Loop Invariant Code Motion

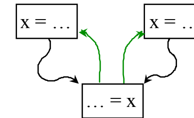
Last Time
- Control flow analysis

Today
- Loop invariant code motion

Next Time
- Induction variable identification and elimination

Loop Invariant Code Motion
Background: ud- and du-chains

ud-Chains
- A ud-chain connects a use of a variable to all defs of a variable that might reach it (a sparse representation of **Reaching Definitions**)

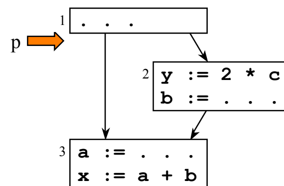


du-Chains
- A du-chain connects a def to all uses that it might reach (a sparse representation of **Upward Exposed Uses**)

How do ud-chains and reaching definitions differ?

Upward Exposed Uses

Definition
- An **upward exposed use** at program point p is a use that may be reached by a definition at p (i.e, no intervening definitions).



How do upward exposed uses differ from live variables?

Identifying Loop Invariant Code

Motivation
- Avoid redundant computations

Example

```
    w = . . .
    y = . . .
    z = . . .
L1: x = y + z
    v = w + x
    . . .
    if . . . goto L1
```

Everything that x depends upon is computed outside the loop, *i.e.*, all defs of y and z are outside of the loop, so we can move x = y + z outside the loop

What happens once we move that statement outside the loop?

Algorithm for Identifying Loop Invariant Code

Input: A loop L consisting of basic blocks. Each basic block contains a sequence of 3-address instructions. We assume ud-chains have been computed.

Output: The set of instructions that compute the same value each time through the loop

Informal Algorithm:

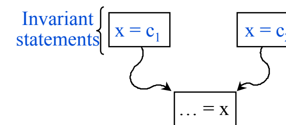
1. Mark "invariant" those statements whose operands are either
   - Constant
   - Have all reaching definitions outside of L
2. Repeat until a fixed point is reached: mark "invariant" those unmarked statements whose operands are either
   - Constant
   - Have all reaching definitions outside of L
   - Have exactly one reaching definition and that definition is in the set marked "invariant"

Is this last condition too strict?

Algorithm for Identifying Loop Invariant Code (cont)

Is the Last Condition Too Strict?

- No
- If there is more than one reaching definition for an operand, then neither one dominates the operand
- If neither one dominates the operand, then the value can vary depending on the control path taken, so the value is not loop invariant



Code Motion

What's the Next Step?

- Do we simply move the "invariant" statements outside the loop?
- No, there are three requirements that ensure that code motion does not change program semantics. For some statement

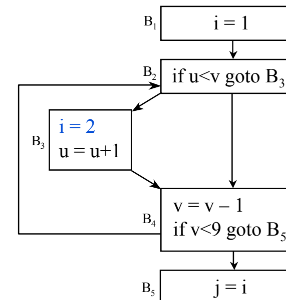
  s: **x = y + z**

  1. The block containing s dominates all loop exits
  2. No other statement in the loop assigns to x
  3. No use of x in the loop is reached by any def of x other than s

Example 1

Condition 1 is Needed

- If the block containing s does not dominate all exits, after the loop might get a different value



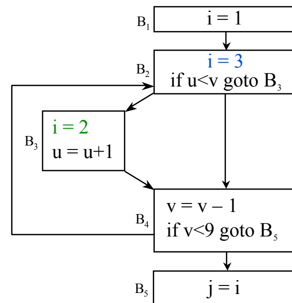
Can we move i=2 outside the loop?

i=2 is loop invariant, but B_3 does not dominate B_4, the exit node, so moving i=2 would change the meaning of the loop for those cases where B_3 is never executed

Example 2

Condition 2 is Needed

- If some other statement in the loop assigns i, the movement of the statement may cause some statement to see the wrong value



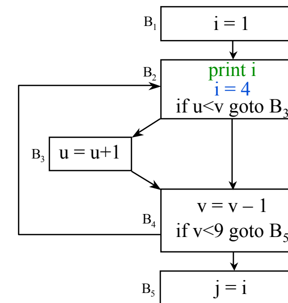
Can we move i=3 outside the loop?

