Project 2 Report

June 11, 2014

1 Overview

> Discuss the high level goals of your work, along with any interesting/key findings.

Our objective was to understand and experience the issues that arise when actually implementing program analyses. To this end, we constructed a dataflow analysis framework based on the LLVM compiler infastructure.

We confirmed through experience that SSA makes flow functions *much* easier to write. We found that the most helpful part of the LLVM API is the object hierarchy for dealing with the graph of Value objects representing LLVM IR. Subclasses of Value are rich, representing functions, basic blocks, instructions, constants, etc. These IR object classes provide many useful convienence functions and make it easy to traverse the program. The least helpful parts of the LLVM API is the pass manager and the special LLVM replacement for C++ run-time type information; these features are obscure and difficult to use.

The most surprising feature of LLVM was the InstVisitor template class. This class made our implementation much easier and cleaner than it would have been otherwise, but examples in the introductory documentation do not use it. For something so helpful to LLVM newcomers, InstVisitor is poorly advertised in the LLVM documentation.

Though the analyses were relatively straightforward in terms of flow functions, the technical hurdles of actually making them work were nontrivial, and we learned a great deal. This project provided a solid foundation of practical experience for building programming-language tools based on LLVM. We document our implementation efforts in the following pages, beginning with the overall design for the dataflow analysis framework.

2 Interface Design

> Describe interface. Discuss what alternative designs you may have also considered, and explain the tradeoffs that ultimately led to your choice.

Our interface

Unsure how honest to be here. Tradeoffs ended up being, how many C++ features can we avoid and still have a functioning C++ program? Other than this issue, describing our interface (flowfunction object, latticepoint object, and a blob of code implementing the worklist algorithm that uses runtime polymorphism to use these objects) is pretty straightforward. I (marco) can write this.

3 Analyses

3.1 Constant Propagation

3.1.1 Mathematical Flow Functions

> define your lattice and flow functions in mathematical notation (i.e., in the style used in the lecture notes and on the midterm).

3.1.2 Implementation Considerations

> discuss how you actually went about implementing the lattice and flow functions. For instance, some interesting questions are: what data structure(s) did you use, and how do you represent potentially infinite sets? How are input facts passed to your flow functions, and how do output facts get propagated?

3.2 Available Expressions

3.2.1 Mathematical Flow Functions

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3.2.2 Implementation Considerations

discuss how you actually went about implementing the lattice and flow functions. For instance, some interesting questions are: what data structure(s) did you use, and how do you represent potentially infinite sets? How are input facts passed to your flow functions, and how do output facts get propagated?

3.3 Range Analysis

3.3.1 Mathematical Flow Functions

Unlike the previous two analyses, range analysis is a 'may' analysis. Thus the most conservative range for a variable is the full set and the most optimistic is the empty set. With these considerations in mind, let us define our lattice and flow functions. The domain of the analysis is the set of maps from variables to the set of ranges specified by the extended integers (i.e. allowing $+\infty$ and $-\infty$). Thus,

$$D = \text{Vars} \to \mathbb{Z}^{\infty} \times \mathbb{Z}^{\infty}.$$

For $A \in D$ and $x \in \text{Vars}$, we will interchangeably think of $A(x) = [a, b]$ as a range (i.e. a set of numbers) and a tuple (a pair of numbers). With this reasoning, let top will correspond to the constant map of full sets, i.e. for any variable $x \in \text{Vars}$,

$$\top(x) = [-\infty, \infty].$$

Similarly, bottom corresponds to the constant map of empty sets, i.e. for any variable $x \in \text{Vars}$,

$$\bot(x) = [\infty, -\infty].$$

Here we take the convention that $[a, b] = \emptyset$ if and only if $b < a$. Given two elements of our domain, $A, B \in D$, we write $A \sqsubseteq B$ if and only if $A(x) \subseteq B(x)$ for all $x \in \text{Vars}$. We can also say for any $x \in \text{Vars}$,

$$A \sqcup B(x) = [\min\{\underline{A(x)}, \underline{B(x)}\}, \max\{\overline{A(x)}, \overline{B(x)}\}]$$

and

$$A \sqcap B(x) = [\max\{\underline{A(x)}, \underline{B(x)}\}, \min\{\overline{A(x)}, \overline{B(x)}\}]$$

where we take the convention that $\overline{[a, b]} = b$ and $\underline{[a, b]} = a$. Now that the lattice has been defined, let's turn our attention to the various flow functions. To make the analysis more concrete, given an element $A \in D$ and variable x, let $A[x \to [a', b']]$ denote the exact same element of D with the exception that $A(x) = [a', b']$. Now we enumerate the various flow functions.

