Prelude

"I predict the Internet... will soon go spectacularly supernova and in 1996 catastrophically collapse."

"I have traveled the length and breadth of this country and talked with the best people, and I can assure you that data processing is a fad that won't last out the year."
- The editor in charge of business books for Prentice Hall, 1957

"A familiar old gadget which has been around for hundreds of years is just about to get pensioned off forever - the key... By the mid-1980's no one will ever need to hide a key under the doormat again."

Motivation

Procedural abstraction
- Cornerstone of programming
- Introduces barriers to analysis

Example
```c
x = 5;
foo(y);
y = x + 1;
```

Does `foo()` modify `x`?

Example
```c
void f(int x)
{
    if (x)
        foo();
    else
        bar();
}
```

Does `foo()` modify `x`?

What is the calling context of `f`?

Interprocedural Analysis

Goal
- Avoid making conservative assumptions about the effects of procedures and the state at call sites

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

```c
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
**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

```
4
5
```

- **Context-insensitive analysis**
  - Computes one answer for all callsites:
    - x is not constant

```
if (x==0)
    x = 4;
else
    x = 5;
print(x)
```

**Path Sensitivity**

- **Path-sensitive analysis**
  - Computes one answer for every execution path
  - Subsumes flow-sensitivity
  - Extremely expensive
  - Used in software verification via model checking

- **Path-insensitive**
  - Assumes current program point can be reached by all possible incoming points

**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

```
if (x==0)
    x = 4;
else
    x = 5;
print(x)
```

- **Path-insensitive analysis**
  - Computes one answer for all path:
    - x is not constant
Interprocedural Analysis: Supergraphs/ICFGs

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 or ICFG

Pros
- Simple
- Intraprocedural analysis algorithms work relatively unchanged
- Reasonably effective
- Flow-sensitive

Example
{ foo (int *p)
  int x, y, a;
  int *p;
  return p;
  p = &a;
  x = 5;
  Is x constant?
  foo(&x);
  y = x + 1;
  -- Determine that x = 5
}

Supergraphs/ICFGs (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 or ICFG

Cons
- Accuracy? Smears information from different contexts.
- Performance? IDFA is O(depth*n^2), graphs can be huge
- No separate compilation

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
- Pros: precise
- Cons: exponentially expensive, recursion is tricky

void foo(int b)
{ hoo(b); }
void goo(int c)
{ hoo(c); }
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 call g()
19 call j()
20 begin
21 call g()
22 call j()

Goal
- Represent procedure call relationships

Definition
- If program P consists of n procedures: p₁, . . . , pₙ
- Static call graph of P is G_P = (N,S,E,r)
  - N = {p₁, . . . , pₙ}
  - S = {call-site labels}
  - E ⊆ N × N × S
  - r ∈ 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

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
- DEF: The set of variables that are definitely defined by a procedure (e.g., killed 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, DEF)
- 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 call sites

Callsite (one level of the call path)
- Forward propagation: Label data-flow information around call site
- 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 = a + 2;
  }
  foo(3);
  ```

Interprocedural Alias Analysis
- Forward propagation: aliasing due to reference parameters
- Side-effects: points-to relationships due to multi-level pointers
Interprocedural Constant Propagation [Callahan, et al '86]

Basic Idea
- Extend the global constant propagation by using an extension of the CFG, the interprocedural value graph, which represents the movement of values across procedure calls
- Can be either context-sensitive or context-insensitive

Jump Functions
- For a call of procedure q at site s, J_s^x determines the value of the formal parameter x based on the inputs to the procedure p that calls q
- The support of J_s^x is the set of inputs to p actually used to compute J_s^x

Interprocedural Value Graph
- Create one node for each jump function J_s^x
- If x ∈ support(J_t^y) for some call site t in the procedure, then construct an edge from J_s^x to J_t^y

Jump Functions

Example
```c
main()
{ 
  int a, b; 
  a = 1; b = 2; 
  s(a, b); 
}

void s (int x, y) 
{ 
  int z, w; 
  z = x + y; 
  w = x - y; 
  t(z, w); 
}
```

IP Value Graph

Exercise: Compute Interprocedural Value Graph

```c
main()
{ 
  int x; 
  f(x, 1); 
}

void f (int i, j) 
{ 
  g(i, j); 
}
```

Jump Functions

More About Jump Functions

How do we handle return values?
- Create return jump functions which pass values from callees to callers
- R_s^x determines the value of x upon return from procedure p
- Add nodes and edges for R_s^x to the interprocedural value graph

Types of jump functions
- Jump functions "determine the value of a parameter"
- How should they determine these values?
  - Symbolic interpretation
  - Conditional constants
  - Simple constants
- Simple constants seem to do well
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
– 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

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
- Pointer analysis
- Look at pointer analysis as an important special case