CS 107 READER

STANFORD COMPUTER SCIENCE DEPARTMENT

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Contents

List of Figures

List of Tables

List of URLs

Introduction

This course reader is meant to be a guide for Stanford students as they progress through CS 107, *Computer Organization & Systems*, which serves as the first systems course in the Stanford Computer Science Curriculum. The guide is not intended to replace the outstanding course textbooks, *Computer Systems, A Programmers Perspective, 3rd Edition* by Randy Bryant and David O'Hallaron[1] and (the ultimate classic) *The C Programming Language* by Brian Kernighan and David Ritchie[2], nor is it intended to replace attending lectures, participating in labs, and completing the course assignments. The only way to really learn the material in CS 107 is by doing the labs and assignments, and the only way to do the labs and assignments is to use the course materials (this guide included) as scaffolding.

The material in this guide follows the outline of the course, though it should not be considered a definitive guide to the class. Some material covered in class may not be in the guide, and vice-versa. During a particular quarter, the course website, at

`http://web.stanford.edu/class/cs107/`

holds up-to-date information about the course, and this guide should be used as an additional reference.

CS 107 is not a trivial course, as many current and former Stanford Computer Science students can attest. The introductory courses, CS 106A, CS 106B, and CS 106X, provide a computer science kiddie pool where students learn how to swim, under the guidance of a flotilla of Section Leader lifeguards who are available in numbers that allow frequent one-on-one guidance. In CS 107, students jump into the ocean, with a few Course Assistant Coast Guardspeople who can provide limited assistance when students are in dire need. In other words, many of the safety nets that students get used to in the introductory courses are not available in CS 107, and we expect students to be better self-learners when they become stuck on a programming problem. This guide can be a good resource, as can the textbook, Piazza, and office hours. Additionally, students should consider doing Internet searches as well, although answers found through Google or Stack Overflow (for example) will not always yield answers that are appropriate for

[1] R.E. Bryant and D.R. O'Hallaron. *Computer Systems : A Programmer's Perspective*. Pearson, 2015. ISBN 9781292101767. URL https://books.google.com/books?id=KfM2rgEACAAJ

[2] B.W. Kernighan and D. Ritchie. *The C Programming Language*. Pearson Education, 1988. ISBN 9780133086218. URL https://books.google.com/books?id=Yi5FI5QcdmYC

the course material. That said, searching online for the meaning of error messages, or for syntax questions is encouraged.

A frequent source of questions about the course material come in a form that could easily be tested by the student with a bit of C code. For example, a student might ask, *"I know that pointer arithmetic cannot be done on* `void*` *pointers. So... if we have two* `void*` *pointers,* `void* x` *and* `void* y`*, can we find the difference between their addresses by doing* `y - x` *or would that count as pointer arithmetic?"* This is a great question! However, it is also a question that can be tested with a little bit of C code, as shown in Figure 1. The student who can produce C code to answer questions such as this one have truly learned to swim in the programming ocean!

Figure 1: `test_void_star.c` Simple test programs can often answer questions about syntax, or language usage, and we encourage students to write short test programs for just such a purpose.

```
// file: piazza_question.c
#include<stdio.h>
#include<stdlib.h>

int main()
{
    int m = 0;
    int n = 1;

    void *x = &m;
    void *y = &n;

    printf("x - y: %lu\n",x - y);

    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall -Wfloat-equal -Wtype-limits \
    -Wpointer-arith -Wlogical-op -Wshadow \
    -fno-diagnostics-show-option void_star_test.c \
    -o void_star_test
void_star_test.c: In function `main':
void_star_test.c:12:29: warning: pointer of type `void *'
used in subtraction
     printf("x - y: %lun",x - y);
                             ^
```

In this course reader I have attempted to produce a detailed overview of what we expect students to be able to do by the end of the course. I have included practice problems that should serve as models of the type of questions that you might see on a CS 107 exam, in a lab, or on a homework assignment. If you can do all of the problems at the end of each chapter, you will be well on your way to a good grade on exams, and you will have a head start on the assignments.

Running the Code in the Reader

Throughout this reader, there are many examples of full (though small) programs that you can run, test, and play around with. We strongly encourage you to try all the programs, and to modify them to test your own understanding of how the programs are run.

The code for the assignments is located here:
`http://stanford.edu/~cgregg/107-Reader/107-Reader-code.zip`

If you are on a Myth machine and want to use the code, type the following (without the $, which is the prompt):

```
$ cd
$ wget http://stanford.edu/~cgregg/107-Reader/107-Reader-code.zip
$ unzip 107-Reader-code.zip
$ cd code
$ make
```

All of the programs will be compiled (there will be a few warnings). All code examples in the text have the file name as the first line of the code, so you should be able to quickly determine which file to run.

The code should work on any Linux system with `gcc` and `make` installed[3], and on a Mac with `XCode` and the "command line tools" installed[4]. The easiest way to install and run the tools on a Windows 10 or higher machine is to enable "Bash" and then install `gcc` and `make`[5]

Once you unzip the file, all the programs can be compiled with the `make` command.

[3] To install the tools on Ubuntu, try the following: `sudo apt-get install gcc make build-essential linux-headers-$(uname -r)`.

[4] To install `XCode`, open the App store and search for `XCode`. You most likely won't have to download anything else, although the first time you try to make a file, you might be prompted to install the command line tools

[5] A web search for "install gcc windows 10 bash" should direct you to some helpful guides.

Links in the Text and Footnotes

This reader has multiple Internet links to extra information, in both the main text, and primarily in the footnotes. The links provide a combination of online reference material, further information, and general information. Many of the links are from Wikipedia, which is a triumph of 21st Century knowledge and information, and completely free.[6]

[6] which means that you should donate to Wikipedia if you use it! My general rule for donating to Wikipedia: one cent per visit. If you find yourself visiting Wikipedia ten times a day, pony up the $36.5 once a year when you see that "donate now!" link!

Contact Information

Please forward any typos or other comments on the text to cgregg@stanford.edu, and I hope you have a terrific experience learning about the lower depths of your computer!

Unix, the Command Line, gcc, and Makefiles

In your introductory CS courses, you may have learned to program using an *Integrated Development Environment* (IDE) such as *Eclipse* or *Qt Creator*. As their name implies, IDEs provide a full toolset to write, build, compile, run, and debug your programs. This is a terrific environment for beginning programmers to start learning the "art of computer programming" (as coined by Donald Knuth[7]). However, IDEs also hide the mechanics of turning text code (e.g., written in `C` or `Java`) into the *binary* representation that we will study in CS 107. Instead of using an IDE to create your programs, you will use a number of tools provided through the *Linux terminal*, and together they will take you from program creation in `C` to compilation (via `make` and `gcc`) to debugging via `gdb` and running your program on the *command line*. If all of those terms are foreign to you, you are not alone – many students who take CS 107 have never used the terminal, nor have they directly used any of the tools used to turn their programs into runnable applications.

In order to get up to speed using the Linux terminal, you should see the course website, which has a number of tutorial videos that describe how to set up your computer to log into the *Myth* computers at Stanford. If you are going through this reader and not at Stanford, unfortunately you won't have access to the Myth computers, but much of the online material can be used on a generic Linux command line. If you don't have a computer that natively runs Linux as its operating system, I suggest installing a virtual machine for Linux.[8] Once you install a virtual machine, you should install the latest version of `gcc` and `gdb`, which will enable you to follow most of the examples in the reader.

[7] Don Knuth, *Professor Emeritus of The Art of Computer Programming* at Stanford, is a legendary computer scientist one of the world's foremost algorithmists. He is the author of a magnum opus, *The Art of Computer Programming*. He is also the creator of TEX, the typesetting engine that this reader was typeset in.

[8] An online search for "how to install a Linux VM" will lead to many results.

Unix and Linux

Unix is an operating system that dates from the early 1970s and was originally created primarily by Ken Thompson[9] and Dennis Ritchie[10] at Bell Labs. It was the first operating system that was written to be portable, and it was completely written in the `C` programming language[11], also created by Dennis Ritchie. In the early 1990s, Linus Torvalds began an open-source version of Unix that he called *Linux*, and Linux has become a standard, free, open source operating system used on millions of computers around the world.

[9] Thompson's Reflections on Trusting Trust is a terrifying look at why you can never completely trust your compiler

[10] See this Wired Magazine tribute about Dennis Ritchie to understand why he deserves more name recognition

[11] Except for the machine specific parts, which were written in Assembly Language for each particular computer. But, the bulk of the operating system was written in `C`

Figure 2 shows an example of the Linux terminal, which is the interface that you will use in CS 107 to edit, compile, run, and debug your programs. Once you have worked out how to log into the Myth machines (again, see the course website), the next critical event is to choose an editor. There are multiple choices, but `vim` and `emacs` are two popular choices. Whichever editor you end up choosing, you should learn as many keyboard shortcuts as you can: the faster you are able to navigate around your programs, the easier it will be to concentrate on the coding itself.

Figure 2: A typical Linux terminal window.

The Unix Philosophy

The Unix creators had a simple philosophy[12]: command-line programs should be simple and should do one thing well. For example, the `cat` program has one job, and that is to read a file and print the file to the terminal. It is a simple program, and it does the job well. We will spend a lot of time in CS 107 writing programs that do one thing well – sometimes you may think we abuse the notion of *simple* (because the programs we write can be complex to write), but all of the programs you write for class will do a single thing.[13]

[12] as described by Ken Thompson.

[13] Possibly in different ways. For example, you will write a sorting program that will sort based on options, such as reverse-ordering, or based on the length of a line.

Compiling programs using `gcc`

CS 107 is taught primarily in the `C` programming language, and the compiler we will use to turn our `C` programs into binary code is the *Gnu Compiler Collection*, otherwise known as `gcc`[14]. `Gcc` has many options for compiling our code, and it can compile code to *binary* (machine) code that can be run directly, or into *assembly* code, which can then be compiled into binary code. For the first half of the course, we will be compiling with the `-O0` *optimization* flag, which will produce code that is able to be debugged easily in the *gdb* debugger (more on the debugger later). Once we begin discussing assembly code, we will compile with the `-Og` optimization flag, which will make less verbose assembly code to look at.

[14] gcc was initially created by Richard Stallman, a unique character in computer science, and the founder of the Free Software Foundation. All of the software we will use in CS 107 is both "free as in speech and free as in beer"

Specifically, we will be compiling our code in the following way:[15]

[15] Only type the code in **bold**. The dollar sign at the beginning of the line is the command-line prompt

```
$ gcc -g -O0 -std=gnu99 -Wall -Wfloat-equal -Wtype-limits \
    -Wpointer-arith -Wlogical-op -Wshadow \
    -fno-diagnostics-show-option program_name.c \
    -o program_name
```

The following briefly describes the options we use (and a backslash means that the line is continued onto the next line, so the entire text above is technically one long line):

`gcc`] The name of the `gcc` program

`-g` Include debugging information (necessary when using `gdb` for debugging)

`-O0` The optimization level (no optimization, good for debugging)

`-std=gnu99` Use the `gnu99` `C` standard, which allows (among other things) the ability to define `for` loop variables inside the loop declaration, e.g., `for (int i=0; i < 10; i++)`

`-Wall, -W...` Warning options, to provide useful warnings when compiling code.

`-fno-diagnostics-show-option` Suppress showing which warning option triggered a particular warning

`program_name.c` The `C` program name that we are compiling.

`-o program_name` The output program name that can be run by typing `./program_name`

Compiling programs using `make`

As the previous section describes, there are a lot of options to compiling a program using `gcc`! There are additional options to compile multiple files into one executable, too, and this will depend on the programs you are writing.

Instead of typing the entire `gcc` line every time you want to compile your program, we will provide you a text file called "`Makefile`" that has all of the necessary commands to properly compile all of your code for the projects. To compile your projects using a `Makefile`, simply run the following command[16]:

[16] `make` is another `GNU` program that automates building programs.

```
$ make
```

That's it! `Make` also performs another helpful function: if any of your source programs have changed, running `make` again re-builds the projects, automatically, and only re-builds the necessary programs.

A `Makefile` can contain instructions to build multiple programs, and many of the CS 107 assignments have multiple programs in them. If you only want to build a particular program, you can do so by telling `make` to build just one. For example, assignment 1 has four programs, called `code`, `sat`, `automata`, and `utf8`. To just build `sat` (for instance), you would type:

```
$ make sat
```

In order to remove the programs and re-compile all of them, you type:

```
$ make clean
$ make
```

Using `git`

You will work on all of your projects for CS 107 in your local directory on the Stanford computer network. However, your code will be copied from a different directory, also located on the network. Specifically, for each assignment, you will run a command similar to the following (which is the command for assignment 0):

```
$ git clone /afs/ir/class/cs107/repos/assign0/{$USER} assign0
```

This command runs a program called `git`[17], which is a *version control system* that is designed to keep versions of your code so that you can always go back to previous versions. One thing that `git` does that might be important as you go through the course is that it can, in essence, keep backups for you. Any time you change the text in a file, you can *commit* that file into the repository, and then you can go back to that version whenever you want. If you want even more backup security, you can *push* your changes to the master repository where the initial cloned version resides. In fact, whenever you run `sanitycheck` (see the next section for details), this is what that program does.

[17] git is distinct from GitHub; the former is the program that provides the versioning tools, and the latter is a website that provides repository storage and sharing.

The following example demonstrates how you might use `git` for assignment 1. Assume you change the `utf8.c` program, and want to save the current state as a backup. You would run the following commands:

```
$ git commit -m "Added code to test on 1-byte examples" utf8.c
$ git push
```

You might get warning message that "warning: push.default is unset;" To stop the warning, type the following: `git config --global push.default simple`

The first command commits the `utf8.c` file to your local repository, with a message (*-m*) that says what the change accomplished[18]

[18] Good commit messages are important for finding old versions!

The second command pushes the change to the master repository, where it originally came from. All previous `commits` are stored, as well.

Let's say that you made another change and committed it, but it turns out that you deleted an important function, accidentally. If you need to go back to a previous commit temporarily, you can do so as follows:

```
$ git log
commit d0fcf945876592e2bb74e26f31fcad7ffb850451
Author: Chris Gregg <tofergregg@gmail.com>
Date:   Fri Dec 15 14:38:27 2017 -0800

    Took out unneeded function

commit fb8f84f57672b0b9ded5cd4dd737141650cf7aea
Author: Chris Gregg <tofergregg@gmail.com>
Date:   Fri Dec 15 14:33:34 2017 -0800

    Added code to test on 1-byte examples
```

```
...

$ git checkout fb8f84f57672b0b9ded5cd4dd737141650cf7aea
M       code.c
Note: checking out 'fb8f84f57672b0b9ded5cd4dd737141650cf7aea'.

You are in 'detached HEAD' state. You can look around, make experimental
changes and commit them, and you can discard any commits you make in this
state without impacting any branches by performing another checkout.

If you want to create a new branch to retain commits you create, you may
do so (now or later) by using -b with the checkout command again. Example:

  git checkout -b new_branch_name

HEAD is now at fb8f84f... Added code to test on 1-byte examples
```

The big long number from the commit log (`fb8f84f57672b0b9ded5cd4dd737141650cf7aea`) is used to uniquely identify that version. Now that you have checked out that version, you can go look at it, and copy anything you need from that file to a temporary file. Then, you can go back to the latest version and fix your error:

```
$ git checkout master
Previous HEAD position was fb8f84f... Added code to test on 1-byte examples
Switched to branch 'master'
Your branch is ahead of 'origin/master' by 2 commits.
  (use "git push" to publish your local commits)
```

Testing and using `sanitycheck`

A critical task you must do while writing your programs is compiling, running, and testing your code regularly, and often. The definition of *often* does not mean "when you are done with the program" – it means every time you make a change to your code. Some programmers compile after *every block of code* they write, and this is a very good idea. A good strategy is to write a block of code, compile it, and then fix all warnings and errors. Then you compile again. You can catch errors quickly, and you know exactly where in the code the error is happening. In CS 107, we frown upon[19] code that has warnings, and your code should always compile cleanly with no errors or warnings. You are not allowed to even submit code with compilation errors, in fact.

[19] i.e., take off points

Learning how to test your code properly takes time. In CS 107, for each assignment we provide you with a program called `sanitycheck` that runs some rudimentary tests on your code. When you run `sanitycheck`, you get a list of tests and whether your code passed or failed each test. When we grade your code, we run an additional set of tests in a similar manner, and those tests are comprehensive and are designed to find any corner cases in your code.

To run sanitycheck on your code, type the following from a project directory:

```
cgregg@myth32:~/cs107/assign1$ tools/sanitycheck

Will run default sanity check for assign1 in current directory
.ir.stanford.edu/users/c/g/cgregg/cs107/assign1.

+++ Test A-Make on .ir.stanford.edu/users/c/g/cgregg/cs107/assign1
Descr:   verify project builds cleanly using 'make'
Command: make
OK:  Clean build

+++ Test B-SatRange on .ir.stanford.edu/users/c/g/cgregg/cs107/assign1
Descr:   min and max value of range for 12-bit signed
Command: ./sat 12
MISMATCH:  Submission output does not match sample
Sample output:
12-bit signed integer range
min: -2048   0xfffffffffffff800
max:  2047   0x00000000000007ff
Your output:
12-bit signed integer range
min: -2048   0xfffffffffffff800
max:  2048   0x0000000000000800

+++ Test C-SatAdd on .ir.stanford.edu/users/c/g/cgregg/cs107/assign1
Descr:   test saturating addition oveflow case
Command: ./sat 8 127 45
MISMATCH:  Submission output does not match sample
Sample output:  127 + 45 = 127
Your output:    127 + 45 = 128
... (more follows)
```

For this example, there was a mismatch with `Test B-SatRange`, and you can see the expected output and your output.

You can also create your own (somewhat rudimentary) tests using sanitycheck, too. Each assignment comes with a `custom_tests` file that you can modify to add your own tests. For example, the default assignment 1 `custom_tests` file is:

```
sat 16 -32768 -32768
automata 90
utf8 0x20AC
```

You run your custom tests as follows:

```
$ tools/sanitycheck custom_tests
```

It is hard to overstate the importance of testing your code for CS 107. Students who learn to test their code early and often have fewer problems writing good code, and they ultimately do better in the course.

Number Formats Used in CS 107

TODAY'S COMPUTERS ARE, at the lowest level, *binary* machines[20], and all numbers in a computer are represented in base 2 notation, which consists entirely of the digits 0 and 1. Humans are generally used to base 10, which has eight additional digits: 2, 3, 4, 5, 6, 7, 8, and 9. Additionally, base 16 is also used when representing numbers in a computer, because 16 is a multiple of 2, and therefore it is easy to convert between base 2 and base 16. Base 16 has the following digits: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, a, b, c, d, e, and f.

Therefore, in CS 107, you must be extremely familiar with all three bases that are used to represent numbers, and you must be able to convert between them quickly (or be familiar with online conversion tools). We will describe what you need to know in this chapter, and you would be well-advised to learn the details as soon as you can.

[20] There have been computers based in a *ternary* format, as well

Base 10

Let's start by reminding ourselves about the number system we use every day. The other two bases we will discuss are analogous, but it might help to think a bit deeper about base 10 before we move onto the other bases.

Base 10 numbers have the digits 0-9, and counting proceeds by adding one digit at at time, until the digits are exhausted, at which point you add a power of 10, and then repeat from 0 again. That is a fancy way of saying that when you get to 9, you continue counting at 10:

$$0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, ..., 97, 98, 99, 100, 101, ..., 998, 999, 1000, ...$$

A base 10 number with three digits, $d_2 d_1 d_0$ is actually represented as follows:

$$d_2 \times 10^2 + d_1 \times 10^1 + d_0 \times 10^0$$

So, for example, the number 425 is:

$$4 \times 10^2 + 2 \times 10^1 + 5 \times 10^0 = 400 + 20 + 5 = 425$$

When adding two base 10 numbers together, we *carry* numbers greater than 9 to the next higher power-of-10 position:

$$\begin{array}{rr} & {\scriptstyle 1\,1} \\ & 178 \\ + & 456 \\ \hline & 634 \end{array}$$

When subtracting two base 10 numbers, we *borrow* when we are trying to subtract a digit from a smaller digit, treating the subtraction as the $10 + d_{smaller} - d_{larger}$, and reducing the digit that was carried from by one:

$$\begin{array}{rr} & {\scriptstyle 2\,14} \\ & 6\not{3}\not{4} \\ - & 416 \\ \hline & 218 \end{array}$$

Two definitions you should become familiar with are *least significant digit* and *most significant digit*:

Least significant digit: The digit farthest to the right of a number.

Most significant digit: The digit farthest to the left of a number.

The least significant digit is the digit that matters the least in a number. In the number 456, the 6 represents just 6, and the 4 represents 400, so the 6 is least significant and the 4 is most significant.

Base 2 (binary)

Base 2, or *binary* notation, has only the digits 0 and 1. Just like counting in base 10, when the digits are exhausted, you must start with a new 1:

$$0, 1, 10, 11, 100, 101, 110, 111, 1000, 1001, 1010, 1011, 1100, 1101, ...$$

As you can see, binary numbers can get long quickly, as there are only two digits to write with!

Base 2 notation is comprised of powers of 2 (instead of powers of 10), so a base 2 number with four digits, $b_3b_2b_1b_0$ is represented as follows:

$$b_3 \times 2^3 + b_2 \times 2^2 + b_1 \times 2^1 + b_0 \times 2^0$$

For example, $1101b$ is:

$$1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 = 8 + 4 + 0 + 1 = 13d$$

To differentiate between binary and decimal representations, we use b and d following each number

In other words, 1101 binary is 13 decimal, and this is the method we use to determine a base 10 number if we have a base 2 number.

To convert a base 10 number into base 2, we must perform a series of divisions, taking the remainder each time, and growing the binary number from least significant digit to most significant digit, until the division produces zero. For example, to convert $1234d$ to binary:

$1234d/2 = 617$, remainder 0	the least significant digit is **0**
$617d/2 = 308$, remainder 1	the next digit to the left is **1**
$308d/2 = 154$, remainder 0	the next digit to the left is **0**
$154d/2 = 77$, remainder 0	the next digit to the left is **0**
$77d/2 = 38$, remainder 1	the next digit to the left is **1**
$38d/2 = 19$, remainder 0	the next digit to the left is **0**
$19d/2 = 9$, remainder 1	the next digit to the left is **1**
$9d/2 = 4$, remainder 1	the next digit to the left is **1**
$4d/2 = 2$, remainder 0	the next digit to the left is **0**
$2d/2 = 1$, remainder 0	the next digit to the left is **0**
$1d/2 = 0$, remainder 1	the next digit to the left is **1**

Therefore, the final result is

$$1234d = 10011010010b$$

We won't expect you to convert from decimal to binary regularly, but you should be able to do it. To convert $10011010010b$ to decimal (it is only necessary to calculate bits that are 1)

$$10011010010b = 2^{10} + 2^7 + 2^6 + 2^4 + 2^1 = 1024 + 128 + 64 + 16 + 2 = 1234d$$

Because we will use them often, you should simply memorize the first ten powers of 2:

$$2, 4, 8, 16, 32, 64, 128, 256, 512, 1024$$

When adding two binary numbers together, there are many more carries than in decimal addition, because every time 1 is added to 1, there is a carry. Also, remember that $1 + 1 = 10$, and $1 + 1 + 1 = 11$:

$$\begin{array}{rr} & {\scriptstyle 11} \\ & 1011 \\ + & 1011 \\ \hline & 10110 \end{array}$$

When subtracting two binary numbers, the borrow happens any time a 1 is subtracted from a 0:

$$\begin{array}{rr} & {\scriptstyle 10} \\ & 1\not{0}110 \\ - & 1010 \\ \hline & 1100 \end{array}$$

Base 16 (hexadecimal)

Base 16 may at first seem like an odd choice for a base for computing. It has more digits than decimal, and computers are fundamentally binary. However, one of the downsides of binary is that binary

numbers are long and difficult for humans to cognitively process.[21] Hexadecimal (hex) numbers, on the other hand, are four times shorter than their equivalent binary representations, and although reading a number with letters for some of the digits does take some time to get used to, reading hex numbers becomes second nature with practice. Additionally, and the underlying reason why we often use hexadecimal notation is because the conversion from binary to hexadecimal, and back again, is extremely easy (as we shall see in a few paragraphs).

[21] i.e., they are hard to read!

A hexadecimal number (represented with `0x` preceding the number, e.g., `0x4a`) has sixteen digits: `0,1,2,3,4,5,6,7,8,9,a,b,c,d,e, and f`. The letters `a-f` represent the numbers `10-15`. When counting, a `1` is added after the last digit is `f`:

```
0,1,2,3,4,5,6,7,8,9,a,b,c,d,e,f,10,11,12,13,...,fc, fd, fe, ff, 100, 101,...
```

Because both the base for both binary and hexadecimal formats are divisible by 2, the conversion between them is straightforward. Every four binary digits (or *bits*) is equivalent to one hexadecimal digit. Tables 1 and 2 show the conversion from hex digit to binary (and decimal). You should memorize the binary representations for each hex digit. One trick is to memorize `A (1010)`, `C (1100)`, and `F (1111)`, and the others are easy to figure out.

Hex digit	0	1	2	3	4	5	6	7
Decimal value	0	1	2	3	4	5	6	7
Binary value	0000	0001	0010	0011	0100	0101	0110	0111

Table 1: Hexadecimal to binary conversion for `0 - 7`

Hex digit	8	9	A	B	C	D	E	F
Decimal value	8	9	10	11	12	13	14	15
Binary value	1000	1001	1010	1011	1100	1101	1110	1111

Table 2: Hexadecimal to binary conversion for `8 - 15`

Translating between binary and hexadecimal is trivial if you know the digits. For example:

`0x135af2` = `0001 0011 0101 1010 1111 0010b`

Each hex digit converts directly to a 4-digit binary number:

```
0x1 = 0001
0x3 = 0011
0x5 = 0101
0xa = 1010
0xf = 1111
0x2 = 0010
```

Translating between hexadecimal and binary is just as easy. For example:

`0101 1111 0111 1100 1111 0010b` = `0x5f7cf2`

Translating from hex to decimal is similar to converting from binary to decimal. A 4-digit hexadecimal number in the form $x_3x_2x_1x_0$ is equal to:

$$x_3 \times 16^3 + x_2 \times 16^2 + x_1 \times 16^1 + x_0 \times 16^0$$

For example:

$$\texttt{0x1ea5} = 1 \times 16^3 + 14 \times 16^2 + 10 \times 16^1 + 5 \times 16^0 = 7845d$$

To translate from decimal to hexadecimal, you perform a series of divisions by 16 with remainders, which is similar to the decimal to binary translation. You will not have to perform those translations by hand in CS 107, and it is reasonable to use a computer to do so.[22]

[22] You can perform the conversion on the command line as follows (this assumes you have Python installed):

```
$ python -c "print bin(1234)"
0b10011010010
$ python -c "print hex(0b1010101)"
0x55
$ python -c "print 0xabcd1234"
2882343476
$ python -c "print bin(0xa1b2)"
0b1010000110110010
```

Using `man ascii`

The **`man`** command in Linux is one of the most helpful commands for quickly finding something out about another command, or a library function. If you need to quickly determine the ASCII character values in decimal or hex, or if you need to quickly determine the decimal or hex conversion for numbers less than 255, you can do so with the **`man ascii`** command:

ASCII(7) Linux Programmer's Manual ASCII(7)

NAME

ascii - ASCII character set encoded in octal, decimal, and hexadecimal

DESCRIPTION

ASCII is the American Standard Code for Information Interchange. It is a 7-bit code. Many 8-bit codes (such as ISO 8859-1, the Linux default character set) contain ASCII as their lower half. The international counterpart of ASCII is known as ISO 646.

The following table contains the 128 ASCII characters.

Oct	Dec	Hex	Char	Oct	Dec	Hex	Char
000	0	00	NUL '\0'	100	64	40	@
001	1	01	SOH (start of heading)	101	65	41	A
002	2	02	STX (start of text)	102	66	42	B
003	3	03	ETX (end of text)	103	67	43	C
004	4	04	EOT (end of transmission)	104	68	44	D
005	5	05	ENQ (enquiry)	105	69	45	E
006	6	06	ACK (acknowledge)	106	70	46	F
007	7	07	BEL '\a' (bell)	107	71	47	G
010	8	08	BS '\b' (backspace)	110	72	48	H
011	9	09	HT '\t' (horizontal tab)	111	73	49	I
012	10	0A	LF '\n' (new line)	112	74	4A	J
013	11	0B	VT '\v' (vertical tab)	113	75	4B	K
014	12	0C	FF '\f' (form feed)	114	76	4C	L
015	13	0D	CR '\r' (carriage ret)	115	77	4D	M
016	14	0E	SO (shift out)	116	78	4E	N
017	15	0F	SI (shift in)	117	79	4F	O
020	16	10	DLE (data link escape)	120	80	50	P
021	17	11	DC1 (device control 1)	121	81	51	Q
022	18	12	DC2 (device control 2)	122	82	52	R
023	19	13	DC3 (device control 3)	123	83	53	S
024	20	14	DC4 (device control 4)	124	84	54	T
025	21	15	NAK (negative ack.)	125	85	55	U
026	22	16	SYN (synchronous idle)	126	86	56	V

Oct	Dec	Hex	Char	Oct	Dec	Hex	Char
027	23	17	ETB (end of trans. blk)	127	87	57	W
030	24	18	CAN (cancel)	130	88	58	X
031	25	19	EM (end of medium)	131	89	59	Y
032	26	1A	SUB (substitute)	132	90	5A	Z
033	27	1B	ESC (escape)	133	91	5B	[
034	28	1C	FS (file separator)	134	92	5C	\ '\\'
035	29	1D	GS (group separator)	135	93	5D	]
036	30	1E	RS (record separator)	136	94	5E	^

037	31	1F	US (unit separator)	137	95	5F	_
040	32	20	SPACE	140	96	60	`
041	33	21	!	141	97	61	a
042	34	22	"	142	98	62	b
043	35	23	#	143	99	63	c
044	36	24	$	144	100	64	d
045	37	25	%	145	101	65	e
046	38	26	&	146	102	66	f
047	39	27	`	147	103	67	g
050	40	28	(	150	104	68	h
051	41	29	)	151	105	69	i
052	42	2A	*	152	106	6A	j
053	43	2B	+	153	107	6B	k
054	44	2C	,	154	108	6C	l
055	45	2D	-	155	109	6D	m
056	46	2E	.	156	110	6E	n
057	47	2F	/	157	111	6F	o
060	48	30	0	160	112	70	p
061	49	31	1	161	113	71	q
062	50	32	2	162	114	72	r
063	51	33	3	163	115	73	s
064	52	34	4	164	116	74	t
065	53	35	5	165	117	75	u
066	54	36	6	166	118	76	v
067	55	37	7	167	119	77	w
070	56	38	8	170	120	78	x
071	57	39	9	171	121	79	y
072	58	3A	:	172	122	7A	z
073	59	3B	;	173	123	7B	{
074	60	3C	<	174	124	7C	|
075	61	3D	=	175	125	7D	}
076	62	3E	>	176	126	7E	~
077	63	3F	?	177	127	7F	DEL

C Primer

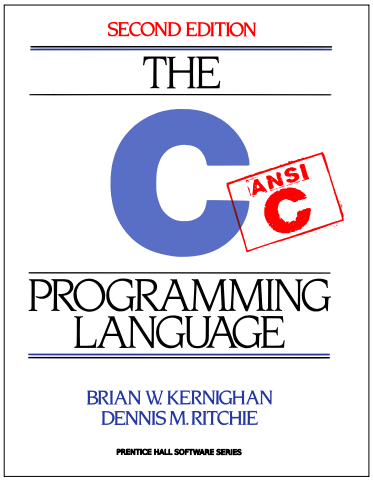
As you begin CS 107, we expect that you have had a good introduction to programming course, and a good follow-on course that covers typical data structures content for a second programming course. At Stanford, CS 106A and CS 106B are excellent preparation for CS 107 and they are taught in Java and C++, which are both based on C syntax, and both have similar function structure, loop constructs, variable naming and scoping. The transition to C after coding in Java and/or C++ is relatively straightforward, and you should quickly feel at home. If your background is in a language like Python, Ruby, R, PHP, or a functional language like Lisp or Haskell, you may need more time to assimilate to C.

Whatever your background, C does come with its own intricacies, some of which are historical in nature, and some of which might be, to some, a bit dated. You will write a great deal of of pointer-based code that provides very little safety, and this is just how C rolls. C does not have any notion of classes, and memory management is neither garbage collected like in Java, nor object-based like in C++. But, C is actually a language that is simple enough that you can become an expert in the language – once you learn a few crucial details, C becomes a language that allows you to do exactly what you want, and fast, though sometimes at the expense of "ease."

As discussed in *Unix, the Command Line, gcc, and Makefiles*, C was invented in the 1970s by Dennis Ritchie as a *systems* language that could be used to write low-level, portable code that could be run on any computer with a C compiler. Ritche and Ken Thompson wrote Unix in C, and the popularity of Unix cemented C into a key role in systems programming ever since.

