Assignment 6

CPSC 457 Fall 2022

Due date is posted on D2L.
Individual assignment. Group work is NOT allowed.
Weight: 15% of the final grade.

Worst-fit dynamic partition simulator

For this assignment, you will write a worst-fit dynamic partition memory allocation simulator that approximates some of the functionality of `malloc()` and `free()` in the standard C library. The input to your simulator will be a page size (a positive integer) and list of allocation and deallocation requests. Your simulator will simulate processing all requests and compute some statistics.

Throughout the simulation your program will maintain an ordered list of dynamic partitions. Some partitions will be marked as occupied, the rest will be marked as free. Occupied partitions will have a numeric tag attached to it. Each partition will also contain its size in bytes, and the starting address. The starting address of the first partition should be 0. Your simulator will manipulate this list of partitions as a result of processing requests. Allocation requests will be processed by finding the most appropriately sized partition and then allocating a memory from it. Deallocation requests will free up any relevant occupied partitions, and also merging any adjacent free partitions.

Start by downloading and compiling the skeleton code:

```
$ git clone https://gitlab.com/cpsc457f22/memsim.git
$ cd memsim
$ make
```

The only file you should modify and submit for grading is `memsim.cpp`, in which you need to implement your simulator in the function:

```
MemSimResult mem_sim(int64_t page_size, const std::vector<Request> & requests);
```

The parameter `page_size` will denote the page size and `requests` will contain a list of all requests to process. The requests are described using the `Request` struct:

```
struct Request { int tag; int size; };
```

When `tag>=0`, then this is an allocation request, and the `size` field will denote the size of the request. If `tag<0` then this is a deallocation request, in which case the `size` field is not used. You will report the results of the simulation by returning an instance of `MemSimResult` structure.

Allocation requests

Each allocation request will have two parameters – a tag and a size. Your program will use **worst-fit algorithm** to find a free partition, by scanning the list of partitions from the start until the end of the list. If more than one partition qualifies, it will pick the first partition it finds (i.e. the one with the smallest address). If the partition is bigger than the requested size, the partition will be split in two – an occupied partition and a free partition. The tag specified with the allocation request will be stored in the occupied partition.

Your simulation will start with an empty list of partitions. When the simulator fails to find a suitably large free partition, it will simulate asking the OS for more memory. The amount of memory that can be requested from OS must be a multiple of `page_size`. The newly obtained memory will be appended at the end of your list of partitions, and if appropriate, merged with the last free partition. Your program must figure out what is the minimum number of pages that it needs to request in order to satisfy the current request.

Deallocation requests

A deallocation request will have a single parameter – a tag. In the input list of requests, this will be denoted by a negative number, which you convert to a tag by using its absolute value. Your simulator will find all allocated partitions with the given tag and mark them free. Any adjacent free partitions will be merged. If there are no partitions with the given tag, your simulator will ignore such deallocation request.

Pseudocode for processing allocation requests:

- *search through the list of partitions from start to end, and find the largest partition that fits requested size*
  - *in case of ties, pick the first partition found*
- *if no suitable partition found:*
  - *get minimum number of pages from OS, but consider the case when last partition is free*
  - *add the new memory at the end of partition list, merge if appropriate*
  - *the last partition will be the best partition*
- *split the best partition in two if necessary*
  - *mark the first partition occupied, and store the tag in it*
  - *mark the second partition free*

Pseudocode for processing deallocation requests:

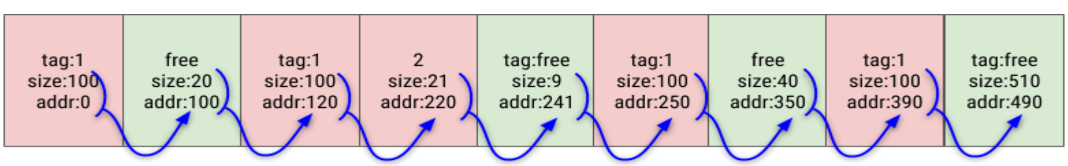
- *for every partition*
  - *if partition is occupied and has a matching tag:*
    - *mark the partition free*
    - *merge it with adjacent free partitions*

Partition addresses

For each partition you need to store the starting address (`addr`) of the block of memory that the partition represents. The first partition should have `addr=0`. The `addr` of any other partition is equal to the previous partition's `addr` plus the previous partition's `size`. If you store partitions in a linked list, such as `std::list<Partition>`, and if `cptr` is an iterator to some partition, then you can calculate its `addr` as:

```
cptr-> addr = std::prev(cptr)-> addr + std::prev(cptr)-> size;
```

Another way to think about a partition's address is that it is the sum of sizes of all partitions preceding it.



