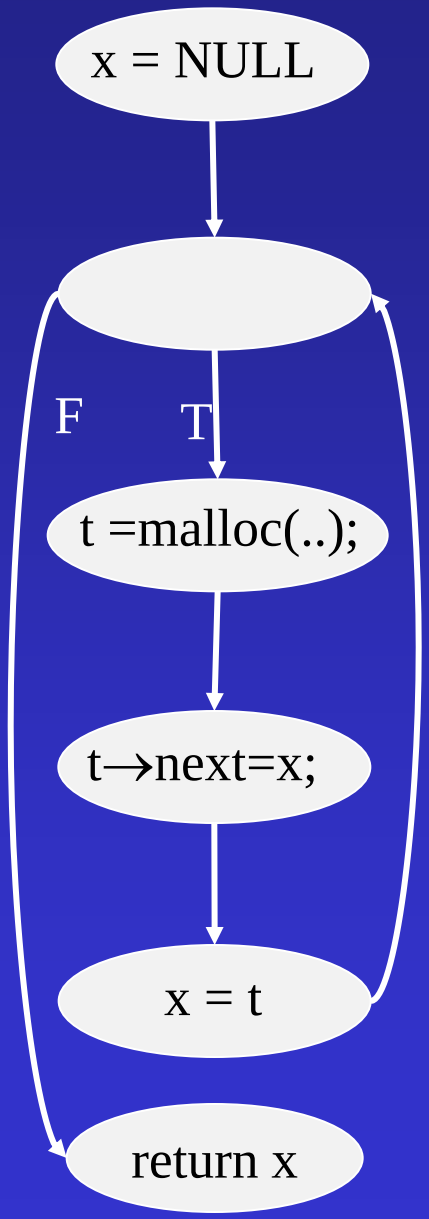
  $\forall v: \vee_{\{x \in PVar\}} \exists w: x(w) \wedge n^*(w, v)$
- Acyclic list(x)

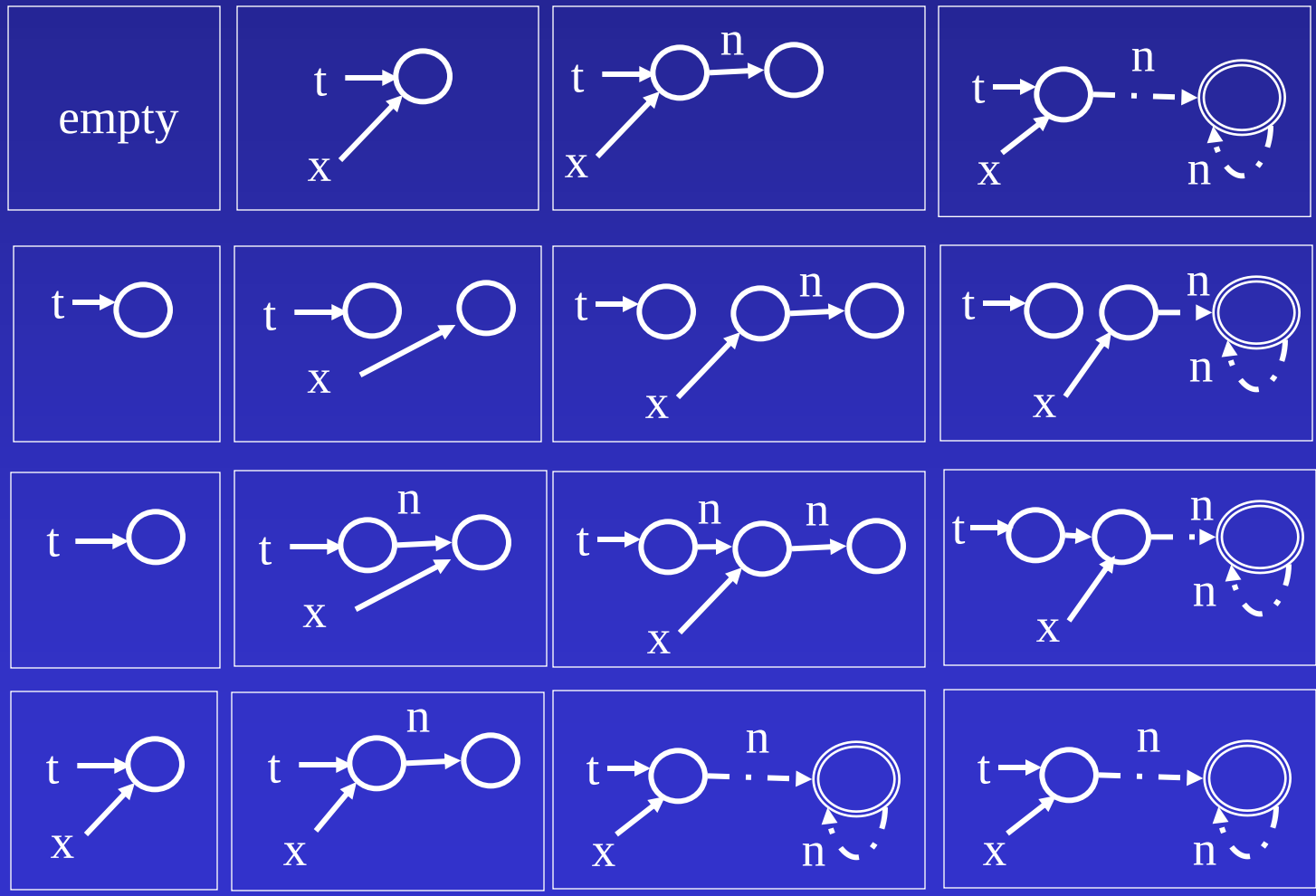
  $\forall v, w: x(v) \wedge n^*(v, w) \rightarrow \neg n^+(w, w)$
- Reverse (x)

  $\forall v, w, r: x(v) \wedge n^*(v, w) \rightarrow$

  $n(w, r) \leftrightarrow n'(r, w)$

Example: Abstract Interpretation





3-Valued Logical Structures

- A set of individuals (nodes) U
- Relation meaning
  - Interpretation of relation symbols in P

    $p^0() \rightarrow \{0,1, 1/2\}$

    $p^1(v) \rightarrow \{0,1, 1/2\}$

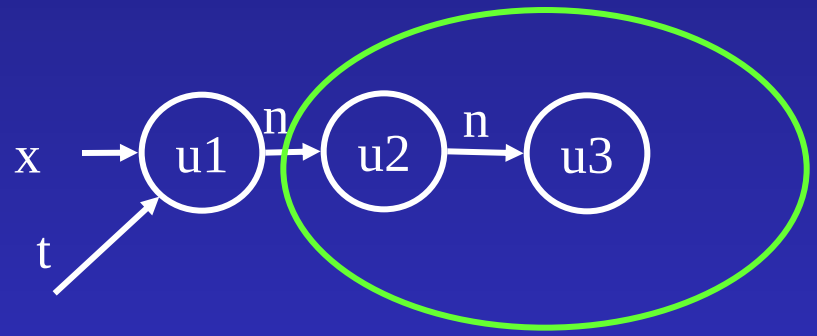
    $p^2(u,v) \rightarrow \{0,1, 1/2\}$
- A join semi-lattice: $0 \sqcup 1 = 1/2$

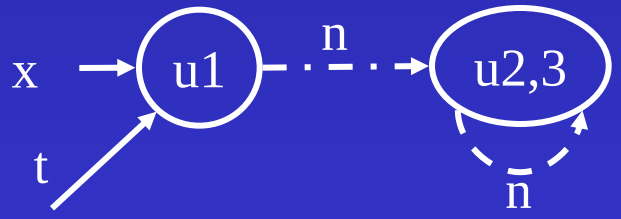
Canonical Abstraction (β)

- Partition the individuals into equivalence classes based on the values of their unary relations
  - Every individual is mapped into its equivalence class
- Collapse relations via ⊔
  - $p^S(u'_1, ..., u'_k) = \sqcup \{p^B(u_1, ..., u_k) \mid f(u_1)=u'_1, ..., f(u_k)=u'_k\}$
- At most 2^A abstract individuals

Canonical Abstraction

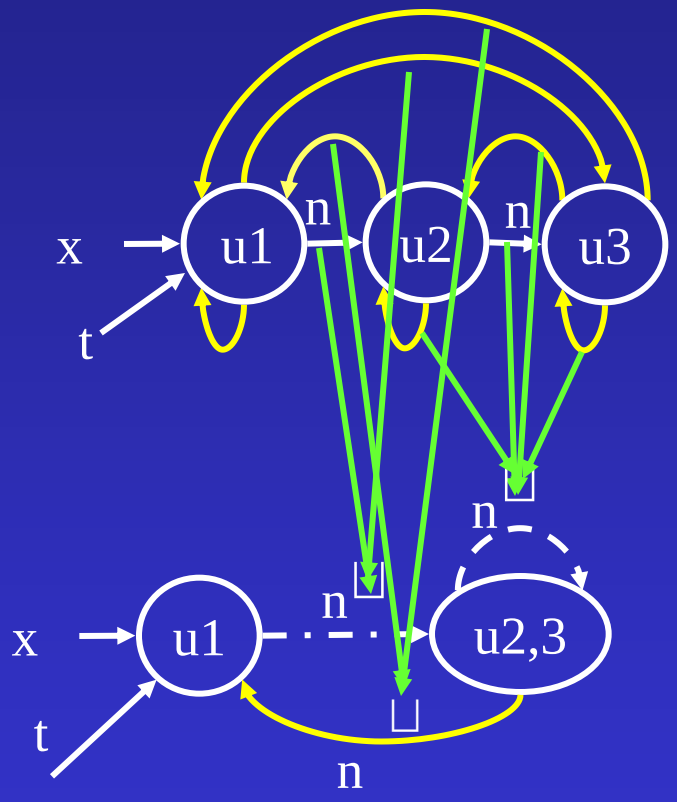
```
x = NULL;
while (…) do {
      t = malloc();
      t →next=x;
     x = t
}
```





Canonical Abstraction

```
x = NULL;
while (…) do {
      t = malloc();
      t →next=x;
     x = t
}
```

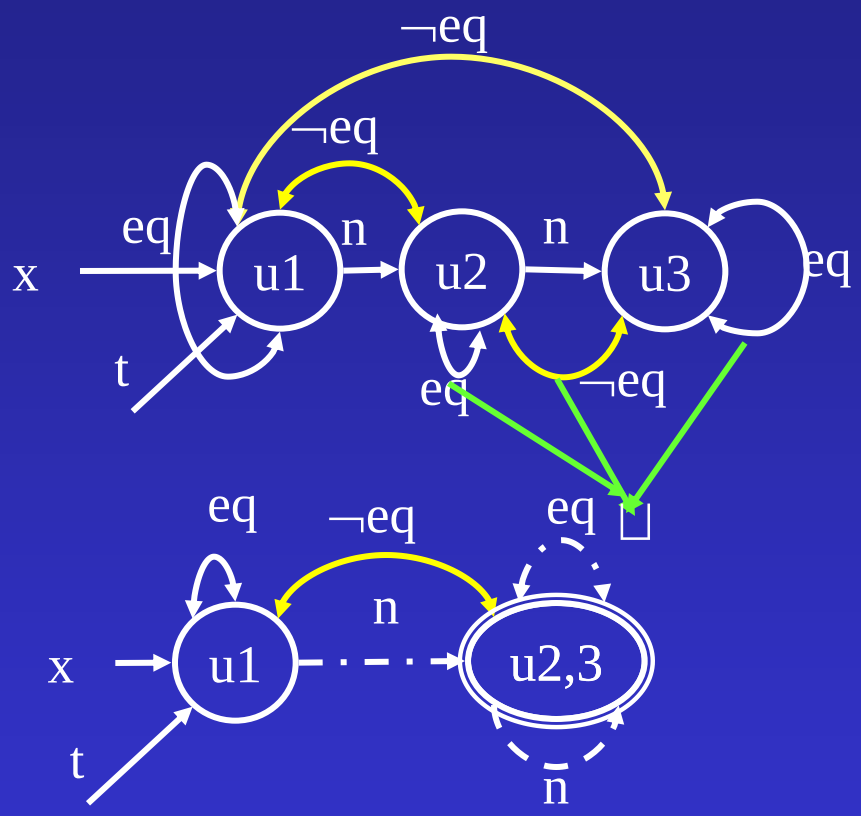


Canonical Abstraction and Equality

- Summary nodes may represent more than one element
- (In)equality need not be preserved under abstraction
- Explicitly record equality
- Summary nodes are nodes with eq(u, u)=1/2

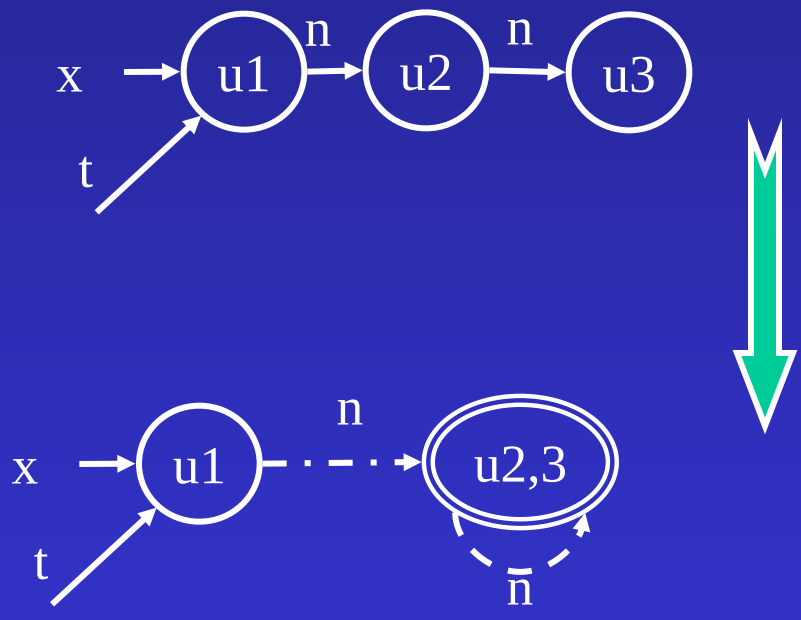
Canonical Abstraction and Equality

```
x = NULL;
while (…) do {
    t = malloc();
    t →next=x;
    x = t
}
```



Canonical Abstraction

```
x = NULL;
while (…) do {
    t = malloc();
    t →next=x;
   x = t
}
```



Canonical Abstraction

- Partition the individuals into equivalence classes based on the values of their unary relations
  - Every individual is mapped into its equivalence class
- Collapse relations via $\sqcup$
  - $p^S(u'_1, ..., u'_k) = \sqcup \{p^B(u_1, ..., u_k) \mid f(u_1)=u'_1, ..., f(u'_k)=u_k\}$
- At most 2^A abstract individuals

