Experience with Generic Shape Analysis

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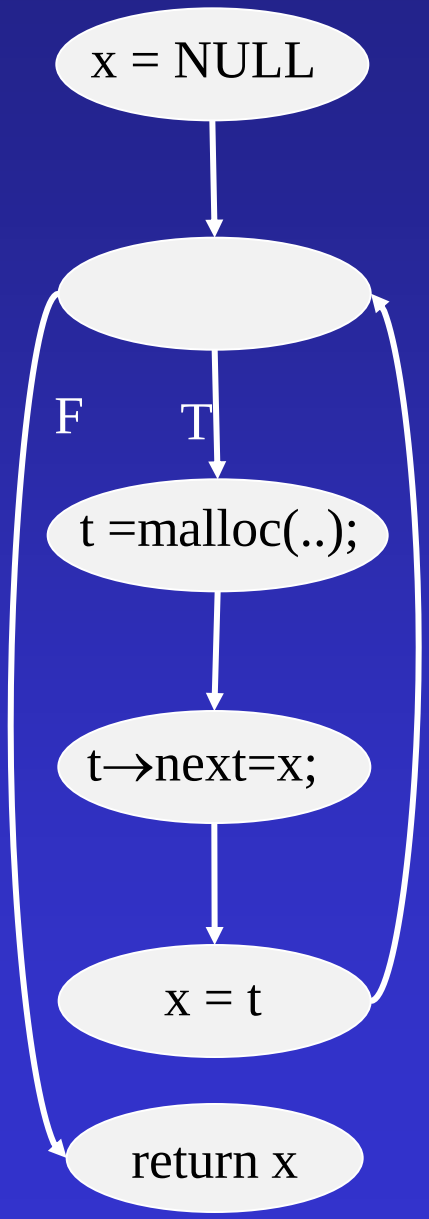
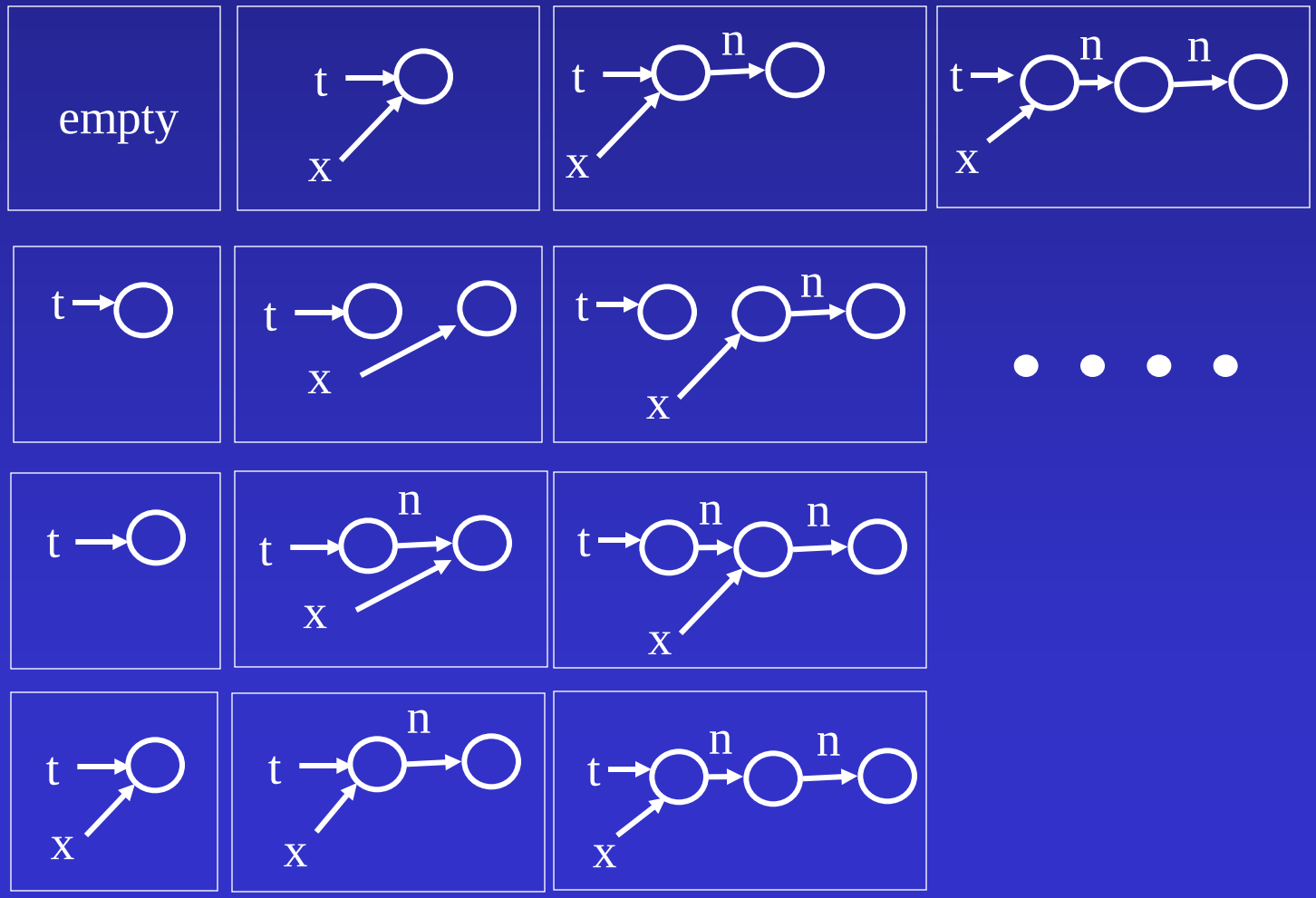
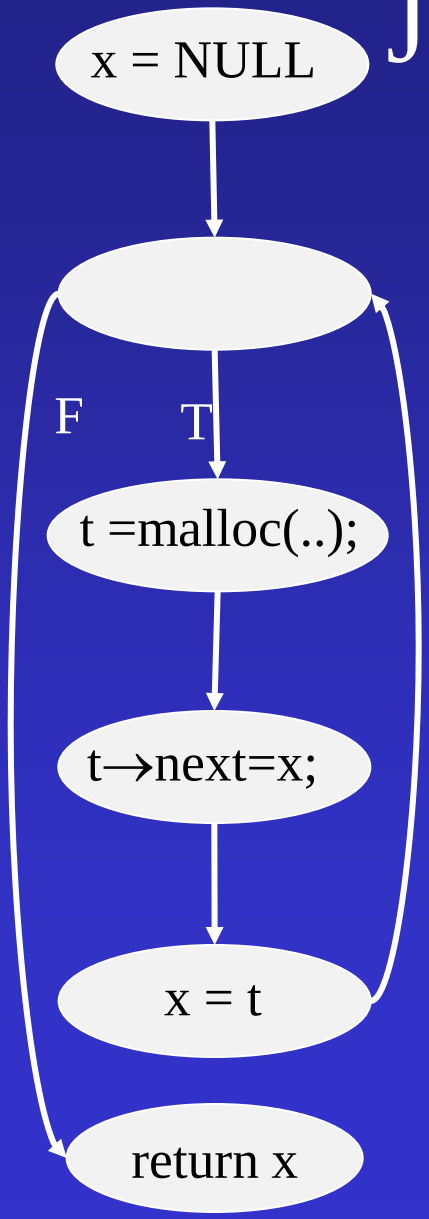
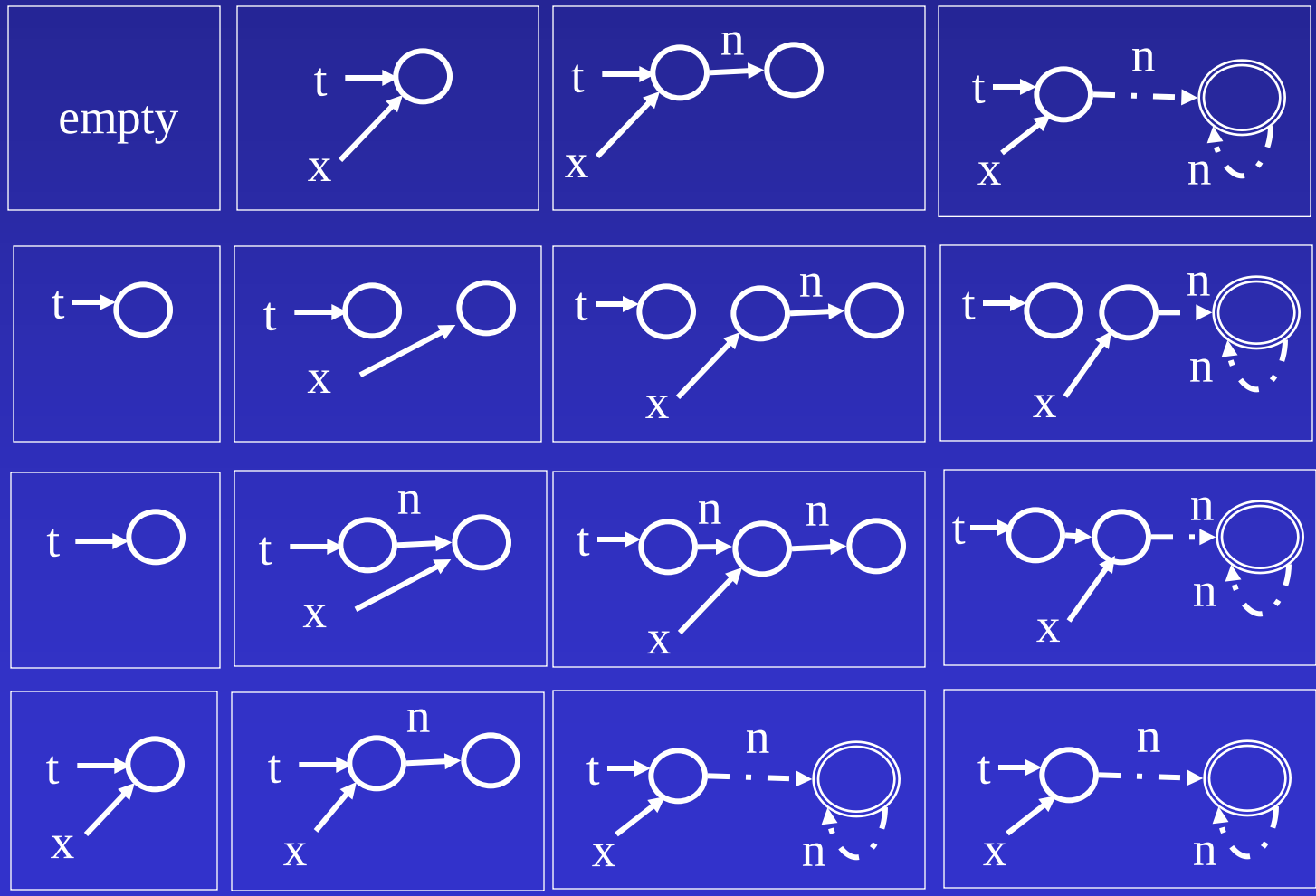
Example: Concrete Interpretation





Example: Shape Analysis
Jones and Muchnick 1981





TVLA: A parametric system for Shape Analysis

- A research tool
- Parameters
  - Concrete Semantics
    - States
    - Interpretation Rules
  - Abstraction
  - Transformers
- Iteratively compute a probably sound solution
- Specialize the shape analysis algorithm to class of programs

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;
  }
  assert sorted[x,n];
 //assert perm[x, n, x, n];
  return x;
}
```

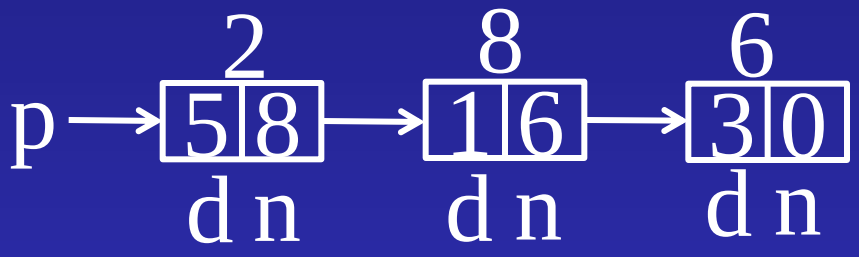
Partial Correctness

```
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;
    assert sorted[low, n];
    return low;
}
```

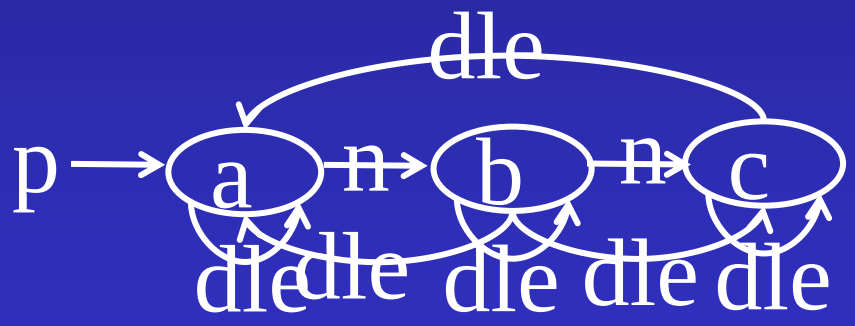
Concrete States in TVLA

- Nodes represent memory locations
