CS 105
Lab 2: Debugger
Playing with X86-64 Assembly

See class calendar for lab due date

Introduction and Goals

NOTE: This lab must be run on Wilkes. If you run it on a different machine, you may get incorrect answers.

The goals of this assignment are to do some basic investigation of the x86-64 architecture and assembly language, and to begin learning how to use `gdb`. The lab pages have links to a quick `gdb` summary and to a printable `gdb` reference card; you can also find other information on Google.

It will be useful to know that you can get the compiler to generate the assembler source for a program by using "`gcc -S foo.c`". You should also know that to use the debugger effectively, you will need to compile with the "`-g`" switch. In fact, you should just get in the habit of always compiling with "`-g`"; the situations where it's undesirable are extremely unusual. (But note that `-S` and `-g` are best kept separate.) Also, it's usually wise to compile with the "`-Og`" switch so that optimization doesn't make debugging more difficult. Remember that debugging is nearly always more important than optimization! (Important detail: you can compile with `-S` and any optimization level, and in fact doing so can produce useful insights.)

Collect your answers to all of the following questions in a plain-text file named "`lab02.txt`". Identify each section by problem number, and each answer by question number.

Submission. Use `cs105submit` to submit ONLY the `lab02.txt` answer file.

NOTE: Do not change either of the programs in this lab!

Problem 1—Debugging Optimized Code (17 Points)

Download the file `problem1.c` from the lab Web site. This file contains a function that has a small `while` loop, and a simple `main` that calls it. Briefly study the `loop_while` function to understand how it works (you don't need to fully decode it; just get a clue about what's going on).

It will also be useful to know what the `atoi` function does. Type "`man atoi`" in a terminal window to find out. (Side note: the function's name is pronounced "ay to eye," not "a toy.")

Finally, it will be useful to have a slight clue about `printf`. Since `printf` is quite complicated, for now we'll just say that it prints answers, and `"%d"` means "print in decimal". We encourage you to read more about `printf` in Kernighan & Ritchie or online (the advantage of reading in K&R is that the description there is less complex; recent versions of `printf` have tons of extensions that aren't particularly useful in this course).

Compile the program with the `-g` switch and with **no** optimization: "`gcc -g -o problem1 problem1.c`". Run `gdb problem1` and set a breakpoint in `main` ("`b main`"). Run the program by typing "`r`" or "`run`". The program will stop in `main`. (Ignore any warnings; they're meaningful but we'll work around them.)

(**Note:** to help you keep track of what you're supposed to doing, we have used italics to list the breakpoints you should have already set at the beginning of each step—except when they don't matter. Also, when possible we have listed the state you should be in.)

1. *Existing breakpoint at* `main`*.*
   Type "`c`" (or "`continue`") to continue past the breakpoint. What happens?

2. *Existing breakpoint at `main`; after the program terminates.*
Type "`bt`" (or "`backtrace`") to get a trace of the call stack and find out how you got where you are. Take note of the numbers in the left column. Type "`up` *n*", where *n* is one of those numbers, to get to `main`'s *stack frame* so that you can look at main's variables. What file and line number are you on?

3. *Existing breakpoint at `main`; after the program terminates.*
Usually when bad things happen in the library it's your fault, not the library's. In this case, the problem is that `main` passed a bad argument to `atoi`. There are two ways to find out what the bad argument is: look at `atoi`'s stack frame, or print the argument. Figure out how to look at `atoi`'s stack frame. Can you see what argument (`nptr`) was passed to `atoi`? (Answer yes or no.)

4. *Existing breakpoint at `main`; after the program terminates.*
The lack of information is sometimes caused by compiler optimizations, other times by minor debugger issues. In either case it's a nuisance. Rerun the program by typing "`r`" (you'll have to confirm that you really want to do that) and let it stop at the breakpoint. Note that in step 2, `atoi` was called with the argument "`argv[1]`". You can find out the value that was passed to `atoi` with the command "`print argv[1]`". What is printed?

5. *Existing breakpoint at `main`; after the program terminates.*
If you took CS 70, you will recognize that number as the value of a NULL pointer. Like many library functions, `atoi` doesn't like NULL pointers. Rerun the program with an argument of 5 by typing "`r 5`". When it reaches the breakpoint, continue (type "`c`"). What does the program print?

