Interprocedural Analysis

Last time

– Introduction to alias analysis

Today

– Interprocedural analysis

Motivation

Procedural abstraction

– Cornerstone of programming
– Introduces barriers to analysis

Example

```
x = 5;
foo(p);
y = x+1;
```

Does `foo()` modify `x`?

Example

```
void f(int x)
{
   if (x)
      foo();
   else
      bar();
}
. . .
f(0);
f(1);
```

What is the calling context of `f()`?

Function Calls and Pointers

Recall

– Function calls can affect our points-to sets

e.g.,

```
p1 = &x;
p2 = &p1;
...
foo();
```

{(**p1**→**x**), (**p2**→**p1**)}

???

Be conservative

– Lose a lot of information

Interprocedural Analysis

Goal

– Avoid making overly conservative assumptions about the effects of procedures and the state at call sites

Terminology

```
int a, e;                // Globals
void foo(int &b, &c)     // Formal parameters (passed
{                        //    by reference)
   b = c;
}
main()
{
   int d;                // Local variables
   foo(a, d);            // Actual parameters
}
```

Interprocedural Analysis vs. Interprocedural Optimization

Interprocedural analysis

- Gather information across multiple procedures (typically across the entire program)
- Can use this information to improve intraprocedural analyses and optimization (*e.g.,* CSE)

Interprocedural optimizations

- Optimizations that involve multiple procedures
  e.g., Inlining, procedure cloning, interprocedural register allocation
- Optimizations that use interprocedural analysis

Dimensions of Interprocedural Analysis

Flow-sensitive vs. flow-insensitive

Context-sensitive vs. context-insensitive

Path-sensitive vs. path-insensitive

Flow Sensitivity

Flow-sensitive analysis

- Computes one answer for every program point
- Requires iterative data-flow analysis or similar technique

Flow-insensitive analysis

- Ignores control flow
- Computes one answer for every procedure
- Can compute in linear time
- Less accurate than flow-sensitive

Flow Sensitivity Example

Is x constant?

```
void f(int x)
{
    x = 4;
    . . .
    x = 5;
}
```

Flow-sensitive analysis

- Computes an answer at every program point:
  - **x** is 4 after the first assignment
  - **x** is 5 after the second assignment

Flow-insensitive analysis

- Computes one answer for the entire procedure:
  - **x** is not constant

Where have we seen examples of flow-insensitive analysis?

- Address Taken pointer analysis

Context Sensitivity

Context-sensitive analysis

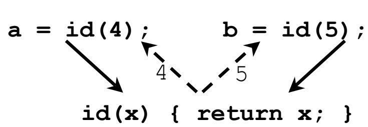
- Re-analyzes callee for each caller
- Also known as polyvariant analysis

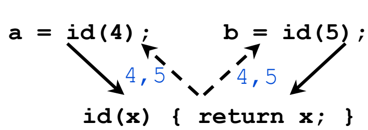
Context-insensitive analysis

- Perform one analysis independent of callers
- Also known as monovariant analysis

Context Sensitivity Example

Is x constant?





Context-sensitive analysis

- Computes an answer for every callsite:
  - **`x`** is 4 in the first call
  - **`x`** is 5 in the second call

Context-insensitive analysis

- Computes one answer for all callsites:
  - **`x`** is not constant
- Suffers from unrealizable paths:
  - Can mistakenly conclude that **`id(4)`** can return **`5`** because we merge (smear) information from all callsites

Path Sensitivity

Path-sensitive analysis

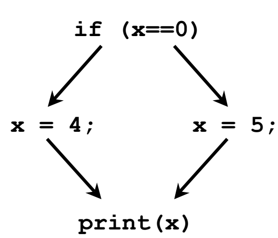
- Computes one answer for every execution path
- Subsumes flow-sensitivity
- Extremely expensive

Path-insensitive

- Not path-sensitive

Path Sensitivity Example

Is x constant?



Path-sensitive analysis

- Computes an answer for every path:
  - **`x`** is 4 at the end of the left path
  - **`x`** is 5 at the end of the right path

Path-insensitive analysis

- Computes one answer for all path:
  - **`x`** is not constant

Dimensions of Interprocedural Analysis (cont)

Flow-insensitive context-insensitive (FICI)

```
int** foo(int **p, **q)
{
   int **x;

   x = p;
   . . .
   x = q;
   return x;
}

int main()
{
   int **a, *b, *d, *f,
         c, e;

   a = foo(&b, &f);
   *a = &c;
   a = foo(&d, &g);
   *a = &e;
}
```

p →

q →

x →

a →

b →

d → {c, e}

f → {c, e}

g → {c, e}

Dimensions of Interprocedural Analysis (cont)

Flow-sensitive context-insensitive (FSCI)

```
int** foo(int **p, **q)
{
   int **x;

   x = p;
   . . .
   x = q;
   return x;
}

int main()
{
   int **a, *b, *d, *f,
         c, e;

   a = foo(&b, &f);
   *a = &c;
   a = foo(&d, &g);
   *a = &e;
}
```