B_2 dominates the exit so condition 1 is satisfied, but code motion will set the value of i to 2 if B_3 is ever executed, rather than letting it vary between 2 and 3.

Example 3

Condition 3 is Needed

- If a use in L can be reached by some other def, then we cannot move the def outside the loop



Can we move i=4 outside the loop?

Conditions 1 and 2 are met, but the use of i in block B_2, can be reached from a different def, namely i=1 from B_1.

If we were to move i=4 outside the loop, the first iteration through the loop would print 4 instead of 1

Loop Invariant Code Motion Algorithm

Input: A loop L with ud-chains and dominator information

Output: A modified loop with a preheader and 0 or more statements moved to the preheader

Algorithm:

1. Find loop-invariant statements
2. Insert preheader
3. For each statement s defining x found in step 1, move s to preheader if:
   a. s is in a block that dominates all exits of L,
   b. x is not defined elsewhere in L, and
   c. x is not live-out of the loop preheader

Correctness

Conditions 2a and 2b ensure that the value of x computed at s is the value of x after any exit block of L. When we move s to the preheader, s will still be the def that reaches any of the exit blocks of L.

Condition 2c ensures that any use of x inside of L used (and continues to use) the value of x computed by s

Loop Invariant Code Motion Algorithm (cont)

Profitability

- Can loop invariant code motion ever increase the running time of the program?
- Can loop invariant code motion ever increase the number of instructions executed?
- Before transformation, s is executed at least once (condition 2a)
- After transformation, s is executed exactly once

Relaxing Condition 1

- If we're willing to sometimes do more work: Change the condition to
  a. The block containing s either dominates all loop exits, or x is dead after the loop

Alternate Approach to Loop Invariant Code Motion

Division of labor

- Move all invariant computations to the preheader and assign them to temporaries
- Use the temporaries inside the loop
- Insert copies where necessary
- Rely on Copy Propagation to remove unnecessary assignments

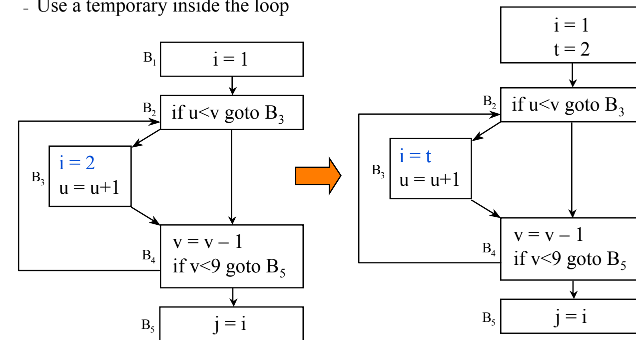
Benefits

- Much simpler: Fewer cases to handle

Example 1 Revisited

Using the alternate approach

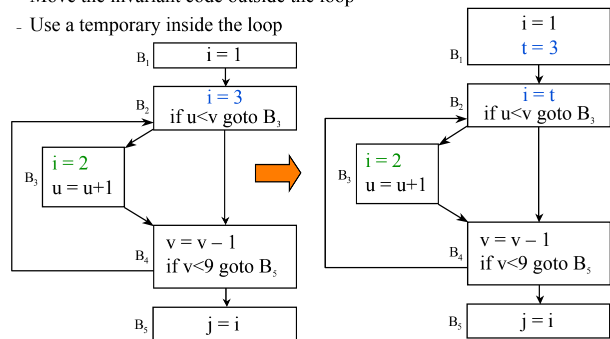
- Move the invariant code outside the loop
- Use a temporary inside the loop



