Problem Set 5: Forensics

due by noon on Thu 10/18

Per the directions at this document's end, submitting this problem set involves submitting source code via `submit50` as well as filling out a Web-based form, which may take a few minutes, so best not to wait until the very last minute, lest you spend a late day unnecessarily.

Goals.

- Better acquaint you with file I/O.
- Get you more comfortable with data structures, hexadecimal, and pointers.
- Introduce you to computer scientists across campus.
- Help Mr. Boddy.

Recommended Reading.[1]

- `http://www.cprogramming.com/tutorial/cfileio.html`
- Chapters 18, 24, 25, 27, and 28 of *Absolute Beginner's Guide to C*
- Chapters 9, 11, 14, and 16 of *Programming in C*

- `http://en.wikipedia.org/wiki/BMP_file_format`
- `http://en.wikipedia.org/wiki/Hexadecimal`
- `http://en.wikipedia.org/wiki/Jpg`

diff pset4.pdf hacker4.pdf.

- Hacker Edition challenges you to implement Hacker Typer.
- Hacker Edition challenges you to reduce (and enlarge) BMPs.

[1] The Wikipedia articles are a bit dense; feel free to skim or skip!

Academic Honesty.

All work that you do toward fulfillment of this course's expectations must be your own unless collaboration is explicitly allowed in writing by the course's instructor. Collaboration in the completion of problem sets is not permitted unless otherwise stated by some problem set's specification.

Viewing or copying another individual's work (even if left by a printer, stored in an executable directory, or posted online) or lifting material from a book, website, or other source—even in part—and presenting it as your own constitutes academic dishonesty, as does showing or giving your work, even in part, to another student or soliciting the work of another individual. Similarly is dual submission academic dishonesty: you may not submit the same or similar work to this course that you have submitted or will submit to another. Nor may you provide or make available solutions to problem sets to individuals who take or may take this course in the future. Moreover, submission of any work that you intend to use outside of the course (*e.g.*, for a job) must be approved by the course's instructor or preceptor.

You are welcome to discuss the course's material with others in order to better understand it. You may even discuss problem sets with classmates, but you may not share code. In other words, you may communicate with classmates in English, but you may not communicate in, say, C. If in doubt as to the appropriateness of some discussion, contact the course's instructor or preceptor.

You may turn to the Web for instruction beyond the course's lectures and sections, for references, and for solutions to technical difficulties, but not for outright solutions to problems on problem sets or your own final project. However, failure to cite (as with comments) the origin of any code or technique that you do discover outside of the course's lectures and sections (even while respecting these constraints) and then integrate into your own work may be considered academic dishonesty.

All forms of academic dishonesty are dealt with harshly. If the course refers some matter to the Administrative Board and the outcome for some student is *Admonish*, *Probation*, *Requirement to Withdraw*, or *Recommendation to Dismiss*, the course reserves the right to impose local sanctions on top of that outcome for that student that may include, but not be limited to, a failing grade for work submitted or for the course itself.

Fine Print.

Your work on this problem set will be evaluated along four axes primarily.

Scope. To what extent does your code implement the features required by our specification?
Correctness. To what extent is your code consistent with our specifications and free of bugs?
Design. To what extent is your code written well (*i.e.*, clearly, efficiently, elegantly, and/or logically)?
Style. To what extent is your code readable (*i.e.*, commented and indented with variables aptly named)?

All students, whether taking the course Pass/Fail or for a letter grade, must ordinarily submit this and all other problem sets to be eligible for a passing grade (*i.e.*, Pass or A to D–) unless granted an exception in writing by the course's instructor or preceptor. No more than one late day may be spent on this, or any other, problem set.

A Section of Questions.

You're welcome to dive into these questions on your own, but know that they'll also be explored in section! Instead of using CS50 Run or CS50 Spaces for these questions, you'll need to use the CS50 Appliance.

☐ Head to

```
https://www.cs50.net/shorts/
```

and watch the short on Redirecting & Pipes. Be prepared to answer the following questions!

- ☐ To which "stream" do functions like `printf` write by default?
- ☐ What's the difference between `>` and `>>`?
- ☐ What pipeline could you use to find the <u>number</u> of unique names in a file called `names.txt`?

☐ You may also want to re-watch the short on GDB!

☐ This section of questions comes with some distribution code that you'll need to download before getting started. Go ahead and execute

```
cd ~/Dropbox
```

in order to navigate to your `~/Dropbox` directory. Then execute

```
wget http://cdn.cs50.net/2012/fall/sections/5/section5.zip
```

in order to download a ZIP (i.e., compressed version) of this section's distro. If you then execute

```
ls
```

you should see that you now have a file called `section5.zip` in your `~/Dropbox` directory. Unzip it by executing the below.

```
unzip section5.zip
```

If you again execute

```
ls
```

you should see that you now also have a `section5` directory. You're now welcome to delete the ZIP file with the below.

```
rm -f section5.zip
```

Now dive into that `section5` directory by executing the below.

```
cd section5
```

Now execute

```
ls
```

and you should see that the directory contains the below.

```
buggy1    buggy2    buggy3    buggy4    cat.c
buggy1.c  buggy2.c  buggy3.c  buggy4.c  cp.c
```

Whereas most of those are source files, `buggy1`, `buggy2`, `buggy3`, and `buggy4` are binary files that we've compiled for you. Indeed, if you try opening the files with `gedit`, you'll see a bunch of binary gobbledygook.

□ By now, you should know what `gdb` is, even though you might not fully appreciate it or understand it. Time to fix!

