15-745: Optimizing Compilers
Assignment 3 Writeup
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Q1: Profiling with LLVM
No work to show

Q2: Loop Invariant Code Motion

Structure:
The LoopInvariantCodeMotion pass is implemented as a *FunctionPass* rather than a *LoopPass* so that we may compute reaching definitions a single time over the whole function, then reuse the results in each loop pass. We compute reaching definitions using a corrected and improved version of our code from Assignment 2.

As in a normal *LoopPass*, loops are processed in order from highest to lowest nesting level to ensure that deeply nested invariant statements may “bubble out”. Processing per loop is split into several distinct subtasks, as outlined in the algorithm for LICM:

- *computeDominance():* Runs a dataflow pass to compute the block dominance information
- *computeImmediateDominance():* Finds immediate dominance relations based on the dominance dataflow results
- *computeCodeMotionCandidateStatements()*: Marks all possible statements (instructions) which may be moved by LICM
- *applyMotionToCandidates()*: Actually mutates the program, moving allowed LICM candidates to the preheader of the loop

Note that the additional invariance checks described in the assignment writeup are necessary for the following reasons:

- *isSafeToSpeculativelyExecute(I):* This prevents moving code which may cause exceptions (like dividing by 0) or which has other side effects, like branches.
- *!I→mayReadFromMemory():* If an instruction reads from memory, then we can’t know statically what value it will read . This will occur, for example, with pointers and array indexing. To be safe, we must assume that the instruction is not loop invariant because of the value it reads.

Usage:
See README. or simply execute "./RUN_ME.sh" from the ClassicalDataflow directory to first compile the passes & benchmarks and then run each of the 3 benchmarks.

The benchmarks include *basic_main, nested_main, and double_nested_main*. A C file for each is found in the "tests" directory; running the "build_and_dis_tests.sh" script followed by the "do_licm_tests.sh" script will recreate our results (or, again, simply run RUN_ME.sh).

Benchmark Results

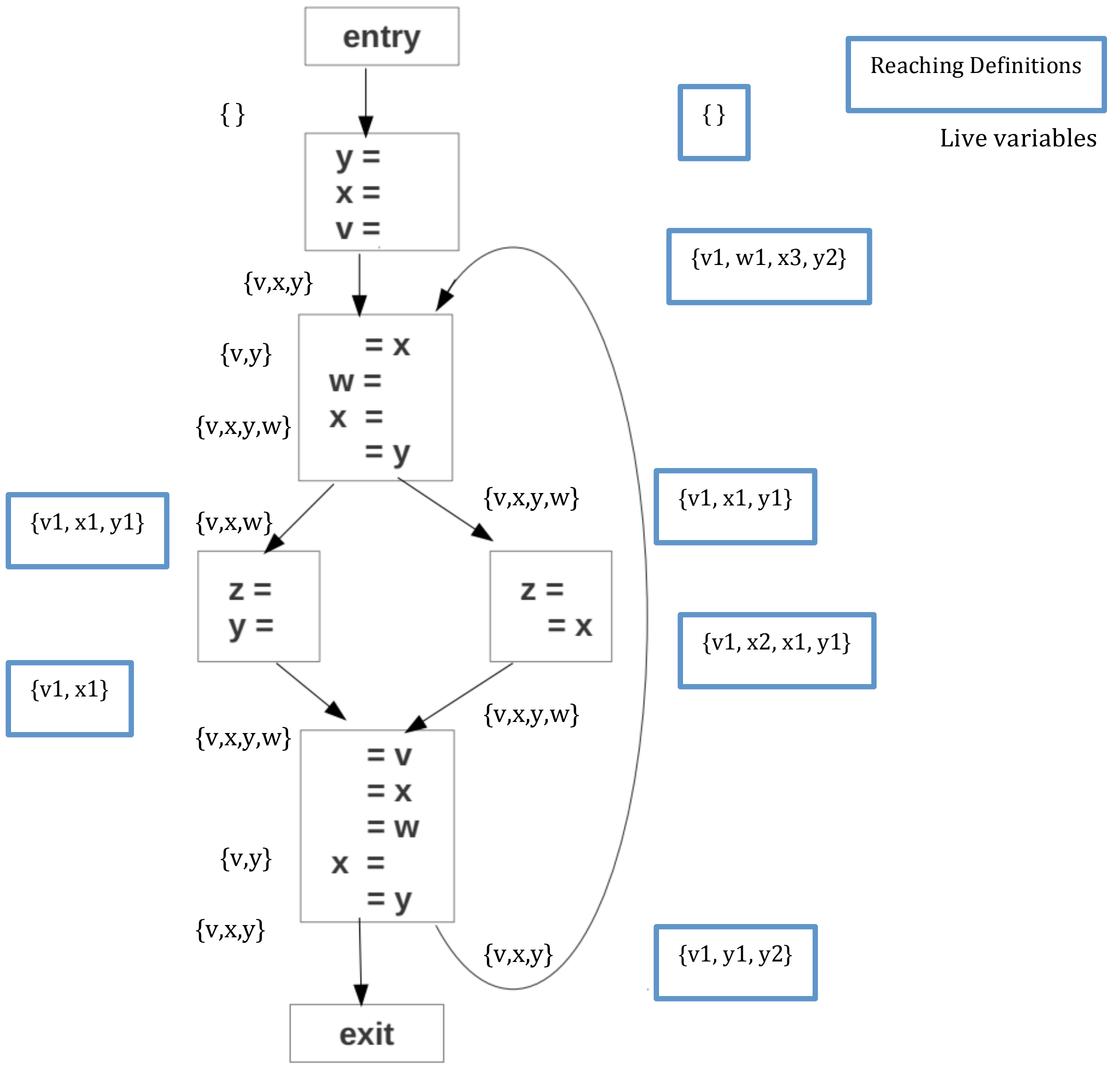
Benchmark	**Original Performance** (Dynamic Instructions)	**Optimized Performance** (Dynamic Instructions)
basic_main.c	1,475	1,265
nested_main.c	864,255	740,795
double_nested_main.c	5,431,905	5,308,445*

**Our LICM implementation appeared not to fully optimize this doubly-nested loop, hence giving only about the same reduction in dynamic instructions as the simpler nested_main.c benchmark.*

Q2.1: Dead Code Elimination
We chose not to implement this pass due to time constraints.

Q3: Questions

3.1 Register Allocation

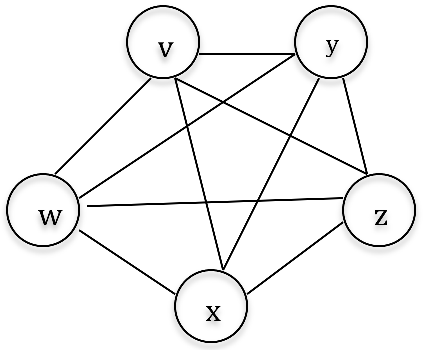


Form live range- eliminate equivalent definitions {y1,y2}

Next step: Interference graph
2 live ranges overlap.
Hence we have 5 nodes for v,x,y,z,w.

Now assume **z is alive at the end of the program**.

Links for the interference graph is drawn for the variables, which are live concurrently.



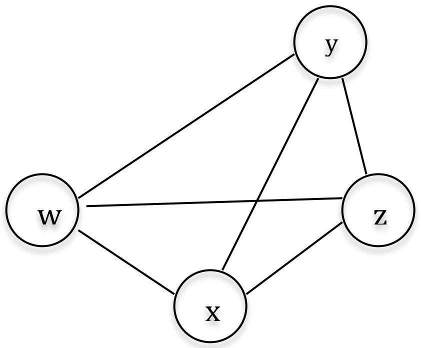
Since the variables are 5 and the register count is only 4, spilling is necessary for live range to not overlap.
Hence Chaitin coloring and spilling algorithm is used.

Step 1: If node with less than 4 neighbors present, place node on stack.
Here all the nodes of the interference graph has 4 neighbors. Hence no node can be removed.

Step 2: else node with highest degree to cost ratio is spilled.
Cost= Number of uses/definitions.
Cost of v=1+1=2
Cost of w=1+1=2
Cost of x=3+2=5
Cost of y=2+2=4
Cost of z=2

Degree to cost ratio for v=2/4=0.5
Degree to cost ratio for w=2/4=0.5
Degree to cost ratio for x=5/4=1.25
Degree to cost ratio for y=4/4=1
Degree to cost ratio for z=2/4=0.5

Hence v has the highest degree to cost ratio. Hence v is spilled.



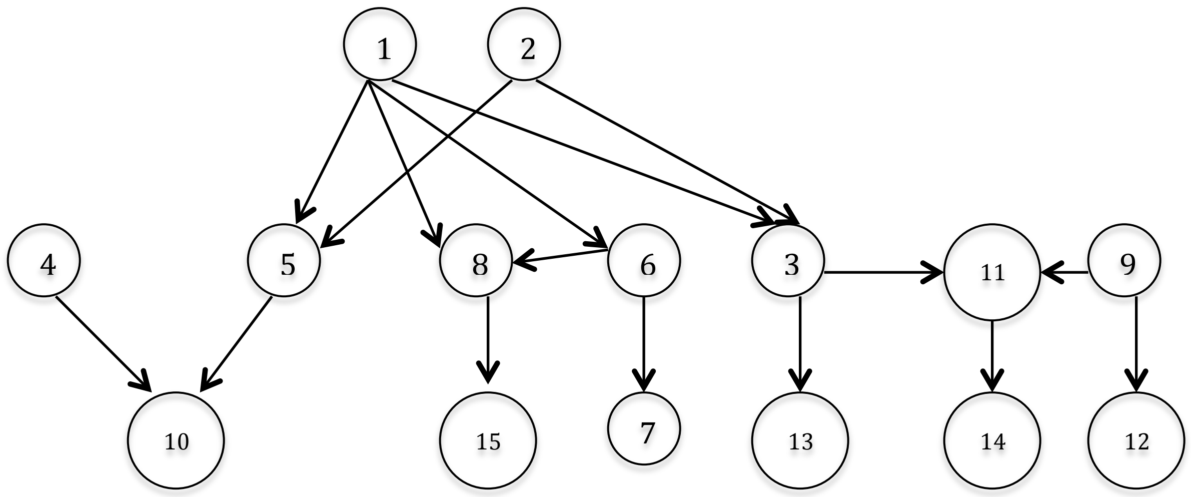
Now the modified interference graph is shown.
Step3: Insert the remaining nodes on stack and allocate different colors for the 4 nodes.
Hence v is spilled and registers allocated for the remaining nodes.

