Lab 0: Introduction to LLVM

Summer Semester 2023

Due: 22 May, 8:00 a.m. Eastern Time

Objective

This lab involves running and extending LLVM, a popular compiler framework for a large class of programming languages that will be used to implement many labs in this course. You will use the LLVM framework in the provided course VM and implement an LLVM pass that will perform simple analytics on an input program. Specifically, your pass will compute the number of functions, instructions and signed division instructions in the input C program. There is an LLVM primer under files > resources on Canvas for more details on the LLVM framework.

Resources

Some past students have requested that we produce a lesson specifically on LLVM. Instead, we are offering you several resources that come from people closely connected to the LLVM project.

- Introduction to LLVM talk from 2019 LLVM Developers' Meeting (1:01:19)
- Introduction to LLVM Program Analysis (1:21:07)
- Basic Overview of LLVM components (20:27)

Setup

The LLVM framework is pre-installed on the course VM and the skeleton code for Lab 0 can be found in Canvas. Navigate to `Assignments` on the left hand module, click on `Lab 0`, and download the `llvmintro.zip` file. Transfer this file to the VM, and unzip it in the VM home directory. This will create a folder in the `~` directory called `llvmintro`.

We will refer to this top-level directory for Lab 0 simply as `llvmintro` when describing file locations for the lab.

Throughout the LLVM labs, we will use `CMake`, a modern tool for managing the build process. If you are unfamiliar with `CMake`, you are strongly advised to read the CMake tutorial first (please pay attention to Step 1 and Step 2 in the tutorial link). Running `cmake` produces a Makefile that you might be more familiar with. If not, read the Makefile tutorial before proceeding further. Once a Makefile is generated, you need only run `make` to rebuild your project after editing the source files.

The following commands set up the lab:

```
$ cd ~/llvmintro
$ mkdir build
$ cd build
$ cmake ..
$ make
```

Among the files generated, you should now see `PrereqPass.so` in the current directory. `PrereqPass.so` is a shared object file built from `llvmintro/src/Prereqs.cpp` which is the source file you will modify in this lab and submit as a deliverable.

You will implement the functionality of this lab as an LLVM pass called `PrereqPass`. LLVM passes are subprocesses of the LLVM framework. They usually perform transformations, optimizations, or analyses on programs. Each pass operates on an intermediate representation of the input program called the LLVM IR. So, to exercise this lab on an input C program, we must first compile the program's source code to LLVM IR:

```
$ cd ~/llvmintro/test
$ clang -emit-llvm -S -fno-discard-value-names -c simple0.c
```

`clang` is a C language compiler that uses LLVM and serves as a drop-in replacement for the `gcc` compiler. If you know how to use gcc, you should be fine with clang. Otherwise, scan the user manual to familiarize yourself with some of clang's command-line options. Briefly, `-S` instructs clang to perform preprocessing and compilation steps only, `-emit-llvm` instructs the compiler to generate LLVM IR (which will be saved to `simple0.ll`), and `-fno-discard-value-names` preserves names of values in the generated LLVM to improve readability.

`opt` is a tool from LLVM that performs analyses and optimizations on LLVM IR. We will use `opt` to run our custom LLVM pass on the compiled C code:

```
$ opt -load ~/llvmintro/build/PrereqPass.so -Prereqs -disable-output \
~/llvmintro/test/simple0.ll
```

The option `-load` loads our LLVM pass library while `-Prereqs` instructs opt to run the pass on `simple0.ll`. (Libraries can and often do contain multiple LLVM passes.) Consult the documentation for opt to understand the potential ways to use the tool; it may help you build and debug your solutions.

You should see the following output from the above command:

```
Analytics of Module llvmintro/test/simple0.ll
  # Functions    : 0
  # Instructions : 0
  # Signed Division Instructions : 0
```

After implementing your pass logic in `Prereqs.cpp`, these numbers will reflect the actual counts of various properties of the C program under analysis; for now, the output only shows the default integer values provided to you as boilerplate.

