Lab 1: Fuzzing

Spring Semester 2020

Due: 27 January, at 8:00 a.m. Eastern Time

Corresponding Lesson: Lesson 3 (Random Testing)

Objective

In Part 1 you will implement a simple tool to automatically check for divide-by-zero errors in C programs at runtime. You will create an LLVM pass that will instrument C code with additional instructions that will perform runtime checks, thus creating a *sanitizer*, a form of lightweight dynamic analysis. In the spirit of automated testing, your tool will provide a code coverage mechanism that will show the actual instructions that execute when a program runs.

In Part 2 you will implement a fuzzer that will create random inputs to automatically test simple programs. As we discussed in the lesson, we hope to get lucky and cause the input program to crash on some randomly generated data. You will see how this specialized form of *mutation analysis* can perform well enough to encourage developers to use this technique to help test their software.

[Extra Credit] In Part 3 you will extend your fuzzer from Part 2 to make more interesting choices about the kinds of input it generates to test a program. The fuzzer will use output from previous rounds of test as *feedback* to *direct* future test generation. You will use the code coverage metrics implemented in Part 1 to help select more interesting seed cases for your fuzzer to mutate.

Resources

- Enumerating basic blocks and instructions in a function:
  - http://releases.llvm.org/8.0.0/docs/ProgrammersManual.html#basic-inspection-and-traversal-routines
- Instrumenting LLVM IR
  - http://releases.llvm.org/8.0.0/docs/ProgrammersManual.html#creating-and-inserting-new-instructions
- Important classes
  - http://releases.llvm.org/8.0.0/docs/ProgrammersManual.html#the-function-class
  - https://llvm.org/doxygen/classllvm_1_1CallInst.html
  - https://llvm.org/doxygen/classllvm_1_1DebugLoc.html
- Fuzzing

    - https://www.fuzzingbook.org/html/Fuzzer.html
- Code Coverage
    - https://www.fuzzingbook.org/html/Coverage.html#Comparing-Coverage

Setup

Download fuzzing.zip from Canvas and unzip in the home directory on the VM (note: there is an extraneous fuzzing directory on the VM already - you can delete or ignore the contents). This will create a fuzzing directory with part1, part2, and part3 subdirectories.

Part 1 - Simple Dynamic Analysis

Setup

The skeleton code is located under `/fuzzing/part1/`. We will refer to the top level directory for Part 1 as `part1` when describing file locations.

Run the following commands to setup this part:

```
$ cd part1
$ mkdir build
$ cd build
$ cmake ..
$ make
```

You should see several files created in the current directory. Among other files, this builds an LLVM pass from code that we provide, `part1/src/Instrument.cpp`, named `InstrumentPass.so`, and an auxiliary runtime library, named `libruntime.so` that contains functionality to help you complete the lab.

Note each time you update `Instrument.cpp` you will need to rerun the make command in the build directory before testing.

Next, let's run our dummy `Instrument` pass over some C code that contains a divide-by-zero error:

```
$ cd part1/test
$ clang -emit-llvm -S -fno-discard-value-names -c -o simple0.ll simple0.c -g
$ opt -load ../build/InstrumentPass.so -Instrument -S simple0.ll -o
simple0.instrumented.ll
$ clang -o simple0 ../lib/runtime.c simple0.instrumented.ll
```

```
$ ./simple0
```

If you've done everything correctly up to this point, you should see `Floating point exception (core dumped)`. For the lab, you will complete the `Instrument` pass to catch this error at runtime.

Format of Input Programs

All C programs are valid input programs.

Lab Instructions

In this lab, you will implement a dynamic analysis tool that catches divide-by-zero errors at runtime. A key component of dynamic analysis is that we inspect a *running* program for information about its state and behavior. We will use an LLVM pass to insert runtime checking and monitoring code into an existing program. In this lab, our instrumentation will perform divide-by-zero error checking, and record coverage information for a running program. In the following part of the lab, we will introduce an automated testing framework using our dynamic analysis.

