Shape Analysis

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CS6843 Program Analysis
IIT Madras
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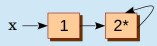
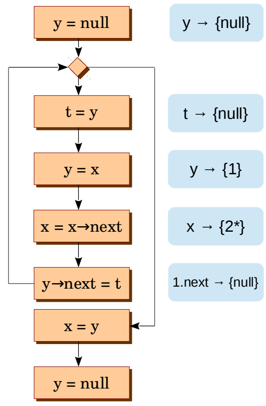
Limitations of Pointer Analysis

```
listReverse(List x) {
  assert("x is an acyclic singly linked list");

  for (y = null; x;) {
      t = y;
      y = x;
      x = x→next;
      y→next = t;
  }
  x = y;
  t = null;
  y = null;
}
```

We model the list as a two node structure.





Outline

- Limitations of pointer analysis
- Identify lists
- Identify trees, DAGs, cyclic graphs
- Identifying rotations
- List reversal and other transformations

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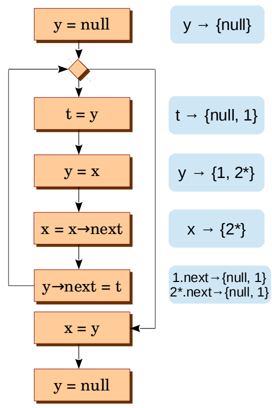

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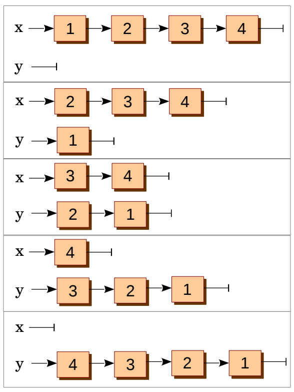
We want to check if x points to a singly linked list at the end of listReverse.
That is,
x → {4}, 4.next → {3}, …, 1.next → {null}



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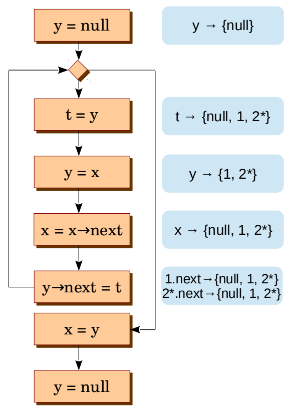

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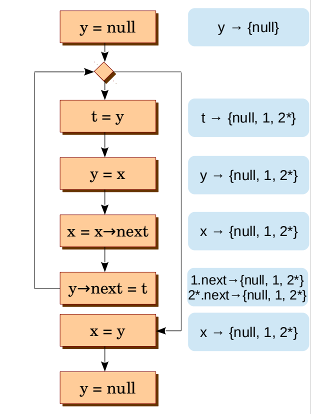