- Unary relations represent:
  - Pointer variables
  - Boolean properties of memory locations
- Binary relations on nodes represent:
  - Pointer fields
  - Relations between locations

Insertion Sort



Concrete



TVLA

p	
a	1
b	0
c	0

n	a	b	c
a	0	1	0
b	0	0	0
c	0	0	0

dle	a	b	c
a	1	1	0
b	1	1	1
c	1	0	1

TVLA

Vanilla Concrete Interpretation Rules

Statement	Precondition	Update formula
x =NULL	true	$x'(v) := 0$
x=y	true	$x'(v) := y(v)$
$x=y \rightarrow f$	$\exists v: y(v)$	$x'(v) := \exists w: y(w) \wedge f(w, v)$
$x \rightarrow f=y$	$\exists v: x(v)$	$f'(v, w) :=$ $\begin{cases} y(w) & x(v) \\ f(v, w) & \neg x(v) \end{cases}$

Concrete Interpretation Rules for dle

Condition	Precondition
$x \rightarrow d <= y \rightarrow d$	$\exists v, w: x(v) \wedge y(w) \wedge dle(v, w)$
sorted [x,n]	$\forall u, v, w: x(u) \wedge n^*(u, v) \wedge n(v, w) \rightarrow dle(v, w)$

3-Valued Logical Structures

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

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

