Pointer/Alias Analysis

Lecture 7: CPEN 400P

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(Based on Stephen Chong's lecture at Harvard Univ., CS252, and Vikram Adve's CS526 at the Univ. of Illinois)

Outline

What is pointer analysis ?

Types of pointer analysis

Anderson’s analysis

Steensgard analysis

What’s pointer analysis ?

Pointer analysis: What memory locations can a pointer expression refer to?

Alias analysis: When do two pointer expressions refer to the same location?

```
int x;

p = &x;

q = p;
```

What locations alias each other ?

*p and *q alias, as do x and *p, and x and *q

What causes Aliasing ?

Pointers, Pointer arithmetic etc.

- See previous slide

Call by reference

Array indexing, e.g., a[i], i = j; a[j] → a[i] and a[j] alias

Virtual functions in C++ (use of vtable)

Many other cases

What’s the use of pointer analysis ?

Useful in many analysis

- Live-out: Can lead to variables being killed

```
p = &x;
*p = a + b;
```

- Constant propagation: can lead to spurious constants

```
x = 3;
p = &x;
*p = 4;
```

Challenges of pointer analysis

1. Pointers to pointers, which can occur in many ways:
   - Take address of pointer
   - Pointer to structure containing pointer
   - Pass a pointer to a procedure by reference

2. Aggregate objects: structures and arrays containing pointers

3. Recursive data structures (lists, trees, graphs, etc.)

   closely related problem: anonymous heap locations

4. Control-flow: analyzing different data paths

5. Inter-procedural analysis is crucial

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Flow-sensitivity

- Computes a distinct result for each program point

- Computes a single result for an entire procedure or an entire program

- Flow-sensitive is too expensive in practice and rarely used
  - All the pointer analysis we'll consider in this class are **flow-insensitive**
  - SSA provides a limited form of flow-sensitivity within a procedure

Context Sensitivity

Context-sensitive interprocedural analysis computes results that may hold only for realizable paths through a program - important for security and reliability

Need to consider many parameters

- Heap cloning vs. no cloning
- Bottom-up vs. top-down
- Handling of recursive functions

Modeling memory locations example

Should we distinguish between calls to goo() ?

```
foo() {
        T* p = goo();
        T* q = goo();
}
goo(int n) {
        return new T(n);
}
```

What about calls to makeList() ?

```
T* makelist(int len) {
        T* newObj = new T;
        // Many distinct objects allocated here
        newObj->next = (--len == 0)?
                                NULL : makelist(len);
        return newObj;
}
```

How do we model memory locations ?

Global variables - Use a single node

Local variables - use a single node *per context*

Dynamically allocated memory - potentially *unbounded* locations at runtime

- One node for entire heap (too imprecise)
- One node for each type (requires type analysis)
- One node per calling site (can lead to conflation across calling context)
- One node per calling context, i.e., for each allocation statement

“May” versus “Must” Analysis

May analysis: Aliasing that *may* occur during execution

Must analysis: Aliasing that *must* occur during execution

Consider liveness analysis: *p = *q + 4;

What’s the VarKill set for the statement ? What about the UEVar set ?

- May analysis: if *q may alias y, then y is in the UEVar set
- Must analysis: if *p must alias x, then x is in the VarKill set

Problem Statement

Flow-insensitive, **May analysis**

Assume program consists of only statements of the forms

- p = &a;
- p = q;
- *p = q;
- p = *q;

Assume pointers, q and address-taken variables are disjoint

We want to compute the points-to pairs, i.e., which pointer points to which variable

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What is pointer analysis ?

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Steensgard analysis

Andersen-style pointer analysis

- View pointer assignments as **subset constraints**
- Use constraints to propagate points-to information

Constraint type	Assignment	Constraint	Meaning
Base	a = &b	a ⊇ {b}	loc(b) ∈ pts(a)
Simple	a = b	a ⊇ b	pts(a) ⊇ pts(b)
Complex	a = *b	a ⊇ *b	∀v∈pts(b). pts(a) ⊇ pts(v)
Complex	*a = b	*a ⊇ b	∀v∈pts(a). pts(v) ⊇ pts(b)

Anderson’s Algorithm: Graph Representation

```
p = &a;

q = &b;

p = q;

r = &p;

*r = &c;

q = *r;
```

Anderson’s Algorithm: Graph Representation

p = &a; p → a

q = &b;

p = q;

r = &p;

*r = &c;

q = *r;

Anderson’s Algorithm: Graph Representation

p = &a;

q = &b;

p = q;

r = &p;

*r = &c;

q = *r;

p → a

q → b

Anderson’s Algorithm: Graph Representation

p = &a;

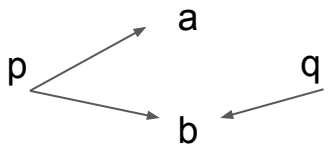
q = &b;

p = q;

r = &p;