The driver program (main.cpp)

The included driver will accept a single command line argument representing the page size in bytes.

The driver will read allocation requests from standard input, until EOF. Lines containing only white spaces will be skipped. Each non-empty line will represent one request, either allocation or deallocation.

Any line with two integers will represent an allocation request. The first integer will represent the tag of the request, and the second one will represent the size of the allocation request in bytes. For example, the line `"3 100"` represents an allocation request for 100 bytes with tag 3.

A line with a single negative integer will represent a deallocation request. The absolute value of the integer will represent the tag to be deallocated. For example, the line `"-3"` will represent a deallocation request for all partitions marked with tag 3.

Reporting Results

At the end of the simulation your simulator must return an instance of `MemSimResult` structure:

- Set `n_pages_requested` to the total number of pages requested during the simulation. Notice that this could be `0`, if there are no allocation requests in the input.
- Set `max_free_partition_size` to the size of the largest free partition at the end of the simulation. If there are no free partitions, set this to `0`.
- Set `max_free_partition_address` to the address of the largest free partition at the end of the simulation. Set this to `0` if there are no free partitions. In case of ties, set this to the smallest address.

Limits

- the number of requests will be in range [0 .. 1,000,000]
- `page_size` will be in range [1 .. 1,000,000]
- each request's `tag` will be in range [-10,000,000 .. 10,000,000]
- each request's `size` will be in range [1 .. 10,000,000]

Marking

- Your code will be marked for correctness and efficiency.
- Your mark will be based on the number of test cases your solution will pass.
- A simple $O(n^3)$ solution, e.g. one that uses a vector to represent partitions, will likely only earn about 55% of marks.
- A simple $O(n^2)$ solution, e.g. one that only uses a linked list to represent partitions, will likely earn about 75% of marks.
- To earn full marks, you will need to be able to process any input with 1 million requests under 10s. I suggest you implement an $O(n \log n)$ algorithm, using advanced data structures as described in the hints section below.
- Small number of test inputs are provided with the starter code, but you should design your own test inputs as well.

Sample input and output

`$ cat test1.txt`
`5 100`
`-5`
`-6`
`1 100`
`2 20`
`1 100`
`2 30`
`1 100`
`2 40`
`1 100`
`-2`
`2 21`
`-1`
`3 220`
`3 759`
`3 1`
`3 5900`
	`$ ./memsim 1000 < test1.txt`
	`pages requested:               8`
	`largest free partition size:    829`
	`largest free partition address: 7171`
	
	`$ ./memsim 1 < test1.txt`
	`pages requested:               7030`
	`largest free partition size:    129`
	`largest free partition address: 221`
	
	`$ ./memsim 33 < test1.txt`
	`pages requested:               214`
	`largest free partition size:    129`
	`largest free partition address: 221`

Few additional test files are provided in the GitLab repository. Make sure to design your own test files. Read the appendix to learn how you can obtain correct results on small test files.

Submission

Only submit `memsim.cpp` file to D2L for this assignment.

General information about all assignments

1. All assignments are due on the date listed on D2L. Late submissions will not be marked.
2. Extensions may be granted only by the course instructor.
3. After you submit your work to D2L, verify your submission by re-downloading it.
4. You can submit many times before the due date. D2L will simply overwrite previous submissions with newer ones. It is better to submit incomplete work for a chance of getting partial marks, than not to submit anything. Please bear in mind that you cannot re-submit a single file if you have already submitted other files. Your new submission would delete the previous files you submitted. So please keep a copy of all files you intend to submit and resubmit all of them every time.
5. Assignments will be marked by your TAs. If you have questions about assignment marking, contact your TA first. If you still have questions after you have talked to your TA, then you can contact your instructor.
6. All programs you submit must run on `linuxlab.cpsc.ucalgary.ca`. If your TA is unable to run your code on the Linux machines, you will receive 0 marks for the relevant question.
7. Unless specified otherwise, you must submit code that can finish on any valid input under 10s on linuxlab.cpsc.ucalgary.ca, when compiled with `-O2` optimization. Any code that runs longer than this may receive a deduction, and code that runs for too long (about 30s) will receive 0 marks.
8. **Assignments must reflect your own individual work**. Here are some examples of what you are not allowed to do for individual assignments: you are not allowed to copy code or written answers (in part, or in whole) from anyone else; you are not allowed to collaborate with anyone; you are not allowed to share your solutions (including code or pseudocode) with anyone; you are not allowed to sell or purchase a solution; you are not allowed to make your code available publicly. This list is not exclusive. For further information on plagiarism, cheating and other academic misconduct, check the information at this link: http://www.ucalgary.ca/pubs/calendar/current/k-5.html.