As those programs' filenames suggest, they're a bit buggy, so your mission is to figure out why using `gdb`! Go ahead and execute the below.

```
./buggy1
```

What happens? How about `buggy2`, `buggy3`, and `buggy4`?[2] Hm, not so good. Let's try to debug `buggy1`. Go ahead and execute the below.

```
gdb ./buggy1
```

Next, set a breakpoint at the start of `main` by executing

```
break main
```

at `gdb`'s prompt. And then execute

```
run
```

at `gdb`'s prompt to get `buggy1` running. From there, see if you can figure out why buggy1 is so buggy. Odds are you'll find the following commands helpful: `r`(`un`), `n`(`ext`), `p`(`rint`), `q`(`uit`), `h`(`elp`), `bt` (`backtrace`), `b`(`reak`), `u`(`p`), `d`(`own`), and `l`(`ist`).

Once you've figured out the source of `buggy1`'s woes, move on to `buggy2`, `buggy3`, and `buggy4`!

Consider these buggy programs an opportunity to practice with `gdb`. No need to fix any bugs; the goal is simply to identify them. You won't be asked to submit anything for these programs.

□ Ready to wow your friends? Impress your enemies? Get ready… and check out the below.

```
http://hackertyper.net
```

[2] Recall that you can force a program to quit with ctrl-c.

Your task is to implement Hacker Typer in C. When you're finished, you should have a binary executable named `hacker_typer` that takes in a single argument, the file to "hacker-type." Running the executable should first clear the screen (recall how we did that in Problem Set 3!) and then print out one character from the passed-in file each time the user presses a key.

Check out the `stdio` library to figure out which function(s) you might want to use. Keep in mind that many of the functions that return characters actually return values of type `int` and **not** of type `char`.

You'll also need to check out the `termios` library in order to stifle the character "echoes" that you normally get when you type in the terminal, since if your friends see those, they'll know that you're not *actually* typing out code! Additionally, the `termios` library will help you ensure that the `stdin` stream "flushes" after each key press.

Use the `man` pages and Google to figure out how best to manage `struct termios`. You'll need to use the `tcgetattr` and `tcsetattr` functions and mess with the structure's `c_lflag` and `c_cc` fields to get the job done. And remember to save a copy of your "normal" terminal settings to restore before your program exits!

Finally, if you really want a challenge, know that real h4ck3rs will code this using

```
cat - > hacker_typer.c
```

;-)

Consider this problem an opportunity to practice; you won't be asked to submit this program.

□ Now that you're a master of reading files, let's add some writing into the mix. By now, you've probably had to copy a file or two using the `cp` command. It turns out that it's not that much more difficult to write now that you've implemented `cat`.

Go ahead and complete the implementation of `cp.c`, per the usage instructions therein, where `source` is the name of the file to be copied, and `destination` is the filename (or path) for the copy.

As with `cat`, you'll probably find `fgetc` (or `fread`) quite handy for reading! For writing, however, you'll now want to use `fputc` instead of `putc`, though `fwrite` will still work if using `fread`.

Thoughts on how best to test your implementation?

Consider this problem an opportunity to practice; you won't be asked to submit this program.

□ No need to worry about `cat.c`!

Getting Started.

☑ Welcome back!

☐ Start up your appliance and, upon reaching John Harvard's desktop, open a terminal window (remember how?) and execute

```
update50
```

to ensure that your appliance is up-to-date!

☐ Like Problem Set 3, this problem set comes with some distribution code that you'll need to download before getting started. Go ahead and execute

```
cd ~/Dropbox
```

in order to navigate to your `~/Dropbox` directory. Then execute

```
wget http://cdn.cs50.net/2012/fall/psets/4/hacker4.zip
```

in order to download a ZIP (i.e., compressed version) of this problem set's distro. If you then execute

```
ls
```

you should see that you now have a file called `hacker4.zip` in your `~/Dropbox` directory. Unzip it by executing the below.

```
unzip hacker4.zip
```

If you again execute

```
ls
```

you should see that you now also have a `hacker4` directory. You're now welcome to delete the ZIP file with the below.

```
rm -f hacker4.zip
```

Now dive into that `hacker4` directory by executing the below.

```
cd hacker4
```

Now execute

```
ls
```

and you should see that the directory contains the below.

```
bmp/  jpg/  questions.txt
```

How fun! Two subdirectories and a file. Who knows what could be inside! Let's get started.

□ If you ever saw Windows XP's default wallpaper (think rolling hills and blue skies), then you've seen a BMP. If you've ever looked at a webpage, you've probably seen a GIF. If you've ever looked at a digital photo, you've probably seen a JPEG. If you've ever taken a screenshot on a Mac, you've probably seen a PNG. Read up a bit on the BMP, GIF, JPEG, and PNG file formats.[3] Then, open up `questions.txt` in `~/Dropbox/hacker4`, as with `gedit`, and tell us the below.

0. How many different colors does each format support?
1. Which of these formats supports animation?
2. What's the difference between lossy and lossless compression?
3. Which of these formats is lossy-compressed?

□ Curl up with the article from MIT below.

```
http://cdn.cs50.net/2012/fall/psets/4/garfinkel.pdf
```

Though somewhat technical, you should find the article's language quite accessible. Once you've read the article, answer each of the following questions in a sentence or more in `~/Dropbox/hacker4/questions.txt`.