Note: Spilling v causes an additional read from memory for every iteration of the loop. Variable z could intuitively be a better option to spill since it has only 1 store every iteration and no uses. From question 3.2's cycle count we can say that 1 store will cost lesser cycles than a load for every iteration and this can utilize the pipeline fully. Additionally v has a definition outside the loop which will be a memory operation and can be avoided if z is spilled to memory and registers are allocated for v, w, x and y.

Thus the 4 registers according to the Chaitin spilling algorithm are allocated to the variables w, x, y and z.

3.2 Instruction Scheduling

1.List Scheduling –Forward Analysis

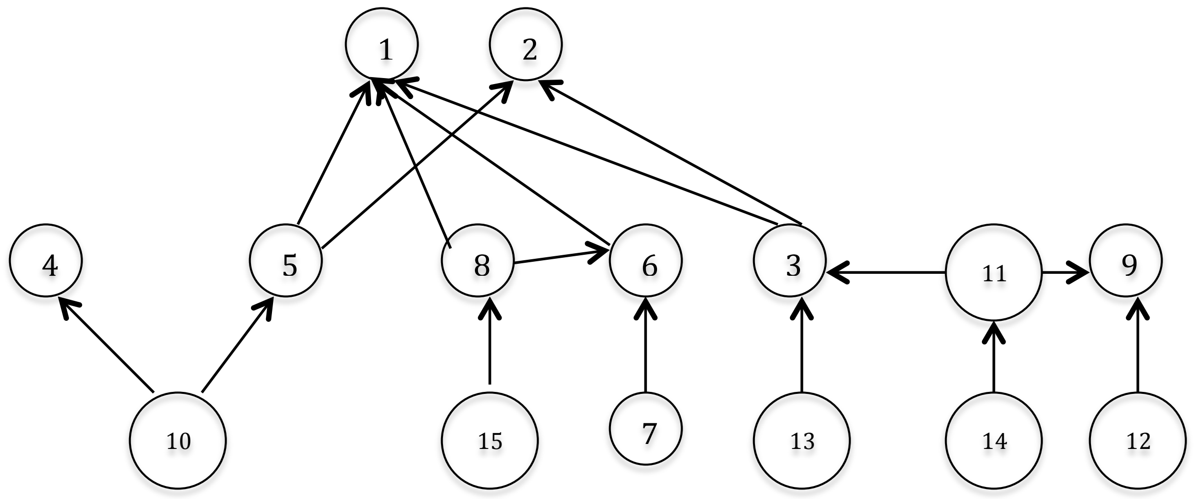


Priority Table

Instruction No	Priority
1	14
2	14
3	3
4	7
5	11
6	3
7	1
8	2
9	3
10	4
11	2
12	1
13	1
14	1
15	1

Cycle No	Ready List	Inflight	I0	I2	L/S	Comments
0	1,2,4,9	1	-	-	1	Add load instruction 1 to inflight list
1	2,4,9	1,2	-	-	2	Add load instruction 2 to inflight list
2	4,9	1,2,4	-	-	4	Add load instruction 4 to inflight list
3	9,6	4,2,6,9	6	-	9	Add load instruction 9 & 6 to inflight list
4	5,3,8,7	9,4,5,3	5	3	-	Add 5,3 to inflight list
5	8,7,13	5,9,8,7	8	-	7	Add 8,7 to inflight list
6	11,12,13	5,11,12	11	-	12	Add 11,12(store) to inflight list
7	13,14	5,13	-	-	13	Add store 13 to inflight list
8	14	5,14	-	-	14	Add store 14 to inflight list.
9	-	5	-	-	-	Wait for div to complete.
10	-	5	-	-	-	
11	-	5	-	-	-	
12	10	10	10	-	-	Add 10 to inflight list.
13	-	10	-	-	-	
14	-	10	-	-	-	
15	-	10	-	-	-	Complete

2.Backward Analysis



Priority Table

Instruction No	Priority
1	3
2	3
3	4
4	3
5	10
6	4
7	5
8	5
9	3
10	14
11	5
12	14
13	5
14	6
15	6