9. We will use automated similarity detection software to check for plagiarism. Your submission will be compared to other students (current and previous), as well as to any known online sources. Any cases of detected plagiarism or any other academic misconduct will be investigated and reported.

Appendix - Hints

If you use only basic data structures, such as dynamic arrays or linked lists, you will likely end up with an $O(n^2)$ or even $O(n^3)$ algorithm, which will make your program too slow for large number of requests. To get full marks, you will need to use smarter data structures. I suggest:

- `std::list` - a linked list to maintain all partitions (to make splitting and merging of blocks constant time operation)
- `std::unordered_map` - hash table to store all partitions belonging to the same tag
  - the data you store here are just pointers to the linked list nodes
  - this will allow you to process deallocation requests very fast
- `std::set` - a balanced binary tree to keep track of free blocks, sorted by size
  - you need to store linked list iterators in this tree (aka pointers to the linked list nodes)
  - you should sort the tree by partition size (primary key), and partition address (secondary key)
  - this will allow you to process allocation requests very fast

If you use the above data structures correctly, they will allow you to process every request in $O(log\ n)$ time. Here are some relevant parts of code that use the above data structures:

```
struct Partition {
  int tag;
  int64_t size, addr;
};

typedef std::list<Partition>::iterator PartitionRef;

struct scmp {
  bool operator()(const PartitionRef & c1, const PartitionRef & c2) const {
    if (c1->size == c2->size)
      return c1->addr < c2->addr;
    else
      return c1->size > c2->size;
  }
};

struct Simulator {
  // all partitions, in a linked list
  std::list<Partition> all_blocks;
  // quick access to all tagged partitions
  std::unordered_map<long, std::vector<PartitionRef>> tagged_blocks;
  // sorted partitions by size/address
  std::set<PartitionRef,scmp> free_blocks;
 ...
}
```

The `free_blocks` will keep the partition pointers sorted so that `free_blocks.begin()` will always return the largest partition, and in case of ties, it will return the partition with the smallest address.

Before you modify a partition, make sure you `free_blocks.erase()` the partition. If you need to keep it in `free_blocks`, you can `free_blocks.insert()` it back after the modification. If you do not do this, you will likely corrupt the tree, and your program will output wrong results and/or crash. For similar reasons, make sure you never remove a partition from the linked list **before** removing it from `free_blocks` or `tagged_blocks`. When you remove an entry from linked list, any iterators to it would become invalid and lead to undefined behavior (likely a crash).

How to start

Step 1 – Start by implementing a basic solution, only using linked lists.

Step 2 – Add support for `tagged_blocks`, which will speed up deallocation requests. You will be able to re-use most of the code from step 1.

Step 3 – Add support for `free_blocks`. This will make allocation requests much faster. You should be able to re-use most of the code from Steps 1 and 2.

Debugging

I suggest you perform a consistency check of your data structures after processing each request. I found the following useful when I was debugging my own code:

- make sure the sum of all partition sizes in your linked list is the same as number of page requests * page_size
- make sure your partition addresses & sizes are consistent
- make sure the number of all partitions in `tagged_blocks` + the number of partitions in `free_blocks` is the same as the size of the linked list
- make sure that every free partition is in `free_blocks`
- make sure that every partition in `free_blocks` is actually free
- check the return values of calls to `free_block.erase()` and `free_block.insert()` to make sure they work as you intended, e.g.:

`auto res = free_blocks.erase(p);` `assert(res == 1);`	`auto res = free_blocks.insert(p);` `assert(res.second);`

Important: these consistency checks will make your code run slower. You should disable these checks before you submit your code for grading.

