

Project #1: Tracing, System Calls, and Processes

Objectives

In this project, you will learn about system calls, process control and several different techniques for tracing and instrumenting process behaviors. You will write two (2) small programs: one that uses a **shim** library (and the `LD_PRELOAD` environment variable) to detect memory leaks, and another that uses the **ptrace** API to report statistics about the system calls made by another program.

Program #1: Memory Leak Detector

Your memory leak detector will be called **leakcount**. It will be run from the command-line with the syntax shown in Listing 1. It will accept a series of arguments—specifying a program to run and its arguments—run that program (either in the current process or in a child process) and inspect its calls to **malloc**, **calloc**, **realloc**, and **free**. For this program, a memory leak is defined as a call to **malloc**, **calloc**, or **realloc** that returns a pointer that is never freed during the course of the program's execution (either by a call to **free** or **realloc**).

Your program must be written in C and consist of two parts: the **leakcount** program, and a shared library, called **mem_shim.so** that will act as a shim for intercepting calls to **malloc**, **calloc**, **realloc** and **free**.

When the **leakcount** program runs, it will execute the specified program using **fork+exec***, **popen**, or **system**. I have implemented the project using all three successfully. However you execute the test program your **leakcount** process will need to set the **LD_PRELOAD** environment variable to be the path to your shim library **mem_shim.so**.

Tip: There are multiple ways to do this. If you go the **fork+exec** route, check-out the environment variable examples we look at in class to see how to use **setenv** and **putenv**. If you want to set the environment explicitly, **execvpe** allows you to specify the environment explicitly as an argument—but this is not the only way to accomplish this task.

Listing 1: Syntax and output format for your memory leak detector.

```
leakcount <command>
Example: ./leakcount ./my_test_program
Example: ./leakcount ./test2 arg1 arg2 ...

Output: (to stderr)
LEAK<tab><num bytes>
LEAK<tab><num bytes>
TOTAL<tab><total count><tab><bytes leaked>

Example Output: (to stderr)
> ./leakcount ./mytest
LEAK 128
LEAK 35
TOTAL 2 163
```

Setting the **LD_PRELOAD** environment variable tells the operating system to load your shim library before any of the other system libraries (like **libc.so**, the C standard library). This allows you to effectively replace any library call you want with your own implementation. This can be extremely useful in testing programs or modifying system or program functionality. Make sure you wrap your head around what we are doing here, because this will come up again later in the course.

In its simplest form, your shim library will be implemented as a single C file, that implements the four functions shown in Listing 2. Your code should keep track of allocations that occur and which ones get freed. Your program should treat **realloc** as if it were a **free** call followed by a **malloc** call. When the test program finishes, your program (**leakcount**) should report the number of leaks that occurred, to **stderr** in the format described in Listing 1. Print out the leaks in the order that they were allocated. Your program should print out a TOTAL leak count even if there are no memory leaks. Your program should not produce any other output (debug statements will likely confuse the autograder).

There are multiple ways to implement this program. Communication between parent and child processes is not necessary—your shim can produce all of the required output if you like. In fact, you don't even need to create a child process. If you choose to have your processes communicate, the communication method is left up to you. Files, pipes, sockets, etc are all fair game. You may also find the **constructor** and **destructor** attributes that are provided by GCC to be useful in this part of the project (it can be done without them, of course). A very good explanation of how these work is provided at the following url.

Listing 2: Memory leak detector hints.

```
//implement these functions
void free (void *ptr);
void *malloc(size_t size);
void *calloc(size_t count, size_t size);
void *realloc(void *ptr, size_t size);

//how to call the original version of malloc
#include <dlfcn.h>
void *(*original_malloc) (size_t size);
original_malloc = dlsym(RTLD_NEXT, "malloc");
void *ptr = original_malloc(17);
```

Listing 3: Syntax and output format for your system call tracer.

sctracer <command>

Example: ./sctracer ../my_random_test_program <output_file>

Example: ./sctracer "../my_test_program arg1 arg2" <output_file>

Output: (to specified output file)

<syscall number><tab><num calls>

<syscall number><tab><num calls>

...

<http://phoxis.org/2011/04/27/c-language-constructors-and-destructors-with-gcc/>

Also, note that there are several things that the child process can do that can make your job more difficult. A program run by leakcount can close **stderr** before returning from **main**. This will cause anything printed by your library's destructor from appearing in the terminal. A program can also terminate abnormally (by calling **abort**) which will prevent library destructors from running, at all. You are not required to handle either of these two cases, though feel free to tackle them, if you like a challenge.

One more thing. You might see calls to **free** pointers that you didn't see allocated (including attempts to **free(NULL)**). You can safely ignore these.

Program #2: System Call Tracer

Your second small program will be called **sctracer**. It will also be run from the command-line, using the syntax shown in Listing 3. Unlike the first program, which accepted a variable number of arguments, **sctracer** will take

a test program and its arguments as a single argument, which it will run, in a child process, and report statistics on the system calls that it uses. These statistics will be reported in an output file, specified on the command-line.

In this program, we will focus on system calls, rather than library calls, and we want to watch *all* system calls, rather than a small set of calls. Using a shim in this instance would require us to write a wrapper for every single system call, which would be really tedious. So, instead of using **LD_PRELOAD** and a shim library, in this program you will use the **ptrace** API.

