

CSC2/455 Software Analysis and Improvement Interprocedural Analyses - I

Sreepathi Pai

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URCS

Outline

Introduction to Points-to analysis

Points-to Analysis

Interprocedural Analyses

Postscript

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Pointers

- Variables that contain addresses
- Support a dereferencing operation
 - translates to a (indirect) function call if pointer to function
 - translates to a memory load/store if pointer to data
- Primary purpose of pointers
 - Treat addresses as data
 - Support indirection

Pointer values

- Language can contain an “address-of” operator
 - e.g. `&` in C
 - allows obtaining address of an object to assign to a pointer
- Some names are addresses
 - Function names are addresses in C
 - Labels are not, at least in standard C
- Languages usually contain facilities to create/destroy *heap* objects
 - i.e. dynamically allocated objects in heap
 - e.g. `new` and `delete` in C++
 - note: `malloc` (and `free`) in C are not part of language
- Most sane languages do not use pointers directly
 - Some notion of a reference
 - e.g. Java, Python, ...

The Points-To Problem

Given a pointer (or reference) variable x , what does it point to?

Data Pointers

```
void f(int *x, int *y, int N) {  
    for(int i = 1; i < N; i++) {  
        x[i] = y[i-1];  
    }  
}
```

Can we execute different iterations of this loop on different processors? I.e., is this loop parallelizable?

Unrolling that loop

```
x[1] = y[0]  
x[2] = y[1]  
x[3] = y[2]  
...
```

Statically examining this code, can we say that each write to `x` is independent?

Parallelization

Case 1:

```
int x[100];  
int y[100];  
f(x, y, 100);
```

Case 2:

```
int x[101];  
f(x, x, 100);
```

Parallelization

The `restrict` keyword tells the compiler that a restricted pointer is the only way to access the memory region it points to.

```
void f(int * restrict x, int * restrict y)
```

would assume no calls like `f(x, x)` are possible.

CPP Reference: [restrict type qualifier](#)

Code/Function Pointers

```
int (*cmp)(int x, int y)
cmp = my_cmp_fn
*(cmp)(1, 2);
```

Code/Function Pointers - II

```
x = my_obj.cmp(1, 2)
```

Which function does `cmp` point to?

What if `cmp` is a virtual function?

- recall a virtual function is a function that can be overridden in a child class
- and is called *even* if the calling object's type is the parent class
- also known as *dynamic dispatch*

Virtual Function Implementation

- Usually through a VTABLE implemented by the parent class
 - An array of function pointers
- Compiler inserts code to fill in this table correctly for each child class
 - points function pointer to child's implementation
- Calls are resolved by looking up this table
 - First look up pointer in vtable
 - Then call function
- Obviously slower than a direct function call
 - Note, all function calls in Python are dynamically dispatched!
- Could be sped up if we knew which function to call at a particular call site

Uses of points-to analysis

- Can be used to disambiguate data pointers
 - Useful for parallelization
- Can be used to identify callees of an indirect function call
 - If there is only one, no need to look up the vtable
- Lots of other uses
 - Security: Can a user-controlled pointer be used to overwrite sensitive data?
 - Program verification: is there a null pointer dereference?

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The end results of points-to analysis

- For each pointer variable
 - Compute the set of objects it can point to
 - Called the points-to set for that variable
- Variant: Alias analysis
 - Do two pointers potentially point to the same thing?
(Intersection of points-to sets of the two pointers is not empty)

Objects that can be pointed to

Points-to sets can contain the following classes of objects:

- Statically known variables
 - These have names
- Heap-allocated variables (e.g. `new`, `malloc`, etc.)
 - These are anonymous
 - How do we handle these?

Basic facts and relations

How should the set `pointsTo[x]` for a pointer `x` be updated?

- Object creation
 - `x = malloc(...)`
- Assignment
 - `x = y` (where both `x` and `y` are pointers)
- `AddressOf`
 - `x = &y`
- Indirect Assignment to a pointer
 - `*p = &y` (what happens if `p` is a pointer to pointer?)
- Indirect Assignment from a pointer
 - `p = *y` (if `y` is a pointer to pointer)

Basic facts and relations - II

- Object creation
 - `x = malloc(...)`
 - `pointsTo[x].append(H)` where H is our way of referring to the anonymous object
- Assignment
 - `x = y` (where both x and y are pointers)
 - `pointsTo[x].union(y)` [inclusion-based]
 - `pointsTo[x].union(y)` and `pointsTo[y].union(x)` [equivalence-based]
- AddressOf
 - `x = &y`
 - `pointsTo[x].append(y)`