Instrumentation and Code Coverage Primer. Consider the following code snippet where we have two potential divide-by-zero errors, one at Line 1, the other at Line 2.

```
int main() {
  int x1 = input();
  int y = 13 / x1;   // Line 1
  int x2 = input();
  int z = 21 / x2;   // Line 2
  return 0;
}
```

If we wanted to program a bit more defensively, we would manually insert checks before these divisions, and print out an error if the divisor is 0:

```
int main() {
  int x1 = input();
  if (x1 == 0) { printf("Detected divide-by-zero error!"); exit(1); }
  int y = 13 / x1;
  int x2 = input();
  if (x2 == 0) { printf("Detected divide-by-zero error!"); exit(1); }
  int z = 21 / x2;
  return 0;
```

```
}
```

Of course, there is nothing stopping us from encapsulating this repeated check into some function, call it `__dbz_sanitizer__`, for reuse.

```
void __dbz_sanitizer__(int divisor) {
  if (divisor == 0) {
    printf("Detected divide-by-zero error!");
    exit(1);
  }
}
int main() {
  int x1 = input();
  __dbz_sanitizer__(x1);
  int y = 13 / x1;
  __dbz_sanitizer__(x2);
  int x2 = input();
  int z = 21 / x2;
  return 0;
}
```

We have transformed our unsafe version of the code in the first example to a safe one by instrumenting all division instructions with some code that performs a divisor check. In this lab, you will automate this process at the LLVM IR level using an LLVM compiler pass.

Debug Location Primer. When you compile C code with the `-g` option, LLVM will include debug information for LLVM IR instructions. Using the aforementioned instrumentation techniques, your LLVM pass can gather this debug information for an `Instruction`, and forward it to `__dbz_sanitizer__` to report the location a divide-by-zero error occurs. We will discuss the specifics of this interface in the following sections.

Instrumentation Pass. We have provided a framework from which to build your LLVM instrumentation pass. You will need to edit the `part1/src/Instrument.cpp` file to implement your divide-by-zero sanitizer, as well as the code coverage analysis `part1/lib/runtime.c` contains functions that you will use in your lab:

- `void __dbz_sanitizer__(int divisor, int line, int col)`
    - Output an error for `line:col` if `divisor` is 0
- `void __coverage__(int line, int col)`
    - Append coverage information for `line:col` in a file for the current executing process

As you will create a runtime sanitizer, your dynamic analysis pass should instrument the code with these functions. In particular, you will modify the `runOnFunction` method in `Instrument.cpp` to perform this instrumentation for all LLVM instructions encountered inside a function.

Note that our `runOnFunction` method returns true whereas the previous LLVM pass entry points into in Lab 0 return false. As we are instrumenting the input code with additional functionality, we return true to indicate that the pass modifies, or *transforms* the source code it traverses over.

In short, part 1 consists of the following tasks:

1. Implement the `instrumentSanitizer` function to insert a `__dbz_sanitizer__` check for a supplied `Instruction`
2. Modify `runOnFunction` to instrument all division instructions with the sanitizer for a block of code
3. Implement the `instrumentCoverage` function to insert `__coverage__` checks for all debug locations
4. Modify `runOnFunction` to instrument all instructions with the coverage check

Inserting Instructions into LLVM code. By now you are familiar with the `BasicBlock` and `Instruction` classes and working with LLVM instructions in general. For this lab you will need to use the LLVM API to insert additional instructions into the code when traversing a `BasicBlock`. There are manys ways to traverse programs in LLVM. One common pattern when working with LLVM is to create a new instruction and insert it directly after some previous instruction.

For example, in the following code snippet:

```
Instruction* Pi = ...;
auto *NewInst = new Instruction(..., Pi);
```

A new instruction (`NewInst`) will get created and implicitly inserted after `Pi`; you need not do anything further with `NewInst`. Other subclasses of Instruction have similar methods for this - consider looking at `llvm::CallInst::Create`.