$$F_{X:=C}(in) = in[X \to [C, C]]$$

$$F_{X:=Y\,\mathrm{op}\,Z}(in) = in[X \to [\min L, \max L]] \text{ where } L = \{a \text{ op } b \,|\, a \in in(Y) \wedge b \in in(Z)\}$$

$$F_{if(X \leq C) \text{ true-branch}}(in) = in[X \to [-\infty, C] \cap in(X)]$$

$$F_{if(X \leq C) \text{ false-branch}}(in) = in[X \to [C+1, \infty] \cap in(X)]$$

$$F_{if(X == C) \text{ true-branch}}(in) = in[X \to [C, C] \cap in(X)]$$

$$F_{if(X == C) \text{ false-branch}}(in) = in$$

$$F_{if(X < C) \text{ true-branch}}(in) = in[X \to [-\infty, C-1] \cap in(X)]$$

$$F_{if(X < C) \text{ false-branch}}(in) = in[X \to [C, \infty] \cap in(X)]$$

$$F_{if(X \geq C) \text{ true-branch}}(in) = F_{if(X < C) \text{ false-branch}}(in)$$

$$F_{if(X \geq C) \text{ false-branch}}(in) = F_{if(X < C) \text{ true-branch}}(in)$$

$$F_{if(X > C) \text{ true-branch}}(in) = F_{if(X \leq C) \text{ false-branch}}(in)$$

$$F_{if(X > C) \text{ false-branch}}(in) = F_{if(X \leq C) \text{ true-branch}}(in)$$

3.3.2 Implementation Considerations

> discuss how you actually went about implementing the lattice and flow functions. For instance, some interesting questions are: what data structure(s) did you use, and how do you represent potentially infinite sets? How are input facts passed to your flow functions, and how do output facts get propagated?

LLVM has a nice data structure for handling ranges called ConstantRange. This is a one-side inclusive interval $[a, b)$ that is meant to be taken as intersection with the integers. ConstantRange even has some convenience functions that make computing some of the above flow functions more bearable.

As with the above analyses, we explicitly specify whether or not a lattice point is top or bottom with boolean variables, and we use algebraic identities when working with these special cases. For the rest of the cases, a range analysis lattice point is represented by a map from LLVM Value pointers to ConstantRange pointers. Since this is an optimistic 'may' analysis, we use the convention that variables that are not in our map have the empty range.

3.4 Intra-Procedural Pointer Analysis

3.4.1 Mathematical Flow Functions

> define your lattice and flow functions in mathematical notation (i.e., in the style used in the lecture notes and on the midterm).

3.4.2 Implementation Considerations

> discuss how you actually went about implementing the lattice and flow functions. For instance, some interesting questions are: what data structure(s) did you use, and how do you represent potentially infinite sets? How are input facts passed to your flow functions, and how do output facts get propagated?

4 Testing

> Make sure to explain assumptions you make about the code you analyze. For instance, for pointer analysis, you may have made some assumptions about the aliasing information known about input parameters. Explain those assumptions and why they are reasonable.
>
> Part of this project is to come up with a useful set of benchmarks on which to test and improve your analysis. Discuss why you chose those benchmarks, and what makes them interesting. If your implementation fails on some benchmarks (there's no shame in it!), then explain why and how the analysis might be improved.

4.1 Benchmarks/Assumptions in Common

Because we have a common pool of benchmarks, we can list them here along with common assumptions on code. More specialized discussion of per-analysis benchmark goes below. Here, we can also introduce the Straight Line Program/Branching Program distinction.

4.2 Constant Propagation

4.3 Available Expressions

4.4 Range Analysis

4.5 Intra-Procedural Pointer Analysis

5 Conclusion/Challenges

> As this project is significantly more exploratory than the first, we want you to tell us what you found particularly interesting/challenging/frustrating. What extensions to the project did you attempt? (for instance, did you try combining the results of analyses, or did you try your hand at interprocedural analysis?). What aspects of LLVM made it easy/hard to implement your design? If you could redo your project with what you know now, what changes would you make?

Also unsure how honest to be here. Most of our challenges had to do with counter-intuitive LLVM design and poor documentation, as well as the unpredictability of C++ features.