Problem Set 5: Forensics

due by 7:00 P.M. on Friday, 7 November 2008

Goals.

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

Recommended Reading.

- Sections 21 – 26, 31, 32, 35, and 40 of `http://www.howstuffworks.com/c.htm`.
- Chapters 18, 24, 25, 27, and 28 of *Absolute Beginner's Guide to C*.
- Chapters 9, 11, 14, and 16 of *Programming in C*.

- Sections 1 – 3 of `http://en.wikipedia.org/wiki/BMP_file_format`.
- Sections 1, 2, and 6 of `http://en.wikipedia.org/wiki/Hexadecimal`.
- Sections 1 – 5 and 7 of `http://en.wikipedia.org/wiki/Jpg`.

Academic Honesty.

All work that you do toward fulfillment of this course's expectations must be your own unless collaboration is explicitly allowed (*e.g.*, by some problem set or the final project). Viewing or copying another individual's work (even if left by a printer, stored in an executable directory, or accidentally shared in the course's virtual terminal room) or lifting material from a book, magazine, 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.

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. Moreover, submission of any work that you intend to use outside of the course (*e.g.*, for a job) must be approved by the staff.

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 staff.

You may even 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.

Grades.

Your work on this problem set will be evaluated along three primary axes.

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)?

Getting Started.

☑ Only a few checkboxes to go!

☐ SSH to `cloud.cs50.net` and recursively copy `~cs50/pub/distributions/pset5/` into your home directory. (Remember how?) Then list the contents of `~/pset5/`. (Remember how?) You should see the below.

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

As this output implies, most of your work for this problem set will be organized within two subdirectories. Let's get started.

☐ Surf on over to the URL below.

```
http://cs50.net/surveys/psets/5/
```

Please take a few minutes to provide candid answers to the survey's questions. Although you may be prompted to authenticate using your CS50 or FAS account, your answers, immediately upon submission, will be anonymized. We will know that you took the survey, but we will not know which answers are yours.

☐ If you've ever seen 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. Read up a bit on the BMP, GIF, and JPEG file formats.[1] Then, in `~/pset5/questions.txt`, tell us the below.

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

[1] 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!

☐ Curl up with the article from MIT below.

`http://www.computer.org/portal/cms_docs_security/security/v1n1/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 `~/pset5/questions.txt`.

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

store.cs50.net.

☐ Per Problem Set 4, we've decided to get on that Internet and set up a shop. Debuting soon at `http://store.cs50.net/` will be CS 50 merchandise, including t-shirts and more, thanks to CafePress.com.[2] But we need help with designs. Ahem, still.

Best to keep your design's focus on 50 and not on Harvard itself, as there are a few policies:

`http://provost.harvard.edu/policies_guidelines/names_insignias.php`

CafePress.com will let us put JPEGs on a whole bunch of merchandise, provided your design adheres to the requirements here:

`http://www.cafepress.com/cp/info/sell/images/images_onesize`

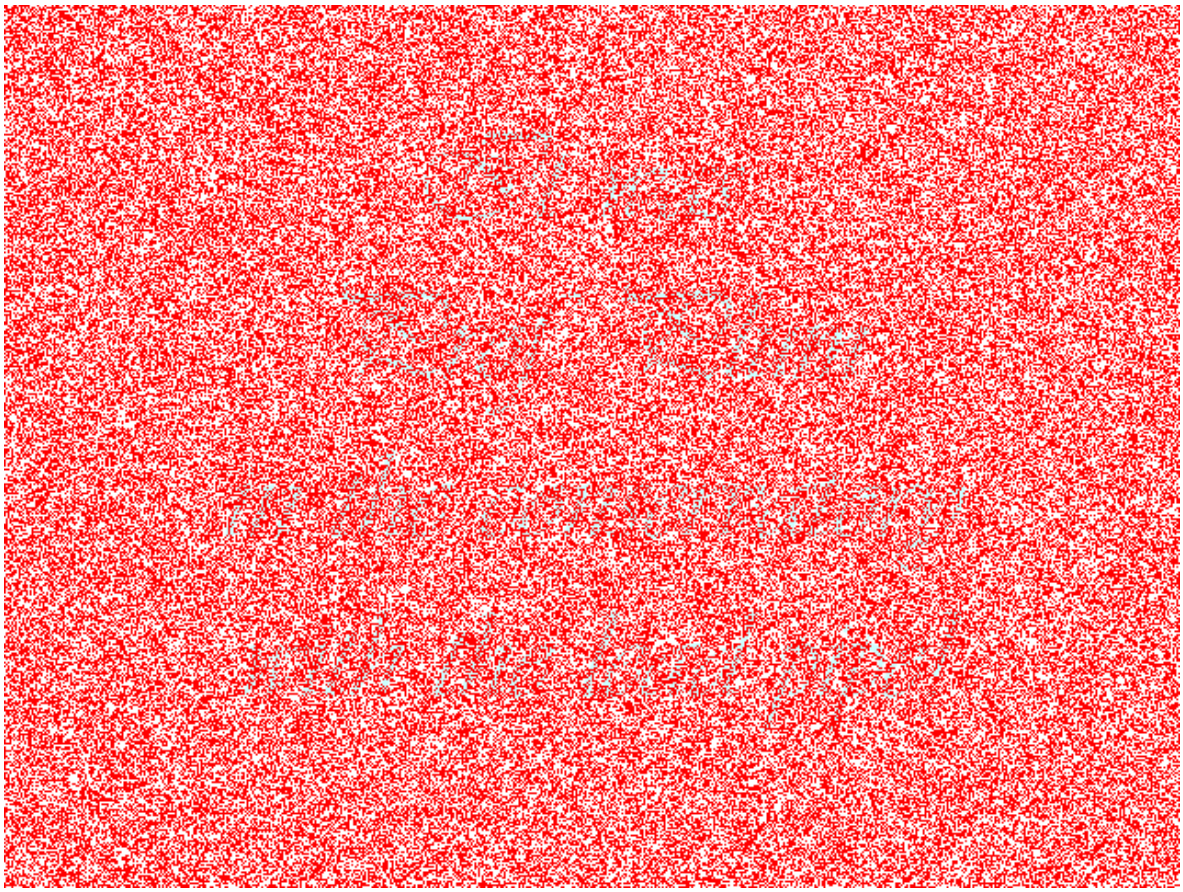
If you would like to submit a possible design for some merchandise, email a 2000px by 2000px JPEG (*i.e.*, 10" by 10" at 200 DPI) to **store@cs50.net** by *this* problem set's deadline!

[2] Who wouldn't want to wear a t-shirt that says **I SURVIVED CS50** or, better yet, **PWNED BY CS 50**?

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 the answer to these three questions: Who done it? Where? And with what weapon?

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 he whipped up for his estranged granddaughter in his final moments.[3] Hidden among this file's red "noise" is a message from Mr. Boddy.

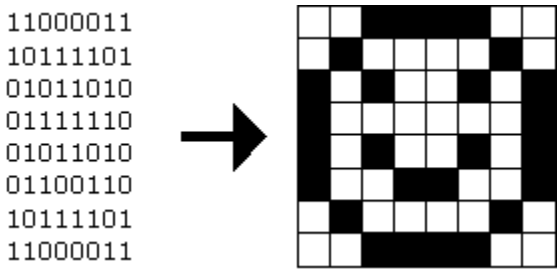


You long ago threw away that piece of red plastic from childhood that would solve this mystery for you, and so you must attack it as the computer scientist that you almost are.

But, first, some background.

[3] 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.[4]



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 or JPEG) that supports "24-bit color" uses 24 bits per pixel.[5]

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, XHTML and CSS (languages in which webpages can be written) model colors in this same way. In fact, for more RGB "codes," see the URL below.

`http://www.w3schools.com/html/html_colors.asp`

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).[6] 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.[7] However, BMP stores these triples backwards (*i.e.*, as BGR), with 8 bits for blue, followed

[4] Image adapted from `http://www.brackeen.com/vga/bitmaps.html`.
[5] BMP actually supports 1-, 4-, 8-, 16-, 24-, and 32-bit color.
[6] 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. Ah, Windows 95.
[7] 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.[8] 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. Navigate your way to `~/pset5/bmp/`. In that directory is a file called `smiley.bmp`. If you feel like SFTPing that file to your desktop and double-clicking it, you'll see that it resembles the below, albeit much smaller (since it's only 8 pixels by 8 pixels).

