

EECS 583 – Class 2

Control Flow Analysis

University of Michigan

September 1, 2021

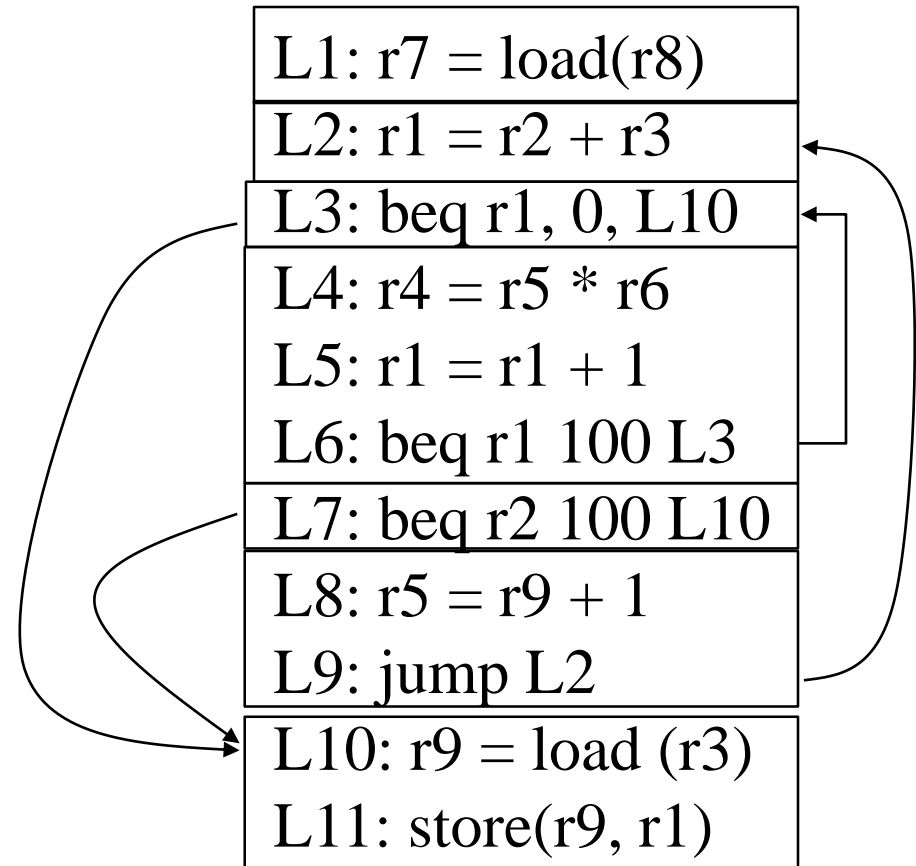
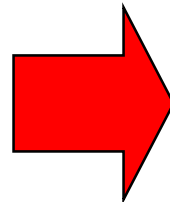
<https://web.eecs.umich.edu/~mahlke/courses/583f21>

Announcements & Reading Material

- ❖ eecs583a,eecs583b.eecs.umich.edu servers are ready
 - » Everyone has home directory and login
- ❖ HW 0 – Due next Wednes, but nothing to turn in
 - » Please get this done ASAP, talk to Yunjie/Ze if you have problems
 - » Needed for HW 1 which goes out next Wednes
 - » Go to <http://llvm.org>
 - » Detailed instructions on piazza
- ❖ Reading
 - » Today's class
 - Ch 9.4, 10.4 (6.6, 9.6) from Compilers: Principles, Techniques Tools Ed 1 (Ed 2)
 - » Next class
 - “Trace Selection for Compiling Large C Applications to Microcode”, Chang and Hwu, MICRO-21, 1988.
 - “The Superblock: An Effective Technique for VLIW and Superscalar Compilation”, Hwu et al., Journal of Supercomputing, 1993

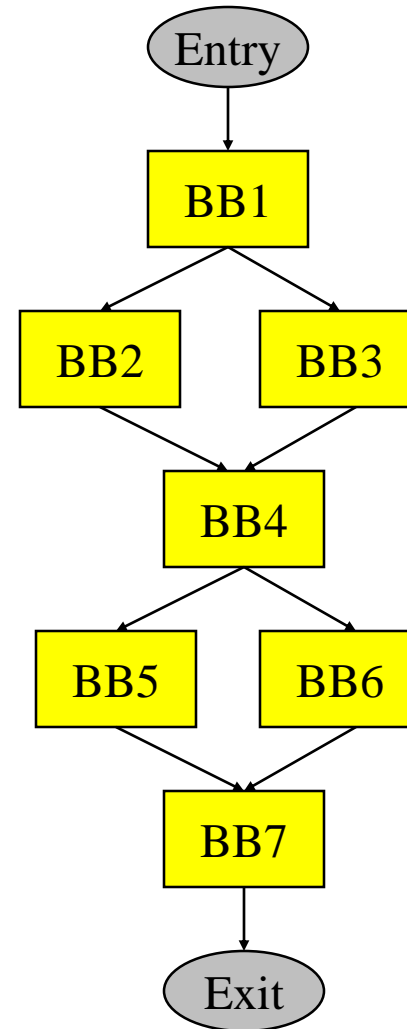
From Last Time: Identifying BBs - Answer