6. *Existing breakpoint at `main`; after the program terminates.*
Without restarting `gdb`, type "`r`" (without any further parameters) to run the program yet again. (If you restarted `gdb`, you must first repeat Step 5.) When you get to the breakpoint, examine the variables `argc` and `argv` by using the `print` command. For example, type "`print argv[0]`." Also try "`print argv[0]@argc`", which is `gdb`'s notation for saying "print elements of the `argv` array starting at element 0 and continuing for `argc` elements." What is the value of `argc`? What are the elements of the `argv` array? Where did they come from, given that you didn't add anything to the `run` command?

7. *Existing breakpoint at `main`; at `main`.*
The `step` or `s` command is a useful way to follow a program's execution one line at a time. Type "`s`". Where do you wind up?

8. *Existing breakpoint at `main`; at `main`.*
`Gdb` always shows you the line that is about to be executed. Sometimes it's useful to see some context. Type "`list`" and the Enter (return) key. What lines do you see? Then hit the Enter key again. What do you see now?

9. *Existing breakpoint at `main`; at `main`.*
Type "`s`" (and return) to step to the next line. Then hit the return key three more times. What do you think the return key does?

10. *Existing breakpoint at `main`; after typing `s` and hitting return three times.*
What are the values of `result`, `a`, and `b`?

11. *Existing breakpoint at `main`; after typing `s` and return, and then hitting return three more times.*
Type "`quit`" to exit `gdb`. (You'll have to tell it to kill the "inferior process", which is the program you are debugging. Insulting!) Recompile the program, this time optimizing it by adding `-O1` after `-g`: "`gcc -g -O1 -o problem1 problem1.c`. (Note that the lowercase "`-o`" is still necessary!) Debug it, set a breakpoint at `loop_while` (not `main`!), and run it with an argument of 10 (not 5!). Step three times. What four lines are shown to you? Why do you think the debugger is showing you those lines in that order?

12. Quit `gdb` again and recompile with `-O2`. Debug the program and set a breakpoint in `loop_while`. Run it with an argument of 20. Where does the program stop?

13. *Existing breakpoint at `loop_while`; after running with argument of 20.*
Hmmm. . . that's kind of odd. Disassemble the `main` function by typing "`disassem main`". What is the address of the instruction that calls `atoi`? What is the address of the instruction that calls `printf`? (You will have to do some inference here, because `gcc` mangles the names a bit.)

14. *Existing breakpoint at `loop_while`; after running with argument of 20.*
That wasn't too hard. Where's the call to `loop_while`?

15. *Existing breakpoint at `loop_while`; after running with argument of 20.*
A handy feature of `print` is that you can use it to convert between bases. For example, what happens when you type "`print/x 42`"? How about "`p 0x2f`"?

16. *Existing breakpoint at `loop_while`; after running with argument of 20.*
We haven't covered it in lecture yet, but functions return results in `%rax`. So the result of `atoi` will be in `%rax` (also known, for this problem, as `%eax`). After the call to `atoi` there is an `lea` (which is `gdb`'s version of `leal` and `leaq`, depending on the destination), an `add`, and a `sub`. Where does the constant in the `sub` come from?

17. Now you (kind of) understand the optimized `main`. What happened to the call to `loop_while`?

18. If you compile with `-O3` and disassemble the main program, you'll discover that the loop has disappeared. We won't try to analyze it—in particular, the instructions starting with "p" aren't covered in this course—but it's useful to know that the compiler has figured out the underlying math of `loop_while` and replaced it with a straight-line calculation. Wow!

19. Recompile once again with optimization level `-Og`. Under the debugger, run the program, set a breakpoint in `main`, and single-step (by first typing `s` and then hitting the return key repeatedly) until an answer is finally printed. Did you see any out-of-order execution as a result of optimizations?

Problem 2—Stepping and Looking at Data (19 Points)

Download the file `problem2.c` from the lab Web site. This file contains three `static` constants and three functions. Read the functions and figure out what they do. (If you're new to C, you may need to consult your C book or some online references.) Here are some hints: `argv` is an array containing the strings that were passed to the program on the command line (or from `gdb`'s `run` command); `argc` is the number of arguments that were passed. By convention, `argv[0]` is the name of the program, so `argc` is always at least 1. The `malloc` line allocates a variable-sized array big enough to hold `argc` integers (which is slightly wasteful, since we only store `argc-1` integers there, but what the heck).

By now we hope you've learned that optimization is bad for debugging. So compile the program with `-Og -g` and bring up the debugger on it.

1. `Gdb` provides you lots of ways to look at memory. For example, type "`print puzzle1`" (something you should already be familiar with). What is printed?

2. Gee, that wasn't very useful. Sometimes it's worth trying different ways of exploring things. How about "`p/x` puzzle1"? What does that print? Is it more edifying?