Cycle No	Ready List	Inflight	I0	I2	L/S	Comments
0	10,14,15,7,13,12	10,14	10	-	14	Add instruction 10,14 to inflight list
1	15,7,13,12,11	10,15	-	-	15	Add instruction 15(load) to inflight
2	7,8,11,12,13	10,7,8	8	-	7	Add 7(load), 8 to inflight list
3	11,13,12,6	10,11,13	11	-	13	Add 11, 13(load) to inflight list
4	12,6,3,4,5	5,3	5	3	-	Add 5,3 to inflight list
5	12,6,4	5,6,12	6	-	12	Add 6,12 to inflight list
6	4,9	5,4	-	-	4	Add 4(load) to inflight list
7	9	5,4,9	-	-	9	Add 9(load) to inflight list
8	-	5,4,9	-	-	-	Add store 14 to inflight list.
9	-	5,9	-	-	-	Wait for div to complete.
10	-	5	-	-	-	
11	1,2	2	-	-	1	Add 1(load) to inflight list
12	2	1,2	10	-	2	Add 2(load) to inflight list.
13	-	1,2	-	-	-	
14	-	1,2	-	-	-	
15	-	1,2	-	-	-	Complete

```
////////////////////////////////////////////////////////////////////////////////
// 15-745 S14 Assignment 3
// Group: bhumbers, psuresh
////////////////////////////////////////////////////////////////////////////////

#ifndef __CLASSICAL_DATAFLOW_LICM_H__
#define __CLASSICAL_DATAFLOW_LICM_H__

#include <deque>

#include "llvm/IR/Function.h"
#include "llvm/Pass.h"
#include "llvm/Support/raw_ostream.h"
#include "llvm/Support/InstIterator.h"
#include "llvm/ADT/SmallPtrSet.h"

#include "llvm/Pass.h"
#include "llvm/Analysis/LoopInfo.h"
#include "llvm/ADT/ValueMap.h"
#include "llvm/ADT/SmallVector.h"

#include "llvm/Analysis/ValueTracking.h"

#include "dataflow.h"
#include "reaching-defs.h"

#include <iomanip>
#include <queue>
#include <map>

using namespace llvm;
using namespace std;

namespace {

/** Runs LICM on a particular function
 * Note that this borrows from LLVM's LoopPass & LPPassManager, in that we run optimizations on each loop
 * in the function. However, this FunctionPass was used so that a reaching definition analysis could be executed
 * on the whole function before the per-loop transforms. */
class LoopInvariantCodeMotion : public FunctionPass {
 public:
  static char ID;

  LoopInvariantCodeMotion();

  bool doInitialization(Module& M);
  virtual bool runOnFunction(Function& F);
  virtual void getAnalysisUsage(AnalysisUsage& AU) const;

 protected:
  deque<Loop *> LQ;

  /** Returns the set of blocks which are part of the given loop and which have at least one successor outside the loop */
  SmallPtrSet<BasicBlock*, 32> getLoopExits(Loop* L);

  /** Returns block dominance info using dataflow framework */
  DataFlowResult computeDominance(Loop* L);

  /** Computes immediate dominance info given dataflow results with basic dominance info */
  map<BasicBlock*, BasicBlock*> computeImmediateDominance(DataFlowResult dominanceResults);

  void printDominanceInfo(DataFlowResult dominanceResults, map<BasicBlock*, BasicBlock*> immDoms);

  /** Returns set of statements (instructions) in given loop which are considered loop invariant */
  set<Value*> computeLoopInvariantStatements(Loop* L, map<Value*, ReachingDefinitionInfo> reachingDefs);

  /** Returns the set of statements (instructions) in given loop which are valid candidates for movement to loop preheader according t
o LICM*/
  set<Value*> computeCodeMotionCandidateStatements(Loop* L, DataFlowResult dominanceResults, set<Value*> invariantStatements);

  /** Applies LICM to given candidates where possible (basically, if all dependencies have also been moved).
   * Returns true if any motions were applied, which modifies the loop code */
  bool applyMotionToCandidates(Loop* L, set<Value*> motionCandidates);

  /** Recurse through all subloops and all loops  into LQ. (Source: LoopPass.cpp) */
  void addLoopIntoQueue(Loop* L);
};

char LoopInvariantCodeMotion::ID = 0;
RegisterPass<LoopInvariantCodeMotion> X("cd-licm", "15-745 Loop Invariant Code Motion");

}

#endif
```

```
////////////////////////////////////////////////////////////////////////////////
// 15-745 S14 Assignment 3
// Group: bhumbers, psuresh
////////////////////////////////////////////////////////////////////////////////

#include "loop-invariant-code-motion.h"

#include "llvm/IR/Function.h"
#include "llvm/Pass.h"
#include "llvm/Support/raw_ostream.h"
#include "llvm/Support/InstIterator.h"
#include "llvm/ADT/SmallPtrSet.h"

#include "llvm/Pass.h"
#include "llvm/Analysis/LoopInfo.h"
#include "llvm/ADT/ValueMap.h"
#include "llvm/ADT/SmallVector.h"

#include "llvm/Analysis/ValueTracking.h"

#include "dataflow.h"

#include <iomanip>
#include <queue>
#include <map>

using namespace llvm;
using namespace std;

namespace {

//////////////////////////////////////////////////////////////////////////////////////////////
//Dataflow analyses

//DOMINANCE
class DominanceDataFlow : public DataFlow {
  protected:
    BitVector applyMeet(std::vector<BitVector> meetInputs) {
      BitVector meetResult;

      //Meet op = intersection of inputs
      if (!meetInputs.empty()) {
        for (int i = 0; i < meetInputs.size(); i++) {
//          errs() << "  " << bitVectorToStr(meetInputs[i]) << ", ";
          if (i == 0)
            meetResult = meetInputs[i];
          else
            meetResult &= meetInputs[i];
        }
      }
//      errs() << "\n";

      return meetResult;
    }

    TransferResult applyTransfer(const BitVector& value, DenseMap<Value*, int> domainEntryToValueIdx, BasicBlock* block) {
      TransferResult transfer;
      transfer.baseValue = value;

//      errs() << "Applying transfer for block: " << block->getName() << "\n";
//      errs() << "Pre: " << bitVectorToStr(value) << "\n";

      //Transfer of dominance is simple: Just add the current block to the dominance set
      unsigned blockIdx = domainEntryToValueIdx[block];
      transfer.baseValue.set(blockIdx);

//      errs() << "Post: " << bitVectorToStr(transfer.baseValue) << "\n";

      return transfer;
    }
};

//Helper for checking dominance. Returns true if A dominates B according to given results
bool dominates(BasicBlock* A, BasicBlock* B, DataFlowResult dominanceResults) {
//  errs() << "Checking whether " << A->getName() << " dominates " << B->getName() << "...";
  DataFlowResultForBlock dominanceOfB = dominanceResults.resultsByBlock[B];
  bool aDomsB = dominanceOfB.out[dominanceResults.domainEntryToValueIdx[A]];
//  errs() << (aDomsB ? "YES" : "NO") << "\n";
  return aDomsB;
}

//////////////////////////////////////////////////////////////////////////////////////////////

LoopInvariantCodeMotion::LoopInvariantCodeMotion() : FunctionPass(ID) { }

bool LoopInvariantCodeMotion::doInitialization(Module& M) {
  return false;
```

```
}

bool LoopInvariantCodeMotion::runOnFunction(Function& F) {
  bool modified = false;

  //Get reaching definitions at each program point over whole function
  map<Value*, ReachingDefinitionInfo> reachingDefs = ReachingDefinitions().computeReachingDefinitions(F);

  //Add all loops into the processing queue. Note that addLoopIntoQueue will recursively add subloops of each
  // top-level loop in front of the parent loop, so that processing will be from most-to-least nested order.
  // This helps guarantee that any loop invariant code motion will "bubble out" to the outer most loop.
  LoopInfo& LI = getAnalysis<LoopInfo>();
  for (LoopInfo::reverse_iterator I = LI.rbegin(), E = LI.rend(); I != E; ++I)
    addLoopIntoQueue(*I);

  //Apply LICM to each loop in the work queue
  while (!LQ.empty()) {
    Loop* L  = LQ.back();

    //Don’t bother with loops without a preheader
    if (L->getLoopPreheader() == NULL)
      return false;

    DataFlowResult dominanceResults = computeDominance(L);
    map<BasicBlock*, BasicBlock*> immDoms = computeImmediateDominance(dominanceResults);
    printDominanceInfo(dominanceResults, immDoms);

    set<Value*> loopInvariantStatements = computeLoopInvariantStatements(L, reachingDefs);

    set<Value*> codeMotionCandidateStatements = computeCodeMotionCandidateStatements(L, dominanceResults, loopInvariantStatements);

    bool loopModified = applyMotionToCandidates(L, codeMotionCandidateStatements);

    modified |= loopModified;

    LQ.pop_back();
  }

  return modified;
}

void LoopInvariantCodeMotion::getAnalysisUsage(AnalysisUsage& AU) const {
  AU.addRequired<LoopInfo>();
}

SmallPtrSet<BasicBlock*, 32> LoopInvariantCodeMotion::getLoopExits(Loop* L) {
  SmallVector<BasicBlock*, 32> loopSuccessors;
  L->getUniqueExitBlocks(loopSuccessors);

  SmallPtrSet<BasicBlock*, 32> loopExits;
  for (SmallVector<BasicBlock*, 32>::iterator i = loopSuccessors.begin(); i < loopSuccessors.end(); ++i) {
    //Note: As a result of the loop-simplify pass, each out-of-loop successor’s sole predecessor should be part of this loop
    loopExits.insert(*pred_begin(*i));
  }

  return loopExits;
}

DataFlowResult LoopInvariantCodeMotion::computeDominance(Loop* L) {
  //Dataflow domain = Set of all basic blocks in the loop (as well as their parents)
  std::set<BasicBlock*> blocksSet;
  std::vector<BasicBlock*> loopBlocks = L->getBlocks();
  for (std::vector<BasicBlock*>::iterator blockIter = loopBlocks.begin(); blockIter != loopBlocks.end(); ++blockIter) {
    BasicBlock* block = *blockIter;
    //Add parents
    for (pred_iterator predBlock = pred_begin(block), E = pred_end(block); predBlock != E; ++predBlock) {
      blocksSet.insert(*predBlock);
    }
    blocksSet.insert(block); //Add block
  }
  std::vector<Value*> domain;
  std::vector<BasicBlock*> blocks;
  for (std::set<BasicBlock*>::iterator it = blocksSet.begin(); it != blocksSet.end(); ++it) {
//    errs() << "Adding to domain for dominance: " << (*it)->getName() << "\n";
    blocks.push_back(*it);
    domain.push_back(*it);
  }

  int numVars = domain.size();

  //Boundary value at entry is just the entry block (entry dominates itself)
  BitVector boundaryCond(numVars, false);

  //Initial interior set is full set of blocks
  BitVector initInteriorCond(numVars, true);

  //Get dataflow values at IN and OUT points of each block
  DominanceDataFlow flow;
  return flow.run(blocks, domain, DataFlow::FORWARD, boundaryCond, initInteriorCond);
}

map<BasicBlock*, BasicBlock*> LoopInvariantCodeMotion::computeImmediateDominance(DataFlowResult dominanceResults) {
  map<BasicBlock*, BasicBlock*> immDoms;

  //We find the immediate dominators in a somewhat less-than-optimally-efficient way: basically,
  //for each block B, walk up the graph toward the root of the CFG in a BFS ordering until we see a node in dom(B)
  //There appear to be better idom algorithms, but I wasn't sure how to make them work nicely with our dataflow framework.

  for (map<BasicBlock*, DataFlowResultForBlock>::iterator resultsIter = dominanceResults.resultsByBlock.begin();