Canonical Abstraction

```
x = NULL;
while (…) do {
      t = malloc();
      t →next=x;
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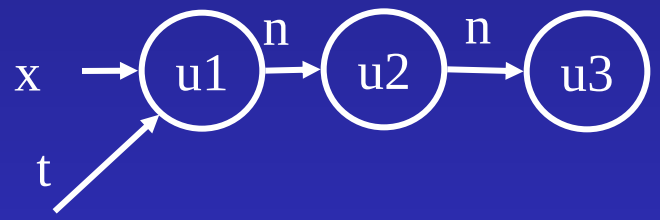
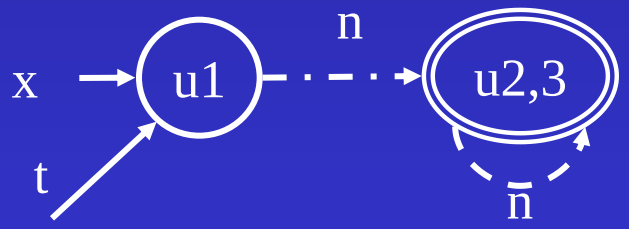
}
```





Limitations

- Information on summary nodes is lost

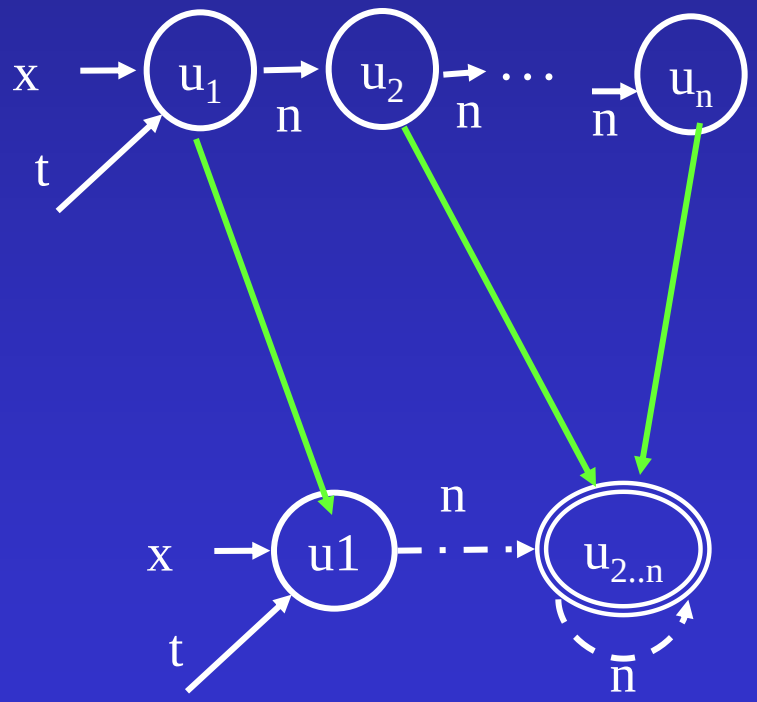
Increasing Precision

- Global invariants
  - User-supplied, or consequence of the semantics of the programming language
  - Naturally expressed in FO^{TC}
- Record extra information in the concrete interpretation
  - Tunes the abstraction
  - Refines the concretization

Cyclicity relation

$c[x]() = \exists v_1, v_2 : x(v_1) \wedge n^*(v_1, v_2) \wedge n^+(v_2, v_2)$

c[x]()=0

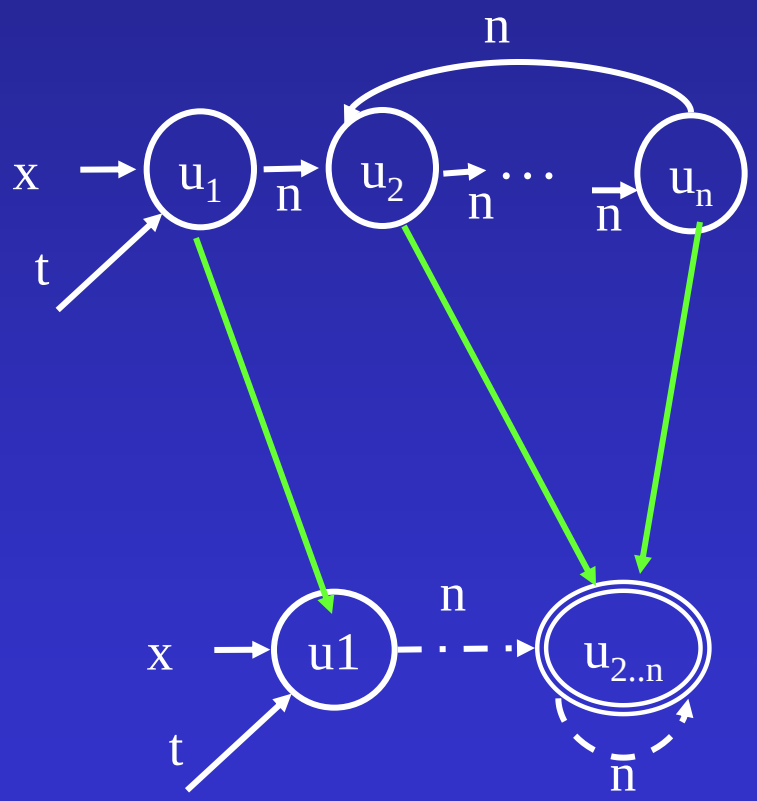


c[x]()=0

Cyclicity relation

$c[x]() = \exists v_1, v_2 : x(v_1) \wedge n^*(v_1, v_2) \wedge n^+(v_2, v_2)$

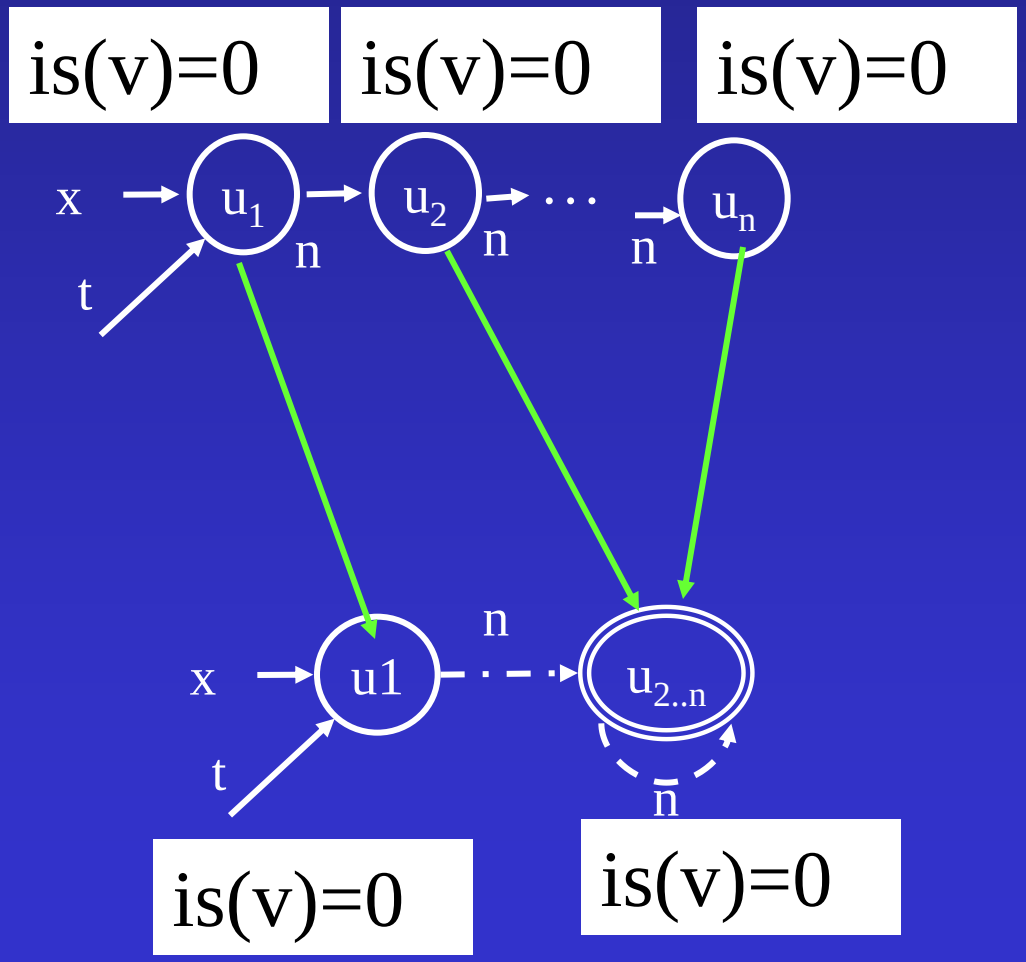
c[x]()=1



c[x]()=1

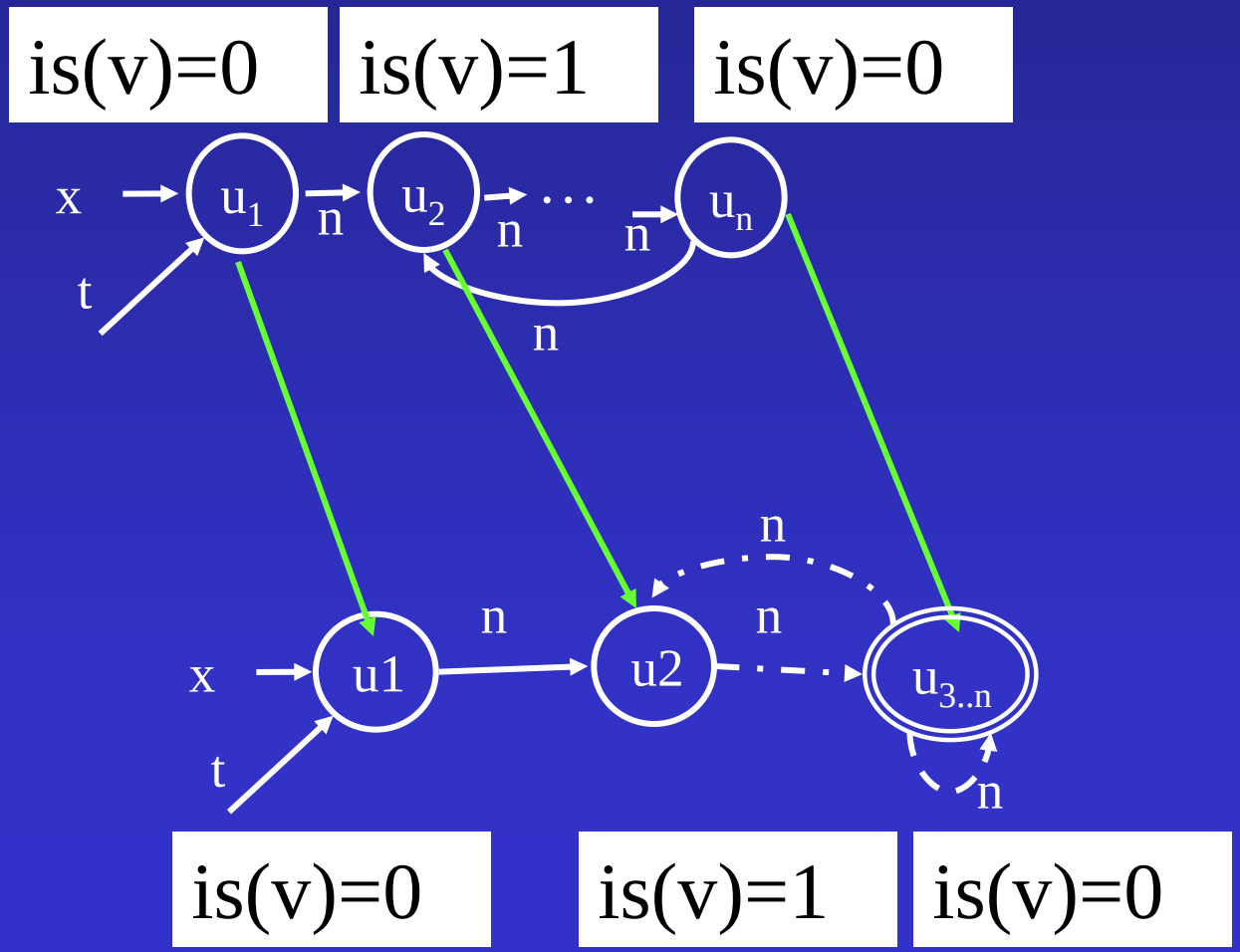
Heap Sharing relation

$is(v) = \exists v_1, v_2 : n(v_1, v) \wedge n(v_2, v) \wedge v_1 \neq v_2$



Heap Sharing relation

$is(v) = \exists v_1, v_2 : n(v_1, v) \wedge n(v_2, v) \wedge v_1 \neq v_2$

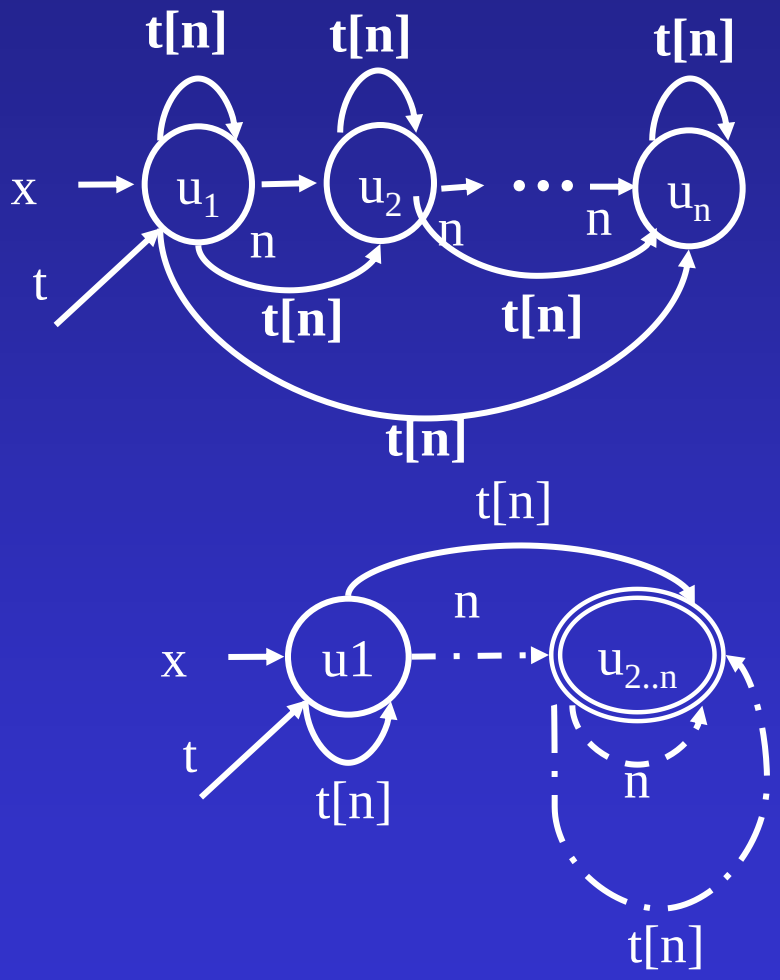


Concrete Interpretation Rules

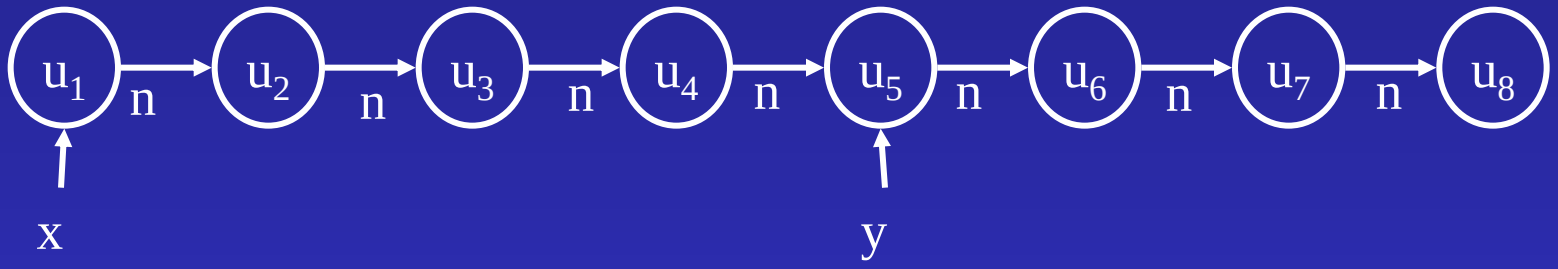
Statement	Update formula
x =NULL	x’(v)= 0
x= malloc()	x’(v) = IsNew(v) is’(v) =is(v) $\wedge \neg$IsNew(v)
x=y	x’(v)= y(v)
x=y $\rightarrow$next	x’(v)= $\exists$w: y(w) $\wedge$ n(w, v)
x $\rightarrow$next=NULL	n’(v, w) = $\neg$x(v)$\wedge$ n(v, w) is’(v) = is(v) $\wedge$ $\exists$v1, v2: n(v1, v) $\wedge \neg$x(v1) $\wedge$ n(v2, v) $\wedge \neg$x(v2) $\wedge$ $\neg$eq(v1, v2)