This chapter is designed to provide an introduction to programming in C *-vs-* other C-syntax based languages – we primarily want to show you some of the nuances in C that you will need to get used to as you start CS 107. C++ actually shares many of the features described in the chapter (and Java shares some, as well), but in CS 106B we generally focus on other C++ features than the ones discussed here. The chapter isn't in any particular order, and can be used as a reference to some of the syntax as you begin CS 107.

Figure 3: *The C Programming Language* by Brian Kernighan and Dennis Ritchie (also known as "K&R") is the definitive text on C and should be in every C programmer's library.



C *Basics*

If you are comfortable with either Java or C++, C will be familiar, although if you haven't used pointers before, you will need to learn about them. The following annotated C program describes many of the typical parts of a C program:

```
/* file: personhours.c
 * Calculates persondays worked for an array
 * of jobs and an array of people per job
 */

#include<stdio.h>
#include<stdlib.h>

#define WORKDAYSPERYEAR 250
#define WORKHOURSPERDAY 8

void scalearray(int *input,const int *scale,
                size_t nelems);
void converttohours(int *input, size_t nelems);
int  workyearstohours(int days);

int main(int argc, char *argv[])
{
   // jobdays initially holds
   // the number of days worked per job
   int jobdays[]      = {1, 5, 7, 2, 4, 8, 3};

   // workersperday holds the number of workers
   // who worked each day on a job
   int workersperday[] = {2, 5, 7, 1, 9, 4, 5};

   size_t arrsz = sizeof(jobdays) /
       sizeof(jobdays[0]);

   converttohours(jobdays,arrsz);
   scalearray(jobdays,workersperday,arrsz);

   for (int i=0; i < arrsz; i++) {
      printf("%d",jobdays[i]);
      i == arrsz-1 ? printf("\n") : printf(", ");
   }
   return 0;
}
```

Comments come in two forms. Multiline comments start with "/*" and end with "*/", and cannot be nested. Single-line comments start with "//" and only go to the end of a line.

These are the two typical library `include` statements, for input/output and the C standard library.

The "`#define`" syntax defines a constant that the C Preprocessor replaces in your code before compilation.

Function prototypes declare functions before they are defined. A function must be declared before it can be used in C, and we normally put function declarations at the top of a file so we can use them from any function below.

All C programs begin at the `main` function, which must return an `int`. See below for more information about the `argc` and `argv` command line arguments.

C arrays can be declared with the "`[]`" notation and an initial comma separated list of values. The compiler will determine the size of the array accordingly.

The `size_t` type is an unsigned integer type that holds the size of an object (like an array).

See *Bits and Bytes* for information about `sizeof`. This is the standard way to determine the number of elements in a fixed-size array. This *does not* work for arrays that are created via `malloc`.

See below for details about `printf`, which is the standard way to print to the terminal in C.

The "ternary operator" is a shorthand if/else statement. The syntax is:

```
a ? x : y
```

and can be read as "if *a* then *x* else *y*".

```c
/* multiply each element in input by the
 * corresponding scaling element in scale
 */
void scalearray(int *input,const int *scale,
                size_t nelems)
{
   for (size_t i=0; i < nelems; i++) {
      input[i] *= scale[i];
   }
}

/* convert workdays array to hours */
void converttohours(int *input, size_t nelems)
{
   for (size_t i=0; i < nelems; i++) {
      *(input+i) = workyearstohours(*(input+i));
   }
}

/* convert a workday into a number of hours */
int workyearstohours(int days)
{
   return days * WORKDAYSPERYEAR *
      WORKHOURSPERDAY;
}
```

Functions must be declared with a return type, although that type can be `void` if nothing will be returned. See below for information about `const`.

`for` loops may declare the loop variable inside the declaration, with `gcc` flag `-std=gnu99`.

Array elements can be accessed using the `[index]` notation. Note that any pointer can act as an array in this way. Also note that arrays and pointers do not carry information about the number of elements, and you need to pass along this information as a parameter (in this case, `nelems`).

Array elements can also be accessed using *pointer arithmetic* with dereferencing.

Function names in `C` are generally either squished together (as in `workyearstohours` or with underscores as separators, e.g., `workyears_to_hours`. You should get used to both. `camelCase` is not generally preferred.

The `printf` *statement*

The `printf` statement is the preferred way in `C` to output text to the screen or to *standard out* (`stdout`). The `printf` function has the following function declaration:

```c
int printf(const char *format, ...);
```

The first parameter is the *format string*, which contains the string that will be printed, along with optional *embedded format specifiers*, which start with the "%" character. For every format specifier, there is an additional parameter that provides the value to be formatted.[23] Most often, the return value for `printf` is ignored, but the return value is the number of characters that were printed. For example,

[23] for a comprehensive list, see this reference.

```c
int x = 5;
char c = 'A';
char *str = "some words";
printf("x: %d, a character: %c, a string: %s\n",x,c,str);
```

Special characters in the format string are prepended with a backslash, "\". The most common special character is the newline

character, \n, which prints a newline (similar to "cout « endl;" in C++).

The output from the above printf statement is:

```
x: 5, a character: A, a string: some words
```

Table 3 shows the common printf specifiers we will use in CS 107.

Table 3: Common printf specifiers

Spec.	Output	Example
d or i	Signed integer	-5
u	Unsigned integer	12
x	Unsigned hex int	9f02
f	Floating point	123.45
g	Alt. floating point	1.23E+02
c	Character	a
s	String	text
p	Pointer addr	b8000000
%%	Prints a single %	%

The print specifier can also have a length sub-specifier, which modifies the length of the data type. For example, if you want to print out an unsigned long, you need to use the %lu format specifier, which will expect an unsigned long variable in the parameter list. E.g.,

```
unsigned long x = 5000000000;
printf("x: %lu\n",x);
```

Output:

```
5000000000
```

Gcc will give a warning if you attempt to specify an incorrect length for the parameter you pass in. E.g.,

```
int x = 50;
printf("x: %lu\n",x);
```

```
$ gcc -g -O0 -std=gnu99 printf_ex.c -o printf_ex
printf_ex.c: In function 'main':
printf_ex.c:7:5: warning: format '%lu' expects argument of type 'long unsigned int',
  but argument 2 has type 'int' [-Wformat=]
     printf("x: %lu\n",x);
     ^
```

The Standard Library

C comes with a robust *standard library* that has hundreds of functions available to C programmers. The two most common libraries are stdlib and stdio, and they will be included in all of our programs. Other common libraries include string, math, assert, errno, limits, and stdbool.[24] We will focus on the string library (string.h in a later chapter. For CS 107, we will have assignments where you will write some standard library functions, and you should be familiar with a number of the libraries.

[24] See a complete list on Wikipedia.

All of the standard library function specifications are available in the Linux reference manual, which you can access via the man command. For example, to look up the atoi function, which converts a string to an integer, you type:

```
$ man atoi
```

which brings up the manual entry for the function from the stdlib library. All the standard library functions are in section 3

of the Linux reference manual, although sometimes there are also Linux command line functions listed, as well. For example, typing `man printf` will bring up the manual page for the Linux command line `printf`, and if you want the `C` library `printf`, you must type `man 3 printf` to bring up the version from the standard library.

For CS 107, you should generally utilize the standard library as often as possible. Unless we specifically ask you to program a particular library function[25], you should always use a library function for the task you are trying to accomplish, if one exists. Many students have tried to re-write standard library functions unsuccessfully, and it isn't worth the time[26] to try and write them on your own. The standard library functions are fast, efficient, and well-tuned, as they are used by millions of programs daily.

[25] For example, you will write a version of `cat`, a version of `ls`, and a version of `which`.

[26] or the potential for missed points because you wrote them incorrectly!

The command line arguments, `argv` *and* `argc`

One way to provide your `C` program data is through *command line arguments*. For example, your program might accept three words as input, and you could type them into the command line when you start the program:

```
$ ./alphabetize dog hamster cat
cat dog hamster
```

The command line arguments are available to `C` programs through two variables, `argc` and `argv`, and are parameters to main:[27]

```
int main(int argc, char *argv[]);
```

or, alternatively (and exactly equivalent):

```
int main(int argc, char **argv);
```

[27] There is a third parameter we will use in assignment 2, called `envp`, which provides access to the Linux environment variables.

`int argc` : This parameter holds the number of parameters, *including the program name*. For our eample above, `argc` would have the value 4, because there are four arguments: `./alphabatize`, `dog`, `hamster`, and `cat`.

`char *argv[]` : This paramter holds an array of `C` string pointers. It is equivalent to `char **argv`. Each string can be accessed using bracket notation, e.g., `argv[1]` or pointer arithmetic and dereference notation, e.g., `*(argv + 1)`.

The following is a full example using the command line arguments:

```
// file: argument_list.c
#include<stdio.h>
#include<stdlib.h>

int main(int argc, char *argv[])
{
    for (int i=0; i < argc; i++) {
```

```
        printf("Argument %d: %s\n",i,argv[i]);
    }
    return 0;
}
```

```
$ ./argument_list dog hamster cat
Argument 0: ./argument_list
Argument 1: dog
Argument 2: hamster
Argument 3: cat
```

C *Arrays and* C *Strings*

Arrays in C are simple, although they have some caveats to be aware of. Arrays are a contiguous block of memory with a fixed length. A programmer can access elements in an array using either bracket notation (e.g., `arr[2]`) or by dereferencing an offset from the beginning of the array (e.g., `*(arr + 2)`). Although arrays sometimes behave like pointers (see below), they are distinct and should not be confused with pointers. The following program is an example of an array declaration and accessing the array elements:

```
// file: array.c
#include<stdio.h>
#include<stdlib.h>

void sizeof_test(int arr[]) {
    printf("sizeof(arr) in function: %lu\n", sizeof(arr));
}

int main()
{
    int arr[] = {1,3,4,2,7,9};

    printf("%d\n",arr[2]); // prints 4
    printf("%d\n",*(arr+5)); // prints 9

    // set the value of the third element
    arr[2] = 42;
    printf("%d\n",arr[2]); // prints 42

    printf("sizeof(arr) in main: %lu\n",sizeof(arr));
    sizeof_test(arr);

    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall array.c -o array
$ ./array
```

```
4
9
42
sizeof(arr) in main: 24
sizeof(arr) in function: 8
```

In the program above, `arr` is an array, but critically, *not* a pointer. When accessing the array elements by either the bracket notation or by dereferencing an offset, the array name is converted to a pointer to the first element of the array to do the calculation[28], however, so it does behave like a pointer in many circumstances.

When applied to arrays, the `sizeof` operator returns the number of bytes of the entire array. For the array in the example above inside `main`, `sizeof(arr)` returned 24 because each `int` is 4-bytes long[29] In the `sizeof_test` function, the array parameter is converted into a pointer to the first element in the array, and therefore `sizeof(arr)` returns the size of a pointer in bytes, which is 8 bytes on the Myth machines.

`C` does not provide any array bounds checking. You as the programmer must ensure that you do not try to read or write past either end of an array, lest you cause a memory error. As seen above, when passing arrays into a function, you must also explicitly pass the number of elements if the function needs that information.

Often, we will declare an array of a particular size, without initializing the values:

```
char buffer[256]; // a 256 byte buffer
```

The scope for the array is within the function (or block) that it is declared in, and it has space for exactly 256 bytes of memory.

Arrays in `C` are not hard to understand, but you do need to be careful to work with them properly.

`C` strings are simply arrays of `chars`, with a truncating 0 byte.[30] Unlike `Java` and `C++`, `C` strings are not objects, and do not have any built-in functionality. They are simply `char` arrays. `C` strings can be declared directly in two different ways, but there are key differences. The following program demonstrates both methods:

```
// file: c_string_decl.c
#include<stdio.h>
#include<stdlib.h>

int main()
{
    char cstr1[] = "A string";
    char *cstr2  = "Another string";

    printf("cstr1: %s\n",cstr1);
    printf("cstr2: %s\n",cstr2);
    return 0;
}
```

[28] See this StackOverflow post for more information.

[29] see Chapter *Bits and Bytes* for information about the size of `C` data types.

[30] This is called "null-terminating" a string. Don't confuse this with the `NULL` pointer. Although `NULL` has the *value* 0, its type is `void *`, and not `char`.

```
$ gcc -g -O0 -std=gnu99 c_string_decl.c -o c_string_decl
$ ./c_string_decl
cstr1: A string
cstr2: Another string
```

Both declarations of strings work, but `cstr1` is an array, and `cstr2` is a pointer to an array. The difference is subtle, but there is another issue that is more insidious: `cstr1` is placed in memory onto the *stack* (which we will discuss in Chapter *Pointers, the Stack, and the Heap, and Pointers to Functions*), and we are able to read *and* write to the string characters. On the other hand, the string that `cstr2` points to gets placed into *read only memory* and we are only allowed to read from the contents pointed to by `cstr2`. The proper declaration for `cstr2` should have been:

```
const char *cstr2 = "Another string";
```

If, in the original program, we had attempted this:

```
// change the first characters to lowercase
cstr1[0] = 'a';
cstr2[0] = 'a';
```

The program would have crashed with a *segmentation fault* when attempting to change the value of `cstr2` (but changing the value of `cstr1` is fine). To be clear: the compiler would not have caught this error, and it would not have produced a warning, either.

Because Cstrings are terminated with a 0 byte, any time you use a string in a function that expects a string, you must ensure that the last byte in the string is a 0. In C, there are (at least) two ways to directly set the last character to `NULL`:

```
char buffer[5];
buffer[4] = '\0';
buffer[4] = 0;
```

The first case, `'\0'` is generally preferred, as it is a proper `char` type. The second, 0, will work, as well (without warning), but 0 on its own has a type of `int`.

Note that we have set buffer's index 4 to 0, because as a 5-integer buffer the indices go from 0-4. This means that a string buffer of length 5 *can only hold 4 meaningful string characters*. The string "hello" needs a buffer of length 6 to be a proper Cstring. Forgetting this causes many off-by-one errors with strings!

Pointers and `void *`

If you took CS 106B, you have worked with pointers before. If you only have Java experience, you may not have seen pointers before. A pointer is, simply, a variable that holds a memory address. On the Myth machines, all pointers are 8 bytes (64 bits) long. Although under the hood all pointers are identical, C enforces a type on pointers so the compiler can calculate the element offsets for arrays.[31]

[31] This has an added benefit of providing some type safety when compiling, and the compiler can warn you when you use a pointer of the incorrect type.

Take, for instance, the following code:

```
// file: array_offsets.c
#include<stdlib.h>
#include<stdio.h>

void print_array(int *arr, size_t nelems)
{
    for (size_t i=0; i < nelems; i++) {
        printf("%d",arr[i]);
        i == nelems - 1 ? printf("\n") :
           printf(", ");
    }
}

int main()
{
    int values[] = {1,3,5,2,4,6};
    print_array(values,sizeof(values) /
       sizeof(values[0]));
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall array_offsets.c -o array_offsets
$ ./array_offsets
1, 3, 5, 2, 4, 6
```

In the function, `print_array`, the compiler knows that each element in the array is an `int`, and it can calculate where in memory the next element is when executing `arr[i]`.[32]

We can access the address of all variables in `C` with the *address-of* operator, "`&`". We say that this address of a value is a *reference* to that value.[33] For example:

```
int x = 12;
int *xptr = &x; // xptr now points to x
```

As we have seen above, we can get to the value stored by a pointer by *dereferencing* the pointer with the "`*`" operator:

```
int y = *xptr; // y now holds the value 12
```

When we have a pointer to a value, we can modify the original value in the location at that pointer. This makes functions such as `swap` possible:

```
// file: swap.c
#include<stdio.h>
#include<stdlib.h>

void swap(int *x, int *y)
{
    int tmp = *x;
```

[32] We will discuss the details in future chapters, but an `int` is a 4-byte value, and memory addresses refer to one-byte locations. Therefore, each `int` in `arr` takes up four memory locations, and the compiler needs to know that fact. If we had instead, declared `values` to be of type `long *`, each element would take up 8 bytes, because a `long` is an 8-byte data type. See Table 4 for more information.

[33] Do not confuse `C` references with `C++` references! `C` references are simply pointers.

```
        *x = *y;
        *y = tmp;
}

int main()
{
    int a = 5;
    int b = 12;
    printf("a: %d, b: %d\n",a,b);
    swap(&a,&b);
    printf("a: %d, b: %d\n",a,b);
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall swap.c -o swap
$ ./swap
a: 5, b: 12
a: 12, b: 5
```

We will spend a lot of time during CS 107 looking at one further level of indirection, the *pointer to a pointer*. A pointer to a pointer is also a memory address, and it holds a pointer type. Take the following swap2 program:

```
// file: swap2.c
#include<stdio.h>
#include<stdlib.h>

void swap2(int **x, int **y)
{
    int *tmp = *x;
        *x = *y;
        *y = tmp;
}

int main()
{
    int arr[] = {5, 12};

    int *aptr = &arr[0];
    int *bptr = &arr[1];

    printf("a: %d, b: %d\n",*aptr,*bptr);
    swap2(&aptr,&bptr);
    printf("a: %d, b: %d\n",*aptr,*bptr);
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall swap.c -o swap
$ ./swap
```

```
a: 5, b: 12
a: 12, b: 5
```

It is helpful to draw pictures for the situation covered in `swap2`. This is a critical understanding point in CS 107 – if you are at all in doubt about pointers or pointers-to-pointers, *draw a picture!* Figure 4 shows a possible memory layout for `swap2`; the addresses are made up for the purpose of this example. The arrows graphically show the pointer references, but often it is instructive to see the numbers, just to make it more concrete. Recall from above that pointers are 8 bytes, and `int`s are 4 bytes. Also note that once in `swap2`, the function no longer has access to the variables from `main`.

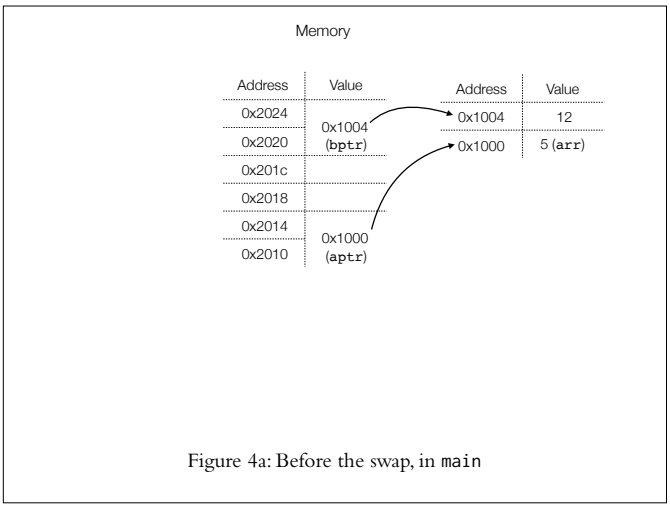


Figure 4a: Before the swap, in `main`

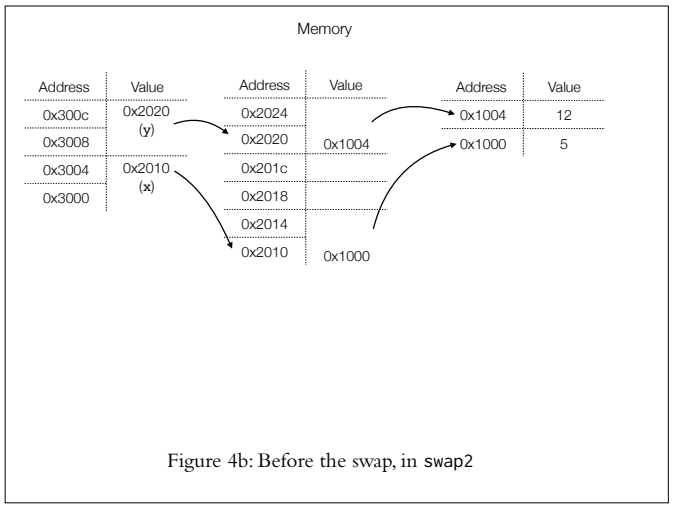


Figure 4b: Before the swap, in `swap2`

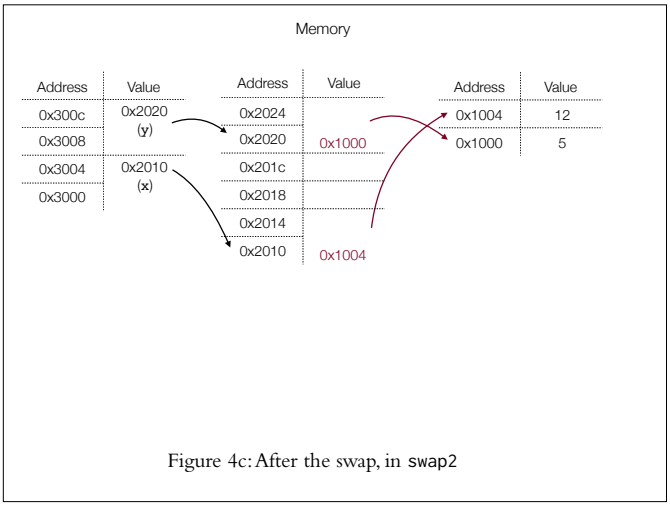


Figure 4c: After the swap, in `swap2`

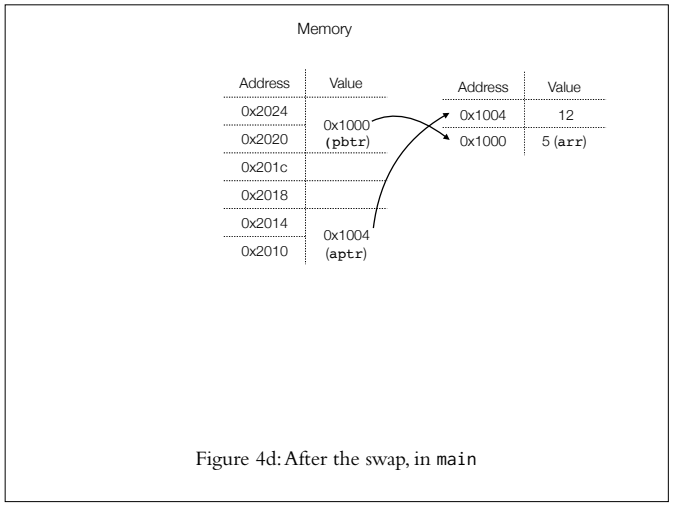


Figure 4d: After the swap, in `main`

Figure 4: Possible memory layout for `swap2`

If our `swap` function actually did want to swap the two values in the original array and still had a pointer to a pointer passed in as a

parameter, it would be possible by *double dereferencing* the pointer:

```
void swap2(int **x, int **y)
{
    int tmp = **x;
        **x = **y;
        **y = tmp;
}
```

Note that a double-dereferenced `int **` is an `int`.

In this case, the diagram would look like Figure 5, where the original array elements were swapped.

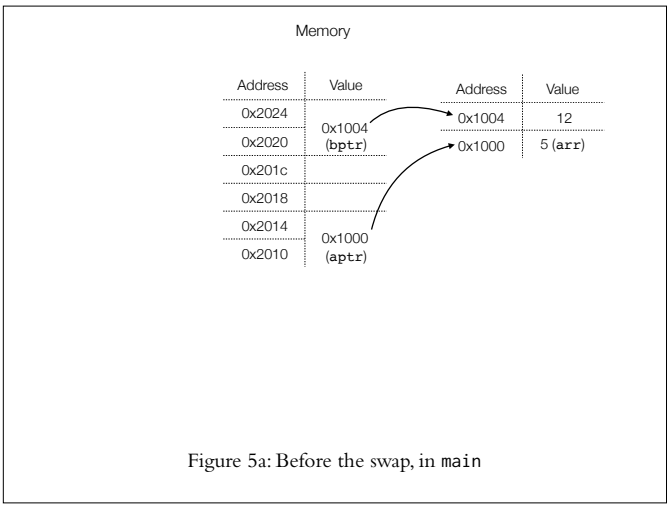


Figure 5a: Before the swap, in `main`

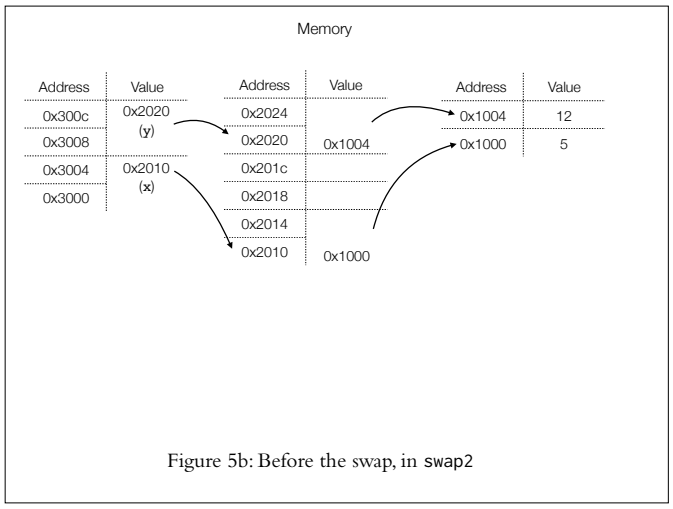


Figure 5b: Before the swap, in `swap2`

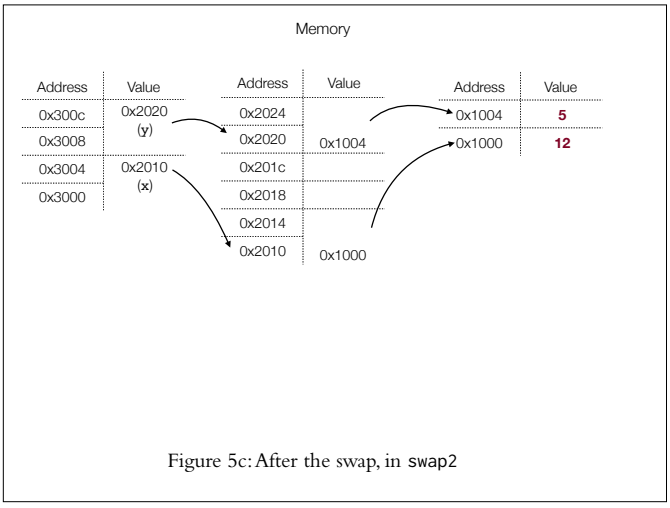


Figure 5c: After the swap, in `swap2`

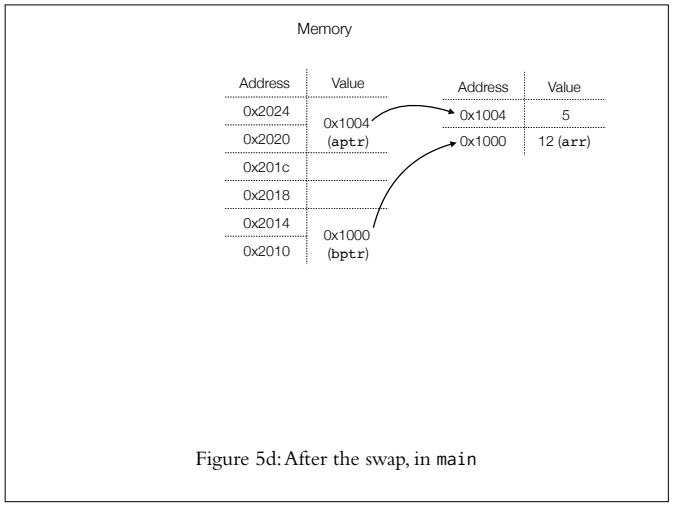


Figure 5d: After the swap, in `main`

Figure 5: Possible memory layout for `swap2` with double dereferencing

The one type of pointer that is significantly different than other pointers is the "`void *`" pointer. A `void *` pointer does not have

any type information associated with the data it points to. This necessarily means that when faced with a `void *` pointer, the compiler must be told to intrepret the pointer as a particular type.[34] This means that you must cast `void *` pointers to some type. Often, we will not have enough information about the type to tell exactly what it is, so we have to rely on simply walking through the bytes one-by-one. In order to walk an array one byte at a time, the compiler must be told to interpret the pointer as pointing to a 1-byte data type. The only 1-byte data type we have in `C` is the `char` type, so we you will frequently see casts to `char *` pointers, even though the underlying data has nothing at all to do with "characters," and are simply bytes of another data type. For example, the following (annotated) program prints out the raw bytes (in hex) of any array, which is passed in as a `void *` array. Notice that we must have the length of the array in bytes:

[34] But not necessarily the exact underlying type!

```
// file: rawbytes.c
#include<stdio.h>
#include<stdlib.h>

void printbytes(const void *arr, size_t size)
{
    for (size_t i = 0; i < size; i++) {
        printf("%x",*((unsigned char *)arr + i));
        i == size-1 ? printf("\n") : printf(", ");
    }
}

int main(int argc, char **argv)
{
    // create buffer to hold longs
    long buffer[argc-1];

    // convert command line args to longs
    for (int i=1; i < argc; i++) {
        buffer[i-1] = atol(argv[i]);
    }

    // print the raw bytes
    printbytes(buffer, (argc-1) * sizeof(long));

    return 0;
}
```

We are casting `arr` to an `unsigned char *` because an `unsigned char` is a 1-byte length data type, and we want the byte it returns to be an unsigned value between 0 and 255. We have to dereference the byte from the array after we do the pointer arithmetic.

We ignore the first argument, which is the program name, so we only need space for `argc-1` values, which are `long`s in this case.

Convert each argument from a string to a `long`.

Pass in the total number of bytes, which is the size of the array times the size of a `long`.

```
$ gcc -g -O0 -std=gnu99 rawbytes.c -o rawbytes
$ ./rawbytes 1234 9876 1111 42
d2, 4, 0, 0, 0, 0, 0, 0, 94, 26, 0, 0, 0, 0, 0, 0, 57, 4,
0, 0, 0, 0, 0, 0, 2a, 0, 0, 0, 0, 0, 0, 0
```

There is a good deal more to pointers that we will cover in *Pointers, the Stack, and the Heap, and Pointers to Functions*!

The memcpy *and* memmove *Functions*

As we go through CS 107, we will quickly reach a point where we need to copy raw bytes around in memory. There are two functions that accomplish this, memcpy and memmove. Both copy the bytes (rather than "moving") them, but the difference is that memcpy is not guaranteed to work on *overlapping* memory. In other words, if you are copying part of an array to another part of the same array, and the bytes overlap, you must use memmove instead of memcpy. You should spend some time understanding how both functions work by looking at their respective man pages[35], but we will go over the details here. The function prototypes are as follows:

[35] man memcpy and man memmove

```
void *memcpy(void *dest, const void *src, size_t n);

void *memmove(void *dest, const void *src, size_t n);
```

Both functions expect a void * pointer to the destination address (dest) to copy the data, a const void * address of the location copying from (the source, src), and the number of bytes to copy.

Much like the example code above, neither function knows the underlying type of the source or destination pointers, but it moves the bytes one at a time.

C structs *and the* typedef *statement*

Although C does not have objects and is not an object oriented programming language, it does have the ability to package data together in the form of a struct. C structs allow you to define a contiguous region of memory that will hold other variables based on their types. To declare a struct, we use the following form:

```
struct tag {
    type a;
    type b;
    ...
};
```

You may have learned about structs in C++, but the C struct has simpler functionality[36]. To declare a variable of a struct type in C, we use the following form:

[36] structs in C++ are true objects, with the ability to include functions as well as data.

```
struct tag varname;
```

This is different from C++, where the struct modifier is not needed. You may optionally typedef a shortcut for the struct, and this can be the same name as the struct tag:

```
typedef struct tag {
    int a;
    char b;
    long c;
} tag;
```

```
...
tag var; // declare var to be of type struct tag
```

To access a struct variable's fields, you use dot notation (e.g., `var.a`), and to access a pointer to a struct variable's fields, you use arrow notation (e.g., `var->a`). Here is a complete example to demonstrate how to use structs:

```
// file: fraction.c
#include<stdio.h>
#include<stdlib.h>

struct fraction {
    int numerator;
    int denominator;
};

struct fraction multiply(struct fraction *a, struct fraction *b);
void printfrac(struct fraction *f);
int gcd(int a, int b);

int main(int argc, char **argv)
{
    struct fraction f1 = {1,2}; // 1/2
    struct fraction f2 = {2,3}; // 2/3

    printfrac(&f1);
    printfrac(&f2);

    struct fraction f3 = multiply(&f1,&f2);
    printfrac(&f3);

    return 0;
}

struct fraction multiply(struct fraction *a, struct fraction *b)
{
    struct fraction f;
    f.numerator = a->numerator * b->numerator;
    f.denominator = a->denominator * b->denominator;

    // reduce
    int fgcd = gcd(f.numerator,f.denominator);
    f.numerator /= fgcd;
    f.denominator /= fgcd;
    return f;
}

void printfrac(struct fraction *f)
{
```

```
    printf("%d/%d\n",f->numerator,f->denominator);
}

int gcd(int a, int b)
{
  if (a==0) return b;
  return gcd(b%a,a);
}
```

```
$ gcc -g -O0 -std=gnu99 fraction.c -o fraction
$ ./fraction
1/2
2/3
1/3
```

C *Memory Management:* `malloc`, `free`, `calloc`, *and* `realloc`

As we have seen earlier, one method for creating an array is by declaring local storage:

```
int values[] = {1,3,5,2,4,6};
```

There are some downsides to this approach:

1. The memory allocated only remains in scope during the function or block where it is declared. This precludes creating an array in a function and returning a pointer to it.
2. The memory is declared on the *stack*, and there is limited stack memory, meaning that the arrays cannot be too large.

