

CS230, Fall 2024

Lab Assignment L6 : Malloc Lab

Due Dec 14th, Sat 11:59:59 PM, KST

Please read the instructions carefully, especially the programming rules and hand-in instructions. If you have questions, please post it in Piazza publicly in English.

1 Introduction

In this lab you will be writing a dynamic storage allocator for C programs, i.e., your own version of the `malloc`, `free` and `realloc` routines. You are encouraged to explore the design space creatively and implement an allocator that is correct, efficient and fast.

2 Logistics

You will work by yourself for the Malloc Lab. We will be strictly checking for cheating, copying, etc. Please try to solve this lab on your own. **You are free to use the code in the text book** as a start (make sure you understand the code!). However, to get higher points, you will need to implement more advanced allocator techniques discussed in the slides/textbook such as *explicit free list* and *segregated free lists*. Any clarifications and revisions to the assignments will be posted on Piazza.

3 Hand Out Instructions

First make sure you fork the CS230/LAB6 repository to your private namespace! If you don't, you won't be able to submit your work. Once you have your private repo, you may clone your private repo. Also, make sure you have added your SSH key to the GitLab Web UI. To check SSH key settings and how to fork and clone, please see previous announcements and Lab 1 README.

```
unix> git clone ssh://git@cs230.kaist.ac.kr/cs[your_student_id]/lab6.git
```

Only two files are modified and handed in : `mm.c` and an additional `document.txt`. The `mdriver.c` program is a driver program that allows you to evaluate the performance of your solution. Use the command `make` to generate the driver code and run it with the command `./mdriver -V`. (The `-V` flag displays helpful summary information.)

4 How to Work on the Lab

Your dynamic storage allocator will consist of the following four functions, which are declared in `mm.h` and defined in `mm.c`.

```
int mm_init(void);
void *mm_malloc(size_t size);
void mm_free(void *ptr);
void *mm_realloc(void *ptr, size_t size);
```

The `mm.c` file we have given you implements the simplest but still functionally correct malloc package that we could think of. Using this as a starting place, modify these functions (and possibly define other private static functions), so that they obey the following semantics:

- **mm_init:** Before calling `mm_malloc`, `mm_realloc` or `mm_free`, the application program (i.e., the trace-driven driver program that you will use to evaluate your implementation) calls `mm_init` to perform any necessary initializations, such as allocating the initial heap area. The return value should be -1 if there was a problem in performing the initialization, 0 otherwise.
- **mm_malloc:** The `mm_malloc` routine returns a pointer to an allocated block payload of at least `size` bytes. The entire allocated block should lie within the heap region and should not overlap with any other allocated chunk.

We will compare your implementation to the version of malloc supplied in the standard C library (`libc`). Since the `libc` malloc always returns payload pointers that are aligned to 8 bytes, your malloc implementation should do likewise and always return 8-byte aligned pointers.

- **mm_free:** The `mm_free` routine frees the block pointed to by `ptr`. It returns nothing. This routine is only guaranteed to work when the passed pointer (`ptr`) was returned by an earlier call to `mm_malloc` or `mm_realloc` and has not yet been freed.
- **mm_realloc:** The `mm_realloc` routine returns a pointer to an allocated region of at least `size` bytes with the following constraints.
 - if `ptr` is NULL, the call is equivalent to `mm_malloc(size)`;
 - if `size` is equal to zero, the call is equivalent to `mm_free`;
 - if `ptr` is not NULL, it must have been returned by an earlier call to `mm_malloc` or `mm_realloc`. The call to `mm_realloc` changes the size of the memory block pointed to by `ptr` (the old block) to `size` bytes and returns the address of the new block. Notice that the address of the new block might be the same as the old block, or it might be different, depending on your implementation, the amount of internal fragmentation in the old block, and the size of the realloc request.

The contents of the new block are the same as those of the old `ptr` block, up to the minimum of the old and new sizes. Everything else is uninitialized. For example, if the old block is 8 bytes and the new block is 12 bytes, then the first 8 bytes of the new block are identical to the first 8 bytes of the old block and the last 4 bytes are uninitialized. Similarly, if the old block is 8 bytes and the new block is 4 bytes, then the contents of the new block are identical to the first 4 bytes of the old block.

These semantics match the semantics of the corresponding `libc` `malloc`, `realloc`, and `free` routines. Type `man malloc` to the shell for complete documentation.

