Interprocedural Analysis

Last time

- Interprocedural analysis

Today

- Interprocedural alias analysis
- Interprocedural optimization

Improving the Efficiency of the Iterative Algorithm

Jump Functions and Return Jump Functions for ICP

$$J^{formal}_{callsite} = f(actuals, globals, constants)$$

$$R^{global \text{ or } refparam}_{function} = f(formals, globals, constants)$$

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

$$J^{e}_{foo(3)} = 3$$

$$R^{d}_{foo} = e + 2$$

$$R^{a}_{foo} = b + c$$

Partial Transfer Functions for Interprocedural Alias Analysis

- funcOutput = PTF(funcInput)
- use memoization
- PTF lazily computed for each input pattern that occurs

Partial Transfer Function [Wilson et. al. 95]

Example [http://www.cs.princeton.edu/~jqwu/Memory/survey.html]

```
main() {
    int *a,*b,c,d;
    a = &c;
    b = &d;
S0  foo(&a, &b);
    for (i = 0; i<2; i++) {
S1    bar(&a,&a);
S2    bar(&b,&b);
S3    bar(&a,&b);
S4    bar(&b,&a);
    }
}
void bar(int **i, int **j) { foo(i,j); }
void foo(int **x, int **y){
  int *temp = *x;
  *x = *y;
  *y = temp;
}
```

Characterizing Interprocedural Analysis

Definiteness

- May (possible) versus must (definite)

Flow sensitivity

- Sensitive (consider control flow)
  - Requires iterative data-flow analysis or similar technique
  - More accurate than flow-insensitive
- Insensitive (ignore control flow)
  - Can compute in linear time
  - May information only

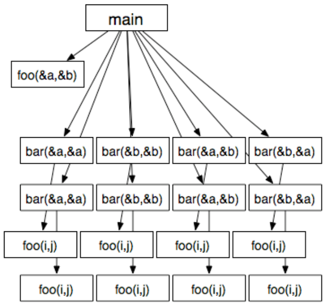
Context sensitivity

- Sensitive (polyvariant analysis)
  - Re-analyze callee for each caller
  - Variations based on how much of the call path is maintained
- Insensitive (monovariant analysis)
  - Perform one analysis independent of callers

Emami 1994

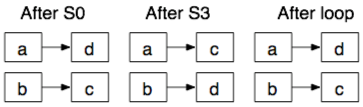
Overview

- Compute L and R locations to implement flow-sensitive data-flow analysis
- Uses invocation graph for full context-sensitivity
- Can be exponential in program size
- Handles function pointers



Characterization of Emami

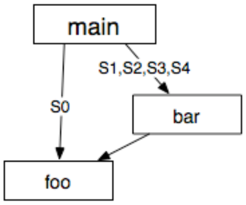
- Whole program
- Flow-sensitive
- Context-sensitive
- May and must analysis
- Alias representation: points-to
- Heap modeling: one heap variable
- Aggregate modeling: fields and first array element



Choi 1993

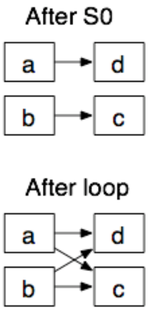
Overview

- Iterates over call graph with callsite labeled edges
- Iterates over Sparse Evaluation Graph for each procedure



Characterization of Choi

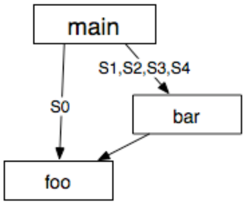
- Whole program
- Flow-sensitive
- Context-sensitive (one-level)
- May analysis
- Alias representation: compact pairs (similar to points-to)
- Heap modeling: k names for each malloc stmt
- Aggregate modeling: fields?



Burke 1995

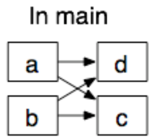
Overview

- Iterates over call graph with callsite labeled edges
- Iterates over Sparse Evaluation Graph for each procedure
- Use kill information before propagating on call graph
- Handles function pointers

