Optimizing Procedure Calls

Procedure calls can be costly

- **direct** costs of call, return, argument & result passing, stack frame maintainance
- **indirect** cost of damage to intraprocedural analysis of caller and callee

Optimization techniques:

- hardware support
- inlining
- tail call optimization
- interprocedural analysis
- procedure specialization

Inlining

(A.k.a. procedure integration, unfolding, beta-reduction, ...)

Replace call with body of callee

- insert assignments for actual/formal mapping, return/result mapping
  - do copy propagation to eliminate copies
- manage variable scoping correctly
  - e.g. α-rename local variables, or tag names with scopes, ...

Pros & Cons:

\+ eliminate overhead of call/return sequence

\+ eliminate overhead of passing arguments and returning results

\+ can optimize callee in context of caller, and vice versa

– can increase compiled code space requirements

– can slow down compilation

In what part of compiler to implement inlining?
front-end? back-end? linker?

What/where to inline?

Inline where highest benefit for the cost

E.g.:

- most frequently executed call sites
- call sites with small callees
- call sites with callees that benefit most from optimization

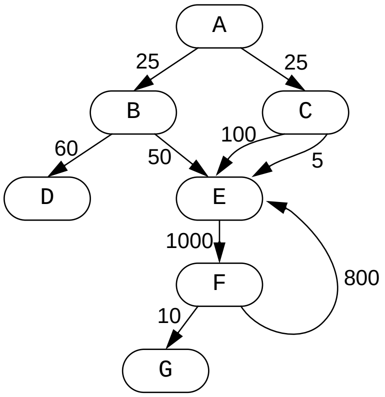
Can be chosen by:

- explicit programmer annotations
  - annotate procedure or call site?
- automatically
  - get execution frequencies from **static estimates** or **dynamic profiles**

Program representation for inlining

Weighted call graph: directed multigraph

- nodes are procedures
- edges are calls, weighted by invocation counts/frequency



Hard cases for building call graph:

- calls to/from external routines
- calls through pointers, function values, messages

Inlining using a weighted call graph

What order to do inlining?

- top-down: local decision during compilation of caller ⇒ easy
- bottom-up: avoids repeated work
- highest-weight first: exploits profile data
  - but highest-benefit first would be better...

Avoid infinite inlining of recursive calls

Assessing costs and benefits of inlining

Strategy 1: superficial analysis

- examine source code of callee to estimate space costs
- – doesn't account for recursive inlining, post-inlining optimizations

Strategy 2: deep analysis, "optimal inlining"

- perform inlining
- perform post-inlining optimizations, estimate benefits from optimizations performed
- measure code space after optimizations
- undo inlining if costs exceed benefits
- \+ better accounts for post-inlining effects
- – much more expensive in compile-time

Strategy 3: amortized version of strategy 2
[Dean & Chambers 94]

- perform strategy 2: an "inlining trial"
- record cost/benefit trade-offs in persistent database
- reuse previous cost/benefit results for "similar" call sites
- \+ **faster** compiles than superficial approach, in Self compiler

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Tail call optimization

Tail call: last thing before return is a call

- callee returns, then caller immediate returns

```
int f(...) {
  ...
  if (...) return g(...);
  ...
  return h(i(...), j(...));
}
```

Can splice out one stack frame creation and tear-down, by **jumping** to callee rather than calling

- \+ callee reuses caller's stack frame & return address
- – effect on debugging?

Tail recursion elimination

If last operation is self-recursive call, turns recursion into loop
⇒ tail recursion elimination

- works for mutually recursive tail calls, too e.g. FSM implementations

```
void state0(...) {
  if (...) state1(...)
  else state2(...);
}
void state1(...) {
  if (...) state0(...)
  else state2(...);
}
void state2(...) {
  if (...) state1(...)
  else state2(...);
}
```

Interprocedural Analysis

Extend intraprocedural analyses to work across calls

- \+ avoid making conservative assumptions about:
  - effect of callee
  - inputs to procedure
- \+ no (direct) code increase

- – doesn’t eliminate direct costs of call
- – may not be as effective as inlining at cutting indirect costs

Interprocedural analysis algorithm #1: supergraph

Given call graph and CFG’s of procedures,
create single CFG (“control flow supergraph”) by

- connecting call sites to entry nodes of callees
- connecting return nodes of callees back to calls

- \+ simple
- \+ intraprocedural analysis algorithms work on larger graph
- \+ decent effectiveness
  (but not as good as inlining)

- – speed?
- – separate compilation?

Interprocedural analysis algorithm #2: summaries

Compute summary info for each procedure

- callee summary:
  summarizes effect/result of callee procedure for callers
- caller summaries:
  summarize effect/input of all callers for callee procedure

Store summaries in database

Use summaries when compiling & optimizing procedures later

For simple summaries:

- \+ compact
- \+ compute, use summaries quickly
- \+ separate compilation practical (once summaries computed)

- – less precise analysis

Examples of callee summaries

MOD

- the set of variables possibly modified by a call to a proc

USE

- the set of variables possibly read by a call to a proc

MOD-BEFORE-USE

- the set of variables definitely modified before use

CONST-RESULT

- the constant result of a procedure, if it’s a constant

Computing callee summaries within a procedure

Flow-insensitive summaries can be computed
without regard to control flow

- \+ calculated in linear time
- – limited kinds of information (e.g. MAY only)

Flow-sensitive summaries must take control flow into account

- – may require iterative dfa
- \+ more precise info possible

Computing callee summaries across procedures

If procedure includes calls, then
its callee summary depends on its callees' summaries, transitively

Therefore, compute callee summaries bottom-up in call graph

What about recursion?

