CS2110 Fall 2015 Homework 11

Nathan Braswell

Rules and Regulations

General Rules

1. Starting with the assembly homeworks, Any code you write (if any) must be clearly commented and the comments must be meaningful. You should comment your code in terms of the algorithm you are implementing we all know what the line of code does.

2. Although you may ask TAs for clarification, you are ultimately responsible for what you submit. This means that (in the case of demos) you should come prepared to explain to the TA how any piece of code you submitted works, even if you copied it from the book or read about it on the internet.

3. Please read the assignment in its entirety before asking questions.

4. Please start assignments early, and ask for help early. Do not email us the night the assignment is due with questions.

5. If you find any problems with the assignment it would be greatly appreciated if you reported them to the author (which can be found at the top of the assignment). Announcements will be posted if the assignment changes.

Submission Conventions

6. All files you submit for assignments in this course should have your name at the top of the file as a comment for any source code file, and somewhere in the file, near the top, for other files unless otherwise noted.
7. When preparing your submission you may either submit the files individually to Canvas or you may submit an archive (zip or tar.gz only please) of the files (preferred). You can create an archive by right clicking on files and selecting the appropriate compress option on your system.
8. If you choose to submit an archive please don't zip up a folder with the files, only submit an archive of the files we want. (See **Deliverables**).
9. Do not submit compiled files that is .class files for Java code and .o files for C code. Only submit the files we ask for in the assignment.
10. Do not submit links to files. We will not grade assignments submitted this way as it is easy to change the files after the submission period ends.

Submission Guidelines

1. You are responsible for turning in assignments on time. This includes allowing for unforeseen circumstances. If you have an emergency let us know ***IN ADVANCE*** of the due time supplying documentation (i.e. note from the dean, doctor's note, etc). Extensions will only be granted to those who contact us in advance of the deadline and no extensions will be made after the due date.

2. You are also responsible for ensuring that what you turned in is what you meant to turn in. After submitting you should be sure to download your submission into a brand new folder and test if it works. No

excuses if you submit the wrong files, what you turn in is what we grade. In addition, your assignment must be turned in via Canvas. When you submit the assignment you should get an email from Canvas telling you that you submitted the assignment. If you do not get this email that means that you did not complete the submission process correctly. Under no circumstances whatsoever we will accept any email submission of an assignment. Note: if you were granted an extension you will still turn in the assignment over Canvas .

3. There is a 6-hour grace period added to all assignments. You may submit your assignment without penalty up until 11:55PM, or with 25% penalty up until 5:55AM. *So what you should take from this is not to start assignments on the last day and plan to submit right at 11:54AM.* You alone are responsible for submitting your homework before the grace period begins or ends; neither Canvas, nor your flaky internet are to blame if you are unable to submit because you banked on your computer working up until 11:54PM. The penalty for submitting during the grace period (25%) or after (no credit) is non-negotiable.

Syllabus Excerpt on Academic Misconduct

Academic misconduct is taken very seriously in this class.

Quizzes, timed labs and the final examination are individual work.

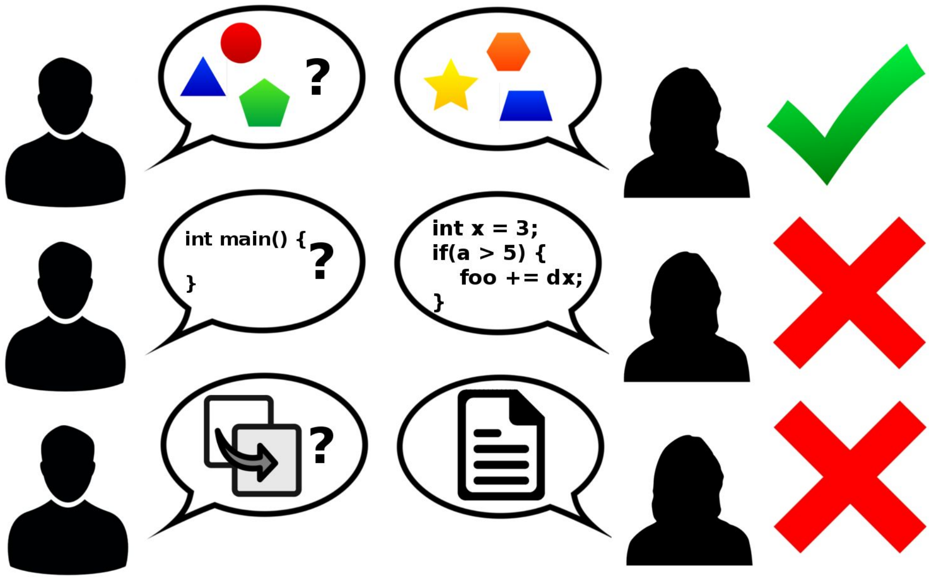
Homework assignments are collaborative, In addition many if not all homework assignments will be evaluated via demo or code review. During this evaluation, you will be expected to be able to explain every aspect of your submission. Homework assignments will also be examined using electronic computer programs to find evidence of unauthorized collaboration.