         resultsIter != dominanceResults.resultsByBlock.end();
         ++resultsIter) {
    DataFlowResultForBlock& blockResult = resultsIter->second;
    BitVector visited(dominanceResults.resultsByBlock.size(), false);
    std::queue<BasicBlock*> work;
    work.push(resultsIter->first);
    while (!work.empty()) {
      BasicBlock* currAncestor = work.front();
      work.pop();
      int currIdx = dominanceResults.domainEntryToValueIdx[currAncestor];
      visited.set(currIdx);

//      errs() << "Checking if idom of block " << resultsIter->first->getName() << " is " << currAncestor->getName() << "\n";

      //If ancestor is contained in dom set for the results block, mark as idom and quit
      if (blockResult.in[currIdx]) {
        immDoms[resultsIter->first] = currAncestor;
        break;
      }

      for (pred_iterator predBlock = pred_begin(currAncestor), E = pred_end(currAncestor); predBlock != E; ++predBlock) {
        int predIdx = dominanceResults.domainEntryToValueIdx[*predBlock];
        if (!visited[predIdx]) {
          work.push(*predBlock);
        }
      }
    }
  }

  return immDoms;
}

void LoopInvariantCodeMotion::printDominanceInfo(DataFlowResult dominanceResults, map<BasicBlock*, BasicBlock*> immDoms) {
  //Output: Print immediate dominance information
  errs() << "Dominance domain: {";
  for (map<BasicBlock*, DataFlowResultForBlock>::iterator resultsIter = dominanceResults.resultsByBlock.begin();
         resultsIter != dominanceResults.resultsByBlock.end();
         ++resultsIter) {
    errs() << resultsIter->first->getName() << "  ";
  }
  errs() << "}\n";

  errs() << "\nImmediate Dominance Relationships: \n";

  for (map<BasicBlock*, DataFlowResultForBlock>::iterator resultsIter = dominanceResults.resultsByBlock.begin();
         resultsIter != dominanceResults.resultsByBlock.end();
         ++resultsIter) {
    char str[100];
    BasicBlock* idom = immDoms[resultsIter->first];
    if (idom) {
      sprintf(str, "%s is idom'd by %s", ((std::string)resultsIter->first->getName()).c_str(), ((std::string)idom->getName()).c_str())
;
      errs() << str << "\n";
    }
    else {
      sprintf(str, "%s has no idom", ((std::string)resultsIter->first->getName()).c_str());
      errs() << str << "\n";
    }
//      sprintf(str, "Dominators for %-20s:", ((std::string)resultsIter->first->getName()).c_str());
//      errs() << str << bitVectorToStr(resultsIter->second.in) << "\n";
  }

  errs() << "\n";
}

std::set<Value*>  LoopInvariantCodeMotion::computeLoopInvariantStatements(Loop* L, map<Value*, ReachingDefinitionInfo> reachingDefs) {
  std::set<Value*> loopInvariantStatements;

  std::vector<BasicBlock*> loopBlocks = L->getBlocks();

  //Initialize invariant statement set
  for (std::vector<BasicBlock*>::iterator blockIter = loopBlocks.begin(); blockIter != loopBlocks.end(); ++blockIter) {
    for (BasicBlock::iterator instIter = (*blockIter)->begin(), e = (*blockIter)->end(); instIter != e; ++instIter) {
      Value* v = instIter;
```

```cpp
      //First, check if this is an easy invariance case
      if (isa<Constant>(v) || isa<Argument>(v) || isa<GlobalValue>(v))
        loopInvariantStatements.insert(v);

      //Otherwise, check more complex conditions for typical instructions:
      //Statement A=B+C+D+... is invariant if all the reaching defs for all its operands (B, C, D, ...) are outside the loop
      //(and a few other misc safety conditions are met)
      else if (isa<Instruction>(v)) {
        Instruction* I = static_cast<Instruction*>(v);

//        errs() << "Considering invariance of: " << valueToStr(v) << "\n";

        bool mightBeLoopInvariant = (isSafeToSpeculativelyExecute(I) && !I->mayReadFromMemory() && !isa<LandingPadInst>(I));

        if (mightBeLoopInvariant) {
          bool allOperandsOnlyDefinedOutsideLoop = true;

          for (User::op_iterator opIter = I->op_begin(), e = I->op_end(); opIter != e; ++opIter) {
            Value* opVal = *opIter;
            ReachingDefinitionInfo varDefsInfo = reachingDefs[opVal];

            vector<Value*> varDefsAtStatement = varDefsInfo.defsByPoint[I];
            for (int i = 0; i < varDefsAtStatement.size(); i++) {
              if (isa<Instruction>(varDefsAtStatement[i])) {
                if (L->contains(((Instruction*)varDefsAtStatement[i])->getParent()))  {
                  allOperandsOnlyDefinedOutsideLoop = false;
                  break;
                }
              }
            }

            if (!allOperandsOnlyDefinedOutsideLoop)
              break;
          }

          if (allOperandsOnlyDefinedOutsideLoop)
            loopInvariantStatements.insert(v);
        }
      }
    }
  }

  //Iteratively update invariant statement set until convergence
  //(since invariant will grow monotonically, we detect this simply by seeing if it stops growing)
  bool converged = false;
  int invariantSetSize = loopInvariantStatements.size();
  while (!converged) {
    int prevInvariantSetSize = invariantSetSize;

    //Check through all statements in the loop, adding statement A=B+C+D+... to the invariant set if
    //all operands B,C,... have a single reaching definition at that statement AND those definitions are loop-invariant

    for (std::vector<BasicBlock*>::iterator blockIter = loopBlocks.begin(); blockIter != loopBlocks.end(); ++blockIter) {
      for (BasicBlock::iterator instIter = (*blockIter)->begin(), e = (*blockIter)->end(); instIter != e; ++instIter) {
        Value* v = instIter;

//        errs() << "Considering invariance of: " << valueToDefinitionVarStr(v) << "\n";

        //If already known to be invariant, skip checking again
        if (loopInvariantStatements.find(v) != loopInvariantStatements.end())
          continue;

        if (isa<Instruction>(v)) {
          Instruction* I = static_cast<Instruction*>(v);

          bool mightBeLoopInvariant = (isSafeToSpeculativelyExecute(I) && !I->mayReadFromMemory() && !isa<LandingPadInst>(I));

          if (mightBeLoopInvariant) {
            bool allOperandsHaveSingleLoopInvariantDef = true;

            for (User::op_iterator opIter = I->op_begin(), e = I->op_end(); opIter != e; ++opIter) {
              Value* opVal = *opIter;
              ReachingDefinitionInfo varDefsInfo = reachingDefs[opVal];

              //Check whether operand has single, loop-invariant definition.
              vector<Value*> varDefsAtStatement = varDefsInfo.defsByPoint[I];
              if (varDefsAtStatement.size() != 1 || loopInvariantStatements.count(varDefsAtStatement[0]) == 0) {
                allOperandsHaveSingleLoopInvariantDef = false;
                break;
              }
            }

            if (allOperandsHaveSingleLoopInvariantDef)
              loopInvariantStatements.insert(v);
          }
        }
      }
    }

    invariantSetSize = loopInvariantStatements.size();
    converged = (invariantSetSize == prevInvariantSetSize);
  }

  //DEBUGGING: Print out loop invariant statements
  errs() << "Loop invariant statements: {\n";
  for (std::set<Value*>::iterator liIter = loopInvariantStatements.begin(); liIter != loopInvariantStatements.end(); ++liIter) {
    errs() << valueToStr(*liIter) << "\n";
  }
  errs() << "}\n\n";

  return loopInvariantStatements;
}

set<Value*> LoopInvariantCodeMotion::computeCodeMotionCandidateStatements(Loop* L, DataFlowResult dominanceResults, set<Value*> invari
antStatements) {
  set<Value*> motionCandidates;

  //Candidate statements for LICM must meet the following:
  //1) Must be loop invariant
  //2) Must be in a block that dominates all exits of the loop
  //3) Must be in a block that dominates all blocks in the loop where the definition variable of the statement is used
  //4) Must assign to a variable that has no other assignments in the loop

  std::vector<BasicBlock*> loopBlocks = L->getBlocks();
  SmallPtrSet<BasicBlock*, 32> loopExits = getLoopExits(L);

  for (std::vector<BasicBlock*>::iterator blockIter = loopBlocks.begin(); blockIter != loopBlocks.end(); ++blockIter) {
    for (BasicBlock::iterator instIter = (*blockIter)->begin(), e = (*blockIter)->end(); instIter != e; ++instIter) {
      Instruction* I = instIter;

//      errs() << "Looking at whether to make LICM candidate: " << valueToStr(I) << "\n";

      //Check invariance
      if (invariantStatements.count(I) == 0)
        continue;

      //Check exit dominance
      bool isInExitDominatingBlock = true;
      for (SmallPtrSet<BasicBlock*, 32>::iterator loopExitIter = loopExits.begin(); loopExitIter != loopExits.end(); ++loopExitIter) {
        //If this block doens't dominate this exit, it's not an exit dominating block
        if (!dominates(*blockIter, *loopExitIter, dominanceResults)) {
          isInExitDominatingBlock = false;
          break;
        }
      }
      if (!isInExitDominatingBlock)
        continue;

      //Check whether statement dominates other uses of the assigned variable in the block
      bool dominatesAllUseBlocksInLoop = true;
      Value* assignedVar = getDefinitionVar(I);
      if (assignedVar) {
        for (Value::use_iterator useIter = assignedVar->use_begin(), e = assignedVar->use_end(); useIter != e; ++useIter) {
          if (Instruction* userInstruction = dyn_cast<Instruction>(*useIter)) {
            BasicBlock* userBlock = userInstruction->getParent();
            if (L->contains(userBlock) && !dominates(*blockIter, userBlock, dominanceResults)) {
              dominatesAllUseBlocksInLoop = false;
              break;
            }
          }
        }
      }
      if (!dominatesAllUseBlocksInLoop)
        continue;


      //Check whether assigned variable has any other assignments in loop... not a candidate if so
      bool hasNoOtherAssignmentsInLoop = true;
      if (assignedVar) {
        string assignedVarStr = valueToDefinitionVarStr(assignedVar);
        //Inefficient, but just loop over all instructions again, checking for other assignments to the same var
        for (std::vector<BasicBlock*>::iterator blockIter = loopBlocks.begin(); blockIter != loopBlocks.end(); ++blockIter) {
          for (BasicBlock::iterator otherInstIter = (*blockIter)->begin(), e = (*blockIter)->end(); otherInstIter != e; ++otherInstIte
r) {
            if (otherInstIter != instIter && valueToDefinitionVarStr(otherInstIter) == assignedVarStr) {
              hasNoOtherAssignmentsInLoop = false;
              break;
            }
          }
          if (hasNoOtherAssignmentsInLoop)