A more robust method for creating an array is by dynamically allocating memory, using the following functions:

`malloc` : request an array of bytes from the operating system.

`free` : return bytes previously requested back to the operating system.

`calloc` : request an array of memory and set the values to zero.

`realloc` : change the size of a previously requested array

Dynamic memory is allocated from the heap[37], and a program has access to that memory for the duration of the program, if desired. Heap allocated memory does not suffer from the same size restrictions as memory from the stack, so it also allows you to request large blocks of memory.

It is good practice to `free` memory that is no longer needed, to avoid *memory leaks*. The operating system will reclaim any unfreed memory when a program ends, but you should ensure that your program frees all of its memory before the program ends[38]

The details for all of the dynamic memory allocation functions are located on `malloc`'s `man` page[39], but here are the function signatures:

[37] more on that in *Pointers, the Stack, and the Heap*, *and Pointers to Functions*

[38] And you will lose points in CS 107 for not freeing memory. We will discuss the use of `valgrind` to find memory errors and leaks as the course progresses.

[39] `man malloc`

```
void *malloc(size_t size);
void *calloc(size_t nmemb, size_t size);
void free(void *ptr);
void *realloc(void *ptr, size_t size);
```

Notes:

1. `malloc`'s only parameter is the number of bytes requested, and it returns a `void *` pointer to the memory allocated (and `NULL` if it cannot allocate the requested number of bytes).

2. `calloc`'s two parameters, when multipled together, give the total number of bytes requested.

3. `free` must be given a previously allocated pointer, or `NULL`. Once `free`d, a program is not allowed to access the memory region again, even though the pointer value has not been changed.

4. `realloc` is given a previously allocated pointer (or `NULL`), and a new size, and returns a pointer to the (potentially) new block (it returns the same pointer if it can do an in-place size change). If it cannot resize the block of memory, it will return `NULL`, and *the original pointer will be unchanged*, allowing the program to clean up if it can. `realloc` also `free`s the old pointer during a size change when a new block is needed.

The following program is an example that uses the dynamic memory functions, and demonstrates how to use the `valgrind` program to check for memory leaks and/or errors:

```
// file: dynamic_memory.c
#include<stdio.h>
#include<stdlib.h>
#include<assert.h>

int main(int argc, char **argv)
{
    int num_ints = atoi(argv[1]);

    int *values = malloc(num_ints * sizeof(int));
    assert(values);

    // fill with even numbers
    for (int i=0; i < num_ints; i++) {
        values[i] = i * 2;
    }

    for (int i=0; i < num_ints; i++) {
        printf("%d",values[i]);
        i == num_ints - 1 ? printf("\n") : printf(", ");
    }

    // double the size
```

```
    int *new_values = realloc(values,num_ints * 2 * sizeof(int));
    assert(new_values);

    values = new_values;
    num_ints *= 2;

    // fill with more even numbers
    for (int i=num_ints / 2; i < num_ints; i++) {
        values[i] = i * 2;
    }

    for (int i=0; i < num_ints; i++) {
        printf("%d",values[i]);
        i == num_ints - 1 ? printf("\n") : printf(", ");
    }

    // clean up
    free(values);
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 dynamic_memory.c -o dynamic_memory
$ ./dynamic_memory
0, 2, 4, 6, 8, 10, 12, 14, 16, 18
0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38
$ valgrind ./dynamic_memory 10
==1797== Memcheck, a memory error detector
==1797== Copyright (C) 2002-2013, and GNU GPL'd, by Julian Seward et al.
==1797== Using Valgrind-3.10.1 and LibVEX; rerun with -h for copyright info
==1797== Command: ./dynamic_memory 10
==1797==
0, 2, 4, 6, 8, 10, 12, 14, 16, 18
0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38
==1797==
==1797== HEAP SUMMARY:
==1797==     in use at exit: 0 bytes in 0 blocks
==1797==   total heap usage: 2 allocs, 2 frees, 120 bytes allocated
==1797==
==1797== All heap blocks were freed -- no leaks are possible
==1797==
==1797== For counts of detected and suppressed errors, rerun with: -v
==1797== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
```

Using the `assert` *Function*

In the program above, we used the `assert` function to ensure that the memory allocation functions were able to allocate the requested number of bytes. The `assert` function has a single expression parameter, and if that expression is `false`, the program aborts

(crashes) with a diagnostic message. Because the program crashes when an assert fails, it is best used as a debugging tool instead of an error checking tool. In CS 107, you should use asserts instead of proper error checking, mainly to save time for concentrating on other details of your program.

Using `cdecl`

Sometimes, it is difficult to tell what a particular type declaration actually means. For example, how does `const` apply in the following declarations?

```
const char **x;
char *const *y;
char **const z;
```

There is a handy tool on the Myth computers called `cdecl` that will decode type declarations for you:[40]

[40] And there is a `cdecl` website as well.

```
$ cdecl explain const char **x
declare x as pointer to pointer to const char

$ cdecl explain char *const *y
declare y as pointer to const pointer to char

$ cdecl explain char **const z
declare z as const pointer to pointer to char
```

In the first case, the `char`s themselves may not be changed, in the second case, the pointer to `char` may not be changed, and in the final case, the pointer to pointer to the `char` may not be changed. The `cdecl` program can come in handy when you start to get confused by type declarations!

Boolean Values

Most languages have a built-in *boolean* type, which provide the common `true` and `false` boolean values. `C` actually does not have built-in boolean values, and in `C`, an integer `0` is considered `false` and *any integer not equal to zero* is considered `true`. In the version of `C` that we are using[41], there is a boolean library you can use to provide the `bool` type, `stdbool.h`:

[41] `gnu C99`

```
#include<stdbool.h>
bool a = true;
```

Final Thoughts

Believe it or not, `C` is a relatively lightweight language, and although there are nuances, the language can be learned thoroughly. Once you have a good grasp of the language, and are comfortable

using the `man` pages to look up library functions, you will be ready to excel in CS 107.

gdb

Probably the most important tool you will use during CS 107 is the command line debugger, `gdb`. `Gdb` allows you to step through your code line-by-line, investigate variables while your program is running, set breakpoints to stop your code at particular lines, look at the assembly code that `gcc` generates, and many more functions that will help you write and debug your code. It is imperative that you become proficient at `gdb` early during CS 107!

For the next part of this chapter, we will use the following buggy example program to demonstrate the use of `gdb`:

```
// file: digits_buggy.c

#include<stdio.h>
#include<stdlib.h>

// returns the number of digits in a base-10
   number
int numdigits(int n)
{
    int count = 0;
    while ((n /= 10) != 0){
        count++;
    }
    return count;
}

// calculates 10^exp
int powerof10(int exp)
{
    int result = 1;
    for (int i=0; i < exp; i++) {
        result *= 10;
    }
    return result;
}

// returns the digit from d at position tensplace
// e.g., digit_place(5678,2) returns 6 because
// 6 is at the 10^2, or 100s place in 5678
```

```
int digit_place(int d, int tensplace)
{
    int p10 = powerof10(tensplace);

    return d / (p10 * 10) % p10;
}

int main(int argc, char **argv)
{
    char *digit_str[] =
        {"zero","one","two","three",
         "four","five","six","seven",
         "eight","nine"};

    int number = atoi(argv[1]); // command line
        arg
    int ndigits = numdigits(number);
    for (int i=ndigits-1; i >= 0; i--) {
        int digit = digit_place(number,i);
        printf("%s ",digit_str[digit]);
    }
    printf("\n");

    return 0;
}
```

We can compile our program as follows:

```
$ gcc -g -O0 -std=gnu99 -Wall digits_buggy.c -o digits_buggy
```

The program is supposed to take a number as an argument to the program, and print out the english version of all the digits. For example, this is what we would like:

```
$ ./digits_buggy 8675309
eight six seven five three zero nine
```

But, what we actually get is:

```
$ ./digits_buggy 8675309
Segmentation fault (core dumped)
```

Obviously, the most expedient method to debug the code would probably be to look at it, and find the bugs! But, this isn't always easy, and we have tools such as gdb to help with the process.

Below is a sample gdb run that demonstrates many of the commands you should become familiar with. When a command is used, it is defined in the right margin.

```
$ gdb digits_buggy
The target architecture is assumed to be i386:x86-64
Reading symbols from digits_buggy...done.
(gdb) run 8675309
Starting program:
/afs/.ir.stanford.edu/users/c/g/cgregg/cs107
/reader/digits_buggy 8675309

Program received signal SIGSEGV, Segmentation fault.
0x00007ffff7a5c943 in _IO_vfprintf_internal
(s=<optimized out>, format=<optimized out>,
    ap=ap@entry=0x7fffffffe888) at vfprintf.c:1661
1661        vfprintf.c: No such file or directory.
(gdb) where
#0  0x00007ffff7a5c943 in _IO_vfprintf_internal
(s=<optimized out>, format=<optimized out>,
    ap=ap@entry=0x7fffffffe888) at vfprintf.c:1661
#1  0x00007ffff7a653d9 in __printf (format=<optimized out>)
at printf.c:33
#2  0x0000000000400720 in main (argc=2, argv=0x7fffffffeab8)
at digits_buggy.c:45
(gdb) up
#1  0x00007ffff7a653d9 in __printf (format=<optimized out>)
at printf.c:33
33        printf.c: No such file or directory.
(gdb) up
#2  0x0000000000400720 in main (argc=2, argv=0x7fffffffeab8)
at digits_buggy.c:45
45                printf("%s ",digit_str[digit]);
(gdb) p digit
$1 = 86
(gdb) p digit_str[digit]
$2 = 0xb <error: Cannot access memory at address 0xb>
(gdb) list
40
41            int number = atoi(argv[1]); // from command line
42            int ndigits = numdigits(number);
43            for (int i=ndigits-1; i >= 0; i--) {
44                int digit = digit_place(number,i);
45                printf("%s ",digit_str[digit]);
```

The **run** command starts the program. It can take command line arguments just as if you were running the program on the command line.

The **where** command provides a stack trace. Assuming that the bug is in your code (and not a library function – a good assumption!), you can look for the first instance down the stack trace where your function appears. In this case, the error seems to be coming from line 45 of the program, even though it technically crashed during the **printf** call.

The **up** command follows the stack trace up one level (to the previous function) and allows you to investigate the variables and program state at that point. In this case, we need to type **up** twice to get to the main function.

The **p** (abbreviated from **print**) command prints variables, constants, etc. To print a hexadecimal digit, type **p/x variable**.

The **list** command lists your C code around the line that is in process. If you continue to type **l**, further lines of code will print.

```
46            }
47            printf("\n");
48
49            return 0;
(gdb) p number
$3 = 8675309
(gdb) p i
$4 = 4
(gdb) call digit_place(number,i)
$10 = 86
(gdb) break 44 if i==4
Breakpoint 1 at 0x4006f2: file digits_buggy.c, line 44.
(gdb) run
The program being debugged has been started already.
Start it from the beginning? (y or n) y

Starting program: /afs/.ir.stanford.edu/users/c/g/cgregg/cs107
/reader/gdb/digits_buggy 8675309

Breakpoint 1, main (argc=2, argv=0x7fffffffeaa8)
at digits_buggy.c:44
44                int digit = digit_place(number,i);
(gdb) p i
$3 = 4
(gdb) step
digit_place (d=8675309, tensplace=4) at digits_buggy.c:30
30            int p10 = powerof10(tensplace);
(gdb) next
32            return d / (p10 * 10) % p10;
(gdb) p d
$4 = 8675309
(gdb) p p10
$5 = 10000
(gdb) p d / (p10 * 10) % p10
$6 = 86
(gdb) p d % (p10 * 10) / p10
$7 = 7
(gdb) quit
A debugging session is active.

        Inferior 1 [process 14432] will be killed.

Quit anyway? (y or n) y
```

We are investigating the **number** and **i** variables.

The **call** command will run a function. Here, we are confirming that the **digit_place** function is giving us an incorrect result (it should be **5** instead of **86**).

The **break** command tells gdb to stop running at a particular line; in this case, line 44. We have also told gdb to stop when **i** is equal to 4, so we can continue at that point (the condition is optional). When we **run** the program again, it uses the last command line arguments, and it starts the program over. Then, it breaks on the line or function where we have set a breakpoint.

The program stopped at line 44 when **i** was equal to **4**, before that line runs, and we use the **step** command to run the next line in the program, which steps into the **digit_place** function. We use the **next** command to run the next line but to run the entire function (in this case, the **powerof10** function).

Now we can start to analyze the bug. We print out the **d** and **p10** variables, and see that they are what we expect.

When we print out the details of the line that is about to be returned, we realize that this is incorrect. We then (hopefully!) recognize that we have the modulus (%) and division swapped, so we print out the expression with the operators in the correct position, and see that we get the correct answer, which is the **7** extracted from **8675309**. We have found a bug, and we can **quit** gdb to go fix it.

After we fix the bug in the **digit_place** function, we re-run the program:

```
$ ./digits_buggy 8675309
six seven five three zero nine
```

This is better! But, we are missing the **eight** that we are expecting. Back to gdb!

```
$ gdb digits_buggy
The target architecture is assumed to be i386:x86-64
Reading symbols from digits_buggy...done.
(gdb) run 8675309
Starting program: /afs/.ir.stanford.edu/users/c/g/cgregg/cs107
/reader/gdb/digits_buggy 8675309
six seven five three zero nine
[Inferior 1 (process 22983) exited normally]
(gdb) l
29        {
30            int p10 = powerof10(tensplace);
31
32            //return d / (p10 * 10) % p10; // fix: swap mod and div
33            return d % (p10 * 10) / p10;
34        }
35
36        int main(int argc, char **argv)
37        {
38            char *digit_str[] = {"zero","one","two","three",
(gdb)
39                "four","five","six","seven",
40                "eight","nine"};
41
42            int number = atoi(argv[1]); // from command line
43            int ndigits = numdigits(number);
44            for (int i=ndigits-1; i >= 0; i--) {
45                int digit = digit_place(number,i);
46                printf("%s ",digit_str[digit]);
47            }
48            printf("\n");
(gdb) break 45
Breakpoint 1 at 0x4006f2: file digits_buggy.c, line 45.
(gdb) run
Starting program: /afs/.ir.stanford.edu/users/c/g/cgregg/cs107
/reader/gdb/digits_buggy 8675309
```

If we run the program from gdb, we find see that it is missing the first digit (**eight**).

We list the program (**l**) to determine where to break.

We decide to break on line 45 to investigate some more.

```
Breakpoint 1, main (argc=2, argv=0x7fffffffea98)
at digits_buggy.c:45
45                int digit = digit_place(number,i);
(gdb) p i
$1 = 5
(gdb) p ndigits
$3 = 6
(gdb) break numdigits
Breakpoint 2 at 0x4005c4: file digits_buggy.c, line 9.
(gdb) info break
Num     Type           Disp Enb Address            What
1       breakpoint     keep y   0x00000000004006f2 in main
at digits_buggy.c:45
        breakpoint already hit 1 time
2       breakpoint     keep y   0x00000000004005c4 in numdigits
at digits_buggy.c:9
(gdb) delete 1
(gdb) run
The program being debugged has been started already.
Start it from the beginning? (y or n) y

Starting program: /afs/.ir.stanford.edu/users/c/g/cgregg/cs107
/reader/gdb/digits_buggy 8675309

Breakpoint 2, numdigits (n=8675309) at digits_buggy.c:9
9            int count = 0;
(gdb) display count
3: count = 32767
(gdb) n
10            while ((n /= 10) != 0){
3: count = 0
(gdb) l
5
6        // returns the number of digits in a base-10 number
7        int numdigits(int n)
8        {
9             int count = 0;
10            while ((n /= 10) != 0){
11                count++;
12            }
13            return count;
14        }
(gdb) break 13
```

Hmm...**ndigits** should be **7**, not **6**.

We will put a breakpoint on the **numdigits** function, to investigate that function. The **info break** command tells us what breakpoints we already have set.

We **delete** the first breakpoint we set because we don't need it any more, and we re-run the program.

The **display count** command will show the **count** variable value after each gdb command. In this case, **count** is a non-initialized value, because we have stopped on line 9, before it has been initialized to 0. The **n** command (**next**) runs line 9, and stops on line 10, where we **l** (**list**) the code. Note that at this point, **count** has been initialized to 0.

We **break** on line 13 to investigate the count at that line.

```
Breakpoint 7 at 0x4005f2: file digits_onefix.c, line 13.
(gdb) continue
Continuing.

Breakpoint 7, numdigits (n=0) at digits_onefix.c:13
13            return count;
3: count = 6
(gdb)
```

The **continue** command continues program execution at the current line (and only stops at breakpoints).

The program breaks at line 13 (as we directed it to do), and we find that we have an off-by-one problem with count, after the while loop. We realize that there must be an error in the while loop, and we find that we should have initialized **count** to **1**.

Other Important gdb *Commands*

The commands in the above gdb traces are probably the most useful commands, and you will use almost all of the them frequently. The list below has other commands that you will want to know when debugging C code, as well.

break 12 if x == 42 This is a conditional breakpoint to break on line 12 when the variable **x** is equal to 42. This command is useful if you need to stop the program in the middle of a loop, when a variable reaches a certain value, so you can investigate the program in that state.

help This is an obvious command, but it is useful to give you information about other commands in gdb. For example, the next command we will look at is the **x** command, and we can find help on it:

```
(gdb) help x
Examine memory: x/FMT ADDRESS.
ADDRESS is an expression for the memory address to examine.
FMT is a repeat count followed by a format letter and a size letter.
Format letters are o(octal), x(hex), d(decimal), u(unsigned decimal),
  t(binary), f(float), a(address), i(instruction), c(char), s(string)
  and z(hex, zero padded on the left).
Size letters are b(byte), h(halfword), w(word), g(giant, 8 bytes).
The specified number of objects of the specified size are printed
according to the format.

Defaults for format and size letters are those previously used.
Default count is 1.  Default address is following last thing printed
with this command or "print".
```

x/16bx 0x4007eb The **x** command prints out a range of memory. The form here will print out a range of bytes at a particular memory location in hexadecimal format, e.g., the following prints out sixteen hexadecimal bytes at memory address **0x4007eb**:

```
(gdb) x/16bx 0x4007eb
0x4007eb:   0x65   0x69   0x67   0x68   0x74   0x00   0x6e   0x69
```

```
0x4007f3:   0x6e   0x65   0x00   0x25   0x73   0x20   0x00   0x00
```

The **x** command is also useful if you want to print out the memory contents of a variable. For example, let's say we had the following function, which simply increments the value of the `int` that **xptr** points to:

```
void add1(int *xptr)
{
    (*xptr)++;
}
```

In gdb, you could investigate **xptr** in a number of different ways:

```
Breakpoint 1, add1 (xptr=0x7fffffffe9b0) at arrays.c:6
(gdb) p *xptr
$1 = 1234
(gdb) x/1d xptr
0x7fffffffe9a0:        1234
(gdb) x/4b xptr
0x7fffffffe9a0:        -46        4        0        0
(gdb) p/x 1234
$2 = 0x4d2
(gdb) x/4bx xptr
0x7fffffffe9a0:        0xd2        0x04        0x00        0x00
(gdb)
```

Dereference the pointer and print it.

Print one 4-byte integer at the address of the pointer.

Print four bytes at the address. This may look strange! In the *Bits and Bytes* chapter, we will see why. Let's print the hexadecimal value for **1234**. If we print the four bytes in hexadecimal, and then print the memory at **xptr** as hex bytes, we can see some similarity, although the bytes seem to be in reverse order. Read ahead in the *Bits and Bytes* chapter for more information!

Bits and Bytes

At the lowest level, computers are good at determining the difference between "on" and "off". They are built using billions of transistors, each of which can either conduct electrical current, or not, based on other transistors connected in a circuit. Together, these fundamental building blocks contribute to a a computer's ability to perform calculations, and logical and numerical calculation is the basis for computation.

We call a single on or off representation a *bit*, and numerically a bit is either a 0 (off) or a 1 (on), representing one state (either off or on). However, having one bit (and a single state) is not particularly helpful! In order to have more states, we simply add more bits. As discussed in *Numerical Formats Used in CS 107*, the binary number format is represented by 0s and 1s, and therefore it is the perfect base to represent a series of bits.

If we have two bits, we have the following four representations:

00
01
10
11

Three bits gives us eight representations: $000, 001, 010, 011, 100, 101, 110, 111$. It follows that adding an extra bit produces two times more states, and therefore for n bits, we have 2^n states available to us.

As you can see, we are actually just counting, assigning each state a different number. In this way, we can encode anything we want with bits. We can encode text characters in the ASCII format, for instance. The character value for "`A`" is `65d`, or `01000001b`[42] We encode images, music, and video numerically, and therefore, using bits.

In this chapter, we will discuss how computers represent and perform calculations on integers[43], and the imporant role bits play in those calculations. We will also delve into the way `C` handles integers, including how the lanugage performs calculations, converts between different integer data types, and prints out integers.

[42] (See Tables 1 and 2 for the decimal and hexadecimal ASCII character values.

[43] We will tackle non-integers, or *floating point numbers* in a later chapter

Unsigned and Signed Integers

There are two forms of integers that we will use in CS 107:

Unsigned Integers: these are the positive integers, and zero.

Signed Integers: these are the negative and positive integers, and zero.

Because computers use a fixed number of bits to represent integers, we have a fixed number of values for a particular number representation. For example, the C **int** data type uses 32 bits to represent a number[44], and therefore we can represent 2^{32} (or 4,294,967,296) different numbers. If we want to represent both negatives and positives, half the numbers in our range will be negative, and the other half will be positive (plus another value for zero). This describes the signed integers, and indeed **int** is a signed representation, able to represent numbers in the range $-2,147,483,648$ through $2,147,483,647$.[45]

[44] on the Myth machines. The **int** data type can have a different number of bits depending on the machine being used

[45] We will soon see why this is the exact range!

But, if we know that we only want to represent positive numbers (e.g., length, or weight), we can double our range by using an unsigned number format. The **unsigned int** data type also uses 32 bits to represent integers, but because they are only positives (and zero), the range is from 0 to 4,294,967,295.

The fixed range for an integer data type leads to interesting issues. Take, for example, the following program:

```
// file: multtest.c

#include<stdio.h>
#include<stdlib.h>

int main() {
    int a = 200;
    int b = 300;
    int c = 400;
    int d = 500;

    int answer = a * b * c * d;
    printf("%d\n",answer);
    return 0;
}
```

When we compile and run the program, we get the following output:

```
$ ./multtest
-884901888
```

Why did we get a negative result? The answer is that we just did not have enough bits to represent the number we were trying to calculate:

$$200 \times 300 \times 400 \times 500 = 12,000,000,000$$

The maximum **`int`** value we can represent is 2,147,483,647, so the number we were trying to calculate *overflowed* our representation, and cannot be represented by an **`int`**. We will cover overlow directly later in the chapter.

Information Storage

Most of CS 107 concentrates on the `C` programming language, and in `C`, all integers can be thought of as blocks of 8 bits, which we call a *byte*. We will discuss how we manipulate integers on a bit-by-bit level, but the C language does not allow us to consider an individual bit on its own.[46]

A computer's memory system is simply a large array of bytes. Each *address* in memory represents a byte. Figure 6 demonstrates this concept for the range of addresses from `200d` to `236d` decimal (`0xc8` to `0xec` hex).

values (ints):	7	2	8	3	14	99	-6	3	45	11
address (decimal):	200d	204d	208d	212d	216d	220d	224d	228d	232d	236d
address (hex):	0xc8	0xcc	0xd0	0xd4	0xd8	0xdc	0xe0	0xe4	0xe8	0xec

Figure 6: Memory address for an array of 4-byte `ints`

You cannot address a particular bit, and you must address at the byte level.

How much memory can our computers address? The limit happens to be the underlying *word size* of the computer, and the Myth computers have a word size of 64 bits.[47] In other words, an address is allocated a 64-bit value, and because each byte is addressable, the Myth machines could reference up to 2^{64} bytes of memory, which is *a lot* of memory. The Linux operating system imposes a memory limit of 2^{48} bytes, which is still a tremendous amount of memory.[48]

Because a byte is made up of 8 bits, the range of a byte is `00000000` to `11111111`. As discussed in *Numerical Formats Used in CS 107*, it is more convenient to represnt bytes in hexadecimal, and the hexadecimal range for a byte is `0x00` to `0xff`.

As discussed above, the Myth computers represent `ints` with 32 bits. Table 4 shows the other representations used by `gcc` on the Myth computers.

[46] The reason is more because the underlying hardware only represents numbers at the byte level, so `C` does not need to represent numbers more granularly than the byte level.

[47] They are *64-bit machines*.

[48] A high-end computer these days might have 64 Gigabytes (GB) of memory, or 68,719,476,736 bytes of memory ("Giga" in this case referring to 2^{30} bytes). Linux is capable of addressing over four thousand times more memory than 64GB. It will be a long time before Linux needs to modify the 2^{48} byte limit.

C Declaration		Bytes
Signed	Unsigned	
char	unsigned char	1
short	unsigned short	2
int	unsigned int	4
long	unsigned long	8
int32_t	uint32_t	4
int64_t	uint64_t	8
char *		8
float		4
double		8

Table 4: C Data Sizes on the Myth Computers

Byte Storage in Memory (Little Endian and Big Endian)

We saw in Figure 6 that a four-byte `int` has a single address that refers to the entire integer. `Gcc` keeps track of these addresses, and we often don't need to know more than this fact to refer to `int`s in our `C` variables. However, there are times when you will need to analyze or manipulate data types at the byte level, so it is imporant to understand how the data is layed out in memory.

A four byte `int` is stored in consecutive bytes in memory, but we actually have a choice on ordering those bytes. For example, we can represent a 4-byte `int` as an 8-digit hexadecimal number (two hex digits represent one byte):

```
0x01234567
```

We can separate out the bytes:

```
0x  01  23  45  67
```

There are two natural orderings for storing those bytes into memory:

Big Endian: the order in memory is from the "big end" of the number (i.e., the *most significant byte*) at the lowest memory location, to the "little end" of the number (i.e., the *least significant byte*) at the highest memory location. Writing out our number from above, big endian format would look like Figure 7:

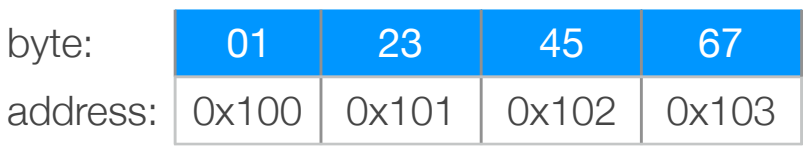


Figure 7: The number `0x01234567` stored in Big Endian Format, at address `0x100`

Little Endian: the order in memory is from the little end of the number at the lowest memory location, to the big end of the number at the highest memory location. Writing out our number from above, little endian format would look like Figure 8, and this is the form in which integers on the Myth computers are stored in:

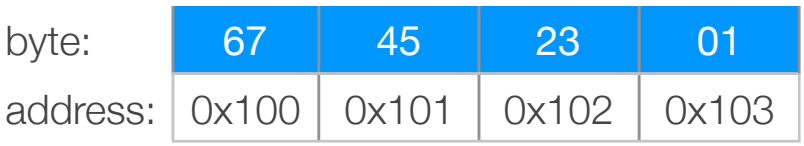


Figure 8: The number `0x01234567` stored in Little Endian Format, at address `0x100`

To be clear: the *endianness* of a number is simply the order of the individual bytes in memory. Big endian numbers have the most significant byte first in memory, and little endian numbers have the least significant byte in memory first. What endianness is not, is a complete reversal of the binary bits of a number, but rather the ordering of the *bytes* in memory. The Intel/AMD x86 computers we use in class are little-endian, although we will rarely need to worry about it.[49]

[49] At the end of the quarter, you may have to think about the endianness of numbers when you are closely analyzing memory for your final project.

[50] Be careful when writing your C programs to diffierentiate the bitwise boolean operators from the *logical* boolean operators. `Gcc` does not always produce a warning when logical AND, `&&`, is substituted for bitwise AND, `&`, and this can lead to difficult-to-track-down bugs.

Boolean Algebra

Because computers store values in binary, we often perform operations on numbers that involve *boolean algebra*, or arithmetic that performs operations directly on the individual bits in a number.

Boolean algebra is defined over a 2-element set, 0 and 1, where 0 represents `false`, and 1 represents `true`. The following `C` operations are defined, and can be used to apply the boolean functions on two numbers (one in the case of the NOT (~) operator):[50]

Bitwise AND, `&`, example: `z = x & y` The `&` operator produces a 1 bit when both operand bits are 1, and a 0 otherwise. Figure 9 shows the AND truth table.

Bitwise OR, `|`, example: `z = x | y` The `|` operator produces a 1 bit when either of the operand bits are 1, and a 0 if both operand bits are 0. Figure 10 shows the truth table for OR.

Bitwise XOR (Exclusive OR), `^`, example: `z = x ^ y` The `^` operator produces a 1 bit when only one of the operand bits is 1, and a 0 otherwise. Figure 11 shows the truth table for XOR.

Bitwise NOT, ~, example: `z = ~x` The ~ operator inverts a bit, so a 0 becomes a 1, and a 1 becomes a 0. Figure 12 shows the truth table for NOT.

The bitwise operators apply to all the bits on a number at once. For example:

Figure 9: The AND truth table.

INPUT		OUTPUT
A	B	A & B
0	0	0
0	1	0
1	0	0
1	1	1

Figure 10: The OR truth table.

INPUT		OUTPUT
A	B	A | B
0	0	0
0	1	1
1	0	1
1	1	1

Figure 11: The XOR truth table.

INPUT		OUTPUT
A	B	A ^ B
0	0	0
0	1	1
1	0	1
1	1	0

Figure 12: The NOT truth table.

INPUT	OUTPUT
A	~A
0	1
1	0

$$\begin{array}{r} 10011001 \\ \&10100111 \\ \hline 10000001 \end{array}$$

The AND operator is applied to the corresponding bits in both numbers to produce the resulting number.

Bit Masking

An important result of being able to perform bitwise boolean operations on numbers is the ability to *mask* an integer variable, to access only particular bits of the number. For example:

```
int x = 0x89ABCDEF;
int y = x & 0xFF; // y now holds the value 0xEF,
                  // which is the low-order byte
                     of x
```

Let's break down what is happening in the code. Here are the values of `x` and `0xFF` in binary:

```
x    == 0b10001001101010111100110111101111
0xFF == 0b00000000000000000000000011111111
```

When the AND operator is appied, the only bits that remain are the lowest eight bits, and we have "masked" `x` to get the lower eight bits alone.

Example: write an expression that sets the most significant byte of a 4-byte integer, `n` to all ones, and all other bytes of the number left unchanged E.g.

```
0x87654321 → 0xFF654321
```

One possible solution would be:

```
x | 0xFF000000
```

Example: write an expression that complements all but the most significant byte of a 4-byte integer, `n`, with the most significant byte unchanged. E.g.

```
0x87654321 → 0x879abcde
```

One possible solution would be:

```
x ^ ~0xFF000000
```

Shift Operations

`C` provides operations to *shift* bit patterns to the left or right. The << operator moves the bits to the left, replacing the lower order bits with zeros and dropping any values that would be bigger than the type can hold:

`x « k` will shift `x` to the left by k number of bits.

Examples for an 8-bit binary number:

```
00100111 << 2  returns 10011100
01101011 << 4 returns 10110000
10011101 << 4 returns 11010000
```

There are actually two flavors of *right shift*, which work differently depending on the value and type of the number you are shifting.

A *logical* right shift moves the values to the right, replacing the upper bits with zeros.

An *arithmetic* right shift moves the values to the right, replacing the upper bits with a copy of the most significant bit.[51]

[51] This may seem weird! But, we will see why this is useful soon!

Example logical shift for an 8-bit binary number:

```
00100111 >> 2  returns 00001001
10100111 >> 2  returns 00101001
01101011 >> 4  returns 00000110
10011101 >> 4  returns 00001001
```

Example arithmetic shift for an 8-bit binary number:

```
00100111 >> 2  returns 00001001
10100111 >> 2  returns 11101001
01101011 >> 4  returns 00000110
10011101 >> 4  returns 11111001
```

There are two important things you need to consider when using the shift operators:

1. The C standard does not precisely define whether a right shift for signed integers is logical or arithmetic. Almost all compilers and computer hardware uses arithmetic shifts for signed integers, and you can most likely assume this. All unsigned integers will always use a logical right shift (more on this later!)

2. Operator precedence can be tricky! Example:

   `1«2 + 3«4` means this: `1 « (2 + 3) « 4`, because addition and subtraction have a higher precedence than shifts!

   Always parenthesize to be sure:

   `(1«2) + (3«4)`

Integer Representations in C

The `C` language has different data types to represent both signed and unsigned integers.[52] `C` also has rules that properly convert between one integer data type and another when moving data between variable types and when performing arithmetic on different integer data types. Table 5 shows the integer data type ranges for the Myth (64-bit) machines.

[52] In fact, `C` and `C++` are is somewhat odd in this regard – most languages stick to signed integers only.