Open this file in `xxd`, a "hex editor," by executing the command below.

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

[8] 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.

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

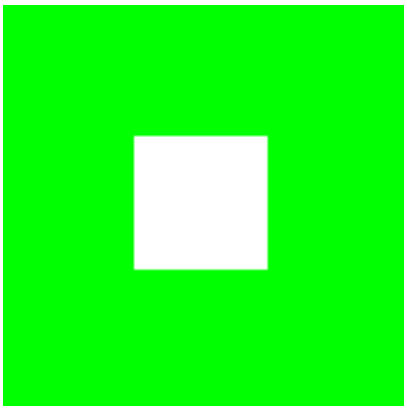
```
0000036: ffffff ffffff 0000ff 0000ff 0000ff 0000ff ffffff ffffff  ........................
000004e: ffffff 0000ff ffffff ffffff ffffff ffffff 0000ff ffffff  ........................
0000066: 0000ff ffffff 0000ff ffffff ffffff 0000ff ffffff 0000ff  ........................
000007e: 0000ff ffffff ffffff 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 feel like SFTPing that file to your desktop and double-clicking it, you'll see that it resembles the below, albeit much smaller.



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.[9] Feel free to SFTP the files to your own desktop 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 Nano), 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`.

[9] Note that some programs (*e.g.*, Photoshop) including 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 · 8 · 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	bOffBits	
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 `structs`' members. Byte 57 is `rgbtBlue` (and not, say, `rgbtRed`), because `rgbtBlue` is defined first in `RGBTRIPLE`.[10]

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

[10] 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 `structs` 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.

```
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 = 248, 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}
```

Answer each of the following questions in a sentence or more in `~/pset5/questions.txt`.

7. How many bytes is a `BYTE`, a `DWORD`, a `LONG`, and a `WORD`, respectively?[11]
8. What (in ASCII, decimal, or hexadecimal) must the first two bytes of any BMP file be?[12]
9. What's the difference between `bfSize` and `biSize`?
10. What does it mean if `biHeight` is negative?
11. What field in `BITMAPINFOHEADER` specifies the BMP's color depth (*i.e.*, bits per pixel)?
12. Why might `fopen` return `NULL` in `copy.c:32`?
13. Why is the third argument to `fread` always 1 in our code?
14. What value does `copy.c:69` assign `padding` if `bi.biWidth` is `3`?
15. What does `fseek` do?
16. 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 final words.

OMG, what? How?

Well, think back to childhood when you held that piece of red plastic over similarly hidden messages.[13] 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 actually legible.

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

[11] Assume a 32-bit x86 architecture like `cloud.cs50.net`.
[12] Leading bytes used to identify file formats (with high probability) are generally called "magic numbers."
[13] If you remember no such piece of plastic, best to ask a friend or TF about his or her childhood.

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.[14]

Rest assured that more than one solution is possible. So long as your program's output is readable (by your teaching fellow), Mr. Boddy will rest in peace.

Be sure to check in your code often with RCS! (You'd better remember how.) And use GDB!

☐ 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 `n`. Your program should accept exactly three command-line arguments, per the below usage, whereby the first (`n`) must be a positive integer less than or equal to 100, the second the name of the file to be resized, and the third the name of the resized version to be written.

```
Usage: resize n 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 (*i.e.*, by multiplying both its width and it s height by 4), per the below.[15]

```
resize 4 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.[16] 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. And be thankful that we don't expect you to support fractional `n` between 0 and 1![17,18]

If you'd like to play with the staff's own implementation of `resize` on `cloud.cs50.net`, you may execute the below.[19]