Pointers to pointers

```
int **p;  
int *a;  
int x, y;  
  
p = &a;    // p points to a  
a = &x;    // a points to x  
*p = &y;   // what does 'p' point to? what does 'a' point to?
```

Basic facts and relations – II contd

- Indirect Assignment to a pointer
 - `*p = &y` (what happens if `p` is a pointer to pointer?)
 - `forall o in pointsTo[p]: pointsTo[o].append(y)`
- Indirect Assignment from a pointer
 - `p = *y` (if `y` is a pointer to pointer)
 - `forall o in pointsTo[y]: pointsTo[p].union(o)`

Flow-insensitive Points-To Analysis

```
h: a = malloc(...)  
i: b = malloc(...)  
j: c = malloc(...)
```

```
a = b;  
b = c;  
c = a;
```

- A flow *insensitive* analysis ignores control flow:
 - $\text{pointsTo}[a] = \{h, i\}$
 - $\text{pointsTo}[b] = \{i, j\}$
 - $\text{pointsTo}[c] = \{j, h, i\}$
- A flow *sensitive* analysis respects control flow:
 - $\text{pointsTo}[a] = \{h\}$ at point h, then $\text{pointsTo}[a] = \{i\}$ at first assignment
 - etc.
- Note: updates in previous relations slides were all flow-insensitive!

What about function calls?

```
int f(int x, int y) {  
    x = y;  
}  
  
a = 1;  
b = 2;  
f(a, b)  
// what are values of a and b?
```

What about function calls?

```
int f(int **x, int *y) {
    *x = y;
}

int *a;
int b, c;

a = &c;
b = 2;
f(&a, &b)
// what does a point to here?
```


Inter-procedural Analysis

- C is call-by-value language
 - Arguments cannot be changed by function
- But pointers can be arguments
 - And *pointees* can be changed!
- In general, incorporating the effects of function calls is called interprocedural analysis
 - Context-insensitive
 - Context-sensitive
- Note: interprocedural analyses aren't limited to functions with pointers as arguments

Flavours of Points-To Analysis

- Flow:
 - Flow-sensitive
 - Flow-insensitive
- Context:
 - Context-sensitive
 - Context-insensitive

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Strategies for handling effects of functions

Can we reuse our CFG-based analyses to handle function calls?

- Inlining, perhaps?
- What are the limitations of inlining?

Context-insensitive analysis

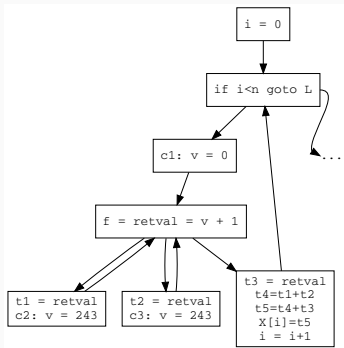
- Treat function calls as control flow
 - Functions form node in CFG
 - Invocations are treated as "gotos" to entry of function
 - The returns as goto to location after function call
- This results in CFG with:
 - multi-entry nodes
 - multi-exit nodes that are not branches (example in a few slides)

Example

```
    for(i = 0; i < n; i++) {  
c1:      t1 = f(0);  
c2:      t2 = f(243);  
c3:      t3 = f(243);  
          X[i] = t1 + t2 + t3;  
    }  
  
int f(int v) {  
    return (v+1);  
}
```

Is the value of $X[i]$ constant?

CFG for Example



- values for:
 - `v` into `f`
 - `retval` out of `f`
 - `t1`, `t2` and `t3`?
 - `X[i]`?

Context-sensitivity

- In treating function calls as control-flow, we lost the ability to detect *context*
- Context is the call stack for the function
 - Can be treated as a string, called a call string
 - If c_1 calls c_2 , which then calls c_3 , the context for c_3 is (c_1, c_2)
- How many contexts can there be?
 - consider indirect function calls
 - consider recursive functions
- k -limiting context sensitivity
 - Limit context to k immediate call *sites* (important!)
 - 0 is context-insensitive

Cloning-based Context-Sensitive Analysis

```
    for(i = 0; i < n; i++) {  
c1:      t1 = f1(0);  
c2:      t2 = f2(243);  
c3:      t3 = f3(243);  
        X[i] = t1 + t2 + t3;  
    }  
  
int f1(int v) {  
    return (v+1);  
}  
  
int f2(int v) {  
    return (v+1);  
}  
  
int f3(int v) {  
    return (v+1);  
}
```

- Create a clone for each unique calling context and then apply context-insensitive analysis
- Is this the same as inlining?
 - See textbook for a differentiating example

Interprocedural Points-To Analysis?

Next class ...

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References

- Chapter 12 of the Dragon Book
 - Section 12.1
 - Section 12.4