Unsigned integers in `C` are simply represented by their true binary representation. For example, an eight-bit unsigned integer (in `C`, this would be declared as an `unsigned char` fourteen would be

C data type	MIN	MAX	Bytes
`char`	-128	127	1
`unsigned char`	0	255	1
`short`	-32,768	32,767	2
`unsigned short`	0	65,535	2
`int, int32_t`	-2,147,483,648	2,147,483,647	4
`unsigned int, uint32_t`	0	4,294,967,295	4
`long, int64_t`	-9,223,372,036,854,775,808	9,223,372,036,854,775,807	8
`unsigned long, uint64_t`	0	18,446,744,073,709,551,615	8

Table 5: Ranges for integer data types on the Myth machines

`00001110`, which is the true binary representation for `14d`. The range for an unsigned integer is $0 \rightarrow 2^w - 1$, where w is the number of bits in our integer. For example, a 32-bit `int` can represent numbers from 0 to $2^{32} - 1$, or 0 to 4,294,967,295.

Signed integers are treated differently than unsigned integers. In particular, we don't specifically have a "negate" sign, as we do in regular mathematics, and we assign a bit to represent whether the number is positive (`0`) or negative (`1`). While this *sign bit* is sufficient to determine whether a number is signed or not, this leads to some irregularities. For example, let's say we have an 4-bit number, and we reserve the most significant bit as the sign bit. We can represent sixteen (or 2^4) total numbers, and we might simply assume that the lower three bits are the magnitude of the number:

```
0 001 = 1          1 001 = -1
0 010 = 2          1 010 = -2
0 011 = 3          1 011 = -3
0 100 = 4          1 100 = -4
0 101 = 5          1 101 = -5
0 110 = 6          1 110 = -6
0 111 = 7          1 111 = -7
```

We have successfully represented fourteen of our sixteen possible representations, but what about the remaining two numbers?

```
0 000 = ?          1 000 = ?
```

It seems that we are left with two representations for zero: positive zero and negative zero. For integers, this does not make sense, and we would rather have a single zero representation.[53] Additionally, and perhaps more imporantly, performing calculations on positive and negative numbers in the representation above is not particularly easy, because there is an inherent need to subtract with numbers that are negative.

[53] In the Floating Point chapter, we will see that we do have two zero representations for non-integers.

Instead of the method outlined above, signed integers in a computer are represented in a format called *Two's complement*. The two's complement of an n-bit number is defined to be the complement of the number with respect to 2^n. For example, the four bit number 0110 has a two's complement of 1010 because

$0110 + 1010 = 10000$.[54] As can be seen, to calculate the two's complement of a number, you must know how many bits the number holds.

The standard method for calcluating the two's complement of a number is to invert all the bits[55], and then add 1. For the example above:

```
~0110 = 1001
1001 + 1 = 1010
```

The process is reversible. To find the two's complement of 1010:

```
~1010 = 0101
0101 + 1 = 0110
```

If a number *overflows* to the left past the bit length, we just ignore the bits that overflowed. For example, to find the two's complement of the four-bit number, 0000:

```
~0000 = 1111
1111 + 1 = 10000
```

Interestingly, there is a second number whose two's complement is itself:

```
~1000 = 0111
0111 + 1 = 1000
```

We will soon see why this is the case!

The Two's Complement Circle

Figure 13 shows the "two's complement circle" for a 4-bit signed integer. The figure shows the correspondence between the decimal and binary numbers in the 4-bit range. There are a few key ideas to take away from the diagram:

1. Positive numbers are simply the binary equivalent of their value.
2. Negative one is comprised of all 1s, which is equal to the binary value $2^n - 1$, where n is the number of bits in the integer (in this case, $n = 4$). Negative two is the binary eqivalent of $2^n - 2$, and the pattern continues as the negative numbers get smaller.
3. The largest positive number is $2^{n-1} - 1$. The number has a 0 as its most significant bit (denoting that it is a positive number), and the rest of the bits are 1s.
4. The smallest negative number is -2^{n-1}. This accounts for the fact that because of 0, there is one more negative than positive.
5. *Overflow* happens at the bottom of the circle. If we try to add two positive numbers together that are bigger than 2^{n-1}, the number will become negative, and be incorrect mathematically.

[54] The Wikipedia article on two's complement is excellent.

[55] called the *one's complement*, or simply the bitwise NOT operation.

Figure 13: The two's complement circle for a signed 4-bit number

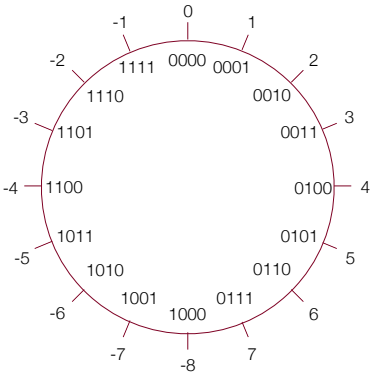
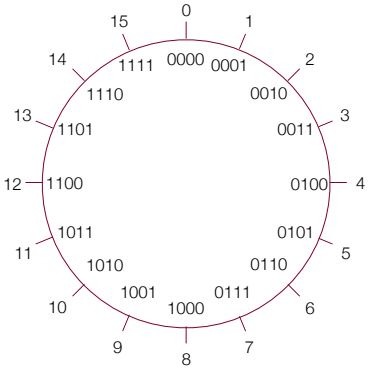


Figure 14: The two's complement circle for an unsigned 4-bit number



Likewise, if we add two negative numbers together and the result will be less than -2^n, the result will become positive and overflow.

6. It is not possible to add a positive and a negative number together and overflow in signed arithmetic.

Figure 14 shows the two's complement circle for a 4-bit unsigned integer. Note the differences between this signed and unsigned circle:

1. All numbers are the binary equivalent of their value.
2. The largest number is $2^n - 1$, where n is the number of bits in the number.
3. Overflow happens at the *top* of the circle. If we try to add two positive numbers together that are bigger than $2^n - 1$, the number will wrap around in a clockwise direction, and be incorrect mathematically. If we subtract two numbers and the result will be less than zero, the result will wrap around in a counterclockwise direction, and the result will be incorrect mathematically.[56]

[56] But correct in a modular sense.

It is important to understand the number circle for both signed and unsigned integers, particularly when considering the overflow points, and the maximum and minimum values. Although Figures 13 and 14 are drawn for 4-bit numbers, they can be extrapolated to any bit length, and the properties remain the same.

Two's Complement Number Properties

So far, you may be asking yourself what the big deal is with two's complement numbers. It turns out that the use of two's complement to store signed integers leads to a number of interesting and helpful properties:

1. There is only one representation for 0. As we saw earlier, a simple sign-bit representation leads to having two zeros, and two's complement avoids this.
2. The most-significant bit is interpreted as a sign bit. It is nice that this property remains when using two's complement.
3. Addition with all numbers is simply addition. This is an amazing development: to add two two's complement numbers together, you simply add them, and throw away any overflow bits. The answer will be correct, as long as the correct mathematical result would not overflow. For example, performing the addition of $-3 + 7$ for our 4-bit numbers, we should get an answer of 4:

$$\begin{array}{rr} 1101 & -3 \\ +0111 & 7 \\ \hline \not{1}0100 & 4 \end{array}$$

and indeed, we do!

4. To subtract two numbers, we first perform a two's complement conversion on the number we are subtracting away, and then we add them. For example, $3 - 5$: Convert 5 from 0101 to its two's complement:

$$\begin{aligned} \sim 0101 &= 1010 \\ 1010 + 1 &= 1011\ (-5) \end{aligned}$$

Add the original number and the converted number:

$$\begin{array}{rr} 0011 & 3 \\ +1011 & -5 \\ \hline 1110 & -2 \end{array}$$

5. Multiplication is also a matter of ignoring the fact that one or both numbers is negative, and simply throwing away overflow bits.[57] For example: -2×3:

$$\begin{array}{rr} 1110 & -2 \\ \times 0011 & 3 \\ \hline 1110 & \\ 1110 & \\ 0000 & \\ 0000 & \\ \hline \cancel{01}01010 & -6 \end{array}$$

As another example, -1×-2:

$$\begin{array}{rr} 1111 & -1 \\ \times 1110 & -2 \\ \hline 0000 & \\ 1111 & \\ 1111 & \\ 1111 & \\ \hline \cancel{1001}0010 & 2 \end{array}$$

One thing to note about two's complement notation is that the bits we are looking at are still powers of two, with the leading bit being a (possibly) negated power of two. For example, let's look at the bit representations for -5 for a 4-bit number:

$$\begin{aligned} -5 = \quad & 1 & 0 & 1 & 1 \\ = \quad & 1 \times -2^3 & +0 \times 2^2 & +1 \times 2^1 & +1 \times 2^0 \end{aligned}$$

Casting Between Signed and Unsigned Integers

In C, we can cast between different number types either explicitly, or implicitly. Figure 15 demonstrates an explicit cast, using parenthesized type notation for the cast. Figure 16 demonstrates an implicit cast, where the compiler performs the cast for us.

When casting, **the underlying bits do not change**. In other words, casting between an unsigned integer and a signed integer

From a hardware perspective, the benefit of two's complement artithmetic is that there is no need for separate subtraction hardware, and performing a two's complement conversion is a simple hardare circuit.

[57] One caveat: multiplication is much more likely to produce actual overflow mathematically. But as long as the product fits into the number of bits in the format, the multiplaction is straighforward.

Figure 15: An explicit cast between signed and unsigned ints.

```
int tx, ty;
unsigned ux, uy;
...
tx = (int) ux;
uy = (unsigned) ty;
```

Figure 16: An implicit cast between signed and unsigned ints.

```
int tx, ty;
unsigned ux, uy;
...
tx = ux; // cast to signed
uy = ty; // cast to unsigned
```

of the same bit-width does not undergo any conversion. Casting does not perform an absolute value function on a negative signed number when converting to a signed number, either. For example, figure 17 shows the output when implicitly casting an 8-bit `unsigned char` to a `signed char` in C. -5 as a `signed char` has the same bit values as 251 as an `unsigned char`, which is 11111011.

Figure 17: A cast in `C` does not change the underlying bit pattern for integers of the same bit width.

```
// file: cast.c
#include<stdio.h>
#include<stdlib.h>

int main()
{
    char tx;
        unsigned char ux;

        tx = -5;
        ux = tx;

        printf("tx: %d\n",tx);
    printf("ux: %u\n",ux);
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 cast.c -o cast
$ ./cast
tx: -5
ux: 251
```

`C`'s `printf` command has three different ways to print an integer[58]:

%d : signed int

%u : unsigned int

%x : hexadecmial formatted int

[58] And there are multiple format-string modifications that can be made to augment these three.

Unless there is an extra width-specifier in the format string, `printf` will treat the number according to the format string. Figure 18 demonstrates this with 32-bit `int`s.

Comparison Between Signed and Unsigned Integers

Often, we want to compare integers to each other. When a `C` expression has combinations of signed and unsigned integers, you have to be careful – if an operation is performed that has both a signed and an unsigned value, **C implicitly casts the signed argument to unsigned** to perform the operation, assuming both integers are non-negative. Table 6 shows the results of such operations.

Figure 18: `printf`'s format string performs a cast on its values.

```
// file: cast_printf.c
#include<stdio.h>
#include<stdlib.h>

int main()
{
        int d = -1;
    unsigned int u = 1<<31;

    printf("d = %d = %u = %x\n", d, d, d);
    printf("u = %d = %u = %x\n", u, u, u);

    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 cast_printf.c -o cast_printf
$ ./cast_printf
d = -1 = 4294967295 = ffffffff
u = -2147483648 = 2147483648 = 80000000
```

Expression	Type	Evaluation
`0 == 0U`	Unsigned	1
`TRUE`	Signed	1
`-1 < 0U`	Unsigned	0
`2147483647 > -2147483647 - 1`	Signed	1
`2147483647U > -2147483647 - 1`	Unsigned	0
`2147483647 > (int)2147483648U`	Signed	1
`(unsigned)-1 > -2`	Unsigned	1

Table 6: `C` expressions that have both unsigned and signed integers perform the calculation assuming all values are unsigned.

The `sizeof` *Operator*

As we have seen, integer data types are limited by the number of bits that they hold. In `C`, we use the `sizeof` operator to determine the size of a variable. The `sizeof` operator is a *compile time* expression, which means that although it looks like a function, the result is *always* determined before the program runs, and the compiler replaces the result as a constant into your code.[59] Figure 19 shows an example program that prints out the number of bytes of each of the variables in the program, and the output is from the Myth machines.

[59] This happens behind the scenes, but you should understand how it works so you don't get caught off-guard when it happens.

Pay close attention to the output of the `sizeof` operator for arrays and pointers. For statically-defined arrays, `sizeof` prints out the number of bytes used by the entire array. In figure 19, the 5-element `int` array is 20 bytes long, becuase each `int` is 4-bytes. Although arrays can act as pointers[60], the compiler can report the actual length. For a pointer, the compiler reports the number of bytes that the pointer itself occupies, which is 8-bytes on the Myth machines.

[60] But they are distinct! We will see this in the chapter on low level `C`.

Expanding the Bit Representation of an Integer

Sometimes we want to convert between two integers having different sizes. E.g., we want to convert a `short` to an `int`, or an `int` to a `long`. We might not be able to convert from a bigger data type to a smaller data type without losing some information by virtue of the fact that there are fewer bits in a smaller data type, but we do want to always be able to convert from a smaller data type to a bigger data type without losing any information.

Conversion is straightforward for unsigned values: simply add leading zeros to the representation. This *zero extension* is analogous to the zero-extension when performing a logical right-shift:

```
unsigned short s = 4;
// short is a 16-bit format, so                    s = 0000 0000 0000 0100b

unsigned int i = s;
// conversion to 32-bit int, so i = 0000 0000 0000 0000 0000 0000 0000 0100b
```

Note that there is an implicit cast, from a 16-bit `unsigned short` to a 32-bit `unsigned int`. As with the casting we saw earlier, the low-order bits that are shared between the two values do not change based on the cast. However, the upper bits of the larger number do change to all zeros.

For signed values, we want the number to remain the same, just with more bits. In this case, we perform a *sign extension* by repeating the sign of the value for the new digits, in an analogous fashion to the way arithmetic right shift works. Recall that negative signed numbers start with all 1s for -1. Table 7 shows a few 4-bit and 8-bit numbers and their respective two's complement representations.

```c
// file: sizeof.c
#include<stdio.h>
#include<stdlib.h>

int main() {
    int iarray[] = {5, 4, 3, 2, 1};
    char *iarr = (char *)iarray;

    printf("sizeof(char): %d\n", (int) sizeof(char));
    printf("sizeof(short): %d\n", (int) sizeof(short));
    printf("sizeof(int): %d\n", (int) sizeof(int));
    printf("sizeof(unsigned int): %d\n", (int) sizeof(unsigned int));
    printf("sizeof(long): %d\n", (int) sizeof(long));
    printf("sizeof(long long): %d\n", (int) sizeof(long long));
    printf("sizeof(size_t): %d\n", (int) sizeof(size_t));
    printf("sizeof(void *): %d\n", (int) sizeof(void *));
    printf("sizeof(iarray): %d\n", (int) sizeof(iarray));
    printf("sizeof(iarr): %d\n", (int) sizeof(iarr));

    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 sizeof.c -o sizeof
$ ./sizeof
sizeof(char): 1
sizeof(short): 2
sizeof(int): 4
sizeof(unsigned int): 4
sizeof(long): 8
sizeof(long long): 8
sizeof(size_t): 8
sizeof(void *): 8
sizeof(iarray): 20
sizeof(iarr): 8
```

Figure 19: Example program demonstrating the `sizeof` operator. Note the difference between the size reported for an array and a pointer to the array.

Notice that the only difference between the negative numbers in both 8-bit and 16-bit representations is the leading 1s in the upper bits of the 16-bit representation.

Table 7: Four and eight bit signed two's complement representation.

Unsigned Integer Two's Complement Representation		
Decimal value	8-bit value	16-bit value
5	00000101	0000000000000101
82	01010010	0000000001010010
127	01111111	0000000011111111
-5	11111011	1111111111111011
-82	10101110	1111111110101110
-127	10000001	1111111110000001

E.g., for positive numbers:

```
short s = 4;
// short is a 16-bit format, so                    s = 0000 0000 0000 0100b

int i = s;
// conversion to 32-bit int, so i = 0000 0000 0000 0000 0000 0000 0000 0100b
```

and for negative numbers:

```
short s = -4;
// short is a 16-bit format, so                    s = 1111 1111 1111 1100b

int i = s;
// conversion to 32-bit int, so i = 1111 1111 1111 1111 1111 1111 1111 1100b
```

Now that we have discussed signed and unsigned integer types in `C`, we can see why there are two types of right shifts in `C`. Unsigned numbers are always logically right-shifted when we use the » operator, and signed numbers are always arithmetically right-shifted when we use the » operator.

Truncating Numbers

In the previous section, we converted numbers from a smaller type to a larger type, and we were able to do this without a loss of information. Negative numbers regain their value by sign-extension, and positive values retain their value by zero-extension. But what if we want to convert from a larger type into a smaller type, e.g., from a 32-bit `int` to a 16-bit `short`? If the magnitude of the number in the larger type contains more bits than the smaller type can hold, we will necessarily lose information. For example, let's look at converting a 32-bit signed `int` with the value 53191 into a signed `short`:

```
53191 = 0000 0000 0000 0000 1100 1111 1100 0111
```

When we convert to a 16-bit short, we *truncate* the number by removing the upper 16-bits, and we are left with:

```
1100 1111 1100 0111
```

In the short form, the number is negative, because the most significant bit is a 1, and the number is now −12345. We have lost the information relating to the positive sign, and we have also lost information about the actual value of the number. Figure 20 shows the result in C.

Figure 20: Example program demonstrating the loss of information when converting from a larger integer type to a smaller integer type.

```
// file: cast_lost_precision.c
#include<stdio.h>
#include<stdlib.h>

int main()
{
    int x = 53191;         // 53191
    short sx = (short) x; // -12345
    int y = sx;

        printf("x:  %d\n",x);
    printf("sx: %d\n",sx);
    printf("y:  %d\n",y);
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 cast_lost_precision.c -o cast_lost_precision
$ ./cast_lost_precision
x:  53191
sx: -12345
y:  -12345
```

This is actually another form of overflow. We have altered the value of the number, and you must be careful to avoid overflows, or to write code that checks for this type of overflow when necessary.[61]

[61] To check for this kind of overflow, you might compare the original number to the maximum of the smaller type, or you might reason about the sign of the number – for instance, if the sign changes, this would indicate overflow.

The truncation works fine if there isn't going to be any loss of information. Figure 21 demonstrates this. The 32-bit and 16-bit values after truncation both represent −3:

```
x:  1111 1111 1111 1111 1111 1111 1111 1101
sx:                   1111 1111 1111 1101
```

We can also lose information when we convert unsigned numbers due to truncation. For example, take the following snippet of code:

```
unsigned int x = 128000;
unsigned short sx = (short) x;
```

the 32-bit unsigned int representation in x of 128,000 is:

```
0000 0000 0000 0001 1111 0100 0000 0000
```

Figure 21: There is no loss of precision when converting from a smaller integer type to a larger integer type.

```
// file: cast_no_lost_precision.c
#include<stdio.h>
#include<stdlib.h>

int main()
{
    int x = -3;
    short sx = (short) x;
    int y = sx;

        printf("x:  %d\n",x);
    printf("sx: %d\n",sx);
    printf("y:  %d\n",y);
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 cast_no_lost_precision.c -o cast_no_lost_precision
$ ./cast_no_lost_precision
x:  -3
sx: -3
y:  -3
```

and the truncated `unsigned short` representation of `sx` is:

```
1111 0100 0000 0000
```

The value of `sx` is 62,464, which has lost the information about the most significant bit in the 32-bit version.

When integer operations overflow in `C`, the runtime does not produce an error. According to the `C` specification, unsigned integers will overflow in a defined behavior (as we saw on the number circle), although you should be wary of using calculations that could potentially overflow, and you should be careful with your code if that is a possibility. Figure 22 demonstrates one way to determine if addition on two unsigned `int`s will overflow.

Figure 22: The following is one way to determine if addition of two unsigned `int`s will overflow

```
#include <limits.h>
unsigned int a = <something>;
unsigned int x = <something>;
if (a > UINT_MAX - x)
    /* 'a + x' would
        overflow */;
```

According to the `C` specification, signed integers *produce undefined behavior* when they overflow. On most machines, the overflow will behave as we saw in the number circle, however, the compiler is free to ignore this and can assume that numbers will not overflow. So, you should write your programs to be careful not to overflow with signed numbers, or to check if that will be the case. Figure 23 demonstrates one way to check for overflow addition.

Figure 23: The following is one way to determine if addition of two signed `int`s will overflow

```
#include <limits.h>
int a = <something>;
int x = <something>;
if ((x > 0) && (a > INT_MAX
    - x))
        /* 'a + x' would
            overflow */;
if ((x < 0) && (a < INT_MIN
    - x))
        /* 'a + x' would
            underflow */;
```

Final Thoughts

Having an excellent grasp of how integers are stored and manipulated in a computer is fundamental to understanding how `C` handles integers in programs. The two's complement format does take

some time to become comfortable with, but it is worth the effort. Understanding the number wheels will enable you to reason out what will happen at overflow and underflow points in your code, as well.

Bits and Bytes Practice Problems

C-Strings and the C String Library

C Strings are simply a sequence of characters (chars), followed by a terminating 0. The char data type represents a fundamental type in C, as a char is 1-byte in length[62], and the byte is the minimal addressable unit on our machines. A char may be signed or unsigned by default[63]

The ASCII character set only defines characters for 0-127 (0x00-0x7f hex). The eighth (most significant) bit was historically used for parity checking, or error detection when transmitting characters, but ASCII is only defined for the low seven bits. There is no standard character representation for char values greater than 127.

There is a standard called Unicode[64] that is much more robust than 7-bit ASCII, and it includes over one hundred thousand characters covering hundreds of languages, scripts, and symbol sets. However, C has no built-in support for Unicode, and we will limit ourselves in CS 107 to ASCII chars.

[62] And defined by C to be 1-byte. There is no need to ever apply sizeof on a char.

[63] C does not specify, and this is up to the compiler. Interestingly, most implementations (including gcc) define char to be signed.

[64] See https://en.wikipedia.org/wiki/Unicode

The ctype *Library*

One of standard libraries for C is ctype, which includes many functions that take an int as a parameter (representing a character[65]), and either test something about the character (e.g, if it is a digit, or punctuation) or to perform an operation on the character (e.g., convert the character to uppercase). The following is a list of ctype functions we will concern ourselves with:[66]

isalpha : returns non-zero (true) if the character is alphabetic.

isdigit : returns non-zero if the character is a digit (0-9).

isalnum : returns non-zero if the character is alphabetic or a digit.

islower : returns non-zero if the character is lowercase.

isupper : returns non-zero if the character is uppercase.

isspace : returns non-zero if the character is whitespace.

isxdigit : returns non-zero if the character is a hex digit (0-*f*).

tolower : converts the character to lowercase, if possible, and returns the lowercase char as an int. If it is not possible, the behaviour is undefined.

[65] The functions' parameter is not an 8-bit char, but a 32-bit int. This is because we want to be able to represent all 256 chars, but also have the ability to determine if the number is "EOF" (end of file), which is not a character in that range.

[66] The full list can be seen with a combination of man isalpha and man tolower

`toupper` : converts the character to uppercase, if possible, and returns the uppercase `char` as an `int`. If it is not possible, the behaviour is undefined.

The following is an example of a program that uses some of the functions above:

```
// file: ctypedemo.c
#include<stdio.h>
#include<stdlib.h>
#include<ctype.h>

int main(int argc, char **argv)
{
    char *string = argv[1];

    // count alpha characters, digits,
    // whitespace, and punctuation
    int alphacount = 0;
    int digitcount = 0;
    int spacecount = 0;
    int punctcount = 0;
    int total = 0;
    int i = 0;
    while (string[i] != 0) {
       if (isalpha(string[i])) alphacount++;
       if (isdigit(string[i])) digitcount++;
       if (isspace(string[i])) spacecount++;
       if (ispunct(string[i])) punctcount++;
       total++;
       i++;
    }
    printf("Alphabetic characters: %d\n",alphacount);
    printf("Digits: %d\n",digitcount);
    printf("Spaces: %d\n",spacecount);
    printf("Punctuation: %d\n",punctcount);
    printf("Total characters: %d\n",total);

    // convert to uppercase
    while (*string) {
        if (isalpha(*string)) {
            printf("%c",toupper(*string));
        } else {
            printf("%c",*string);
        }
        string++;
    }
    printf("\n");
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall ctypedemo.c -o ctypedemo
$ ./ctypedemo "The Earth has a radius of 6,353km."
Alphabetic characters: 22
Digits: 4
Spaces: 6
Punctuation: 2
Total characters: 34
THE EARTH HAS A RADIUS OF 6,353KM.
```

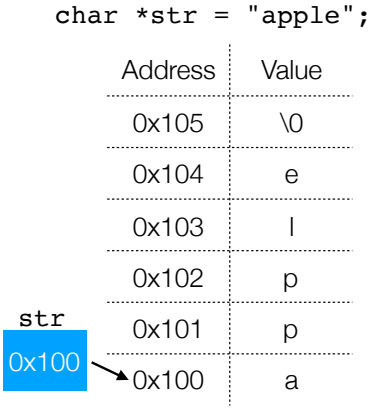
C *Strings in Memory*

A C string is referenced by a pointer to its first character[67], as seen in Figure 24. We have drawn the string vertically, with the lower memory on the bottom, as this is the way we will depict memory for most of the class. Because a string is an array, regular pointer arithmetic can be used to traverse the string, as seen in the example above. A properly null-terminated string has 0 as its last byte, so a loop traversing the string can stop based on the null value.

Because C strings are referenced by a pointer, it is generally meaningless to compare two strings via their pointers. E.g., in the following program, the comparison is between the *addresses* of the first byte of each string, not the value of the char at the respective locations:

[67] Or by an array variable, which is converted to a pointer when we need to access the elements

Figure 24: A C string pointer and the associated memory




```
// file: pointer_compare.c
#include<stdio.h>
#include<stdlib.h>

int main(int argc, char **argv)
{
    char *s1 = argv[1];
    char *s2 = argv[2];

    // the following two lines do not compare
    // the two strings!
    if (s1 < s2) printf("%s is less than %s\n",s1,s2);
    if (s1 == s2) printf("%s is equal to %s\n",s1,s2);
    if (s1 > s2) printf("%s is greater than %s\n",s1,s2);

    printf("%s address: %p\n",s1,s1);
    printf("%s address: %p\n",s2,s2);

    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall pointer_compare.c -o pointer_compare
$ ./pointer_compare cat dog
cat is less than dog
cat address: 0x7ffeef0e9962
dog address: 0x7ffeef0e9966
```

```
$ ./pointer_compare dog cat
dog is less than cat
dog address: 0x7ffeeb6b7962
cat address: 0x7ffeeb6b7966
```

Assigning one string pointer to another string pointer does not make a copy of the original string. Instead, both pointers point to the same string. In the following example, because the two pointers point to the same string, changing a character via either pointer changes the same string:

```
// file: string_pointers.c
#include<stdio.h>
#include<stdlib.h>

int main(int argc, char **argv)
{
    if (argc < 2) {
        printf("usage\n\t%s string\n",argv[0]);
        return -1;
    }
    char *s1 = argv[1];
    char *s2 = s1; // not a copy!

    s1[0] = 'x';
    s2[1] = 'y';

    printf("address: %p, string:%s\n",s1,s1);
    printf("address: %p, string:%s\n",s2,s2);

    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall string_pointers.c -o string_pointers
$ ./string_pointers cs107
$ ./string_pointers cs107
address: 0x7ffee837f962, string:xy107
address: 0x7ffee837f962, string:xy107
```

The `string` *Library*

One of the more important libraries we will discuss is the `string` library. You must be familiar with all of the following library functions, and you should rely on them for your assignments and on the exams. Unless explicitly directed to re-write part or all of a `string` library function, you should always utilize the functions from the library in your code. A general overview of the functions and their declarations can be found with `man string`, and as always, `man function_name` will provide a more detailed reference.

All strings are expected to be `null`-terminated. Note: all string functions have a worst-case complexity of $\mathcal{O}(n)$, where n is the length of the string (or both strings in such cases), including `strlen`. The functions must traverse the entire string or strings.

`strlen` : Calculates and returns the length of the string. Prototype:

```
size_t strlen(const char *str);
```

`strcmp` : Compares two strings, character-by-character, and returns 0 for identical strings, < 0 if `s` is before `t` in the alphabet, and > 0 if `s` is after `t` (digits are less than alphabetic characters). Prototype:

```
int strcmp(const char *s, const char *t);
```

`strncmp` : Performs the same comparison as `strcmp` except that it stops after `n` characters (and does not traverse past `null` characters). Prototype:

```
int strncmp(const char *s, const char *t, size_t n);
```

`strchr` : Returns a pointer to the first occurrence of `ch` in `s`, or `NULL` if the character is not in the string. Prototype:

```
char *strchr(const char *s, int ch);
```

`strstr` : Locate a substring. Returns a pointer to the first occurrence of `needle` in `haystack`, or `NULL` if the substring does not exist. Prototype:

```
char *strstr(const char *haystack, const char *needle);
```

`strcpy` : Copies `src` to `dst`, including the `null` byte. The caller is responsible for ensuring that there is enough space in `dst` to hold the entire copy. The strings may not overlap.[68] Prototype:

```
char *strcpy(char *dst, const char *src);
```

`strncpy` : Similar to `strcpy`, except that at most `n` bytes will be copied. If there is no `null` byte in the first `n` bytes of `src`, then `dst` will *not* be `null`-terminated![69] Prototype:

```
char *strncpy(char *dst, const char *src, size_t n);
```

`strcat` : Appends `src` onto the end of `dst`.[70] The `null`-terminator in `dst` is overwritten by the first character in `src`. The two strings may not overlap, and the caller is responsible for ensureing that there is enough space in `dst` to hold the resulting string.[71] Prototype:

```
char *strcat(char *dst, const char *src);
```

`strncat` : Similar to `strcat` but only copies at most `n` bytes. `dst` is always `null`-terminated, and the caller must be careful to ensure that this is taken into account. Prototype:

```
char *strncat(char *dst, const char *src, size_t n);
```

[68] Be careful! `strcpy` is responsible for many *buffer overruns*, which are a primary attack vector for malicious programmers.

[69] `strcpy` and `strncpy` are not replacements for `memcpy`, although they perform similar functions.

[70] The `cat` stands for "concatenate," or to link together.

[71] This is another relatively unsafe function!

`strspn` : Calculates and returns the length in bytes of the initial part of `s` which contains only characters in `accept`. For example, `strspn("hello","efgh")` returns 2 because only the first two characters in "`hello`" are in "`efgh`." Prototype:

```
size_t strspn(const char *s, const char *accept);
```

`strcspn` : Similar to `strspn` except that `strcspn` returns the length in bytes of the initial part of `s` which *does not* contain any characters in `reject`. For example, `strspn("hello","mnop")` returns 4 because the first four characters in "`hello`" are not in "`mnop`." Prototype:

```
size_t strcspn(const char *s, const char *reject);
```

`strdup` : Returns a pointer to a heap-allocated string[72] which is a copy of `s`. It is the responsibility of the caller to `free` the pointer when it is no longer needed. Prototype:

[72] Obtained with `malloc`.

```
char *strdup(const char *s);
```

`strndup` : Like `strdup` but only copies up to `n` bytes. The resulting string will be `null`-terminated. Prototype:

```
char *strdup(const char *s, size_t n);
```

The following program demonstrates the use of some of the string library functions.

```
// file: extract_numbers.c
// purpose: print all numbers in the first
// command line argument
#include<stdio.h>
#include<stdlib.h>
#include<string.h>

int main(int argc, char **argv)
{
    char *s = argv[1];
    const char *digits = "0123456789";

    while (*s) {
        // count how many digits are at the front of s
        size_t prefixDigits = strspn(s,digits);

        // copy just the initial digits
        char *numstr = strndup(s,prefixDigits);

        printf("%s\n",numstr);

        // clean up
        free(numstr);

        // update s
```

```
        s += prefixDigits + strcspn(s+prefixDigits,digits);
    }

    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall extract_numbers.c -o extract_numbers
$ ./extract_numbers 123abc456x7b9
123
456
7
9
```

Final Thoughts

Strings in C are a simply a string of chars, followed by a 0 byte. The character and string libraries in C provide a robust set of string manipulation tools, butit takes practice to understand them. There are many caveats to using C strings, and you should be careful to understand the nuances present when using the libraries on C strings. But, when you do understand the details, using the string libraries can save you time when writing your programs.

C *Strings Practice Problems*

*Pointers, Generic functions with void *, and Pointers to Functions*

IT IS TIME TO DIG DEEPER into C than we did in the *C Primer*. We will investigate C pointers in more detail, and we will look at the differences between stack-allocated memory and heap-allocated memory. Finally, we will look at how we can pass pointers to functions, which will allow us to make functions that are more generic.