Loading C functions into LLVM. We have provided the auxiliary functions `__dbz__sanitizer` and `__coverage__` for you, but you have to insert them into the code as LLVM `Instructions`.

You can load a function into the `Module` with `Module::getOrInsertFunction`. `getOrInsertFunction` requires a string reference to a function to load, and a `FunctionType` that matches the function type of the actual function to be load (you will have to construct these items). It's up to you to take the loaded `Function` and invoke it with an LLVM `instruction`.

Debug Locations. As we alluded to in the primer, LLVM will store code location information of the *original C program* for LLVM instructions when compiled with `-g`. This is done through the DebugLoc class:

```
Instruction* I1 = …;
DebugLoc &Debug = I1->getDebugLoc();
printf("Line No: %d\n", Debug.getLine());
```

You will need to gather and forward this information to the sanitizer functions. As a final hint, not every *single* LLVM instruction corresponds to a specific line in its source C code. You will have to check which instructions have debug information. Use this to help build the code coverage metric instrumentation.

Example Input and Output

Your sanitizer should run on any C code that compiles to LLVM IR. For each test program, you will need to run the following the following command substituting your program name for `simple0`. (Note: there is also a Makefile provided for you that will run the commands for all the programs at once by executing the "make" command)

```
$ cd part1/test
$ clang -emit-llvm -S -fno-discard-value-names -c -o simple0.ll simple0.c -g
```

As we demonstrated in the Setup section, we will create an instrumented executable using your LLVM compiler pass. To test a different program, replace `simple0` with your program name.

```
$ opt -load ../build/InstrumentPass.so -Instrument -S simple0.ll -o
simple0.instrumented.ll
$ clang -o simple0 ../lib/runtime.c simple0.instrumented.ll
$ ./simple0
```

If there is a divide by zero error in the code, your code should output the following (recall the print statement is already set up in `/lib/runtime.c` - the line and column number will come from your code).

```
Divide-by-zero detected at line 4 and col 13
```

Code coverage information should be printed out in a file named `EXE.cov` where `EXE` is the name of the executable that is run (in the above case, look for `simple0.cov`.) Our auxiliary functions will handle the creation of the file; your instrumented code should populate it with line:col information:

```
2,7
2,7
3,7
3,11
3,7
4,7
4,11
4,15
```

Part 2 - Mutational Fuzzing

Setup

The skeleton code for Part 2 is located under `/fuzzing/part2`. We will refer to the top level directory for Part 2 as `part2` when describing file locations.

This lab builds off the work you did in Part 1. Copy InstrumentPass.so from `/fuzzing/part1/build` to `part2/reference`.

```
$ cp ~/fuzzing/part1/build/InstrumentPass.so ~/fuzzing/part2/reference
```

The following commands setup the lab:

```
$ cd part2
$ mkdir build
$ cd build
$ cmake ..
$ make
```

This time we will use the `fuzzer` tool to feed randomized input (that you will create) into compiled C programs that will run with your sanitizer from Part 1:

```
$ cd part2/test
$ make
$ mkdir fuzz_output
$ timeout 1 ../build/fuzzer ./sanity fuzz_input fuzz_output MutationA
```

In the above command, `sanity` will receive randomized input from `fuzzer` starting from an initial seed file at `part2/test/fuzz_input/seed.txt` located in `fuzz_input`. Cases that cause a program crash will get stored in `part2/test/fuzz_output/failure`. Note that since we can theoretically generate random input forever, we wrap the fuzzer in a `timeout` that will stop program execution after a specified interval. In the above case, we run for 1 second.

Format of Input Programs

All C programs that read from stdin are valid input programs.

Lab Instructions

In this lab, we will build a small fuzzer that feeds a C program random input to try and cause it to crash. A full-fledged fuzzer consists of three key features: i) test case generation matching the grammar of the program input, ii) mutation strategies on test input to increase code coverage, iii) a feedback mechanism to help drive the types of mutation used. We will focus on the first two features in this lab, and restrict the testable C programs to those that read strings from the command line. In the next part, we will focus on the third feature.