Shape Analysis

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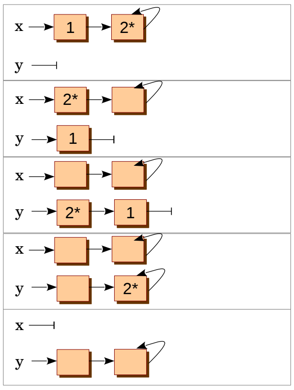
```

Maintain additional information with 2* that it is acyclic. Use the fact that node removal maintains acyclicity.



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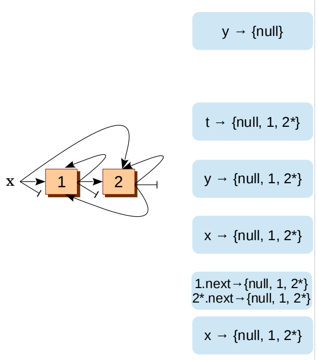


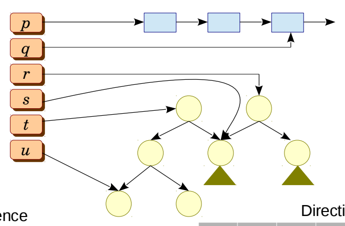
Tree, DAG, Cycle?

- Maintains three data structures:
  - Interference matrix: encodes common reachability
  - Direction matrix: encodes direct reachability
  - Shape
- Performs iterative data-flow analysis to update D, I and shape information

Shape Analysis

- Identify structural / topological properties of a data structure under manipulation.
- Usually categorized as slist, tree, DAG or cycle.
- Precision reduces along slist → tree → DAG → cycle.

Tree, DAG, Cycle?



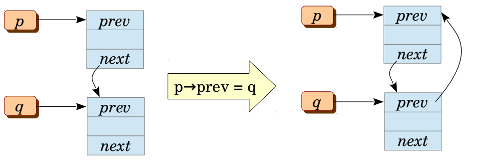
Interference

	p	*q*	*r*	*s*	*t*	*u*
p	1	**1**	0	0	0	0
q		1	0	0	0	0
r			1	**1**	**1**	0
s				1	**1**	0
t					1	**1**
u						1

Direction

	p	*q*	*r*	*s*	*t*	*u*
p	1	**1**	0	0	0	0
q	**0**	1	0	0	0	0
r	0	0	1	**1**	**0**	0
s	0	0	**0**	1	**0**	0
t	0	0	**0**	**1**	1	**1**
u	0	0	0	0	**0**	1

Shape Estimation



D[p][q] = 1, D[q][p] = 0
p.shape = Tree
q.shape = Tree

D[p][q] = 1, D[q][p] = **1**
p.shape = **Cycle**
q.shape = **Cycle**

Inference Rules

p = malloc(...)	D_kill and I_kill sets same as for allocation statement.
p = q p = q→f p = &(q→f) p = q op k p = null	D_gen = {D[s][p] ∣ D[s][q] and s ≠ p} U {D[p][s] ∣ D[q][s] and s ≠ p} U {D[p][p] ∣ D[q][q]} I_gen = {I[p][s] ∣ I[q][s] and s ≠ p} U {I[p][p] ∣ I[q][q]}
p->f = q p->f = null	p.shape = q.shape

Inference Rules

p = malloc(...)	
p = q p = q→f p = &(q→f) p = q op k p = null	
p->f = q p->f = null	

Inference Rules

p = malloc(...)	D_kill and I_kill sets same as for allocation statement.
p = q p = q→f p = &(q→f) p = q op k p = null	D_gen = {D[s][p] ∣ I[s][q] and s ≠ p} U {D[p][s] ∣ D[q][s] and s ≠ p and s ≠ q} U {D[p][q] ∣ q.shape == Cycle} U {D[p][p] ∣ D[q][q]} I_gen = {I[p][s] ∣ I[q][s] and s ≠ p} U {I[p][p] ∣ I[q][q]}
p->f = q p->f = null	p.shape = q.shape

Inference Rules

p = malloc(...)	D_kill = {D[p][s] ∣ D[p][s] == 1} U {D[s][p] ∣ D[s][p] == 1} I_kill = {I[p][s] ∣ I[p][s] == 1}
p = q p = q→f p = &(q→f) p = q op k p = null	D_gen = {D[p][p]} I_gen = {I[p][p]} p.shape = Tree
p->f = q p->f = null	

Inference Rules

p = malloc(...)	Processing is the same as for p = q statement. This means the analysis loses field-sensitivity.
p = q p = q→f p = &(q→f) p = q op k p = null	A recent work from IITK (Dasgupta, Karkare, Reddy) addresses this issue.
p->f = q p->f = null	

Inference Rules

p = malloc(...)	D_kill and I_kill sets same as for allocation statement.
p = q p = q→f p = &(q→f) p = q op k p = null	D_gen = { } I_gen = { } p.shape = Tree
p->f = q p->f = null	

Example

```
listReverse(List x) {
  assert("x is an acyclic singly linked list");

  for (y = null; x;) {
      t = y;
      y = x;
      x = x→next;
      y→next = t;
  }
  x = y;
  t = null;
  y = null;
}
```

Interference

	x	y	t
x		0	0
y			0
t			

Direction

	x	y	t
x	1	0	0
y	0	0	0
t	0	0	0

Shape

x	tree
y	tree
t	tree

Inference Rules

p = malloc(...)	D_kill = { }, I_kill = { }
p = q p = q→f p = &(q→f) p = q op k p = null	D_gen = {D[r][s] | D[r][p] and D[q][s]} I_gen = {I[r][s] | D[r][p] and I[q][s]} D[q][p] and D[s][q] ⇒ s.shape = Cycle D[q][p] and D[s][p] ⇒ s.shape = Cycle !D[q][p] and D[s][p] and I[s][q] and q.shape == Tree ⇒ s.shape = max(s.shape, DAG)
p->f = q p->f = null	!D[q][p] and D[s][p] and q.shape != Tree ⇒ s.shape = max(s.shape, q.shape)

	Tree	DAG	Cycle
Tree	Tree	DAG	Cycle
DAG	DAG	DAG	Cycle
Cycle	Cycle	Cycle	Cycle

max(shape1, shape2)

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}
```

Interference

	x	y	t
x		0	0
y			0
t			

Direction

	x	y	t
x	1	0	0
y	0	0	0
t	0	0	0

Shape

x	tree
y	tree
t	tree

Inference Rules

p = malloc(...)	D_kill = { }, I_kill = { }
p = q p = q→f p = &(q→f) p = q op k p = null	D_gen = { } I_gen = { } No changes to the shape of p.
p->f = q p->f = null	

Example

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Interference

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x		1	0
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We need to assume a finite representation for the data structure.

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Since we do not model fields, we can't say that x is unreachable from y.

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Shape

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t	cycle

Improvements

- SSA form
- Field-sensitivity
- Heap modeling

Summary

- Shape analysis helps several transforms.
- Existing techniques often trade off precision for efficiency.
- We are still far away from a precise and scalable analysis.