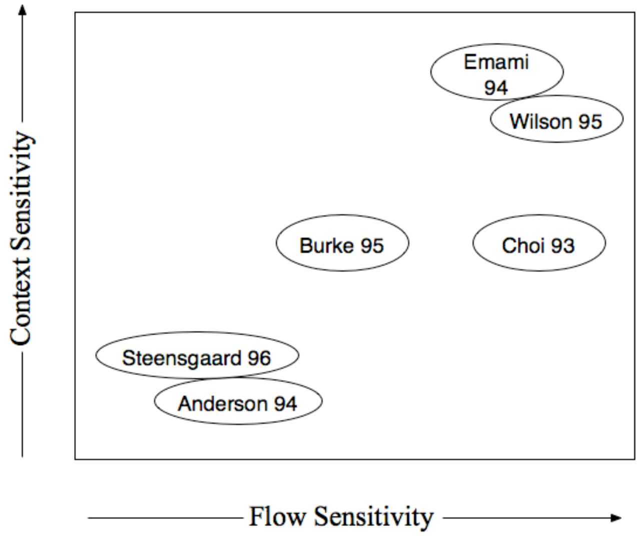


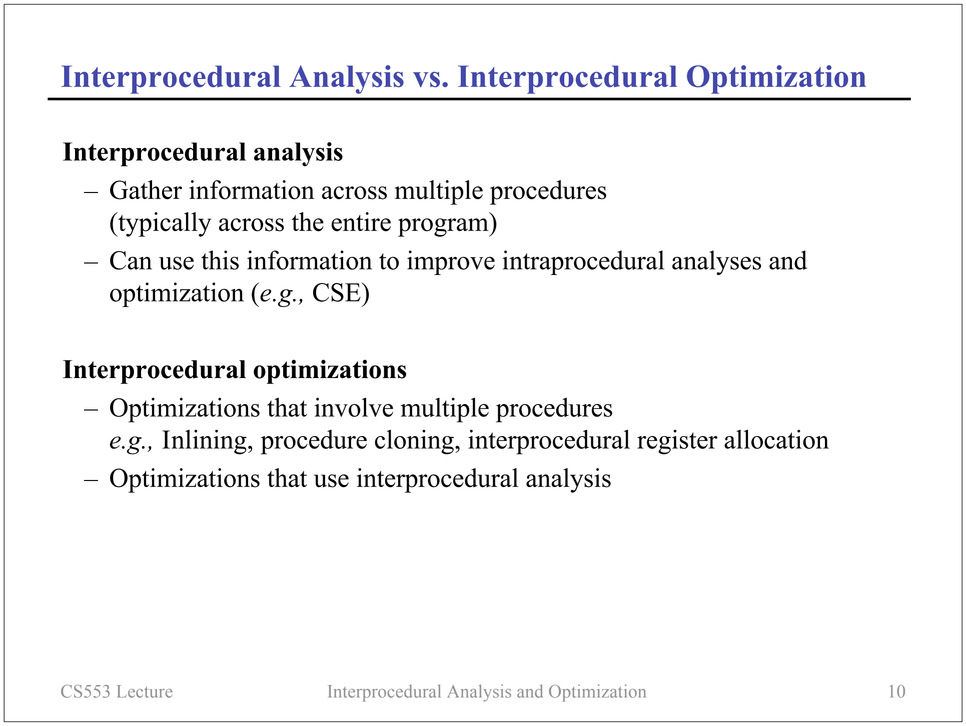
Characterization of Burke

- Whole program
- Flow-insensitive (kill info is propagated along call edges)
- Context-sensitive
- May analysis
- Alias representation: compact pairs (similar to points-to)
- Heap modeling: k names for each malloc stmt?
- Aggregate modeling: fields?