Mutation-Fuzzing Primer. Consider the following code that reads some string input from the command line:

```
int main() {
  char input[65536];
  fgets(input, sizeof(input), stdin);
  int x = 13;
  int z = 21;

  if (strlen(input) % 13 == 0) {
    z = x / 0;
  }

  if (strlen(input) > 100 && input[25] == 'a') {
    z = x / 0;
  }

  return 0;
}
```

We have two very obvious cases that cause divide-by-zero errors in in the program: (1) if the length of the program input is divisible by 13, and (2) if the length of the input is greater than 100 and the 25th character in the string is an '`a`'. Now, let's imagine that this program is a black box, and we can only search for errors by running the code with different input.

We would likely try a random string, say "`abcdef`", which would give us a successful run. From there, we could take our first string as a starting point and add some new characters, "`ghi`", giving us "`abcdefghi`". Here we have *mutated* our original input string to generate a new test case. We might repeat this process, finally stumbling on "`abcdefghijklm`" which is divisible by 13 and causes the program crash.

How about the second case? We could keep inserting characters onto the end of our string, which would eventually get us some large string that satisfies the first condition of the if statement (input length greater than 100), but we need to perform an additional type of mutation - randomly changing characters in the string - to eventually satisfy the second condition in the if statement.

Through various mutations on an input string, we ended up exhausting all program execution paths, i.e., more varied mutation in the input increased our code coverage. In its simplest form, this is exactly what a fuzzer does.

Building the Fuzzer. In this lab, you will implement three mutation functions, `mutateA`, `mutateB`, and `mutateC` in `part2/src/Mutate.cpp` to perform some form of mutation on its input. You will decide how to implement each mutate function. There are many ways to go about this, but for starters, consider creating strings of different lengths. Additionally, you can look at some of the programs that we will run the fuzzer on, like `easy.c`, and see what input could cause a crash. If you can randomly generate such input, your `mutate` will likely cause other similar programs to crash.

Note each time you update `Mutate.cpp` you will need to rerun the make command in the build directory to build your changes before testing.

After you have filled in your first mutate function, you should move on to create additional mutations. The specific mutation that will be run on the seed inputs is determined from the command line input. For example, `../build/fuzzer ./easy fuzz_input fuzz_output MutationA` will run your `mutateA` function on the input. Likewise, you can run `mutateB` and `mutateC` on the input by passing `MutationB` and `MutationC` instead of `MutationA`.

The fuzzer will start by mutating the seed values based on the mutation you've selected on the command line. The mutated value will be run on the input program, and then inserted as an additional seed in the `SeedInput` vector which causes the mutated input to again be mutated. This process continues until the fuzzer gets interrupted (via timeout, or on the terminal by `Ctrl`+`C`). The following code snippet illustrates this main loop:

```
std::string CampaignStr(argv[4]);
Campaign FuzzCampaign;
if (!toCampaign(CampaignStr, FuzzCampaign)) {
  return 1;
}

initialize(OutDir);

if (readSeedInputs(SeedInputDir)) {
  fprintf(stderr, "Cannot read seed input directory\n");
  return 1;
}

while (true) {
  for (auto i = 0; i < SeedInputs.size(); i++) {
    auto I = SeedInputs[i];
    std::string Mutant = mutate(I, FuzzCampaign);
    test(Target, Mutant, OutDir);
    SeedInputs.push_back(Mutant);
  }
}
```

Fuzzing the Binaries. We have provided three binary programs `hidden1`, `hidden2`, and `hidden3`. These programs serve as more challenging test cases for your fuzzer. We will not provide the raw source; instead, your mutations should be versatile enough to find test cases that crash these programs. Try each of your three fuzzing strategies; it's likely that some mutation strategies won't find the bugs, and some will find them faster than others.