Reachability relation

$$t[n](v1, v2) = n^*(v1,v2)$$

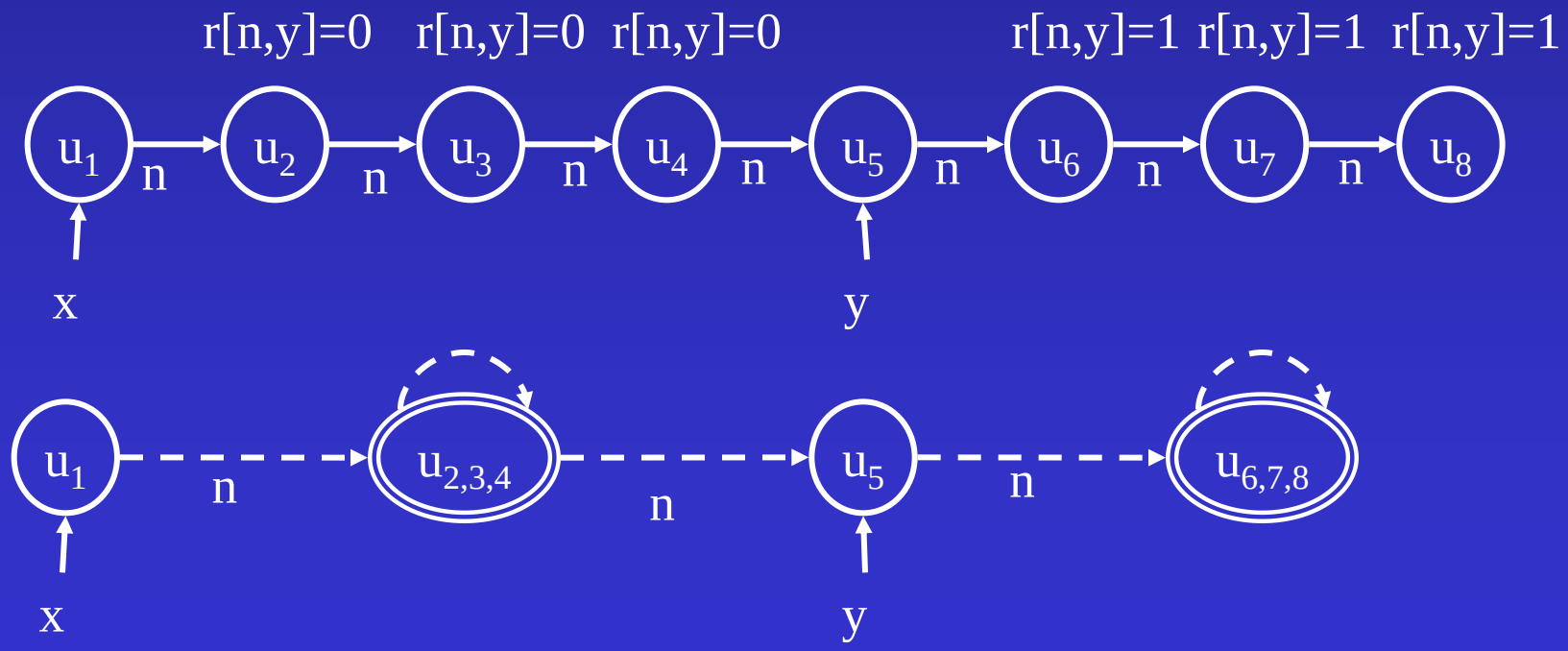


List Segments



Reachability from a variable

- $r[n,y](v) = \exists w: y(w) \wedge n^*(w, v)$



Additional Instrumentation relations

- inOrder(v) = $\forall$w: n(v, w) $\rightarrow$ data(v) $\leq$ data(w)
- $c_{fb}(v)$ = $\forall$w: f(v, w) $\rightarrow$b(w, v)
- tree(*v*)
- dag(*v*)
- Weakest Precondition
  [Ramalingam, PLDI'02]
- Learned via Inductive Logic Programming
  [Loginov, CAV'05]
- Counterexample guided refinement

Instrumentation (Summary)

- Refines the abstraction

$$is(v) = \exists v_1, v_2 : n(v_1, v) \wedge n(v_2, v) \wedge v_1 \neq v_2$$

- Adds global invariants

$$is(v) \leftrightarrow \exists v_1, v_2 : n(v_1, v) \wedge n(v_2, v) \wedge v_1 \neq v_2$$

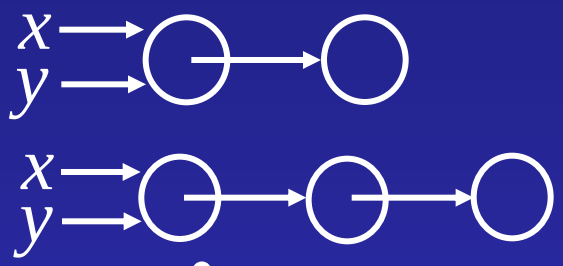
$$\gamma(S^{\#}) = \{S : S \models \Sigma,\ \beta(S) = S^{\#}\}$$

- But requires update-formulas (generated automatically in TVLA2)

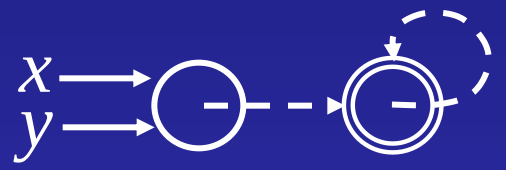
Abstract Interpretation

- Best Transformers
- Kleene Evaluation
- Kleene Evaluation + semantic reduction
  - Focus Based Transformers

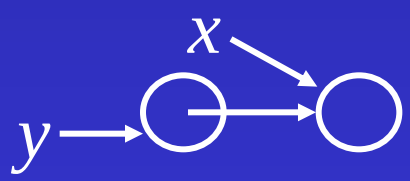
Best Transformer Transformer ($x = x \rightarrow n$)

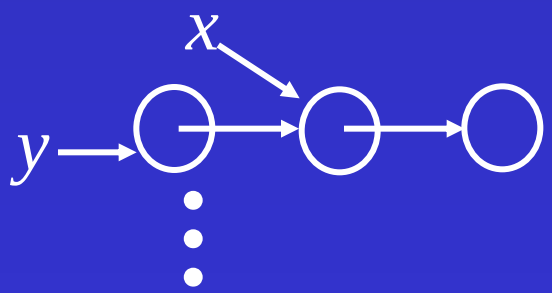


inverse canonical

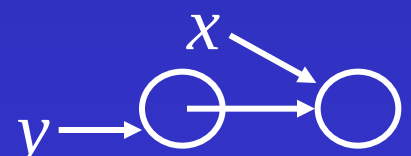


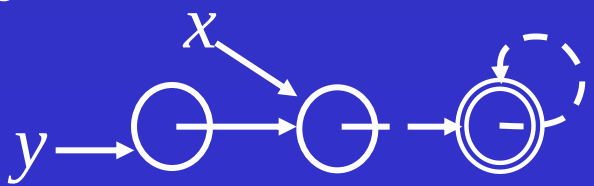
Evaluate
update
formulas





canonical abstraction






Then a Miracle Occurs
"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Boolean Connectives [Kleene]

$\wedge$	0	1/2	1
0	0	0	0
1/2	0	1/2	1/2
1	0	1/2	1

$\vee$	0	1/2	1
0	0	1/2	1
1/2	1/2	1/2	1
1	1	1	1

Boolean Connectives [Kleene]

$\wedge$	0	1/2	1
0	0	0	0
1/2	0	1/2	1/2
1	0	1/2	1

$\vee$	0	1/2	1
0	0	1/2	1
1/2	1/2	1/2	1
1	1	1	1

Embedding

- A logical structure B can be embedded into a structure S via an onto function f ($B \sqsubseteq^{f} S$) if the basic relations are preserved, i.e.,

$$p^{B}(u_1, .., u_k) \sqsubseteq p^{S}(f(u_1), ..., f(u_k))$$

- S is a tight embedding of B with respect to f if:
  - S does not lose unnecessary information, i.e.,
  - $p^{S}(u^{\#}_1, .., u^{\#}_k) = \sqcup\{p^{B}(u_1 ..., u_k) \mid f(u_1)=u^{\#}_1, ..., f(u_k)=u^{\#}_k\}$
- Canonical Abstraction is a tight embedding

Embedding and Concretization

- Two natural choices
  - B $\in \gamma_1(S)$ if B can be embedded into S via an onto function f ($B \sqsubseteq^f S$)
  - B $\in \gamma_2(S)$ if S is a tight embedding of B

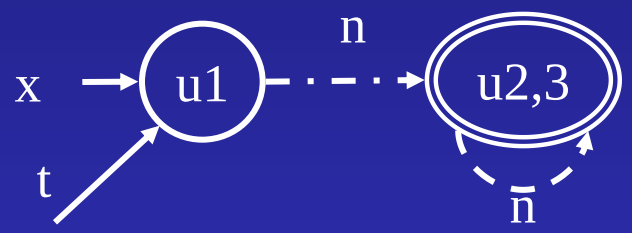
Embedding Theorem

- Assume $B \sqsubseteq^{f} S$,

$$p^{B}(u_1, .., u_k) \sqsubseteq p^{S}(f(u_1), ..., f(u_k))$$

- Then every formula φ is preserved:
  - If $[\![\varphi]\!] = 1$ in S, then $[\![\varphi]\!] = 1$ in B
  - If $[\![\varphi]\!] = 0$ in S, then $[\![\varphi]\!] = 0$ in B
  - If $[\![\varphi]\!] = 1/2$ in S, then $[\![\varphi]\!]$ could be 0 or 1 in B

Embedding Theorem



$\exists v: x(v)$ — 1=Yes

$\exists v: x(v) \wedge t(v)$ — 1=Yes

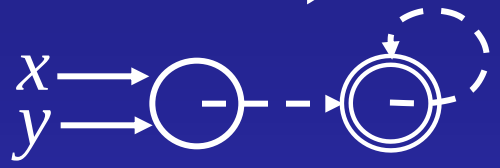
$\exists v: x(v) \wedge y(v)$ — 0=No

$\exists v_1, v_2: x(v_1) \wedge n(v_1, v_2)$ — ½=Maybe

$\exists v_1, v_2: x(v_1) \wedge n(v_1, v_2) \wedge n^*(v_2, v_1)$ — 0=No

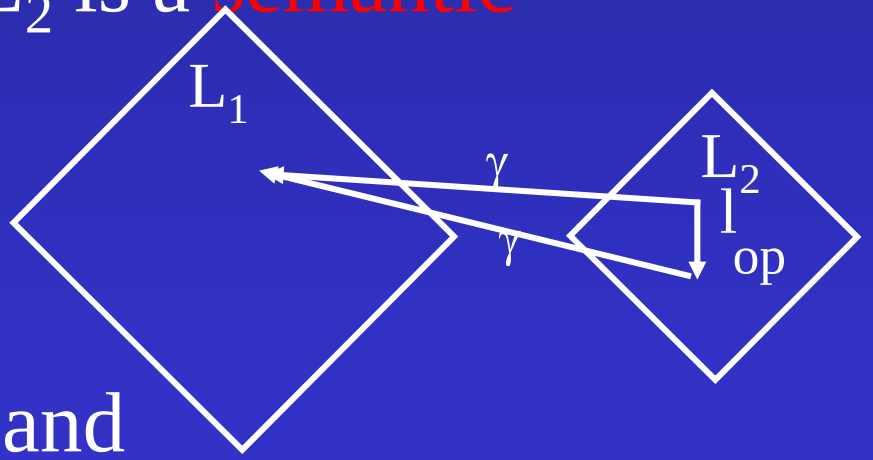
$\exists v_1, v_2: x(v_1) \wedge n^*(v_1, v_2) \wedge n+(v_2, v_2)$ — 1/2=Maybe

Kleene Transformer ($x = x \rightarrow n$)

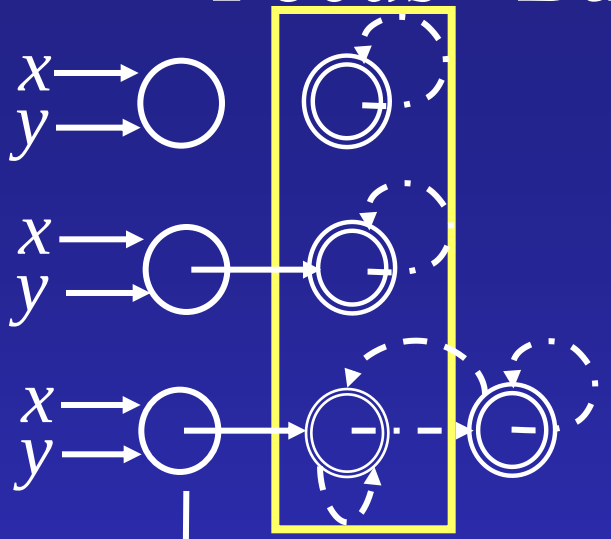


Semantic Reduction

- Improve the precision of the analysis by recovering properties of the program semantics
- A Galois connection (L_1, α, γ, L_2)
- An operation op:$L_2 \rightarrow L_2$ is a semantic reduction
  - $\forall l \in L_2$ $op(l) \sqsubseteq l$
  - $\gamma(op(l)) = \gamma(l)$
- Can be applied before and after basic operations

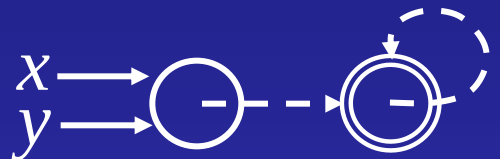


"Focus"-Based Transformer ($x = x \rightarrow n$)

