# CS6013 - Modern Compilers: Theory and Practise

## Interprocedural Analysis

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## 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:

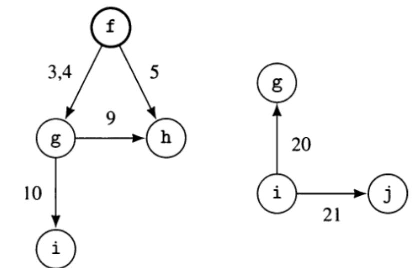
- Inter-procedural analysis.

## Interprocedural CFA - Call graph

- Inter-procedural CFA constructs a static Call graph
  - A directed multigraph.
- Given a program $P$, consisting of procedures $p_1, p_2 \ldots p_n$, the call grpah $G = \langle N, S, E, r \rangle$
- $N$ 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 $(p_1, s, p_2)$ indicates a call from $p_1$ to $p_2$ at site $s$.

## 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;
        $v =$ 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**

## Initialization and modification to to CP algorithm

**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 $a = foo(\cdots)$, set the constant value of $a$ to that of the function.

## Definitions for a formal algorithm

- 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 parametes 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

```
procedure Intpr_Const_Prop(P,r,Cval)
   P: in set of Procedure
   r: in Procedure
   Cval: out Var ⟶ ICP
begin
   WL := {r}: set of Procedure
   p, q: Procedure
   v: Var
   i, j: integer
   prev: ICP
   Pars: Procedure ⟶ set of Var
   ArgList: Procedure × integer × Procedure
      ⟶ sequence of (Var ∪ Const)
   Eval: Expr × ICP ⟶ ICP
   || construct sets of parameters and lists of arguments
   || and initialize Cval( ) for each parameter
   for each p ∈ P do
      Pars(p) := ∅
      for i := 1 to nparams(p) do
         Cval(param(p,i)) := ⊤
         Pars(p) ∪= {param(p,i)}
      od
      for i := 1 to numinsts(p) do
         for each q ∈ callset(p,i) do
            ArgList(p,i,q) := []
            for j := 1 to nparams(q) do
               ArgList(p,i,q) ⊕= [arg(p,i,j)]
            od
         od
      od
   od
```

## Algorithm

```
   while WL ≠ ∅ do
      p := ◆WL; WL -= {p}
      for i := 1 to numinsts(p) do
         for each q ∈ 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)) ⊆ Pars(p) then
                  prev := Cval(param(q,j))
                  Cval(param(q,j)) ⊓= Eval(J(p,i,
                     ArgList(p,i,q),param(q,j)),Cval)
                  if Cval(param(q,j)) ⊏ prev then
                     WL ∪= {q}
                  fi
               fi
            od
         od
      od
   od
end    || Intpr_Const_Prop
```

## Discussion

- The function 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 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 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.

## Closing remarks

What have we done today?

- Call graphs.
- Inter-procedural constant propagation.

To read

- Muchnick - Ch 19.1, 19.3.