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 L3
L7: beq r2 100 L10
L8: r5 = r9 + 1
L9: jump L2
L10: r9 = load (r3)
L11: store(r9, r1)



From Last Time: Control Flow Graph (CFG)

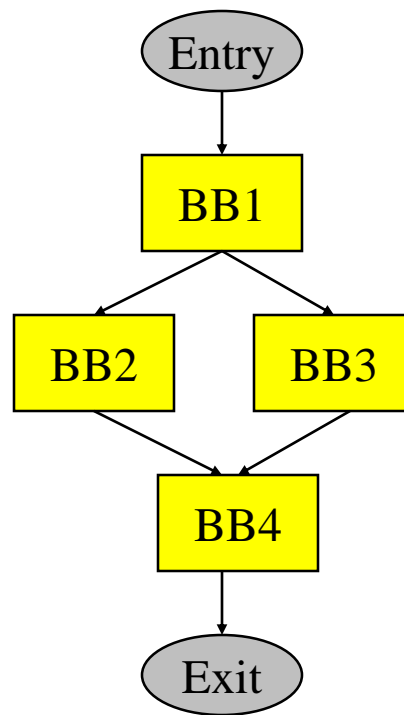
- ❖ Defn Control Flow Graph –
Directed graph, $G = (V, E)$
where each vertex V is a
basic block and there is an
edge E , $v_1 (BB1) \rightarrow v_2$
(BB2) if BB2 can
immediately follow BB1 in
some execution sequence
 - » A BB has an edge to all
blocks it can branch to
 - » Standard representation used
by many compilers
 - » Often have 2 pseudo vertices
 - entry node
 - exit node



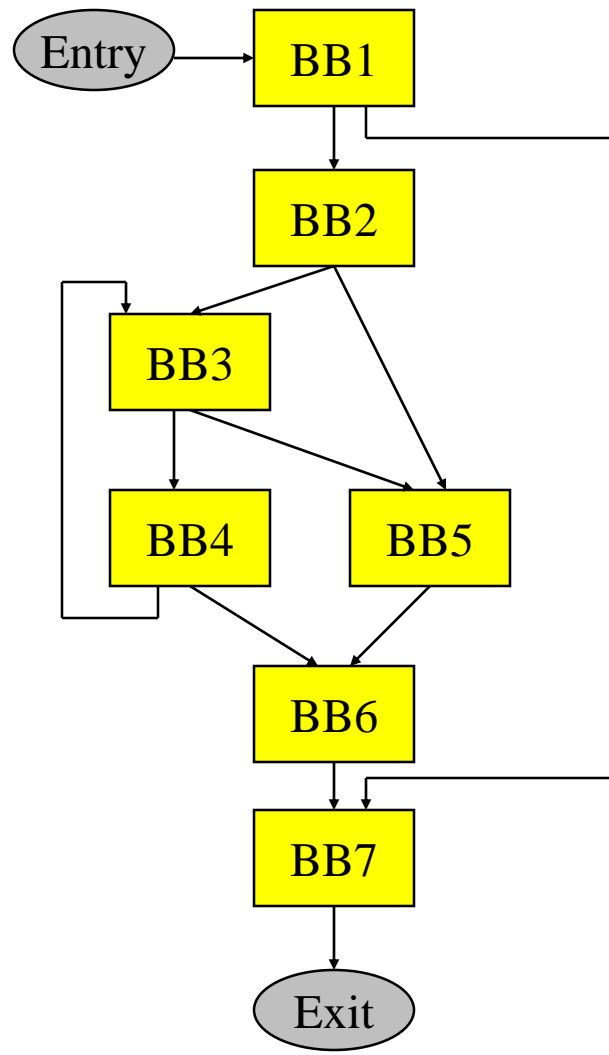
Property of CFGs: Dominator (DOM)

- ❖ Defn: Dominator – Given a CFG($V, E, \text{Entry}, \text{Exit}$), 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, which blocks are guaranteed to have executed prior to executing the BB