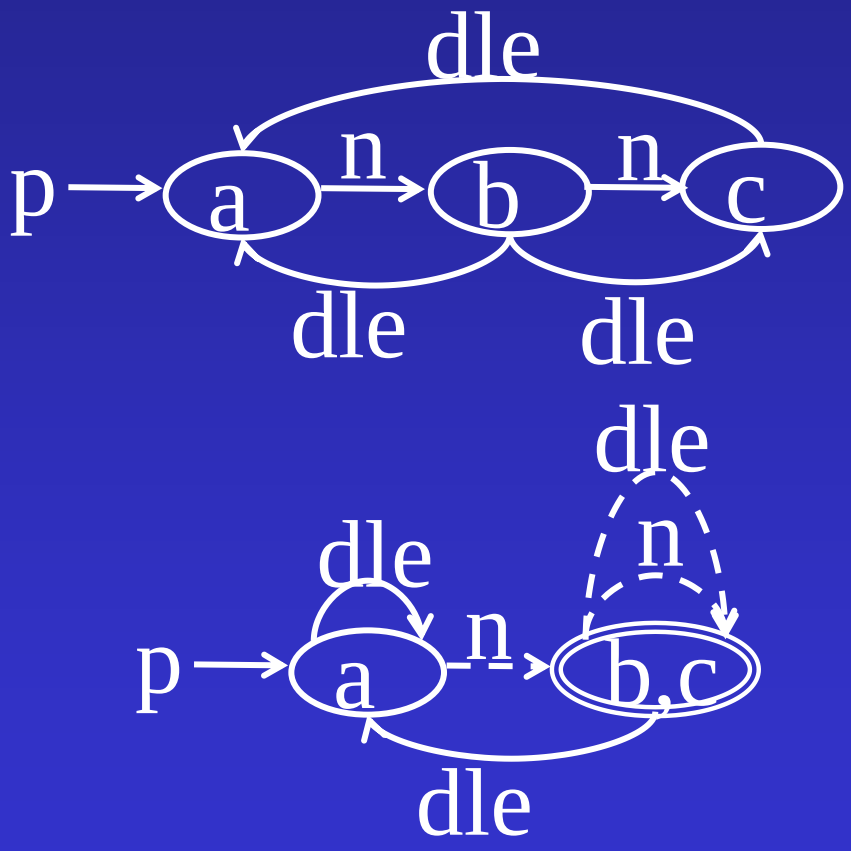
    $p^1(v) \rightarrow \{0,1, 1/2\}$

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

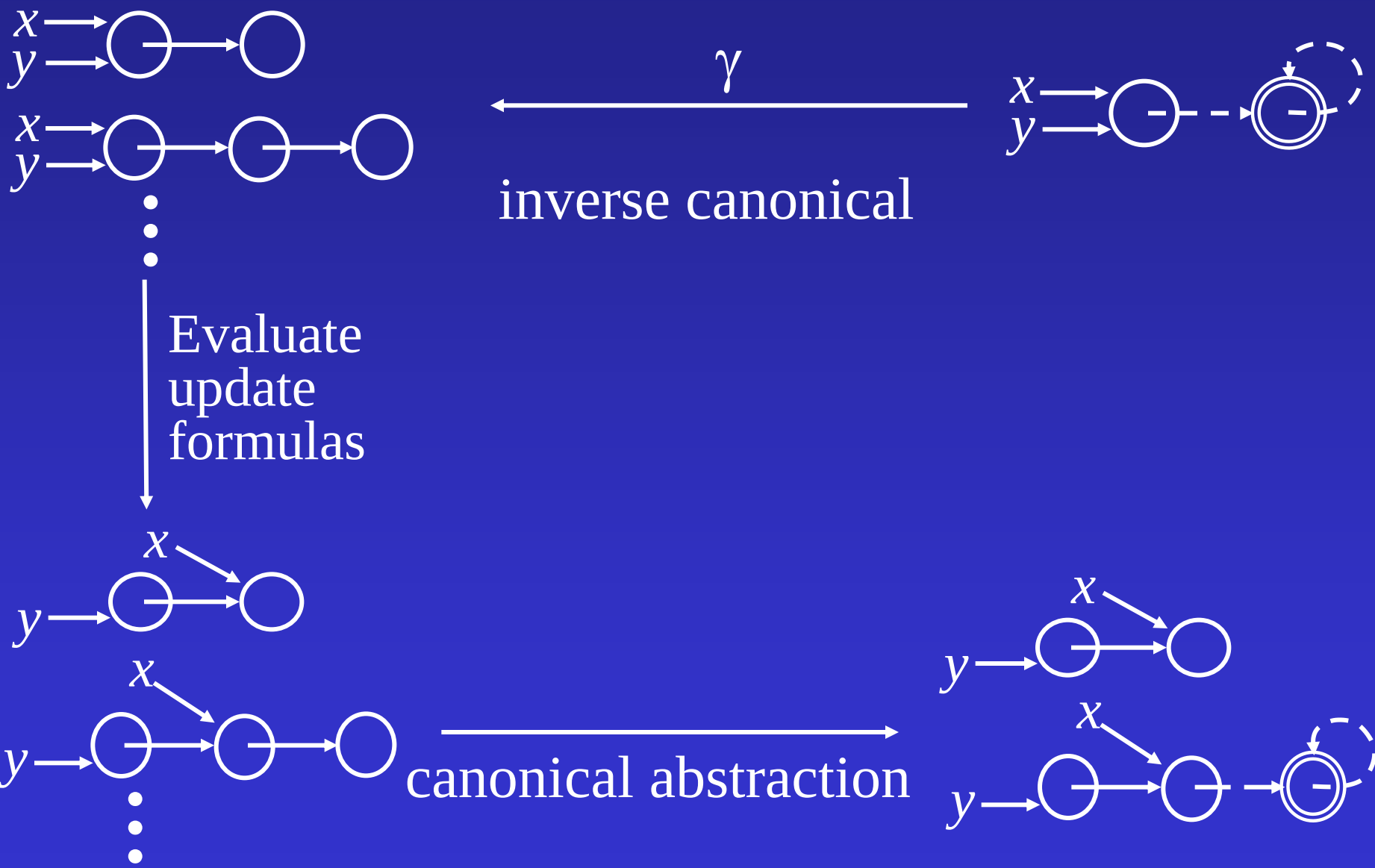
Canonical Abstraction (β)

- 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

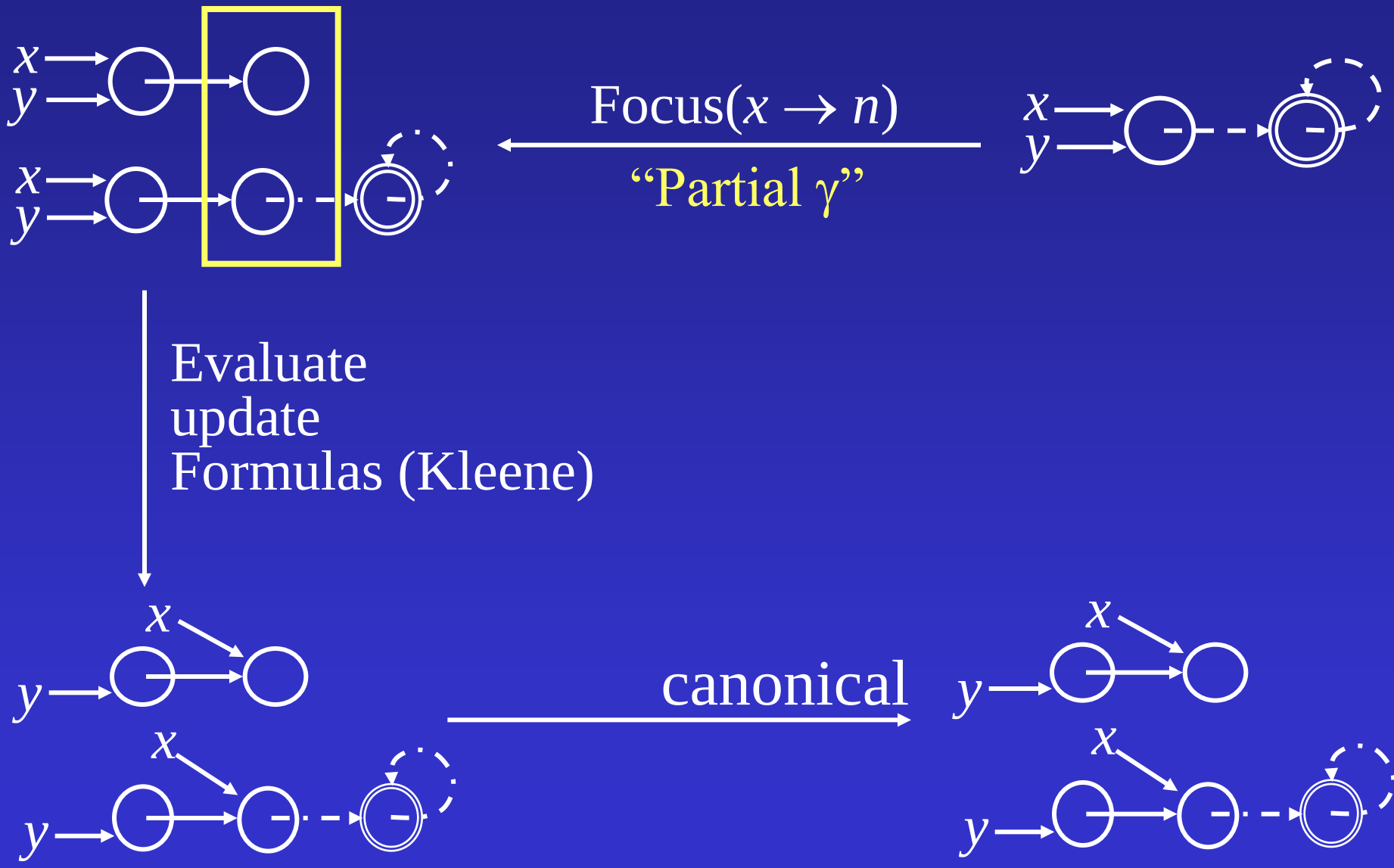
Sorting



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



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



Increasing Precision

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

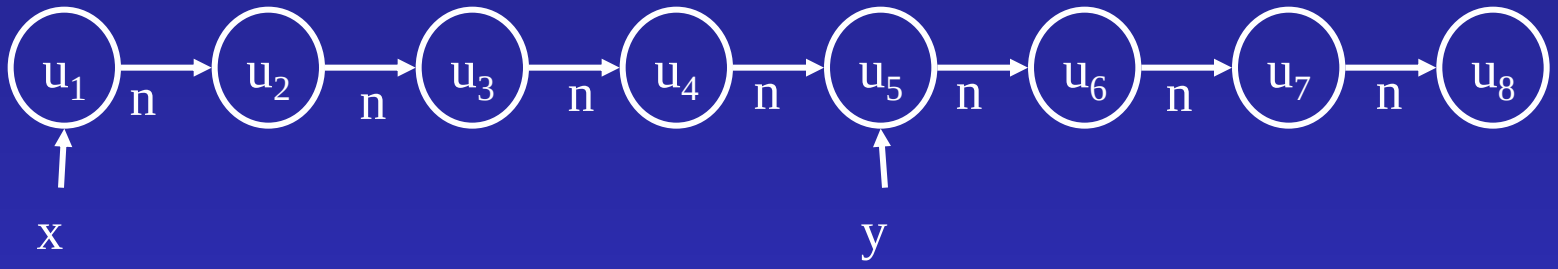
Global Invariants (Sorting)

- For all pointer variables x:
  $\forall v, w: x(v) \wedge x(w) \rightarrow v = w$
- For all pointer fields:
  $\forall u, v, w: f(u, v) \wedge f(u, w) \rightarrow v = w$
- $\forall u: dle(u, u)$
- $\forall u, v: dle(u, v) \wedge dle(v, w) \rightarrow dle(u, w)$
- $\forall u, v: dle(u, v) \vee \neg dle(v, u)$

Instrumentation Principle

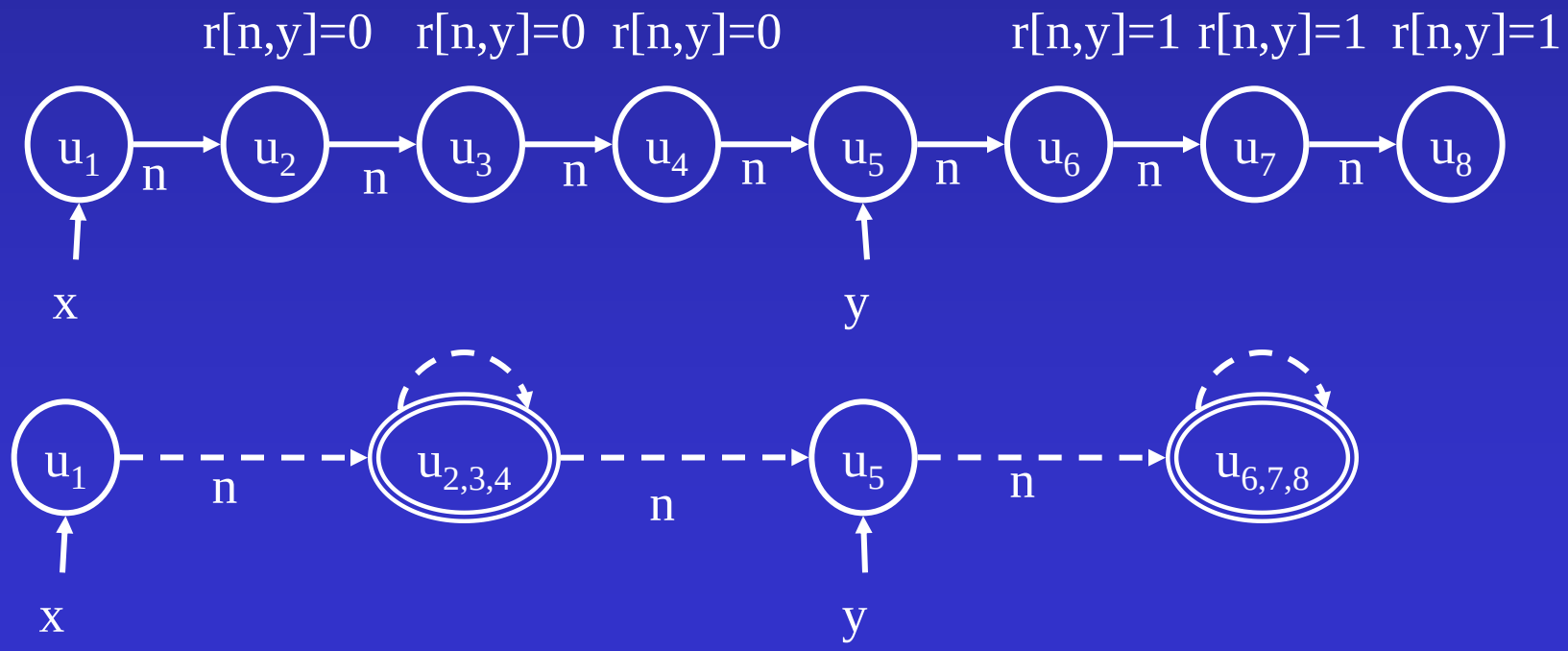
- Refine the abstraction by explicitly recording information lost by the abstraction