Possible Mutations. The following is a list of potential suggestions for your mutations:

- Replace bytes with random values
- Swap adjacent bytes
- Cycle through all values for each byte
- Remove a random byte
- Insert a random byte

Feel free to play around with additional mutations, and see if you can speed up the search for bugs on the binaries.

In short, this part consists of the following tasks:

1. Decide on a mutation to implement from the aforementioned list of mutations.
2. Implement your mutation in one of the templated mutate functions (`mutateA`, `mutateB`, or `mutateC`).
3. Repeat 1-2 for the remaining mutation functions.
4. Test the strength of your fuzzer by trying to crash the three binaries, `hidden1`, `hidden2`, and `hidden3`.

Example Input and Output

Your fuzzer should run on any valid C code that accepts standard input:

```
$ cd part2/test
$ timeout 1 ../build/fuzzer ./sanity fuzz_input fuzz_output MutationA
```

Expect fuzz_output to get populated with several files that contain the random input that caused the crash, e.g,

```
fuzz_output/failure/input1-MutationA
fuzz_output/failure/input2-MutationA
 …
fuzz_output/failure/inputN-MutationA
```

with N being the last case that caused a crash before the timeout. As you can see, the name of the mutation that was used to cause the crash is included in the filename.

As a sanity check, you can feed these inputs directly into the program at test:

```
$ cd part2/test
$ cat fuzz_output/failure/input1-MutationA | ./sanity
```

Expect to see `Divide-by-zero detected at line 8 and col 13`. `sanity` happens to fail on all input, and is a good sanity check, but for a slightly more challenging test case, try `easy`.

[Extra credit] Part 3 - Feedback-Directed Fuzzing

Setup

The skeleton code for Part 3 is located under `/fuzzing/part3`. We will refer to the top level directory for Part 3 as `part3` when describing file locations.

This lab builds off the work you did in Part 1 and Part 2. Copy InstrumentPass.so from `fuzzing/part1/build` to `part3/reference`.

```
$ cp ~/fuzzing/part1/build/InstrumentPass.so ~/fuzzing/part3/reference
```

Copy your Mutate.cpp from `fuzzing/part2/src` to `part3/src`.

```
$ cp ~/fuzzing/part2/src/Mutate.cpp ~/fuzzing/part3/src
```

The following commands setup the lab:

```
$ cd part3
$ mkdir build
$ cd build
$ cmake ..
$ make
```

We will again use our `fuzzer` tool to feed randomized input (that you will create) into compiled C programs that will run with your sanitizer:

```
$ cd part3/test
$ make
$ mkdir fuzz_output
$ ../build/fuzzer ./sanity fuzz_input fuzz_output
```

Except this time, you will use information about the program run, specifically, coverage information, to drive the fuzzing.