Dominator Example 1

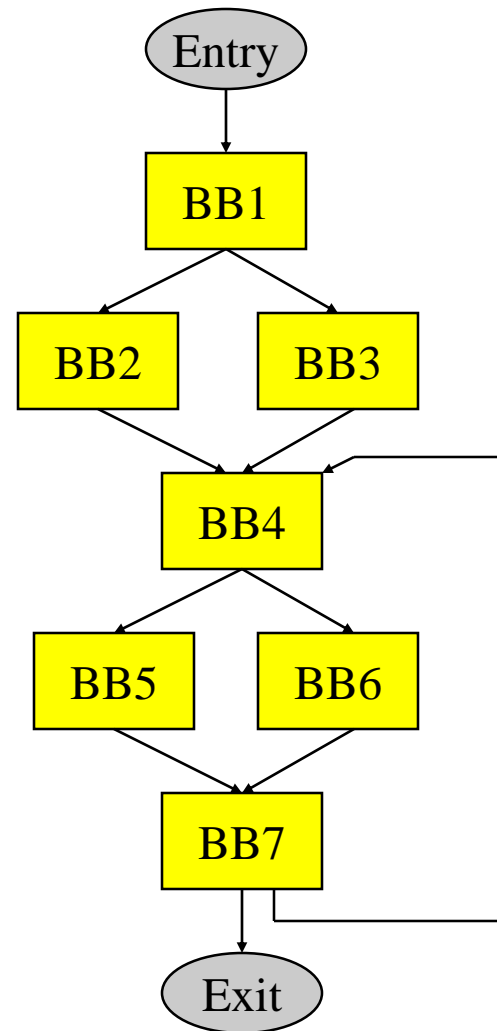


Dominator Example 2



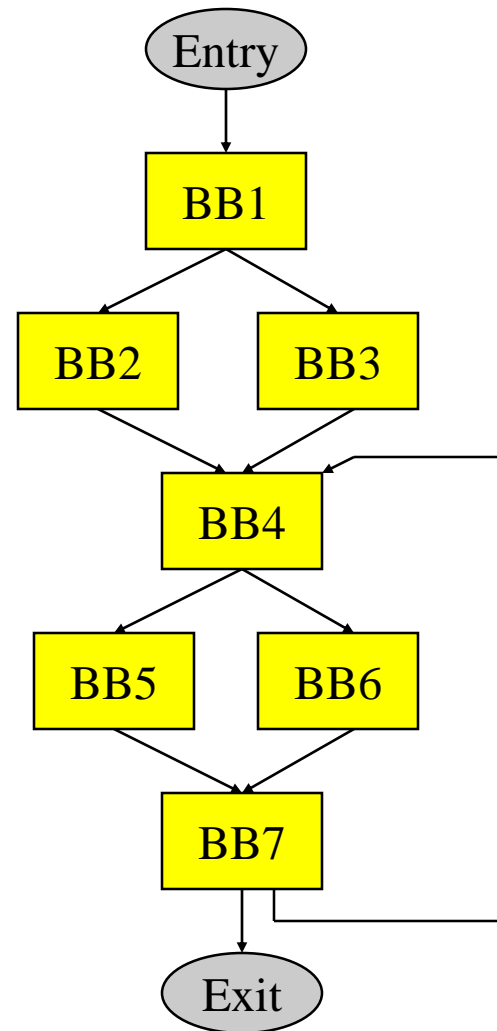
Dominator Analysis

- ❖ Compute $\text{dom}(\text{BB}_i)$ = set of BBs that dominate BB_i
- ❖ Initialization
 - » $\text{Dom}(\text{entry}) = \text{entry}$
 - » $\text{Dom}(\text{everything else}) = \text{all nodes}$
- ❖ Iterative computation
 - » while change, do
 - $\text{change} = \text{false}$
 - for each BB (except the entry BB)
 - ♦ $\text{tmp}(\text{BB}) = \text{BB} + \{\text{intersect of Dom of all predecessor BB's}\}$
 - ♦ if $(\text{tmp}(\text{BB}) \neq \text{dom}(\text{BB}))$
 - $\text{dom}(\text{BB}) = \text{tmp}(\text{BB})$
 - $\text{change} = \text{true}$