- TVLA users define extra information
- Automatically maintained by the system

List Segments

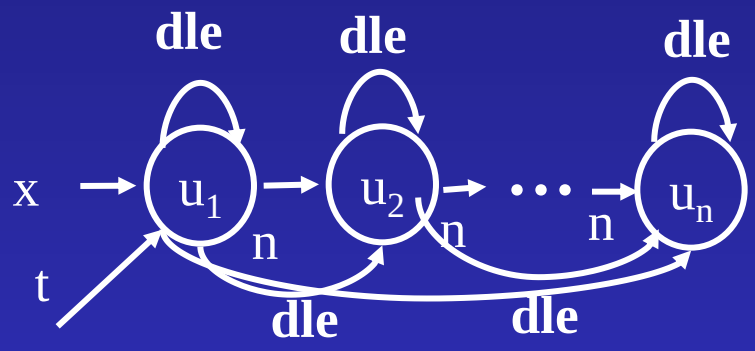


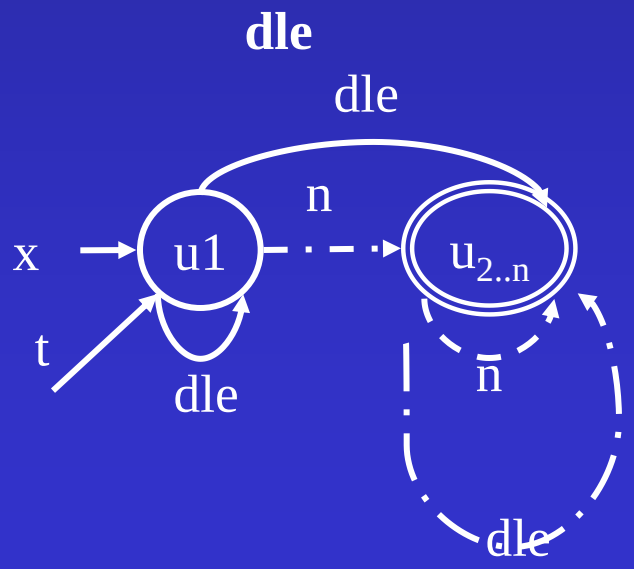
Reachability from a Variable

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



Sortedness

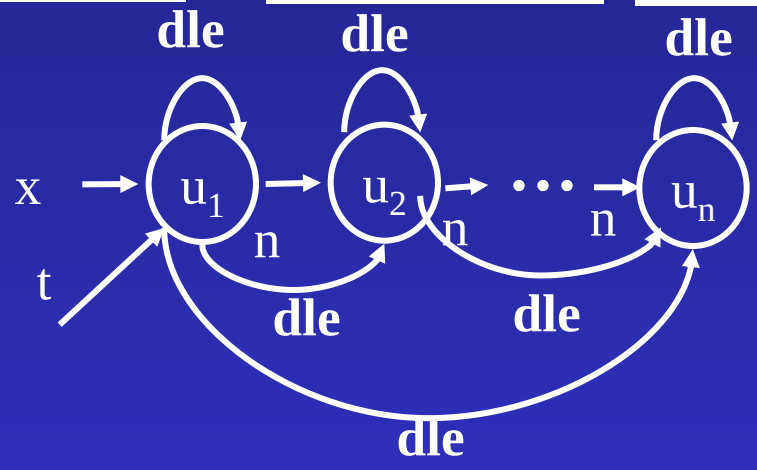


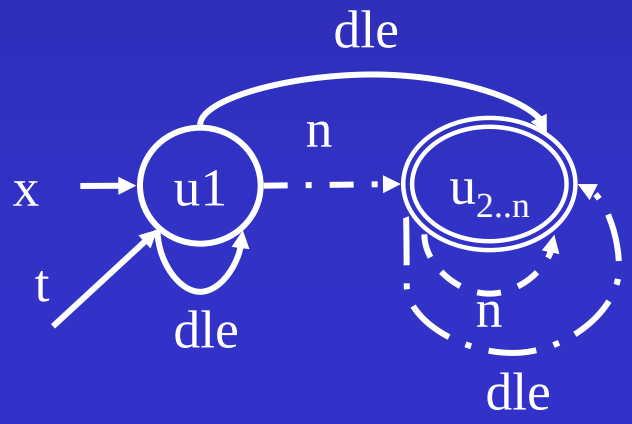


Example: Sortedness

$$\text{inOrder}(v) = \forall v1: n(v,v1) \rightarrow \text{dle}(v, v1)$$

inOrder = 1 inOrder = 1 inOrder = 1





inOrder = 1 inOrder = 1

Additional Instrumentation Relations

- is[f](v) $\exists w1, w2: w1 \neq w2 \wedge f(w1, v) \wedge f(w2, v)$
- c[f,b](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]
- Relevance heuristics

Automatically Maintaining Instrumentation

$inOrder(v) = \forall v1: n(v,v1) \rightarrow dle(v, v1)$

Statement	Precondition	Update formula
$x \rightarrow n = NULL$	$\exists v: x(v)$	$n'(v, w) := \begin{cases} 0 & x(v) \\ n(v, w) & \neg x(v) \end{cases}$ $InOrder'(v) := \begin{cases} 1 & x(v) \\ inOrder(v) & \neg x(v) \end{cases}$