What is unauthorized collaboration? Each individual programming assignment should be coded by you. You may work with others, but each student should be turning in their own version of the assignment. Submissions that are essentially identical will receive a zero and will be sent to the Dean of Students' Office of Academic Integrity. Submissions that are copies that have been superficially modified to conceal that they are copies are also considered unauthorized collaboration.

You are expressly forbidden to supply a copy of your homework to another student via electronic means. This includes simply e-mailing it to them so they can look at it. If you supply an electronic copy of your homework to another student and they are charged with copying, you will also be charged. This includes storing your code on any site which would allow other parties to obtain your code such as but not limited to public repositories (Github), pastebin, etc. If you would like to use version control, use github.gatech.edu

Is collaboration allowed?

Collaboration is allowed on a high level, meaning that you may discuss design points and concepts relevant to the homework with your peers, as well as help each other debug code. What you shouldn't be doing, however, is paired programming where you collaborate with each other on a low level. Furthermore, sending an electronic copy of your homework to another student for them to look at and figure out what is wrong with their code is not an acceptable way to help them, and it is often the case that the recipient will simply modify the code and submit it as their own.



Overview

Warning:
Your submission must compile with our flags or we will simply not grade it and give it a zero. After you submit download your submission again and unzip in a clean directory and build it.

==
TURN IN THIS ASSIGNMENT ELECTRONICALLY USING CANVAS.
SUBMISSIONS WHICH ARE LATE WILL NOT BE ACCEPTED.
==

For this assignment you will be implementing a memory allocator. A memory allocator is code that is linked with user programs and provides functions to allocate and deallocate blocks of dynamic memory. In other words, you will be writing the heart and soul of two big dynamic memory allocation functions: malloc() and free(). It is worth noting that the remainder of this document assumes a thorough knowledge of how to use these functions. If you have any questions about them, resolve them *before* attempting to write the assignment.

The Basics

It is the job of the memory allocator to process and satisfy the memory requests of the user. But where does the allocator get *its* memory? Let us recall the structure of a program's memory footprint.

```
+-------------------+ (low memory)
|       CODE        |
+-------------------+
|       DATA        |
+-------------------+ <<-- Break
|                   |
|                   |
+-------------------+
|       STACK       |
+-------------------+ (high memory)
```

When a program is loaded into memory there are various "segments" created for different purposes: code, stack, data, etc. In order to create some dynamic memory space, otherwise known as the heap, it is possible to move the "break", which is the first address after the end of the process's uninitialized data segment. A function called "brk" is provided to set this address to a different value. There is also a function called "sbrk" which moves the break by some amount specified as a parameter.

For simplicity, a wrapper for the system call sbrk has been provided for you in the file named 'my_sbrk.c'. Make sure to use this call rather than a real call to sbrk, as doing this can potentially cause a lot of problems. Note that any problems introduced by calling the real sbrk will not be regraded, so make sure that everything is correct before turning in.