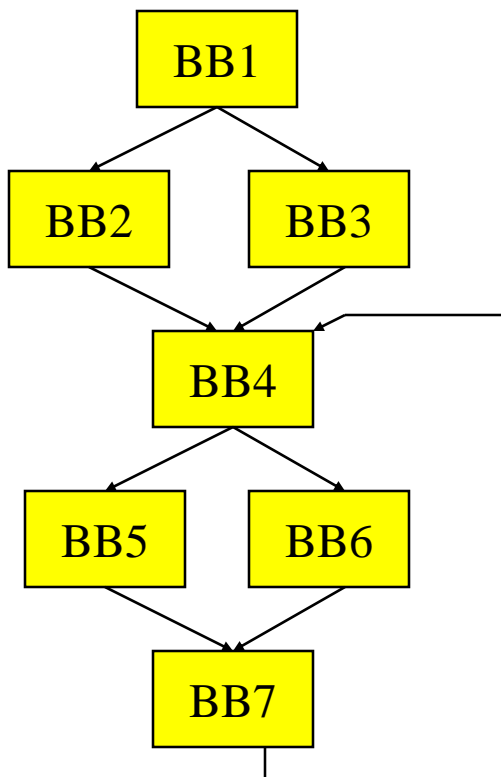
Immediate Dominator

- ❖ Defn: 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

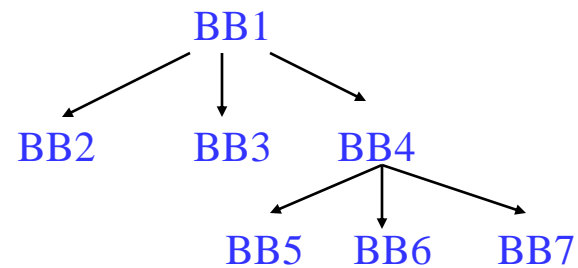


Dominator Tree

First BB is the root node, each node dominates all of its descendants



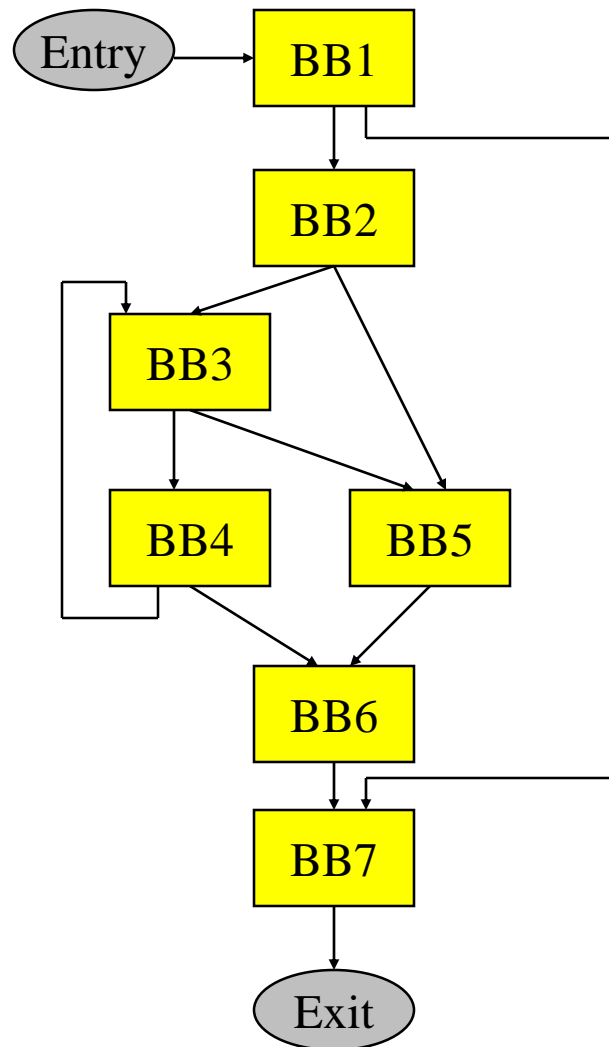
BB	DOM	BB	DOM
1	1	5	1,4,5
2	1,2	6	1,4,6
3	1,3	7	1,4,7
4	1,4		



