Compilers

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Control-Flow Analysis

Sample Exercises and Solutions

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Problem1

For the source code program below:

1. Determine the corresponding control flow graph.
2. Determine the dominators of each node in the CFG
3. Determine the immediate dominator tree
4. Identify the set of nodes in each natural loop. Are there any nested loops? Why or why not.

```
i = 0;
while (i < N) do
  for(i=0; j < i; j++)
     if(a[i] < a[j]) then
        tmp = a[j];
        a[j] = a[i]
        a[i] = tmp;
      else
        if(a[i] == a[j]) then
          continue;
        else
          break;
   end for
   i = i + 1;
end while
```

Note: Assume there are *entry* and *exit* nodes corresponding to the entry point and exit points of the code segment, which would correspond to the prologue and epilogue sections of the procedure's generated code.

Solution:

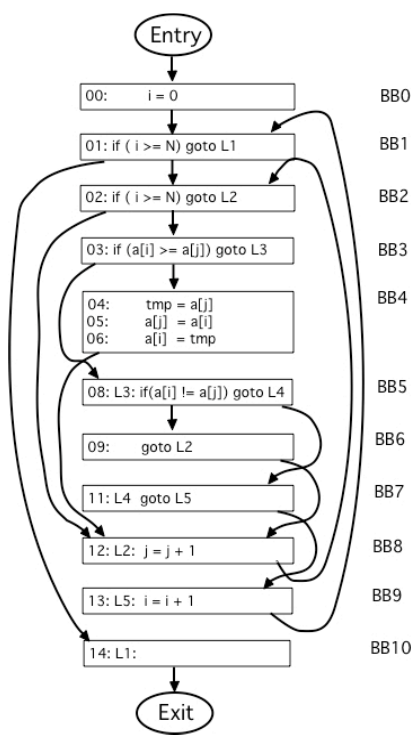
1. A possible control flow graph is as show on the right.

2. Node Dominators

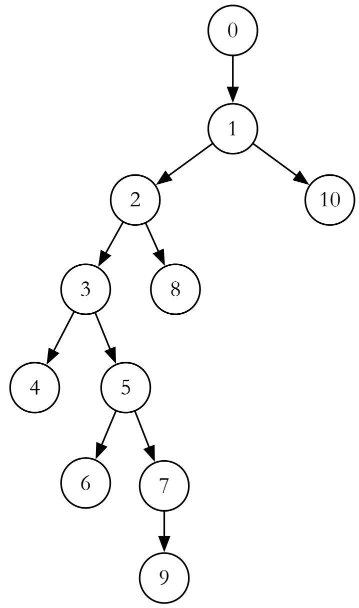
Node	Dominators
0	{0}
1	{0, 1}
2	{0, 1, 2}
3	{0, 1, 2, 3}
4	{0, 1, 2, 3, 4}
5	{0, 1, 2, 3, 5}
6	{0, 1, 2, 3, 5, 6}
7	{0, 1, 2, 3, 5, 7}
8	{0, 1, 2, 8}
9	{0, 1, 2, 3, 5, 7, 9}
10	{0, 1, 10}

For instance, node 4 does not dominate node 8 as there is a path from the entry node that goes to node 8 and does not pass through node 4.

While there is an algorithm to determine the dominator relationship one can derive the dominator tree by inspection of control-flow paths.



3. Immediate dominator tree: 0→1, 1→2, 1→10, 2→3, 3→4, 3→5, 2→8, 5→6, 5→7, 7→9 as shown below.

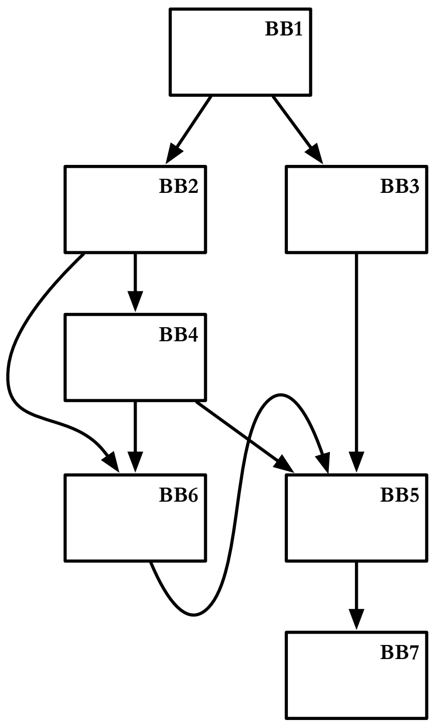


4. Natural loops: The natural loops are determined by observing the back-edges. A back-edge is an edge in the original control-flow graph such that the node pointed to by its head dominates the node pointed to by its tail. To find a natural loop we traverse the back-edge against the control flow and all the edges in the CFG until e reach the node pointed to by the head in a breath-first traversal.