            break;
        }
      }
      if (!hasNoOtherAssignmentsInLoop)
```

```
        continue;


      //At this point, we know this statement is a good LICM candidate
      motionCandidates.insert(I);
    }
  }

  return motionCandidates;
}

bool LoopInvariantCodeMotion::applyMotionToCandidates(Loop* L, set<Value*> motionCandidates) {
  bool motionApplied = false;

  BasicBlock* preheader = L->getLoopPreheader();

  set<Instruction*> toMoveSet;

  //Algorithm: Do a DFS over the blocks of the loop and move each candidate to end of preheader if all
  //of its dependencies have also been moved to the preheader

  set<BasicBlock*> visited;

  stack<BasicBlock*> work;
  work.push(*succ_begin(preheader)); //start at loop header... the sole successor of the pre-header
  while (!work.empty()) {
    BasicBlock* block = work.top();
    work.pop();
    visited.insert(block);

    //For each instruction in the block, move to preheader if it’s a code motion candidate and conditions are met
    for (BasicBlock::iterator instIter = block->begin(), e = block->end(); instIter != e; ++instIter) {
      Instruction* I = instIter;

      if (motionCandidates.count(I) > 0) {
        motionApplied = true;
        toMoveSet.insert(I);
      }
    }

    //Add successors to search
    for (succ_iterator successorBlock = succ_begin(block), E = succ_end(block); successorBlock != E; ++successorBlock) {
      if (L->contains(*successorBlock)) {
        if (visited.count(*successorBlock) == 0)
          work.push(*successorBlock);
      }
    }
  }

  //Move all the to-move items now (a bit too tricky to do it while iterating over blocks)
  for (set<Instruction*>::iterator it = toMoveSet.begin(); it != toMoveSet.end(); ++it) {
    Instruction* instructionToMove = *it;

    //Insert as the next-to-last instruction of preheader (last needs to remain the block’s control flow branch)
    Instruction* preheaderEnd = &(preheader->back());

//    errs() << "Preheader end: " << valueToStr(preheaderEnd) << "\n";

    instructionToMove->removeFromParent();
    instructionToMove->insertBefore(preheaderEnd);
  }

  return motionApplied;
}

void LoopInvariantCodeMotion::addLoopIntoQueue(Loop* L) {
  this->LQ.push_back(L);
  for (Loop::reverse_iterator I = L->rbegin(), E = L->rend(); I != E; ++I)
    addLoopIntoQueue(*I);
}

}
```

```
////////////////////////////////////////////////////////////////////////////////
// 15-745 S14 Assignment 3
// Group: bhumbers, psuresh
////////////////////////////////////////////////////////////////////////////////

#ifndef __CLASSICAL_DATAFLOW_DATAFLOW_H__
#define __CLASSICAL_DATAFLOW_DATAFLOW_H__

#include <stdio.h>

#include "llvm/IR/Instructions.h"
#include "llvm/ADT/BitVector.h"
#include "llvm/ADT/DenseMap.h"
#include "llvm/ADT/SmallSet.h"
#include "llvm/ADT/ValueMap.h"
#include "llvm/Support/CFG.h"

#include <vector>
#include <map>

using namespace std;

namespace llvm {

/** Returns the variable that is defined by the given value (argument, instruction, etc.),
* or null if the given value is not a definition */
Value* getDefinitionVar(Value* v);

/** Util to create string representation of given BitVector */
std::string bitVectorToStr(const BitVector& bv);

/** Util to output string representation of an llvm Value */
std::string valueToStr(const Value* value);

/** Returns string representation of a set of domain elements with inclusion indicated by a bit vector
 Each element is output according to the given valFormatFunc function */
std::string setToStr(std::vector<Value*> domain, const BitVector& includedInSet, std::string (*valFormatFunc)(Value*));

/** Returns string version of definition if the Value is in fact a definition, or an empty string otherwise.
 * eg: The defining instruction "%a = add nsw i32 %b, 1" will return exactly that: "%a = add nsw i32 %b, 1"*/
std::string valueToDefinitionStr(Value* v);

/** Returns the name of a defined variable if the given Value is a definition, or an empty string otherwise.
 * eg: The defining instruction "%a = add nsw i32 %b, 1" will return "a"*/
std::string valueToDefinitionVarStr(Value* v);

/** An intermediate transfer function output entry from a block. In addition to the main value,
 * may include a list of predecessor block-specific transfer values which are appended (unioned)
 * onto the main value for the meet operator input of each predecessor (used to handle SSA phi nodes) */
struct TransferResult {
  BitVector baseValue;
  DenseMap<BasicBlock*, BitVector> predSpecificValues;
};

struct DataFlowResultForBlock {
  //Final output
  BitVector in;
  BitVector out;

  //Intermediate results
  TransferResult currTransferResult;

  DataFlowResultForBlock() {}
  DataFlowResultForBlock(BitVector in, BitVector out) {
    this->in = in;
    this->out = out;
    this->currTransferResult.baseValue = out; //tra
  }
};

struct DataFlowResult {
  /** Mapping from domain entries to linear indices into value results from dataflow */
  DenseMap<Value*, int> domainEntryToValueIdx;

  /** Mapping from basic blocks to the IN and OUT value sets for each after analysis converges */
  map<BasicBlock*, DataFlowResultForBlock> resultsByBlock;
};

/** Base interface for running dataflow analysis passes.
 * Must be subclassed with pass-specific logic in order to be used.
*/
class DataFlow {
  public:
    enum Direction {
      FORWARD,
      BACKWARD
    };
    /** Run this dataflow analysis on the given list of blocks using given parameters.*/
    DataFlowResult run(std::vector<llvm::BasicBlock*> blocks,
                       std::vector<Value*> domain,
                       Direction direction,
                       BitVector boundaryCond,
                       BitVector initInteriorCond);

    /** Prints a representation of F to raw_ostream O. */
    void ExampleFunctionPrinter(raw_ostream& O, const Function& F);

    void PrintInstructionOps(raw_ostream& O, const Instruction* I);

  protected:
    /** Meet operator behavior; specific to the subclassing data flow */
    virtual BitVector applyMeet(std::vector<BitVector> meetInputs) = 0;

    /** Transfer function behavior; specific to a subclassing data flow
     * domainEntryToValueIdx provides mapping from domain elements to the linear bitvector index for that element. */
    virtual TransferResult applyTransfer(const BitVector& value, DenseMap<Value*, int> domainEntryToValueIdx, BasicBlock* block) = 0;
};

}

#endif
```

```
////////////////////////////////////////////////////////////////////////////////
// 15-745 S14 Assignment 3
// Group: bhumbers, psuresh
////////////////////////////////////////////////////////////////////////////////

#include <set>
#include <sstream>

#include "dataflow.h"

#include "llvm/Support/raw_ostream.h"

#include "llvm/Support/CFG.h"

namespace llvm {

/* Var definition util */
Value* getDefinitionVar(Value* v) {
  // Definitions are assumed to be one of:
  // 1) Function arguments
  // 2) Store instructions (2nd argument is the variable being (re)defined)
  // 3) Instructions that start with "  %" (note the 2x spaces)
  //      Note that this is a pretty brittle and hacky way to catch what seems the most common definition type in LLVM.
  //      Unfortunately, we couldn't figure a better way to catch all definitions otherwise, as cases like
  //      "%0" and "%1" don't show up  when using "getName()" to identify definition instructions.
  //      There's got to be a better way, though...

  if (isa<Argument>(v)) {
    return v;
  }
  else if (isa<StoreInst>(v)) {
    return ((StoreInst*)v)->getPointerOperand();
  }
  else if (isa<Instruction>(v)){
    std::string str = valueToStr(v);
    const int VAR_NAME_START_IDX = 2;
    if (str.length() > VAR_NAME_START_IDX && str.substr(0,VAR_NAME_START_IDX+1) == "  %")
      return v;
  }
  return 0;
}

/*******************************************************************************************
 * String output utilities */
std::string bitVectorToStr(const BitVector& bv) {
  std::string str(bv.size(), '0');
  for (int i = 0; i < bv.size(); i++)
    str[i] = bv[i] ? '1' : '0';
  return str;
}

std::string valueToStr(const Value* value) {
  std::string instStr; llvm::raw_string_ostream rso(instStr);
  value->print(rso);
  return instStr;
}

const int VAR_NAME_START_IDX = 2;

std::string valueToDefinitionStr(Value* v) {
  //Verify it's a definition first
  Value* def = getDefinitionVar(v);
  if (def == 0)
    return "";

  std::string str = valueToStr(v);
  if (isa<Argument>(v)) {
    return str;
  }
  else {
      str = str.substr(VAR_NAME_START_IDX);
      return str;
  }

  return "";
}

std::string valueToDefinitionVarStr(Value* v) {
  //Similar to valueToDefinitionStr, but we return just the defined var rather than the whole definition

  Value* def = getDefinitionVar(v);
  if (def == 0)
    return "";

  if (isa<Argument>(def) || isa<StoreInst>(def)) {
    return "%" + def->getName().str();
  }
  else {
    std::string str = valueToStr(def);
    int varNameEndIdx = str.find(' ',VAR_NAME_START_IDX);
    str = str.substr(VAR_NAME_START_IDX,varNameEndIdx-VAR_NAME_START_IDX);
    return str;
  }
}

std::string setToStr(std::vector<Value*> domain, const BitVector& includedInSet, std::string (*valFormatFunc)(Value*)) {
  std::stringstream ss;
  ss << "{\n";
  int numInSet = 0;
  for (int i = 0; i < domain.size(); i++) {
    if (includedInSet[i]) {
      if (numInSet > 0) ss << " \n";
      numInSet++;
      ss << "    " << valFormatFunc(domain[i]);
    }
  }
  ss << "}";
  return ss.str();
}

/* End string output utilities *
******************************************************************************************/


DataFlowResult DataFlow::run(std::vector<llvm::BasicBlock*> blocks,
                              std::vector<Value*> domain,
                              Direction direction,
                              BitVector boundaryCond,
                              BitVector initInteriorCond) {
  map<BasicBlock*, DataFlowResultForBlock> resultsByBlock;
  bool analysisConverged = false;

  //Create mapping from domain entries to linear indices
  //(simplifies updating bitvector entries given a particular domain element)
  DenseMap<Value*, int> domainEntryToValueIdx;
  for (int i = 0; i < domain.size(); i++)
    domainEntryToValueIdx[domain[i]] = i;

  std::set<BasicBlock*> blocksSet;
  for (int i = 0; i < blocks.size(); i++) blocksSet.insert(blocks[i]);

  //Set initial val for boundary blocks, which depend on direction of analysis