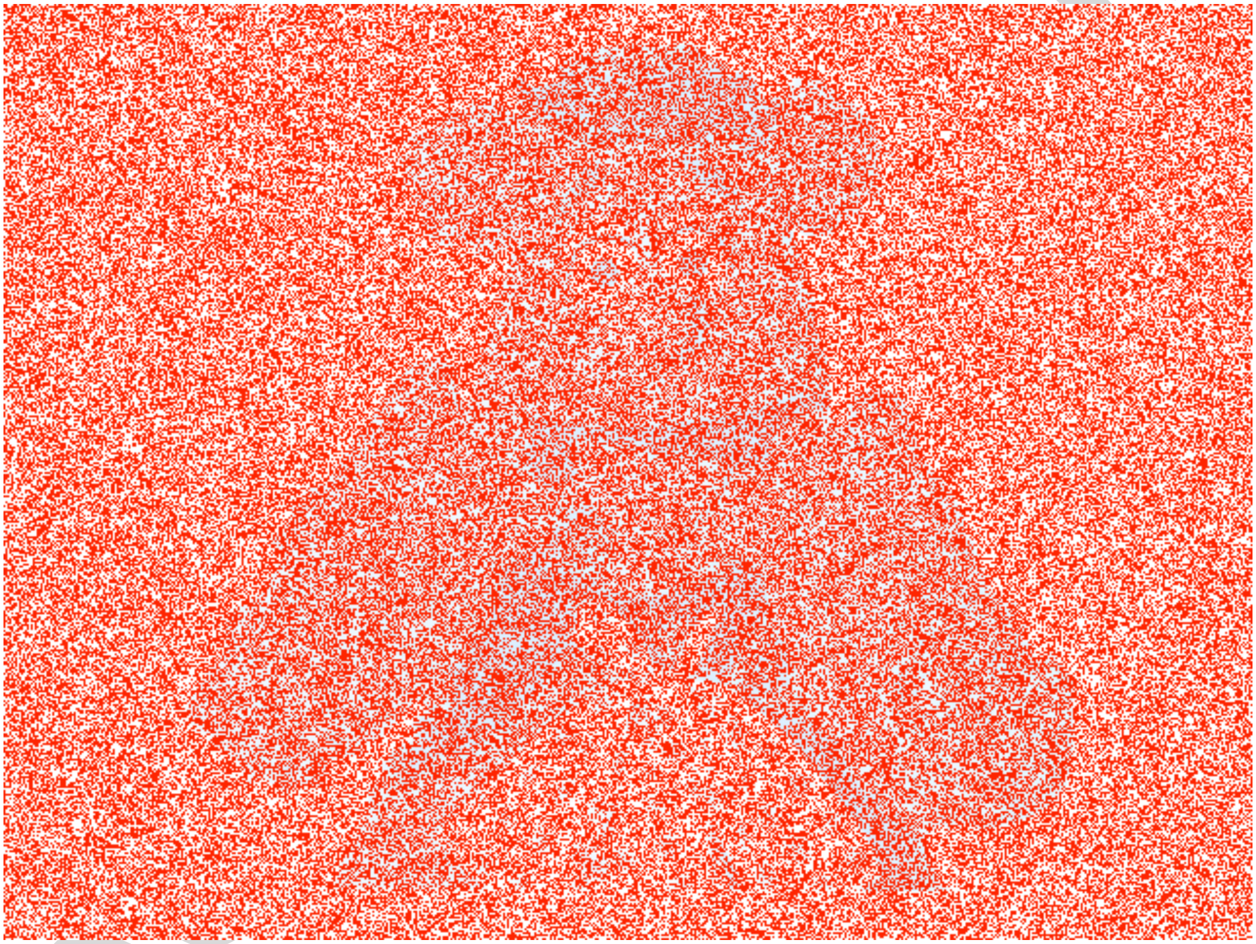
4. What happens, technically speaking, when a file is deleted on a FAT file system?
5. What can someone like you do to ensure (with high probability) that files you delete cannot be recovered?

[3] For this question, you're welcome to consult *How Computers Work*, Google, Wikipedia, a friend, or anyone else, so long as your words are ultimately your own!

Whodunit.

□ Welcome to Tudor Mansion. Your host, Mr. John Boddy, has met an untimely end—he's the victim of foul play. To win this game, you must determine whodunit.

Unfortunately for you (though even more unfortunately for Mr. Boddy), the only evidence you have is a 24-bit BMP file called `clue.bmp`, pictured below, that Mr. Boddy whipped up on his computer in his final moments.[4] Hidden among this file's red "noise" is a picture of whodunit.

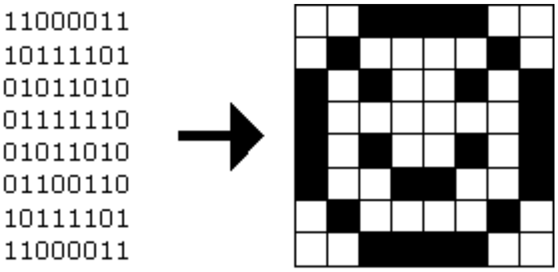


You long ago threw away that piece of red plastic from childhood that would solve this mystery for you, and so you must attack it as a computer scientist instead.

But, first, some background.

[4] Realize that this BMP is in color even though you might have printed this document in black and white.

☐ Perhaps the simplest way to represent an image is with a grid of pixels (*i.e.*, dots), each of which can be of a different color. For black-and-white images, we thus need 1 bit per pixel, as 0 could represent black and 1 could represent white, as in the below.[5]



```
11000011
10111101
01011010
01111110
01011010
01100110
10111101
11000011
```

In this sense, then, is an image just a bitmap (*i.e.*, a map of bits). For more colorful images, you simply need more bits per pixel. A file format (like GIF) that supports "8-bit color" uses 8 bits per pixel. A file format (like BMP, JPEG, or PNG) that supports "24-bit color" uses 24 bits per pixel.[6]

A 24-bit BMP like Mr. Boddy's uses 8 bits to signify the amount of red in a pixel's color, 8 bits to signify the amount of green in a pixel's color, and 8 bits to signify the amount of blue in a pixel's color. If you've ever heard of RGB color, well, there you have it: red, green, blue.