Dom tree

Dominator Tree Example

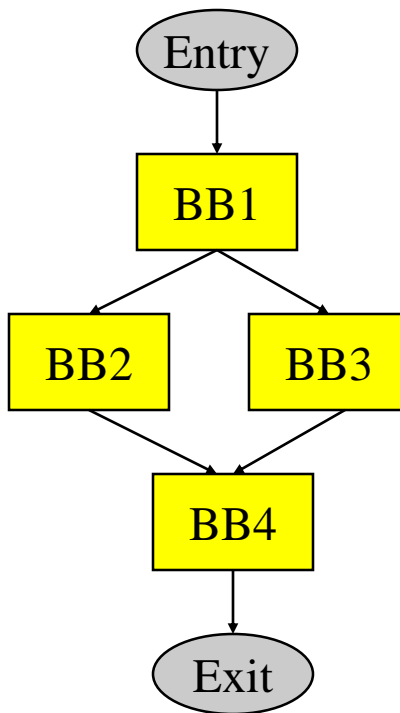
Draw the dominator tree



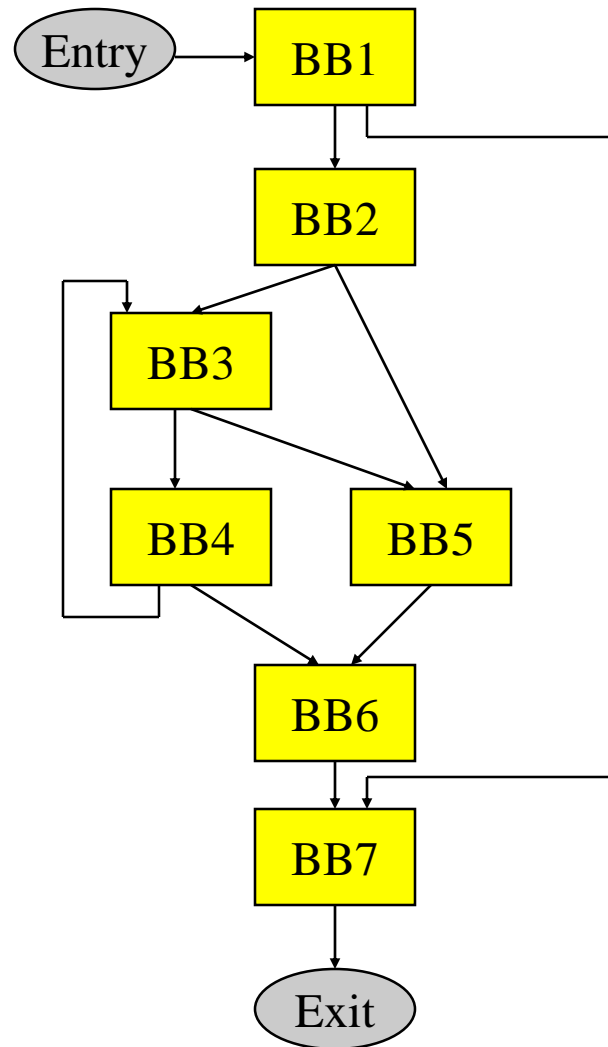
Post Dominator (PDOM)

- ❖ Reverse of dominator
- ❖ Defn: Post Dominator –
Given a CFG($V, E, \text{Entry}, \text{Exit}$), a node x post dominates a node y , if every path from y to the Exit contains x
- ❖ Intuition
 - » Given some BB, which blocks are guaranteed to have executed after executing the BB
- ❖ $\text{pdom}(\text{BB}_i) = \text{set of BBs that post dominate BB}_i$
- ❖ Initialization
 - » $\text{Pdom}(\text{exit}) = \text{exit}$
 - » $\text{Pdom}(\text{everything else}) = \text{all nodes}$
- ❖ Iterative computation
 - » while change, do
 - $\text{change} = \text{false}$
 - for each BB (except the exit BB)
 - ♦ $\text{tmp}(\text{BB}) = \text{BB} + \{\text{intersect of pdom of all successor BB's}\}$
 - ♦ if $(\text{tmp}(\text{BB}) \neq \text{pdom}(\text{BB}))$
 $\text{pdom}(\text{BB}) = \text{tmp}(\text{BB})$
 $\text{change} = \text{true}$