Lab Instructions

We have provided a pass skeleton for you to modify; in particular, you will need to edit the `runOnModule` function in the pass file (`llvmintro/src/Prereqs.cpp`) so that it correctly prints the number of functions, instructions and signed division instructions for an input C program compiled to LLVM IR.

LLVM IR Primer. Consider the following example of an LLVM IR instruction:

```
%1 = add i32 %2, 4
```

This instruction performs the add operation on 32-bit integers (`i32`). It adds the number in register 2 (`%2`) and the constant number 4 and places its result in register 1 (`%1`).

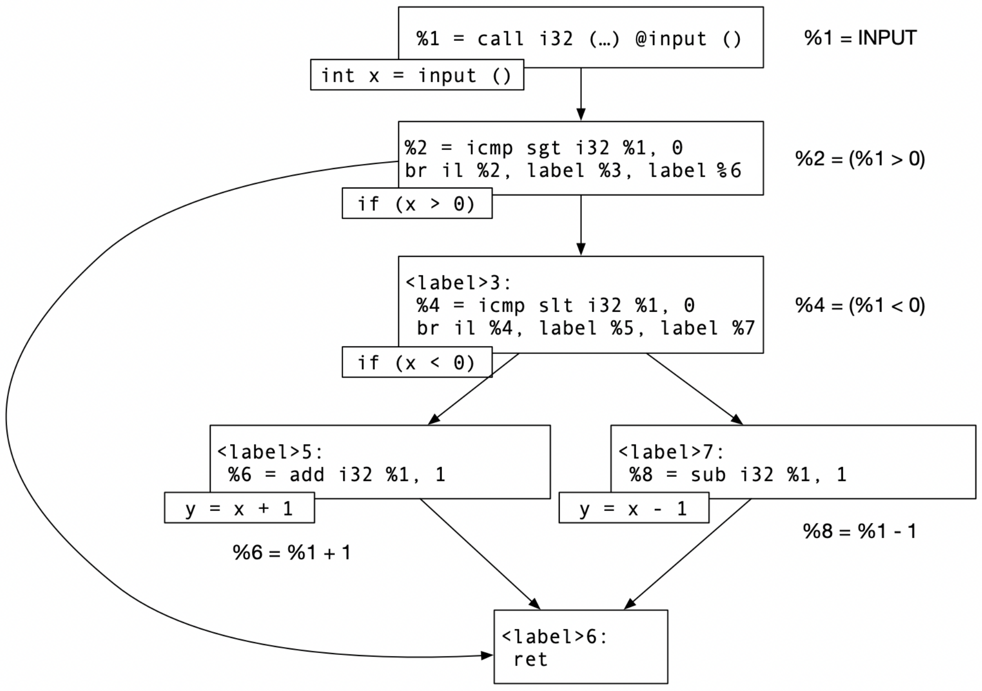
Now, consider a more complicated example. We show the LLVM IR of the code highlighted in green in the right column.

```
int x = input();
if (x > 0) {
  if (x < 0) {
    int y = x + 1;
  } else {
    int y = x - 1;
  }
}
```

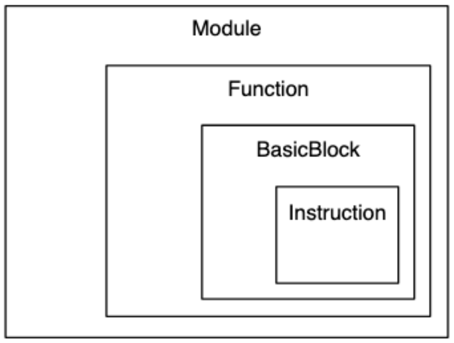
```
I1: %1 = call i32 (...) @input()
I2: %2 = icmp sgt i32 %1, 0
I3: br i1 %2, label %3, label %6
```

In `I1`, variable `%1` refers to the integer value from the user input. In `I2`, the return value of icmp (integer comparison) is stored to a temporary variable `%2`. Lastly, in `I3`, the program execution jumps to either label `%3` or `%6` depending on the value of `%2`.

The following figure shows the control-flow graph of the full LLVM IR code for our preceding example. In it, we show the LLVM IR for each basic block.