```
~cs50/pub/solutions/pset5/resize
```

[14] Or maybe there is a message hidden in `smiley.bmp` too. No, there's not. Though maybe there is. No. Maybe.
[15] And yet we used Photoshop.
[16] You may assume that `n` times the size of `infile` will not exceed $2^{32} - 1$.
[17] As we do in the Hacker Edition!
[18] But we do expect you to support `n = 1`, the result of which should 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.

CSI.[20]

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

Just the other day, I took a stroll around campus with a friend (Dan Armendariz of MIT, whose skills with a camera outshine my point-and-shoot tendencies) snapping photos, all of which were stored as JPEGs on a 1GB CompactFlash (CF) card. Rather than act like typical tourists, taking photos of John Harvard's foot (ugh) and squirrels (I mean really, why?), we opted to shoot identifiable but non-obvious persons, places, and things on campus.

Unfortunately, I somehow corrupted that CF card the moment I got home.[21] Both my Mac and PC refuse to recognize the card now as having any photos, even though I'm pretty sure we took them. Both operating systems want to format the card, but, thus far, I've refused to let them, hoping instead someone can come to the rescue.

Write a program in `~/pset5/jpg/` called `recover` that recovers these photos. (Please!)

Oh not again. What?

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
```

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.

[20] Computer Science Investigation
[21] I'm not very technical.
[22] To be sure, you might encounter these patterns on some disk purely by chance, so data recovery isn't an exact science.

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. Fortunately, I bought a brand-new CF card for my stroll about campus. Odds are, that CF card was "zeroed" (*i.e.*, filled with 0s) by the manufacturer. Because I didn't outright delete any photos we took, the only bits on that CF card should belong to actual photos or be 0s. And it's okay if some trailing 0s (*i.e.*, slack space) end up in the JPEGs your program spits out; they should still be viewable.

Since I've but one CF card, I've gone ahead and created a "forensic image" of the card, storing its contents, byte after byte, in a file called `card.raw` in `~cs50/pub/share/pset5/`. So that you don't waste time iterating over millions of 0s unnecessarily, I've only imaged the first 35 MB of the CF card. Since you're only going to be reading it, you don't need your own copy of this forensic image. (Might as well save space!) Simply open our copy with `fopen` via its full path, as in the below.[23]

```
FILE *fp = fopen("/home/cs50/pub/share/pset5/card.raw", "r");
```

You should find that this image contains 42 JPEGs, most of which are less than 1 MB in size.[24]

Notice, incidentally, that `~/pset5/jpg/` is empty. It's up to you to create, at least, a `Makefile` and `recover.c` for this program. You probably don't need a `recover.h`, but you're welcome to create one. 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 the JPEGs' original names. To check whether the JPEGs your program spit out are correct, simply SFTP them to your own desktop, 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
```

[23] It's fine to hard-code this path into your program rather than define it as some constant.
[24] Some, um, might not actually have been taking on my stroll.

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. Be sure to check in your code often with RCS, especially since you'll likely be executing `rm` quite a bit!

☐ And now the proverbial icing on the cake. You are hereby challenged to find as many of the persons, places, and things that we photographed on campus as possible. To prove that you found some place or thing, take a photo of yourself (or of someone in your section) posing next to or near that same person, place, or thing! Put your section's photos (*i.e.*, the photos you took, not the ones that we took that you recovered) online somewhere (*e.g.*, Picasa Web Albums) and link to those photos on a Google Map that indicates where you found each person, place, or thing.[25] Then have your TF email your map's URL to `sysadmins@cs50.net` before lecture on Monday, 24 November 2008!

Here's how to create a map for your section:

Creating and Editing a Map
`http://local.google.com/support/bin/answer.py?hl=en&answer=68480`

Adding Photos
`http://local.google.com/support/bin/answer.py?hl=en&answer=68480#photos`

The section whose students collectively identify the most photographs shall win an amazing prize.[26] The TFs did not accompany me on my stroll, so yours is welcome to join forces with you on this quest. In the event of a tie, the section that submits the most photos (and their URL) first shall be declared Fall 2008's winner.

Submitting Your Work.

☐ Ensure that your work is in `~/pset5/` on `cloud.cs50.net`. Submit your work by executing the command below.

```
cs50submit pset5
```

Thereafter, follow any on-screen instructions until you receive visual confirmation of your work's successful submission. You will also receive a "receipt" via email to your FAS account, which you should retain until term's end. You may re-submit as many times as you'd like; each resubmission will overwrite any previous submission. But take care not to re-submit after the problem set's deadline, as only your latest submission's timestamp is retained.

[25] You should probably nominate someone(s) in your section to take charge.
[26] Prize may not actually be amazing.