Pointers

As covered in the *C Primer*, pointers are integers that hold a memory address. On our 64-bit Myth machines, pointers are 8-byte `unsigned long` values, which means that they are, ultimately, just numbers. Because of this, we can perform *pointer arithmetic* on pointers, and access addresses nearby – this is the basis for accessing an array's values.

Every pointer has a type, declared as follows:

```
type *varname;
```

where `type` is any type (e.g., `int`, `char`, etc.). When declared as above, the initial value of the pointer is undefined. Pointers that have the value 0 are called `NULL` pointers.

The value of a pointer can be set to the address of another variable by using the "`&`" character:

```
int x = 7;
int *xptr = &x; // xptr points to x
```

To reitierate, the value of `xptr` in this case is the *address* of `x` in memory, whatever that may be.

If a pointer has a non-`NULL` value that points to a memory location a program can access, the value at that location can be *dereferenced* using the `*` operator:[73]

```
printf("%d\n",*xptr); // prints 7
```

When compiling the above code, `gcc` knows that `xptr` points to an `int`, and therfore it knows that when it dereferences the value, it needs to get four bytes from the address pointed to by `xptr`. This is a key benefit of having typed pointers: if `gcc` only knew that

[73] Yes, this is an *overloaded* meaning for the asterisk character. It can be used to define a pointer, or to dereference a pointer (and it can also be used as the multiplication operator).

xptr held an address, but it didn't know what that address pointed to, it could not successfully determine how to encode the printf function parameters.[74]

The type information that is embedded into the pointer is also necessary for performing pointer arithmetic on arrays. Take the following example:

```
void printarr(long *array, size_t nelems)
{
    for (size_t i=0; i < nelems; i++) {
       printf("%lu", array[i]);
       i == nelems - 1 ? printf("\n") : printf(", ");
    }
}
```

Figure 25 shows the layout of memory – note that each long takes up 8 bytes of memory. Also note that in hexadecimal, 0x8 + 0x8 is 0x10.

Another way to express the printf statement from above would be:

```
       printf("%lu", *(array + i));
}
```

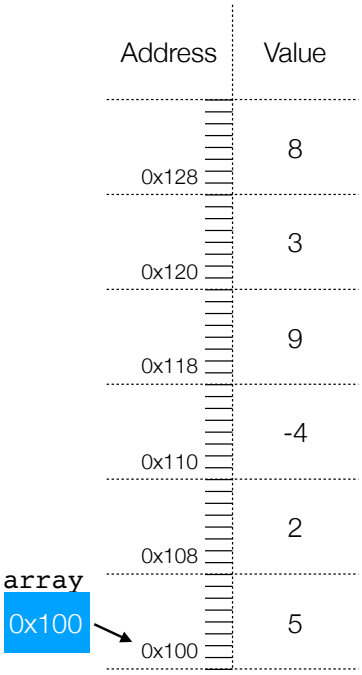
In order to dereference the proper element in the array, gcc needs to know that each element in the array has a width of 8 bytes, and assuming the value of array is 0x100 (as in Figure 25), the calculation of the address of the i^{th} element of the array is:

```
array + i * sizeof(long)
```

which would be 0x100 + i * 8, leading to the addresses seen in Figure 25.

[74] Well, it probably could use the printf string as a guide, knowing that %d expects an int. But, take the following example:
`long z = *xptr;`
gcc could assume that xptr pointed to a long, but that would be incorrect.

Figure 25: An array of longs in memory



Pointers -vs- Arrays

Although we covered this in the *C Primer*, it is worth repeating the differences between pointer and array variables. Pointers are variables that have enough space to hold an unsigned long, which is assumed to be a valid address, or NULL. As variables, they can be changed to have a different address. E.g., xptr++ increments the pointer to point to the next element in an array.

Array variables are defined locally as follows:

```
int nums[10]; //space for 10 ints
```

The type of nums above is "10-element array of int." The type is *not* "pointer to int." Array variables cannot be re-assigned to a different array, and they always point to the same array in memory for their lifetime. The compiler keeps track of array locations automatically (much like it keeps track of variable locations like int x; automatically), and there is not an actual pointer associated with an array declared in this way.

It can be instructive to look at the memory layout for a program that uses both an array and a pointer the array:

```c
// file: array_vs_pointer.c
#include<stdio.h>
#include<stdlib.h>

int main(int argc, char **argv)
{
    int nums[5];
    int nelems_nums = sizeof(nums) / sizeof(int);
    for (int i=0; i < nelems_nums; i++) {
        // fill with index
        nums[i] = i;
    }
    int *numsptr = nums;
    // this is equivalent to:
    // int *numsptr = &nums[0]

    for (int i=0; i < nelems_nums; i++) {
        printf("%d, ",nums[i]); // one way of printing
        printf("%d, ",*(nums + i));    // print again
        printf("%d, ",numsptr[i]);     // print again
        printf("%d",  *(numsptr + i)); // print again
        i == nelems_nums - 1 ? printf("\n")
                             : printf(", ");
    }
    return 0;
}
```

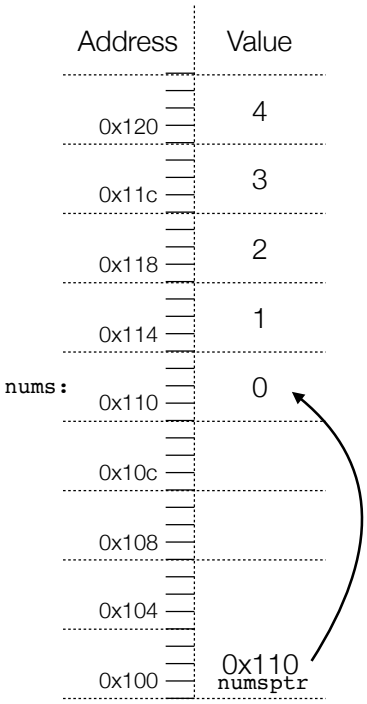
```
$ gcc -g -O0 -std=gnu99 array_vs_pointer.c -o array_vs_pointer
$ ./array_vs_pointer
0, 0, 0, 0, 1, 1, 1, 1, 2, 2, 2, 2, 3, 3, 3, 3, 4, 4, 4, 4
```

Figure 26 shows a potential memory layout for the array and pointer. Notice that the pointer `numsptr` has a location in memory dedicated to hold the address, and the array variable `nums` just refers to the location of the array, without dedicating a pointer to hold the value.

Because arrays can be dereferenced and because you can use bracket notation to refer to the elements of an array, they behave like a pointer when used that way. In the code above, we have printed each array element in four different ways.

For more detailed inofrmation on Dennis Ritchie's reasoning behind developing arrays the way he did, see the article he wrote on his process.[75]

Figure 26: Possible memory layout for `nums` array and `numsptr`



[75] Dennis M Ritchie. The development of the c language. 1993. URL https://www.bell-labs.com/usr/dmr/www/chist.pdf

Generic functions with `void *`

The beauty of C's type system as it applies to pointers is that the compiler has the ability to automatically handle the underlying data type that a pointer points to. However, this necessitates associating a pointer to a particular type, and this results in functions

that only work on a specific type of data. Take the following program, which swaps the beginning and end elements of an array, as an example:

```
// file: nongeneric.c
#include<stdio.h>
#include<stdlib.h>

void swap_ends_short(short *arr, size_t nelems)
{
    short tmp = *arr;
    *arr = *(arr + nelems - 1);
    *(arr + nelems - 1) = tmp;
}

void swap_ends_int(int *arr, size_t nelems)
{
    int tmp = *arr;
    *arr = *(arr + nelems - 1);
    *(arr + nelems - 1) = tmp;
}

void swap_ends_long(long *arr, size_t nelems)
{
    long tmp = *arr;
    *arr = *(arr + nelems - 1);
    *(arr + nelems - 1) = tmp;
}

int main(int argc, char **argv)
{
    short s_array[] = {1,4,8,2,-3,5};
    size_t s_nelems = sizeof(s_array) / sizeof(s_array[0]);

    int i_array[]   = {10,40,80,20,-30,50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[]  = {100,400,800,200,-300,500};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    swap_ends_short(s_array,s_nelems);
    swap_ends_int(i_array,i_nelems);
    swap_ends_long(l_array,l_nelems);

    printf("s_array[0]:%d\t",s_array[0]);
    printf("s_array[%lu]:%d\n",s_nelems - 1,s_array[s_nelems-1]);

    printf("i_array[0]:%d\t",i_array[0]);
    printf("i_array[%lu]:%d\n",i_nelems - 1,i_array[i_nelems-1]);
```

```
    printf("l_array[0]:%lu\t",l_array[0]);
    printf("l_array[%lu]:%lu\n",l_nelems - 1,l_array[l_nelems-1]);

    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 nongeneric.c -o nongeneric
$ ./nongeneric
s_array[0]:5,   s_array[5]:1
i_array[0]:50,  i_array[5]:10
l_array[0]:500, l_array[5]:100
```

We had to write three virtually identical functions to perform the same work, because we have three different types of arrays that we want to perform the swap on. This is a problem with the type system, and we would like to only have to write a function once to accomplish the task. Our goal fits into the category called *generic programming*, and while it may be easier to accomplish in other languages, we can write generic functions in `C`.

To do so, we are going to utilize the `void *` pointer, which we saw briefly in the *C Primer*. Recall that a `void *` pointer is a pointer without an associated type, and it can point to any underlying type. Because we necessarily lose that information, we will have to pass along the type information in a generic way in our functions.

With a `void *` pointer, the missing piece turns out to be, simply, the width of the type that we are passing in. In other words, as Figure 25 showed, each element in an array has a width, and we can perform a calculation to get to the next element if we know the width. Because we are losing the width information by using a `void *` pointer, we will have to perform the calculation manually, without the help of the compiler.

When we perform the array-offset calculation, we will have to fool the compiler into providing us with the correct offset in our pointer. To do this, we cast the `void *` pointer to a 1-byte representation, which, in `C`, is the `char *` pointer. Now, when we perform pointer arithmetic on the `char *` pointer, we can get the address of the type by manually mulitiplying by the width.

This is best described with an example. The following program in a generic version of the program above. The key ideas are:

1. The pointer type information in the parameter is now `void *`.
2. We have added a `width` parameter, to be able to determine how far apart each element is in the array. We must calculate and pass the width information to the function.
3. We cannot simply use an assignment to swap the values, as the compiler does not know the width of the type on its own, and assignments (e.g., `tmp = arr[0]`) is not possible unless the information is known at compile time. So, instead, we create a `char` array that allocates the space we need, in this case, the

width of one element. We then use the `memmove` function to move `width` number of bytes to perform the swap.

4. We must manually do the pointer calculation, remembering to cast the pointer to `char *` (fooling the compiler).

```
// file: generic.c
#include<stdio.h>
#include<stdlib.h>
#include<string.h>

void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp,arr,width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width,width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width,tmp,width);
}

int main(int argc, char **argv)
{
    short s_array[] = {1,4,8,2,-3,5};
    size_t s_nelems = sizeof(s_array) / sizeof(s_array[0]);

    int i_array[]   = {10,40,80,20,-30,50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[]  = {100,400,800,200,-300,500};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    swap_ends(s_array,s_nelems,sizeof(s_array[0]));
    swap_ends(i_array,i_nelems,sizeof(i_array[0]));
    swap_ends(l_array,l_nelems,sizeof(l_array[0]));

    printf("s_array[0]:%d,\t",s_array[0]);
    printf("s_array[%lu]:%d\n",s_nelems - 1,s_array[s_nelems-1]);

    printf("i_array[0]:%d,\t",i_array[0]);
    printf("i_array[%lu]:%d\n",i_nelems - 1,i_array[i_nelems-1]);

    printf("l_array[0]:%lu,\t",l_array[0]);
    printf("l_array[%lu]:%lu\n",l_nelems - 1,l_array[l_nelems-1]);
```

```
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 generic.c -o generic
$ ./generic
s_array[0]:5,   s_array[5]:1
i_array[0]:50,  i_array[5]:10
l_array[0]:500, l_array[5]:100
```

Generic programming takes some time to understand! Look over the examples above carefully, and ensure that you are completely clear on why we needed each change from the non-generic functions to the single generic function.

Pointers to Functions

Looking at the generic example program in the previous section, you might have some lingering concerns about the necessity of having to create a char array to store the data for the swap. What if we had to perform some application where we really did need to know the type of the data – could we still use a generic function?

Let's look at the following example:

```
// file: printf_generic_problem.c
#include<stdio.h>
#include<stdlib.h>

void print_array(void *arr,size_t nelems,int width)
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        printf("%?",element); // what goes in place of the ?
        i == nelems - 1 ? printf("\n") : printf(", ");
    }
}

int main(int argc, char **argv)
{
    int i_array[] = {0,1,2,3,4,5};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    int l_array[] = {0,10,20,30,40,50};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    print_array(i_array,i_nelems,sizeof(i_array[0]));
    print_array(l_array,l_nelems,sizeof(l_array[0]));

    return 0;
}
```

We have a problem. The `printf` call in the `print_array` function needs a format specifier, which is dependent on the type of data we have in the array. For standard data types, we might be able to get away with passing in the correct format specifier, but what if our array had pointers to a struct, or something else that we wanted to print in a custom way?

What we really want is to have the `print_array` function perform a custom function, based on the type of data, and that is exactly what a *pointer to a function* provides. A pointer to a function allows the generic function to pass its data to a custom function, provided by the calling function, that will handle the individual array element in the way that makes sense to the calling function. In the case of our example, the calling function can provide a print function that will do the work, and the `print_array` function only needs to know how to provide the function the data, which is going to be embedded into the type of the function pointer.

The function pointer syntax can be confusing, and it takes practice to get used to reading the function signature. Here is an example, which we will use for our `print_array` function:

```
void(*pr_func)(void *)
```

This is interpreted from the inside out, starting with the pointer to the function name, which is `pr_func`. The function takes one parameter, which is a `void *`, and the function's return value is `void`. Functions that would meet this definition (which we will use in our program) is:

```
void print_int(void *arr);
void print_long(void *arr);
```

In other words, we will pass in one of the functions above into our `print_array` function. We have to write a custom `pr_func` for any data type that we want to use in the `print_array` function. For example, here is the full `print_int` function:

```
void print_int(void *arr)
{
    int i = *(int *)arr;
    printf("%d",i);
}
```

A key idea about this function is that because it is custom-built to take an `int *`, we *know* that the `void *` can be cast to an `int *` inside the function. The function signature must use a `void *`, but inside the function we know that it will be an `int *`, and we can cast it.

The following is the completed program that includes the function pointer in the `print_array` function:

```
// file: printf_generic.c
#include<stdio.h>
#include<stdlib.h>
```

```
void print_array(void *arr,size_t nelems,int width,void(*pr_func)(void *))
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        pr_func(element);
        i == nelems - 1 ? printf("\n") : printf(", ");
    }
}

void print_int(void *arr)
{
    int i = *(int *)arr;
    printf("%d",i);
}

void print_long(void *arr)
{
    long l = *(long *)arr;
    printf("%lu",l);
}

int main(int argc, char **argv)
{
    int i_array[] = {0,1,2,3,4,5};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[] = {0,10,20,30,40,50};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    print_array(i_array,i_nelems,sizeof(i_array[0]),print_int);
    print_array(l_array,l_nelems,sizeof(l_array[0]),print_long);

    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 printf_generic.c -o printf_generic
$ ./printf_generic
0, 1, 2, 3, 4, 5
0, 10, 20, 30, 40, 50
```

The following is an example of how we could use the same function[76] to use a more complicated printing function:

[76] with a minor adjustment to the list format to take out the newline and comma.

```
// file: printf_coords.c
#include<stdio.h>
#include<stdlib.h>
#include<math.h>

struct coordinate {
    double lat;
```

```
    double lon;
};

void print_array(void *arr,size_t nelems,int width,void(*pr_func)(void *))
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        pr_func(element);
    }
}

void print_coord(void *arr)
{
    struct coordinate *coord = (struct coordinate *)arr;
    int lat_deg = (int)coord->lat;
    double lat_minsec = fabs((coord->lat - lat_deg) * 60.0);
    int lat_min = (int)lat_minsec;
    double lat_sec = (lat_minsec - lat_min)* 60.0;

    int lon_deg = (int)coord->lon;
    double lon_minsec = fabs((coord->lon - lon_deg) * 60.0);
    int lon_min = (int)lon_minsec;
    double lon_sec = (lon_minsec - lon_min)* 60.0;

    printf("%f Latitude, %f Longitude =\n",coord->lat,coord->lon);
    printf("Latitude: %d deg %d min %f sec\n",lat_deg,lat_min,lat_sec);
    printf("Longitude: %d deg %d min %f sec\n\n",lon_deg,lon_min,lon_sec);
}

int main(int argc, char **argv)
{
    struct coordinate coords[] = {{37.4301566,-122.1756849},
                                  {38.8975062,-77.0388237},
                                  {-82.8627513,134.9978113},
                                  {51.5287718,-0.2416818}
                                 };
    size_t coords_nelems = sizeof(coords) / sizeof(coords[0]);

    print_array(coords,coords_nelems,sizeof(coords[0]),print_coord);

    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 printf_coords.c -o printf_coords
$ ./printf_coord
37.430157 Latitude, -122.175685 Longitude =
Latitude: 37 deg 25 min 48.563760 sec
Longitude: -122 deg 10 min 32.465640 sec
```

```
38.897506 Latitude, -77.038824 Longitude =
Latitude: 38 deg 53 min 51.022320 sec
Longitude: -77 deg 2 min 19.765320 sec

-82.862751 Latitude, 134.997811 Longitude =
Latitude: -82 deg 51 min 45.904680 sec
Longitude: 134 deg 59 min 52.120680 sec

51.528772 Latitude, -0.241682 Longitude =
Latitude: 51 deg 31 min 43.578480 sec
Longitude: 0 deg 14 min 30.054480 sec
```

You must be careful with the arguments and return values for functions to pointers, and we will show an additional example that demonstrates this.

A frequent use of functions to pointers is the *comparison function*. The standard `C` comparison function compares to elements, and returns a negative value if the first element is less than the second element, zero if the elements are the same, and a positive value if the first element is larger than the second element. The definition of "less than," "equal to," and "greater than" depends on the things that are being compared[77] One example of a standard library function that accepts a generic comparison funtion is the `qsort` function, which (as its name suggests) performs a sort on an array of elements. The prototype for `qsort` is:

[77] although it is normally based on a numeric property of the elements.

```
void qsort(void *base, size\_t nmemb, size\_t size,
                  int (*compar)(const void *, const void *));
```

The `compar` argument in `qsort` is a function pointer that takes two `const void *` pointers to compare, and returns an `int`. The following program sorts the command line arguments (after the program name) by *the sum of the character values in the names*:

```
// file: compare_words.c
#include<stdio.h>
#include<stdlib.h>

int compare_words(const void *p, const void *q)
{
    int psum = 0;
    int qsum = 0;

    char *pword = *(char **)p;
    while (*pword) psum += *(pword++);

    char *qword = *(char **)q;
    while (*qword) qsum += *(qword++);

    return psum - qsum;
}
```

`qsort` passes in a pointer to the pointer of the two words to compare!

```
int main(int argc, char **argv)
{
    qsort(argv+1,argc-1,sizeof(argv[0]),compare_words);
    for (int i=1; i < argc; i++) {
        printf("%s",argv[i]);
        i == argc - 1 ? printf("\n") : printf(", ");
    }
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 compare_words.c -o compare_words
$ ./compare_words apple nectarine banana orange peach pear
pear, peach, apple, banana, orange, nectarine
```

Students tend to gloss over some of the critical details of this example, and it is instructive to take a good look at the various pointers and the memory footprint of what is happening here. Figure 27 shows the layout in memory of the command line arguments.

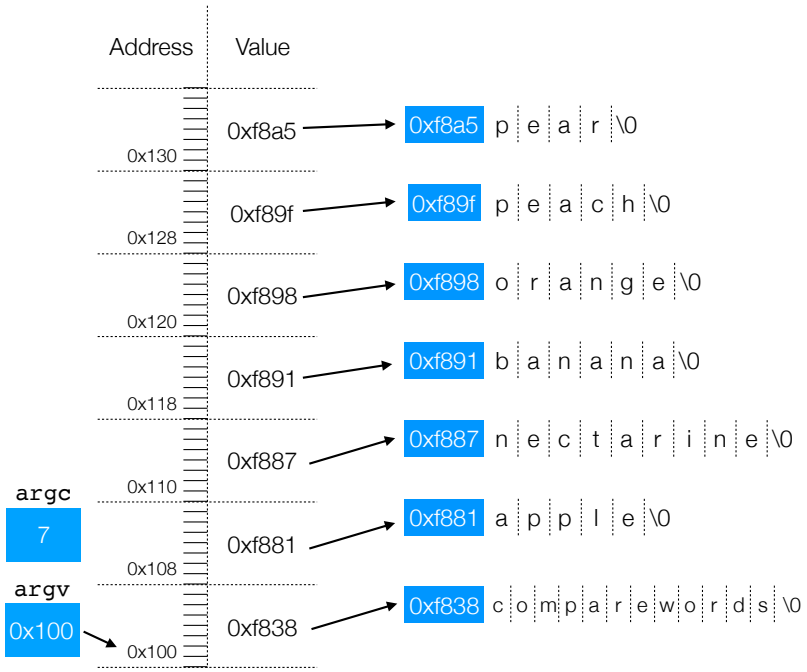


Figure 27: The command line arguments array

The argv variable is a pointer to an array of char * pointers. Because it is an array, the pointers must be contiguous in memory, and they are, from address 0x100 through 0x128. Because they are pointers, they each take up 8 bytes in memory (e.g., argv[0]'s bytes are from 0x100 - 0x107).

The pointers for each char * *do not have to be in any particular place in memory*. Notice that they are not a fixed distance apart. Because they are command line arguments, each string happens to be next to each other, but *this is not a critical point*.

The `qsort` function is passed in the value for `(argv + 1)`[78], which (in our diagram) is the value `0x108`. As far as `qsort` is concerned, it simply has an array of some type of pointer, and it will rearrange those pointers in the array based on the comparison function. For example, `qsort` may, at some point, pass the values `0x108` and `0x110` to the comparison function. Those values are still pointers to `char *` pointers, although `qsort` does not know this information (it simply knows that they are pointers). This is why the comparison function, `compare_words` knows that the arguments are both `char **` pointers, because that is what it must receive from `qsort`.

The `qsort` function sorts the array, and by this we mean that it *rearranges the elements in the array itself*. This is critical to understand: `qsort` never touches the characters in the strings (though the comparison function does) – it simply moves the pointers in the array to correctly sort the elements. Figure 28 shows the result after the sort.

[78] Because we are ignoring the program name, `argv[0]`.

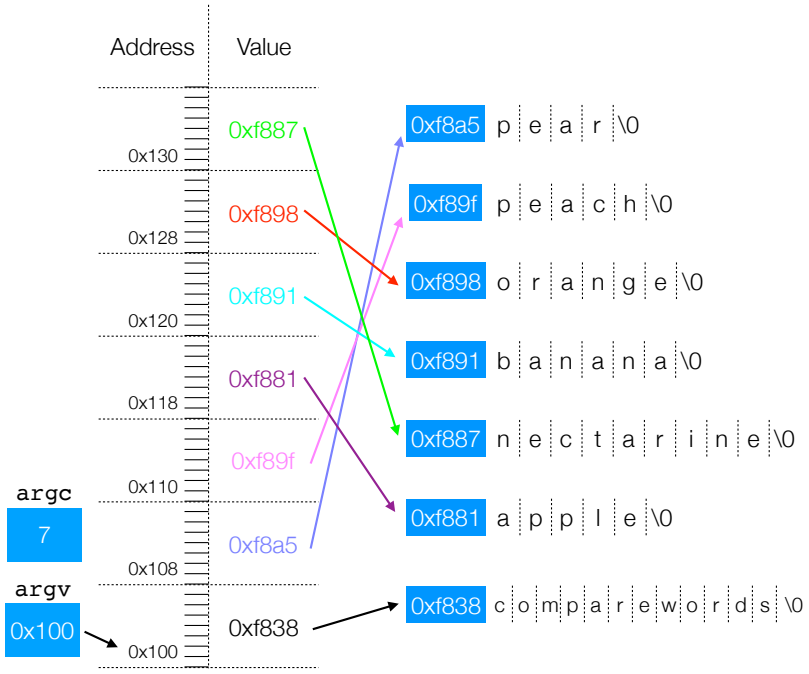


Figure 28: The command line arguments array after being sorted by the sum of the character values of each argument string (except the program name): pear, peach, apple, banana, orange, nectarine.

Final Thoughts

Pointers take time to understand, especially when it comes to pointers to pointers, `void *`, generic functions, and pointers to functions. It would be well-worth your time to go back over this chapter and really understand the nuances of the code.

Pointer Practice Problems

IEEE Floating Point

As we have learned, all data used by a computer is represented by bits and bytes. Integer types each have a fixed number of bytes that represent their exact numeric value, characters are represented by 1-byte ASCII encodings, and strings are simply arrays of `null`-terminated characters. For a given integer type, we know the range[79] and we have the exact representations of each integer in that range.

[79] `INT_MIN` to `INT_MAX` for the `int` type, for example.

The real world, however, does not fit perfectly into this completely-representable model – numbers such as $\frac{1}{3}$ and π cannot be simply broken down into a data type that can exactly represent their values.[80] Additionally, between any two numbers there is an infinite number of rational and real numbers, so representing ranges of numbers exactly is impossible. Therefore, computer designers are forced to compromise when creating a type to hold real numbers, and one of the most successful solutions to the problem is called *The IEEE Standard for Floating Point Arithmetic* (IEEE 754, or IEEE Floating Point)[81], which has become a standard that is implemented in most computer hardware today. The IEEE Floating Point standard was designed to encode the representation of real numbers into a fixed-width format, and to provide a large range with a definable precision, precise rounding rules, and special values such as negative and positive infinity, and special *not a number* (NaN) values that denote a calculation that has become not-real[82]. The IEEE Floating Point format is a clever solution to the problem, and in this chapter we will take a look at the format, and we will investigate some of the decisions that were made and the trade-offs that this implies. We will learn how to convert between a decimal representation and the binary IEEE Floating Point representation, and you should become familiar enough with the format to convert some categories of numbers[83] between the two formats.

[80] Rational numbers can be exactly represented with a numerator / denominator model.

[81] The Wikipedia Page is outstanding.

[82] e.g., division by zero, or the square root of -1.

[83] For example, powers of two, and other small numbers such as 1.25.

Fixed Point Format

When deciding how to represent real numbers in binary form, we have some choices:

1. We want to represent real numbers in a fixed number of bits. This means that we aren't going to be able to represent all real

numbers exactly, nor even all rational numbers exactly. Furthermore, we can't even represent all rational numbers in a range exactly (there are infinitely many rational numbers in any fixed range).

2. We want to represent a large range of numbers.

3. We want to be able to perform calculations on the numbers.

One idea we might consider is called *fixed point* format. Integers represent a fixed point format, with the decimal point (or binary point) located implicitly to the right of the least significant digit. We also limited ourselves to numbers with factors that were positive multiples of the base. E.g., the decimal integer 1234 is really 1234.000..., and the binary equivalent, 10011010010 is really 10011010010.000.... If we wanted to, we could have a system for representing real numbers just move the point to the left some number of digits, so that we can represent numbers between 0 and 1. Maybe we want to have two decimal digits of precision:

$$d_2 d_1 d_0 . d_{-1} d_{-2} = d_2 \times 10^2 + d_1 \times 10^1 + d_0 \times 10^0 + d_{-1} \times 10^{-1} + d_{-2} \times 10^{-2}$$

E.g., we could now represent numbers like 123.45. The range of those numbers would be between 0 and 999.99, and we have five decimal digits of precision, to the 100^{th} decimal place. With our format, however, we cannot represent some numbers exactly, e.g., 123.456 or 0.33....

Arithmetic with fixed point numbers is relatively easy, because we simply line up the decimal place:

$$\begin{array}{rr} & 123.45 \\ + & 678.90 \\ \hline & 802.35 \end{array}$$

and

$$\begin{array}{rr} & 100.22 \\ * & 1.08 \\ \hline & 80176 \\ & 000000 \\ & 1002200 \\ \hline & 1082376 \end{array} = 108.2376 = 108.24 \text{ (rounded)}$$

Fixed point format has one glaring problem: the range of our numbers is severely limited. For our 5-digit example above, if we set the decimal point to the left of the most significant digit, we could only represent numbers in the range of 0 to 0.99999. Although fixed point format has its place,[84] it is too limiting for a general format for real numbers.

[84] It can provide better accuracy in some cases.

Floating Point Format

The way we obtain a worthwhile range for our number format is to take advantage of the fact that we can scale numbers efficiently by

multiplying them by a power of the base we are working in. We can thus decide to represent the numbers as follows:

$$N = x \times 10^y \text{ (decimal)}$$

or

$$N = x \times 2^y \text{ (binary)}$$

We will concentrate on the binary representation from now on, as it is the way we will eventually encode the data. When representing binary numbers, digits after the *binary point* are represented by negative powers of two:

$$b_2 b_1 b_0 . b_{-1} b_{-2} = b_2 \times 2^2 + b_1 \times 2^1 + b_0 \times 2^0 + b_{-1} \times 2^{-1} + b_{-2} \times 2^{-2}$$

For example, 101.11b is:

$$\begin{aligned} 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 + 1 \times 2^{-1} + 1 \times 2^{-2} \\ = 4 + 0 + 1 + \frac{1}{2} + \frac{1}{4} = 5\frac{3}{4} \end{aligned}$$

We have written an online binary to decimal (and vice-versa) calculator that you can play with: `https://stanford.edu/~cgregg/107-Reader/float/convert.html`. If you type in 101.11 into the Binary to Decimal converter, you will find that it is 5.75, as we calculated above.

Just like in decimal format, binary cannot represent numbers such as $\frac{1}{3}$ and $\frac{1}{6}$ exactly, nor can binary represent some other numbers that can be represented in base 10 exactly, like $\frac{1}{10}$. If you type 0.1 into the Decimal to Binary converter mentioned above, you will get:

$$0.0001100110\overline{0011}\ldots$$

which, as you can see, is a non-terminating rational number when expressed in binary. Binary notation can exactly represent numbers in the form

$$x \times 2^y$$

where x and y are integers.

Once we decide to use this format for representing real numbers, we have entered the realm of *floating point* formats. In other words, we will keep track of the values of x and y, and the binary point will "float" in a particular number. For a large number, the binary point might be far to the right of the significant digits, and for a small number the binary point might be far to the left of the significant digits. In other words, the power 2^y scales the location of the binary point.

The IEEE Floating Point standard was first designed by William Kahan[85], and he had many choices to make while arhitecting the format. As we go through the format, we will see some of those choices, and why they ended up being good ones.[86]

[85] Kahan is known as *The father of Floating Point*.

[86] And sometimes confusing ones, too.

The IEEE Floating Point format defines a bit pattern to represent real numbers in the following form:

$$V = (-1)^s \times M \times 2^E$$

where:

- s is a sign bit (0 for positive, 1 for negative, with the sign for numerical zero as a special case)
- M is the *significand*[87], which represents the fractional binary number in the range of $1 \leq M < 2$, or in the range of $0 \leq M < 1$ for special cases (which we will discuss).
- E is the exponent, which scales the value by a (possibly negative) power of 2.

[87] sometimes called the *mantissa* (thus the M designation).

For example, if we have $s = 0$, $M = 1.5$, and $E = 9$:

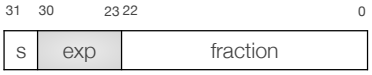
$$V = (-1)^0 \times 1.5 \times 2^9 = 768$$

To encode the bits themselves, IEEE Floating Point defines many bit-widths, but we will concentrate on the 32-bit format (and briefly discuss some details about the similar 64-bit format). The bit representation of a floating point number is divided into three fields to encode s, M, and E:

- A single sign bit, s directly encodes the sign.
- A k-bit exponent field (8-bits for the 32-bit format), $e_{k-1} \cdots e_1 e_0$ encodes the exponent, E (though not directly, as we shall see).
- An n-bit fraction field (23-bits for the 32-bit format), $f_{n-1} \cdots f_1 f_0$ encodes the significand, M, and this value depends on whether or not the exponent field equals zero.

Figure 29 shows the bit representation for a *single precision* (32-bit) floating point number in IEEE Floating Point format.

Figure 29: Single precision (32-bit) IEEE floating point format



Normalized Floats

The IEEE Floating Point format has three different possible intrepetations, depending on the value of the exponent field: *normalized*, *denormalized*, and *exceptional*. Most of our time will be spent learning about the normalized form, which handles the vast majority of the numbers represented by the format. The denormalized numbers are a special case for numbers with the very smallest magnitude, and exceptional numbers are numbers such as infinity and *NaN*.