You will learn how to utilize many classes in the LLVM API throughout the labs in this course. Some of the more general ones that you will frequently use are `Module`, `Function`, `BasicBlock`, and `Instruction`. You should get in the habit of scanning some of the LLVM class documentation, as each contains many useful methods that you might find helpful in implementing some of the labs. We recommend following the LLVM coding standards for code (names of variables, types, classes, etc.); at the very least, you should consult the relevant section, but the standard serves as a good programming guideline.



Now, returning to the task at hand, think of the `runOnModule` function as the main entry point to your compiler pass. Inside a `Module`, you can find all program `Functions`. In LLVM, a function consists of one or more `BasicBlocks` that contain `Instructions`. The hierarchy is summarized in the figure.

Traversing over these program elements is common when working with LLVM and you should expect to get familiar with various traversal techniques.

The recommended approach is to break down the lab into the following tasks:

1. Find the count of the functions in the `Module &M` object and update the `NumOfFunctions` integer to match your result.
2. For each `Function`, count the number of instructions it contains and update the `NumOfInstructions` variable accordingly. This variable represents the total instruction count for all `Function`s in the module.
3. For each `Function`, count the number of signed division instructions it contains and update the `NumOfSDivInstructions` variable accordingly. This variable represents the total number of signed division instructions for all `Function`s in the module. The only class to compare an instruction's opcode against in computing this count is `LLVM::SDivOperator`. Do not include unsigned integer division, float division, modulus and any other operator other than `LLVM::SDivOperator` in this count.

Note that there are multiple ways to accomplish the above counting tasks. As long as your code compiles on the course VM and produces correct results, you may employ any function or construct provided by LLVM to achieve it.

LLVM Pass Structure. In `Prereqs.h`, you will notice some additional code:

```
char Prereqs::ID = 1;
static RegisterPass<Prereqs> X("Prereqs", "Prereqs", false, false);
```

The code hooks our `Prereqs` class into the LLVM framework so we can use it via the `opt` command. We register our `Prereqs` pass via `RegisterPass<Prereqs>`, and instruct LLVM to identify it on the command line as "Prereqs" with the arguments to `X`. It will be helpful to familiarize yourself with the basic code to set up a new LLVM pass.

Example Input and Output

Your pass should run on any C program that compiles to LLVM IR. As we demonstrated in the Setup section, we will compile some C programs to LLVM IR and then run your pass on them using `opt`:

```
$ opt -load ~/llvmintro/build/PrereqPass.so -Prereqs -disable-output \
~/llvmintro/test/simple0.ll
```

If completed correctly, you should see the analysis output for the provided `simple0.c` test case as follows:

```
Analytics of Module llvmintro/test/simple0.ll
  # Functions    : 1
  # Instructions : 22
  # Signed Division Instructions : 1
```

You can look at the C code for `simple0.c` to verify that these counts match your expectations. Writing additional test cases is a good way to ensure your counting approach is robust to different programs.

Please Note: It is important that you preserve the formatting of the above result output in your submitted code by using the provided `print_module_info` function. Deductions may be applied to your score if the grading script is unable to parse the standard output from your pass.

Items to Submit

For this lab, we will be using Gradescope to submit and grade your assignment. For full credit, the files must be properly named and there must not be any subfolders or additional files or folders. Submit the following files through Gradescope.

- Submit your modified version of `Prereqs.cpp`

Do not submit anything else. Make sure all of your code modifications are in the files listed above as your other files will not be submitted. In particular, past students have modified header files to import additional headers, leading to a compile error in their submission.

Through Gradescope, you will have immediate feedback from the autograder as to whether the submission was structured correctly as well as verification that your code successfully runs the public tests on the grading machine. The public tests are the same tests provided to you as part of the lab, but these tests won't (and are not intended to) catch everything. You will get your final score after the assignment due date.

Grading Rubric

The grader will run your counting pass on IR generated for four C programs:

- `simple0.c`: a test case provided to you with the lab. 20% of grade.