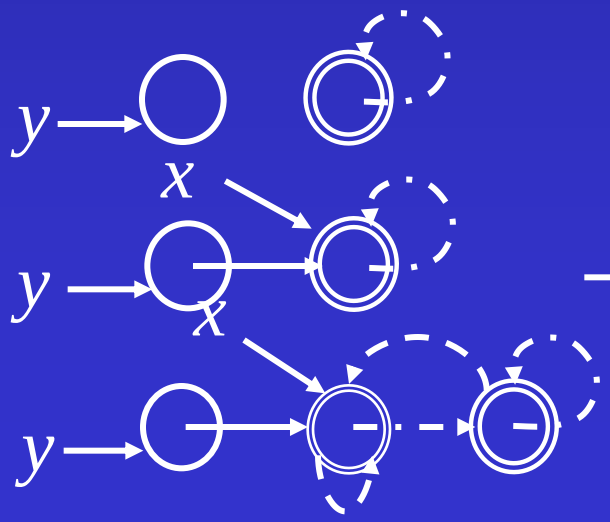


Focus($x \rightarrow n$)

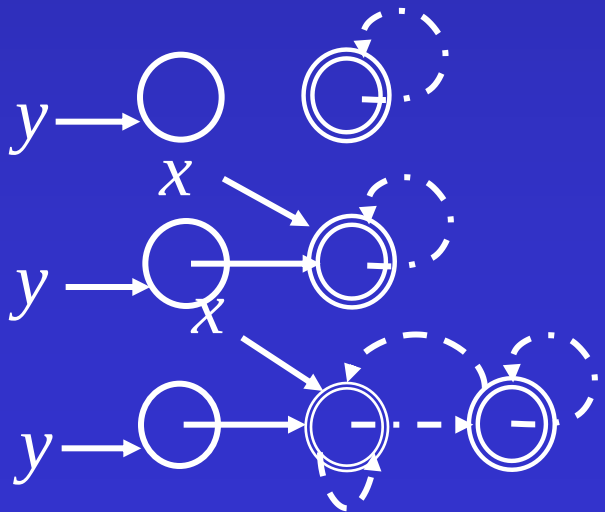
"Partial γ"



Kleene Evaluation



canonical

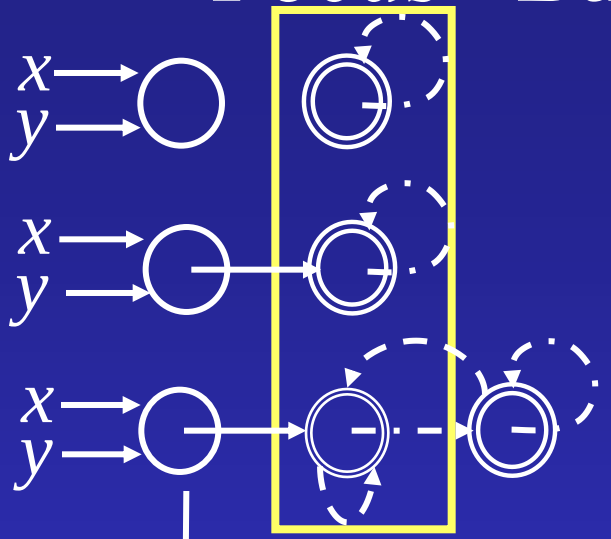


The Focus Operation

- Focus: Formula$\rightarrow$(P(3-Struct) $\hookrightarrow$P(3-Struct))
- Generalizes materialization
- For every formula φ
  - Focus(φ)(X) yields structure in which φ evaluates to a definite values in all assignments
  - Only maximal in terms of embedding
  - Focus(φ) is a semantic reduction
  - But Focus(φ)(X) may be undefined for some X

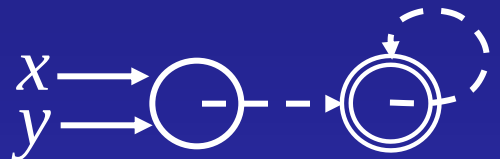
"Focus"-Based Transformer ($x = x \rightarrow n$)

$\exists w: x(w) \wedge n(w, v)$

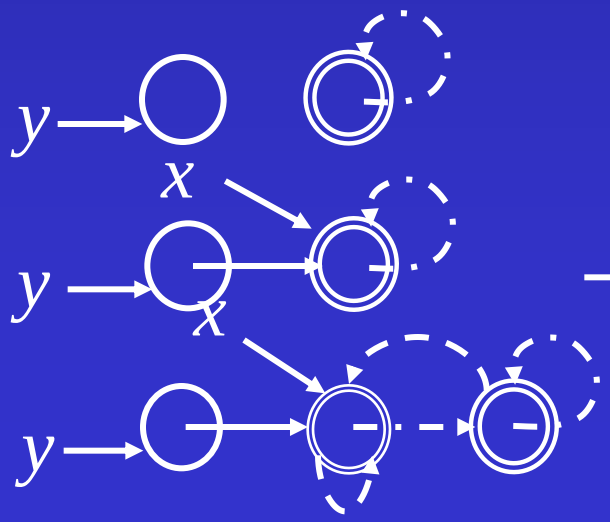


Focus($x \rightarrow n$)

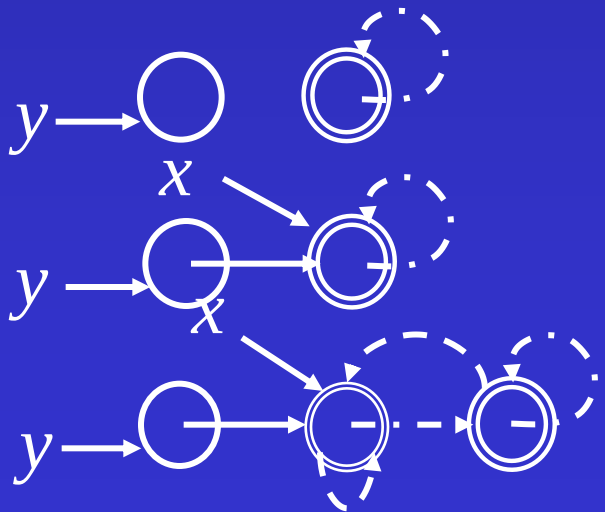
"Partial γ"



Kleene Evaluation



canonical

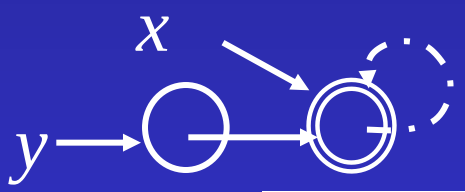


The Coercion Principle

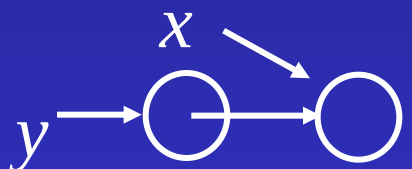
- Another Semantic Reduction
- Can be applied after Focus or after Update or both
- Increase precision by exploiting some structural properties possessed by all stores (Global invariants)
- Structural properties captured by constraints
- Apply a constraint solver

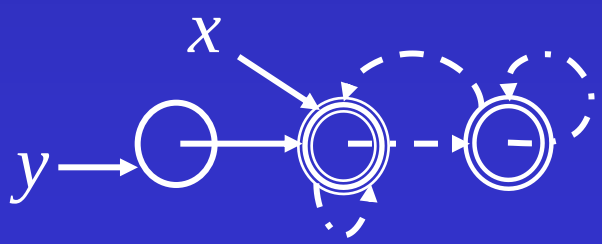
Apply Constraint Solver

r[n,y](v)=1

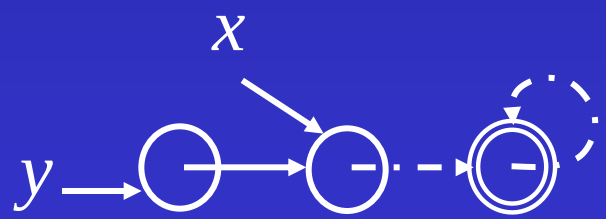


is(v)=0





is(v)=0



Sources of Constraints

- Properties of the operational semantics
- Domain specific knowledge
  - Instrumentation predicates
- User supplied

Example Constraints

$$x(v1) \wedge x(v2) \rightarrow eq(v1, v2)$$

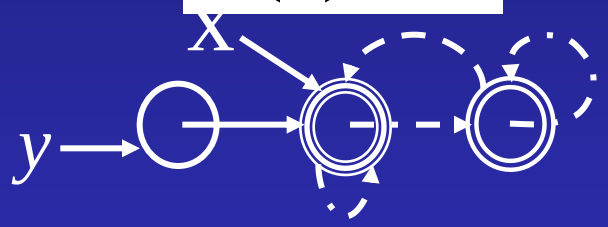
$$n(v, v1) \wedge n(v,v2) \rightarrow eq(v1, v2)$$

$$n(v1, v) \wedge n(v2,v) \wedge \neg eq(v1, v2) \leftrightarrow is(v)$$

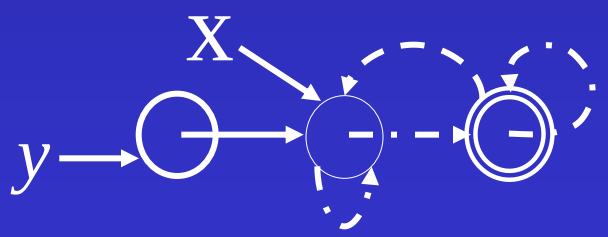
$$n^*(v3, v4) \leftrightarrow t[n](v1, v2)$$

Apply Constraint Solver

is(v)=0

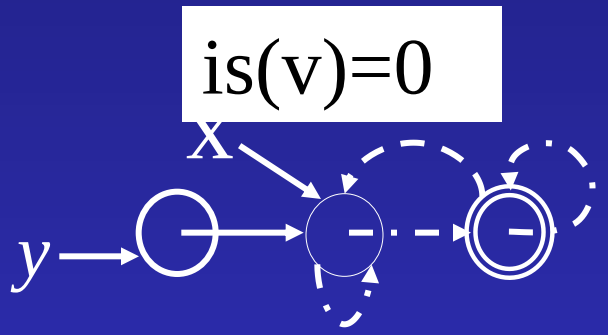


$x(v1) \wedge x(v2) \rightarrow eq(v1, v2)$



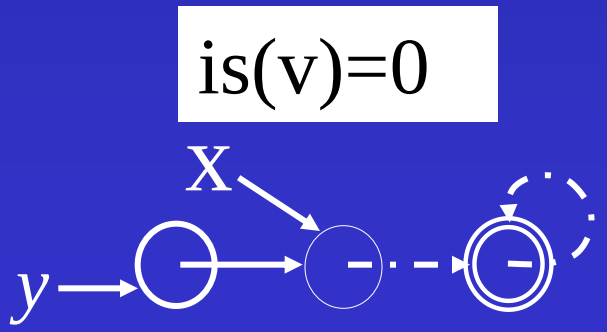
is(v)=0

Apply Constraint Solver



$n(v1, v) \wedge n(v2,v) \wedge \neg eq(v1, v2) \leftrightarrow is(v)$

$n(v1, v) \wedge \neg is(v) \wedge \neg eq(v1, v2) \rightarrow \neg n(v2, v)$



Summary Transformers

- Kleene evaluation yields sound solution
- Focus is statement specific implements partial concretization
- Coerce applies global constraints

Three Valued Logic Analysis (TVLA)
T. Lev-Ami & R. Manevich

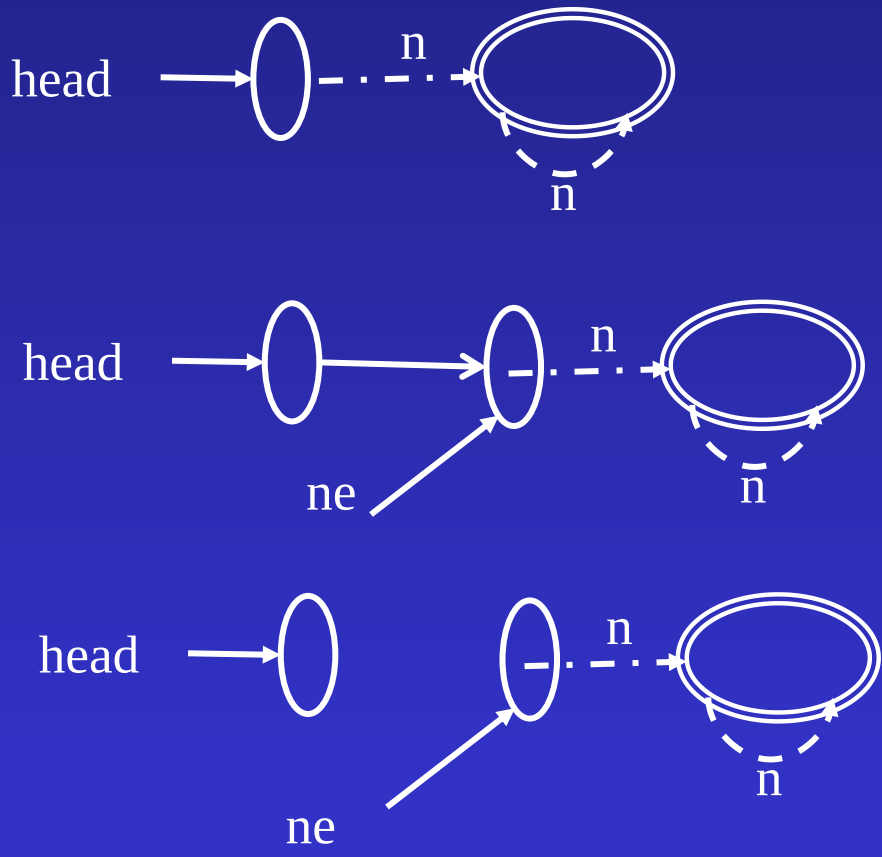
- Input ($FO^{TC)}$
  - Concrete interpretation rules
  - Definition of instrumentation relations
  - Definition of safety properties
  - First Order Transition System (TVP)
- Output
  - Warnings (text)
  - The 3-valued structure at every node (invariants)

TVLA inputs

- TVP - **T**hree **V**alued **P**rogram
  - Predicate declaration
  - Action definitions SOS
    - Statements
    - Conditions
  - Control flow graph
- TVS - **T**hree **V**alued **S**tructure

Memory Leakage

```
List reverse(Element *head)
{
    List rev, ne;
    rev = NULL;
    while (head != NULL) {
        ne = head →next;
        head → next = rev;
        head = ne;
        rev = head;
    }
    return rev;
}
```



leakage of address pointed to by head

Memory Leakage

```
Element* reverse(Element *head)
{
   Element *rev, *ne;
    rev = NULL;
    while (head != NULL) {
          ne = head → next;
          head → next = rev;
          rev = head;
          head = ne;
    }
    return rev;
}
```

