

CS 745, Spring 2011
Homework Assignment 2
Assigned: Thursday, January 27
Due: Thursday, February 10, 9:00AM

Introduction

In class, we discussed many interesting data flow analyses like Liveness, Reaching Definitions, and Available Expressions. Although these analyses are different in certain ways, for example they compute different program properties and analyze the program in different directions (forwards, backwards), they share some common properties such as iterative algorithms, transfer functions, and meet operators (Slide 23 in Lecture notes 4). These commonalities make it worthwhile to write a generic framework that can be parameterized appropriately for solving a specific data flow analysis. In this assignment, you and your partner will implement such an iterative data flow analysis framework in LLVM, and use it to implement a forward data flow analysis (Reaching Definitions) and a backward data flow analysis (Liveness). Although Liveness and Reaching Definitions implementations are available in some form in LLVM, they are not of the iterative flavor, and the objective of this assignment is to create a generic framework for solving iterative bit-vector dataflow analysis problems, and use it to implement Liveness and Reaching Definitions analysis.

Policy

You will work in groups of two people to solve the problems for this assignment. Turn in a single writeup per group, indicating all group members.

Logistics

Any clarifications and revisions to the assignment will be posted on the “assignments” page on the class web page.

In the following, *HOMEDIR* refers to the directory:

```
/afs/cs.cmu.edu/academic/class/15745-s11/public
```

and *ASSTDIR* refers to the subdirectory *HOMEDIR/asst/asst2*.

1 Iterative Data Flow Analysis Framework

A well written iterative data flow analysis framework significantly reduces the burden of implementing new data flow passes, the developer only writes pass specific details such as the meet operator, transfer function, analysis direction e.t.c. In particular, the framework should solve any unidirectional data flow analysis as long the analysis supplies the following:

1. Domain including the semi-lattice

2. Direction (forwards or backwards)
3. Transfer function
4. Meet operation
5. Boundary condition
6. Initial interior points

To simplify the design process, the domain of values should be represented as bit vectors so that the semi-lattice and set operations (union, intersection) are easy to implement. Careful thought should be given to how the analysis parameters are represented. For example, *direction* could reasonably be represented as a boolean, while function pointers may seem more appropriate for representing transfer functions.

2 Data Flow Analyses

You will now use your iterative data flow analysis framework to implement Liveness and Reaching Definitions. As explained below in more details, each analysis should perform computation at program points. As defined in class, program points are assumed to lie *between* instructions (not in the middle of instructions).

Liveness On convergence, your Liveness pass should report all variables that are “live” at each program point. A useful debugging strategy might be to use results of the LLVM Liveness pass as a reference.

Reaching Definitions On convergence, your Reaching Definitions pass should report all the definition sites that “reach” each program point.

```

define i32 @sum(i32 %a, i32 %b) nounwind readnone ssp {
entry:
    %0 = icmp slt i32 %a, %b
    br i1 %0, label %bb.nph, label %bb2

bb.nph: ; preds = %entry
    %tmp = sub i32 %b, %a
    br label %bb

bb:     ; preds = %bb, %bb.nph
    %indvar = phi i32 [ 0, %bb.nph ], [ %indvar.next, %bb ]
    %res.05 = phi i32 [ 1, %bb.nph ], [ %1, %bb ]
    %i.04 = add i32 %indvar, %a
    %1 = mul nsw i32 %res.05, %i.04
    %indvar.next = add i32 %indvar, 1
    %exitcond = icmp eq i32 %indvar.next, %tmp
    br i1 %exitcond, label %bb2, label %bb

int sum (int a, int b)
{
    int i;
    int res = 1;

    for (i = a; i < b; i++)
    {
        res *= i;
    }
    return res;
}

```

(a) (b)

Figure 1: (a) Simple loop code, and (b) corresponding optimized (-O) LLVM bytecode.

2.1 Implementation Issues¹

The Single Static Assignment (SSA) form of LLVM intermediate representation presents some unique challenges when performing iterative data flow analysis.