A float is considered to have a normalized value if the exponent is not all 0s, and not all 1s. In a normalized number, the exponent is encoded as a *signed integer*[88] that is in *biased* form. The exponent has a value of $exp - bias$, where $bias$ is $2^{k-1} - 1$, and where k is the number of bits in the exponent. For a 32-bit number, there are

[88] Not a two's complement number! It is an 8-bit binary number that is intrepeted as a signed number, based on the bias.

eight bits in the exponent field, so $bias = 2^{8-1} - 1 = 2^7 - 1 = 127$. As an example, if the exp field has a value of 10000001 (129, decimal), the value of the numerical exponent would be intrepeted as $129 - 127 = 2$. The range of exponents for a normalized number is -126 to 127, because the range of the exp field is between 1 and 254 (because normalized numbers are only defined when the exp field is not all 0s (00000000) or all 1s (11111111)).[89]

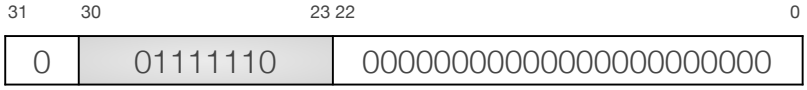
[89] For example, if the exponent of the real number we wanted to encode was -126, we would add 127 to bias the number giving us 00000001 for the exp field. We could not encode an exponent of -127 because $-127 + 127 = 0$, or 00000000, which would not represent a normalized number.

For normalized numbers, the $fraction$ is interpreted as having a fractional value f, where $0 \leq f < 1$, and having a value of $0.f_{n-1} \cdots f_1 f_0$, with the binary point to the left of the most significant bit. However, this is not yet the significand!

The significand is defined to be $M = 1 + f$. This is an *implied leading 1 representation*, and it is a trick for getting an actual digit of precision for free. Here is why: for any number that has ones in it at all, we can always adjust the exponent so that the significand is in the range of $1 \leq M < 2$. When multiplying by a power of two (the exponent), this simply shifts the number to the left or to the right, so we can always adjust the exponent to shift the number into a form of $1.f$. Therefore, because this is *always* possible, it is unnecessary to actually encode the 1 into the representation of the number.[90]

[90] This is an example of where the designers of the IEEE Floating Point format did something extremely clever, at the possible expense of being harder to understand.

Let's take a look at an example, which should clear up potential misconceptions:



The sign bit, 0 means that the number is positive.

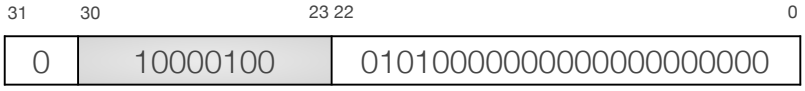
The exp field has the value of 01111110, or 126 decimal, and it has been biased by 127. Therefore, the exponent value we will intrepet exp as will be $126 - 127 = -1$.

The $fraction$ field has a value of all 0s, but we intrepet this as the binary value of $1.000\cdots$.

Therefore, the number represents:

$$+1.0 \times 2^{-1} = 0.5$$

Let's look at another example:



The sign bit, 0 means that the number is positive.

The exp field has the value of 10000100, or 132 decimal, and it has been biased by 127. Therefore, the exponent value we will intrepet exp as will be $132 - 127 = 5$.

The $fraction$ field has a value of 01010000000000000000000, but we intrepet this as the binary value of $1.01010\cdots$:

$$1 \times 2^0 + 0 \times 2^{-1} + 1 \times 2^{-2} + 0 \times 2^{-3} + 1 \times 2^{-4} = 1.3125$$

We can check this at the website from above: https://stanford.edu/~cgregg/107-Reader/float/convert.html

Therefore, the number represents:

$$+1.3125 \times 2^5 = 42.0$$

To put a decimal number into normalized 32-bit floating point format, we must determine the bits for each of the three parts of the number. Let's take the example of converting the decimal number 0.4. If we plug that number into the Decimal to Binary converter at https://stanford.edu/~cgregg/107-Reader/float/convert.html, we get the following number:

$$0.0\overline{1100110011001100110011}$$

This is a non-terminating rational number, so we *won't be able to represent it exactly*. Next, we find the most significant 1 in the number, and then take the following 23 bits after that, in order to form the significand (in bold, below):

$$0.01\mathbf{10011001100110011001100}11$$

In this case, we have one more tiny step to do: we must round the number. Notice that the number after the 23rd digit is a 1. Because 0.1 in binary is $\frac{1}{2}$, the rest of the number is *greater than one half*. Therefore, just like when we round up in decimal when digits when the digit after the rounding place is 5, we round up when the number after the 23rd digit is 1 and there are any more 1s after it (and we do not round up if the number is 0, or if there is a single 1[91]. In order to round up a number, add 1 to it. So, we have:

$$0.01\mathbf{10011001100110011001101}$$

The number in bold above will be the 23 bits of the significand.

Next, we have to scale the number so that it falls between 1.0 and 2, which would look like this:

$$1.\mathbf{10011001100110011001101}$$

Notice that we had to shift the number two binary places to the *right*. Therefore, the exponent of two that we will multiply by is going to be -2. We need to bias this number by 127, so the exponent will be $-2 + 127 = 125$, or 01111101, which is the exponent field for the number.

Finally, we know that the sign bit will be 0 because it is a positive number. The following depicts the bits in the floating point representation for 0.4:

There are websites to check if you are correct[92], or you can write a quick program and run it in gdb. The gdb command "`x/tw &f`" means, *print the memory located at the address of* `f` *in binary ("t") and in word size ("w", or 4-bytes).*

```
// file: floatingpt.c
#include<stdio.h>
#include<stdlib.h>
```

[91] This is called *rounding towards nearest, ties to even.* There are actually five rounding rules, but they are beyond the scope of CS 107. See the Wikipedia page for more information.

[92] This is an outstanding site: https://www.h-schmidt.net/FloatConverter/IEEE754.html

```
int main(int argc, char **argv)
{
    float f = 0.4;
    printf("%g\n",f);
    return 0;
}
```

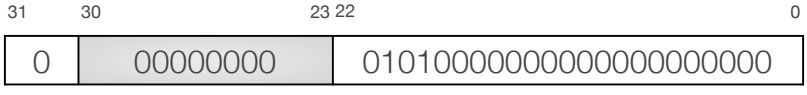
```
$ gcc -g -O0 -std=gnu99 floatingpt.c -o floatingpt
$ gdb floatingpt
The target architecture is assumed to be i386:x86-64
Reading symbols from floatingpt...done.
(gdb) break main
Breakpoint 1 at 0x40053c: file floatingpt.c, line 7.
(gdb) run
Starting program: /afs/.ir.stanford.edu/users/c/g/cgregg/cs107/
reader/107-Reader-code/floatingpt

Breakpoint 1, main (argc=1, argv=0x7fffffffeaa8) at floatingpt.c:7
7           float f = 0.4;
(gdb) n
8           printf("%g\n",f);
(gdb) x/tw &f
0x7fffffffe9bc:        00111110110011001100110011001101
(gdb)
```

Denormalized Floats

When the exponent is all zeros, this is called *denormalized* form. We interpret the exponent differently: the exponent is now $1 - bias$ (or, you can think of the bias now being 1 less, or 126 instead of 127 in the case of 32-bit floats). The significand value is simply the fraction, without a leading 1. Why do we do this? For one, we now have a way to represent zero (all 0s for the entire number). All 0s is $+0.0$, and a 1 followed by all 0s is -0.0. A nice effect is that just like integers, when all the bits in a floating point number are zero, the number means zero.

Second, changing the bias to 126 leads to *gradual underflow*, meaning that it allows us to extend the lower range of representable numbers, and to limit the amount of error with very small numbers.[93] Here is an example of interpreting a denormalized number:



The sign bit, 0 means that the number is positive.

The *exp* field has the value of 00000000, meaning that the number is denormalized, and has a bias of 126. Therefore, the exponent value we will intrepet *exp* as will be $0 - 126 = -126$.[94]

The *fraction* field has a value of 01010000000000000000000, and

[93] See here for more information than you may ever want: https://docs.oracle.com/cd/E19957-01/816-2464/ncg_math.html

[94] and all denormalized numbers have that exponent.

we intrepet this as the binary value of $0.01010\cdots$:

$$0 \times 2^{-1} + 1 \times 2^{-2} + 0 \times 2^{-3} + 1 \times 2^{-4} = 0.3125$$

Therefore, the number represents:

$$+0.3125 \times 2^{-126} = 3.67341985 \times 10^{-39}$$

The following program and gdb trace demonstrates that we are correct:

```
// file: denormalized.c
#include<stdio.h>
#include<stdlib.h>

int main(int argc, char **argv)
{
    float f = 3.6734198463196485e-39;
    printf("%g\n",f);
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 denormalized.c -o denormalized
$ gdb denormalized
The target architecture is assumed to be i386:x86-64
Reading symbols from denormalized...done.
(gdb) break main
Breakpoint 1 at 0x40053c: file denormalized.c, line 7.
(gdb) run
Starting program: /afs/.ir.stanford.edu/users/c/g/cgregg/cs107/
reader/107-Reader-code/denormalized

Breakpoint 1, main (argc=1, argv=0x7fffffffeaa8) at denormalized.c:7
7           float f = 3.67341985e-39;
(gdb) n
8           printf("%g\n",f);
(gdb) x/tw &f
0x7fffffffe9bc:        00000000001010000000000000000000
(gdb)
```

Exceptional Floats

When the exponent bits in an IEEE float are all 1s, the number is considered *exceptional*. Two interesting exceptional numbers are ∞, which is 0 11111111 00000000000000000000000 (for a 32-bit float), and $-\infty$, which is 1 11111111 00000000000000000000000. Positive infinity can can arise when a floating point number overflows, and negative infinity can arise when a number underflows (even smaller than the denormalized values), and other calculations such as $\frac{1}{0}$ can also produce infinity.

The other exceptional numbers[95] are either NaNs, or representations that have a special meaning for a particular processor.

[95] and there are over 8-million of them!

Unrepresentable Numbers

An imporant understanding of floating point numbers is that while the range is large (roughly 2^{-126} to 2^{127} for 32-bit floats, and 2^{-1022} to 2^{1023} fo 64-bit floats), there are infinitely many real numbers that cannot be represented by the format. We have already seen that 0.4 decimal cannot be exactly represented. A 32-bit `float` can, by definition, only represent 2^{32} values, so most, including many integers, are not representable in the format. 0.4 is an example of a non-terminating rational number that cannot be represented in binary, and irrational numbers such as π and $\sqrt{2}$ also (by definition) cannot be exactly represented. Another category of number that fit within the floating point range but cannot be represented are numbers that "run out of bits" in the significand. Let's look at an example. Let's convert 16,777,217 to normalized 32-bit floating point format.

First, we calculate the binary representation, which is

$$100000000000000000000001$$

Next, we put a binary point to the right of the most significant 1:

$$1.00000000000000000000001$$

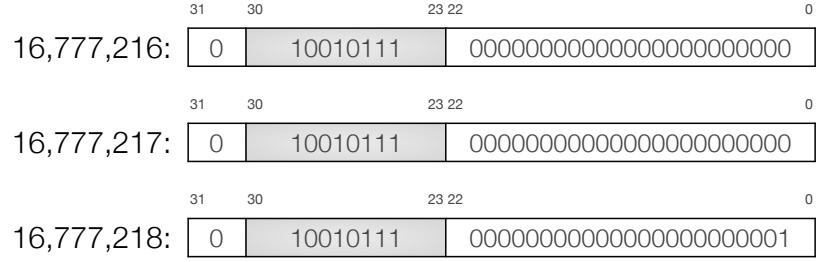
Next, we count off the 23-bits after the binary point, which will become our significand (in bold, below):

$$1.\mathbf{00000000000000000000001}$$

This forms the significand, and it has lost information, so we cannot represent it exactly.

To finish off the conversion, we calculate the exponent, which is 24 (because we have to shift left by 24 places to get a number between 1 and 2), and after biasing, our exponent bits are $24 + 127 = 151$, or 10010111. The sign bit is 0 because the number is positive.

Below are the binary representations of 16,777,216, 16,777,217, and 16,777,218 – notice that the representations for 16,777,216 and 16,777,217 are identical:



The following program demonstrates that even if we set a float to the integer 16,777,217, it cannot be represented:

```
// file: unrepresentable.c
#include<stdio.h>
```

```c
#include<stdlib.h>

int main(int argc, char **argv)
{
    float f1 = 16777216.0;
    float f2 = 16777217.0;
    float f3 = 16777218.0;

    printf("16,777,216: %f\n",f1);
    printf("16,777,217: %f\n",f2);
    printf("16,777,218: %f\n",f3);

    printf("f1 == f2? %s",f1 == f2 ? "true" : "false");
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 unrepresentable.c -o unrepresentable
$ ./unrepresentable
16,777,216: 16777216.000000
16,777,217: 16777216.000000
16,777,218: 16777218.000000
f1 == f2? true
```

Comparing Floating Point Values

As the last example in the previous section demonstrated, comparing floating point values can be troublesome, and in fact it is unwise to compare floating point values directly without using the idea of an *epsilon*, which is a value that you determine is within the error bounds of your calculation. Let's look at an example:

```c
// file: double_comparisons.c
#include<stdio.h>
#include<stdlib.h>

int main(int argc, char **argv)
{
    double a = 0.1;
    double b = 0.2;
    double c = 0.3;
    double d = a + b;

    printf("a (0.1): %.30g\n",a);
    printf("b (0.2): %.30g\n",b);
    printf("c (0.3): %.30g\n",c);
    printf("d (0.3): %.30g\n",d);
    printf("c == d? %s\n", c == d ? "true" : "false");
    printf("c < d?  %s\n", c < d ? "true" : "false");
    return 0;
}
```

The "`.30g`" formatter means *print the floating point value to a precision of 30 decimal places.*

```
$ gcc -g -O0 -std=gnu99 double_comparisons.c -o double_comparisons
$ ./double_comparisons
a (0.1): 0.100000000000000005551115123126
b (0.2): 0.200000000000000011102230246252
c (0.3): 0.299999999999999988897769753748
d (0.3): 0.300000000000000044408920985006
c == d? false
c < d?  true
```

What can we do to see if c is equal to d above, with some error bounds? One option is to choose a value (called the epsilon) that is known to us to be within the bounds. For example, let's presume that for our case above, we want to determine if our result is within 0.1% of the value we think it should be. We could re-write our program as follows:

An outstanding and more detailed description of using epsilons to compare floats is here: https://randomascii.wordpress.com/2012/02/25/comparing-floating-point-numbers-2012-edition/

```
// file: double_comparisons_epsilon.c
#include<stdio.h>
#include<stdlib.h>
#include<math.h>

const float EPSILON = 0.001; // 1 %

int main(int argc, char **argv)
{
    double a = 0.1;
    double b = 0.2;
    double c = 0.3;
    double d = a + b;

    printf("a (0.1): %.30g\n",a);
    printf("b (0.2): %.30g\n",b);
    printf("c (0.3): %.30g\n",c);
    printf("d (0.3): %.30g\n",d);

    float max_cd_percent = fmax(fabs(c),fabs(d)) * EPSILON;
    float diff_cd = fabs(c-d);

    printf("c == d? %s\n", (diff_cd <= max_cd_percent) ? "true" : "false");
    printf("c < d?  %s\n", (diff_cd <= max_cd_percent) ? "false" : "true");
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 double_comparisons_epsilon.c -o double_comparisons_epsilon
$ ./double_comparisons_epsilon
a (0.1): 0.100000000000000005551115123126
b (0.2): 0.200000000000000011102230246252
c (0.3): 0.299999999999999988897769753748
d (0.3): 0.300000000000000044408920985006
c == d? true
c < d?  false
```

Floating Point Arithmetic

The following program demonstrates another issue with floating point calculations: floating point addition is not associative:

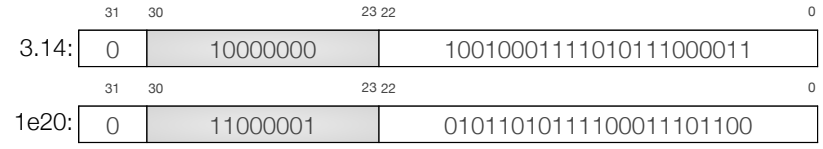
```
// file: float_associativity.c
#include<stdio.h>
#include<stdlib.h>

int main(int argc, char **argv)
{
    float a = 3.14;
    float b = 1e20;

    printf("(3.14 + 1e20) - 1e20 = %f\n", (a + b) - b);
    printf("3.14 + (1e20 - 1e20) = %f\n", a + (b - b));
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 float_associativity.c -o float_associativity
$ ./float_associativity
(3.14 + 1e20) - 1e20 = 0.000000
3.14 + (1e20 - 1e20) = 3.140000
```

the binary representations of 3.14 and 3×10^{20}:



Notice the difference in scale for the exponents of each number. When adding two numbers, we must line up the binary point (or decimal point, in the case of decimal numbers). Let's expand the binary representations, including the implied leading 1 to do so:

```
+ 10101101011110001110110000000000000000000000000000000000000000000000000.00000000000000000000 (1e20)
                                                                11.00100011110101111000011 (3.14)
-------------------------------------------------------------------------------------------------
  10101101011110001110110000000000000000000000000000000000000000000000011.00100011110101111000011
```

If we convert the result back to a binary floating point value, we lose all of the significant digits from 3.14 (the resulting significand is in bold):

```
1**01011010111100011101100**00000000000000000000000000000000000000000011.00100011110101111000011
```

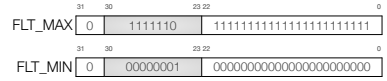
Notice that the significand from the result of our addition is the same as the significand for 1×10^{20}, and therefore, the calculation loses the significant digits from 3.14.

Floating Point Maximums and Minimums

Much like the integers, there are defined maximum and minimum values for floating point numbers, which can be derived from the

floating point formats we have been discussing. Figure 30 shows the 32-bit FLT_MAX and FLT_MIN values (defined in float.h).

Figure 30: 32-bit FLT_MAX and FLT_MIN values



We can generate those values directly in a roundabout way, as demonstrated with the following program:

```
// file: float_extremities.c
#include<stdio.h>
#include<stdlib.h>
#include<float.h>

int main(int argc, char **argv)
{
    int flt_max_int_form = 0b01111111011111111111111111111111;
    int flt_min_int_form = 0b00000000100000000000000000000000;

    float flt_max = *((float *)&flt_max_int_form);
    float flt_min = *((float *)&flt_min_int_form);

    printf("flt_max: %g = %g\n",flt_max,FLT_MAX);
    printf("flt_min: %g = %g\n",flt_min,FLT_MIN);
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 float_extrimities.c -o float_extremities
$ gdb float_extremities
flt_max: 3.40282e+38 = 3.40282e+38
flt_min: 1.17549e-38 = 1.17549e-38
```

There are some properties of FLT_MAX and FLT_MIN that you should be aware of:

1. FLT_MAX is the largest normalized representable number, which is similar to the integer definition of INT_MAX. Infinity is a larger number, but not finite.

2. FLT_MIN is the smallest *in magnitude* normalized number. It is still a positive number, and in fact it is not the smallest representable number, which would be a denormalized number.

Final Thoughts

The IEEE Floating Point Standard was a carefully thought out way to get the most out of a discrete set of bits. It may not be simple, but it is a great study in good engineering design. Floating point numbers represent a very large range, in a limited number of bits. A 32-bit float can only hold a bit over 4 billion numbers but it has a range of -3.4×10^{38} to $+3.4 \times 10^{38}$. Not only is this literally an infinite number of reals that the format must try and represent, but that is a phenomenal range of numbers. The 64-bit double range is -1.7×10^{308} to $+1.7 \times 10^{308}$, which is enormous. Most numbers are,

therefore, only represented approximately in float format, including many integers.

When working with floating point numbers, we as programmers must be cognizant of the limitations and the nuances, but it is an excellent and versitile format for representing the real numbers.

Floating Point Practice Problems

x86-64 Assembly Language

Every microprocessor has an underlying *machine code* that it uses to perform calculations and to write and read data to and from memory. It is this machine code that high level languages like `C` get compiled into by `gcc` and other compilers and intrepeters. The machine code is in binary, and the binary directly maps to a textual and human-readable representation, called *assembly language*. One assembly language instruction generally maps to one (or possibly two) machine code instructions, based on simple rules. In this chapter, we will investigate the assembly lanugage used in the Intel / AMD *x86-64* series of microprocessors, which are the microprocessors used in the Myth machines.[96] Other microprocessor families, like the one that is in your phone, use a different assembly language *instruction set*, and unlike higher level languages, assembly language programs are not compatible with one another, and do not enable portable programs. However, once you learn assembly language for one family of processors, learning a different assembly language is a bit like learning a dialect of a spoken language, and the skills are largely transferable.

Because assembly language is low level, everything in the language is explicit, and assembly language programs do not have features you might be used to from `C`, such as loops and variables. This means that assembly language tends to be much more verbose than an equivalent high level language, and it does make reading it more involved. That said, there is a simplicity to assembly language that enables you to get a feel for the actual way a computer is processing your data that is illuminating.

One goal of this chapter is for you to understand how a section of assembly language code translates into `C` code, and we will build up to those constructs as we go along. We don't expect you to necessarily translate in the other direction (from `C` to assembly language), nor do we expect you to write much assembly language code. Programmers used to write in assembly language when they wanted to tune their code for maximum efficiency, but compiler optimization technology has advanced such that most compilers can turn `C` code into extremely efficient assembly code and it is usually not worth the effort to try and do better by hand.

The Intel-based Myth computers we use are direct descendants of Intel's 16-bit, 1978 processor with the name 8086.[97] Intel has

[96] The comprehensive set of x86-64 manuals can be found here: `https://software.intel.com/en-us/articles/intel-sdm`. We are going to be using `AT&T` syntax; see the following for information on the differences between `AT&T` and `Intel` format: `http://www.imada.sdu.dk/Courses/DM18/Litteratur/IntelnATT.htm`

[97] See the excellent Wikipedia article on the history of the x86 family of processors

taken a strict backwards-compatibility approach to new processors, and their 32- and 64-bit processors have built upon the original 8086 Assembly code. These days, when we learn x86 assembly code, we have to keep this history in mind. Naming of *registers*, for example, has historical roots, and there is some terminology based on the original processor that has remained to this day.

The Intel Instruction Set Architecture and a Sample Program

The machine code for a processor is based on the *instruction set architecture (ISA)* for a processor. The ISA defines the behavior and layout of a system, and the behavior is defined as if instructions are run one after the other. Memory appears as a very large byte-addressable array.[98] There are a number of parts of the underlying machine that we have not discussed yet (in some sense, they have been hidden from us by `C`), but that will be necessary to understand how the machine works. Some of these ideas are listed below:

[98] As you may guess, `C` is a high level language that is based on an underlying machine architecture that is byte-addressable, and operates linearly. Unlike some other languages, `C` code translates in a relatively straightforward manner into assembly code.

- Program values are stored in a *register file*, and there are sixteen named locations that store 64-bit values, plus other registers that hold information you cannot directly access. Registers are the fastest memory on your computer. Registers can hold addresses, or integer data. Some registers are used to keep track of your program's state, and others hold temporary data. Registers are used for arithmetic, local variables, and return values for functions, and your entire processor core shares the small number of registers.
- The computer has a register *program counter* called either `%rip` or `%pc`[99] which indicates the address of the next machine code instruction.
- The condition code registers hold status information about the most recently executed arithmetic or logical instruction. These are used to control program flow – e.g., if the result of an addition is negative, exit a loop.
- There are registers called *vector registers* which are specifically designed for integer and floating point calculations.

[99] *r* stands for *register*, *ip* stands for *instruction pointer*, and *pc* stands for *program counter*.

Unlike in `C`, assembly language and the ISA does not differentiate between signed and unsigned integers, between different types of pointers, or even between pointers and integers. As we will see, there is a set of data widths that can be referred to when moving data between registers and memory, and these do map onto specific `C` data types, depending on the machine[100]

[100] We will discuss the mapping for 64-bit machines, as you might expect.

A single machine instruction performs only a very elementary operation. For example, there is an instruction to add two numbers in registers, there is an instruction that transfers data between a register and memory, and there is an instruction that conditionally

branches to a new instruction address. As you shall see, assembly instructions are simple, and often, one C statement generates multiple assembly code instructions.

Let's start by looking at some assembly code. We will compile with the `-S` flag to tell gcc to create the assembly code output of our program. We will also use the `-Og` optimization flag to produce lightly optimized code that will be easy to debug. The gcc output has more detail then we really care about at this point, and we have annotated the interesting portions. We will show a different view of it below the following code.

```
#include<stdlib.h>
#include<stdio.h>

int main()
{
    int i = 1;
    printf("Hello, World %d!\n", i);
    return 0;
}
```

```
$ gcc -S -Og -std=gnu99 -Wall simpleasm.c
$ cat simpleasm.s
```

```
        .file   "simpleasm.c"
        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0:
        .string "Hello, World %d!\n"
        .text
        .globl  main
        .type   main, @function
main:
.LFB39:
        .cfi_startproc
        subq    $8, %rsp
        .cfi_def_cfa_offset 16
        movl    $1, %edx
        movl    $.LC0, %esi
        movl    $1, %edi
        movl    $0, %eax
        call    __printf_chk
        movl    $0, %eax
        addq    $8, %rsp
        .cfi_def_cfa_offset 8
        ret
        .cfi_endproc
.LFE39:
        .size   main, .-main
        .ident  "GCC: (Ubuntu 5.4.0-6ubuntu1~16.04.5) 5.4.0 20160609"
        .section        .note.GNU-stack,"",@progbits
```

The string is placed into memory, and there is a label called `.LC0`

The `main` function begins here.

The `movl` instruction moves information between registers, and between registers and memory. This is actually setting up the arguments for the `printf` function.

The call to the `printf` function.

If we compile the code to a binary program as we normally do (using the `-Og` optimization flag), we can look at the assembly in `gdb` as well:

```
$ gcc -g -Og -std=gnu99 -Wall simpleasm.c -o simpleasm
$ gdb simpleasm
The target architecture is assumed to be i386:x86-64
Reading symbols from simpleasm...done.
(gdb) disas main
Dump of assembler code for function main:
   0x0000000000400546 <+0>:    sub    $0x8,%rsp
   0x000000000040054a <+4>:    mov    $0x1,%edx
   0x000000000040054f <+9>:    mov    $0x4005f4,%esi
   0x0000000000400554 <+14>:   mov    $0x1,%edi
   0x0000000000400559 <+19>:   mov    $0x0,%eax
   0x000000000040055e <+24>:   callq  0x400430 <__printf_chk@plt>
   0x0000000000400563 <+29>:   mov    $0x0,%eax
   0x0000000000400568 <+34>:   add    $0x8,%rsp
   0x000000000040056c <+38>:   retq
End of assembler dump.
```

By the end of this chapter, you will have no trouble understanding the code above, although at this point it may look confusing! For now, notice how many `mov` instructions there are – these are the instructions that move data between registers and memory. Also notice on line `<+9>` that there is a value of `0x4005f4` – that happens to be the location where the `Hello, World \%d!\n` is kept, which we can also see in `gdb`:

```
(gdb) p (char *)(0x4005f4)
$2 = 0x4005f4 "Hello, World %d!\n"
```

A couple of other things to point out about the assembly code above:

- A single `C` statement can lead to multiple assembly instructions.
- Setting up function calls takes some work.
- The `%rsp` register refers to the stack, so something is happening on the stack.
- Two instructions before the `ret` (*return*) instruction, a value is placed into the `%eax` register, which will become the return value for the `main` function. In this case, we are returning 0.

Data Formats

Intel assembly language has four basic data width formats, to denote byte widths of 1 (*b*), 2 (*w*), 4 (*l*), and 8 (*q*). Because of its 16-bit origins, Intel uses `word` to mean 16-bits, or 2 bytes. Thirty-two bit words are referred to *double words*, and 64-bit words are referred to as *quad words*. Table 8 shows how the assembly code suffix aligns with common `C` data types.

Table 8: Intel Data Types

C type	Suf.	B	Intel data type
`char`	b	1	Byte
`short`	w	2	Word
`int`	l	4	Double word
`long`	q	8	Quad word
`char *`	q	8	Quad word
`float`	s	4	Sing. precision
`double`	l	8	Dbl. precision

x86-64 Registers

x86 CPUs have 16 general purpose registers, which store 64-bit values. Registers store integer data and pointers. Register names begin with *r*, but the naming is historical: the original 16-bit registers were `%ax`, `%bx`, `%cx`, `%dx`, `%si`, `%di`, `%bp`, and `%sp`. Each register had a purpose, and were named as such.

When 32-bit x86 arrived, the register names expanded to 32-bits each, and changed to `%eax`, `%ebx`, etc. When x86-64 arrived, the registers were again renamed to `%rax`, `%rbx`, etc., and expanded to 64-bits. Additionally, eight more registers were added, `%r8` - `%r15`.

Figure 31 shows the integer registers, which are *nested* such that (for example), `%rax` is the full 64-bit register, and `%eax` is the low 32 bits of the register, `%ax` is the low 16 bits of the register, and `%al` is the low 8 bits of the register.

Operand Forms and the `mov` *and* `lea` *Instructions*

Most assembly language instructions take one or two *operands* to perform an operation on, and there are multiple operand forms. These forms can be broken down into a few general examples.

`$IMM` *:* An *immediate* value is a constant, which is preceded by a dollar sign. Examples: `$1`, `$0x1A`, `$-42`.

`%r`$_a$ *:* A register. Examples: `%rax`, `%edx`, `%r8d`.

`Imm(r`$_b$`,r`$_i$`,s)` The general form of a *scaled indexed* operand. The value is computed with the following linear formula:

```
Imm + r_b + s * r_i
```

The `s` stands for the *scaling factor*, and it is limited to either 1, 2, 4, or 8. Each part may be left out, except that if `r_i` is left out, then `s` must, as well. Examples:

```
4(%rax,%rdx,2) = 4 + %rax + 2 * %rdx
(%rdx,%rax,4)  = %rdx + 4 * %rax
5(%rax)        = 5 + %rax
-7(,%rdx,8)     = -7 + 8 * %rdx
(%rax, %rdx)   = %rax + %rdx
```

The most common x86-64 assembly instruction is the `mov` instruction[101], which copies *immediate* data (e.g., constant numbers) into a register or memory, copies values between two registers, or copies values between a register and memory (in either direction). In x86-64 assembly, it is not legal to copy directly from one memory location to another memory location without first copying the data into a register. The general form of the `mov` instruction is as follows:

`mov`*x* `src, dest`

where *x* can be replaced by *b*, *w*, *l*, or *q* to denote the width of the value being moved. The register source and/or destination must

[101] See an interesting pie chart about it at https://www.strchr.com/x86_machine_code_statistics

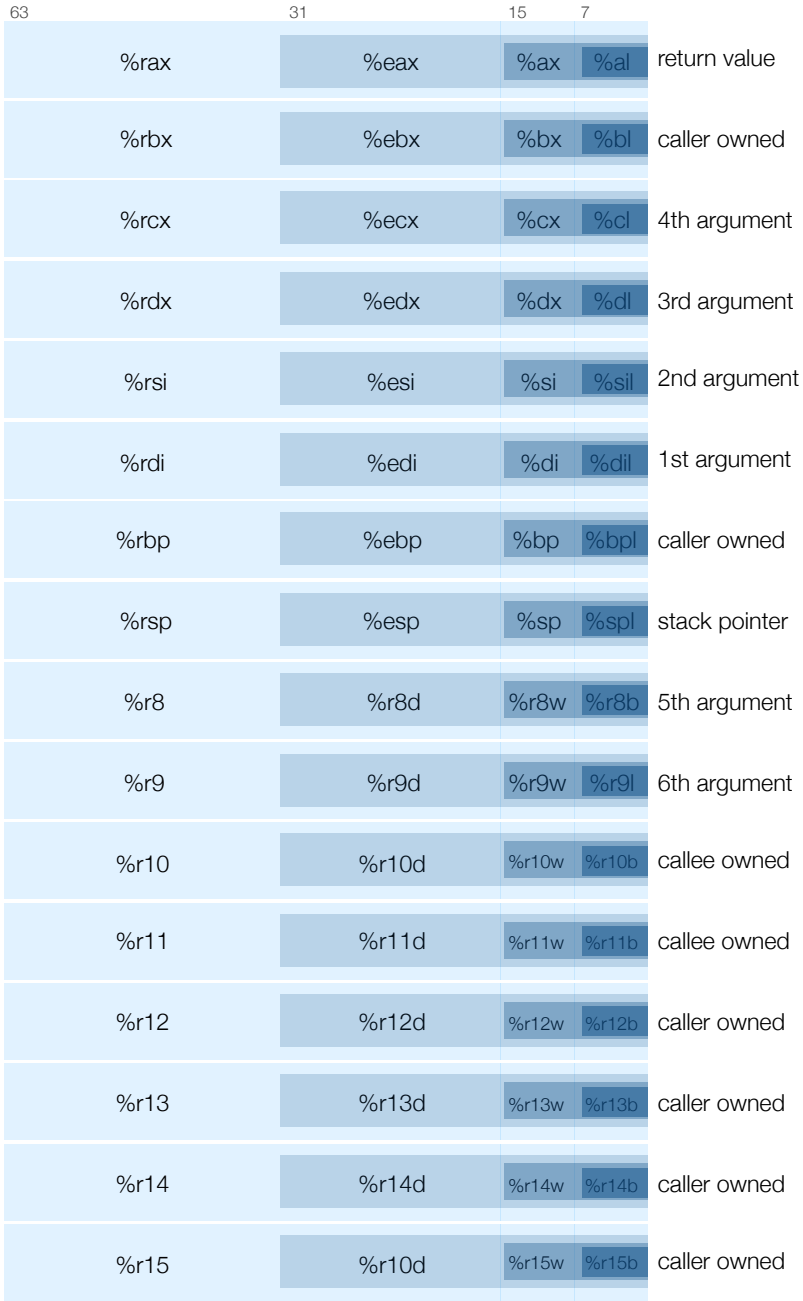


Figure 31: The sixteen x86-64 integer registers

also be the proper width for the instruction (see the examples below), and in most cases, only the bits in the specified width are modified in a 64-bit register. For example, if you are moving 1 byte (with the *b* specifier), only the lowest byte of a destination register will be affected, and the rest will remain the same. There is one exception: the *movl* instruction moves 32-bits into the low bits of a register, and *clears the upper 32-bits* with zeros.