If you glance at the code for my_sbrk, you will quickly notice that upon the first call it always allocates 8 KB. For the purposes of your program, you should treat the returned amount as whatever you requested. For instance, the first time I call my_sbrk it will be done like this:

```
my_sbrk(SBRK_SIZE); /* SBRK_SIZE == 2 KB */

 ----------------------------------------
|                   8 KB                 |
 ----------------------------------------
^
|
`------ The pointer returned to me by my_sbrk
```

Even though you have a full 8 KB, you should treat it as if you were only returned SBRK_SIZE bytes. Now when you run out of memory and need more heap space you will need to call my_sbrk again. Once again, the call is simply:

```
my_sbrk(SBRK_SIZE);

 ----------------------------------------
|    2 KB   |             6 KB          |
 ----------------------------------------
             ^
             |
             `---- The pointer returned to me by my_sbrk
```

Notice how it returned a pointer to the address after the end of the 2 KB I had requested the first time. my_sbrk remembers the end of the data segment you request each time and is able to return that value to you as the beginning of the new data segment on a following call. Keep this in mind as you write the assignment!

Block Allocation

Trying to use sbrk (or brk) exclusively to provide dynamic memory allocation to your program would be very difficult and inefficient. Calling sbrk involves a certain amount of system overhead, and we would prefer not to have to call it every single time a small amount of memory is required. In addition, deallocation would be a problem. Say we allocated several 100 byte chunks of memory and then decided we were done with the first. Where would the break be? There's no handy function to move the break back, so how could we reuse that first 100 byte chunk?

What we need are a set of functions that manage a pool of memory allowing us to allocate and deallocate efficiently. Typically, such schemes start out with no free memory at all. The first time the user requests memory, the allocator will call sbrk as discussed above to obtain a relatively large chunk of memory. The user will be given a block with as much free space as he requested, and if there is any memory left over it will be managed by placing information about it in a data structure where information about all such free blocks is kept. We'll call this structure the free list, and we'll revisit it a little later.

In order to keep track of allocated blocks we will create a structure to store the information we need to know about a block. Where should we put this structure? Can we simply call malloc to allocate space for the information?

No we can't! We're writing malloc, we can't use it or we'd end up with infinite recursion. However, there's an easier way that will keep our bookkeeping structure right with the data we're allocating for easy access.

The trick we will use is that we will store this information, called metadata, about the block inside the block itself! **For this assignment, we are also implementing canaries to make sure that accesses do not overrun their space.** (https://en.wikipedia.org/wiki/Buffer_overflow_protection#Canaries, though note this will be a canary for memory allocated by malloc, not static arrays). We will have two canaries, one right before the space the user will use and one right after. Each **canary will be an int** with the value defined in the #define canary. We still want the user to have as much space as he requested, though, so when he wants a block of size x we will actually allocate a block of size "x + sizeof(the metadata) + 2*sizeof(int)". What this actually looks like:

```
<----- Memory Chunk with metadata -------------------->

+----------+--------+------------------------+--------+
| metadata | canary | free space for the user | canary |
+----------+--------+------------------------+--------+
                    ^
                    |
                    `--- pointer returned to the user
```

The user still only sees a block of the size he requested, but the metadata hangs out in the space right before that block so our allocation and deallocation algorithms can use it. The canaries surround the space the user gets so that if they overwrite the amount of space they are given, your functions can detect it and print an error message on free. Now that you know this, you may see why we're so bothered by writing over the bounds of dynamically allocated blocks: write over the metadata and chaos ensues!

Here's a list of the things that your metadata will need to contain:

1) the real size of the block (again, this includes the size of the metadata structure itself)
2) the size that the user asked for
3) a pointer to the previous block in the freelist
4) a pointer to the next block in the freelist

Additionally, remember that you will have a canary after the metadata and after the end of the free space reserved for the user. Note that the metadata does not contain the canary.

For ease of reading, the included struct definition found in 'my_malloc.h' has been pasted below for a better overview of what we're dealing with.

```c
typedef struct metadata
{
  short block_size;
  short request_size;
  struct metadata *prev;
  struct metadata *next;
} metadata_t;
```

The Freelist

When we allocate memory or take pieces of blocks we already allocated, there may be blocks we don't automatically use. For this reason, we keep a structure called the freelist that holds metadata about blocks that aren't currently in use.