Post Dominator Example 1



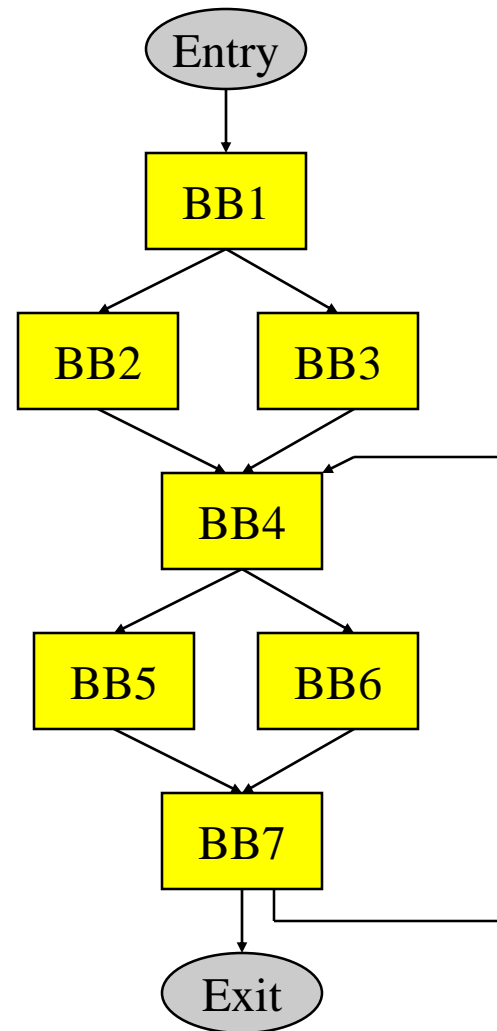
Post Dominator Example 2



Immediate Post Dominator

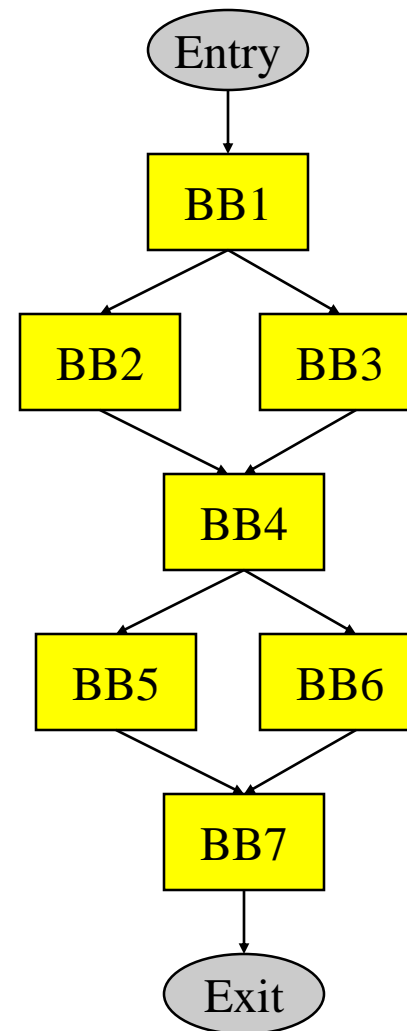
❖ Defn: Immediate post dominator (ipdom) –
Each node n has a unique immediate post dominator m that is the first post dominator of n on any path from n to the Exit

- » Closest node that post dominates
- » First breadth-first successor that post dominates a node



Why Do We Care About Dominators?

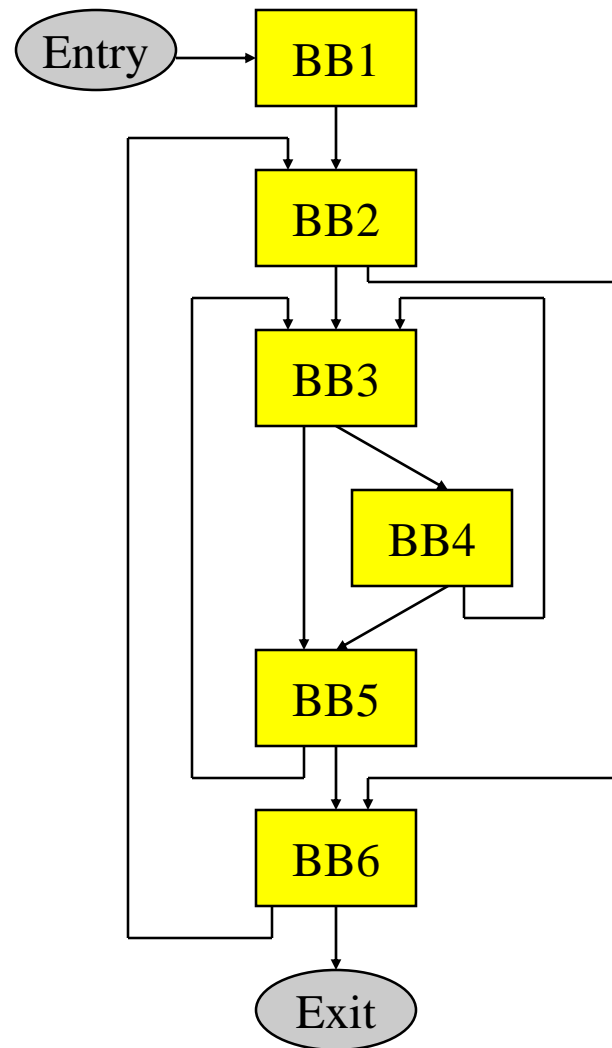
- ❖ Loop detection – next subject
- ❖ Dominator
 - » Guaranteed to execute before
 - » Redundant computation – an op is redundant if it is computed in a dominating BB
 - » Most global optimizations use dominance info
- ❖ Post dominator
 - » Guaranteed to execute after
 - » Make a guess (ie 2 pointers do not point to the same locn)
 - » Check they really do not point to one another in the post dominating BB



Natural Loops

- ❖ Cycle suitable for optimization
 - » Discuss optimizations later
- ❖ 2 properties
 - » Single entry point called the header
 - Header dominates all blocks in the loop
 - » Must be one way to iterate the loop (ie at least 1 path back to the header from within the loop) called a backedge
- ❖ Backedge detection
 - » Edge, $x \rightarrow y$ where the target (y) dominates the source (x)