What about calls to external, unknown library functions?

What about program changes?

Examples of caller summaries

CONST-ARGS

- the constant values of the formal parameters of a procedure, for those that are constant

ARGS-MAY-POINT-TO

- may-point-to info for formal parameters

LIVE-RESULT

- whether result may be live in caller

Computing caller summaries across procedures

Caller summary depends on all callers

- requires knowledge of all call sites, e.g. whole-program info

Therefore, compute caller summaries top-down in call graph

If procedure contains a call,
merge info at call site with caller summary of callee

What about recursion?

What about calls to external, unknown library functions?

What about calls from external, unknown library functions?

Summary functions

Idea: generalize callee summary into a callee summary function

- take info at call site (**calling context**) as argument
- compute info after call site as result

Also called **context-sensitive** or **polyvariant** interprocedural analysis

Previous callee summaries are just constant summary functions, insensitive to calling context

Example calling contexts:

- which formal parameters have what constant values
- what alias patterns are present on entry
- whether the result is live

Key design point for context-sensitive interprocedural analysis: how precise is the calling context?

+ more precise contexts give more precise result info
– more precise contexts take longer to produce summaries

Kinds of summary functions

Total function: handles all possible call site info

+ compute once for callee, e.g. bottom-up
+ reuse for all callers
– can be expensive to compute/represent precise total function

Partial function: handles only subset of possible call site infos, e.g. those actually occurring in a program

+ compute on demand when encountering new call sites, top-down
+ can be easier to represent partial functions precisely
– can analyze callee several times
– not modular

Interprocedural Constant Propagation

[Callahan, Cooper, Kennedy, & Torczon, PLDI 86]

Goal: for each procedure, for each formal, identify whether all calls of procedure pass a particular constant to the formal

- e.g. stride argument passed to LINPACK library routines

Sets up lattice-theoretic framework for solving problem

- store const-prop domain element for each formal
  - initialize all formals to T
- worklist-based algorithm to find interprocedural fixed-point:

```
worklist := {Main};
while worklist ≠ ∅ do
  proc := remove_any(worklist);
  process(proc);
end
process(proc) {
  forall call sites c in proc do
    compute c’s actuals from proc’s formals;
    c’s callee’s formals meet= c’s actuals;
      if changed, push callee on worklist;
}
```

Jump functions

How to quickly compute info at c’s actuals from `proc`’s formals?

Define *jump functions* to relate actual parameter at a call site to formal parameters of enclosing procedure

Different degrees of sophistication:

- **all-or-nothing**: only if actual is an intraprocedural constant
- **pass-through**: also, if formal a constant, then actual a constant
- **symbolic interpretation**: do full intraprocedural constant propagation

Can define similar jump functions for procedure results, too

- a kind of total summary function for callers
- push callers on worklist if procedure’s result info changes

Results

“We have not yet tried the system on a large variety of programs, so it would be premature to report any empirical evidence about the value of interprocedural constant propagation.”

A negative paper, with experimental data

Richardson & Ganapathi [89]

Studied interprocedural analysis of Pascal programs optimized for RISC uniprocessors

- interprocedural USE, MOD, ALIASES summaries
- found little benefit (< 2%)

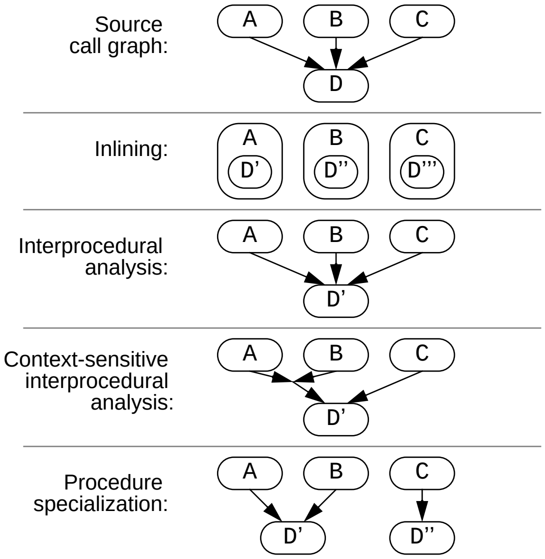
Studied simple link-time inlining

- inline after optimization
- respectable benefits (~ 10%)

Procedure specialization

A.k.a. procedure cloning, customization

Halfway between inlining and interprocedural analysis, similar to context-sensitive interprocedural analysis



Abstract process

Given set of call sites of procedure `P`
e.g. $\{c_1, c_2, c_3, c_4, c_5\}$

Partition into equivalence classes of “similar” call sites (for instance, those with same calling context)
e.g. $\{\{c_1, c_2\}, \{c_3, c_4\}, \{c_5\}\}$

Copy `P` for each class, change calls accordingly

Do (context-insensitive) interprocedural analysis on changed call graph

Versus inlining:

+ less code explosion
+ works in presence of recursion

Versus interprocedural analysis:

+ better optimization of caller and callee

Versus context-sensitive interprocedural analysis:

+ better optimization of callee