3. You've just looked at puzzle1 in decimal and hex. There's also a way to treat it as a string, although the notation is a bit inconvenient. The "`x`" (examine) command lets you look at arbitrary memory in a variety of formats and notations. For example, "`x/bx`" examines bytes in hexadecimal. Let's give that a try. Type "`x/4bx &puzzle1`" (the "`&`" symbol means "address of"; it's necessary because the `x` command requires addresses rather than variable names). How does the output you see relate to the result of "`p/x puzzle1`"? (Incidentally, you can look at any arbitrary memory location with `x`, as in "`x/wx 0x400674`".)

4. OK, that was interesting and a bit weird (thanks to all the Little-Endians in Lilliput). But we still don't know what's in `puzzle1`. We need help! And fortunately `gdb` has help built in. So type "`help x`". Then experiment on `puzzle1` with various forms of the `x` command. For example, you might try "`x/16i &puzzle1`". (`x/16i` is one of our favorite `gdb` commands—but since here we suspect that `puzzle1` is data, not instructions, the results might be interesting but probably not correct.) Keep experimenting until you find a sensible value for `puzzle1`. (**Hint:** Although `puzzle1` is declared as an `int`, it's not. But on a 32-bit machine an int is 4 bytes, 2 halfwords, or one (in `gdb` terms) word.) What is the human-friendly value of `puzzle1`? (Hints: Don't accept an answer that is partially garbage! Try all the different formats, and all the sizes that make sense.)

5. Having solved `puzzle1`, look at the value carefully. Is it correct? (You might wish to check it online.) If it's wrong, why is it wrong?

6. Now we can move on to `puzzle2`. It pretends to be an *array* of `int`s, but you might suspect that it isn't. Using your newfound skills, figure out what it is. (**Hint:** since there are two `int`s, the entire value occupies 8 bytes. So you'll need to use some of the size options to the `x` command) What is the human-friendly value? (Hint: it's not "105". Nor is there garbage in it.)

7. Are you surprised?

8. Is it correct?

9. We have one puzzle left. By this point you may have already stumbled across its value. If not, figure it out; it's often the case that in a debugger you need to make sense of apparently random data. What is stored in `puzzle3`?

10. We've done all this without actually running the program. But now it's time to execute! Set a breakpoint in `fix_array`. Run the program with the arguments `1 1 2 3 5 8 13 21 44 65`. When it stops, print `a_size` and verify that it is 10. Did you really need to use a `print` command to find the value of `a_size`? (**Hint:** look carefully at the output produced by `gdb`.)

11. *Existing breakpoint at `fix_array`; stopped at that breakpoint.*
    What is the value of `a`?

12. *Existing breakpoint at `fix_array`; stopped at that breakpoint.*
    Type "`display a`" to tell `gdb` that it should display `a` every time you stop (although `gdb` will only obey part of the time). Step six times. You'll note that one of the lines executed is a right curly brace; this is common when you're in `gdb` and often indicates the end of a loop or the return from a function. At the curly brace, what is the value of `a`?

13. *Existing breakpoint at `fix_array`; after hitting that breakpoint and then stepping six times.*
    Step again (a seventh time). What is the value of `a` now? What is `i`?

14. *Existing breakpoint at `fix_array`; after hitting that breakpoint and then stepping seven times.*
    At this point you should (again) be at the call to `hmc_pomona_fix`. You already know what that function does, and stepping through it is a bit of a pain. The authors of debuggers are aware of that fact, and they always provide two ways to step line-by-line through a program. The one we've been using (`step`) is traditionally referred to as "step into"—if you are at the point of a function call, you move stepwise *into* the function being called. The alternative is "step over"—if you are at a normal line it operates just like `step`, but if you are at a function call it does the whole function just as if it were a single line. Let's try that now. In `gdb`, it's called `next` or just `n`. What line do we wind up at? (Recall that in `gdb` as in most debuggers, the line shown is the *next* line to be executed.)

15. *Existing breakpoint at `fix_array`; after hitting that breakpoint, stepping seven times, and typing `next` (whew!).*
    Use `n` to step past that line, verifying that it works just like `s` when you're not at a function call. What's `a` now?

16. *Existing breakpoint at `fix_array`; after hitting that breakpoint, stepping seven times, and typing `next` twice.*
    It's often useful to be able to follow pointers. `Gdb` is unusually smart in this respect; you can type complicated expressions like `p *a.b->c[i].d->e`. Here, we have kind of lost track of `a`, and we just want to know what it's pointing at. Type "`p *a`". What do you get?