*r = &c;

q = *r;



Anderson’s Algorithm: Graph Representation

p = &a;

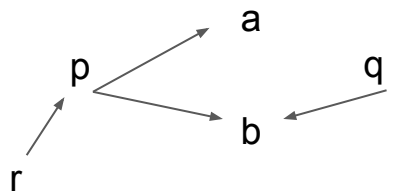
q = &b;

p = q;

r = &p;

*r = &c;

q = *r;



Anderson’s Algorithm: Graph Representation

p = &a;

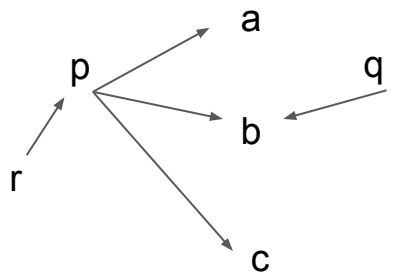
q = &b;

p = q;

r = &p;

***r = &c;**

q = *r;



Anderson’s Algorithm: Graph Representation

p = &a;

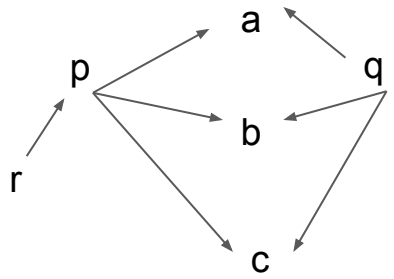
q = &b;

p = q;

r = &p;

*r = &c;

q = *r;



Points-to	Set
p	{a, b, c}
q	{a, b, c}
r	{p}
a	{}
b	{ }
c	{ }

Class Activity: Anderson's analysis

p = &a

q = &b

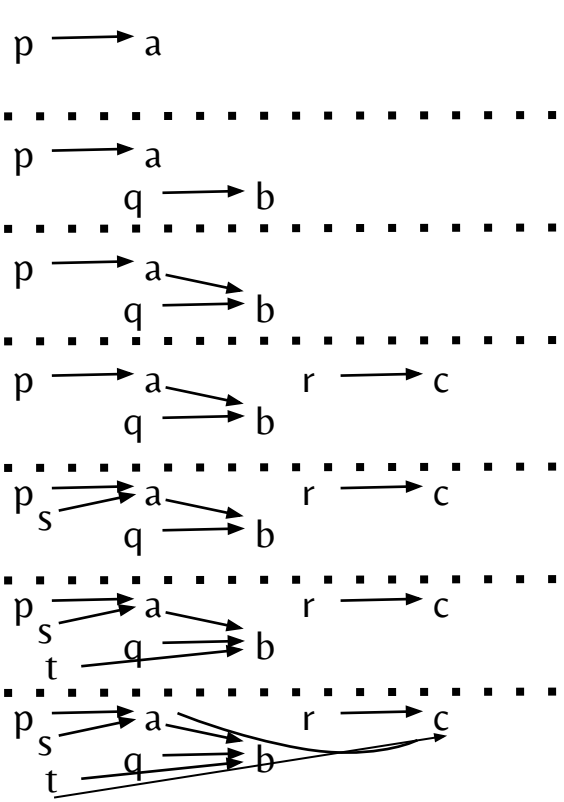
*p = q;

r = &c;

s = p;

t = *p;

*s = r;



Points-to	Set
p	{a}
q	{b}
r	{c}
s	{a}
t	{b, c}
a	{b, c}
b	{ }
c	{ }

Andersen-style as graph closure

- One node for each pts(p), pts(a)

Assgmt.	Constraint	Meaning	Edge
a = &b	$a \supseteq \{b\}$	$b \in pts(a)$	no edge
a = b	$a \supseteq b$	$pts(a) \supseteq pts(b)$	$b \rightarrow a$
a = *b	$a \supseteq *b$	$\forall v \in pts(b).\ pts(a) \supseteq pts(v)$	no edge
*a = b	$*a \supseteq b$	$\forall v \in pts(a).\ pts(v) \supseteq pts(b)$	no edge

- Each node has an associated points-to set
- Compute transitive closure of graph, and add edges according to complex constraints: O(N^3)

Outline

What is pointer analysis ?