✓ No memory leaks

Mark and Sweep

```
void Mark(Node root) {
  if (root != NULL) {
    pending = ∅
    pending = pending ∪ {root}
    marked = ∅
    while (pending ≠ ∅) {
      x = SelectAndRemove(pending)
      marked = marked ∪ {x}
      t = x → left
      if (t ≠ NULL)
        if (t ∉ marked)
          pending = pending ∪ {t}
      t = x → right
      if (t ≠ NULL)
        if (t ∉ marked)
          pending = pending ∪ {t}
    }
  }
  assert(marked = = Reachset(root))
}
```

```
void Sweep() {
  unexplored = Universe
  collected = ∅
  while (unexplored ≠ ∅) {
    x = SelectAndRemove(unexplored)
    if (x ∉ marked)
      collected = collected ∪ {x}
  }
  assert(collected = =
          Universe – Reachset(root)
        )
}
```

$\forall v: marked(v) \Leftrightarrow reach[root](v)$

Mark

```
void Mark(Node root) {
  if (root != NULL) {
    pending = ∅
    pending = pending ∪ {root}
    marked = ∅
    while (pending ≠ ∅) {
      x = SelectAndRemove(pending)
      marked = marked ∪ {x}
      t = x → left
      if (t ≠ NULL)
        if (t ∉ marked)
          pending = pending ∪ {t}
      t = x → right
      if (t ≠ NULL)
        if (t ∉ marked)
          pending = pending ∪ {t}
    }
  }
}
```

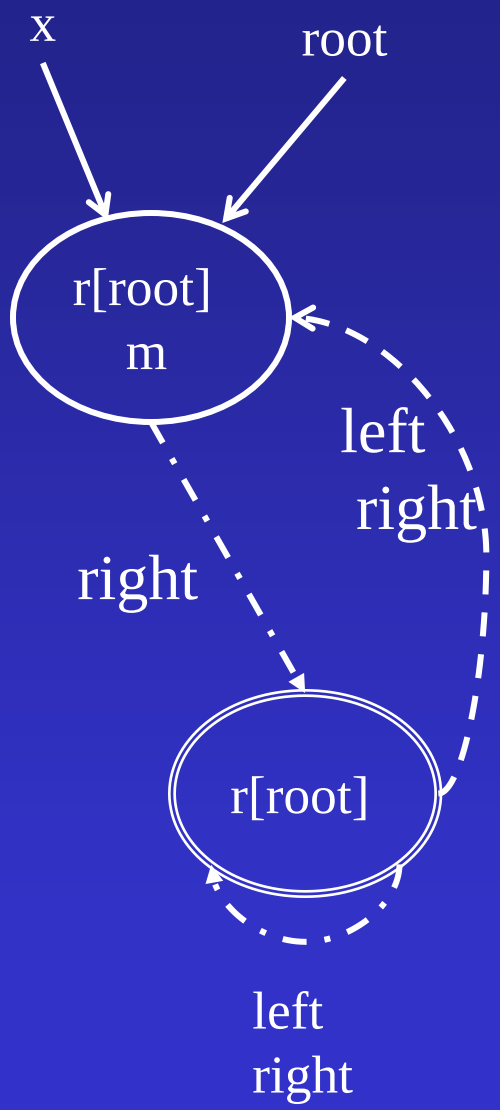
$\exists r: root(r) \wedge (p(r) \vee m(r)) \wedge$
$\forall v: ((m(v) \vee p(v)) \rightarrow reach[root](v)) \wedge$
$\neg(p(v) \wedge m(v))$
$\wedge \quad \forall v, w: \quad ((m(v) \wedge \neg m(w) \wedge \neg p(w)) \rightarrow$
$\neg successor(v, w))$

$\forall v: marked(v) \Leftrightarrow reach[root](v)$

Example: Mark

```
void Mark(Node root) {
  if (root != NULL) {
    pending = ∅
    pending = pending ∪ {root}
    marked = ∅
    while (pending ≠ ∅) {
      x = SelectAndRemove(pending)
      marked = marked ∪ {x}
      t = x → left
      if (t ≠ NULL)
        if (t ∉ marked)
          pending = pending ∪ {t}
/*    t = x → right
 *    if (t ≠ NULL)
 *      if (t ∉ marked)
 *        pending = pending ∪ {t}
 */ }
  }
  assert(marked = = Reachset(root))
}
```

Bug Found



- There may exist an individual that is reachable from the root, but not marked

$$\exists r: root(r) \wedge r[root](r) \wedge \neg p(r) \wedge m(r) \wedge$$
$$\exists e: r[root](e) \wedge \neg m(e) \wedge \neg root(e) \wedge \neg p(e)$$
$$\forall r, e: (root(r) \wedge r[root](r) \wedge \neg p(r) \wedge m(r) \wedge$$
$$r[root](e) \wedge \neg m(e)) \wedge \neg root(e) \wedge \neg p(e))$$
$$\rightarrow \neg left(r,e)$$

Scaling for Larger Programs

- Staged Analyses
- Represent 3-valued structures with BDDs [Manevich SAS'02]
- Coercer Abstractions [Manevich SAS'04]
- Reduce static costs
- Handling procedures
- Assume/Guarantee Reasoning
  - Use procedure specifications [Yorsh, TACAS'04]
  - Decision procedures for linked data structures [Immerman, CAV'04, Lev-Ami, CADE'05, Yorsh FOSSACS06]

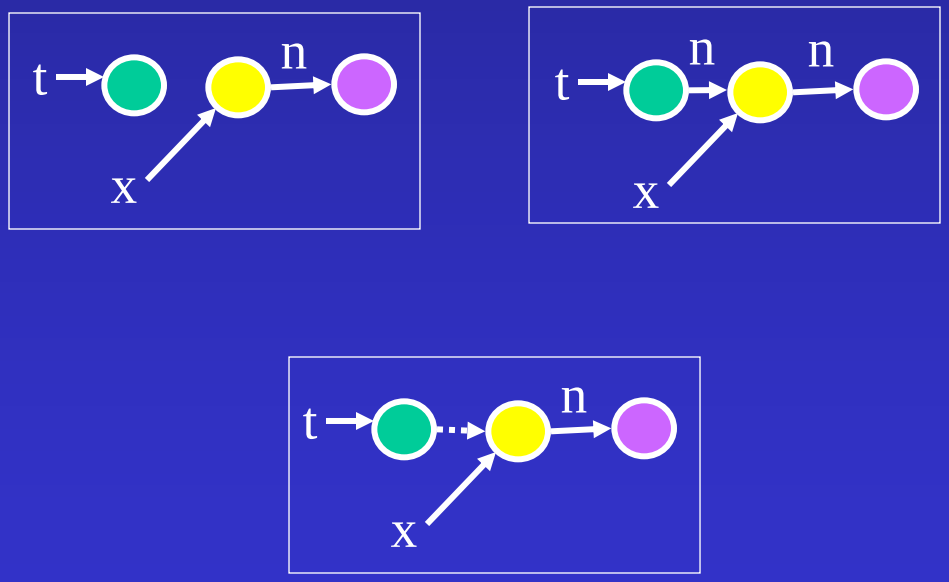
Scaling

- Staged analysis
- Reduce static costs
- Controlled complexity
  - More coarse abstractions [Manevich SAS'04]
  - Counter example based refinement
- Exploit "good" program properties
  - Encapsulation & Data abstraction
- Handle procedures efficiently

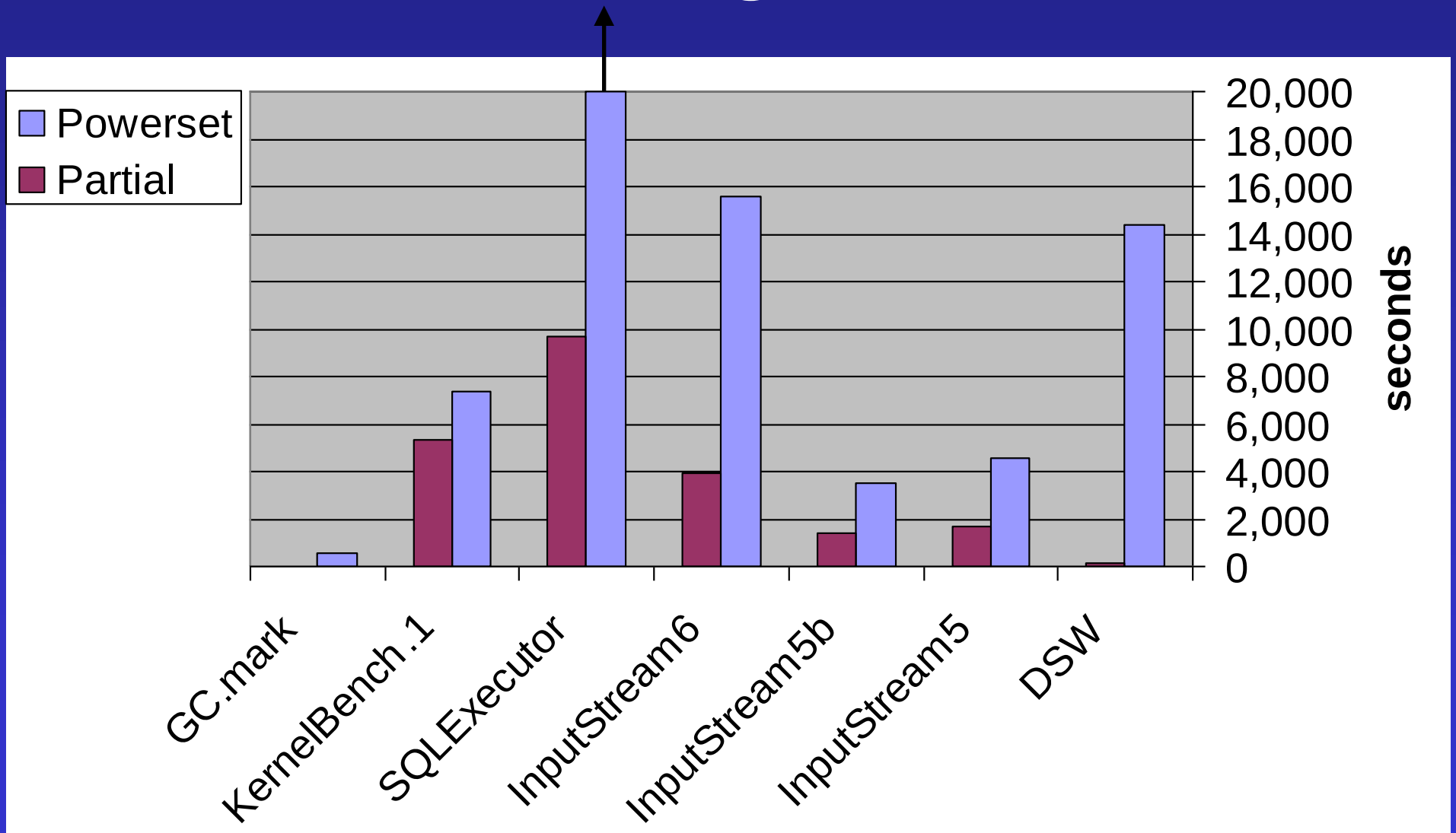
Partially Disjunctive Heap Abstraction (Manevich, SAS'04)

- Use a heap-similarity criterion
  - We defined similarity by universe congruence
- Merge similar heaps
- Avoid merging dissimilar heaps
- The same concrete state can belong to more than one abstract value

Partially Disjunctive Abstraction



Running times



Interprocedural Analysis

Noam Rinetzky

www.cs.tau.ac.il/~maon

How to handle procedures?

- Pure functions
  - Procedure ≡ input/output relation
  - No side-effects

```
main() {
  int w=0,x=0,y=0,z=0;
  w = inc(y);
  x = inc(z);
  assert: w+x is even
}
```

p	ret
0	1
1	2
2	3
..	…

```
int inc(int p) {
  return 2 + p - 1;
}
```

How to handle procedures?

- Pure functions
  - Procedure ≡ input/output relation
  - No side-effects

```
main() {
  int w=0,x=0,y=0,z=0;
  w = inc(y);
  x = inc(z);
  assert: w+x is even
}
```

w	x	y	z
E	E	E	E
O	E	E	E
O	O	E	E

p	ret
Even	Odd
Odd	Even

```
int inc(int p) {
  return 2 + p - 1;
}
```

What about global variables?

- Procedures have side-effects
- Easy fix

p	g	ret	g’
0	0	1	0
…	…	…	…

p	g	ret	g’
Even	E/O	Odd	Even
Odd	E/O	Even	Odd

```
int g = 0;
main() {
  int w=0,x=0,y=0,z=0;
  w = inc(y);
  x = inc(z);
  assert: w+x+g is even
}
```

```
int inc(int p) {
  g = p;
  return 2 + p - 1;
}
```

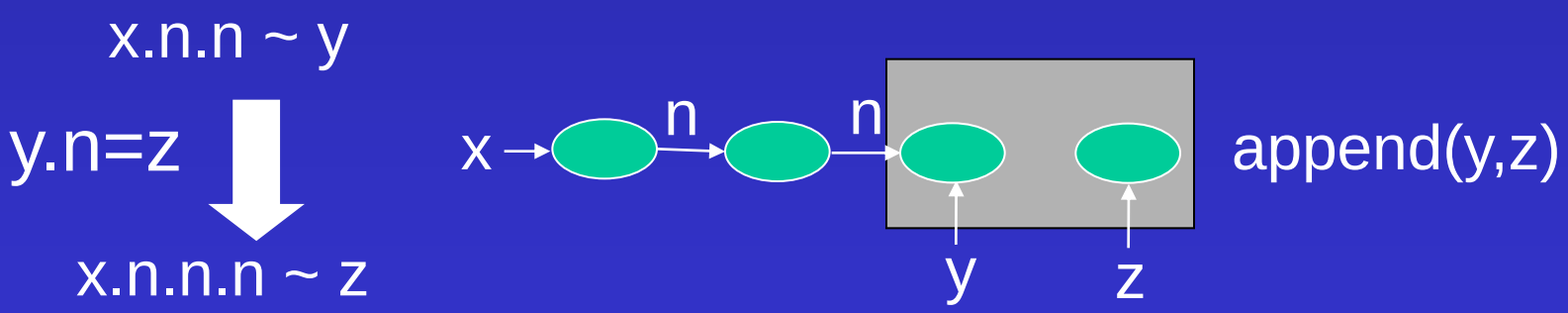
But what about pointers and heap?

