

CS6013 - Modern Compilers: Theory and Practise

Interprocedural Analysis

V. Krishna Nandivada

IIT Madras

Interprocedural CFA - Call graph

- Inter-procedural CFA constructs a static Call graph
 - A directed multigraph.
- Given a program P , consisting of procedures $p_1, p_2 \dots p_n$, the call graph $G = \langle N, S, E, r \rangle$
- N is the set of procedures.
- S is the set of call sites labels (e.g. line numbers in TAC).
- $E \subseteq N \times S \times N$: An edge from (p_1, s, n_2) indicates a call from p_1 to p_2 at site s .



Opening remarks

What have we done so far?

- Compiler overview.
- Scanning and parsing.
- JavaCC, visitors and JTB
- Semantic Analysis - specification, execution, attribute grammars.
- Type checking, Intermediate Representation, Intermediate code generation.
- Control flow analysis.
- Data flow analysis, intra-procedural constant propagation.
- Loop optimizations.

Announcement:

- Assignment 4: ten days to go.

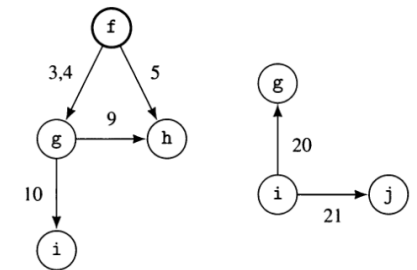
Today:

- Inter-procedural analysis.



Example call graph

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



Constructing the call graph

LabeledEdge = Procedure × integer × Procedure

```
procedure Build_Call_Graph(P,r,N,E,numinsts)
  P: in set of Procedure
  r: in Procedure
  N: out set of Procedure
  E: out set of LabeledEdge
  numinsts: in Procedure → integer
begin
  i: integer
  p, q: Procedure
  OldN := ∅: set of Procedure
  N := {r}
  E := ∅
  while OldN ≠ N do
    p := ♦(N - OldN)
    OldN := N
    for i := 1 to numinsts(p) do
      for each q ∈ callset(p,i) do
        N ∪= {q}
        E ∪= {⟨p,i,q⟩}
      od
    od
  od
end || Build_Call_Graph
```



Challenges

- Separate compilation – we would not know the complete call graph; wait till the whole program is available.
- Function pointers.
- Overloaded functions and inheritance.

Read yourself.



Interprocedural constant propagation

Two flavors of inter-procedural constant propagation.

- Context insensitive (call site independent) constant propagation.
 - For each procedure in a program identify the subset of its parameters, such that each of the parameter will get a constant value, in every invocation.
 - The return value may be constant for every invocation or none.
- Context sensitive (call site dependent) constant propagation:
 - for each particular procedure called from each particular site, the subset of parameters that have the same constant value each time the procedure is called at that site.
 - For each call site, the return value may be constant or not.



Interprocedural constant propagation overview

Function constantProp()

begin

```
worklist = {root};
while worklist is not empty do
  p = worklist.dequeue();
  foreach callsite s in p do
    compute the actuals of s using the formals of p;
    // Intra-procedural constant propagation
    Say the function being called at s is q;
    Compute the meet of the current values for the formals of q and the
    actuals at s;
    if constant values of q has changed then
      □ add q to the worklist;
  end
  v = compute the meet of all the return values of p;
  Set the return value of p to v;
  foreach call function q that calls p do
    □ add q to the worklist
end
```

end



Initialization

- The return value of each function is initialized to \top .
- The constant value of each formal argument is initialized to \top .

Modification to the CP

- Constant value of a function call is given by the constant-return value of the function.
- If the statement is of the form $a = foo(\dots)$, set the constant value of a to that of the function.



Algorithm

```

procedure Intrpr_Const_Prop(P,r,Cval)
  P: in set of Procedure
  r: in Procedure
  Cval: out Var  $\rightarrow$  ICP
begin
  WL := {r}: set of Procedure
  p, q: Procedure
  v: Var
  i, j: integer
  prev: ICP
  Pars: Procedure  $\rightarrow$  set of Var
  ArgList: Procedure  $\times$  integer  $\times$  Procedure
     $\rightarrow$  sequence of (Var  $\cup$  Const)
  Eval: Expr  $\times$  ICP  $\rightarrow$  ICP
  || construct sets of parameters and lists of arguments
  || and initialize Cval( ) for each parameter
  for each p  $\in$  P do
    Pars(p) :=  $\emptyset$ 
    for i := 1 to nparams(p) do
      Cval(param(p,i)) :=  $\top$ 
      Pars(p)  $\cup$ = {param(p,i)}
    od
    for i := 1 to numinsts(p) do
      for each q  $\in$  callset(p,i) do
        ArgList(p,i,q) := []
        for j := 1 to nparams(q) do
          ArgList(p,i,q)  $\cup$ = [arg(p,i,j)]
        od
      od
    od
  od
end

```



- Jump function: $J(p,i,L,x)$
 - i - call site
 - p - caller procedure
 - L - formal arguments of caller
 - x - a formal parameter of the callee.
 - The jump function maps information about the actual arguments of the call at the call site i to x .
- Return-jump function: $R(p,L)$
 - p - procedure
 - L - formal parameters
 - Maps the formal parameters to the return value of the function.
 - If the language admits call-by references: $R(p,L,x)$, where x - a formal parameter of the callee. Maps the value returned by the formal parameter x .



Algorithm

```

while WL  $\neq$   $\emptyset$  do
  p :=  $\diamond$ WL; WL -= {p}
  for i := 1 to numinsts(p) do
    for each q  $\in$  callset(p,i) do
      for j := 1 to nparams(q) do
        || if q( )'s jth parameter can be evaluated using values that
        || are arguments of p( ), evaluate it and update its Cval( )
        if Jsupport(p,i,ArgList(p,i,q),param(q,j))  $\subseteq$  Pars(p) then
          prev := Cval(param(q,j))
          Cval(param(q,j))  $\cap$ = Eval(J(p,i,
            ArgList(p,i,q),param(q,j)),Cval)
          if Cval(param(q,j))  $\subset$  prev then
            WL  $\cup$ = {q}
          fi
        fi
      od
    od
  od
end || Intrpr_Const_Prop

```



- The function \mathcal{J} can be thought of as
 - 1 a function that does all the computation required to compute the actual arguments to the callee in terms of the formal arguments of the caller. And `Eval` evaluates the return value of \mathcal{J} .
 - 2 It is a simple function that just represents the argument text. And the `Eval` function does the actual constant propagation.
- the precision of the constant propagation will depend on the precision of \mathcal{J} and `Eval`
Examples (assuming scheme 1):
 - Literal constant: If the argument passed is a constant, then a constant, else \perp
 - Pass-through parameter: If a formal parameter is directly passed or a constant, then pass the constant value, else \perp
 - Constant if intra-procedural constant.
 - Do a full fledged analysis to determine its value.



What have we done today?

- Call graphs.
- Inter-procedural constant propagation.

To read

- Muchnick - Ch 19.1, 19.3.

Next:

- Control tree based data flow analysis, du-chains.