Alias/Pointer Analysis Summary





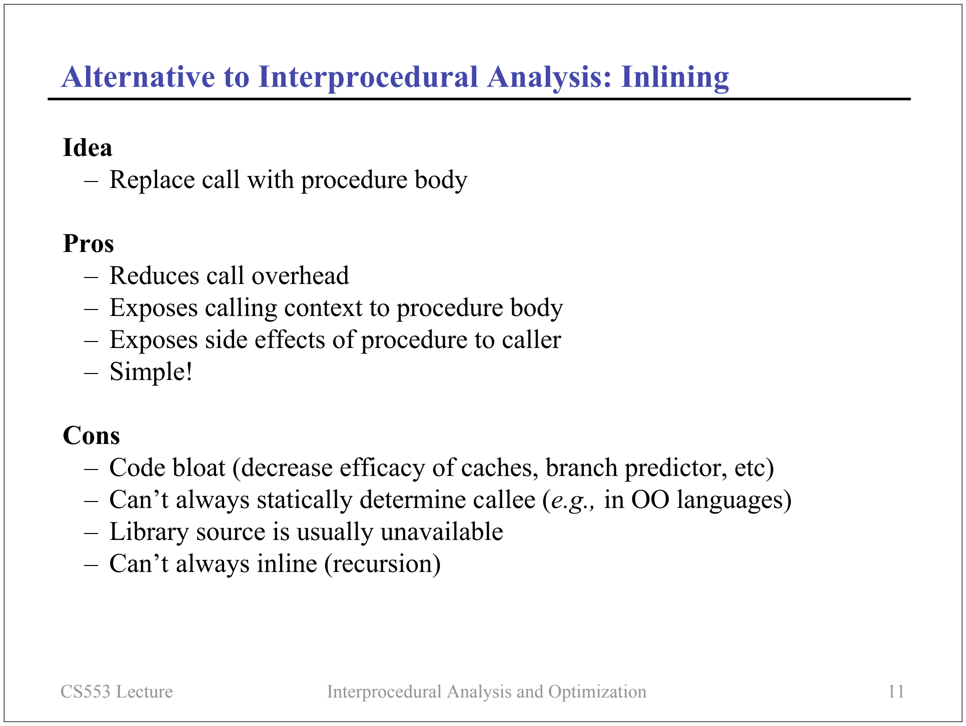
Interprocedural Analysis vs. Interprocedural Optimization