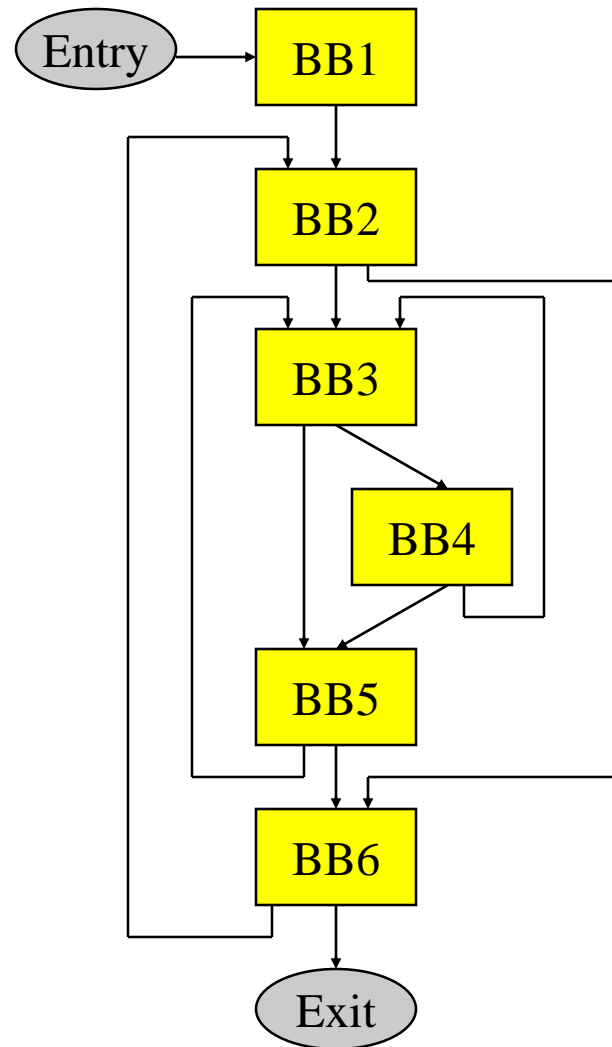
Backedge Example



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
- ❖ Merge loops with the same header
 - » I.e., a loop with 2 continues
 - » $\text{LoopBackedge} = \text{LoopBackedge1} + \text{LoopBackedge2}$
 - » $\text{LoopBB} = \text{LoopBB1} + \text{LoopBB2}$
- ❖ Important property
 - » Header dominates all LoopBB

