Lecture 2: Basic Control Flow Analysis

COS 598C – Advanced Compilers

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Control Flow

- Control transfer = branch (taken or fall-through)
- Control flow
  - Branching behavior of an application
  - What sequences of instructions can be executed
- Execution → Dynamic control flow
  - Direction of a particular instance of a branch
  - Predict, speculate, squash, etc.
- Compiler → Static control flow
  - Not executing the program
  - Input not known, all outcomes possible (conservative)
- Control Flow Analysis
  - Determining properties of the program branch structure
  - Determining instruction execution conditions

Compiler Backend IR

- Variable home location
  - Front-end – every variable in memory
  - Back-end – maximal but safe register promotion
    - All temporaries put into registers
    - All local scalars put into registers, except those accessed via &
    - All globals, local arrays/structs, unpromotable local scalars put in memory. Accessed via load/store.
- Backend IR (intermediate representation)
  - Machine independent assembly code – really resource indep!
  - AKA: RTL (register transfer language) or 3-address code
  - \( r_1 = r_2 + r_3 \) or equivalently \( \text{add } r_1, r_2, r_3 \)
  - Opcode – not machine independent
  - Operands
    - Virtual registers – infinite number of these
    - Special registers – stack pointer (SP), PC, etc. (AKA Macro Regs)
    - Literals – compile-time constants

Basic Block (BB)

- Main Idea: Group operations into units with equivalent execution conditions
- Basic block – a sequence of consecutive operations in which flow of control enters at the beginning and leaves at the end without halt or possibility of branching except at the end
  - Straight-line sequence of instructions
  - If one operation is executed in a BB, they all are
- Finding BB’s
  - The first operation in a program/function starts a BB
  - Any operation that is the target of a branch starts a BB
  - Any operation that immediately follows a branch starts a BB
Identifying BBs – Example

L1: r7 = load(r8)
L2: r1 = r2 + r3
L3: beq r1, 0, L10
L4: r4 = r5 * r6
L5: r1 = r1 + 1
L6: beq r1 100 L2
L7: beq r2 100 L10
L8: r5 = r9 + 1
L9: r7 = r7 & 3
L10: r9 = load(r3)
L11: store(r9, r1)

Control Flow Graph (CFG)

- Control Flow Graph – Directed graph, G = (V,E) where each vertex V is a basic block and there is an edge E, v1 (BB1) → v2 (BB2) if BB2 can immediately follow BB1 in some execution sequence
  - A BB has an edge to all blocks it can target
  - Standard representation used by many compilers
  - Often have 2 pseudo V’s
    - entry node
    - exit node

Weighted CFG

- Profiling – Run the application on 1 or more sample inputs, record some behavior
  - Control flow profiling**
    - edge profile
    - block profile
    - path profiling
  - Cache profiling
  - Memory dependence profiling
- Annotate control flow profile onto a CFG → weighted CFG
- Key idea: optimize more effectively with profile info
  - Optimize for the common case
  - Make educated guesses

Dominator

- Dominator – Given a CFG(V, E, Entry, Exit), a node x dominates a node y, if every path from the Entry block to y contains x
- 3 properties of dominators
  - Each BB dominates itself
  - If x dominates y, and y dominates z, then x dominates z
  - If x dominates z and y dominates z, then either x dominates y or y dominates x
- Intuition
  - Given some BB, DOM blocks are guaranteed to have executed prior to executing the BB
Dominator Examples

Dominator Analysis

- Compute $\text{DOM}(BB_i) =$ set of BBs that dominate $BB_i$

Algorithm:

$$
\text{DOM(entry)} = \text{entry} \\
\text{DOM(everything else)} = \text{all nodes} \\
\text{change} = \text{true}
$$

while change, do

- Change = false

  for each BB (except the entry BB)

  $\text{TMP}(BB) = BB + (\text{intersect of DOM of all predecessor BB's})$

  if ($\text{TMP}(BB) \neq \text{DOM}(BB)$)