The freelist is a linked list of blocks which should be defined as a file static variable. To help you out we have already defined a variable 'freelist' in the file 'my_malloc.c' for you.

static metadata_t* freelist;

Remember that since this variable is declared static it will be automatically initialized to 0 by the compiler for us! This means that we do not have to do any special work to initialize the freelist (head) pointer to NULL.

Since the freelist actually holds pointers to metadata, and metadata structures all have pointers to the 'previous' and 'next' metadata, the freelist lends itself to a linked list implementation. Keep in mind that 'previous' and 'next' don't necessarily mean consecutive - these pointers just exist to maintain links between blocks that are free. It is okay if a high address comes before a low address in the freelist for any block size so long as the freelist holds all the blocks that are free at any time. You may choose to sort the freelist if you think it will make your job easier, but you do not have to.

Simple Linked List – Allocating

When we first allocate space for the heap, it is in our best interest not to just request what we need immediately but rather to get a sizable amount of space, use a piece of it now, and keep the rest around in the freelist until we need it. This reduces the amount of times we need to call sbrk, the real version of which, as we discussed earlier, involves significant system overhead. So how do we know how much to allocate, how much to give to the user, and how much to keep?

For this assignment we will request blocks of size 2048 from my_sbrk. We don't want to waste space, though, so we want to give to the user the smallest size block in which his request would fit. For example, the user may request 256 bytes of space. It is tempting to give him a block of size 256, but remember we are also storing the metadata inside the block. If our metadata and canaries takes up 12 bytes, we need at least a 256+12=268 byte block.

How do we get from one big free block of size 2048 to the block of size 268 we want to give to the user? In this simple implementation, you will traverse the freelist to find the smallest block in the freelist that is larger than what we want, and “split” off however much you need from the front.
So we start with one big block in the freelist:

```
---       -------------------------------------------------------
FL | --> | block_size=2048; request_size=0; next=NULL; prev=NULL; |
---       -------------------------------------------------------
```

We want a block of size 268, so we look at the smallest size block that we can split, which is the 2048 block. The free list now looks like this after splitting the 2048 block:

```
----    NULL <---    --------------------------------
|FL |   -------->    |block_size=1780; requst_size=0;| --> NULL
----                 ---------------------------------
```

And you will have a temporary pointer to the block you will return to your user:

```
------------------        ------------------------------------
Your Tmp Pointer | -----> |block_size=268; request_size=256; |
------------------        ------------------------------------
```

Don't forget to set both canaries and move the pointer to the beginning of the space the user uses after the end of the metadata and canary before returning the block to the user.

Tips

1. Make helper functions if you want! Other good ones include functions to add and remove nodes from the freelist
2. **Test Test Test!** Test a bunch! Test after having malloced multiple things! Test freeing in a different order than malloced! Test actually using the data returned!

Simple Linked List – Deallocating

When we deallocate memory, we simply check the block's canaries and return the block to the free list in the appropriate position. (Notice we don't clear out all the data. That really just takes too long when we're not supposed to care about what's in memory after we free it anyway. For all of you who were wondering why sometimes you can still access data in a dynamically allocated block even after you call free on its pointer, this is why!) We like the freelists to contain fairly large blocks so that large requests can be allocated quickly, so if the block on either side of the block we're freeing is also free, we can coalesce them, or join them into the bigger block like they were before we split them.

How do we know what blocks we can join with? The left side one will have it's address+ it's (real) size = your block's address, and the right one will be your block's (real) size + it's address. This means that you will have to traverse the freelist to find the left and right side blocks to see if they are free and can be joined.

my_malloc

You are to write your own version of malloc that implements simple linked-list based allocation. To jog your memory, this is what that entails:

1) Figure out what size block you need to satisfy the user's request. Remember that the 'real size' field in our metadata structure includes the size of the metadata structure itself, so take the user size, sizeof(metadata_t), and sizeof(canary)*2 into account. **(If this size is over request size, set the right ERRNO and return null).**

2) Now that we have the size we care about, we need to iterate through our freelist at the to see if there is a free block big enough in that list. If there is one, we need to split off the portion we will use, remove that portion from the freelist, set its canaries, and return the block to the user. Note that the user should not be returned the pointer to our metadata structure, so the pointer we actually return to the user is **something like** 'metadata_pointer + sizeof(metadata_t) + sizeof(int)'.