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



Alternative to Interprocedural Analysis: Inlining

Idea

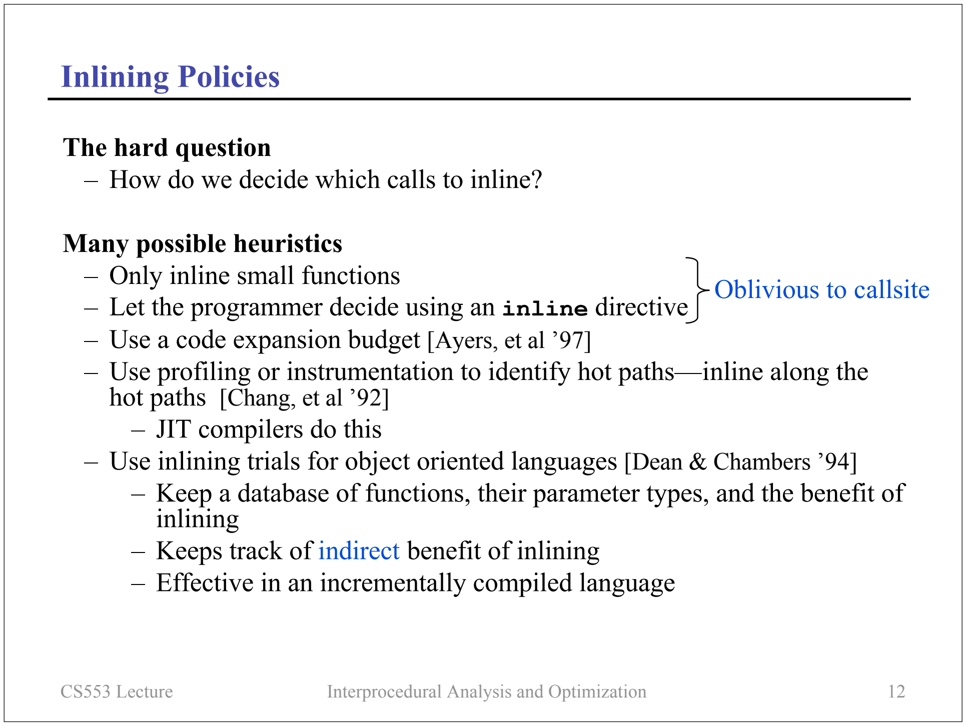
- Replace call with procedure body

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

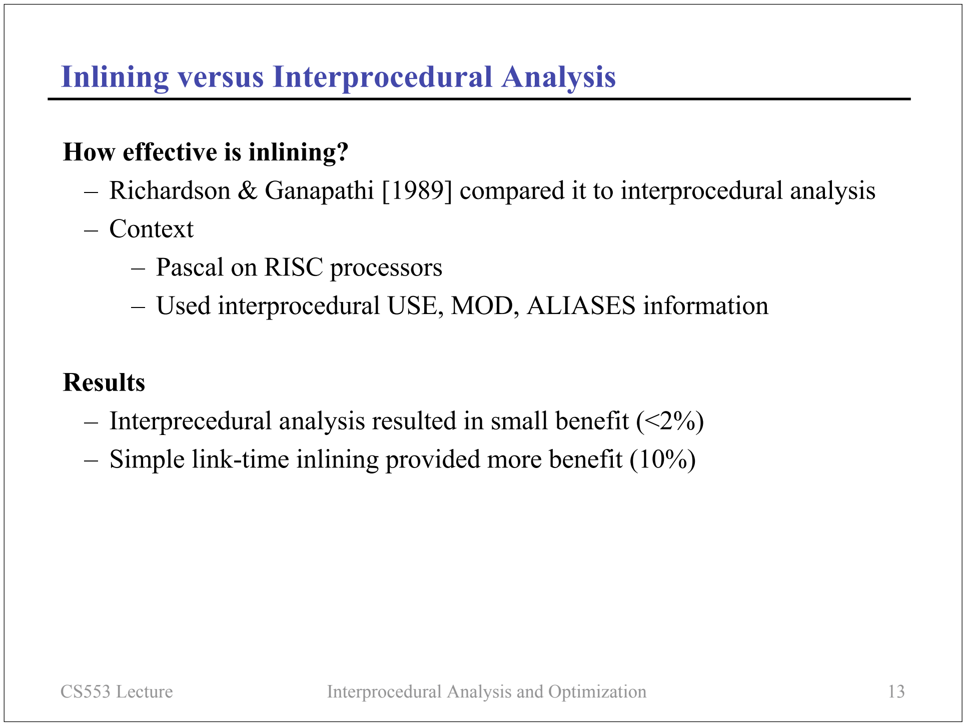
- How do we decide which calls to inline?

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



Inlining versus Interprocedural Analysis

How effective is inlining?

- Richardson & Ganapathi [1989] compared it to interprocedural analysis
- Context
  - Pascal on RISC processors
  - Used interprocedural USE, MOD, ALIASES information

Results

- Interprecedural analysis resulted in small benefit (<2%)
- Simple link-time inlining provided more benefit (10%)

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

Procedure Cloning

Abstract implementation

- Given a set of call sites to procedure p
  e.g., $\{c_1,c_2,c_3,c_4,c_5,c_6\}$
- Partition them into equivalence classes of “similar” call sites
  e.g., $\{\{c_1,c_4\},\{c_2,c_3\},\{c_6\}\}$
- Meaning of “similar” depends on the intended benefit
  e.g., For constant propagation, partition according to constant valued actual parameters

Important question

- How do we partition the call sites?

Evaluation

Why don't many compilers use interprocedural analysis?

- Benefits on optimization have not been well explored
- Common view: not beneficial for most scalar optimizations
- It's expensive and complex
- Separate compilation + interprocedural analysis requires recompilation analysis [Burke and Torczon'93]
- Can't analyze library code

When is it useful?

- Pointer analysis
- Parallelization
- Constant propagation
- Object oriented class analysis
- Error checking