Appendix – python solution for Q1

The starter code contains a Python solution called `memsim.py`. It is a very **inefficient** solution, so do not expect it to run very fast for large inputs. By default, it shows you the partition states after processing each request. To turn off this extra debugging output, you can specify the page size as a negative number on the command line. Here is the output it generates on `test1.txt`:

```
./memsim.py 1000 < test1.txt
alloc 5 100
  ------+-----+-----
    tag |  5  | -1
   size | 100 | 900
   addr |  0  | 100
  ------+-----+-----
free 5
  ------+------
    tag |  -1
   size | 1000
   addr |  0
  ------+------
free 6
  ------+------
    tag |  -1
   size | 1000
   addr |  0
  ------+------
alloc 1 100
  ------+-----+-----
    tag |  1  | -1
   size | 100 | 900
   addr |  0  | 100
  ------+-----+-----
alloc 2 20
  ------+-----+-----+-----
    tag |  1  |  2  | -1
   size | 100 | 20  | 880
   addr |  0  | 100 | 120
  ------+-----+-----+-----
alloc 1 100
  ------+-----+-----+-----+-----
    tag |  1  |  2  |  1  | -1
   size | 100 | 20  | 100 | 780
   addr |  0  | 100 | 120 | 220
  ------+-----+-----+-----+-----
alloc 2 30
  ------+-----+-----+-----+-----+-----
    tag |  1  |  2  |  1  |  2  | -1
   size | 100 | 20  | 100 | 30  | 750
   addr |  0  | 100 | 120 | 220 | 250
  ------+-----+-----+-----+-----+-----
alloc 1 100
  ------+-----+-----+-----+-----+-----+-----
    tag |  1  |  2  |  1  |  2  |  1  | -1
   size | 100 | 20  | 100 | 30  | 100 | 650
   addr |  0  | 100 | 120 | 220 | 250 | 350
  ------+-----+-----+-----+-----+-----+-----
alloc 2 40
  ------+-----+-----+-----+-----+-----+-----+-----
    tag |  1  |  2  |  1  |  2  |  1  |  2  | -1
   size | 100 | 20  | 100 | 30  | 100 | 40  | 610
   addr |  0  | 100 | 120 | 220 | 250 | 350 | 390
  ------+-----+-----+-----+-----+-----+-----+-----
```

```
alloc 1 100
  ------+-----+-----+-----+-----+-----+-----+-----+-----
    tag |  1  |  2  |  1  |  2  |  1  |  2  |  1  | -1
   size | 100 | 20  | 100 | 30  | 100 | 40  | 100 | 510
   addr |  0  | 100 | 120 | 220 | 250 | 350 | 390 | 490
  ------+-----+-----+-----+-----+-----+-----+-----+-----
free 2
  ------+-----+-----+-----+-----+-----+-----+-----+-----
    tag |  1  | -1  |  1  | -1  |  1  | -1  |  1  | -1
   size | 100 | 20  | 100 | 30  | 100 | 40  | 100 | 510
   addr |  0  | 100 | 120 | 220 | 250 | 350 | 390 | 490
  ------+-----+-----+-----+-----+-----+-----+-----+-----
alloc 2 21
  ------+-----+-----+-----+-----+-----+-----+-----+-----+-----
    tag |  1  | -1  |  1  | -1  |  1  | -1  |  1  |  2  | -1
   size | 100 | 20  | 100 | 30  | 100 | 40  | 100 | 21  | 489
   addr |  0  | 100 | 120 | 220 | 250 | 350 | 390 | 490 | 511
  ------+-----+-----+-----+-----+-----+-----+-----+-----+-----
free 1
  ------+-----+-----+-----
    tag | -1  |  2  | -1
   size | 490 | 21  | 489
   addr |  0  | 490 | 511
  ------+-----+-----+-----
alloc 3 220
  ------+-----+-----+-----+-----
    tag |  3  | -1  |  2  | -1
   size | 220 | 270 | 21  | 489
   addr |  0  | 220 | 490 | 511
  ------+-----+-----+-----+-----
alloc 3 759
  ------+-----+-----+-----+-----+------
    tag |  3  | -1  |  2  |  3  |  -1
   size | 220 | 270 | 21  | 759 | 730
   addr |  0  | 220 | 490 | 511 | 1270
  ------+-----+-----+-----+-----+------
alloc 3 1
  ------+-----+-----+-----+-----+------+------
    tag |  3  | -1  |  2  |  3  |  3   |  -1
   size | 220 | 270 | 21  | 759 |  1   | 729
   addr |  0  | 220 | 490 | 511 | 1270 | 1271
  ------+-----+-----+-----+-----+------+------
alloc 3 5900
  ------+-----+-----+-----+-----+------+------+------
    tag |  3  | -1  |  2  |  3  |  3   |  3   |  -1
   size | 220 | 270 | 21  | 759 |  1   | 5900 | 829
   addr |  0  | 220 | 490 | 511 | 1270 | 1271 | 7171
  ------+-----+-----+-----+-----+------+------+------

----- Results ---------------------------------
pages requested:                8
largest free partition size:    829
largest free partition address: 7171
elapsed time:                   0.001
```