Back edge	**Nodes in natural loop**
9 → 1	{1, 2, 3, 4, 5, 6, 7, 8, 9}
8 → 2	{2, 3, 4, 5, 6, 8}

There are two nested because they have different headers, and natural loops with different headers can either be nested or disjoint. They are not disjoint, so they must be nested.

Problem 2
Consider the Control-Flow Graph (CFG) shown below.

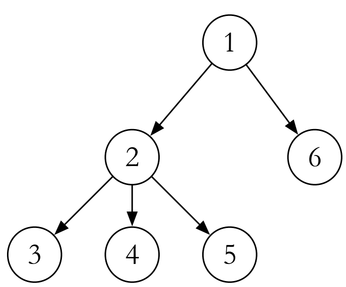


For this CFG determine the following:

a. The dominator tree.
b. The back edges, if any, and the corresponding natural loops and associated loop bodies.

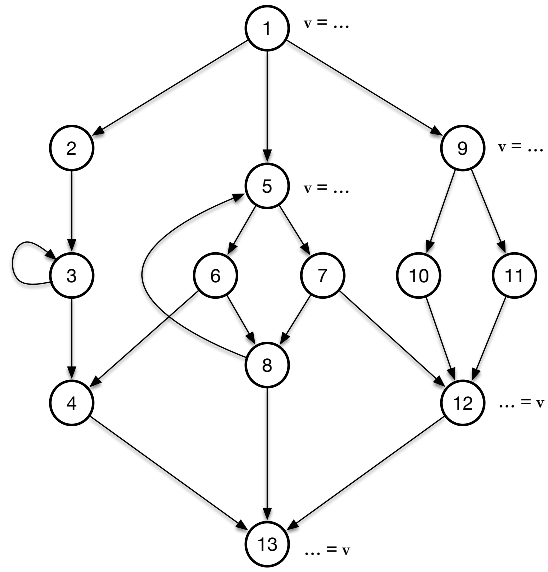
Solution:

a. The dominator tree is show below
b. For this particular case there are no edges in the CFG



Problem 3

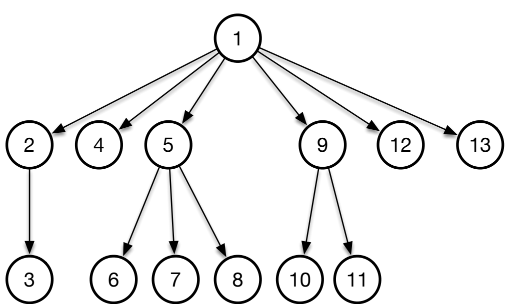
Consider the Control-Flow Graph (CFG) shown below.

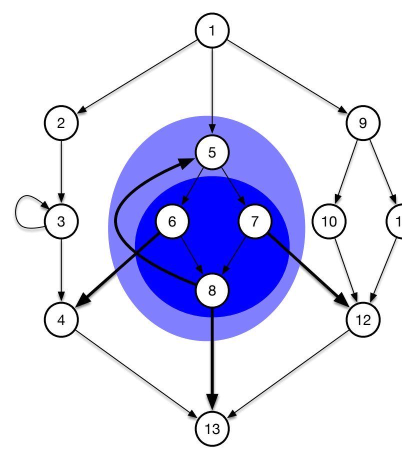


For this CFG determine the dominator tree and the dominance frontier of node 5 and 9 and indicate where SSA-form representation ϕ-nodes should be placed relative to a variable, say v whose value is set in nodes 1, 5 and 9 and read in nodes 12 and 13.

Solution:

The dominator tree is shown below on the left. On the right-hand-side we show the nodes that are dominated by node 5 and the nodes that are strictly dominated by 5, in the latter case nodes 6, 7 and 8.





In case of an assignment to v in basic blocks corresponding to nodes 5 and 9, we first need to determine the dominance frontier of these nodes which is where possible ϕ-nodes will be placed. Specifically, DF(5) = {4,5,12,13} and DF(9) = {12}. For this particular case, we would have to include ϕ-nodes for the variable v at the beginning of the basic blocks corresponding to nodes 4, 5, 12 and 13.