We'll see examples of FICS and FSCS later

p →

q →

x_1 →

x_2 →

a_1 →

a_2 →

f_1 →

g_1 →

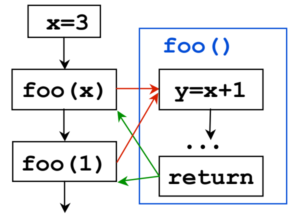
f_2 → eak update)

g_2 →

Interprocedural Analysis: Supergraphs

Compose the CFGs for all procedures via the call graph

- Connect call nodes to entry nodes of callees
- Connect return nodes of callees back to calls
- Called **control-flow supergraph**



Pros

- Simple
- Intraprocedural analysis algorithms work unchanged
- Reasonably effective

Monday's Example Revisited

```
{
    int x, y, a;
    int *p;

    p = &a;
    x = 5;
    foo(&x);
    y = x + 1;
}
```

```
foo (int *p)
{
    return p;
}
```

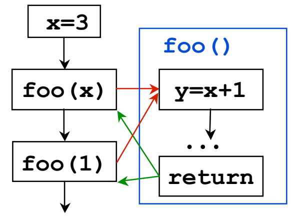
Is `x` constant?

- With a supergraph, run our same IDFA algorithm
- Determine that **`x`** = **5**

Supergraphs (cont)

Compose the CFGs for all procedures via the call graph

- Connect call nodes to entry nodes of callees
- Connect return nodes of callees back to calls
- Called **control-flow supergraph**



Cons

- Accuracy? Smears information from different contexts.
- Performance? IDFA is $O(n^4)$, graphs can be huge
- No separate compilation IDFA converges in d+2 iterations, where d is the Number of nested loops [Kam & Ullman '76]. Graphs will have many cycles (one per callsite)

Brute Force: Full Context-Sensitive Interprocedural Analysis

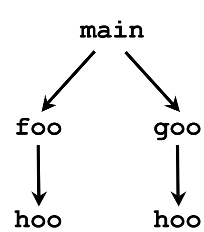
Invocation Graph [Emami94]

- Use an invocation graph, which distinguishes all calling chains
- Re-analyze callee for all distinct calling paths
- Pro: precise
- Cons: exponentially expensive, recursion is tricky

```
void foo(int b)
{   hoo(b); }

void goo(int c)
{   hoo(c); }

main()
{
    int x, y;
    foo(x);
    goo(y);
}
```

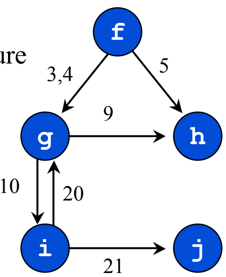


Middle Ground: Use Call Graph and Compute Summaries

```
1   procedure f()
2   begin
3       call g()
4       call g()
5       call h()
6   end
7   procedure g()
8   begin
9       call h()
10      call i()
11  end
12  procedure h()
13  begin
14  end
15  procedure i()
16      procedure j()
17      begin
18      end
19  begin
20      call g()
21      call j()
22  end
```

Goal

– Represent procedure call relationships



Definition

– If program P consists of n procedures: $p_1, \ldots, p_n$

– Static **call graph** of P is $G_P = (N,S,E,r)$

– $N = \{p_1, \ldots, p_n\}$

– S = {call-site labels}

– $E \subseteq N \times N \times S$

– $r \in N$ is **start node**

Interprocedural Analysis: Summaries

Compute summary information for each procedure

- Summarize effect of called procedure for callers
- Summarize effect of callers for called procedure

Store summaries in database

- Use later when optimizing procedures

Pros

- Concise
- Can be fast to compute and use
- Separate compilation practical

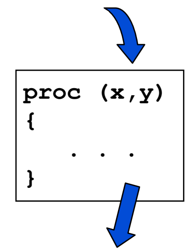
Cons

- Imprecise if only have one summary per procedure

Two Types of Information

Track information that flows into a procedure

- Sometimes known as **propagation problems**
  e.g., What formals are constant?
  e.g., Which formals are aliased to globals?



Track information that flows out of a procedure

- Sometimes known as **side effect problems**
  e.g., Which globals are def'd/used by a procedure?
  e.g., Which locals are def'd/used by a procedure?
  e.g., Which actual parameters are def'd by a procedure?