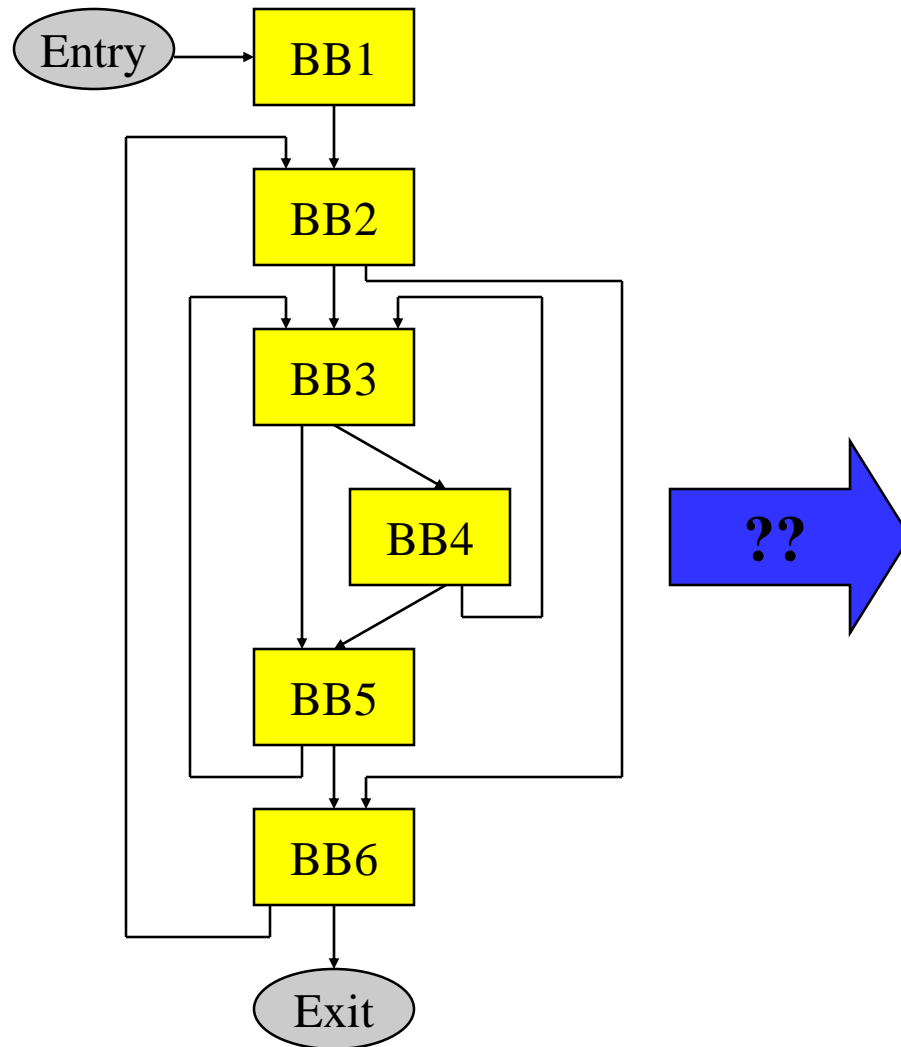
Loop Detection Example



Important Parts of a Loop

- ❖ Header, LoopBB
- ❖ Backedges, BackedgeBB
- ❖ Exitedges, ExitBB
 - » 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

Find the Preheaders for each Loop

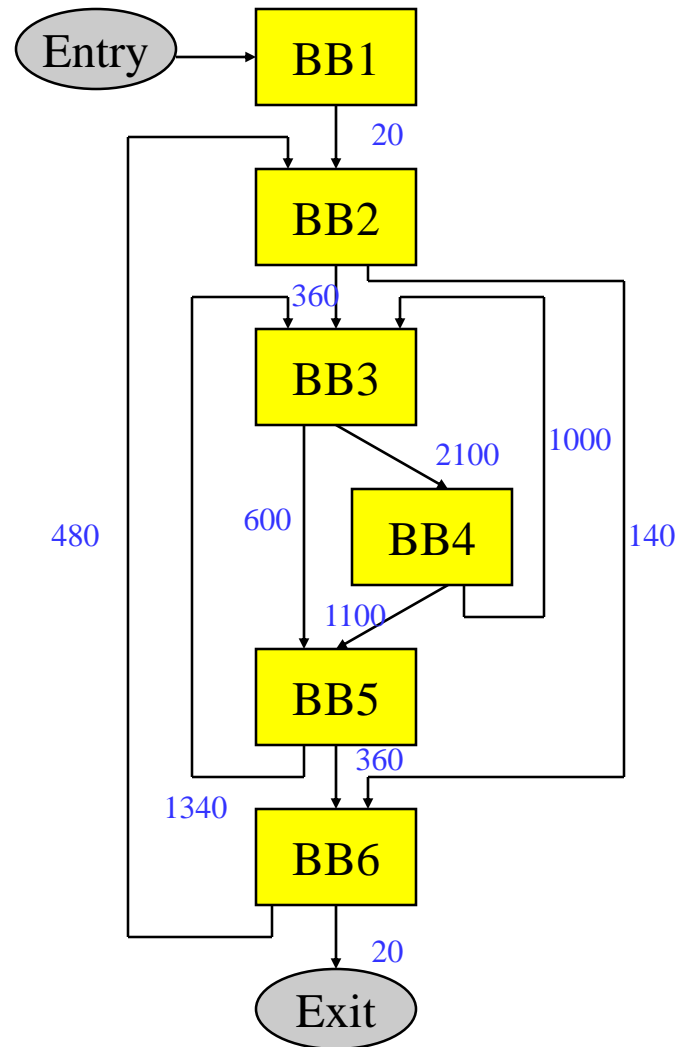


Characteristics of a Loop

- ❖ 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
 - $\text{depth}(\text{outer loop}) = 1$
 - $\text{depth} = \text{depth}(\text{parent or containing loop}) + 1$
- ❖ Trip count (average trip count)
 - » How many times (on average) does the loop iterate
 - » `for (I=0; I<100; I++)` → trip count = 100
 - » With profile info:
 - $\text{Ave trip count} = \text{weight}(\text{header}) / \text{weight}(\text{preheader})$

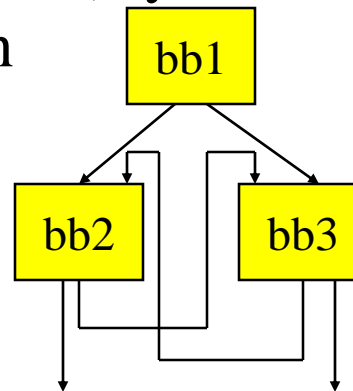
Trip Count Calculation Example

Calculate the trip counts for all the loops in the graph



Reducible Flow Graphs

- ❖ A flow graph is reducible if and only if we can partition the edges into 2 disjoint groups often called forward and back edges with the following properties
 - » The forward edges form an acyclic graph in which every node can be reached from the Entry
 - » The back edges consist only of edges whose destinations dominate their sources
- ❖ More simply – Take a CFG, remove all the backedges ($x \rightarrow y$ where y dominates x), you should have a connected, acyclic graph



Non-reducible!