17. *Existing breakpoint at `fix_array`; after hitting that breakpoint, stepping seven times, and typing `next` twice.*
    Often when debugging, you know that you don't care about what happens in the next three or twelve lines. You could type "`s`" or "`n`" that many times, but we're computer scientists, and CS types sneer at doing work that computers could do for them—especially mentally taxing tasks like counting to twelve. So on a guess, type "`next 12`". What line are you at?

18. *Existing breakpoint at `fix_array`; after hitting that breakpoint, stepping seven times, typing `next` twice, and then typing `next 12` (wow!).*
    What is the value of `a` now?

19. *Existing breakpoint at `fix_array`; after hitting that breakpoint, stepping seven times, typing `next` twice, and then typing `next 12`.*
    What is the value of `*a`?

Finally, a small side comment: if you've set up a lot of `display` commands and want to get rid of some of them, investigate `info display` and `undisplay`.

Problem 3—Assembly-Level Debugging (19 Points)

So far, we've mostly been taking advantage of the fact that `gdb` understands your program at the source level: it knows about strings, source lines, call chains, and even complicated C++ data structures. But sometimes it's necessary to get down and dirty with the assembly code.

Note: If you get to this point before we've done the lecture on "flow control", this would be a good time to take a break and work on some other class.

To be sure we're all on the same page, let's quit `gdb` and bring it up on `problem2` again. Run the program with arguments of `1 42 2 47 3`.

1. *No breakpoints; after running `problem2`.*
   What is the output? Whoop-tee-doo.

2. *No breakpoints.*
   Set a breakpoint in `main`. Run the program again. What line does it stop at?

3. *Existing breakpoint at `main`; after running the program.*
   Boooooooooooring. Type "list" and then Enterto see what's nearby, then type "`b 35`" and "`c`". Where does it stop now?

4. *Existing breakpoints at `main` lines 29 and 35; after running and continuing.*
   Shocking. But since that's the start of the loop, typing "`c`" will take you to the next iteration, right?

5. *Existing breakpoints at `main` lines 29 and 35; after running and continuing twice.*
   Oops. Good thing we can start over by just typing "`r`". Continue past that first breakpoint to the second one, which is what we care about. But why, if we're in the `for` statement, didn't it stop the second time? Type "`info b`" (or "`info breakpoints`" for the terminally verbose). Lots of good stuff there. The important thing is in the "address" column. Take note of the address given for breakpoint 2, and then type "`disassem main`". You'll note that there's a helpful little arrow right at breakpoint 2's address, since that's the instruction we're about to execute. Looking back at the corresponding source code, what part of the `for` statement does this assembly code correspond to?

6. *Existing breakpoints at `main` lines 29 and 35; after running and continuing once.*
   The code at `main+28` jumps to `main+68`, which has two instructions that jump back to `main+35`. This is all part of the `for` loop pattern we covered in class. We've successfully breaked ("broken?" "set a breakpoint?") at the loop initialization. But we'd like to have a breakpoint *inside* the for loop, so we could stop on every iteration. The jump to `main+35` tells us that we want to stop there. But that's not a source line; it's in the middle clause of the `for` statement. No worries, though, because `gdb` will let us set a breakpoint on *any* instruction even if it's in the middle of a statement. Just type "`b *(main+35)`" or "`b *0x400697`" (assuming that's the address of `main+35`, as it was when we wrote these instructions). The asterisk tells `gdb` to interpret the rest of the command as an address in memory, as opposed to a line number in the source code. What does "`info b`" tell you about the line number you chose? (Fine, we could have just set a breakpoint at that line. But there are more complicated situations where there isn't a simple line number, so it's still useful to know about the asterisk.)

7. *Existing breakpoints at `main` lines 29 and 35, and instruction `main+35`; after running and continuing twice before setting the third breakpoint.*
   We can look at the current value of the array by typing "`p array[0]@argc`" or "`p array[0]@6`". But the current value isn't interesting. Let's continue a few times and see what it looks like then. Typing "`c`" over and over is tedious (especially if you need to do it 10,000 times!) so let's continue to breakpoint 3 and then try "`c 4`". What are the full contents of `array`?

8. *Existing breakpoints at `main` lines 29 and 35, and instruction `main+35`; after continuing until breakpoint 3 has been hit and then typing `c 4`.*
   Perhaps we wish we had done "`c 3`" instead of "`c 4`". We can rerun the program, but we really don't need all the breakpoints; we're only working with breakpoint 3. Type "`info b`" to find out what's going on right now. Then use "`d 1`" or "`delete 1`" to completely get rid of breakpoint 1. But maybe breakpoint 2 will be useful in the future, so type "`disable 2`". Use "`info b`" to verify that it's no longer enabled ("Enb"). Run the program again. Where do we stop? (Well, that was hardly a surprise.)