5 Heap Consistency Checker

Dynamic memory allocators are notoriously tricky beasts to program correctly and efficiently. They are difficult to program correctly because they involve a lot of untyped pointer manipulation. **You will find it very helpful to write a heap checker** that scans the heap and checks it for consistency. Some examples of what a heap checker might check are:

- Is every block in the free list marked as free?

- Are there any contiguous free blocks that somehow escaped coalescing?
- Is every free block actually in the free list?
- Do the pointers in the free list point to valid free blocks?
- Do any allocated blocks overlap?
- Do the pointers in a heap block point to valid heap addresses?

Your heap checker will consist of the function `int mm_check(void)` in `mm.c`. It will check any invariants or consistency conditions you consider prudent. It returns a nonzero value if and only if your heap is consistent. You are not limited to the listed suggestions nor are you required to check all of them. You are encouraged to print out error messages when `mm_check` fails.

This consistency checker is for your own debugging during development. When you submit `mm.c`, make sure to remove any calls to `mm_check` as they will slow down your throughput.

6 Support Routines

The `memlib.c` package simulates the memory system for your dynamic memory allocator. You can invoke the following functions in `memlib.c`:

- `void *mem_sbrk(int incr)`: Expands the heap by `incr` bytes, where `incr` is a positive non-zero integer and returns a generic pointer to the first byte of the newly allocated heap area. The semantics are identical to the Unix `sbrk` function, except that `mem_sbrk` accepts only a positive non-zero integer argument.
- `void *mem_heap_lo(void)`: Returns a generic pointer to the first byte in the heap.
- `void *mem_heap_hi(void)`: Returns a generic pointer to the last byte in the heap.
- `size_t mem_heapsize(void)`: Returns the current size of the heap in bytes.
- `size_t mem_pagesize(void)`: Returns the system's page size in bytes (4K on Linux systems).

7 The Trace-driven Driver Program

The driver program `mdriver.c` distribution tests your `mm.c` package for correctness, space utilization, and throughput. The driver program is controlled by a set of *trace files*. Each trace file contains a sequence of allocate, reallocate, and free directions that instruct the driver to call your `mm_malloc`, `mm_realloc`, and `mm_free` routines in some sequence. The driver and the trace files are the same ones we will use when we grade your handin `mm.c` file.

The driver `mdriver.c` accepts the following command line arguments:

- `-t <tracedir>`: Look for the default trace files in directory `tracedir` instead of the default directory defined in `config.h`. Trace files for grading are provided in `/traces`
- `-f <tracefile>`: Use one particular `tracefile` for testing instead of the default set of tracefiles.
- `-h`: Print a summary of the command line arguments.
- `-l`: Run and measure `libc malloc` in addition to the student's `malloc` package.
- `-v`: Verbose output. Print a performance breakdown for each tracefile in a compact table.
- `-V`: More verbose output. Prints additional diagnostic information as each trace file is processed. Useful during debugging for determining which trace file is causing your `malloc` package to fail.

8 Programming Rules

- You should not change any of the interfaces in `mm.c`.
- You should not invoke any memory-management related library calls or system calls. This excludes the use of `malloc`, `calloc`, `free`, `realloc`, `sbrk`, `brk` or any variants of these calls in your code.
- You are not allowed to define any global or static compound data structures such as arrays, structs, trees, or lists in your `mm.c` program. However, you are allowed to declare global scalar variables such as integers, floats, and pointers in `mm.c`.
- For consistency with the `libc` malloc package, which returns blocks aligned on 8-byte boundaries, your allocator must always return pointers that are aligned to 8-byte boundaries. The driver will enforce this requirement for you.

9 Evaluation

You will receive zero points if you break any of the rules or your code is buggy and crashes the driver. Otherwise, your grade will be calculated as follows:

Correctness (30 points)

You will receive full points if your solution passes the correctness tests performed by the driver program. You will receive partial credit for each correct trace.

Performance (70 points)

Two performance metrics will be used to evaluate your solution:

- **Space utilization:** The peak ratio between the aggregate amount of memory used by the driver (i.e., allocated via `mm_malloc` or `mm_realloc` but not yet freed via `mm_free`) and the size of the heap used by your allocator. The optimal ratio equals to 1. You should find good policies to minimize fragmentation in order to make this ratio as close as possible to the optimal.
- **Throughput:** The average number of operations completed per second.

The driver program summarizes the performance of your allocator by computing a performance index, P , which is a weighted sum of the space utilization and throughput,

$$P = wU + (1 - w) \min \left(1, \frac{T}{T_{\text{libc}}} \right),$$

where U is your space utilization, T is your throughput, and T_{libc} is the estimated throughput of `libc malloc` on your system on the default traces.