If the R, G, and B values of some pixel in a BMP are, say, 0xff, 0x00, and 0x00 in hexadecimal, that pixel is purely red, as 0xff (otherwise known as 255 in decimal) implies "a lot of red," while 0x00 and 0x00 imply "no green" and "no blue," respectively. Given how red Mr. Boddy's BMP is, it clearly has a lot of pixels with those RGB values. But it also has a few with other values.

Incidentally, HTML and CSS (languages in which webpages can be written) model colors in this same way. If curious, see the URL below for more details.

`http://en.wikipedia.org/wiki/Web_colors`

Now let's get more technical. Recall that a file is just a sequence of bits, arranged in some fashion. A 24-bit BMP file, then, is essentially just a sequence of bits, (almost) every 24 of which happen to represent some pixel's color. But a BMP file also contains some "metadata," information like an image's height and width. That metadata is stored at the beginning of the file in the form of two data structures generally referred to as "headers" (not to be confused with C's header files).[7] The first of these headers, called `BITMAPFILEHEADER`, is 14 bytes long. (Recall that 1 byte equals 8 bits.) The second of these headers, called `BITMAPINFOHEADER`, is 40 bytes long. Immediately following these headers is the actual bitmap: an array of bytes, triples of which represent a pixel's color.[8] However, BMP stores these triples backwards (*i.e.*, as BGR), with 8 bits for blue, followed

[5] Image adapted from `http://www.brackeen.com/vga/bitmaps.html`.

[6] BMP actually supports 1-, 4-, 8-, 16-, 24-, and 32-bit color.

[7] Incidentally, these headers have evolved over time. This problem set only expects that you support version 4.0 (the latest) of Microsoft's BMP format, which debuted with Windows 95.

[8] In 1-, 4-, and 16-bit BMPs (but not 24- or 32-), there's an additional header right after `BITMAPINFOHEADER` called `RGBQUAD`, an array that defines "intensity values" for each of the colors in a device's palette.

by 8 bits for green, followed by 8 bits for red.[9] In other words, were we to convert the 1-bit smiley above to a 24-bit smiley, substituting red for black, a 24-bit BMP would store this bitmap as follows, where `0000ff` signifies red and `ffffff` signifies white; we've highlighted in red all instances of `0000ff`.

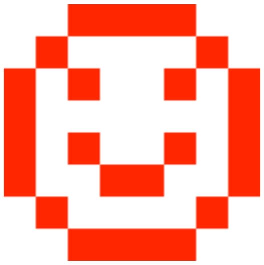
```
ffffff   ffffff   0000ff   0000ff   0000ff   0000ff   ffffff   ffffff
ffffff   0000ff   ffffff   ffffff   ffffff   ffffff   0000ff   ffffff
0000ff   ffffff   0000ff   ffffff   ffffff   0000ff   ffffff   0000ff
0000ff   ffffff   ffffff   ffffff   ffffff   ffffff   ffffff   0000ff
0000ff   ffffff   0000ff   ffffff   ffffff   0000ff   ffffff   0000ff
0000ff   ffffff   ffffff   0000ff   0000ff   ffffff   ffffff   0000ff
ffffff   0000ff   ffffff   ffffff   ffffff   ffffff   0000ff   ffffff
ffffff   ffffff   0000ff   0000ff   0000ff   0000ff   ffffff   ffffff
```

Because we've presented these bits from left to right, top to bottom, in 8 columns, you can actually see the red smiley if you take a step back.

To be clear, recall that a hexadecimal digit represents 4 bits. Accordingly, `ffffff` in hexadecimal actually signifies `111111111111111111111111` in binary.

Okay, stop! Don't proceed further until you're sure you understand why `0000ff` represents a red pixel in a 24-bit BMP file.

□ Okay, let's transition from theory to practice. Double-click **Home** on John Harvard's desktop and you should find yourself in John Harvard's home directory. Double-click **hacker4**, double-click **bmp**, and then double-click **smiley.bmp** therein. You should see a tiny smiley face that's only 8 pixels by 8 pixels. Select **View > Zoom > Zoom Fit**, and you should see a larger, albeit blurrier, version. (So much for "enhance," huh?) Actually, this particular image shouldn't really be blurry, even when enlarged. The program that launched when you double-clicked **smiley.bmp** (called Ristretto Photo Viewer) is simply trying to be helpful (CSI-style) by "dithering" the image (*i.e.*, by smoothing out its edges). Below's what the smiley looks like if you zoom in without dithering. At this zoom level, you can really see the image's pixels (as big squares).



[9] Some BMPs also store the entire bitmap backwards, with an image's top row at the end of the BMP file. But we've stored this problem set's BMPs as described herein, with each bitmap's top row first and bottom row last.

Okay, go ahead and return your attention to a terminal window, and navigate your way to `~/Dropbox/hacker4/bmp`. (Remember how?) Let's look at the underlying bytes that compose `smiley.bmp` using `xxd`, a command-line "hex editor." Execute:

```
xxd -c 24 -g 3 -s 54 smiley.bmp
```

You should see the below; we've again highlighted in red all instances of `0000ff`.