The **ptrace** API is extremely powerful. You can read or write to another process's memory or registers, monitor the signals received by the process, stop and start the process when a system call occurs, and of course kill the process. In this project, we will only focus on a subset of this functionality. At the bare minimum, you will need to use the `PTRACE_TRACEME`, `PTRACE_SYSCALL`, `PTRACE_PEEKUSER`, `PTRACE_SETOPTIONS` requests and the `PTRACE_O_TRACESYSGOOD` option, and I will provide a **ptrace** example in the Git repository; however, you should start this project by reading the **man** page on **ptrace**. Not reading the relevant parts of the documentation carefully, would be unwise. I also recommend brushing up on **waitpid**, **getpid**, and other process management functions.

In this program, I strongly recommend that you use **fork** to create the new process. The child process should call **ptrace(PTRACE_TRACEME)** before calling **exec***.

Once the child process has completed, your program will write the results into the output file, in the format specified in Listing 3. Each system call should be on its own line. You should report the system call number, followed by a tab character, followed by the number of times that system call was called. The results should be ordered in order of increasing system call number (smallest sys-call number first). You should not report an entry for system calls that were not called (no zero entries).

Other thoughts, hints, and warnings

Your programs should be written in C and use good programming style. Your code should be **-Wall**¹ clean, and most importantly it should be your own. Both programs will be tested on single-threaded terminal programs. You don't need to correctly support multithreaded or multiprocess applications. Also, your **leakcount** program is not required to correctly count leaks in pro-

¹**"-Wall clean"** = If compiled with the **-Wall** flag, it should not produce any warnings.

grams that close `stderr` or terminate with `_exit`, `abort`, or any other method other than returning from `main`. Depending on how you approach this project, handling these cases can be tricky.

For this project, there are several tools that will be very helpful. The **strace** and **ltrace** tools can be used to sanity check your results. If you haven't before, I also recommend that you become familiar with **valgrind**, a tool that can help you find memory leaks and other memory errors. Finally, those of you who use **printf** to debug will find that this may not work well on the first program. The reason is that **printf** allocates memory, so calling it within your shim library's **malloc** or **free** function will likely cause the process being checked to go down in flames (infinite recursion). I'm often surprised at how many students don't use **gdb**, which I think makes life much easier. I strongly recommend it.

Make sure that your code compiles, runs and has been thoroughly tested on the lab machines.

Submission Instructions

This project has two deadlines. Absolutely no late assignments will be accepted, and deadline extensions typically require a documented medical emergency or natural disaster.

Compile deadline: 4:00 PM, January 28th — This is a preliminary deliverable worth 10 points. For this, you simply need to submit a valid `tgz` file (more info below on this) with code and a `Makefile` that compiles without any errors or warnings and produces three files, called **leakcount**, **mem_shim.so**, and **sctracer**. These compiled programs (and library) do not need to work correctly. For this deliverable, submit to the **compile1** assignment on Canvas.

Functional deadline: 4:00 PM, February 11th — This is the final submission deadline worth the remaining 90 points. For this deliverable, submit to the **project1** assignment on Canvas.

Creating your submission: When your project is complete, archive your source materials, using the following command:

```
> tar cvzf project1.tgz README Makefile <list of source files>
```

Your **Makefile** should build your program (when I run **make**). It should produce three files, called **leakcount**, **mem_shim.so**, and **sctracer**.

The **README** file should include your name, a short description of your project,

and any other comments you think are relevant to the grading. It should have two clearly labeled sections titled with KNOWN PROBLEMS, and DESIGN. The KNOWN PROBLEMS section should include a specific description of all known problems or program limitations. This will not hurt your grade and may (in rare cases) improve it. I am more sympathetic when students have thoroughly tested their code and clearly understand their shortcomings, and less so when I find bugs that students are ignorant of or have tried to hide. You should also include references to any materials that you referred to while working on the project. Please do not include special instructions for compilation. The compilation and running of the tests will be automated (see details below), and your instructions will not be followed.

Please make sure you include only the source files, not the object files or compiled binaries. Also, make sure that your files are not in a subdirectory within the tar ball. Before you submit this single file, please use the following commands to check and make sure you have everything in the **project1.tgz** file:

```
> mkdir test; cd test
> tar xvzf <path to tgz file>/project1.tgz
> make
```

This should put all of your source files in the current directory, and compile your two programs.

Submit your **project1.tgz** file via **Canvas**. You must name your archive **project1.tgz**, and it must compile and run on the McAdams Lab machines. We will compile your code using your **Makefile**, and run it using the syntax described in Listings 1 and 3.

1 Grading

Your project will be graded based on the results of functional testing and the design of your code. We will run several tests to make sure it works properly and correctly handles various error conditions. We will test your programs against custom test programs that we have written. Your code should not crash. You will receive 10% credit if your code successfully compiles, and 10% for code style and readability. The rest of your score will be determined by the number of tests that your programs pass.

Your source materials should be readable, properly documented and use good coding practices (avoid magic numbers, use appropriately-named variables, use good indentation, etc). Your code should be -Wall clean (you should

not have any warnings during compilation). **Our testing of your code will be thorough. Be sure you test your application thoroughly.**

Reminders: You can submit to Canvas multiple times before the deadline. Your final submission will be the one that counts even if you have a previous submission with a higher score. The autograder will run once a day. Starting early means you can get more autograder attempts.

2 Collaboration

You will work independently on this project. You must *not* discuss your solution with classmates, and all of your code must be your own code (no AI-generated or borrowed code), produced by your own brain. If the code generation capabilities in your editor are too tempting, consider using something like Vim.

You may, of course, discuss the project with me, and you may discuss conceptual issues related to the project that we have already discussed in lecture or on Piazza. For example, it would be OK to discuss how **ptrace** works (in general) since this is something we have discussed in class. It is NOT OK to discuss how you specifically used **ptrace** to solve any part of this project. **Collaborating with peers on this project, in this or any other manner will be treated as academic misconduct.**