If the operand is in the form **Imm(r_b,r_i,s)**, then the location is a *memory address*, and the copy will be from the location calculated with the linear equation above.

Examples:

movl $0x20,%eax	copies the immediate value 0x20 into the low 32 bits of %rax, and clears the upper 32 bits to zero.
movq 4(%rax,%rdx,2),%rax	copies the 64-bit (8 byte) value at memory location 4 + %rax + 2 * %rdx into register %rax.
movw %bx, (%rdx,%rax,4)	copies two bytes from %bx into the memory location %rdx + 4 * %rax
movl %eax,%edx	copies the low 32-bits (four bytes) of %eax into the low 32-bits of %rdx, and clears the upper 32 bits to zero.
movb (,%rdx,8),%al	copies one byte from 8 * %rdx to the lowest 8 bits of %rax.
movq %rcx, (%rax, %rdx)	copies the 64-bit value in %rcx into the memory location at %rax + %rdx.

There is another `mov` instruction, `movabsq $IMM, Reg`, which is used to put a 64-bit immediate value into a register. This instruciton is needed because in the regular `mov` instruction, the maximum immediate value is only 32 bits. Example:

```
movabsq $0x0011223344556677, %rax
```

There are two additional `mov` instructions, which are used to copy a smaller source into a larger destination (which must be a register): `movz` and `movs`. These instructions perform either a zero-fill of the remaining bytes, or a *sign-extension* of the remaining bytes. There are six ways to move a 1- or 2-byte operand into a 2-, 4- or 8-byte operand. There is not an explicit instruction to zero-extend a 4-byte source into an 8-byte destination, because the `movl` instruction already accomplishes the zero-fill operation. Note that the instructions have the size designations embedded in each instruction:

`movzbw` *and* `movsbw` *:* move zero- or sign-extended byte to word.

`movzbl` *and* `movsbl` *:* move zero- or sign-extended byte to double word.

`movzbq` *and* `movsbq` *:* move zero- or sign-extended byte to quad word.

`movzwl` *and* `movswl` *:* move zero- or sign-extended word to double word.

`movzwq` *and* `movswq`*:* move zero- or sign-extended word to quad word.

`movslq`*:* move sign-extended double word to quad word.

An important instruction that is related to `movq` is the `leaq` instruction. The difference is that instead of actually reading from memory, it simply puts the result of the calculation of the operand into the destination. You can think of it as the *address of* (`&`) operator in `C`:

```
leaq src, dest
```

where the destination is a register. For example:

```
leaq (%rax,%rdx,4), %rax          copies the value of %rax + 4 * %rdx into %rax
```

Often, you will see the `leaq` instruction used to perform arithmetic on values in registers, and the registers do not have to hold addresses.[102]

[102] Keep this in mind! You may see the `leaq` instruction in what seem like odd sections of code (where there are no memory references), but in those cases it is being used for arithmetic.

The Linux Address Space, and the Stack and the Heap

At this point, we will take a brief detour into the land of the *stack* and the *heap* in a program. We have discussed stack variables (local variables and local arrays), and heap allocation (using `malloc` and `free`), but as we get into assembly language, we need to discuss how the stack and heap are layed out in memory.

Figure 32 shows the layout of the Linux address space.

The following is a brief introduction to each section of memory:

stack The stack grows *downward* in memory, and every program is, by default, given an 8MB stack partition.[103] The stack holds local variables, arrays, and parameters[104], and it is fast to allocate variable space on the stack, because a program already "owns" the memory when it begins. Addresses on the stack are in the `0x7ffffxxxxxxx` range.

heap The heap grows *upward* in memory, and the heap holds values allocated with `malloc` and `calloc`. The heap is typically much larger (measured in GB instead of MB), and is managed by the operating system. It is slower to request heap memory because the operating system is directly involved. The heap grows as is necessary for a program (i.e., there isn't a fixed limit). Heap memory begins in the range `0x602010`, and we will see many addresses in this range as we continue the chapter.

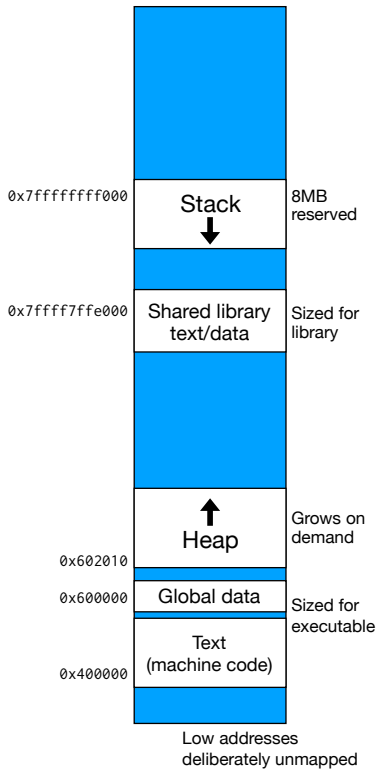
shared library text and data The `C` libaries (and other shared libraries) are placed into a location accessable by all programs. Each program gets its own data segment for shared libraries, but the code is completely shared.

global data Any global or static variables get stored in global memory.

text The text segment (in the `0x400000` range is where a program's code resides. You will see these addresses when you analyze code in more detail.

low addresses The low addresses are used by the operating system and hardware.

Figure 32: The Linux address space (not to scale)



[103] But the hardware memory manager only doles out the memory as needed.

[104] It actually infrequently holds the paramaters, as we will see later in the chapter

Pushing and Popping from the Stack

As we saw in the previous section, the stack is an important part of our program. Assembly language has two built-in instructions, called `push` and `pop` to place values onto, and to take values off of the stack. Just like the stack abstract data type, the instructions have a last-in-first-out discipline.

We saw above that the stack grows downward in memory. The `push` instruction places a value from a register onto the stack at location of the stack pointer, `%rsp`. Then it *decrements* `%rsp` by the amount of bytes that it pushed. The `pop` instruction accomplishes

the reverse process: it saves the value at the location of `%rsp` into a register, and then it increments `%rsp` by the amount of bytes that it popped. Figure 33 demonstrates a `push` followed by a `pop`.

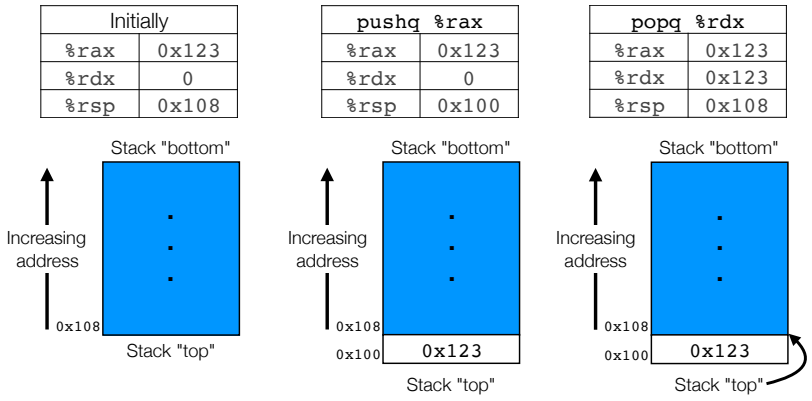


Figure 33: A `push` followed by a `pop`. Notice that after the `push %rax`, the stack pointer has been decremented by 8, and after the `pop %rdx`, the stack pointer has been incremented by 8. Also note that the value on the stack after the `pop` has not been cleared.

Arithmetic in Assembly

In assembly languages, arithmetic forms a substantial set of the instructions. The *unary* instructions act on a single operand (register or memory), and the *binary* operations act on two operands (one of which can be memory). There are also some special instructions (e.g., `mul` and `div`) that act one one operand but affect other operands, as well. The *shift* instructions operate on one operand, but take a second argument to determine how much to shift the operand by.

The unary instructions we care about are defined as follows:

`inc dst` : Increments the register or memory location by 1. Example: `incq %rax`

`dec dst` : Decrements the register or memory location by 1. Example: `decq 4(%rdx)`

`neg dst` : Performs a two's complement conversion on the operand. Example: `negl %eax`

`not dst` : Performs a bitwise complement on the operand. Example: `notb %ax`

The binary instructions are defined as follows[105]:

`add src,dst` : Adds *src* to *dst* and puts the result into *dst*. Example: `addq %rax,%rdx`

`sub src,dst` : Subtracts *src* from *dst* and puts the result into *dst*.[106]. Example: `subl %eax,%edx`

`imul src,dst` : Peforms a signed multiply on *src* and *dst*, and puts the result into *dst*. There is a possibility of losing information, as

[105] Note the lack of a division instruction; we will cover division as a special case below

[106] This syntax can be tricky. `addq %rax, %rdx` is read "subtract %rax from %rdx."

the result of two n-bit multiplications can produce a $2n$-bit product.[107] Can be used on unsigned operands as well, because the lower half of the product is the same. Example: `imulb %al,%dl`

[107] See below for a different form of `imul` that does not lose information.

`xor src,dst` : Performs the *exclusive-OR* operation on *src* and *dst* and puts the result into *dst*. Example: `addq %rax,%rdx`

`or src,dst` : Performs the *OR* operation on *src* and *dst* and puts the result into *dst*. Example: `andl (%rax,%rdx,2),%edx`

`and src,dst` : Performs the *AND* operation on *src* and *dst* and puts the result into *dst*. Example: `andw %ax,%dx`

The shift instructions are defined as follows. Note that the first operand can be either an immediate value or `%cl` (and only `%cl`):

`sal k,dst` *or* **`shl src,dst`** : Performs a left shift of k bits on *dst* and puts the result into *dst*.[108] Example: `shlq $4,%rdx`

[108] The reason there are two instructions that do the exact same thing is simply to be analogous to the right shift instructions, which have a logical and artihmetic form.

`sar k,dst` : Performs an arithmetic right shift of k bits on *dst* and puts the result into *dst*. Example: `sarb $2,%dl`

`shr k,dst` : Performs an logical right shift of k bits on *dst* and puts the result into *dst*. Example: `shrq %cl,8(%rax)`

Because the multiplication of two n-bit numbers can produce a $2n$-bit product, we have a different form of `imul` and and additional `mul` instruction to perform the multiplication of two 64-bit operands without losing information. Both instructions take a single 64-bit operand, but also implicitly use the `%rax` register as one of the multiplicands. The 128-bit result is *always* put into the combination of `%rdx:%rax`, with the upper 64-bits placed into `%rdx` and the lower 64-bits place into `%rax`. The following example demonstrates the idea:

```
// file: octmult.c
#include<stdio.h>
#include<stdlib.h>

// multiply64
// x : the first multiplicand
// y : the second multiplicand
// result : a pointer to an array of 2 longs
//          that will be in little-endian format
void multiply64(unsigned long x, unsigned long y, unsigned long *result);

int main(int argc, char **argv)
{
    unsigned long x = strtol(argv[1],NULL,0);
    unsigned long y = strtol(argv[2],NULL,0);

    unsigned long result[] = {0,0};
```

```
    multiply64(x,y,result);

    printf("0x%016lx%016lx\n",result[1],result[0]);
    return 0;
}
```

```
# File: multiply64.s
# ---------------
# Demonstrates the 1-operand imul / mul
# instructions with two signed 64-bit multiplicands
# and the result placed into %rdx:%rax

.section .text

        .type   multiply64, @function
        .globl multiply64

# %rdi will hold first multiplicand
# %rsi will hold the second multiplicand
# %rdx will hold a pointer to an array
# for the little endian 128-bit result
multiply64:
        # store %rdx in %r8 because %rdx will
        # hold the upper bits of the product
        movq %rdx,%r8

        # copy the first multiplicand into %rax
        movq %rdi,%rax

        # perform the multiplication
        mulq %rsi

        # result is now in %rdx:%rax
        # now we copy the result into
        # the array
        movq %rax,(%r8)
        movq %rdx,8(%r8)
        ret
```

```
$ gcc -g -Og -std=gnu99 -Wall octmult.c -x assembler multiply64.s -o octmult
$ ./octmult 0x3000000000000000 0x2000000000000000
x06000000000000000000000000000000
```

The division instruction seemed to be missing from the list of arithmetic instructions above. However, division is another special case. There are two division instructions (`idivq` and `divq`), and a third helper instruction (`ctqo`) that is used as well (described below). Instead of using a single 64-bit dividend, the `div` instructions take a 128-bit dividend, located in `%rdx:%rax`, and then divide the single operand into the 128-bit dividend. The resulting quotient is

placed into `%rax`, and the *remainder* of the integer division is placed into `%rdx`. If the quotient ends up as too large for the destination register, `%rax`), the runtime throws an exception.[109] The divide instructions are explained below:

[109] One way to check for this potential case is to ensure that `%rdx` is less than the divisor operand.

`idivq src` : Divides the signed 128-bit combination of `%rdx:%rax` by the signed *src*, and puts the quotient into `%rax`, and puts the remainder into `%rdx`. Example: `idivq %rdi`

`divq src` : Divides the unsigned 128-bit combination of `%rax:%rdx` by the unsigned *src*, and puts the quotient into `%rax`, and puts the remainder into `%rdx`. Example: `idivq %rdi`

`cqto` : Sign-extends `%rax` into `%rdx` to produced a correctly-signed 128-bit `%rdx:%rax` combination.

The following shows an example of the `idiv` instruction:

```
// file: div_example.c
#include<stdio.h>
#include<stdlib.h>

long divide_with_remainder(long x, long y, long *rem)
{
    *rem = x % y;
    return x / y;
}

int main(int argc, char **argv)
{
    long x = strtol(argv[1],NULL,0);
    long y = strtol(argv[2],NULL,0);
    long remainder;
    long quotient = divide_with_remainder(x,y,&remainder);
    printf("%ld / %ld = %ld remainder %ld\n",x,y,quotient,remainder);
    return 0;
}
```

```
$ gcc -Og -std=gnu99 -Wall div_example.c
$ ./div_example 10000 3
10000 / 3 = 3333 remainder 1
$ gdb div_example
The target architecture is assumed to be i386:x86-64
Reading symbols from div_example...done.
(gdb) disas divide_with_remainder
Dump of assembler code for function divide_with_remainder:
   0x0000000000000760 <+0>:     mov    %rdi,%rax
   0x0000000000000763 <+3>:     mov    %rdx,%rcx
   0x0000000000000766 <+6>:     cqto
   0x0000000000000768 <+8>:     idiv   %rsi
   0x000000000000076b <+11>:    mov    %rdx,(%rcx)
```

```
   0x000000000000076e <+14>:    retq
End of assembler dump.
```

Control

So far, we have only been discussing "straight-line" code, where one instruction happens directly after the previous instruction. However, it is often necessary to perform one instruction or another instruction based on the logic in our programs, and assembly code gives us tools to do this. We can alter the flow of code using a *jump* instruction, which indicates that the next instruction will be somewhere else in the program (this is called a *branch*), or we can modify the instruction path by calling and returning from functions. We will start by discussing *condition codes* that are set when we do arithmetic and some other operations, and then we will talk about jump instructions to change control flow.

Besides the registers we have already discussed, the x86-64 processors have a separate set of single-bit *condition code* registers that describe attributes of the result of recent instructions. We can use the registers (by testing them) to perform branches in our code.

The condition code registers we will use in class are:

`CF` *:* Carry flag. The most recent instruction generated a carry out of the most significant bit. The carry flag is used to detect overflow for unsigned operations.

`ZF` *:* Zero flag. The most recent instruction yielded zero.

`SF` *:* Sign flag. The most instruction yielded a negative value.

`OF` *:* Overflow flag. The most recent instruction caused a two's-complement overflow, either negative or positive.

For example, if `%rax` contains 5 and `%rdx` contains -5, the instruction `add %rax,%rdx` will set the `ZF` flag, because the result of the addition was 0. If, instead, `%rdx` holds -20, then the same instruction would set the `SF` flag, because the result of the addition is negative.

The `leaq` and `mov` instructions do not set any condition codes, but the arithmetic instructions do set them, as do the logical instructions[110]. For shift instructions, the carry flag is set to the last bit shifted out, while the overflow flag is set to zero. For historical reasons, the `inc` and `dec` instructions do not set the carry flag, but do set the overflow and zero flags.

[110] The logical instructions, e.g., `xor` set the carry and overflow flags to 0.

There are two types of instructions, `cmp` and `test` that we can use to set condition codes without altering any other registers:

`cmp`*x* **`s1,s2`***:* Compares two numbers by subtracting `s2-s1`.[111] The *x* is replaced by a bit width, `b`, `w`, `l`, or `q`. Example:

[111] Be careful to get the order correct! Think, "subtract `s1` from `s2`."

```
movl $5,%eax
movl $1,%edx
```

```
cmpl %eax,%edx  # sets the sign flag because 1-5 is less than 0
                # also sets the carry flag, because adding
                # -1 to 5 produces a carry-out
```

test*x* **s1,s2**: Compares two numbers by performing a bitwise AND on the operands. The *x* is replaced by a bit width, `b`, `w`, `l`, or `q`. The result from the AND sets the flags; for instance, a result that has its most significant bit set would set the Sign Flag, and a number that is all zeros would set the zero flag. We often use the `test` instruction with the same register as both operands in order to determine if the register's value is negative, positive, or zero. Example:

```
movl $0,%eax
test %eax,%eax  # sets the zero flag because 0 AND 0 == 0
```

There are three common ways to use the condition codes to affect assembly language behavior. The `set` instruction will set a single byte based on condition codes. The `j` (jump) instruction sets the instruction pointer to a different instruction than the one that is next in the program.[112] The `cmov` (conditional move) instruction performs a regular `mov` instruction based on the condition codes.

[112] There is also an *unconditional jump* instruction, `jmp`, which changes the instruction pointer unconditionally.

All three conditional instructions use the same suffixes to determine which flags will affect their behavior. Table 9 shows the suffix, english description, and the condition code flags. The suffixes are preceded by either `set` (e.g., `setz`), `j` (e.g., `jz`, or `cmov` (e.g., `cmovz`):

Suffix	Behavior	Flags used
`e / z`	set, jump, move if equal/zero	`ZF`
`ne / nz`	set, jump, move if not equal/nonzero	`~ZF`
`s`	set, jump, move if negative	`SF`
`ns`	set, jump, move if nonnegative	`~SF`
`g / nle`	set, jump, move if greater (signed)	`~(SF ^ OF) & ~ZF`
`ge / nl`	set, jump, move if greater or equal (signed)	`~(SF ^ OF)`
`l / nge`	set, jump, move if less (signed)	`SF ^ OF`
`le / ng`	set, jump, move if less or equal	`(SF ^ OF) | ZF`
`a / nbe`	set, jump, move if above (unsigned)	`~CF & ~ZF`
`ae / nb`	set, jump, move if above or equal (unsigned)	`~CF`
`b / nae`	set, jump, move if below (unsigned)	`CF`
`be / na`	set, jump, move if below or equal (unsigned)	`CF|ZF`

Table 9: The common conditional suffixes for `set` / `j` / `cmov`

For completeness, we have put all of the flags used in the table above. However, most of the time it is far simpler to think about the behavior as it relates to the suffix, and to think about two instructions at a time. For example:

```
cmpq $0x5,%rax
jg   0x821 <main+193>
```

To read this, say, "jump if `%rax` is greater than 5."

Here is another example:

```
cmpw %dx,%ax
cmovne %rcx,%r8
```

To read this, say, "move `%rcx` to `%r8` if `%ax` is not equal to `%dx`."

The `jmp` instruction is *unconditional*, meaning that it always performs the requested jump to a different instruction:

`jmp` *Label :* Directly jump to the *Label*, which is usually replaced in `C` generated code with an offset (e.g., a certain number of bytes away from the instruction pointer). Example: `jmp .L0`

`jmp` **Operand :* Jump indirectly, based on the value in memory pointed to by the operand. This is used when we have a function pointer. Example: `jmp *(%rdx)`

The following program demonstrates how an unconditional and a conditional jump work in a loop in `C`:

```
// file: loopjumps.c
#include<stdio.h>
#include<stdlib.h>

void loop()
{
    int i = 0;
    while (i < 100) {
        printf("i:%d\n",i);
        i++;
    }
}
int main(int argc, char **argv)
{
    loop();
    return 0;
}
```

```
$ gcc -Og -std=gnu99 -Wall loopjumps.c -o loopjumps
$ gdb loopjumps
The target architecture is assumed to be i386:x86-64
Reading symbols from loopjumps...done.
(gdb) disas loop
Dump of assembler code for function loop:
   0x0000000000400546 <+0>:     push   %rbx
   0x0000000000400547 <+1>:     mov    $0x0,%ebx
   0x000000000040054c <+6>:     jmp    0x400567 <loop+33>
   0x000000000040054e <+8>:     mov    %ebx,%edx
   0x0000000000400550 <+10>:    mov    $0x400614,%esi
   0x0000000000400555 <+15>:    mov    $0x1,%edi
   0x000000000040055a <+20>:    mov    $0x0,%eax
   0x000000000040055f <+25>:    callq  0x400430 <__printf_chk@plt>
   0x0000000000400564 <+30>:    add    $0x1,%ebx
```

```
   0x0000000000400567 <+33>:    cmp    $0x63,%ebx
   0x000000000040056a <+36>:    jle    0x40054e <loop+8>
   0x000000000040056c <+38>:    pop    %rbx
   0x000000000040056d <+39>:    retq
End of assembler dump.
```

Let's take a closer look at the assembly code above. We will refer to the code by the values in angle brackets (<>), which are actually counts of how many bytes the instruction is away from the beginning of the function.[113]

The function starts on line `<+0>` by pushing the register `%rbx` onto the stack, to save it.[114]

The value of `%rbx`, which is the loop counter, `i`, is set to 0 on line `<+1>`.

The unconditional `jmp` on line `<+6>` sets the instruction pointer to instruction `<+33>` (address `0x400567`), where the initial `while` loop check for `i < 100` is completed.

The `jle` instruction on line `<+36>` jumps back to line `<+8>` if `%rbx` is less than or equal to 99 (`0x63`), at which point the function enters into the `while` loop body.

Lines `<+8>` through `<+25>` set up and call the `printf` function.

On line `<+30>`, the counter is incremented, and the code falls through to the loop counter check again. When the counter has reached a value of 99, the `jle` instruction does *not* branch, and the code continues with line `<+38>`, restoring `%rbx` (line `<+38>` and returning from the function (line `<+39>`.

[113] x86-64 instructions are *variable length*, and generally take between 1 and 5 bytes. The address of each instruction is, therefore, not exactly the same number of bytes from the previous instruction.

[114] We will discuss why this is the case soon!

More on Conditional Moves

The conditional moves we discussed in the previous section have an interesting use, especially in today's computers. Some times, a program that has a conditional statement that normally requires a conditional jump can be re-written to use a conditional move, instead. Although the resulting change may take extra lines of assembly code, the removal of a branch can actually speed up the program. Modern processors perform what is called *brach prediction* when they read a conditional branch; i.e., they *guess* whether the program will branch, or not. The reason this is necessary is because modern processors have the ability to perform many[115] of instructions in parallel, and by guessing which way a conditional branch will go can keep the processor working on instructions before it actually gets to a point where it knows whether the branch will happen or not. Branch prediction technology has an extremely high rate of correct behavior (over 90% correct), but when it mispredicts, the processor has to *stall* and throw away the result of instructions that it thought would get executed.

[115] sometimes up to hundreds

Therefore, if we can remove a branch from our programs, this can often speed up the program, at the cost of a few extra instructions.

Take the following two C functions that accomplish the same thing:

```
// file: conditionalmov_prog.c
#include<stdio.h>
#include<stdlib.h>

int maxdifference_A(int a, int b)
{
    int diffab;
    if (a - b >= b - a) {
        diffab = a - b;
    } else {
        diffab = b - a;
    }
    return diffab;
}

int maxdifference_B(int a, int b)
{
    int diffab = a - b;
    int diffba = b - a;
    int maxab = diffab < diffba;
    if (maxab) diffab = diffba;

    return diffab;
}

int main(int argc, char **argv)
{
    int a = atoi(argv[1]);
    int b = atoi(argv[2]);
    printf("max_diff_A: %d\n",maxdifference_A(a,b));
    printf("max_diff_B: %d\n",maxdifference_B(a,b));

    return 0;
}
```

```
$ gcc -O3 -std=gnu99 -Wall conditionalmov.c -o conditionalmov
$ ./conditionalmov 4 5
max_diff_A: 1
max_diff_B: 1
```

In `maxdifference_A`, there is an explicit `if/else` statement, and it would seem that a conditional jump is warranted. In `maxdifference_B`, there is no `else` statement to go along with the `if` statement, because both calculations, `diffab` and `diffba` are actually computed. Now take a look at the output the compiler produces when the optimization level is set to a high level of optimization, `-O3`:

```
$ gdb conditionalmov
```

```
The target architecture is assumed to be i386:x86-64
Reading symbols from conditionalmov...done.
(gdb) disas maxdifference_A
Dump of assembler code for function maxdifference_A:
   0x0000000000400620 <+0>:     mov    %edi,%eax
   0x0000000000400622 <+2>:     sub    %esi,%eax
   0x0000000000400624 <+4>:     sub    %edi,%esi
   0x0000000000400626 <+6>:     cmp    %esi,%eax
   0x0000000000400628 <+8>:     cmovl  %esi,%eax
   0x000000000040062b <+11>:    retq
End of assembler dump.
(gdb) disas maxdifference_B
Dump of assembler code for function maxdifference_B:
   0x0000000000400630 <+0>:     mov    %edi,%eax
   0x0000000000400632 <+2>:     sub    %esi,%eax
   0x0000000000400634 <+4>:     sub    %edi,%esi
   0x0000000000400636 <+6>:     cmp    %esi,%eax
   0x0000000000400638 <+8>:     cmovl  %esi,%eax
   0x000000000040063b <+11>:    retq
End of assembler dump.
```

Notice that the compiler has discovered that both of the loops can be re-written using the `cmovl` instruction, without needing to use any conditional jumps.

From C to Assembly: `while` *Loops*

In this and the following sections, we are going to analyze how the compiler creates code for various `C` programs. Note that these are unoptimized compilations, and in many cases the compiler can make faster and more efficient code (as we saw in the last section) when it is allowed to optimize. However, for instructional purposes, we will look at the unoptimized code.

The first code transformation we will look at is the `while loop`. There are two forms that we will look at, and depending on what the compiler can deduce from your code, it will perform one of the following transformations.

In `C`, the general form of the `while` loop is as follows:

```
while (test_expr)
          body\_statement
```

`Gcc` often translates a while loop into assembly that looks like this:

```
   jmp test  // unconditional jump
loop:
   body_statement instructions
test:
   cmp ...   // comparison instruction
```

```
    j.. loop  // conditional jump based on comparison
              // can think of as "if test, goto loop"
```

The following program demonstrates a real example (with comments manually added to the gdb output):

```
// file: whileloop1.c
#include<stdio.h>
#include<stdlib.h>

long fact_while(long n)
{
    long result = 1;
    while (n > 1) {
        result *= n;
        n = n - 1;
    }
    return result;
}

int main(int argc, char **argv)
{
    long x = 5;
    long x_fact = fact_while(x);
    printf("%ld! = %ld\n",x,x_fact);
    return 0;
}
```

```
$ gcc -Og -std=gnu99 -Wall whileloop1.c
$ ./whileloop1
5! = 120
$ gdb whileloop1
The target architecture is assumed to be i386:x86-64
Reading symbols from whileloop1...done.
(gdb) disas fact_while
Dump of assembler code for function fact_while:
   0x000000000040055d <+0>:     mov    $0x1,%eax               # set result to 1
   0x0000000000400562 <+5>:     jmp    0x40056c <fact_while+15> # jump to test
   0x0000000000400564 <+7>:     imul   %rdi,%rax   # loop start, compute result *= n
   0x0000000000400568 <+11>:    sub    $0x1,%rdi               # decrement n
   0x000000000040056c <+15>:    cmp    $0x1,%rdi               # compare n:1
   0x0000000000400570 <+19>:    jg     0x400564 <fact_while+7>  # if >, jmp to loop
   0x0000000000400572 <+21>:    repz retq                       # return from function
End of assembler dump.
(gdb)
```

From C to Assembly: `for` *Loops*

The next code transformation we will look at is the `for` loop. The general form of a `for` loop in `C` is as follows:

```
for (init_expr; test_expr; update_expr)
          body_statement
```

A `for` loop can be re-written as a `while` loop as follows:[116]

[116] Except in the case where there is a `continue` statement in the loop.

```
init_expr;
while (test_expr) {
    body_statement
        update_expr;
    }
```

The program first evaluates `init_expr`. Then it enters the loop where it first evaluates the test condition, `test_expr`, exiting if the test fails. Then, it continues the `body_statement`, and finally evaluates the update expression, `update_expr`.

Gcc has two different forms of assmebly that it prefers for a `for` loop in assembly. The first looks like this:

```
    init_expression
    jmp test   // unconditional jump
 loop:
    body_statement instructions
    update_expression
 test:
    cmp ...   // comparison instruction
    j.. loop  // conditional jump based on comparison
              // can think of as "if test, goto loop"
```

The second form looks like this:

```
    init_expression
    cmp ...  // comparison instruction
    j.. done // conditional jump based on comparison
             // can think of as "if not test, goto done"
loop:
    body_statement instructions
    update_expression
    cmp ...  // comparison instruction
    j.. loop // "if test, goto loop"
done:
```

Here is a full example of a factorial function using a `for` loop:

```
// file: forloop1.c
#include<stdio.h>
#include<stdlib.h>

long fact_for(long n)
{
    long i;
    long result = 1;
    for (i = 2; i <= n; i++)
       result *= i;
```

```
    return result;
}

int main(int argc, char **argv)
{
    long x = 5;
    long x_fact = fact_for(x);
    printf("%ld! = %ld\n",x,x_fact);
    return 0;
}
```

```
$ gcc -Og -std=gnu99 -Wall forloop1.c -o forloop1
$ ./forloop1
5! = 120
$ gdb forloop1
The target architecture is assumed to be i386:x86-64
Reading symbols from forloop1...done.
(gdb) disas fact_for
Dump of assembler code for function fact_for:
   0x0000000000400546 <+0>:     mov    $0x1,%eax              # set result to 1
   0x000000000040054b <+5>:     mov    $0x2,%edx              # set i = 2
   0x0000000000400550 <+10>:    jmp    0x40055a <fact_for+20> # jump to test
   0x0000000000400552 <+12>:    imul   %rdx,%rax              # compute the result *=i
   0x0000000000400556 <+16>:    add    $0x1,%rdx              # increment i
   0x000000000040055a <+20>:    cmp    %rdi,%rdx              # compare n:i
   0x000000000040055d <+23>:    jle    0x400552 <fact_for+12> # if <=, jump to loop
   0x000000000040055f <+25>:    repz retq                     # return
End of assembler dump.
(gdb)
```

From C to Assembly: Functions

Functions[117] are an important software abstraction that creates a reusable section of code that can be called from anelsewhere in the program, accepts zero or more arguments, and has an optional return value. In C, there are multiple things a function must accomplish, based on an x86-64 standard for calling functions:

1. Programs pass control to a function by updating the instruction pointer, `%rip`, to point to the first instruction in the function. When the function ends, it must change `%rip` to point to the next instruction after the call in the calling function.

2. The calling function must be able to pass arguments to the function it calls, and the function that is called must be able to return a value back.

3. There must be a way to save the state of the calling function, and to recover the saved state when control is returned to the calling function.

[117] also called "procedures," although procedures are generally described as not returning any value, while functions do return a value. In C, of course, a function can return `void`, which means that it doesn't return anything.

4. The called function must be able to allocate and deallocate memory (normally on the stack) to use while it is running.

The x86-64 processors have special assembly instructions that allow function calls to happen correctly, based on a standard that all programs should meet.

From C to Assembly: The Stack Frame

As we have seen earler, the stack holds local data that a function uses for variables, arrays, etc. Figure 34[118] shows the stack with more detail than we have seen before – in particular, it shows the "stack frames" for two functions, a calling function (P), and an executing function (Q).