    $\text{DOM}(BB) = \text{TMP}(BB)$

    change = true

Immediate Dominator

- Immediate Dominator (IDOM)—Each node $n$ has a unique immediate dominator $m$ that is the last dominator of $n$ on any path from the initial node to $n$
- Closest node that dominates

Class Problem 1

Calculate the DOM set for each BB
Post Dominator

- Post Dominator – Given a CFG(V, E, Entry, Exit), a node x post dominates a node y, if every path from y to the Exit contains x

- Reverse of dominator

- Intuition
  - Given some BB, which blocks are guaranteed to have executed after executing the BB

Post Dominator Examples

Immediate Post Dominator

- Immediate post dominator (IPDOM) – Each node n has a unique immediate post dominator m that is the first post dominator of n on any path from n to the Exit
  - Closest node that post dominates
  - First breadth-first successor that post dominates a node

Post Dominator Analysis

- Compute PDOM(BB_i) = set of BBs that post dominate BB_i
  
  PDOM(exit) = exit
  PDOM(everything else) = all nodes
  change = true

  while change, do
    change = false
    for each BB (except the exit BB)
      TMP(BB) = BB + (intersect of PDOM of all successor BB’s)
      if (TMP(BB) != PDOM(BB))
        PDOM(BB) = TMP(BB)
        change = true
Why Do We Care About Dominators?

- For Loop detection (next subject)
- Dominator
  - Guaranteed to execute before
  - Redundant computation – a result is redundant if it is computed in a dominating BB
  - Most global optimizations use dominance info
- Post dominator
  - Guaranteed to execute after
  - Make a guess (i.e., 2 stores do not access the same location)
  - Check they really do not point to one another in the post dominating BB

Natural Loops

- Cycle suitable for optimization
  - Discuss optimization later

- 2 properties
  - Single entry point called the header
    - Header dominates all blocks in the loop
  - Must be one way to iterate the loop (i.e., at least 1 path back to the header from within the loop) called a backedge

- Backedge detection
  - Edge, \( x \to y \) where the target (\( y \)) dominates the source (\( x \))
Loop Detection

- Identify all backedges using DOM info
- Each backedge ($x \rightarrow y$) defines a loop
  - Loop header is the backedge target ($y$)
  - Loop BB – basic blocks that comprise the loop
    - All predecessor blocks of $x$ for which control can reach $x$ without going through $y$ are in the loop
- Common: Merge loops with the same header
  - For example, a loop with 2 continues
  - $\text{LoopBackedge} = \text{LoopBackedge1} + \text{LoopBackedge2}$
  - $\text{LoopBB} = \text{LoopBB1} + \text{LoopBB2}$
- Important property maintained
  - Header dominates all LoopBB
  - All backedges target header

Class Problem 3

- Header, LoopBB
- Backedges, LoopBackedge
- Exitedges, LoopExitBB
  - For each LoopBB, examine each outgoing edge
  - If the edge is to a BB not in LoopBB, then its an exit
- Preheader (Preloop)
  - New block before the header (falls through to header)
  - Whenever you invoke the loop, preheader executed
  - Whenever you iterate the loop, preheader NOT executed
  - All edges entering header
    - Backedges – no change
    - All others, retarget to preheader
- Postheader (Postloop) - analogous

Important Parts of a Loop
**Characteristics of a Loop**

- **Nesting (generally within a procedure scope)**
  - Inner loop – Loop with no loops contained within it
  - Outer loop – Loop contained within no other loops
  - Nesting depth
    - depth(outer loop) = 1
    - depth = depth(parent or containing loop) + 1
- **Invocation count**
  - How many times the loop is activated (loop header weight)
- **Trip count (average trip count)**
  - How many times (on average) does the loop iterate
  - for (I=0; I<100; I++) → trip count = 100
  - Average trip count = weight(header) / weight(preheader)

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**Class Problem 4: Trip Count Calculation**

Calculate the invocation and trip counts for all the loops in the graph.