- `simple1.c`: a hidden test case which is of similar complexity to `simple0.c`. 20% of grade.
- `complex0.c`: a hidden test case which involves an additional function. 30% of grade.
- `complex1.c`: a handful of arbitrary functions and instructions. 30% of grade.

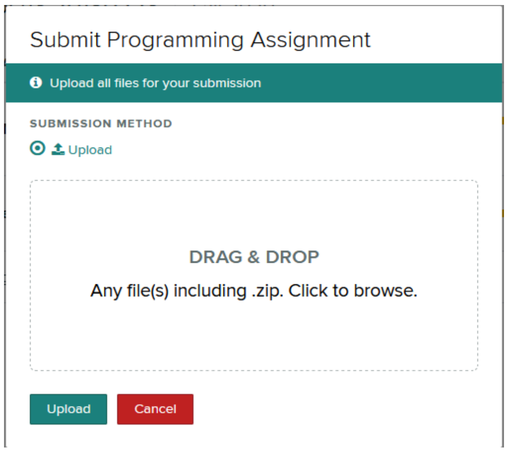
Each test case is graded on an all-or-nothing basis, meaning your counts must match the expected counts exactly to receive credit for that test.

How Do We Use It?

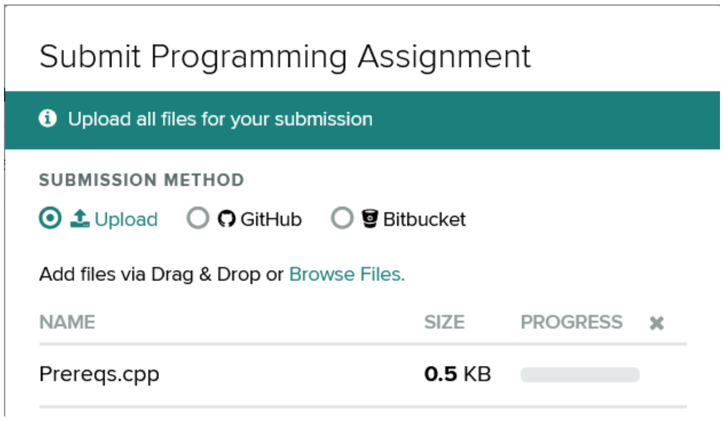
LLVM is a powerful compiler framework used by many industry leaders such as Apple, Adobe, Cray, Electronic Arts, Intel, NVIDIA, and Sony. Most of the labs in this class use LLVM. Typically, you will be directly writing LLVM code. In others, you will not interact with LLVM, but the tool you will use was built on top of it. Since LLVM is one of the leading compiler toolchains today and it is open source, with a robust set of tools for users to write their own analyses, it is the primary system we will use to explore software analysis through labs. While this lab does not on the surface seem that useful, completing it means you have successfully written an analysis pass using LLVM. This foundation will enable you to do more interesting analyses in future labs.

Tips for submitting your assignment with Gradescope

- When you go to the Canvas Assignment, you will see a blank Gradescope submission window embedded in the Canvas Page. Follow the on-screen prompt to submit your files.


Submit Programming Assignment
Upload all files for your submission
SUBMISSION METHOD
Upload
DRAG & DROP
Any file(s) including .zip. Click to browse.
Upload
Cancel

- If there are multiple files in this lab, you can zip the files together and upload the single zip file to the submittal page, or you may select each file individually on the page. If you select the files individually, they must all be uploaded in the same submission.
- A correct submission should look like this image (ignoring size and order):


Submit Programming Assignment
Upload all files for your submission
SUBMISSION METHOD
Upload
GitHub
Bitbucket
Add files via Drag & Drop or Browse Files.

NAME	SIZE	PROGRESS
Prereqs.cpp	0.5 KB	

- You may resubmit your assignment as many times as you want up to the assignment due date. The **Active** submission will be the final grade. By default, every time you upload a new submission, it will become the **Active** submission, but you can change the **Active** submission in your **Submission History** window if needed.
- If you resubmit your assignment, you must include all files as part of the new submissions.
- We provide comments as output of your submission. Use these to make sure your submission is as complete as possible. For example, if you see a compile error, you will not receive any points for that part of the assignment.