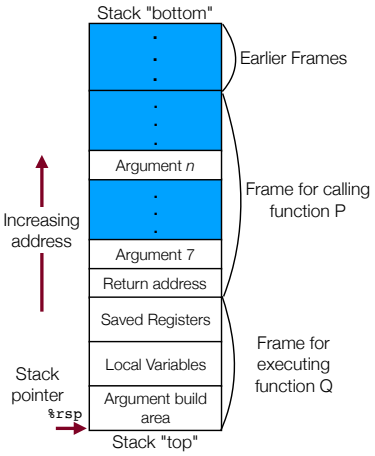
The calling function, P, generally stores its arguments in registers, but if there are more than six arguments to a function, they get placed onto the stack before calling the function, Q. Additionally, the return address of the next instruction after the instruction that calls Q is stored on the stack, and when Q is called, the stack pointer points to the location on the stack where that return address is stored. The arguments passed on the stack and the return address are all considered part of Q's stack frame.

While function Q is executing, P (along with all of the calls up to P) is temporily suspended. Q may need stack space for its own variables, and it may also call other functions, so it uses stack space below the return address (labeled as "Frame for executing function Q in Figure 34). Function Q allocates this space by either pushing and popping values onto and off of the stack, or by decrementing the stack pointer appropriately. When function Q ends, it must return the stack pointer to point to the location of the return address (thereby cleaning up after itself).

As an example of the stack frame structure, we will use the following program, which has three functions (`main`, `first_function`, and `leaf`). The program listing is shown along with a partial listing of the dissassembly (to just show the relevant functions):

[118] R.E. Bryant and D.R. O'Hallaron. *Computer Systems : A Programmer's Perspective*. Pearson, 2015. ISBN 9781292101767. URL https://books.google.com/books?id=KfM2rgEACAAJ

Figure 34: The stack frame structure, borrowed from Figure 3.25, Bryant and O'Halloran




```
// file: run_time_stack.c
#include<stdio.h>
#include<stdlib.h>

int leaf(int x)
{
    x *= 3;
    return x;
}

int first_function(int a)
{
    a--;
    a = leaf(a);
```

```
    return a;
}
int main(int argc, char **argv)
{
    int n = 10;
    n = first_function(n);
    printf("n: %d\n",n);
    return 0;
}
```

```
$ gcc -Og -std=gnu99 -Wall run_time_stack.c
$ objdump -d run_time_stack
0000000000400546 <leaf>:
  400546:       8d 04 7f                lea    (%rdi,%rdi,2),%eax
  400549:       c3                      retq

000000000040054a <first_function>:
  40054a:       83 ef 01                sub    $0x1,%edi
  40054d:       e8 f4 ff ff ff          callq  400546 <leaf>
  400552:       83 c0 03                add    $0x3,%eax
  400555:       c3                      retq

0000000000400556 <main>:
  400556:       48 83 ec 08             sub    $0x8,%rsp
  40055a:       bf 0a 00 00 00          mov    $0xa,%edi
  40055f:       e8 e6 ff ff ff          callq  40054a <first_function>
  400564:       89 c2                   mov    %eax,%edx
  400566:       be 14 06 40 00          mov    $0x400614,%esi
  40056b:       bf 01 00 00 00          mov    $0x1,%edi
  400570:       b8 00 00 00 00          mov    $0x0,%eax
  400575:       e8 b6 fe ff ff          callq  400430 <__printf_chk@plt>
  40057a:       b8 00 00 00 00          mov    $0x0,%eax
  40057f:       48 83 c4 08             add    $0x8,%rsp
  400583:       c3                      retq
```

Table 10 shows a stack trace for the above code, starting at instruction `40055f`:

Instruction		State values (at beginning)				
PC	Instruction	%rdi	%rax	%rsp	*%rsp	Description
0x40055f	callq	10	–	0x7fffffffe940	–	Call call first_function(10)
0x40054a	sub	10	–	0x7fffffffe938	0x400564	Entry of first_function
0x40054d	callq	9	–	0x7fffffffe938	0x400564	Cal leaf(9)
0x400546	lea	9	–	0x7fffffffe930	0x400552	Entry of leaf
0x400549	retq	9	27	0x7fffffffe930	0x400552	Return 27 from leaf
0x400552	add	9	27	0x7fffffffe938	0x400564	Resume first_function
0x400551	retq	9	30	0x7fffffffe938	0x400564	Return 30 from first_function
0x400564	mov	9	30	0x7fffffffe940	–	Resume main

Table 10: Stack Trace Example

From C to Assembly: Data Transfer

Procedure calls can pass data as arguments (either via the stack or registers), and a function can return a value to the calling function

as well.[119] Most often, arguments can fit into registers, so we don't need to involve the stack. However, if there are more than six arguments (or the argument is a struct[120], the calling function allocates space on the stack for those arguments, in a well-defined way. The first six arguments are placed into the following registers, in the order of the arguments to the function: `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, and `%r9`. Arguments seven and above are placed onto the stack in 8-byte chunks, even if smaller values are passed.[121] The return value is (for integer values) placed in the `%rax` register.

[119] Normally through the `%rax` register for integer return values, and through a floating point register for floats, or via the stack for structs.

[120] though not a struct pointer, of course – that is sent as the value of the address of the struct.

[121] e.g., a `char` argument will take up 8 bytes on the stack.

In the following listing, when `stackargs` is called, the arguments are passed as described in Table **??**:

Table 11: Arguments for the `stackargs` function.

Argument	Register	Bytes
`a1`	`%rdi`	8
`a2`	`%esi`	4
`a3`	`%dx`	2
`a4`	`%rcx`	8
`a5`	`%r8`	8
`a6`	`%r9`	8
`a7`	`%rsp + 8`	8
`a8`	`%rsp + 16`	8

```
// file: stackargs.c
#include<stdio.h>
#include<stdlib.h>

long stackargs(long a1, int a2, short a3, long *a4,
               int *a5, short *a6, char a7, char *a8)
{
    long sum = a1 + a2 + a3 + *a4 + *a5 + *a6 + a7 + *a8;
    *a4 = *a5 = *a6 = 0;
    *a8 = 'y';
    return sum;
}
int main(int argc, char **argv)
{
    long  a = 0xabcdefabcdef;
    int   b = 0x1234567;
    short c = 0xabcd;
    char  d  = 'x';

    printf("%lx, %x, %x, %c\n",a,b,c,d);
    long sum = stackargs(a,b,c,&a,&b,&c,d,&d);
    printf("%lx, %x, %x, %c\n",a,b,c,d);
    printf("sum: %lx\n",sum);

    return 0;
}
```

```
$ gcc -Og -std=gnu99 -Wall stackargs.c -o stackargs
$ ./stackargs
abcdefabcdef, 1234567, ffffabcd, x
0, 0, 0, y
sum: 1579be19d7f36
```

The following code is the dissassembly of the `stackargs` function:

```
movq   0x10(%rsp), %r10
movslq %esi, %rax
addq   %rdi, %rax
```

```
movslq %edx, %rdx
addq   %rax, %rdx
movslq (%r8), %rsi
movswq (%r9), %rdi
movsbq (%rsp), %rax
movsbq (%r10), %r11
addq   %rdx, %rax
addq   (%rcx), %rax
addq   %rsi, %rax
addq   %rdi, %rax
addq   %r11, %rax
movw   $0x0, (%r9)
movl   $0x0, (%r8)
movq   $0x0, (%rcx)
movb   $0x79, (%r10)
retq
```

From C to Assembly: Local Stack Storage

In x86-64 assembly, the stack can be used to hold data for a function aside from the arguments. When the "address of" operator, `&` is applied to a local variable, the value must be copied onto the stack because registers do not have addresses, and a proper address needs to be generated that points to the variable. Also, if the local variables are arrays or structs, these must also be placed onto the stack. Whenever a function uses the stack, it must return the stack pointer to its original value when the function was called in order to properly return to the calling function.[122]

[122] Remember, this is because at the end of the function, the stack pointer must point to the return address of the calling function.

In the following example, `main` puts the address values onto the stack, which get used by the `settomin` function:

```
// file: localstack.c
#include<stdio.h>
#include<stdlib.h>

int settomin(int *a, int *b)
{
    int aval = *a;
    int bval = *b;
    if (aval < bval) {
      *b = aval;
      return aval;
    } else {
      *a = bval;
      return bval;
    }

}
```

```
void setvals(int x, int y)
{
    printf("x:%d, y:%d\n",x,y);
    int min = settomin(&x,&y);
    printf("x:%d, y:%d, min:%d\n",x,y,min);
}

int main(int argc, char **argv)
{
    if (argc < 3) {
        printf("Usage:\n\t%s x y\n",argv[0]);
        return -1;
    }
    int x = atoi(argv[1]);
    int y = atoi(argv[2]);
    setvals(x,y);
    return 0;
}
```

```
$ gcc -Og -std=gnu99 -Wall localstack.c -o localstack
$ ./localstack 2 1
x:2, y:1
x:1, y:1, min:1
```

The following code is the dissassembly of the `setvals` function. Notice that it puts the original arguments onto the stack in order to pass them to the `settomin` function:

```
(gdb) disas setvals
Dump of assembler code for function setvals:
   0x00000000004005a6 <+0>:     sub    $0x18,%rsp
   0x00000000004005aa <+4>:     mov    %edi,%edx
   0x00000000004005ac <+6>:     mov    %edi,0xc(%rsp)
   0x00000000004005b0 <+10>:     mov    %esi,%ecx
   0x00000000004005b2 <+12>:     mov    %esi,0x8(%rsp)
   0x00000000004005b6 <+16>:     mov    $0x4006f4,%esi
   0x00000000004005bb <+21>:     mov    $0x1,%edi
   0x00000000004005c0 <+26>:     mov    $0x0,%eax
   0x00000000004005c5 <+31>:     callq  0x400480 <__printf_chk@plt>
   0x00000000004005ca <+36>:     lea    0x8(%rsp),%rsi
   0x00000000004005cf <+41>:     lea    0xc(%rsp),%rdi
   0x00000000004005d4 <+46>:     callq  0x400596 <settomin>
   0x00000000004005d9 <+51>:     mov    %eax,%r8d
   0x00000000004005dc <+54>:     mov    0x8(%rsp),%ecx
   0x00000000004005e0 <+58>:     mov    0xc(%rsp),%edx
   0x00000000004005e4 <+62>:     mov    $0x400700,%esi
   0x00000000004005e9 <+67>:     mov    $0x1,%edi
   0x00000000004005ee <+72>:     mov    $0x0,%eax
   0x00000000004005f3 <+77>:     callq  0x400480 <__printf_chk@plt>
   0x00000000004005f8 <+82>:     add    $0x18,%rsp
   0x00000000004005fc <+86>:     retq
```

Caller owned and callee owned registers

Function calling on an x86-64 processor follows conventions, as we have seen. One convention we haven't yet discussed is the idea of "caller owned" and "callee owned" registers. This convention designates six of the sixteen general purpose registers to be *caller owned*,[123] meaning that the calling function is guaranteed that the values stored in those registers will be the same after any function is called. On the other hand, when a function is called, it must ensure that those registers are the same as when the function started when it finishes. The *callee owned* registers are just the opposite: a calling function cannot expect that those registers will be the same after it makes a function call, and a function itself can modify callee owned registers without concern about their original value (when the function started). The list of caller owned registers is `%rbx`, `%rbp`, and `%r12` - `%r15`. The callee-owned registers are `%rax`, `%rcx`, `%rdx`, `%rdi`, `%rsi`, and `%r8` - `%r11`. The final register, `%rsp` is the stack pointer, and we have already discussed the limitations placed on its value.

[123] These registers are also called *callee saved*.

Often, `gcc` will use caller owned registers to ensure that data does not get overwritten when making a function call. For example, it may move `%rdi` (the first argument) into `%rbx` in order to call another function (and, perhaps, to free up `%rdi` to be used as the first argument to the funciton it will call). Before replacing `%rbx`'s value, however, it must first save the value so it can return it to the original value when the function ends. Normally, this saving is done via a push of `%rbx` onto the stack at the beginning of the function, and a pop of `%rbx` at the end of the function. This same push/pop dance is played with all of the caller owned registers, so you may see a large number of pushes at the beginning of a function in anticipation of using those registers, and you may likewise see a number of pops at the end of the function, to clean up and restore the original values.

From C to Assembly: Recursion

Recursive functions in assembly are not significantly different than any other functions, except that they rely heavily on the caller owned and callee owned registers and on the stack itself because at some point a recursive function calls itself, and the state of the calling function must be saved. We can use recursive functions to demonstrate how a *stack overflow* can occur, and we can see this particularly well by looking at a recursive function in `gdb`, where we can show that the stack is heavily used.

Managing the Heap

In this chapter, we will investigate different options for the *heap allocator*, which performs the `malloc`, `calloc`, `realloc`, and `free` functions in a `C` program. The heap allocator manages large memory blocks that it receives from the operating system.[124] The heap allocator needs to partition this memory block into smaller blocks, and it provides pointers to these smaller blocks to programs as they request specified numbers of bytes. The heap allocator also has to be able to recapture the memory as programs `free` it, and it has to re-use memory in an efficient way in order to reduce *fragmentation* of the memory.

[124] The heap allocator requests the blocks of memory from Linux using the `sbrk` and/or `mmap` functions, but that is beyond the scope of this text. Suffice it to say that has a large memory block to dole out to programs that request memory.

What Does it Mean to Allocate Memory?

Your programs have two areas of main memory: the stack and the heap. On a Linux system, programs have (by default) 8MB of stack space that they must manage based on the conventions we discussed in *x86-64 Assembly Language*. The heap, on the other hand, is ultimately controlled by the operating system, and a heap allocator maintains the heap as a collection of contiguous memory blocks that are either free or allocated.

An allocated block has been reserved for a particular application. When a program calls `malloc`, it has access to an allocated block, and only that program can modify or read the values in that block. Allocated blocks remain allocated for the rest of the program, or until the program `free`s them. If the program ends, the heap allocator frees the block.

As we have discussed before, stack memory is limited and serves as a scratch-pad for functions, and it is continually being re-used by a program's functions. Stack memory isn't persistent, but because it is already allocated to a program, it is fast.

Heap memory takes more time to set up (a program has to go through the heap allocator), but it is unlimited,[125] and persistent for the rest of a program.

[125] For all intents and purposes it is unlimited. Operating systems and hardware are excellent at allocating memory, and they will even use (slow) hard disk or SSD memory to fulfill requests if necessary.

Heap Allocator Requirements

The heap allocator must be able to service any sequence of `malloc`, `calloc`, `free`, and `realloc` requests. Recall that `malloc` must return

a pointer to a contigous area of memory that is equal to or greater than the requested size, or `NULL` if it can't satisfy the request. The area that the pointer returned by `malloc` points to is called the *payload*, and the program can legally modify any byte in the range from the pointer to the number of bytes requested.[126] The contents of the memory requested are unspecified, and they can be `0`s or be filled with any value.[127]

If the client[128] introduces an error, then the behavior is undefined. Often this will result in a *seg fault*, but it could be ignored by `malloc`, or the problem could manifest itself later in the program.[129] For example, if the client tries to free non-allocated memory, or tries to use freed memory, the operations are undefined.

The heap allocator has some constraints. It cannot control the number, size, or lifetime of the allocated blocks. It must be flexible enough to handle any sequence of `mallocs`, `frees`, `reallocs`, etc. The heap allocator must also respond immediately to each malloc request, and it cannot buffer the requests to try and find a better allocation strategy. Although this may seem obvious, the first request must be handled first. However, the heap allocator can defer, ignore, or reorder requests to `free`, and this may be useful for efficiency reasons (as we shall see).

The heap allocator must align blocks so that they satisfy alignment constraints, which vary from system to system. In a 64-bit Linux system, the alignment must be on 16-byte boundaries.[130] Importantly, the memory that has already been allocated must be maintained throughout the life of a program. This is critical, because the program has no way of updating its pointers if the allocation were to change. On the other hand (as mentioned above), the allocator can manipulate and move free memory blocks around as much as is necessary. We call this *coalescing* free memory, and will will discuss it below.

[126] In fact, as we shall see, the program often has slightly more memory that it can access, but it does not have this information available to take advantage of it.

[127] For `calloc`, of course, the memory is initialized to `0`s. In fact, the first time a program allocates a region of memory, it must be requested from the operating system, and that memory is zeroed by the OS for security reasons. When a program calls `free` and then subsequently calls `malloc` again, if the pointer returned is in the same range as the original memory, it will be recycled and will hold values that were leftover from the previous allocation. See `https://stackoverflow.com/a/8029624/561677` for more information.

[128] the function calling `malloc`, `free`, etc.

[129] this is a source of hard to find bugs – make sure you use the functions correctly!

[130] e.g., the block returned by `malloc` or `realloc` will always be a multiple of 16.

Heap Allocator Goals

First and foremost, a heap allocator must attempt to meet `malloc` and `free` requests as efficiently and as quickly as possible. If possible (and it is not always possible), requests should be handled in constant time, and should not degrade to linear time. A poor heap allocator can be a bottleneck to programs, as it is used frequently, and a finely tuned and fast heap allocator is an important part of a standard library. The GNU Standard library comes with an excellent heap allocator, and although in CS 107 we will practice writing one, you should virtually always prefer to simply use the library's allocator.

A heap allocator should also attempt to utilize space in memory efficiently. In other words, it should try to serve requests in a way that minimizes *fragmentation* of the heap (areas where there are many small free blocks that are unlikely to be used), and that provides large free blocks for use if needed. A heap allocator should

also be written in a way that minimizes the overhead per block. Because `free` simply provides a pointer to a block to be freed, the heap allocator must inherently keep track of the amount of bytes requested for every `malloc`, and this incurs an overhead. Minimizing that overhead is important.

A heap allocator should provide good *locality* for blocks – this means that blocks that are allocated one after the other should ideally be located near each other. Additionally, blocks that are similar to each other in size should be allocated close to each other, as well. This is a secondary concern, but important nonetheless.

A good heap allocator will also limit undefined behavior due to client error, to the extent possible. If a client makes a mistake, the heap allocator should either crash the program at that point, and it should report a good error. This is not always possible, of course, but it is a good goal to have.

From a coding perspective, heap allocator functions (like all programs) should be clearly written so that they are easy to maintain. As we shall see, using `*(void **)` all across your code is inherently hard to understand, and often `typedefs` and `structs` can be used to create cleaner code.

A Simple Heap Allocation Example

We will investigate heap allocation for the following program:

```
// file: heapalloc_ex1.c
#include<stdio.h>
#include<stdlib.h>
#include<string.h>

int main(int argc, char **argv)
{
    void *a, *b, *c, *d, *e, *f;
    a = malloc(16);
    memset(a,'a',16);

    b = malloc(8);
    memset(b,'b',8);

    c = malloc(24);
    memset(c,'c',16);

    d = malloc(16);
    memset(d,'d',16);

    free(a);
    free(c);

    e = malloc(8);
```

Table 12: Stack at beginning of heap trace (values are uninitialized)

Variable	Address	Value
f	0xffffe828	0xfeed
e	0xffffe820	0xabcde
d	0xffffe818	0xf0123
c	0xffffe810	0x0
b	0xffffe808	0x0
a	0xffffe800	0xbeef

Table 13: Stack after `a = malloc(16)`

Variable	Address	Value
f	0xffffe828	0xfeed
e	0xffffe820	0xabcde
d	0xffffe818	0xf0123
c	0xffffe810	0x0
b	0xffffe808	0x0
a	0xffffe800	0x100

Table 14: Stack after `b = malloc(8)`

Variable	Address	Value
f	0xffffe828	0xfeed
e	0xffffe820	0xabcde
d	0xffffe818	0xf0123
c	0xffffe810	0x0
b	0xffffe808	0x110
a	0xffffe800	0x100

Table 15: Stack after `c = malloc(24)`

Variable	Address	Value
f	0xffffe828	0xfeed
e	0xffffe820	0xabcde
d	0xffffe818	0xf0123
c	0xffffe810	0x118
b	0xffffe808	0x110
a	0xffffe800	0x100

```
    memset(e,'e',8);

    b = realloc(b, 24);
    memset(b,'b',24);

    e = realloc(e, 24);
    memset(e,'e',24);

    f = malloc(24);
    memset(f,'f',24);

    free(b);
    free(d);
    free(e);
    free(f);

    return 0;
}
```

The heap we will look at will be limited to 96 bytes (and yes, this is a very small heap!). The initial heap is shown in Figure 35. The numbers in Figure 35 are left-aligned to their start locations, and each minor hash-mark represents 4 bytes. Table 12 shows the stack after the pointer variables are declared in the program, and note that the variables have uninitialized values. We will investigate partitioning the heap as if we were simply filling in locations in our block of memory – we will soon see that this is not the way most heaps are organized.

Table 16: Stack after `d = malloc(16)`

Variable	Address	Value
f	0xffffe828	0xfeed
e	0xffffe820	0xabcde
d	0xffffe818	0x130
c	0xffffe810	0x118
b	0xffffe808	0x110
a	0xffffe800	0x100

Table 17: Stack after `e = malloc(8)`

Variable	Address	Value
f	0xffffe828	0xfeed
e	0xffffe820	0x100
d	0xffffe818	0x130
c	0xffffe810	0x118
b	0xffffe808	0x110
a	0xffffe800	0x100

Table 18: Stack after `f = malloc(24)`

Variable	Address	Value
f	0xffffe828	0x0
e	0xffffe820	0x100
d	0xffffe818	0x130
c	0xffffe810	0x118
b	0xffffe808	0x110
a	0xffffe800	0x100

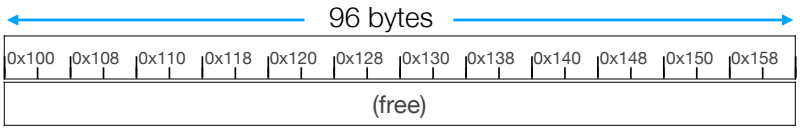


Figure 35: Empty 96-byte heap

Figure 36 shows the heap after the `a = malloc(16);` line. The as are only supposed to represent that a has access to that block of memory.

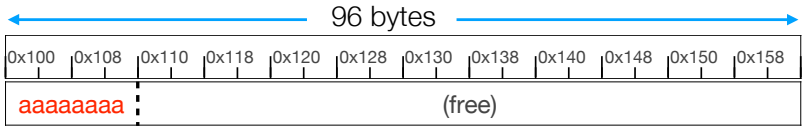


Figure 36: Heap after `a = malloc(16);`

Figure 37 shows the heap after the `b = malloc(8);` line. The heap allocator was able to put the b range directly after the a range.

Figure 38 shows the heap after the `c = malloc(24);` line. Again, the heap allocator was able to put the c range directly after the b range.

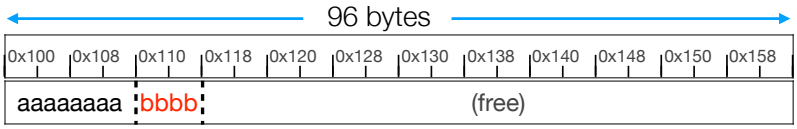


Figure 37: Heap after `b = malloc(8);`

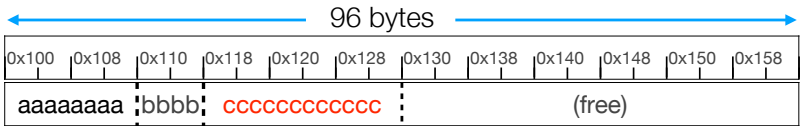


Figure 38: Heap after `c = malloc(24);`

Figure 39 shows the heap after the `d = malloc(16);` line. The heap allocator was able to put the `d` range directly after the `c` range.

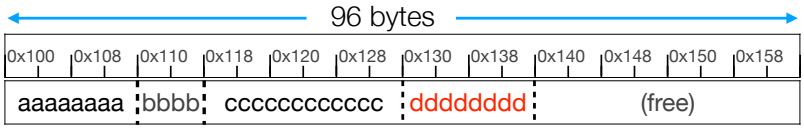


Figure 39: Heap after `d = malloc(16);`

Figure 40 shows the heap after the `free(a);` line. Note that the only information the `free` line provides is the pointer, and the heap allocator must keep track of the amount of space allocated to `a` in order to free it.

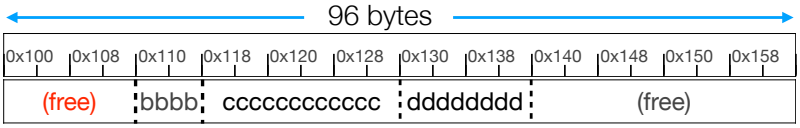


Figure 40: Heap after `free(a);`

Figure 41 shows the heap after the `free(c);` line.

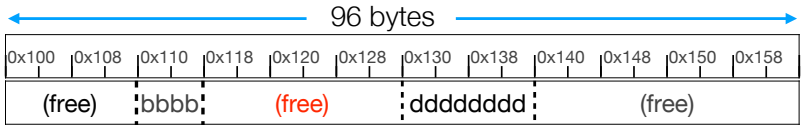


Figure 41: Heap after `free(c);`

Figure 42 shows the heap after the `e = malloc(8);` line. The heap allocator was able to give `e` the same pointer as `a` was originally given, because `a` has been freed.

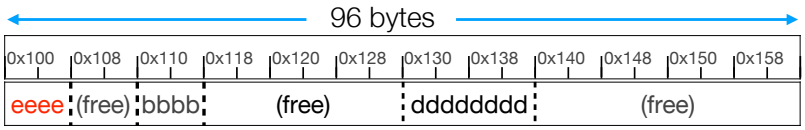


Figure 42: Heap after `e = malloc(8);`

Figure 43 shows the heap after the `b = realloc(b,24);` line.[131]

[131] Yes, it is bad practice to not check the return value for `realloc`, but we are leaving that out here in the interest of making the code relatively concise.

Because c was already freed, the heap allocator was able to extend b's allocation, and returned the same pointer.

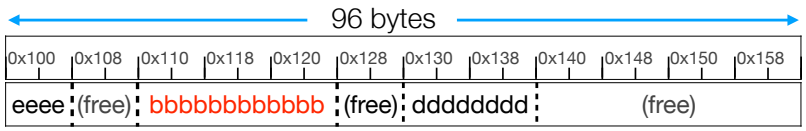


Figure 43: Heap after `b = realloc(b,24);`

Figure 44 shows the heap after the `e = realloc(e,24);` line. Notice that the heap allocator needed to move e's range because there was not enough contiguous bytes in the original location.

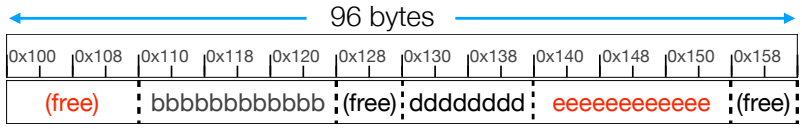


Figure 44: Heap after `e = realloc(e,24);`

Figure 45 shows the heap after the `f = malloc(24);` line. The heap allocator ran out of contiguous space in the block, and therefore it returns `NULL`, failing to allocate the space for `f`. Even though the heap does indeed have 24 bytes free, they must be contigous for `malloc` to successfully allocate the region.

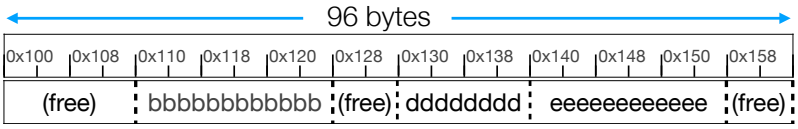


Figure 45: Heap after `f = malloc(24);`

The above description of a heap allocator is a simple way to demonstrate the basic idea. In order to implement the heap allocator as described above, the `malloc`, `realloc`, and `free` functions would have to keep a global state of the heap, most likely in a linked list, array, or table. This separate list or table is reasonable, but it would likely be slow, and potentially have considerable overhead to keep track of the details of the list. In practice, it is rare to see such a heap allocator, though programs that need more information about the heap (for profiling, for instance), such as `Valgrind` do use such a list. The next two sections describe a different method for heap allocation, and both are more frequently used in real heap allocators.

Using an Embedded Implicit Free List

The second possible method used to create a heap allocator is to use a *block header* that is stored in the heap memory itself, alonside the data, which is known as the *payload*. In other words, the memory block that the heap alloctor uses to allocate to programs is the

same memory that keeps track of the used and free information. Figure 46 shows a 96-byte, completely free heap. The first eight bytes make up the block header, and the rest of the bytes are free.

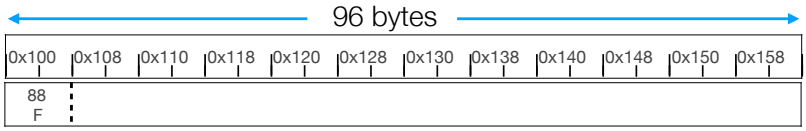


Figure 46: Empty, 96-byte Implicit Heap

The block header in this case has both the amount of free bytes following it (88, in this case), and an "F" to designate that it is free.

Figure 47 shows how the heap memory changes after a `a = malloc(16);` statement is executed. Memory for the requested bytes is allocated to `a` after the first block header, and the header is updated to reflect the amount of memory (16 bytes), and the fact that it is now used ("U"). After the allocated memory, another block header is created in order to designate the smaller free block that is left after the allocation. This second block header uses an additional 8 bytes from the available memory, so there are only 64 bytes in the free block.

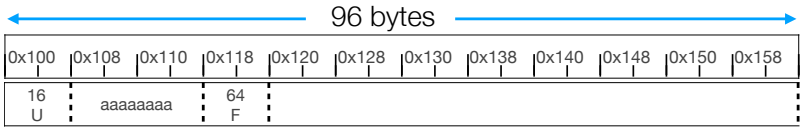


Figure 47: Implicit Heap after a call to `a = malloc(16);`

Figure 48 shows how the heap memory changes after a `b = malloc(8);` statement is executed. Again, memory for the requested bytes is allocated to `b` from the free block, and the header is updated to reflect the amount of memory (8 bytes), and the fact that it is now used ("U"). Another block header is created in order to designate the smaller free block that is left after the allocation.

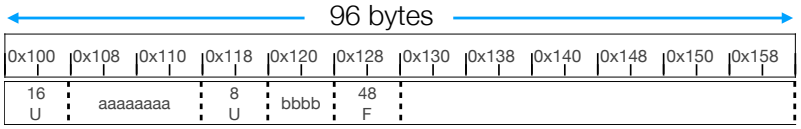


Figure 48: Implicit Heap after a call to `b = malloc(8);`

Figure 49 shows how the heap memory changes after a `c = malloc(24);` statement is executed, and follows the same pattern.

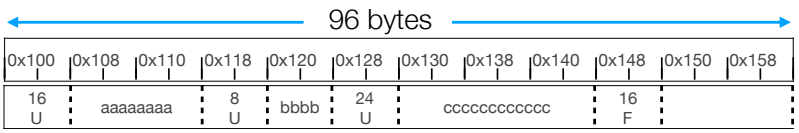


Figure 49: Implicit Heap after a call to `c = malloc(24);`

Figure 50 shows how the heap memory changes after a `free(a)` statement. The `free` statement only provides a pointer to the memory that will be freed, but we know that the prior 8 bytes to that pointer holds the block header, so we can perform a small amount of arithmetic to find that location to retrieve the data. We can then update the block to be free, with the same number of bytes. Note that the heap allocator does not clear the memory, though the diagram seems to indicate this.

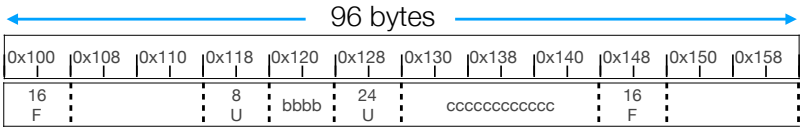


Figure 50: Implicit Heap after a call to `free(a);`

Figure 51 shows how the heap memory changes after a `free(c)` statement. At this point, there are two free blocks that are contiguous, with a block header in between. This situation wastes memory (in the form of the block header), and it also fragments the memory – although there should be 48 free bytes, there are two smaller blocks of 24 bytes and 16 bytes respectively.

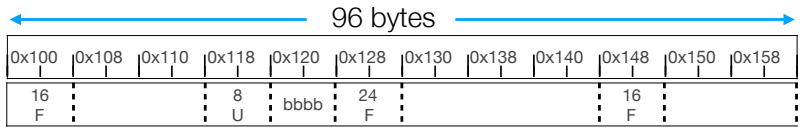


Figure 51: Implicit Heap after a call to `free(a);`

When faced with this situation, a heap allocator should *coalesce* the free memory into a more appropriate, larger block. To do this, the heap allocator simply starts searching forward from the freed block to see if the next block is indeed free. When the heap allocator decides to perform the coalesce is a design decision – it can perform it immediately, during the free function, or it can postpone the coalesce until a future `malloc` or `realloc`. We will discuss how a heap allocator can perform a reverse-coalesce (in the case where a block is freed that is directly after an already free block) shortly. Figure 52 shows the result of a coalesce after the `free(c)` statement.

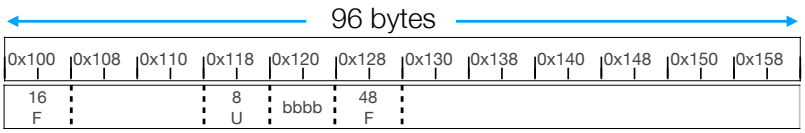


Figure 52: The result after coalescing.

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Index