$x \rightarrow n = y$	$\exists v: x(v) \wedge$ $\forall w: \neg n(v, w)$	$n'(v, w) := \begin{cases} y(w) & x(v) \\ n(v, w) & \neg x(v) \end{cases}$ $InOrder'(v) := \begin{cases} \exists w: y(w) \wedge dle(v, w) & x(v) \\ inOrder(v) & \neg x(v) \end{cases}$

Instrumentation (Summary)

- Refines the abstraction

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

- Adds global invariants

$$\forall v{:}\ r[n, y](v) \leftrightarrow \exists w{:}\ y(w) \wedge n^*(w, v)$$

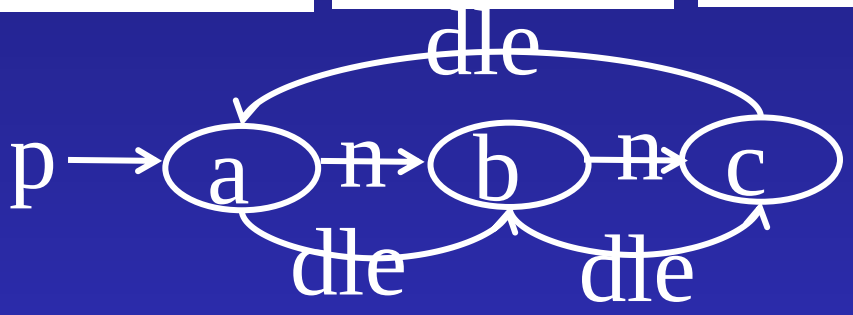
$$\gamma(S^{\#}) = \{S : S \vDash \Sigma,\ \beta(S) = S^{\#}\}$$

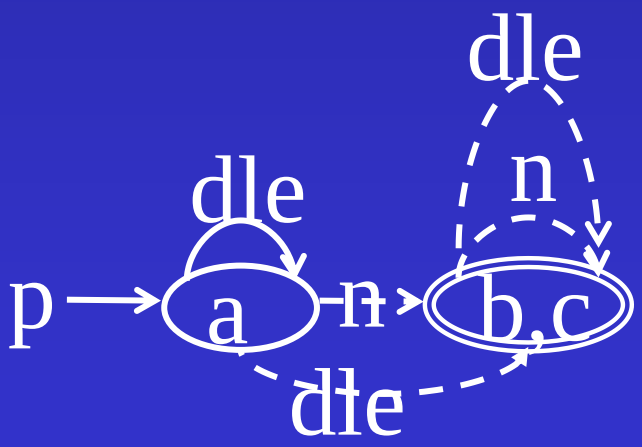
Scaling

- Reducing the number of shape nodes
  - Abstraction vs. Non-Abstraction Predicates
- Reducing the number of shape graphs
  - Partial Join [Manevich, SAS'04]
  - Heap Decomposition [Manevich, SAS'08]
- Handling procedures [Rintezkey, POPL'05, Jeanneat, TOPLAS'09]
  - Relational analysis with only local pointers
- Handling concurrency

InOrder as distinction

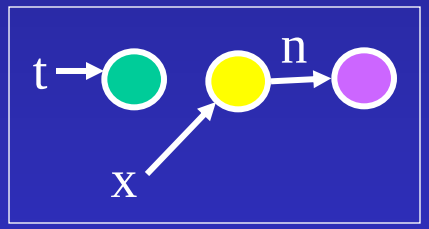