Pointers

- Aliasing
- Destructive update

Heap

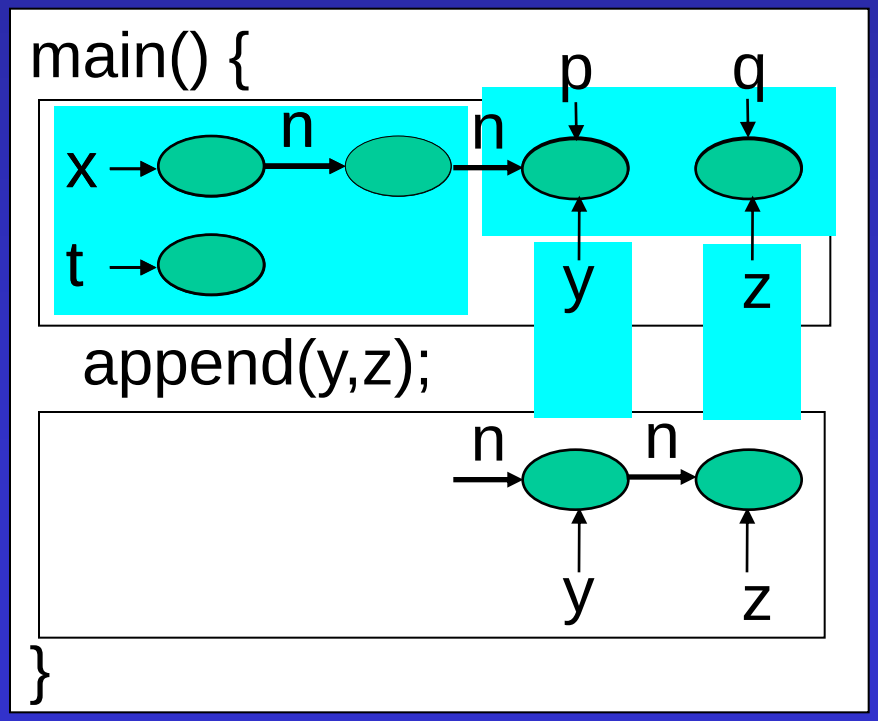
- Global resource
- Anonymous objects

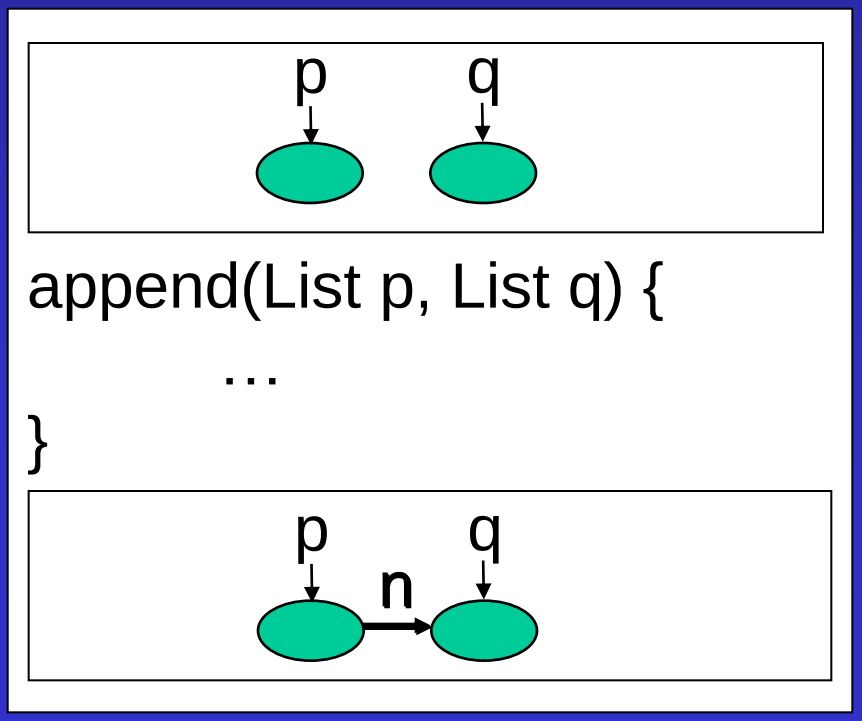


How to tabulate append?

How to tabulate procedures?

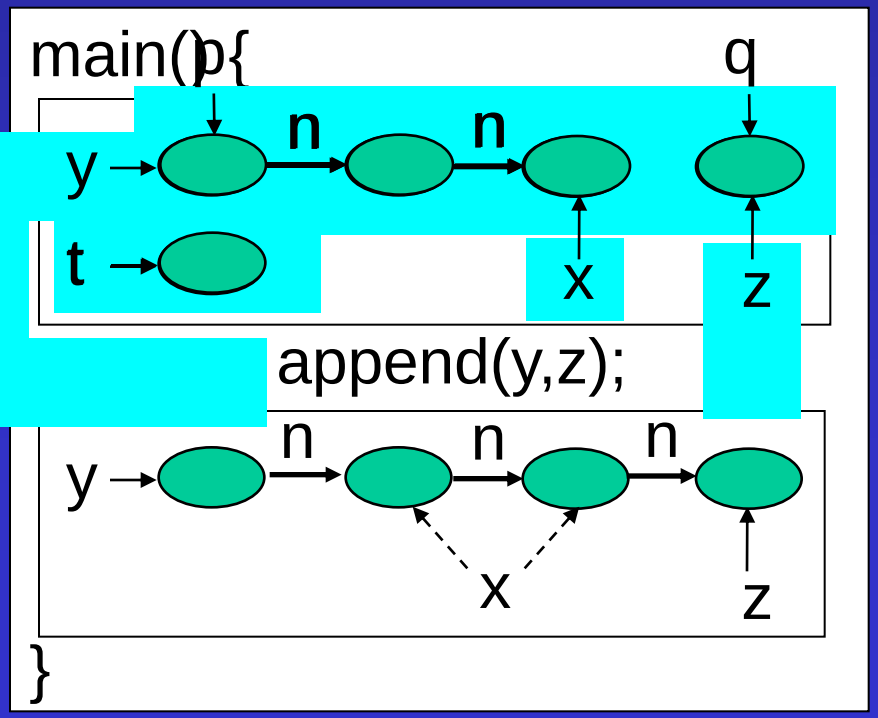
- Procedure ≡ input/output relation
  - Not reachable ➔ Not effected
  - proc: local (≡reachable) heap ➔ local heap

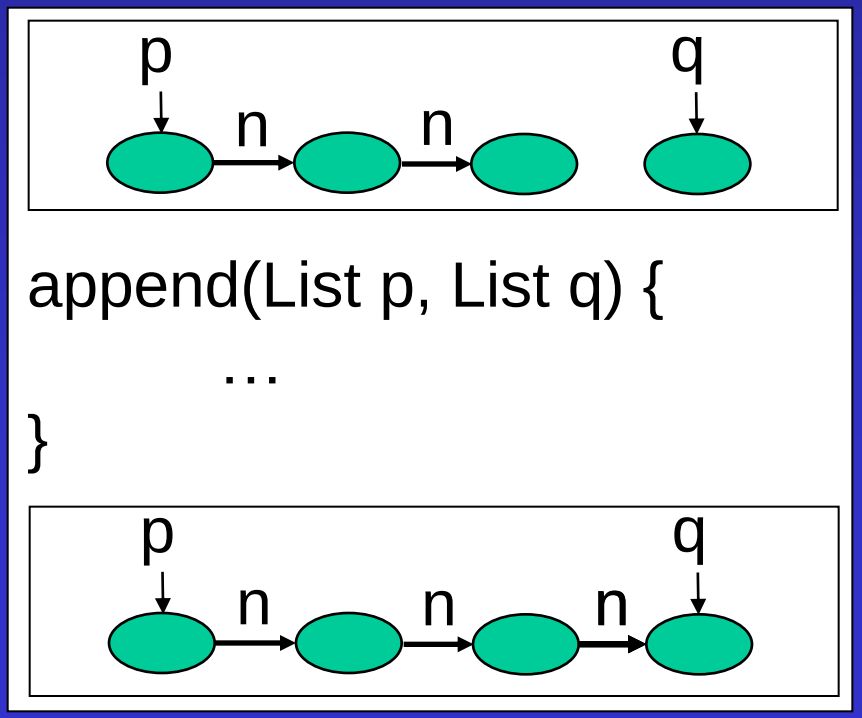




How to handle sharing?

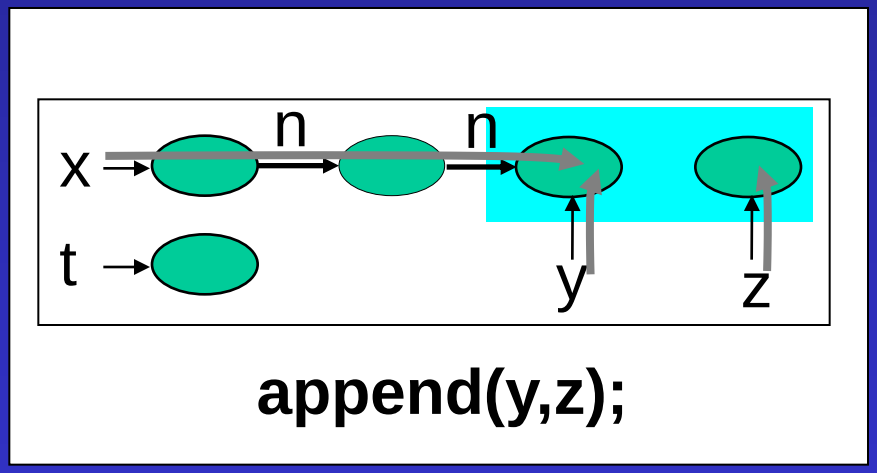
- External sharing may break the functional view





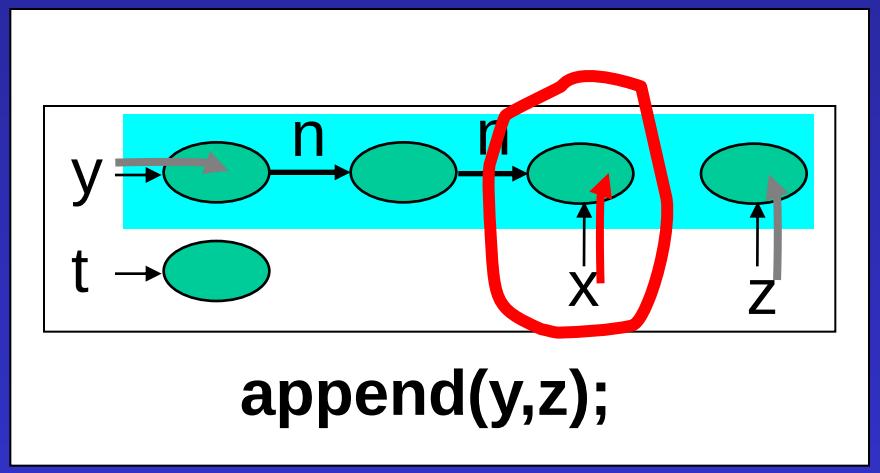
What's the difference?

1st Example



append(y,z);

2nd Example

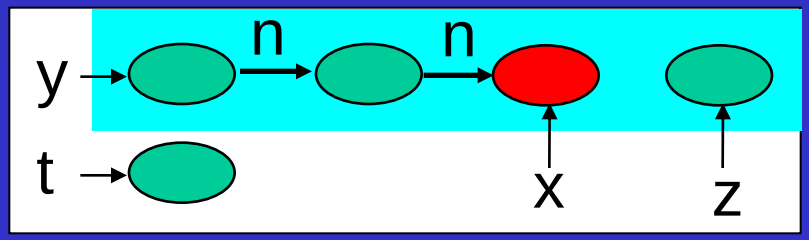


append(y,z);

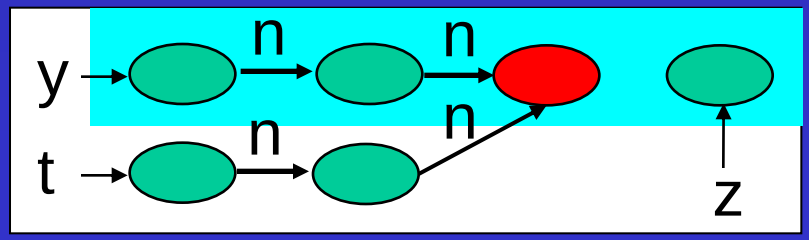
Cutpoints

- An object is a **cutpoint** for an invocation
  - Reachable from actual parameters
  - Not pointed to by an actual parameter
  - Reachable without going through a parameter

append(y,z)



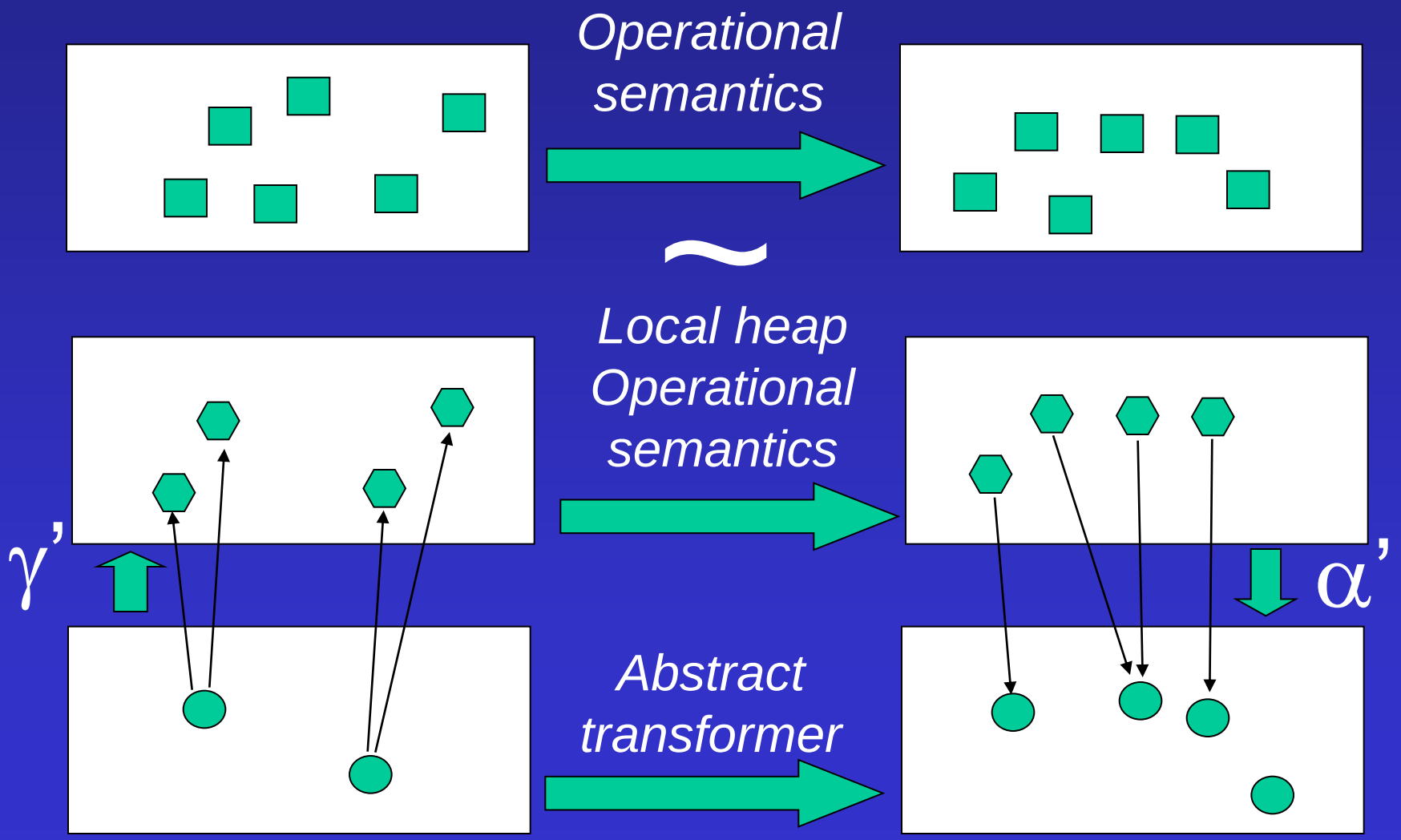
append(y,z)