Types of pointer analysis

Anderson’s analysis

Steensgard analysis

Steensgaard-style analysis

- Also a constraint-based analysis
- Uses **equality constraints** instead of subset constraints
- Less precise than Andersen-style, thus more scalable
  - Almost linear time as opposed to O(N^3)

Constraint type	Assignment	Constraint	Meaning
Base	a = &b	a ⊇ {b}	loc(b) ∈ pts(a)
Simple	a = b	a = b	pts(a) = pts(b)
Complex	a = *b	a = *b	∀ v∈pts(b). pts(a) = pts(v)
Complex	*a = b	*a = b	∀ v∈pts(a). pts(v) = pts(b)

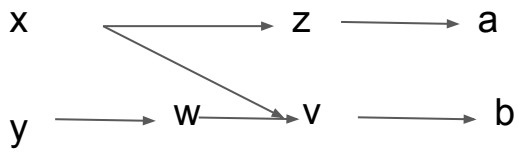
Implementing Steensgaard-style analysis

- **Restrict every node to only one outgoing edge**
  If p → x and p → y , merge x and y (“Unify”)

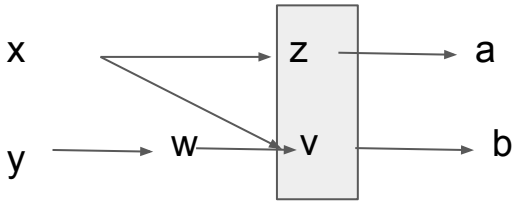
All objects “pointed to” by p - same equivalence class

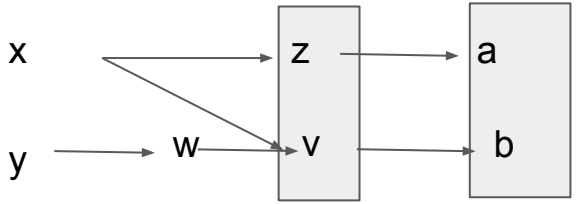
- Can be efficiently implemented using Union-Find algorithm
  - Nearly linear time: O(n): Tarjan’s data-structure
  - Each statement needs to be processed just once

Example: Steensgard's algorithm



x = *y



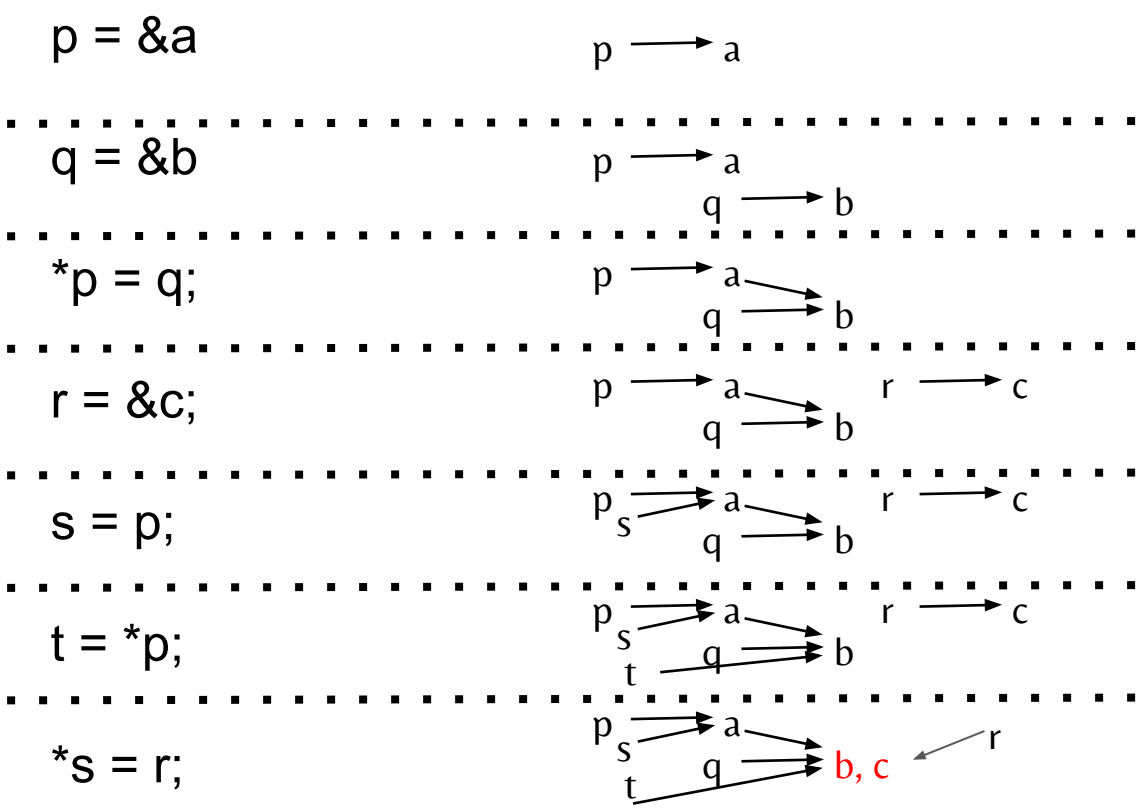


What's the consequence of this merging ?

Class Activity: Perform Steensgard-style Analysis here

```
p = &a

q = &b

*p = q;

r = &c;

s = p;

t = *p;

*s = r;
```

Activity Solution (Unification)



Points-to	Set
p	{a}
q	{b, c}
r	{b, c}
s	{a}
t	{b, c}
a	{b, c}
b	{ }
c	{ }