Another note: remember that you want the address you return to be 'sizeof(metadata_t)+sizeof(canary)' **bytes** away from the metadata pointer. Pointer arithmetic can be unforgiving - if our pointer was of type int* (which it's not, this is just an example), adding 4 to it would result in an address that is 4 ints away from the original address. ints are not byte sized, so maybe a cast should be involved?

3) If the there is no block large enough, use my_sbrk to get more memory.

A couple of other things that are worth noting for the my_malloc functions.

1) The first call to malloc should call my_sbrk. Note that malloc should call my_sbrk when it doesn't have a block to satisfy the user's request anyway, so this **isn't a special case**.

2) If the user request exceeds 2048 bytes (note that this number is what is calculated *AFTER* my_malloc adds on the obligatory sizeof(metadata_t)+2*sizeof(canary)), then **return NULL and set the error code**.

3) In the event that there are no blocks currently available in the freelist that satisfy the user's request (note that you must attempt the procedure described above before determining this), then you should issue a call to my_sbrk to expand the heap size by SBRK_SIZE bytes. Failure to use this macro to expand the heap may result in a lower grade than you think you deserve. Please make *SURE* to use this macro when calling my_sbrk to avoid any possible problems. Also note that in the event that my_sbrk returns failure (by returning NULL), you should **return NULL and set the error code**.

4) If there is a block large enough to satisfy the request, but it's not large enough where you could split off the block you need and still have enough left over for another block (that is, having less than sizeof(metadata)+2*sizeof(int)+1 left), then you should return the entire block to the user with the block size set to the full size of the block. **The canary should still be at the end of the space the user asked for**, so in this case there will actually be some space in the block after the canary. This is why we are having you record both the block size and the request size - so you can find both the end of the block and the ending canary.

<u>my_free</u>

You are also to write your own version of free that implements deallocation. This means:

1) Calculate the proper address of the block to be freed, keeping in mind that the pointer passed to any call of my_free is the pointer that the user was working with, not the pointer to the block's metadata.

2) Check the canaries of the block, starting with the one by the metadata (so that if it is wrong you don't try to use corrupted metadata to find the second canary) to make sure they are still their original value. If the canary has been corrupted, set the CORRUPTED error and return.

2) Attempt to merge the block with blocks with that are consecutive in address space with it if those blocks are free. Don't forget to try to **merge with the block** to its left and its right in memory. Finally, place the resulting block in the freelist.

Error codes

For this assignment, you will also need to handle cases where users of your malloc do improper things with their code. For instance, if a user asks for 12 gigabytes of memory, this will clearly be too much for your 8kb heap. It is important to let the user know what he or she is doing wrong. This is where the enum in the my_malloc.h comes into play. You will see the four types of error codes for this assignment listed inside of it. They are as follows:

NO_ERROR: set whenever my_calloc, my_malloc, my_free, or my_memmove complete successfully.
OUT_OF_MEMORY: set whenever the user request cannot be met b/c there's not enough heap space.
SINGLE_REQUEST_TOO_LARGE: set whenever the user's request is beyond our biggest block size.
CANARY_CORRUPTED whenever either canary is corrupted in the freed block.

Inside the .h file, you will see a variable of type my_malloc_err called ERRNO. Whenever any of the cases above occur, you are to set this variable to the appropriate type of error. You may be wondering what happens if a single request is too large AND it causes malloc to run out of memory. In this case, we will let the SINGLE_REQUEST_TOO_LARGE take precedence over OUT_OF_MEMORY. So in the case of a request of 9kb, which is clearly beyond our biggest block and total heap size, we set ERRNO to SINGLE_REQUEST_TOO_LARGE.

Code Documentation

YOU MUST COMMENT YOUR CODE for this assignment! We don't expect every line of code to have comments, but we expect that you will have some comments so that we can figure out what you are trying to do in your code.