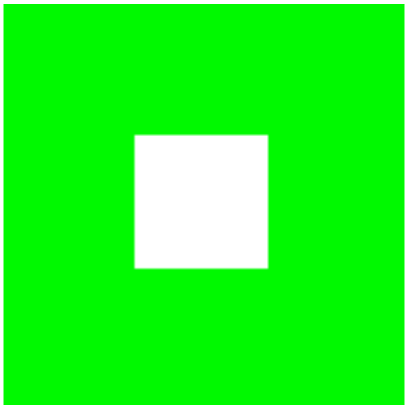
```
0000036: ffffff ffffff 0000ff 0000ff 0000ff 0000ff ffffff ffffff  ........................
000004e: ffffff 0000ff ffffff ffffff ffffff ffffff 0000ff ffffff  ........................
0000066: 0000ff ffffff 0000ff ffffff ffffff 0000ff ffffff 0000ff  ........................
000007e: 0000ff ffffff ffffff ffffff ffffff ffffff ffffff 0000ff  ........................
0000096: 0000ff ffffff 0000ff ffffff ffffff 0000ff ffffff 0000ff  ........................
00000ae: 0000ff ffffff ffffff 0000ff 0000ff ffffff ffffff 0000ff  ........................
00000c6: ffffff 0000ff ffffff ffffff ffffff ffffff 0000ff ffffff  ........................
00000de: ffffff ffffff 0000ff 0000ff 0000ff 0000ff ffffff ffffff  ........................
```

In the leftmost column above are addresses within the file or, equivalently, offsets from the file's first byte, all of them given in hex. Note that `00000036` in hexadecimal is `54` in decimal. You're thus looking at byte `54` onward of `smiley.gif`. Recall that a 24-bit BMP's first 14 + 40 = 54 bytes are filled with metadata. If you really want to see that metadata in addition to the bitmap, execute the command below.

```
xxd -c 24 -g 3 smiley.bmp
```

If `smiley.bmp` actually contained ASCII characters, you'd see them in `xxd`'s rightmost column instead of all of those dots.

□ So, `smiley.bmp` is 8 pixels wide by 8 pixels tall, and it's a 24-bit BMP (each of whose pixels is represented with 24 ÷ 8 = 3 bytes). Each row (aka "scanline") thus takes up (8 pixels) × (3 bytes per pixel) = 24 bytes, which happens to be a multiple of 4. It turns out that BMPs are stored a bit differently if the number of bytes in a scanline is not, in fact, a multiple of 4. In `small.bmp`, for instance, is another 24-bit BMP, a green box that's 3 pixels wide by 3 pixels wide. If you view it with Ristretto Photo Viewer (as by double-clicking it), you'll see that it resembles the below, albeit much smaller. (Indeed, you might need to zoom in again to see it.)



Each scanline in `small.bmp` thus takes up (3 pixels) × (3 bytes per pixel) = 9 bytes, which is not a multiple of 4. And so the scanline is "padded" with as many zeroes as it takes to extend the scanline's length to a multiple of 4. In other words, between 0 and 3 bytes of padding are needed for each scanline in a 24-bit BMP. (Understand why?) In the case of `small.bmp`, 3 bytes' worth of zeroes are needed, since (3 pixels) × (3 bytes per pixel) + (3 bytes of padding) = 12 bytes, which is indeed a multiple of 4.

To "see" this padding, go ahead and run the below.

```
xxd -c 12 -g 3 -s 54 small.bmp
```

Note that we're using a different value for `-c` than we did for `smiley.bmp` so that `xxd` outputs only 4 columns this time (3 for the green box and 1 for the padding). You should see output like the below; we've highlighted in green all instances of `00ff00`.

```
0000036: 00ff00 00ff00 00ff00 000000  ............
0000042: 00ff00 ffffff 00ff00 000000  ............
000004e: 00ff00 00ff00 00ff00 000000  ............
```

For contrast, let's use `xxd` on `large.bmp`, which looks identical to `small.bmp` but, at 12 pixels by 12 pixels, is four times as large. Go ahead and execute the below; you may need to widen your window to avoid wrapping.

```
xxd -c 36 -g 3 -s 54 large.bmp
```

You should see output like the below; we've again highlighted in green all instances of `00ff00`

```
0000036: 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00  ....................................
000005a: 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00  ....................................
000007e: 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00  ....................................
00000a2: 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00  ....................................
00000c6: 00ff00 00ff00 00ff00 00ff00 ffffff ffffff ffffff ffffff 00ff00 00ff00 00ff00 00ff00  ....................................
00000ea: 00ff00 00ff00 00ff00 00ff00 ffffff ffffff ffffff ffffff 00ff00 00ff00 00ff00 00ff00  ....................................
000010e: 00ff00 00ff00 00ff00 00ff00 ffffff ffffff ffffff ffffff 00ff00 00ff00 00ff00 00ff00  ....................................
0000132: 00ff00 00ff00 00ff00 00ff00 ffffff ffffff ffffff ffffff 00ff00 00ff00 00ff00 00ff00  ....................................
0000156: 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00  ....................................
000017a: 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00  ....................................
000019e: 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00  ....................................
00001c2: 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00 00ff00  ....................................
```

Worthy of note is that this BMP lacks padding! After all, (12 pixels) × (3 bytes per pixel) = 36 bytes is indeed a multiple of 4.

Knowing all this has got to be useful!

□ Okay, `xxd` only showed you the bytes in these BMPs. How do we actually get at them programmatically? Well, in `copy.c` is a program whose sole purpose in life is to create a copy of a BMP, piece by piece. Of course, you could just use `cp` for that. But `cp` isn't going to help Mr. Boddy. Let's hope that `copy.c` does!

Go ahead and compile copy.c into a program called copy. (Remember how?) Then execute a command like the below.

```
./copy smiley.bmp copy.bmp
```

If you then execute ls (with the appropriate switch), you should see that smiley.bmp and copy.bmp are indeed the same size. Let's double-check that they're actually the same! Execute the below.

```
diff smiley.bmp copy.bmp
```

If that command tells you nothing, the files are indeed identical.[10] Feel free to open both files in Ristretto Photo Viewer (as by double-clicking each) to confirm as much visually. But diff does a byte-by-byte comparison, so its eye is probably sharper than yours!