  std::set<BasicBlock*> boundaryBlocks;
  switch (direction) {
    case FORWARD:
      //Post-"entry" block assumed to be the first one without a predecessor, or whose predecessors aren't in the given blocks list
      for(std::vector<BasicBlock*>::iterator blockIter = blocks.begin(), E = blocks.end(); blockIter != E; ++blockIter) {
        if (pred_begin(*blockIter) == pred_end(*blockIter)) {
          boundaryBlocks.insert(*blockIter);
        }
        else {
         bool predsNotInList = true;
         for (pred_iterator predBlock = pred_begin((*blockIter)), E = pred_end((*blockIter)); predBlock != E; ++predBlock) {
           if (blocksSet.count(*predBlock) > 0) {
            predsNotInList = false;
            break;
           }
         }
         if (predsNotInList)
           boundaryBlocks.insert(*blockIter);
        }
      }
      break;
    case BACKWARD:
      //Pre-"exit" blocks = those that have a return statement
      for(std::vector<BasicBlock*>::iterator blockIter = blocks.begin(), E = blocks.end(); blockIter != E; ++blockIter)
        if (isa<ReturnInst>((*blockIter)->getTerminator()))
          boundaryBlocks.insert((*blockIter));
      break;
  }
  for (std::set<BasicBlock*>::iterator boundaryBlock = boundaryBlocks.begin(); boundaryBlock != boundaryBlocks.end(); boundaryBlock++)
 {
    DataFlowResultForBlock boundaryResult = DataFlowResultForBlock();
    //Set either the "IN" of post-entry blocks or the "OUT" of pre-exit blocks (since entry/exit blocks don't actually exist...)
    BitVector* boundaryVal = (direction == FORWARD) ? &boundaryResult.in : &boundaryResult.out;
    *boundaryVal = boundaryCond;
    boundaryResult.currTransferResult.baseValue = boundaryCond;
    resultsByBlock[*boundaryBlock] = boundaryResult;

//    errs() << "Boundary block init for " << (*boundaryBlock)->getName() << ": IN = " << bitVectorToStr(resultsByBlock[*boundaryBlock
].in)
//        << "; OUT = " << bitVectorToStr(resultsByBlock[*boundaryBlock].out) << "\n";
  }
  //Set initial vals for interior blocks (either OUTs for fwd analysis or INs for bwd analysis)
  //NOTE: Since we don't actually have a dedicated boundary block like ENTRY/EXIT, we include the "boundary"
  //blocks in the initial interior condition setup (otherwise, initial vals for "boundary" blocks is indeterminate)
  for (std::vector<BasicBlock*>::iterator blockIter = blocks.begin(); blockIter != blocks.end(); ++blockIter) {

    DataFlowResultForBlock interiorInitResult;
    if (boundaryBlocks.find((*blockIter)) != boundaryBlocks.end())
      interiorInitResult = resultsByBlock[*blockIter];
    BitVector* interiorInitVal = (direction == FORWARD) ? &interiorInitResult.out : &interiorInitResult.in;
    *interiorInitVal = initInteriorCond;
    interiorInitResult.currTransferResult.baseValue = initInteriorCond;
    resultsByBlock[*blockIter] = interiorInitResult;
//    errs() << "Interior block init for " << (*blockIter)->getName() << ": IN = " << bitVectorToStr(resultsByBlock[*blockIter].in)
//        << "; OUT = " << bitVectorToStr(resultsByBlock[*blockIter].out) << "\n";
  }

  //Generate analysis "predecessor" list for each block (depending on direction of analysis)
  //Note that we only include as predecessors those blocks which are included in the input list
  //Will be used to drive the meet inputs.
  DenseMap<BasicBlock*, std::vector<BasicBlock*> > analysisPredsByBlock;
  for (std::vector<BasicBlock*>::iterator blockIter = blocks.begin(); blockIter != blocks.end(); ++blockIter) {
      std::vector<BasicBlock*> analysisPreds;

//      errs() << "Building predecessor list for : " << (*blockIter)->getName().str() << "\n";

      switch (direction) {
        case FORWARD:
          for (pred_iterator predBlock = pred_begin((*blockIter)), E = pred_end((*blockIter)); predBlock != E; ++predBlock) {
            if (blocksSet.count(*predBlock) > 0)
              analysisPreds.push_back(*predBlock);
          }
          break;
        case BACKWARD:
          for (succ_iterator succBlock = succ_begin((*blockIter)), E = succ_end((*blockIter)); succBlock != E; ++succBlock) {
            if (blocksSet.count(*succBlock) > 0)
              analysisPreds.push_back(*succBlock);
          }
          break;
      }

      analysisPredsByBlock[(*blockIter)] = analysisPreds;
  }

  //Iterate over blocks in function until convergence of output sets for all blocks
  while (!analysisConverged) {
    analysisConverged = true; //assume converged until proven otherwise during this iteration

    //TODO: if analysis is backwards, may want instead to iterate from back-to-front of blocks list

    for (std::vector<BasicBlock*>::iterator blockIter = blocks.begin(); blockIter != blocks.end(); ++blockIter) {
      DataFlowResultForBlock& blockVals = resultsByBlock[*blockIter];

      //Store old output before applying this analysis pass to the block (depends on analysis dir)
      DataFlowResultForBlock oldBlockVals = blockVals;
      BitVector oldPassOut = (direction == FORWARD) ? blockVals.out : blockVals.in;

      //If any analysis predecessors have outputs ready, apply meet operator to generate updated input set for this block
      BitVector* passInPtr = (direction == FORWARD) ? &blockVals.in : &blockVals.out;
      std::vector<BasicBlock*> analysisPreds = analysisPredsByBlock[*blockIter];
      std::vector<BitVector> meetInputs;
      //Iterate over analysis predecessors in order to generate meet inputs for this block
      for (std::vector<BasicBlock*>::iterator analysisPred = analysisPreds.begin(); analysisPred < analysisPreds.end(); ++analysisPred
) {
        DataFlowResultForBlock& predVals = resultsByBlock[*analysisPred];

        BitVector meetInput = predVals.currTransferResult.baseValue;

        //If this pred matches a predecessor-specific value for the current block, union that value into value set
        DenseMap<BasicBlock*, BitVector>::iterator predSpecificValueEntry = predVals.currTransferResult.predSpecificValues.find(*block
Iter);
        if (predSpecificValueEntry != predVals.currTransferResult.predSpecificValues.end()) {
//            errs() << "Pred-specific meet input from " << (*analysisPred)->getName() << ": " <<bitVectorToStr(predSpecificValueEntry
->second) << "\n";
            meetInput |= predSpecificValueEntry->second;
        }

        meetInputs.push_back(meetInput);
      }
//      errs() << "Meeting inputs for block: " << (*blockIter)->getName() << "\n";
      if (!meetInputs.empty())
        *passInPtr = applyMeet(meetInputs);

      //Apply transfer function to input set in order to get output set for this iteration
      blockVals.currTransferResult = applyTransfer(*passInPtr, domainEntryToValueIdx, *blockIter);
      BitVector* passOutPtr = (direction == FORWARD) ? &blockVals.out : &blockVals.in;
      *passOutPtr = blockVals.currTransferResult.baseValue;
      //Update convergence: if the output set for this block has changed, then we’ve not converged for this iteration
      if (analysisConverged) {
        if (*passOutPtr != oldPassOut)
          analysisConverged = false;
        else if (blockVals.currTransferResult.predSpecificValues.size() != oldBlockVals.currTransferResult.predSpecificValues.size())
          analysisConverged = false;
        //(should really check whether contents of pred-specific values changed as well, but
        // that doesn’t happen when the pred-specific values are just a result of phi-nodes)
      }
    }
  }

  DataFlowResult result;
  result.domainEntryToValueIdx = domainEntryToValueIdx;
  result.resultsByBlock = resultsByBlock;
  return result;
}

void DataFlow::PrintInstructionOps(raw_ostream& O, const Instruction* I) {
  O << "\nOps: {";
  if (I != NULL) {
    for (Instruction::const_op_iterator OI = I->op_begin(), OE = I->op_end();
        OI != OE; ++OI) {
      const Value* v = OI->get();
      v->print(O);
      O << ";";
    }
  }
  O << "}\n";
}

void DataFlow::ExampleFunctionPrinter(raw_ostream& O, const Function& F) {
  for (Function::const_iterator FI = F.begin(), FE = F.end(); FI != FE; ++FI) {
    const BasicBlock* block = FI;
    O << block->getName() << ":\n";
    const Value* blockValue = block;
    PrintInstructionOps(O, NULL);
    for (BasicBlock::const_iterator BI = block->begin(), BE = block->end();
        BI != BE; ++BI) {
      BI->print(O);
      PrintInstructionOps(O, &(*BI));
    }
  }
}

}
```

```
////////////////////////////////////////////////////////////////////////////////
// 15-745 S14 Assignment 3
// Group: bhumbers, psuresh
////////////////////////////////////////////////////////////////////////////////

#ifndef __CLASSICAL_DATAFLOW_REACHING_DEFS_H__
#define __CLASSICAL_DATAFLOW_REACHING_DEFS_H__

#include "llvm/IR/Function.h"
#include "llvm/Pass.h"
#include "llvm/Support/raw_ostream.h"
#include "llvm/Support/InstIterator.h"

#include "dataflow.h"

#include <map>

using namespace llvm;
using namespace std;

namespace llvm {

struct ReachingDefinitionInfo {
  //The variable for which the definitions apply
  Value* variable;

  //Mapping from program points (just above instruction key) to definitions that reach that point (values) for this variable
  map<Instruction*, vector<Value*> > defsByPoint;

  ReachingDefinitionInfo() {
    variable = 0;
  }
};

/** A modified version of our reaching definitions function from A2 which
 * now returns a mapping from variables to reaching definitions.
 * Includes fixes for more correct handling of definitions both with and without SSA form. */
class ReachingDefinitions {

 public:

  /** For the given function, returns lookup to reaching definitions for each variable*/
  map<Value*, ReachingDefinitionInfo> computeReachingDefinitions(Function& F);
};

}

#endif
```

```
////////////////////////////////////////////////////////////////////////////////
// 15-745 S14 Assignment 3
// Group: bhumbers, psuresh
////////////////////////////////////////////////////////////////////////////////

#include "reaching-defs.h"

namespace llvm {

//////////////////////////////////////////////////////////////////////////////////////////////
//Dataflow analysis
class ReachingDefinitionsDataFlow : public DataFlow {

  protected:
    BitVector applyMeet(std::vector<BitVector> meetInputs) {
      BitVector meetResult;

      //Meet op = union of inputs
      if (!meetInputs.empty()) {
        for (int i = 0; i < meetInputs.size(); i++) {
//          if (i > 0) errs() << ", ";
//          errs() << bitVectorToStr(meetInputs[i]);
          if (i == 0)