1. Values in LLVM are represented by the Value class. In SSA every value is guaranteed to have only a single definition point point, so instead of representing values as some distinct variable or pseudo register class, LLVM represents values defined by instructions by the *defining instruction*. That is, Instruction is a subclass of Value. There are other subclasses of Value, such as basic blocks, constants, and function arguments. For this assignment, we will only track the liveness of instruction-defined values and function arguments. That is, when determining what values are used by an instruction, you will use code like this:

```

User::op_iterator OI, OE;
for (OI = insn->op_begin(), OE = insn->op_end(); OI != OE; ++OI)
{
    Value *val = *OI;
    if (isa<Instruction>(val) || isa<Argument>(val)) {
        // val is used by insn
    }
}

```

2. ϕ instructions are pseudo instructions that are used in the SSA representation and need to be handled specially by both Liveness and Reaching Definitions. Although SSA will be covered in more details in class, a brief description is appropriate here, especially with regards to ϕ instructions. Since SSA requires that values have a unique definition at any

¹Based on earlier editions of the class. Credits to Seth Goldtein and David Koes.

```

define i32 @sum(i32 %a, i32 %b) nounwind readnone ssp {
entry:
    {%a,%b}
    %0 = icmp slt i32 %a, %b
    {%a,%b,%0}
    br i1 %0, label %bb.nph, label %bb2
    bb.nph: ; preds = %entry
    {%a,%b}
    %tmp = sub i32 %b, %a
    {%a,%tmp}
    br label %bb
    bb: ; preds = %bb, %bb.nph
    %indvar = phi i32 [ 0, %bb.nph ], [ %indvar.next, %bb ]
    %res.05 = phi i32 [ 1, %bb.nph ], [ %1, %bb ]
    {%a,%tmp,%indvar,%res.05}
    %i.04 = add i32 %indvar, %a
    {%a,%tmp,%indvar,%res.05,%i.04}
    %1 = mul nsw i32 %res.05, %i.04
    {%a,%tmp,%indvar,%1}
    %indvar.next = add i32 %indvar, 1
    {%a,%tmp,%1,%indvar.next}
    %exitcond = icmp eq i32 %indvar.next, %tmp
    {%a,%tmp,%1,%indvar.next,%exitcond}
    br i1 %exitcond, label %bb2, label %bb
    bb2: ; preds = %bb, %entry
    %res.0.lcssa = phi i32 [ 1, %entry ], [ %1, %bb ]
    {%res.0}
    ret i32 %res.0.lcssa
}

```

Figure 2: Output of Liveness on the bytecode in Figure 1(b).

program program point (P), it is natural to wonder how a value that is live at P, but has different definitions on the paths leading to is handled. The SSA solution is to introduce ϕ instructions at the beginning of the basic block containing P, to “combine” all the different definitions, so that all the uses in the block (including at P), see only the definition by the *phi* instruction. Consider the uses of ϕ (*phi*) instructions in Figure 1(b) as illustrations. You should carefully consider how your analysis passes are affected by ϕ instructions. For example, your passes should not output results for the program point preceding a *phi* instruction since they are pseudo instructions which will not appear in the executable. To guide you in formatting the output of your passes, the expected output of running Liveness analysis on the bytecode from Figure 1(b) is shown in Figure 2.

3 Hand In

Electronic submission:

- The source code for your framework and passes, the associated Makefiles, and a README describing how to build and run them. Do this by creating a tar file with the last name of at least one of your group members in the filename, and copying this tar file into the directory

ASSTDIR/handin

Include as comments near the beginning of your source files the identities of all members of your group. Also remember to do a good job of commenting your code.

Hard-copy submission:

1. A report that briefly describes the design and implementation of your framework and passes. In particular, describe the interface of your framework clearly, so that someone else (e.g the grader) could write a pass that will work with it.
2. A listing of your source code.