So how now did that copy get made? It turns out that copy.c relies on bmp.h. Let's take a look. Open up bmp.h (as with gedit), and you'll see actual definitions of those headers we've mentioned, adapted from Microsoft's own implementations thereof. In addition, that file defines BYTE, DWORD, LONG, and WORD, data types normally found in the world of Win32 (*i.e.*, Windows) programming. Notice how they're just aliases for primitives with which you are (hopefully) already familiar. It appears that BITMAPFILEHEADER and BITMAPINFOHEADER make use of these types. This file also defines a struct called RGBTRIPLE that, quite simply, "encapsulates" three bytes: one blue, one green, and one red (the order, recall, in which we expect to find RGB triples actually on disk).

Why are these structs useful? Well, recall that a file is just a sequence of bytes (or, ultimately, bits) on disk. But those bytes are generally ordered in such a way that the first few represent something, the next few represent something else, and so on. "File formats" exist because the world has standardized what bytes mean what. Now, we could just read a file from disk into RAM as one big array of bytes. And we could just remember that the byte at location [i] represents one thing, while the byte at location [j] represents another. But why not give some of those bytes names so that we can retrieve them from memory more easily? That's precisely what the structs in bmp.h allow us to do. Rather than think of some file as one long sequence of bytes, we can instead think of it as a sequence of structs.

[10] Note that some programs (e.g., Photoshop) include trailing zeroes at the ends of some BMPs. Our version of copy throws those away, so don't be too worried if you try to copy a BMP (that you've downloaded or made) only to find that the copy is actually a few bytes smaller than the original.

Recall that `smiley.bmp` is 8 by 8 pixels, and so it should take up $14 + 40 + 8 \cdot 8 \cdot 3 = 246$ bytes on disk. (Confirm as much if you'd like using `ls`.) Here's what it thus looks like on disk according to Microsoft:

offset	type	name	
0	WORD	bfType	**BITMAPFILEHEADER**
2	DWORD	bfSize	
6	WORD	bfReserved1	
8	WORD	bfReserved2	
10	DWORD	bfOffBits	
14	DWORD	biSize	**BITMAPINFOHEADER**
18	LONG	biWidth	
22	LONG	biHeight	
26	WORD	biPlanes	
28	WORD	biBitCount	
30	DWORD	biCompression	
34	DWORD	biSizeImage	
38	LONG	biXPelsPerMeter	
42	LONG	biYPelsPerMeter	
46	DWORD	biClrUsed	
50	DWORD	biClrImportant	
54	BYTE	rgbtBlue	**RGBTRIPLE**
55	BYTE	rgbtGreen	
56	BYTE	rgbtRed	
57	BYTE	rgbtBlue	**RGBTRIPLE**
58	BYTE	rgbtGreen	
59	BYTE	rgbtRed	
...			
243	BYTE	rgbtBlue	**RGBTRIPLE**
244	BYTE	rgbtGreen	
245	BYTE	rgbtRed	

As this figure suggests, order does matter when it comes to `struct`s' members. Byte 57 is `rgbtBlue` (and not, say, `rgbtRed`), because `rgbtBlue` is defined first in `RGBTRIPLE`.[11]

Now go ahead and pull up the URLs to which `BITMAPFILEHEADER` and `BITMAPINFOHEADER` are attributed, per the comments in `bmp.h`. You're about to start using MSDN (Microsoft Developer Network)!

Rather than hold your hand further on a stroll through `copy.c`, we're instead going to ask you some questions and let you teach yourself how the code therein works. As always, `man` is your friend, and so, now, is MSDN. If not sure on first glance how to answer some question, do some quick research and figure it out! You might want to turn to the below resource as well.

`http://www.cs50.net/resources/cppreference.com/stdio/`

[11] Our use, incidentally, of the `__attribute__` called `__packed__` ensures that `gcc` does not try to "word-align" members (whereby the address of each member's first byte is a multiple of 4), lest we end up with "gaps" in our `struct`s that don't actually exist on disk.

Allow us to suggest that you also run copy within gdb while answering these questions. Set a breakpoint at main and walk through the program. Recall that you can tell gdb to start running the program with a command like the below at gdb's prompt.

```
run smiley.bmp copy.bmp
```

If you tell gdb to print the values of bf and bi (once read in from disk), you'll see output like the below, which we daresay you'll find quite useful.

```
{bfType = 19778, bfSize = 246, bfReserved1 = 0, bfReserved2 = 0,
  bfOffBits = 54}

{biSize = 40, biWidth = 8, biHeight = -8, biPlanes = 1, biBitCount = 24,
  biCompression = 0, biSizeImage = 192, biXPelsPerMeter = 2834,
  biYPelsPerMeter = 2834, biClrUsed = 0, biClrImportant = 0}
```

In ~/Dropbox/hacker4/questions.txt, answer each of the following questions in a sentence or more.

6. What's stdint.h?
7. What's the point of using uint8_t, uint32_t, int32_t, and uint16_t in a program?
8. How many bytes is a BYTE, a DWORD, a LONG, and a WORD, respectively?[12]
9. What (in ASCII, decimal, or hexadecimal) must the first two bytes of any BMP file be?[13]
10. What's the difference between bfSize and biSize?
11. What does it mean if biHeight is negative?
12. What field in BITMAPINFOHEADER specifies the BMP's color depth (*i.e.*, bits per pixel)?
13. Why might fopen return NULL in copy.c:37?
14. Why is the third argument to fread always 1 in our code?
15. What value does copy.c:70 assign padding if bi.biWidth is 3?
16. What does fseek do?
17. What is SEEK_CUR?

