CSC2/455 Software Analysis and Improvement
Interprocedural Analyses - I

Sreepathi Pai

URCS

April 8, 2019

Outline

Outline

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
- Language can contain an "address-of" operator
  - e.g. `&` is C
  - allows assignment to a pointer
- 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 explicitly
  - 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];
   }
}
```

Is this loop parallelizable?

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?

Outline

The end results of points-to analysis

- For each pointer variable
  - Compute the set of objects it can point to
- 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)`

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:
  - `pointsTo[a]` = {`h, i`}
  - `pointsTo[b]` = {`i, j`}
  - `pointsTo[c]` = {`j, h, i`}
- A flow *sensitive* analysis respects control flow:
  - `pointsTo[a]` = {`h`} at point h, then `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;
}

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

Outline

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)

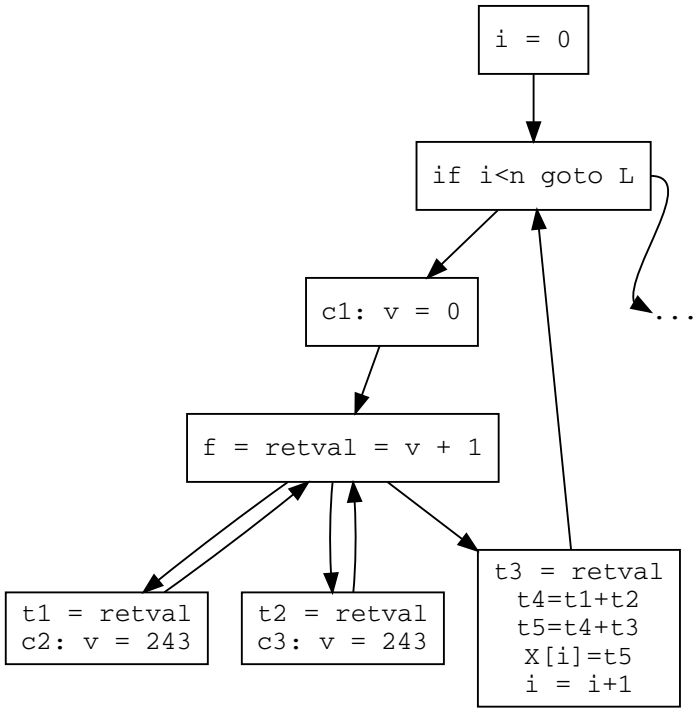
Example

```
   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 `c1` calls `c2`, which then calls `c3`, the context for `c3` is `(c1, c2)`
- 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 ...

Outline

References

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