The value for T_{libc} is a constant in the driver (15,000 Kops/s) that your instructor established when they configured the program. The performance index will equally consider both utilization and throughput : $w = 0.5$.

Observing that both memory and CPU cycles are expensive system resources, we adopt this formula to encourage balanced optimization of both memory utilization and throughput. Ideally, the performance index will reach $P = w + (1 - w) = 1$ or 100%. Since each metric will contribute at most w and $1 - w$ to the performance index, respectively, you should not go to extremes to optimize either the memory utilization or the throughput only. To receive a good score, you must achieve a balance between utilization and throughput.

Final Score (100 points)

Final score will be weighted sum of Correctness and Performance.

$$\text{Final Score} = \text{num_correct}/15 \times 0.3 + P \times 0.7$$

10 Hand In Instructions

10.1 Handing your assignment in

Once you have finished your implementation and your test cases have passed, you can submit your code. It's similar to what you have done in Lab 5. Make sure that you add the `mm.c` file, and commit your changes. You can do so with the following commands

```
unix> git add mm.c
unix> git add document.txt
unix> git commit -m "Your commit message"
```

First command adds `mm.c` to your next commit. Then, you can commit it by typing commit command. Execute following command to make sure that you do not have any uncommitted changes to the `mm.c` file.

```
unix> git status
```

To hand in your lab, execute the following command

```
unix> make handin
```

This step will push your local commits onto your GitLab remote repository. Make sure that your remote repository is your forked version of the Lab 6. Your remote URL should be something like `ssh://git@cs230.kaist.ac.kr/[Your_user_name]/lab6.git`.

You can check your remote URL using the following command:

```
unix> git remote -v
```

Check the tags section in the GitLab Web interface to see if your latest code has been pushed onto the server. The URL to check your tags is `https://cs230.kaist.ac.kr/[Your_user_name]/lab6/tags`. Same as previous lab, if you can see the tag on GitLab, your submission is successfully uploaded.

10.2 Cheating

We will be strict on detecting cheating. We will automatically compare your submission against other students' code, as well as submissions of previous years and code available on the Internet.

You must submit a text file (filename **document.txt**) that explains your implementation. There are no required format or length rules to adhere to, but the following information is recommended :

- Overview of general design. What strategy did you use? Did you try anything else? How did it fail?
- The general flow of logic and details of key functions(malloc, free, realloc, or any other helper functions).
- What parts of this assignment did you struggle with? Were there any bugs / errors that took a long time to handle?

You can write in both **English** and **Korean** as long as it is written by human. This file itself will not be graded, but you **MUST** submit this file (failure to include this file will result in a ZERO). We will use your document to verify that you have implemented malloc without cheating. Write down your reasoning on the provided document.txt and submit this with mm.c.

11 Hints

- **Use the `mdriver -f` option.** During initial development, using tiny trace files will simplify debugging and testing. We have included two such trace files (`short{1,2}-bal.rep`) that you can use for initial debugging.
- **Use the `mdriver -v` and `-V` options.** The `-v` option will give you a detailed summary for each trace file. The `-V` will also indicate when each trace file is read, which will help you isolate errors.
- **Compile with `gcc -g` and use a debugger.** A debugger will help you isolate and identify out of bounds memory references.
- **Understand every line of the malloc implementation in the textbook.** The textbook has a detailed example of a simple allocator based on an implicit free list. Use this as a point of departure. Don't start working on your allocator until you understand everything about the simple implicit list allocator.
- **Encapsulate your pointer arithmetic in C preprocessor macros.** Pointer arithmetic in memory managers is confusing and error-prone because of all the casting that is necessary. You can reduce the complexity significantly by writing macros for your pointer operations. See the textbook for examples.
- **Do your implementation in stages.** A few traces only contain requests to `malloc` and `free`. A few contain `realloc`, `malloc`, and `free`. We recommend that you start by getting your `malloc` and `free` routines working correctly and efficiently. Only then should you turn your attention to the `realloc` implementation. For starters, build `realloc` on top of your existing `malloc` and `free` implementations. But to get really good performance, you will need to build a stand-alone `realloc`.
- **Use a profiler.** You may find the `gprof` tool helpful for optimizing performance.
- **Start early!** It is possible to write an efficient malloc package with a few pages of code. However, we can guarantee that it will be some of the most difficult and sophisticated code you have written so far in your career. So start early, and good luck!