Ex:
```
void* my_malloc(size_t size) {
      /* Declaration of variables*/
      int a,b;
      int *c;

      /* Looks for large-enough block */
      ...your code here...
}
```

Testing!

We've given you two ways to test!

1. A test file where you can write some of your own tests that get run in a loop and give you timing information
2. **An autograder that will be very similar to the one we use to grade your work!** (we reserve the right to change the autograder to fix bugs or concerns that come up, but we're not trying to trick you)

The first one works like this – a test.c file has been provided with an empty main function. Feel free to modify anything in test.c to your heart's content to test your code as strictly as possible.

The autograder has been included in a subfolder of this assignment – just navigate into that folder and run 'make' to have the autograder evaluate your homework! Feel free to modify the grader's test files to add your own tests if you wish!
The autograder runs a bunch of tests in different processes - to run just one specify it as a parameter (./grader 4). Run it in gdb with “gdb grader” and then “run 5(or whatever test number)” after **removing the alarm function call in grader.c** (which kills the process after 5 seconds to deal with infinite loops, but will also kill the process inside of gdb).

The Assignment

1) You must use the allocation system exactly as described in this file.

2) The functionality for my_malloc and my_free should reside in the provided file 'my_malloc.c' file.

3) We have provided you with a blank tester file (test.c). The supplied Makefile assumes you will use test.c to test your code. If you choose to use a different file you will have to modify your Makefile to do so. Note that we are asking you to submit a library so no file with a main function should be submitted (No need to submit test.c). But more importantly, make sure there is no main file in any of your other code (ex:my_malloc.c). If any linking errors are encountered while attempting to grade, including 'multiple definition of main', you ***WILL* receive a ZERO.**

4) You may NOT core dump (cause a segmentation fault).

5) You may NOT maintain the freelist/heap in such a way that normal usage of your library would cause a core dump (ie, returning a block of size 4 when a block of size 32 was requested, returning a block which isn't properly aligned, etc.)

6) You may not call any C library functions which are in any way related to memory management (ie malloc, calloc, etc.).

7) Your code must compile cleanly with the flags provided in the Makefile. If your code does not compile with these flags, or if it cannot be compiled using the Makefile, you **WILL receive a ZERO.**

8) You should turn in all of your files. Above we told you there was no need to turn in test.c, but if you are having trouble with the assignment it would not hurt for the grader to see your test code (however, this is not a requirement).

9) Test as much as you want - just make sure no tester output comes out when we run your library files. Bon courage!

10) Be sure to comment your code thoroughly! You will lose points if it is not commented!

11) Deliverables

hw11_submission.tar.gz, which is created by the command **make submit**

FAQ

1. For code like "void* ptr = my_malloc(18);" does the block associated with ptr have a size of 18 + sizeof(metadata_t) + 2*sizeof(int)?

   Yes, that is correct.

2. Why am I getting a segfault in....
   Use GDB to debug! Also see FAQ #7.

3. The hw assignment says to just call my_sbrk again. But won't this mean we then have 2 heaps?

   Not exactly, it will expand the heap by another 2KB. You don't get two heaps.
   Once it has been expanded to 8KB, calls to my_sbrk will return NULL

4. When splitting a block into two blocks, do we use malloc to create a metadata for the second block?

   No! The use of the already coded malloc in C is expressly forbidden!
   Instead, you simply use pointer arithmetic to get a pointer into the middle of the block you're splitting and then set the data as necessary so that they function as two blocks.

5. Can we build our freelists with list heads/dummy nodes?
   No. No dummy nodes. The autograder checks the state of the freelist and if you have dummy nodes it will throw it off.

6. Should we first initialize the freelist to NULL?
   No, it is static and is therefore already NULL

7. How do I use gdb?
   There is a debugging.nfo text file that comes with the assignment that gives an introduction to using gdb. Some useful gdb one liners for this assignment:

x/16xw freelist	- e**x**amine **16** he**x**adecimal **w**ords by the freelist
print *freelist	- print the freelist (pretty printed as a struct)
display *freelist	- this will print the freelist after ever gdb command
watch freelist	- sets a breakpoint anytime freelist is modified

   Note that you can call the above commands on any variable you're have issues with - not just the freelist.