Format of Input Programs

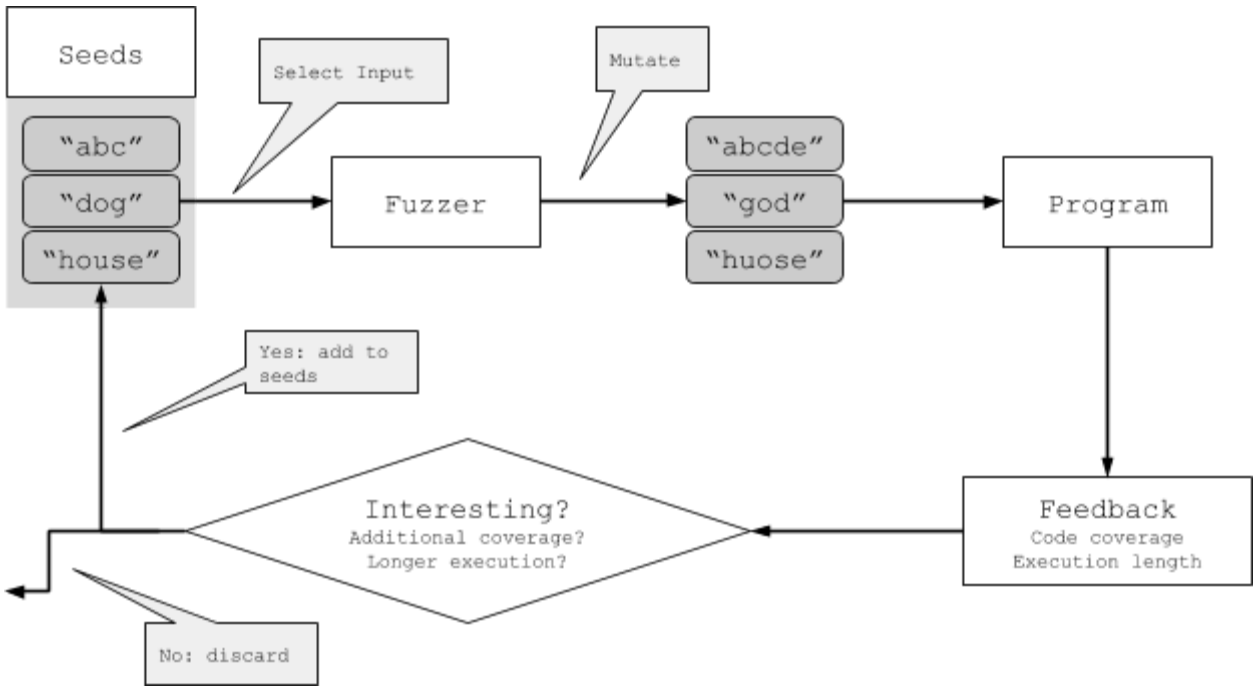
All C programs that read from stdin are valid input programs for this lab.

Lab Instructions

In the previous section, we built a small fuzzer to automate the testing of C code. Recall that a full-fledged fuzzer consists of three key features: i) test case generation matching the grammar of the program input, ii) mutation strategies on test input to increase code coverage, iii) a feedback mechanism to help drive the types of mutation used. We will now extend our fuzzer with the third feature to build feedback-directed fuzzing.

Feedback-Directed Fuzzing. Thus far, we have seen how randomized testing can find bugs and is a useful software analysis tool; however, we currently brute force generate test cases which results in a lot of redundant testing.

We can gather additional information about a program's execution and use it as *feedback* to our fuzzer. The following figure shows at a high level what this process looks like:



Generating new, *interesting* seeds is the goal of feedback directed fuzzing. What does *interesting* mean? We might consider whether a test increases code coverage. If so, we have found new execution pathways that we want to continue to explore. Another test might significantly increase program runtime, in which case we might discover some latent performance bugs. In both cases, the tests increased our knowledge of the program; hence, we insert these tests into our set of seeds and use them as a starting point for future test generation.

Extending the Fuzzer. Thus far, you defined three generic mutation functions, `mutateA`, `mutateB`, and `mutateC`, to fuzz a given program. We iteratively applied a selected mutation to a set of `SeedInputs`. As you saw, this strategy worked well for some programs, and performed poorly on others. In this lab, you will guide the direction of the fuzzing using feedback metrics from a program's execution.

We have adjusted the scaffolding in Part 2 to give you an idea of how to structure your implementation. Previously, we only cared about performing the fuzzing for a selected `Campaign`; now we wish to use each `Campaign` to guide our search. As such, it may help to track separate seeds for each `Campaign`. We now maintain a mapping from a `Campaign` to a list of seeds for that campaign:

```
std::map<Campaign,std::vector<std::string>> SeedInputs;
```

In addition, we have rewritten the main run loop of the fuzzer to better fit the feedback-directed pattern shown in the figure at the start of the section:

```
while (true) {
  // NOTE: You should feel free to manipulate this run loop
  std::pair<std::string,Campaign> SC = selectSeedAndCampaign();
  auto Mutant = mutate(SC.first, SC.second);
  auto Success = test(Target, Mutant, SC.second, OutDir);
  updateSeedInputs(Target, Mutant, SC.second, Success);
}
```

Here we select a seed and a fuzzing campaign to mutate the seed, perform the mutation, run the program on the resulting mutant, and then decide how we wish to update the set of seed inputs. The specifics are left to you; moreover, you should consider the structure as a guide and modify the scaffolding as needed. Be creative: we will test your fuzzer for performance as well as correctness.