inOrder = 1 | inOrder = 0 | inOrder = 1

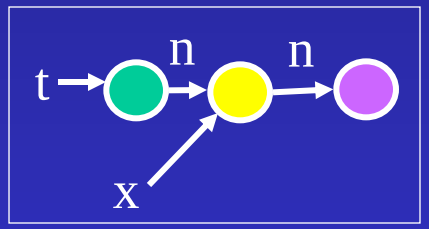


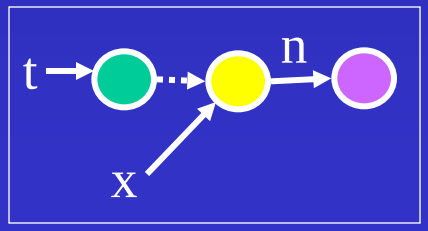


inOrder = 1 | inOrder = 1/2

Partially Disjunctive vs. Powerset Abstraction







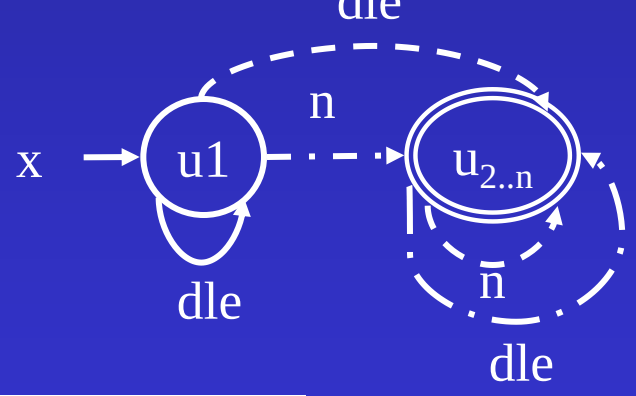
Example: InsertSort

Abstraction	Time sec.	#Structures
∪/abs inorder	>1800	> 166,000
∪/nonabs inorder	12.5	6,938
⊔/abs inorder	72.6	16,612
⊔/nonabs inorder	2.2	1,489

```
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;
  }
  assert(sorted[n,x]);
  return x;
}
```

Example: InsertSort (with bug)

"Unable to prove that the list pointed by x is sorted"



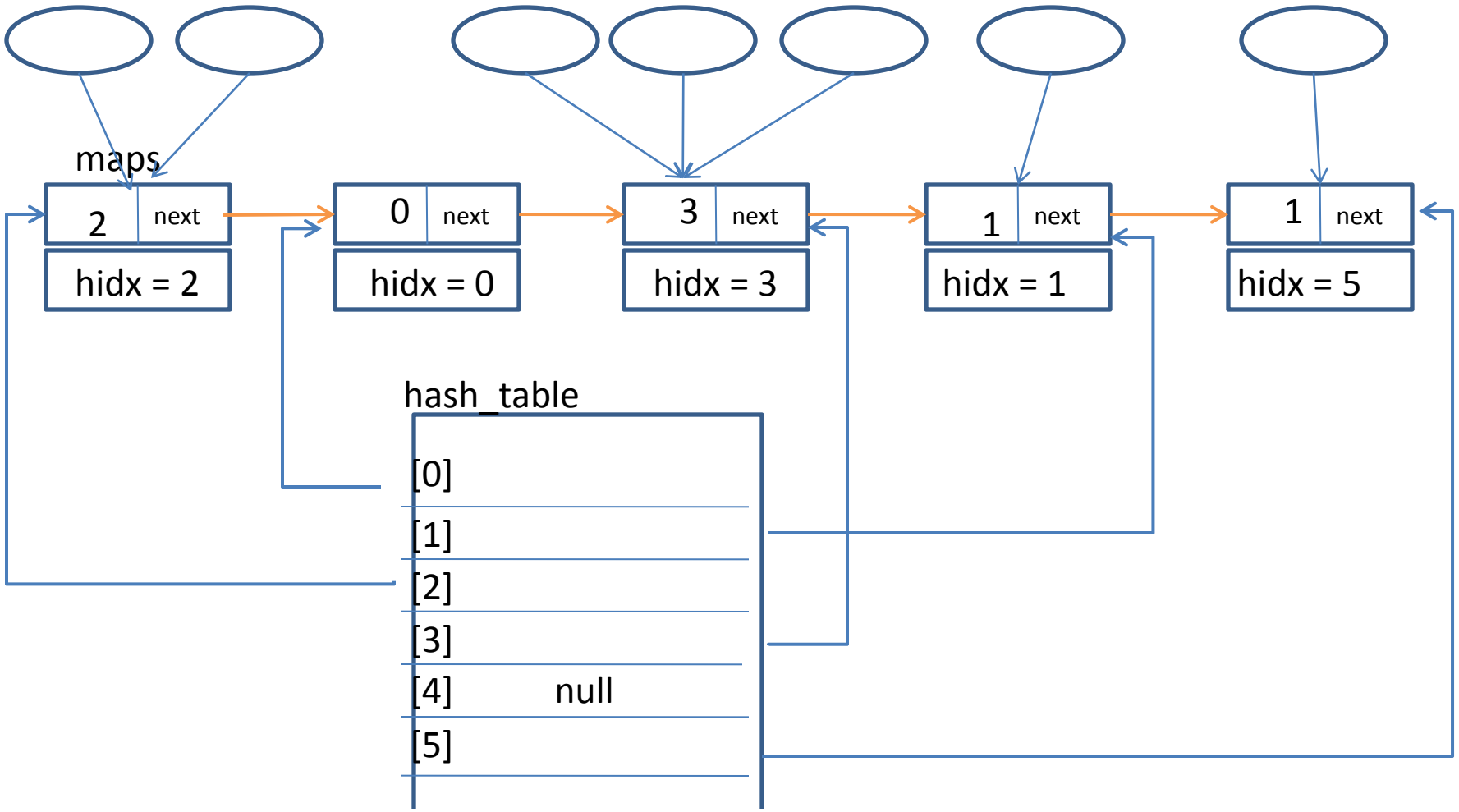
inOrder = 1/2 | inOrder = 1

```
List InsertSort(List x) {
 if (x == NULL)    return NULL
 pr = x;  r = x->n;
 while (r != NULL) {
          pl = x; rn = r->n; l = x->n;
          while (l != r) {
                    pr->n = rn ;
                    r->n = l;
                   pl->n = r;
                    r = pr;
                    break;
                         }