Main Results(POPL'05)

- Concrete operational semantics
  - Sequential programs
  - Local heap
  - Track cutpoints
  - Storeless
    - good for shape abstractions
  - Observational equivalent with "standard" global store-based heap semantics
    - Java and "clean" C
- Abstractions
  - Shape Analysis of singly-linked lists
  - May-alias [Deutsch, PLDI 04]

Introducing local heap semantics



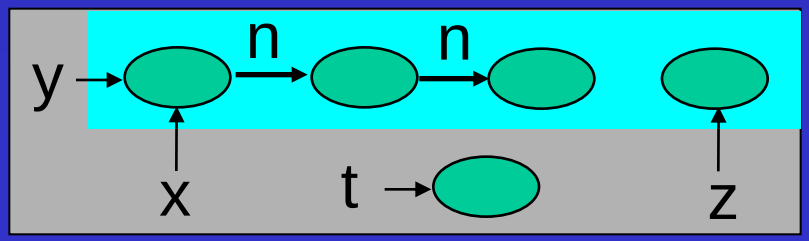
Main results(SAS'05)

- Cutpoint freedom
- Non-standard concrete semantics
  - Verifies that an execution is cutpoint-free
  - Local heaps
- Interprocedural shape analysis
  - Conservatively verifies
    - program is cutpoint free
    - Desired properties
      - Partial correctness of quicksort
  - Procedure summaries
- Prototype implementation

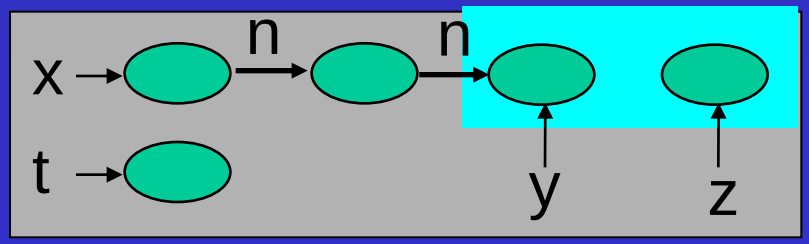
Cutpoint freedom

- **Cutpoint-free**
  - Invocation: has no cutpoints
  - Execution: every invocation is cutpoint-free
  - Program: every execution is cutpoint-free

append(y,z)



append(y,z)

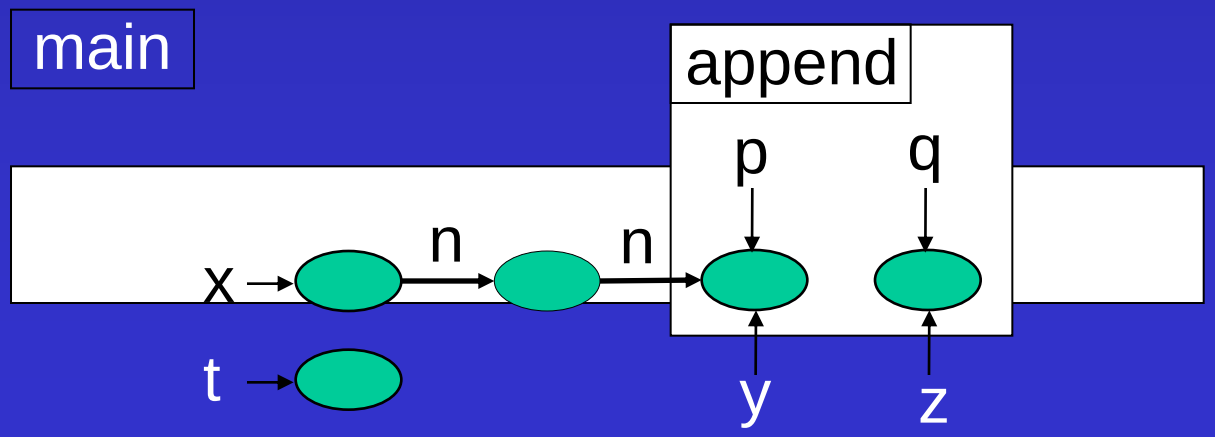


Programming model

- Single threaded
- Procedures
  - ✓Value parameters
    - Formal parameters not modified
  - ✓Recursion
- Heap
  - ✓Recursive data structures
  - ✓Destructive update
  - ✘No explicit addressing (&)
  - ✘No pointer arithmetic

Memory states

- A memory state encodes a **local heap**
  - Local variables of the **current procedure invocation**
  - Relevant part of the heap
    - Relevant ≡ Reachable

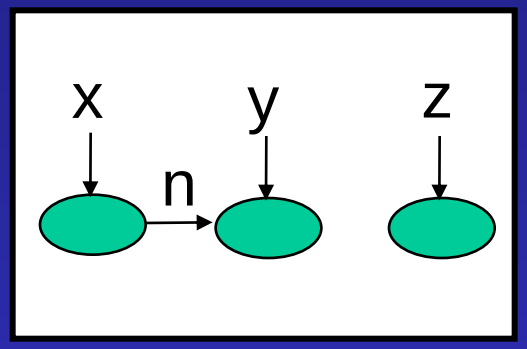


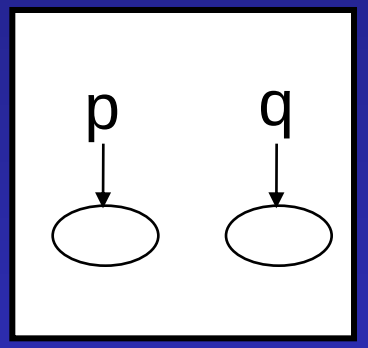
Abstract semantics

- Conservatively apply statements using 3-valued logic (with the non-standard semantics)
  - Use canonical abstraction
  - Reinterpret FO formulas using Kleene value

Procedure calls

append(p,q)

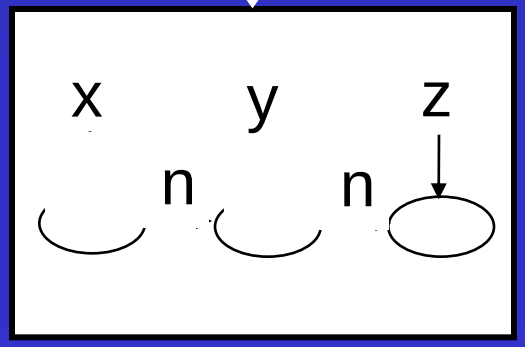


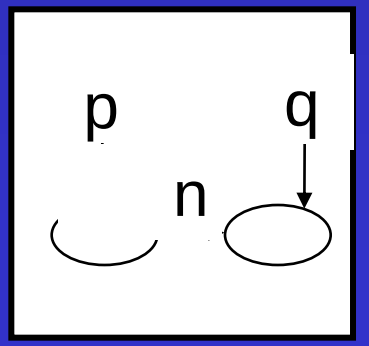


1. Verify cutpoint freedom
2 Compute input
... Execute callee ...
3 Combine output

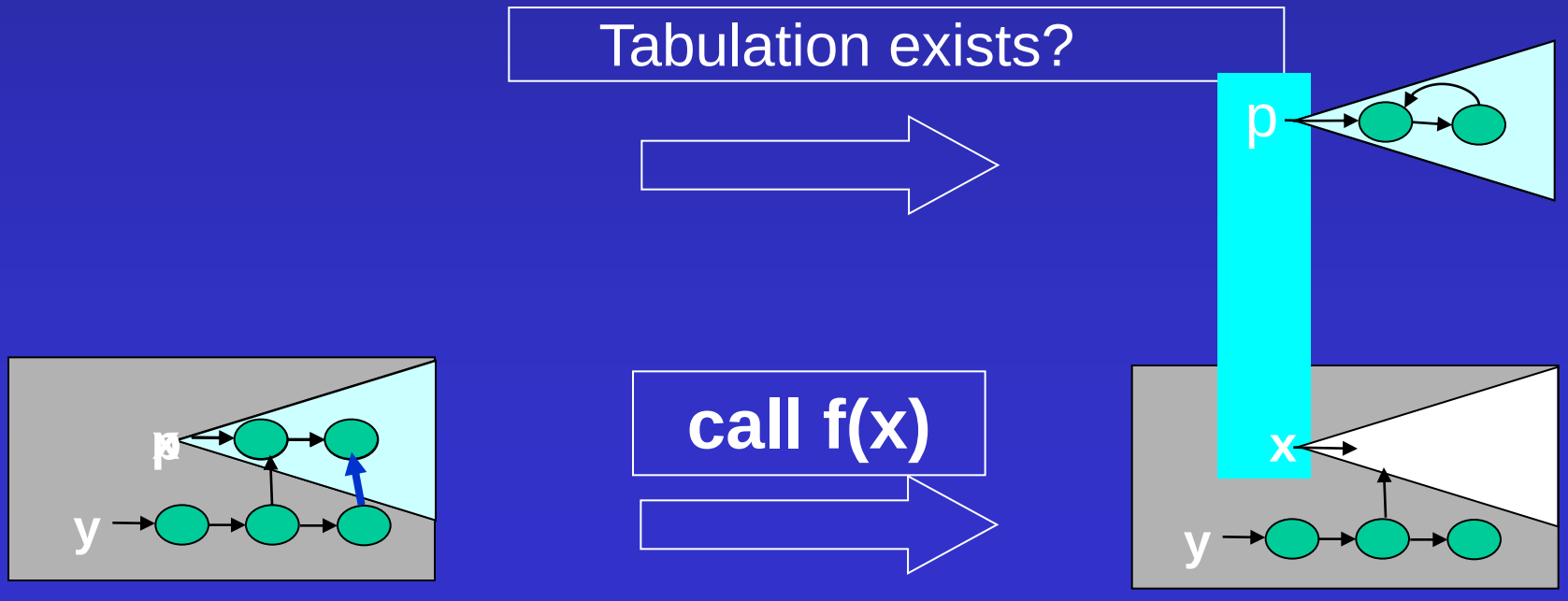
appe d(y,z)

appe body



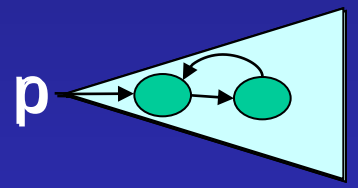


Interprocedural shape analysis

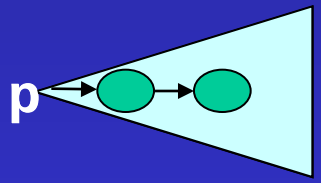


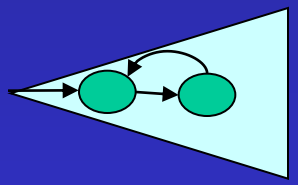
Interprocedural shape analysis

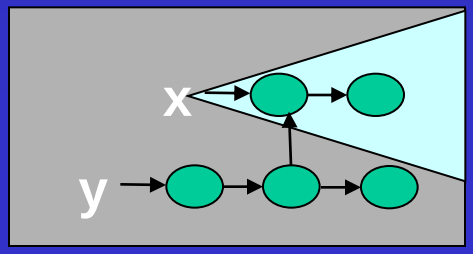
Analyze f



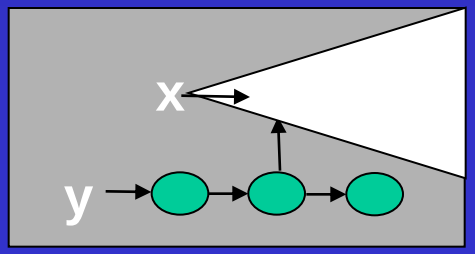
Tabulation exists?





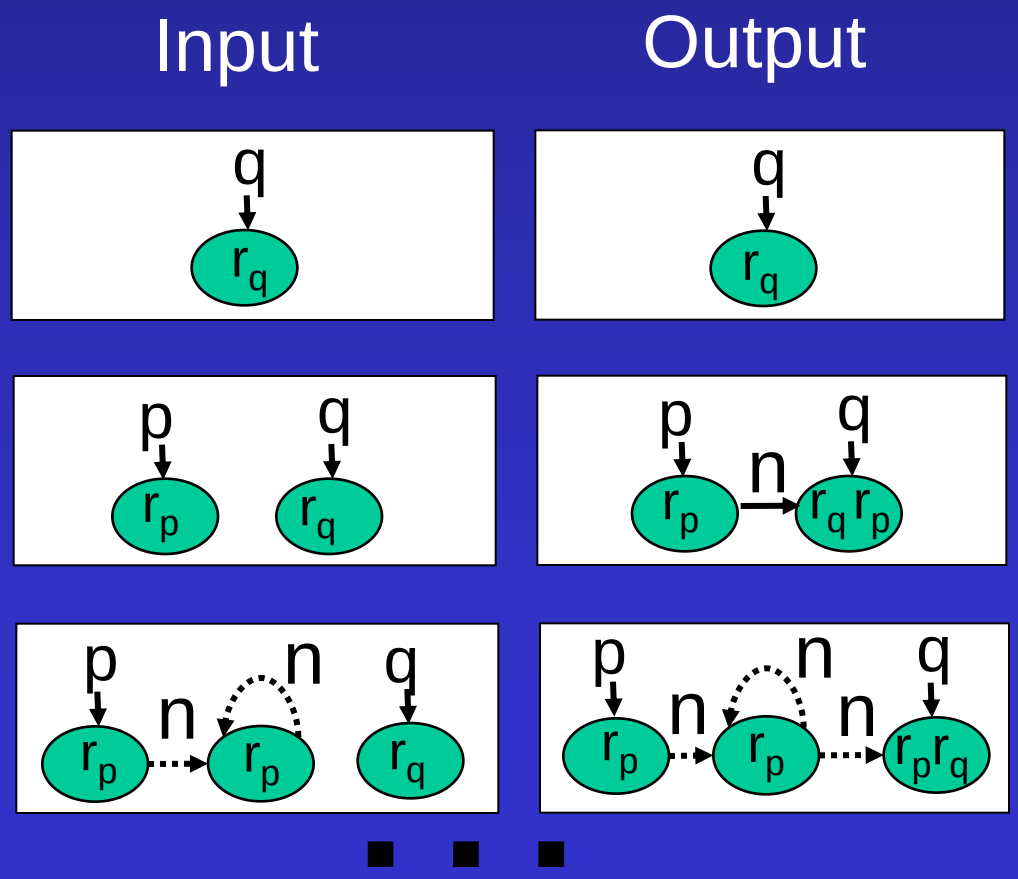


call f(x)