In short, the lab consists of the following tasks:

1. Select a seed and fuzzing campaign to generate the next test case. You may follow our groundwork and fill in `selectSeedAndCampaign`.
2. Decide whether the mutation was *interesting* based on success or failure of the program, code coverage, and any additional metrics you feel will increase the performance of your fuzzer. Again, you may follow our groundwork and fill in `updateSeedInputs`.
3. Insert the `Mutant` into the pool of `SeedInput` to drive further mutation.

Code Coverage Metric. Recall that you have a way of checking how much of a particular program gets executed with the coverage information output by your sanitizer. A `.cov` file will get generated from your sanitizer in the working directory for the program that is getting fuzzed. For example, running:

```
$ ../build/fuzzer ./path fuzz_input fuzz_output
```

Will create and update `path.cov` in the working directory that your `updateSeedInputs` function should read and use between each test.

A Few More Hints. Do not be afraid to keep state between rounds of the fuzzing. You may want to try each of your fuzzing campaigns initially to see which generate a test that increases code coverage, and then exploit that campaign. Unlike your implementation in Part 2, we expect this fuzzer to be versatile; it should generate crashing tests on all inputs.

Example Input and Output

Your fuzzer should run on any valid C code that accepts standard input:

```
$ cd part3/test
$ timeout 1 ../build/fuzzer ./path fuzz_input fuzz_output
```

Expect fuzz_output to get populated with several files that contain the random input that caused the crash, e.g,

```
fuzz_output/failure/input1-MutationA
fuzz_output/failure/input2-MutationA
 …
fuzz_output/failure/inputN-MutationA
```

with N being the last case that caused a crash before the timeout. As you can see, the name of the mutation that was used to cause the crash is included in the filename. We will also output test cases that resulted in a successful program run under `fuzz_output/success/`; however, since it's likely you will get many successful program runs before a failure, we write every 1000th successful run. You can adjust this frequency by supplying an additional optional argument to the fuzzer:

```
$ ../build/fuzzer ./path fuzz_input fuzz_output 100
```

Grading

For each part, your solution will be tested against the provided test cases as well as some additional hidden test cases that are similar to the provided ones. For the fuzzer, we'll be using a timeout of 30 seconds.

Items to Submit

We expect your submission to conform to the standards specified below. To ensure that your submission is correct, you should run the provided file validator. You should not expect submissions that have an improper folder structure, incorrect file names, or in other ways do not conform to the specification to score full credit. The file validator will check folder structure and names match what is expected for this lab, but won't (and isn't intended to) catch everything.

The command to run the tool is: `python3 zip_validator.py lab1 lab1.zip`
Note that the validator assumes you have completed all three parts of the lab. If you did not do optional part 3, you can ignore the validation warnings about missing `part3/` files.

Submit the following files in a single compressed file (`.zip` format) named `lab1.zip`. For full credit, the file must be properly named and there must not be any subfolders beyond the `part3` folder or extra files contained within your zip file.

- Part 1 - Submit file `Instrument.cpp` (50 points)
- Part 2 - Submit file `Mutate.cpp` (50 points)
- Part 3 - Submit files `part3/Mutate.cpp` and `part3/Fuzzer.cpp` (50 points total)
    - Note: If you did Part 3 without changing `Mutate.cpp` from Part 2, you must still submit `part3/Mutate.cpp` - just submit a duplicate of your Part2 version.

Note that the available points add up to 150 but this lab is out of 100 points. You can earn extra credit on it, and these points will be the **only** opportunity to earn extra credit on labs this semester.

Upload your zip file to Canvas. Make sure the spelling of the filenames and the extensions are exactly as indicated above. Misspellings in filenames may result in a deduction to your grade.