            meetResult = meetInputs[i];
          else
            meetResult |= meetInputs[i];
        }
      }
//      errs() << "\n";

      return meetResult;
    }

    TransferResult applyTransfer(const BitVector& value, DenseMap<Value*, int> domainEntryToValueIdx, BasicBlock* block) {
      TransferResult transfer;

//      errs() << "Applying transfer for block: " << block->getName() << "\n";
//      errs() << "Pre: " << bitVectorToStr(value) << "\n";

      //First, calculate the set of downwards exposed definition generations and the set of killed definitions in this block
      int domainSize = domainEntryToValueIdx.size();
      BitVector genSet(domainSize);
      BitVector killSet(domainSize);
      for (BasicBlock::iterator instruction = block->begin(); instruction != block->end(); ++instruction) {
        DenseMap<Value*, int>::const_iterator currDefIter = domainEntryToValueIdx.find(&*instruction);
        if (currDefIter != domainEntryToValueIdx.end()) {
          //Kill prior definitions for the same variable (including those in this block’s gen set)
          for (DenseMap<Value*, int>::const_iterator prevDefIter = domainEntryToValueIdx.begin();
               prevDefIter != domainEntryToValueIdx.end();
               ++prevDefIter) {
            std::string prevDefStr = valueToDefinitionVarStr(prevDefIter->first);
            std::string currDefStr = valueToDefinitionVarStr(currDefIter->first);
            if (prevDefStr == currDefStr) {
              killSet.set(prevDefIter->second);
              genSet.reset(prevDefIter->second);
            }
          }

          //Add this new definition to gen set (note that we might later remove it if another def in this block kills it)
          genSet.set((*currDefIter).second);
        }
      }

      //Then, apply transfer function: Y = GenSet \union (X - KillSet)
      transfer.baseValue = killSet;
      transfer.baseValue.flip();
      transfer.baseValue &= value;
      transfer.baseValue |= genSet;

//      errs() << "Post: " << bitVectorToStr(transfer.baseValue) << "\n";

      return transfer;
    }
};
//////////////////////////////////////////////////////////////////////////////////////////////

map<Value*, ReachingDefinitionInfo> ReachingDefinitions::computeReachingDefinitions(Function& F) {
  map<Value*, ReachingDefinitionInfo> reachingDefs;

  //NOTE: Unfortunately, we don’t have enought time to handle SSA aliasing correctly

  //Set domain = definitions in the function
  std::vector<Value*> domain;
  for (Function::arg_iterator arg = F.arg_begin(); arg != F.arg_end(); ++arg)
    domain.push_back(arg);
  for (inst_iterator instruction = inst_begin(F), e = inst_end(F); instruction != e; ++instruction) {
    //If instruction is nonempty when converted to a definition string, then it’s a definition and belongs in our domain
    if (!valueToDefinitionStr(&*instruction).empty())
      domain.push_back(&*instruction);
  }

  //Initialize keys for reaching definition lookup (consists of the defined variables in our domain(
  for (int i = 0; i < domain.size(); i++) {
    Value* definedVar = getDefinitionVar(domain[i]);
    reachingDefs[definedVar] = ReachingDefinitionInfo();
  }

  int numVars = domain.size();

  //Set the initial boundary dataflow value to be the set of input argument definitions for this function
  BitVector boundaryCond(numVars, false);
  for (int i = 0; i < domain.size(); i++)
    if (isa<Argument>(domain[i]))
      boundaryCond.set(i);

  //Set interior initial dataflow values to be empty sets
  BitVector initInteriorCond(numVars, false);

  //Get dataflow values at IN and OUT points of each block
  ReachingDefinitionsDataFlow flow;
  vector<BasicBlock*> blocks;
  for (Function::iterator blockIter = F.begin(); blockIter != F.end(); ++blockIter)
    blocks.push_back(blockIter);
  DataFlowResult dataFlowResult = flow.run(blocks, domain, DataFlow::FORWARD, boundaryCond, initInteriorCond);

  //Then, extend those values into the interior points of each block, outputting the result along the way
//  errs() << "\n****************** REACHING DEFINITIONS OUTPUT FOR FUNCTION: " << F.getName() << " *****************\n";
//  errs() << "Domain of values: " << setToStr(domain, BitVector(domain.size(), true), valueToDefinitionStr) << "\n";
//  errs() << "Variables: "   << setToStr(domain, BitVector(domain.size(), true), valueToDefinitionVarStr) << "\n";

  //Print function header (in hacky way... look for "definition" keyword in full printed function, then print rest of that line only)
  std::string funcStr = valueToStr(&F);
  int funcHeaderStartIdx = funcStr.find("define");
  int funcHeaderEndIdx = funcStr.find('{', funcHeaderStartIdx + 1);
//  errs() << funcStr.substr(funcHeaderStartIdx, funcHeaderEndIdx-funcHeaderStartIdx) << "\n";

  //Now, use dataflow results to output reaching definitions at program points within each block
  for (Function::iterator basicBlock = F.begin(); basicBlock != F.end(); ++basicBlock) {
    DataFlowResultForBlock blockReachingDefVals = dataFlowResult.resultsByBlock[basicBlock];

    //Print just the header line of the block (in a hacky way... blocks start w/ newline, so look for first occurrence of newline beyo
nd first char
    std::string basicBlockStr = valueToStr(basicBlock);
//    errs() << basicBlockStr.substr(0, basicBlockStr.find(':', 1) + 1) << "\n";

    //Initialize reaching definitions at the start of the block
    BitVector reachingDefVals = blockReachingDefVals.in;

    std::vector<std::string> blockOutputLines;

    //Output reaching definitions at the IN point of this block (not strictly needed, but useful to see)
    blockOutputLines.push_back("\nReaching Defs: " + setToStr(domain, reachingDefVals, valueToDefinitionStr) + "\n");

    //Iterate forward through instructions of the block, updating and outputting reaching defs
    for (BasicBlock::iterator instruction = basicBlock->begin(); instruction != basicBlock->end(); ++instruction) {
      //In the output data, mark all the reaching defs just before this instruction
      for (int i = 0; i < domain.size(); i++) {
        if (reachingDefVals[i]) {
          Value* definition = domain[i];
          Value* definedVar = getDefinitionVar(definition);
          ReachingDefinitionInfo& defsInfoForVar = reachingDefs[definedVar];
          if (defsInfoForVar.defsByPoint.find(instruction) == defsInfoForVar.defsByPoint.end())
            defsInfoForVar.defsByPoint[instruction] = vector<Value*>();
          defsInfoForVar.defsByPoint[instruction].push_back(definition);
        }
      }

      //REACHING DEF UPDATE FOR INSTRUCTION
      {
        DenseMap<Value*, int>::const_iterator defIter;

        std::string currDefStr = valueToDefinitionVarStr(instruction);

        //Kill (unset) all existing defs for this variable
        //(is there a better way to do this than string comparison of the defined var names?)
        for (defIter = dataFlowResult.domainEntryToValueIdx.begin(); defIter != dataFlowResult.domainEntryToValueIdx.end(); ++defIter)
 {
          std::string prevDefStr = valueToDefinitionVarStr(defIter->first);
          if (prevDefStr == currDefStr)
            reachingDefVals.reset(defIter->second);
        }

        //Add this definition to the reaching set
        defIter = dataFlowResult.domainEntryToValueIdx.find(&*instruction);
        if (defIter != dataFlowResult.domainEntryToValueIdx.end())
          reachingDefVals.set((*defIter).second);
      }

      //Add debugging output lines for the reaching defs
      {
        //Output the instruction contents
        blockOutputLines.push_back(valueToStr(&*instruction));

        //Output the set of reaching definitions at program point just past instruction
        //(but only if not a phi node... those aren't "real" instructions)
        if (!isa<PHINode>(instruction)) {
          blockOutputLines.push_back("\nReaching Defs: " + setToStr(domain, reachingDefVals, valueToDefinitionStr) + "\n");
        }
      }
    }

    //CONSOLE OUTPUT (for debugging)
//    for (std::vector<std::string>::iterator i = blockOutputLines.begin(); i < blockOutputLines.end(); ++i)
//      errs() << *i << "\n";
  }
//  errs() << "****************** END REACHING DEFINITION OUTPUT FOR FUNCTION: " << F.getName() << " ******************\n\n";

  return reachingDefs;
}

}
```

```c
int main(void)
{
  int x = 5;
  int r = 10;
  for (int i = 0; i < 42*x; i++) {
    int y = 5;
    r += y;
  }
  return 0;
};
```

```
; ModuleID = 'basic_main.bc'
target datalayout = "e-p:64:64:64-i1:8:8-i8:8:8-i16:16:16-i32:32:32-i64:64:64-f32:32:32-f64:64:64-v64:64:64-v128:128:128-a0:0:64-s0:64
:64-f80:128:128-n8:16:32:64-S128"
target triple = "x86_64-unknown-linux-gnu"

; Function Attrs: nounwind uwtable
define i32 @main() #0 {
entry:
  br label %for.cond

for.cond:                                         ; preds = %for.inc, %entry
  %r.0 = phi i32 [ 10, %entry ], [ %add, %for.inc ]
  %i.0 = phi i32 [ 0, %entry ], [ %inc, %for.inc ]
  %mul = mul nsw i32 42, 5
  %cmp = icmp slt i32 %i.0, %mul
  br i1 %cmp, label %for.body, label %for.end

for.body:                                         ; preds = %for.cond
  %add = add nsw i32 %r.0, 5
  br label %for.inc

for.inc:                                          ; preds = %for.body
  %inc = add nsw i32 %i.0, 1
  br label %for.cond

for.end:                                          ; preds = %for.cond
  ret i32 0
}

attributes #0 = { nounwind uwtable "less-precise-fpmad"="false" "no-frame-pointer-elim"="true" "no-frame-pointer-elim-non-leaf" "no-in
fs-fp-math"="false" "no-nans-fp-math"="false" "stack-protector-buffer-size"="8" "unsafe-fp-math"="false" "use-soft-float"="false" }

!llvm.ident = !{!0}

!0 = metadata !{metadata !"clang version 3.4 (tags/RELEASE_34/final)"}
```

```
; ModuleID = 'basic_main-opt.bc'
target datalayout = "e-p:64:64:64-i1:8:8-i8:8:8-i16:16:16-i32:32:32-i64:64:64-f32:32:32-f64:64:64-v64:64:64-v128:128:128-a0:0:64-s0:64
:64-f80:128:128-n8:16:32:64-S128"
target triple = "x86_64-unknown-linux-gnu"

; Function Attrs: nounwind uwtable
define i32 @main() #0 {
entry:
  %mul = mul nsw i32 42, 5
  br label %for.cond

for.cond:                                         ; preds = %for.inc, %entry
  %r.0 = phi i32 [ 10, %entry ], [ %add, %for.inc ]
  %i.0 = phi i32 [ 0, %entry ], [ %inc, %for.inc ]
  %cmp = icmp slt i32 %i.0, %mul
  br i1 %cmp, label %for.body, label %for.end

for.body:                                         ; preds = %for.cond
  %add = add nsw i32 %r.0, 5
  br label %for.inc