9. *No previous state.*
   Sometimes, instead of stepping through a program line by line, we want to see what the individual instructions do. Of course, instructions manipulate registers. Quit `gdb` and restart it, setting a breakpoint in `fix_array`. Run the program with arguments of `1 42 2 47 3`. Type "`info registers`" (or "`info r`" for the lazy) to see all the processor registers in both hex and decimal. How many registers have *not* been covered in class?

10. *Existing breakpoint at `fix_array`; after running and hitting the breakpoint.*
    Well, that's because they're weird and not terribly important. (Except `eflags`, which holds the condition codes among other things. Note that instead of being given in decimal, it's given symbolically—things like `CF`, `ZF`, etc.) Of the flags we have discussed in class, which ones are set right now? What preceding instruction caused those flags to be set?

    NOTE: If you haven't been through the "x86 control flow" lecture, you will have to return to this step after that.

11. *Existing breakpoint at `fix_array`; after running and hitting the breakpoint.*
    Often, looking at *all* the registers is excessive. Perhaps we only care about one. Type "`p $rcx`". What is the value? Is "`p/x $rcx`" more meaningful? How about "`p $ecx`" and "`p/x $ecx`"? Do you see any relationship between the values printed?

12. *Existing breakpoint at `fix_array`; after running and hitting the breakpoint.*
    We mentioned a fondness for "`x/16i`". Actually, what we really like is "`x/16i $rip`". Compare that to the result of "`disassem fix_array`". Then, immediately after typing "`x/16i $eip`", hit the return key. What do you see?

13. *Existing breakpoint at `fix_array`; after running and hitting the breakpoint.*
Finally, we mentioned stepping by instructions. That's done with "`stepi`" ("step one instruction"). Type that now, and note that `gdb` gives a new instruction address but says that you're in the left curly brace. Hit return to `stepi` again, and keep hitting return until the displayed line `doesn't` contain a hexadecimal instruction address. Where are you?

14. *Existing breakpoint at `fix_array`; after hitting the breakpoint and then stepping until there is no hexadecimal address.*
It's useful to use "`x/16i $rip`" here to make sure we understand what's about to happen. You should see a `mov`, a `jmp`, and a `mov`, followed by a `call`. Looking at the target of the `jmp`, you can see that it has two instructions that will take you back to the `mov` at `fix_array+17`. Use `stepi 5` to get past the `mov`s and `jmp`s. What instruction address will be executed next?

15. *Existing breakpoint at `fix_array`; after hitting the breakpoint and then stepping until there is no hexadecimal address and then doing `stepi 5`.*
As with source-level debugging, at the assembly level it's often useful to skip over function calls. At this point you have a choice of typing "`stepi`" or "`nexti`". If you type "`stepi`", what do you expect the next instruction to be (hexadecimal address)? What about "`nexti`"? (By now, your debugging skills should be strong enough that you can try one, restart the program, and try the other, so there's little excuse for getting this one wrong!)

16. *Existing breakpoint at `fix_array`; after experimenting with `stepi` and `nexti`.*
Almost there! Stepping one instruction at a time can be tedious. You can always use "`stepi` *n*" to zip past a bunch of them, but when you're dealing with loops and conditionals it can be hard to decide whether it's going to be 1,042 or 47,093 instructions before you reach the next interesting point in your program. Sure, you could set a breakpoint at the next suspect line. But sometimes the definition of "interesting" is *inside* a line. Let's say, just for the sake of argument, that you are interested in how the `retq` instruction works. You can set a breakpoint there by typing "`b *0x400673`" (assuming that 0x400673 is its address, as it was when we wrote these instructions). Do so, and then continue. What source line is listed?

17. *Existing breakpoints at `fix_array` and *0x400673; stopped at `lretq` instruction.*
The `retq` instruction manipulates registers in some fashion. Start by looking at what `%rsp` points to. You can find out the address with "`p $rsp`" and then use the `x` command, or you could just try "`x/x $rsp`". Or you could get wild and use C-style typecasting: "`p/x *(int *)$ebp`" (try it!). What is the value?

18. *Existing breakpoints at `fix_array` and *0x400673; stopped at `retq` instruction.*
Use "`info reg`" to find out what all the registers are. Then use "`stepi`" to step past the `retq` instruction, and look at all the registers again. Which registers have changed, and what are their old and new values?