Example 2 Revisited

Using the alternate approach

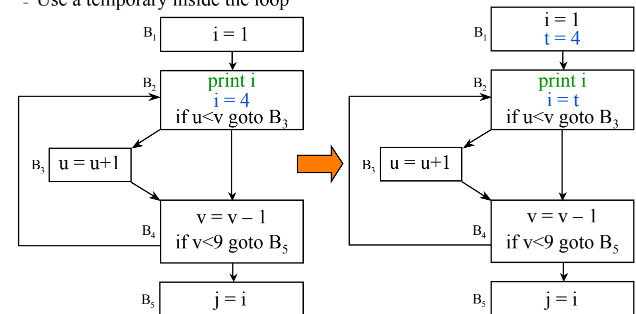
- Move the invariant code outside the loop
- Use a temporary inside the loop



Example 3 Revisited

Using the alternate approach

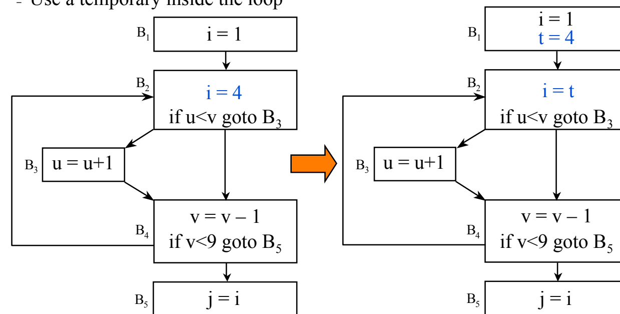
- Move the invariant code outside the loop
- Use a temporary inside the loop



Case where copy prop and dead code do code motion

Using the alternate approach

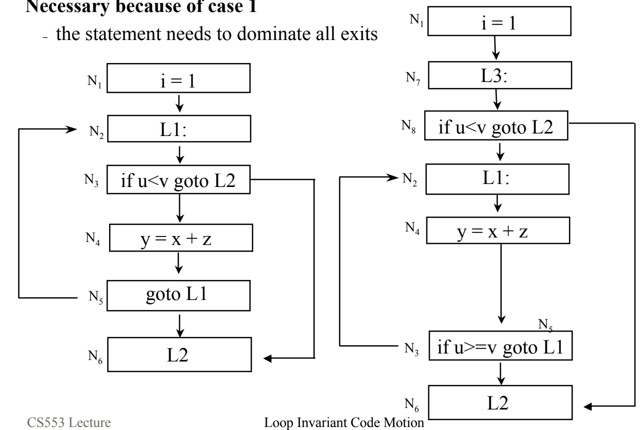
- Move the invariant code outside the loop
- Use a temporary inside the loop



Converting while loops to do while loops

Necessary because of case 1

- the statement needs to dominate all exits



Converting While Loops to Do-While Loops

Input: AssemFlowGraph

Output: Modified AssemFlowGraph with loop checks at bottom of loop.

Algorithm:

1. Find loops. Each loop has a set of nodes, a header, an exit node, and a tail node.
2. Insert preheader. A new node with a newly generated label instruction.
3. Find LoopCheck subgraph. Set of nodes and edges not including the header that are reachable from the header and end at the exit node. Does include the exit node.
4. Move LoopCheck subgraph between preheader and header. Make exit node fall through be the header.
5. Replace the loop tail with a copy of the LoopCheck subgraph.
    1. Reverse logic in exit node. NE should become EQ.
    2. Cjump should jump to loop header.
    3. Previous jump should become the fall through.

Lessons

Why did we study loop invariant code motion?

- Loop invariant code motion is an important optimization
- Because control flow, it's more complicated than you might think
- The notion of dominance is useful in reasoning about control flow
- Division of labor can greatly simplify the problem

Next Time

Reading

- Ch 9.1.7, pg. 641-642, handout

Lecture

- Induction variable elimination