for.inc:                                          ; preds = %for.body
  %inc = add nsw i32 %i.0, 1
  br label %for.cond

for.end:                                          ; preds = %for.cond
  ret i32 0
}

attributes #0 = { nounwind uwtable "less-precise-fpmad"="false" "no-frame-pointer-elim"="true" "no-frame-pointer-elim-non-leaf" "no-in
fs-fp-math"="false" "no-nans-fp-math"="false" "stack-protector-buffer-size"="8" "unsafe-fp-math"="false" "use-soft-float"="false" }

!llvm.ident = !{!0}

!0 = metadata !{metadata !"clang version 3.4 (tags/RELEASE_34/final)"}
```

```c
////////////////////////////////////////////////////////////////////////////////
// 15-745 S14 Assignment 3
// Group: bhumbers, psuresh
////////////////////////////////////////////////////////////////////////////////

//Tests LICM for nested loops

int main(void)
{
  int x = 5;
  int y = 1;
  int r = 10;
  for (int i = 0; i < 2*x; i++) {
    for (int j = 0; j < 12345*y; j++) {
      r += y;
    }
  }
  return r;
};
```

```
; ModuleID = 'nested_main.bc'
target datalayout = "e-p:64:64:64-i1:8:8-i8:8:8-i16:16:16-i32:32:32-i64:64:64-f32:32:32-f64:64:64-v64:64:64-v128:128:128-a0:0:64-s0:64
:64-f80:128:128-n8:16:32:64-S128"
target triple = "x86_64-unknown-linux-gnu"

; Function Attrs: nounwind uwtable
define i32 @main() #0 {
entry:
  br label %for.cond

for.cond:                                         ; preds = %for.inc5, %entry
  %r.0 = phi i32 [ 10, %entry ], [ %r.1, %for.inc5 ]
  %i.0 = phi i32 [ 0, %entry ], [ %inc6, %for.inc5 ]
  %mul = mul nsw i32 2, 5
  %cmp = icmp slt i32 %i.0, %mul
  br i1 %cmp, label %for.body, label %for.end7

for.body:                                         ; preds = %for.cond
  br label %for.cond1

for.cond1:                                        ; preds = %for.inc, %for.body
  %r.1 = phi i32 [ %r.0, %for.body ], [ %add, %for.inc ]
  %j.0 = phi i32 [ 0, %for.body ], [ %inc, %for.inc ]
  %mul2 = mul nsw i32 12345, 1
  %cmp3 = icmp slt i32 %j.0, %mul2
  br i1 %cmp3, label %for.body4, label %for.end

for.body4:                                        ; preds = %for.cond1
  %add = add nsw i32 %r.1, 1
  br label %for.inc

for.inc:                                          ; preds = %for.body4
  %inc = add nsw i32 %j.0, 1
  br label %for.cond1

for.end:                                          ; preds = %for.cond1
  br label %for.inc5

for.inc5:                                         ; preds = %for.end
  %inc6 = add nsw i32 %i.0, 1
  br label %for.cond

for.end7:                                         ; preds = %for.cond
  ret i32 %r.0
}

attributes #0 = { nounwind uwtable "less-precise-fpmad"="false" "no-frame-pointer-elim"="true" "no-frame-pointer-elim-non-leaf" "no-in
fs-fp-math"="false" "no-nans-fp-math"="false" "stack-protector-buffer-size"="8" "unsafe-fp-math"="false" "use-soft-float"="false" }

!llvm.ident = !{!0}

!0 = metadata !{metadata !"clang version 3.4 (tags/RELEASE_34/final)"}
```

```
; ModuleID = 'nested_main-opt.bc'
target datalayout = "e-p:64:64:64-i1:8:8-i8:8:8-i16:16:16-i32:32:32-i64:64:64-f32:32:32-f64:64:64-v64:64:64-v128:128:128-a0:0:64-s0:64
:64-f80:128:128-n8:16:32:64-S128"
target triple = "x86_64-unknown-linux-gnu"

; Function Attrs: nounwind uwtable
define i32 @main() #0 {
entry:
  %mul = mul nsw i32 2, 5
  br label %for.cond

for.cond:                                         ; preds = %for.inc5, %entry
  %r.0 = phi i32 [ 10, %entry ], [ %r.1, %for.inc5 ]
  %i.0 = phi i32 [ 0, %entry ], [ %inc6, %for.inc5 ]
  %cmp = icmp slt i32 %i.0, %mul
  br i1 %cmp, label %for.body, label %for.end7

for.body:                                         ; preds = %for.cond
  %mul2 = mul nsw i32 12345, 1
  br label %for.cond1

for.cond1:                                        ; preds = %for.inc, %for.body
  %r.1 = phi i32 [ %r.0, %for.body ], [ %add, %for.inc ]
  %j.0 = phi i32 [ 0, %for.body ], [ %inc, %for.inc ]
  %cmp3 = icmp slt i32 %j.0, %mul2
  br i1 %cmp3, label %for.body4, label %for.end

for.body4:                                        ; preds = %for.cond1
  %add = add nsw i32 %r.1, 1
  br label %for.inc

for.inc:                                          ; preds = %for.body4
  %inc = add nsw i32 %j.0, 1
  br label %for.cond1

for.end:                                          ; preds = %for.cond1
  br label %for.inc5

for.inc5:                                         ; preds = %for.end
  %inc6 = add nsw i32 %i.0, 1
  br label %for.cond

for.end7:                                         ; preds = %for.cond
  ret i32 %r.0
}

attributes #0 = { nounwind uwtable "less-precise-fpmad"="false" "no-frame-pointer-elim"="true" "no-frame-pointer-elim-non-leaf" "no-in
fs-fp-math"="false" "no-nans-fp-math"="false" "stack-protector-buffer-size"="8" "unsafe-fp-math"="false" "use-soft-float"="false" }

!llvm.ident = !{!0}

!0 = metadata !{metadata !"clang version 3.4 (tags/RELEASE_34/final)"}
```

```
////////////////////////////////////////////////////////////////////////////////
// 15-745 S14 Assignment 3
// Group: bhumbers, psuresh
////////////////////////////////////////////////////////////////////////////////

//Tests LICM for doubly nested loops

int main(void)
{
  int x = 5;
  int y = 1;
  int r = 10;
  for (int i = 0; i < 2*x; i++) {
    for (int j = 0; j < 12345*y; j++) {
      for (int k = 0; k < 5; k++) {
        int a = 5;
        r += a + y;
      }
    }
  }
  return r;
};
```

```
; ModuleID = 'double_nested_main.bc'
target datalayout = "e-p:64:64:64-i1:8:8-i8:8:8-i16:16:16-i32:32:32-i64:64:64-f32:32:32-f64:64:64-v64:64:64-v128:128:128-a0:0:64-s0:64
:64-f80:128:128-n8:16:32:64-S128"
target triple = "x86_64-unknown-linux-gnu"

; Function Attrs: nounwind uwtable
define i32 @main() #0 {
entry:
  br label %for.cond

for.cond:                                         ; preds = %for.inc12, %entry
  %r.0 = phi i32 [ 10, %entry ], [ %r.1, %for.inc12 ]
  %i.0 = phi i32 [ 0, %entry ], [ %inc13, %for.inc12 ]
  %mul = mul nsw i32 2, 5
  %cmp = icmp slt i32 %i.0, %mul
  br i1 %cmp, label %for.body, label %for.end14

for.body:                                         ; preds = %for.cond
  br label %for.cond1

for.cond1:                                        ; preds = %for.inc9, %for.body
  %r.1 = phi i32 [ %r.0, %for.body ], [ %r.2, %for.inc9 ]
  %j.0 = phi i32 [ 0, %for.body ], [ %inc10, %for.inc9 ]
  %mul2 = mul nsw i32 12345, 1
  %cmp3 = icmp slt i32 %j.0, %mul2
  br i1 %cmp3, label %for.body4, label %for.end11

for.body4:                                        ; preds = %for.cond1
  br label %for.cond5

for.cond5:                                        ; preds = %for.inc, %for.body4
  %r.2 = phi i32 [ %r.1, %for.body4 ], [ %add8, %for.inc ]
  %k.0 = phi i32 [ 0, %for.body4 ], [ %inc, %for.inc ]
  %cmp6 = icmp slt i32 %k.0, 5
  br i1 %cmp6, label %for.body7, label %for.end

for.body7:                                        ; preds = %for.cond5
  %add = add nsw i32 5, 1
  %add8 = add nsw i32 %r.2, %add
  br label %for.inc

for.inc:                                          ; preds = %for.body7
  %inc = add nsw i32 %k.0, 1
  br label %for.cond5

for.end:                                          ; preds = %for.cond5
  br label %for.inc9

for.inc9:                                         ; preds = %for.end
  %inc10 = add nsw i32 %j.0, 1
  br label %for.cond1

for.end11:                                        ; preds = %for.cond1
  br label %for.inc12

for.inc12:                                        ; preds = %for.end11
  %inc13 = add nsw i32 %i.0, 1
  br label %for.cond

for.end14:                                        ; preds = %for.cond
  ret i32 %r.0
}

attributes #0 = { nounwind uwtable "less-precise-fpmad"="false" "no-frame-pointer-elim"="true" "no-frame-pointer-elim-non-leaf" "no-in
fs-fp-math"="false" "no-nans-fp-math"="false" "stack-protector-buffer-size"="8" "unsafe-fp-math"="false" "use-soft-float"="false" }

!llvm.ident = !{!0}

!0 = metadata !{metadata !"clang version 3.4 (tags/RELEASE_34/final)"}
```

```
; ModuleID = 'double_nested_main-opt.bc'
target datalayout = "e-p:64:64:64-i1:8:8-i8:8:8-i16:16:16-i32:32:32-i64:64:64-f32:32:32-f64:64:64-v64:64:64-v128:128:128-a0:0:64-s0:64
:64-f80:128:128-n8:16:32:64-S128"
target triple = "x86_64-unknown-linux-gnu"

; Function Attrs: nounwind uwtable
define i32 @main() #0 {
entry:
  %mul = mul nsw i32 2, 5
  br label %for.cond

for.cond:                                         ; preds = %for.inc12, %entry
  %r.0 = phi i32 [ 10, %entry ], [ %r.1, %for.inc12 ]
  %i.0 = phi i32 [ 0, %entry ], [ %inc13, %for.inc12 ]
  %cmp = icmp slt i32 %i.0, %mul
  br i1 %cmp, label %for.body, label %for.end14

for.body:                                         ; preds = %for.cond
  %mul2 = mul nsw i32 12345, 1
  br label %for.cond1

for.cond1:                                        ; preds = %for.inc9, %for.body
  %r.1 = phi i32 [ %r.0, %for.body ], [ %r.2, %for.inc9 ]
  %j.0 = phi i32 [ 0, %for.body ], [ %inc10, %for.inc9 ]
  %cmp3 = icmp slt i32 %j.0, %mul2
  br i1 %cmp3, label %for.body4, label %for.end11

for.body4:                                        ; preds = %for.cond1
  br label %for.cond5

for.cond5:                                        ; preds = %for.inc, %for.body4
  %r.2 = phi i32 [ %r.1, %for.body4 ], [ %add8, %for.inc ]
  %k.0 = phi i32 [ 0, %for.body4 ], [ %inc, %for.inc ]
  %cmp6 = icmp slt i32 %k.0, 5
  br i1 %cmp6, label %for.body7, label %for.end

for.body7:                                        ; preds = %for.cond5
  %add = add nsw i32 5, 1
  %add8 = add nsw i32 %r.2, %add
  br label %for.inc

for.inc:                                          ; preds = %for.body7
  %inc = add nsw i32 %k.0, 1
  br label %for.cond5

for.end:                                          ; preds = %for.cond5
  br label %for.inc9

for.inc9:                                         ; preds = %for.end
  %inc10 = add nsw i32 %j.0, 1
  br label %for.cond1

for.end11:                                        ; preds = %for.cond1
  br label %for.inc12

for.inc12:                                        ; preds = %for.end11
  %inc13 = add nsw i32 %i.0, 1
  br label %for.cond

for.end14:                                        ; preds = %for.cond
  ret i32 %r.0
}

attributes #0 = { nounwind uwtable "less-precise-fpmad"="false" "no-frame-pointer-elim"="true" "no-frame-pointer-elim-non-leaf" "no-in
fs-fp-math"="false" "no-nans-fp-math"="false" "stack-protector-buffer-size"="8" "unsafe-fp-math"="false" "use-soft-float"="false" }

!llvm.ident = !{!0}

!0 = metadata !{metadata !"clang version 3.4 (tags/RELEASE_34/final)"}
```