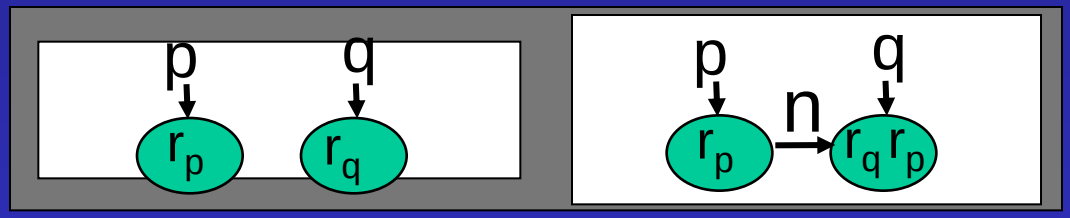
Interprocedural shape analysis

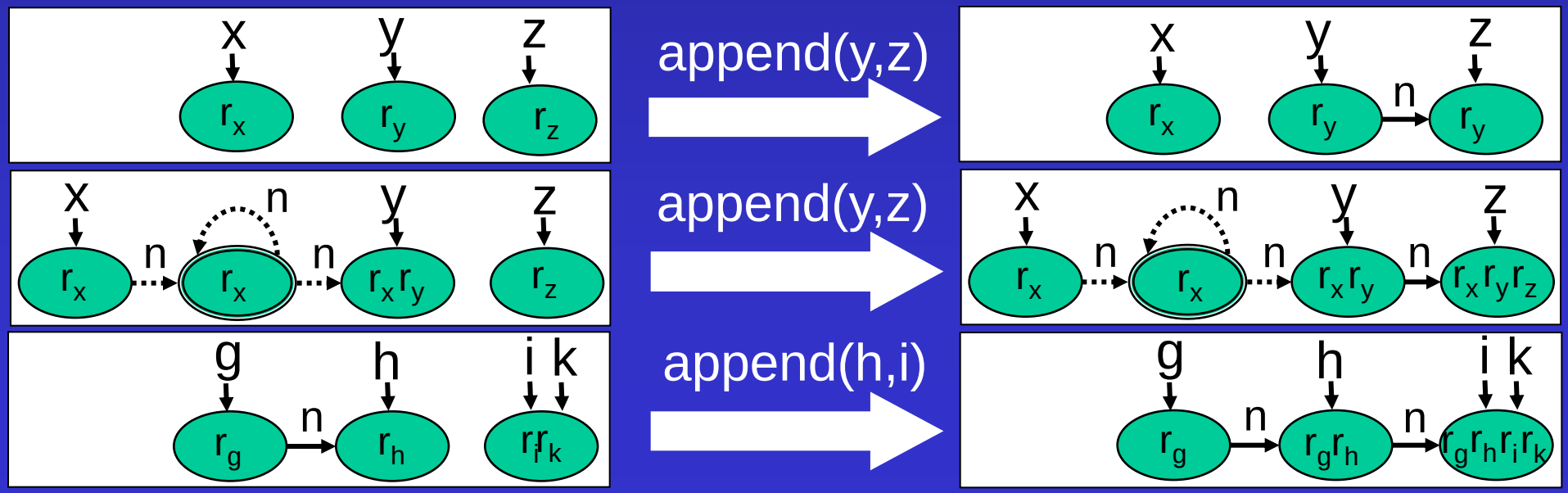
- Procedure ≡ input/output relation



Interprocedural shape analysis

- Reusable procedure summaries
  - Heap modularity



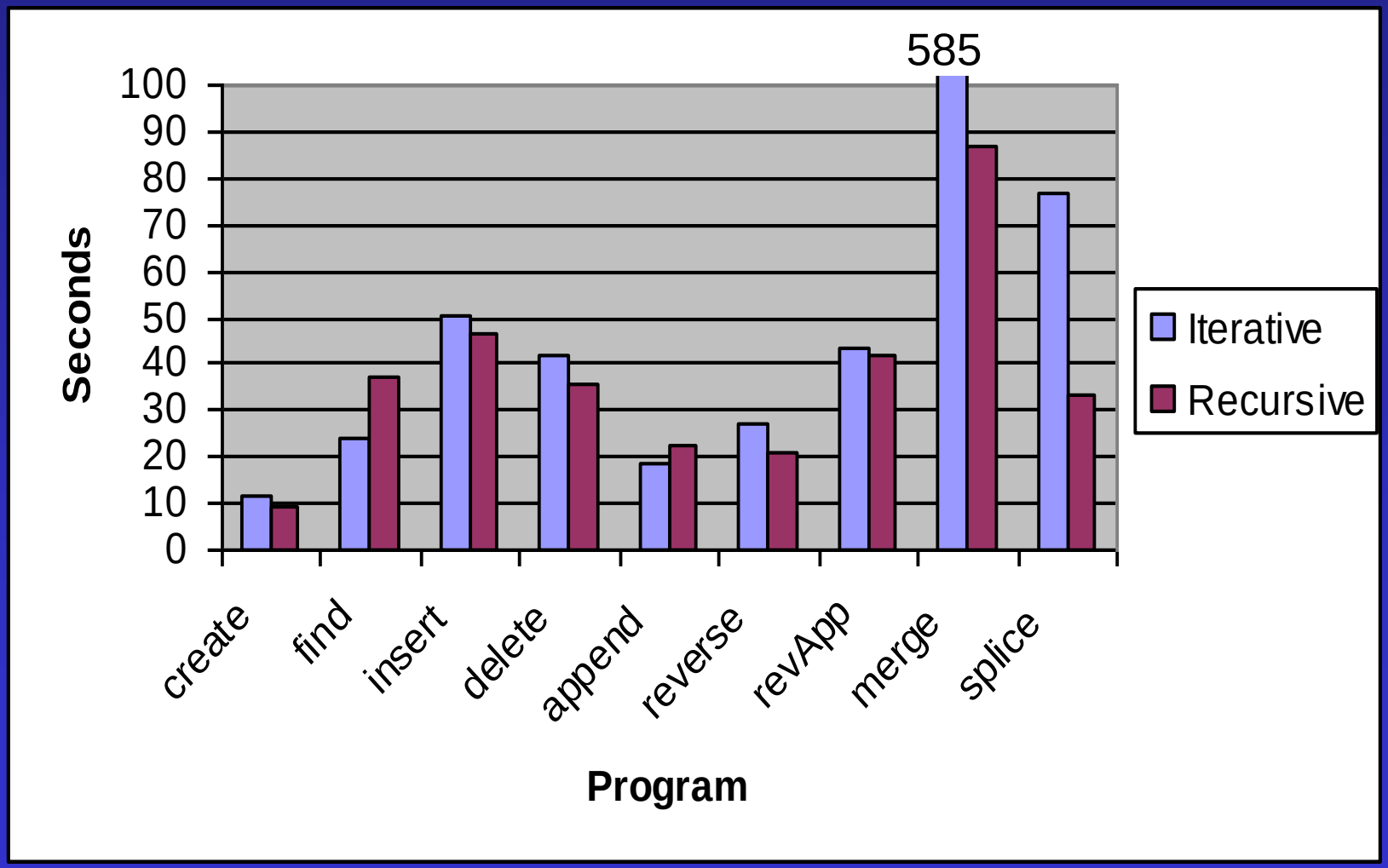


Prototype implementation

- TVLA based analyzer
- Soot-based Java front-end
- Parametric abstraction

Data structure	**Verified properties**
Singly linked list	Cleanness, acyclicity
Sorting (of SLL)	+ Sortedness
Unshared binary trees	Cleaness, tree-ness

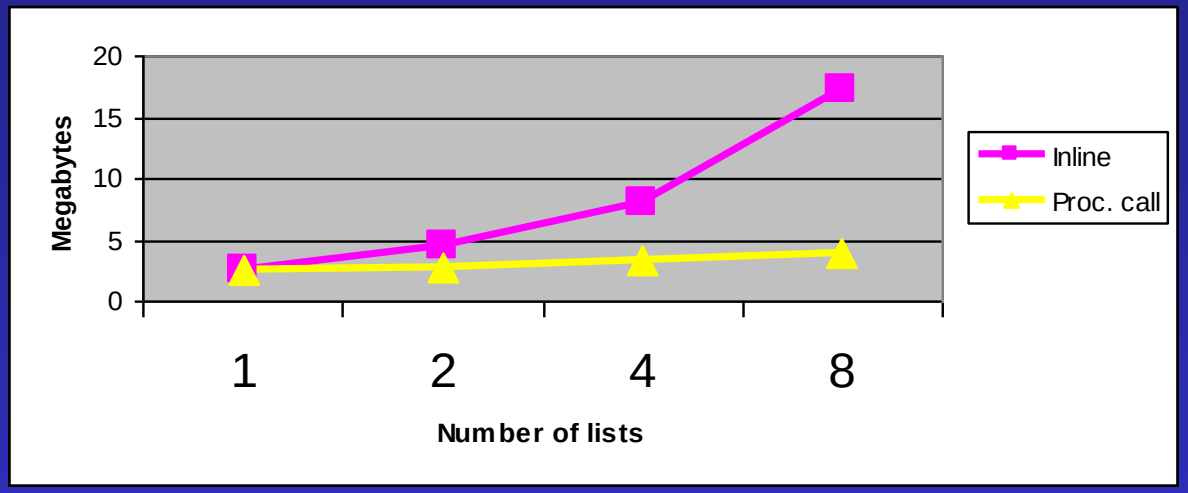
Iterative vs. Recursive (SLL)

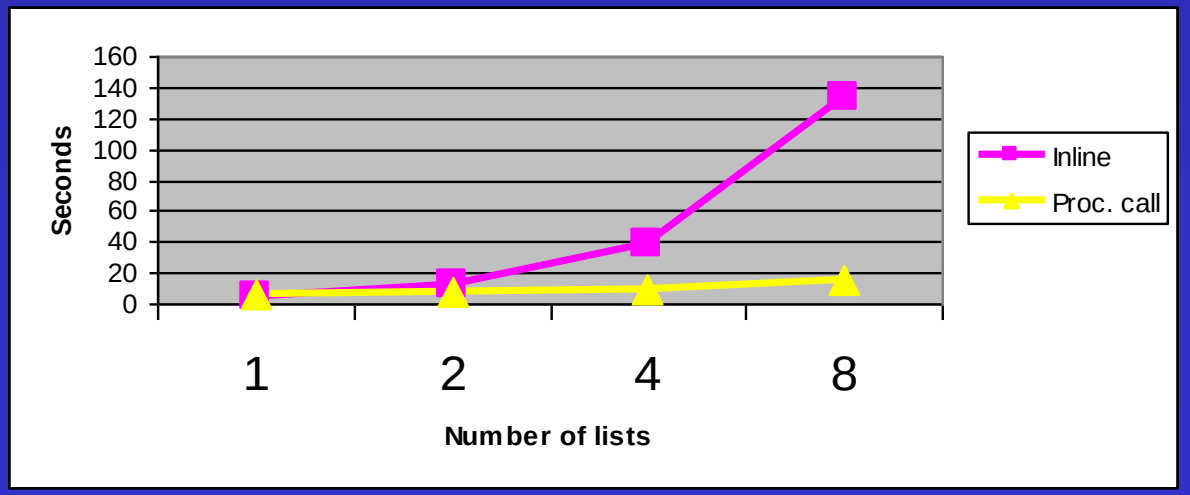


Inline vs. Procedural abstraction

```
// Allocates a list of
// length 3
List create3(){
   …
}

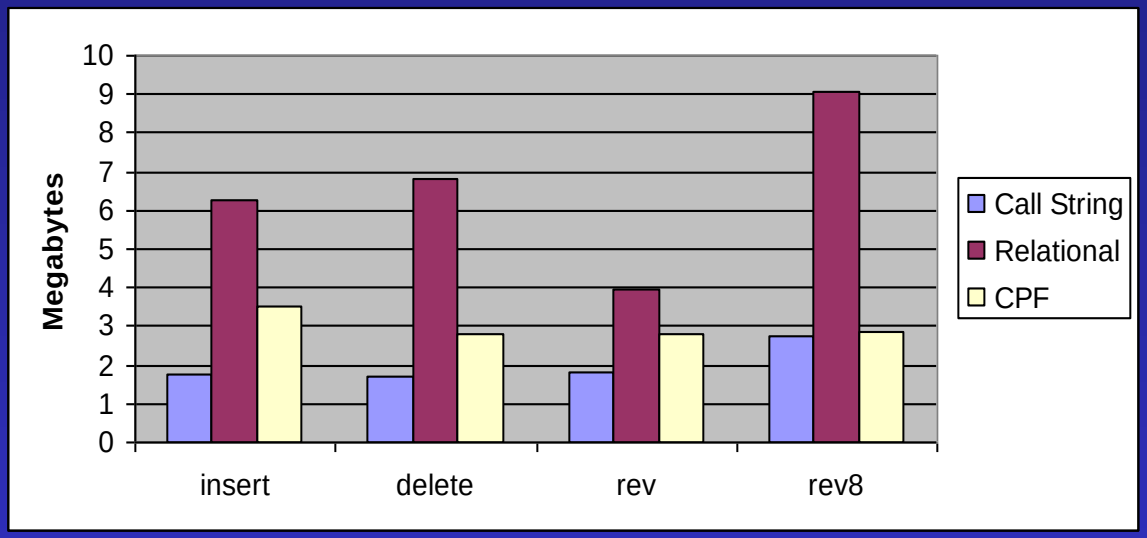
main() {
  List x1 = create3();
  List x2 = create3();
  List x3 = create3();
  List x4 = create3();
  …
}
```

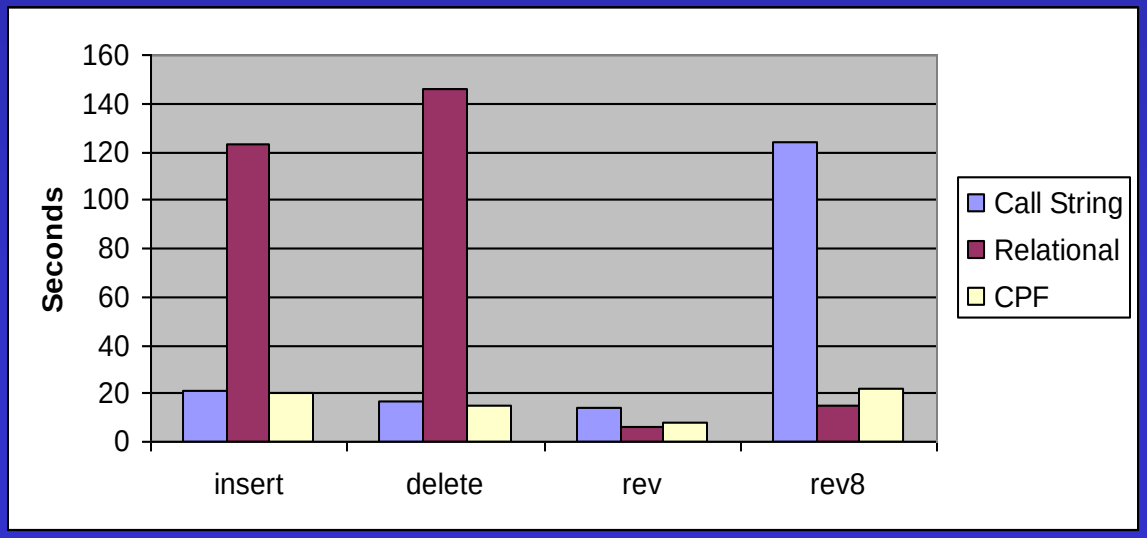




Call string vs. Relational vs. CPF

[Rinetzky and Sagiv, CC'01] [Jeannet et al., SAS'04]





Summary

- Cutpoint freedom
- Non-standard operational semantics
- Interprocedural shape analysis
  - Partial correctness of quicksort
- Prototype implementation

Summary

- Reasoning about the heap is challenging
- [Parametric] Abstraction is necessary
- Canonical abstraction is powerful
- Useful for programs with arrays [Gopan POPL'05]
- Information lost by canonical abstraction
  - Correlations between list lengths