                  pl = l;
                  l = l->n;
                  }
          pr = r;
          r = rn;
assert(sorted[n,x]);
          }
```

DESKCHECK: Bill McCloskey

- Inspired by TVLA
- Combines Canonic Abstraction with Numeric Analysis
- Richer modeling language
- Nelson & Oppen like architecture
- More automatic
- Used to prove memory safety of real system's code

thttpd: Web Server



$\forall$n: maps. $\forall$v: Z. hash_table[v] ==n → n->hash_idx==v

$\forall$ n: maps. n→rc = | {n' : http_conn . n'->file_data == n} |

thttptd:add_hash

```
static int
add_hash( Map* m )
    {
    unsigned int h, he, i;

    h = hash( m->ino, m->dev, m->size, m->ctime );
    he = ( h + hash_size - 1 ) & hash_mask;
    for ( i = h; ; i = ( i + 1 ) & hash_mask )
       {
       if ( hash_table[i] == (Map*) 0 )
          {
          hash_table[i] = m;
          m->hash = h;
          m->hash_idx = i;
          return 0;
          }
       if ( i == he )
          break;
       }
    return -1;
    }
```

Analysis of thttpd web server

Function	Analysis time (s)
mmc_map	28.23
mmc_unmap	9.08
mmc_cleanup	76.81
mmc_destroy	5.80
Total	**123.47**

Other Applications

- Absence of Concurrent Modification Exceptions [Ramalingam, PLDI'02]
- Linearizability of lock-free concurrent linked-list implementations [Amit CAV'07, Berdine CAV'08, Manevich SAS'08]

Some Mistakes

- Not thinking of intended users
- The modeling language (TVP) is terrible
  - Transition System
  - Combines UI with semantics
  - Two low leveled
  - Uses CPP
  - Untyped
  - …
- Insufficient documentation
- Interacting with other systems
- Java frontend came out too late
  - No user interaction
- Not going open source

Questions

- Can programmers specialize program analysis?
- Interactive program analysis?

Lessons Learned

- TVLA can successfully model complex system code
- Prove interesting properties of small intricate programs
- Useful research tool
- Specialize the analysis to a class of programs
- Repeatable
  - A single TVP suffices for all the linked list sorting routines