Okay, back to Mr. Boddy.

☐ Write a program called whodunit in a file called whodunit.c that reveals Mr. Boddy's drawing.

Ummm, what?

[12] Assume a 32-bit architecture like the CS50 Appliance.

[13] Leading bytes used to identify file formats (with high probability) are generally called "magic numbers."

Well, think back to childhood when you held that piece of red plastic over similarly hidden messages.[14] Essentially, the plastic turned everything red but somehow revealed those messages. Implement that same idea in `whodunit`. Like `copy`, your program should accept exactly two command-line arguments. And if you execute a command like the below, stored in `verdict.bmp` should be a BMP in which Mr. Boddy's message is no longer covered with noise.

```
whodunit clue.bmp verdict.bmp
```

Allow us to suggest that you begin tackling this mystery by executing the command below.

```
cp copy.c whodunit.c
```

Wink wink. You may be amazed by how few lines of code you actually need to write in order to help Mr. Boddy.

There's nothing hidden in `smiley.bmp`, but feel free to test your program out on its pixels nonetheless, if only because that BMP is small and you can thus compare it and your own program's output with `xxd` during development.[15]

Rest assured that more than one solution is possible. So long as Mr. Boddy's drawing is identifiable (by your teaching fellow), no matter its color(s), Mr. Boddy will rest in peace.

□ In `~/Dropbox/hacker4/questions.txt`, answer the question below.

18. Whodunit?

□ Well that was fun. Bit late for Mr. Boddy, though.

Let's have you write more than, what, two lines of code? Implement now in `resize.c` a program called `resize` that resizes 24-bit uncompressed BMPs by a factor of `f`. Your program should accept exactly three command-line arguments, per the below usage, whereby the first (`f`) must be a floating-point value in (0.0, 100.0), the second the name of the file to be resized, and the third the name of the resized version to be written.

```
Usage: resize f infile outfile
```

With a program like this, we could have created `large.bmp` out of `small.bmp` by resizing the latter by a factor of 4.0 (*i.e.*, by multiplying both its width and it s height by 4.0), per the below.[16]

```
./resize 4.0 small.bmp large.bmp
```

You're welcome to get started by copying (yet again) `copy.c` and naming the copy `resize.c`. But spend some time thinking about what it means to resize a BMP, particularly if `f` is

[14] If you remember no such piece of plastic, best to ask a friend or TF about his or her childhood.
[15] Or maybe there is a message hidden in `smiley.bmp` too. No, there's not.
[16] And yet we used Photoshop.

in (0.0, 1.0).[17,18] How you handle floating-point imprecision and rounding is entirely up to you, as is how you handle inevitable loss of detail. Decide which of the fields in `BITMAPFILEHEADER` and `BITMAPINFOHEADER` you might need to modify. Consider whether or not you'll need to add or subtract padding to scanlines.

If you'd like to play with the staff's own implementation of `resize` in the appliance, you may execute the below.[19]

```
~cs50/hacker4/resize
```

☐ Best to run

```
submit50 ~/Dropbox/hacker4
```

from time to time in order to back up your code to CS50's servers. (Your TF will grade your final submission.)

CSI.[20]

☐ Alright, now let's put all your new skills to the test.

In anticipation of this problem set, I spent the past several days snapping photos of people I know, all of which were saved by my digital camera as JPEGs on a 1GB CompactFlash (CF) card.[21] Unfortunately, I'm not very good with computers, and I somehow deleted them all! Thankfully, in the computer world, "deleted" tends not to mean "deleted" so much as "forgotten." My computer insists that the CF card is now blank, but I'm pretty sure it's lying to me.

Write a program in `~/Dropbox/hacker4/jpg/` called `recover` that recovers these photos.

Ummm.

Well, here's the thing. Even though JPEGs are more complicated than BMPs, JPEGs have "signatures," patterns of bytes that distinguish them from other file formats. In fact, most JPEGs begin with one of two sequences of bytes. Specifically, the first four bytes of most JPEGs are either

```
0xff 0xd8 0xff 0xe0
```

or

```
0xff 0xd8 0xff 0xe1
```

[17] You may assume that `f` times the size of `infile` will not exceed $2^{32} - 1$.
[18] As for `f = 1.0`, the result should indeed be an `outfile` with dimensions identical to `infile`'s.
[19] We've not made solutions available for this problem set's other programs, lest they spoil the forensic fun.
[20] Computer Science Investigation
[21] It's possible I actually spent the past several days on Facebook instead.

from first byte to fourth byte, left to right. Odds are, if you find one of these patterns of bytes on a disk known to store photos (*e.g.*, my CF card), they demark the start of a JPEG.[22]

Fortunately, digital cameras tend to store photographs contiguously on CF cards, whereby each photo is stored immediately after the previously taken photo. Accordingly, the start of a JPEG usually demarks the end of another. However, digital cameras generally initialize CF cards with a FAT file system whose "block size" is 512 bytes (B). The implication is that these cameras only write to those cards in units of 512 B. A photo that's 1 MB (*i.e.*, 1,048,576 B) thus takes up 1048576 ÷ 512 = 2048 "blocks" on a CF card. But so does a photo that's, say, one byte smaller (*i.e.*, 1,048,575 B)! The wasted space on disk is called "slack space." Forensic investigators often look at slack space for remnants of suspicious data.

The implication of all these details is that you, the investigator, can probably write a program that iterates over a copy of my CF card, looking for JPEGs' signatures. Each time you find a signature, you can open a new file for writing and start filling that file with bytes from my CF card, closing that file only once you encounter another signature. Moreover, rather than read my CF card's bytes one at a time, you can read 512 of them at a time into a buffer for efficiency's sake. Thanks to FAT, you can trust that JPEGs' signatures will be "block-aligned." That is, you need only look for those signatures in a block's first four bytes.