Examples

Propagation Summaries

- MAY-ALIAS: The set of formals that may be aliased to globals and each other
- MUST-ALIAS: The set of formals that are definitely aliased to globals and each other
- CONSTANT: The set of formals that must be constant

Side-effect Summaries

- MOD: The set of variables possibly modified (defined) by a call to a procedure
- REF: The set of variables possibly read (used) by a call to a procedure
- KILL: The set of variables that are definitely killed by a procedure (*e.g.*, in the liveness sense)

Computing Interprocedural Summaries

Top-down

- Summarize information about the caller (MAY-ALIAS, MUST-ALIAS)
- Use this information inside the procedure body

```
int a;
void foo(int &b, &c){
    . . .
}
foo(a,a);
```

Bottom-up

- Summarize the effects of a call (MOD, REF, KILL)
- Use this information around procedure calls

```
x = 7;
foo(x);
y = x + 3;
```


Context-Sensitivity of Summaries

None (zero levels of the call path)

- Forward propagation: Meet (or smear) information from all callers to particular callee
- Side-effects: Use side-effect information for callee at all callsites

Callsite (one level of the call path)

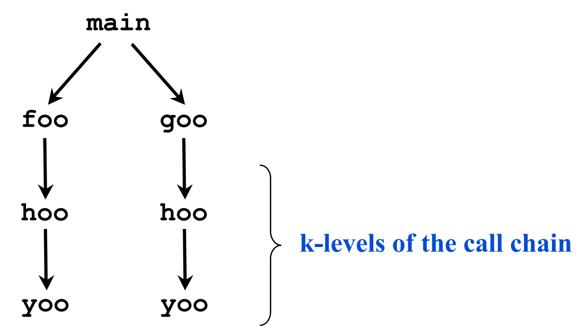
- Forward propagation: Label data-flow information with callsite
- Side-effects: Affects alias analysis, which in turn affects side-effects

Context-Sensitivity of Summaries (cont)

k levels of call path (k-limiting)

– Forward propagation: Label data-flow information with k levels of the call path

– Side-effects: Affects alias analysis, which in turn affects side-effects



Bi-Directional Interprocedural Summaries

Interprocedural Constant Propagation (ICP)

– Information flows from caller to callee and back

```
int a,b,c,d;
void foo(e){
   a = b + c;
   d = e + 2;
}
foo(3);
```

The calling context tells us that the formal `e` is bound to the constant 3, which enables constant propagation within `foo()`

After calling `foo()` we know that the constant 5 (3+2) propagates to the global `d`

Interprocedural Alias Analysis

– Forward propagation: aliasing due to reference parameters

– Side-effects: points-to relationships due to multi-level pointers

Alternative to Interprocedural Analysis: Inlining

Idea

- Replace call with procedure body

Pros

- Reduces call overhead
- Exposes calling context to procedure body
- Exposes side effects of procedure to caller
- Simple!

Cons

- Code bloat (decrease efficacy of caches, branch predictor, etc)
- Can't always statically determine callee (*e.g.,* in OO languages)
- Library source is usually unavailable
- Can't always inline (recursion)

Inlining Policies

The hard question

- How do we decide which calls to inline?

Many possible heuristics

- Only inline small functions
- Let the programmer decide using an `inline` directive

Oblivious to callsite

- Use a code expansion budget [Ayers, et al '97]
- Use profiling or instrumentation to identify hot paths—inline along the hot paths [Chang, et al '92]
  - JIT compilers do this
- Use inlining trials for object oriented languages [Dean & Chambers '94]
  - Keep a database of functions, their parameter types, and the benefit of inlining
  - Keeps track of indirect benefit of inlining
  - Effective in an incrementally compiled language

Alternative to Interprocedural Analysis: Cloning

Procedure Cloning/Specialization

- Create a customized version of procedure for particular call sites
- *Compromise* between inlining and interprocedural optimization

Pros

- Less code bloat than inlining
- Recursion is not an issue (as compared to inlining)
- Better caller/callee optimization potential (versus interprocedural analysis)

Cons

- Still some code bloat (versus interprocedural analysis)
- May have to do interprocedural analysis anyway
  - *e.g.* Interprocedural constant propagation can guide cloning

Evaluation

Most compilers avoid interprocedural analysis

- It's expensive and complex
- Not beneficial for most classical optimizations
- Separate compilation + interprocedural analysis requires recompilation analysis [Burke and Torczon'93]
- Can't analyze library code

When is it useful?

- Pointer analysis
- Constant propagation
- Object oriented class analysis
- Security and error checking
- Program understanding and re-factoring
- Code compaction
- Parallelization

"Modern" uses of compilers

Other Trends

Cost of procedures is growing
- More of them and they're smaller (OO languages)
- Modern machines demand precise information (memory op aliasing)

Cost of inlining is growing
- Code bloat degrades efficacy of many modern structures
- Procedures are being used more extensively

Programs are becoming larger

Cost of interprocedural analysis is shrinking
- Faster machines
- Better methods

Concepts

Call graphs, invocation graphs
Analysis versus optimization
Characteristic of interprocedural analysis
- Flow sensitivity, context sensitivity, path sensitivity
- Smearing

Approaches
- Context sensitive, supergraph, summaries
- Bottom-up, top-down, bi-directional, iterative

Propagation versus side-effect problems
Alternatives to interprocedural analysis
- Inlining
- Procedure cloning

Next Time

Lecture

- Flow-insensitive analysis
- Look at pointer analysis as an important special case