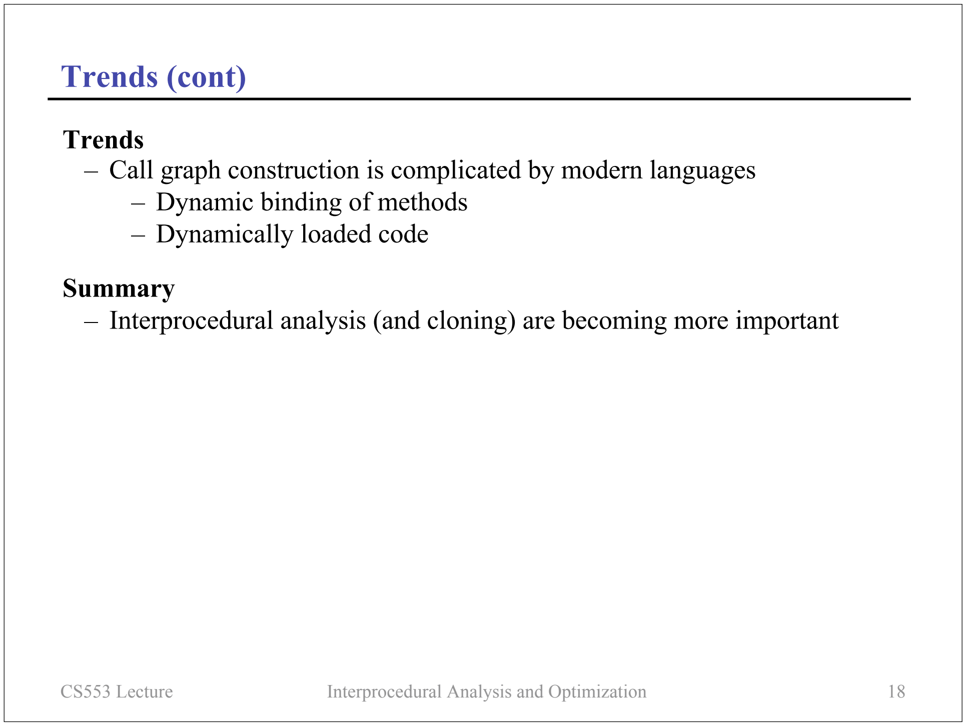
Trends

Questions

- Is interprocedural analysis really useful?
- Is it worth doing anything beyond inlining?

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



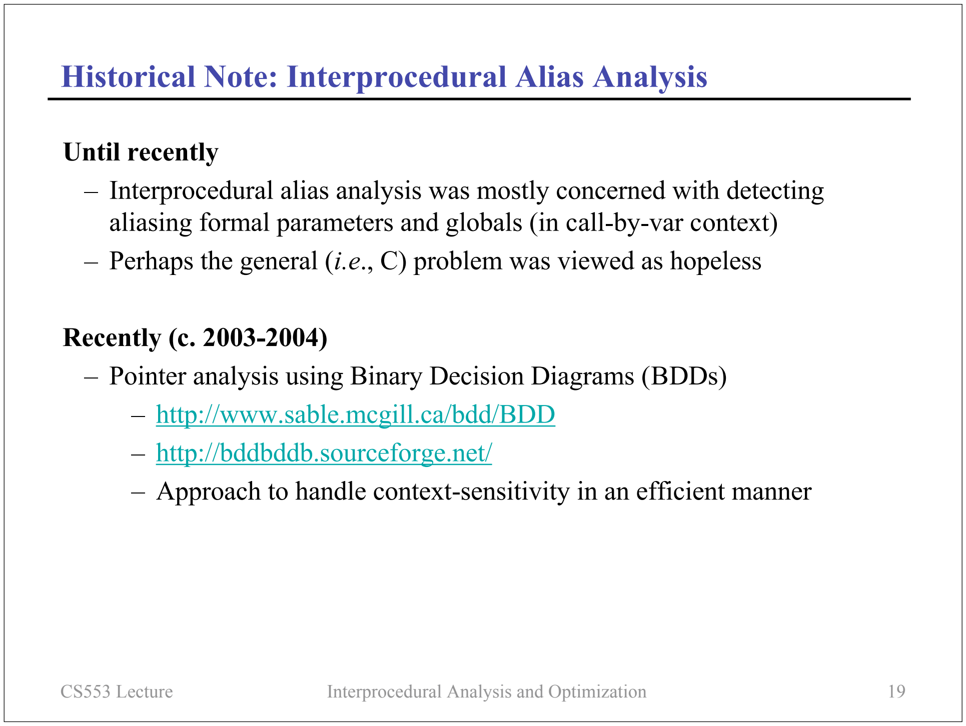
Trends (cont)

Trends

- Call graph construction is complicated by modern languages
  - Dynamic binding of methods
  - Dynamically loaded code

Summary

- Interprocedural analysis (and cloning) are becoming more important



Historical Note: Interprocedural Alias Analysis

Until recently

- Interprocedural alias analysis was mostly concerned with detecting aliasing formal parameters and globals (in call-by-var context)
- Perhaps the general (*i.e.*, C) problem was viewed as hopeless

Recently (c. 2003-2004)

- Pointer analysis using Binary Decision Diagrams (BDDs)
  - http://www.sable.mcgill.ca/bdd/BDD
  - http://bddbddb.sourceforge.net/
  - Approach to handle context-sensitivity in an efficient manner

Concepts

Partial transfer functions for context-sensitive alias analysis

Different kinds of context-sensitivity

Comparison of alias analysis algorithms in terms of context and flow sensitivity

Alternatives to interprocedural analysis

– Inlining
– Procedure cloning

Next Time

Reading

– Ch 16 in Muchnick, focus on 16.3.11

Next lecture

– Register allocation