Realize, of course, that JPEGs can span contiguous blocks. Otherwise, no JPEG could be larger than 512 B. But the last byte of a JPEG might not fall at the very end of a block. Recall the possibility of slack space. But not to worry. Because this CF card was brand-new when I started snapping photos, odds are it'd been "zeroed" (*i.e.*, filled with 0s) by the manufacturer, in which case any slack space will be filled with 0s. It's okay if those trailing 0s end up in the JPEGs you recover; they should still be viewable.

Now, I only have one CF card, but there are a whole lot of you! And so I've gone ahead and created a "forensic image" of the card, storing its contents, byte after byte, in a file called `card.raw`. So that you don't waste time iterating over millions of 0s unnecessarily, I've only imaged the first few megabytes of the CF card. But you should ultimately find that the image contains 51 JPEGs. As usual, you can open the file programmatically with `fopen`, as in the below.[23]

```
FILE* fp = fopen("card.raw", "r");
```

Notice, incidentally, that `~/Dropbox/hacker4/jpg/` contains only `recover.c`, but it's devoid of any code. (We leave it to you to decide how to implement and compile `recover`!) For simplicity, you may hard-code the path to `card.raw` in your program; your program need not accept any command-line arguments. When executed, though, your program should recover every one of the JPEGs from `card.raw`, storing each as a separate file in your current working directory. Your program should number the files it outputs by naming each `###.jpg`, where `###` is three-digit decimal number from `000` on up. (Befriend `sprintf`.) You need not try to recover

[22] To be sure, you might encounter these patterns on some disk purely by chance, so data recovery isn't an exact science.
[23] It's fine to hard-code this path into your program rather than define it as some constant.

the JPEGs' original names. To check whether the JPEGs your program spit out are correct, simply double-click and take a look! If each photo appears intact, your operation was likely a success!

Odds are, though, the JPEGs that the first draft of your code spits out won't be correct. (If you open them up and don't see anything, they're probably not correct!) Execute the command below to delete all JPEGs in your current working directory.

```
rm *.jpg
```

If you'd rather not be prompted to confirm each deletion, execute the command below instead.

```
rm -f *.jpg
```

Just be careful with that `-f` switch, as it "forces" deletion.

□ Don't forget to run

```
submit50 ~/hacker4
```

from time to time in order to back up your code to CS50's servers!

I Saw You Harvard.

□ And now the real fun begins. You and your section are hereby challenged to find as many of the computer scientists featured in these photos as possible. To prove that you found someone, take a photo of yourself (or of someone in your section) posing with the computer scientist. Upload your section's photos (*i.e.*, the photos you took, not the ones that you recovered) to an album somewhere (e.g., Facebook, Flickr, Picasa Web Albums, *etc.*); just be sure your TF can access the album.[24] Then have your TF email your album's URL to `heads@cs50.net` by noon on Wed 10/31!

The section that identifies and photographs the most computer scientists shall win a fabulous prize. In the event of a tie, the section that submitted first shall be decreed the winner.

[24] You should probably nominate someone(s) in your section to take charge.

Sanity Checks.

Before you consider this problem set done, best to ask yourself these questions and then go back and improve your code as needed! Do not consider the below an exhaustive list of expectations, though, just some helpful reminders. The checkboxes that have come before these represent the exhaustive list! To be clear, consider the questions below rhetorical. No need to answer them in writing for us, since all of your answers should be "yes!"

☐ Did you fill `questions.txt` with answers to all questions?
☐ Is the BMP that `whodunit` outputs legible?
☐ Does `resize` accept three and only three command-line arguments?
☐ Does `resize` ensure that `f` is in (1.0, 100)?
☐ Does `resize` update `bfSize`, `biHeight`, `biSizeImage`, and `biWidth` correctly?
☐ Does `resize` add or remove padding as needed?
☐ Does `recover` output 51 JPEGs? Are all 51 viewable?
☐ Does `recover` name the JPEGs `###.jpg`, where `###` is a three-digit number from `000` through `050`?
☐ Are all of your files where they should be in `~/Dropbox/hacker4/`?

As always, if you can't answer "yes" to one or more of the above because you're having some trouble, do drop by office hours or turn to `cs50.net/discuss`!

How to Submit.

In order to submit this problem set, you must first execute a command in the appliance and then submit a (brief) form online.

☐ Open a terminal window (as via **Menu > Programming > Terminal** or within `gedit`) then execute

```
update50
```

to ensure you have the latest release of the appliance. Then execute:

```
cd ~/Dropbox/hacker4
```

And then execute:

```
ls
```

At a minimum, you should see `bmp/`, `jpg/`, and `questions.txt`. If not, odds are you skipped some step(s) earlier! If you do see those files, you are ready to submit your source code to us. Execute

```
submit50 ~/Dropbox/hacker4
```

and follow the on-screen instructions. That command will essentially upload your entire `~/Dropbox/hacker4` directory to CS50's servers, where your TF will be able to access it. The command will inform you whether your submission was successful or not. And you may inspect your submission at `cs50.net/submit`.

You may re-submit as many times as you'd like; we'll grade your most recent submission. But take care not to submit after the problem set's deadline, lest you spend a late day unnecessarily or risk rejection entirely.

If you run into any trouble at all, let us know via `cs50.net/discuss` and we'll try to assist! Just take care to seek help well before the problem set's deadline, as we can't always reply right away!

☐ Head to the URL below where a short form awaits:

```
https://www.cs50.net/psets/4/
```

Once you have submitted that form (as well as your source code), you are done!

This was Problem Set 4.