A Malloc Tutorial*

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1 Introduction

What is malloc? If you don’t even know the name, you might begin to learn C in the Unix environment prior to read this tutorial. For a programmer, malloc is the function to allocate memory blocks in a C program, most people don’t know what is really behind, some even thinks its a syscall or language keyword. In fact malloc is nothing more than a simple function and can be understood with a little C skills and almost no system knowledge.

The purpose of this tutorial is to code a simple malloc function in order to understand the underlying concepts. We will not code an efficient malloc, just a basic one, but the concept behind can be useful to understand how memory is managed in every day processes and how-to deal with blocks allocation, reallocation and freeing.

From a pedagogical standpoint, this is a good C practice. It is also a good document to understand where your pointers come from and how things are organized in the heap.

What is malloc
malloc(3) is a Standard C Library function that allocates (i.e. reserves) memory chunks. It complies with the following rules:

• malloc allocates at least the number of bytes requested;

• The pointer returned by malloc points to an allocated space (i.e. a space where the program can read or write successfully;)

• No other call to malloc will allocate this space or any portion of it, unless the pointer has been freed before.

• malloc should be tractable: malloc must terminate in as soon as possible (it should not be NP-hard!)

• malloc should also provide resizing and freeing.

The function obey to the following signature:

```c
void* malloc(size_t size);
```

Where size is the requested size. The returned pointer should be NULL in case of failure (no space left.)
2 The Heap and the \texttt{brk} and \texttt{sbrk} syscalls

Prior to write a first \texttt{malloc}, we need to understand how memory is managed in most multitask systems. We will keep an abstract point of view for that part, since many details are system and hardware dependant.
2.1 The Process’s Memory

Each process has its own virtual adress space dynamically translated into physical memory adress space by the MMU (and the kernel.) This space is devided in sevral part, all that we have to know is that we found at least some space for the code, a stack where local and volatile data are stored, some space for constant and global variables and an unorganized space for program’s data called the heap.

The heap is a continuous (in terme of virtual adresses) space of memory with three bounds: a starting point, a maximum limit (managed through sys/ressource.h’s functions getrlimit(2) and setrlimit(2)) and an end point called the break. The break marks the end of the mapped memory space, that is, the part of the virtual adress space that has correspondance into real memory. Figure 1 sketches the memory organisation.

![Memory organisation diagram](image)

Figure 1: Memory organisation

In order to code a malloc, we need to know where the heap begin and the break position, and of course we need to be able to move the break. This the purpose of the two syscalls brk and sbrk.

2.2 brk(2) and sbrk(2)

We can find the description of these syscalls in their manual pages:

```c
int brk(const void *addr);
void* sbrk(intptr_t incr);
```

brk(2) place the break at the given adress addr and return 0 if successful, −1 otherwise. The global errno symbol indicate the nature of the error.

sbrk(2) move the break by the given increment (in bytes.) Depending on system implementation, it returns the previous or the new break adress. On failure, it returns (void *)−1 and set errno. On some system sbrk accepts negative values (in order to free some mapped memory.)

Since sbrk’s specification does not fix the meaning of its result, we won’t use the returned value when moving the break. But, we can use a special case of sbrk: when increment is nul (i.e. sbrk(0)), the returned value is the actual break adress (the previous and the new break adresses are the same.) sbrk is thus used to retrieve the begining of the heap which is the initial position of the break.

We will use sbrk as our main tool to implement malloc. All we have to do is to acquire more space (if needed) to fulfil the query.
2.3 Unmapped Region and No-Man’s Land

We saw earlier that the break mark the end of the mapped virtual adress space: accessing addresses above the break should trigger a bus error. The remaining space between the break and the maximum limit of the heap is not associated to physical memory by the virtual memory manager of the system (the MMU and the dedicated part of the kernel.)

But, if you know a little about virtual memory (and even if use your brain 5 seconds), you know that memory is mapped by pages: physical memory and virtual memory is organize in pages (frames for the physical memory) of fixed size (most of the time.) The page size is by far bigger than one byte (on most actual system a page size is 4096 bytes.) Thus, the break may not be on pages boundary.

![Figure 2: Pages and Heap](image)

Figure 2 presents the previous memory organisation with page boundaries. We can see the break may not correspond to a page boundary. What is the status of the memory between the break and the next page boundary ? In fact, this space is available ! You can access (for reading or writing) bytes in this space. The issue is that you don’t have any clue on the position of the next boundary, you can find it but it is system dependant and badly advise.

This no-man’s land is often a root of bugs: some wrong manipulations of pointer outside of the heap can success most of the time with small tests and fail only when manipulating larger amount of data.

2.4 mmap(2)

Even if we won’t use it in this tutorial, you should pay attention to the `mmap(2)` syscall. It has an anonymous mode (mmap(2) is usually used to directly map files in memory) which can used to implement `malloc` (completely or for some specific cases.)

`mmap` in anonymous mode can allocate a specific amount of memory (by page size granularity) and `munmap` can free it. It is often simpler and more efficient than classical `sbrk` based `malloc`. Many malloc implementation use `mmap` for large allocation (more than one page.) The OpenBSD’s `malloc` uses only `mmap` with some quirks in order to improve security (preferring page’s borders for allocation with holes between pages.)

3 Dummy malloc

First, we will play with `sbrk(2)` to code a dummy `malloc`. This `malloc` is probably the worst one, even if it is the simplest and quiet the fastest one.
3.1 Principle
The idea is very simple, each time malloc is called we move the break by the amount of space required and return the previous address of the break. It is simple and fast, it takes only three lines, but we cannot do a real free and of course realloc is impossible.

This malloc waste a lot of space in obsolete memory chunks. It is only here for educational purpose and to try the sbrk(2) syscall. For educational purposes, we will also add some error management to our malloc.

3.2 Implementation

```c
/* An horrible dummy malloc */
#include <sys/types.h>
#include <unistd.h>

void *malloc(size_t size)
{
    void *p;
    p = sbrk(0);
    /* If sbrk fails, we return NULL */
    if (sbrk(size) == (void*)-1)
        return NULL;
    return p;
}
```

4 Organizing the Heap

In Section 3 on the preceding page, we present a first attempt to code a malloc function, but we failed to fulfil all the requirements. In this section we will try to find an organisation of the heap so that we can have an efficient malloc but also a free and a realloc.

4.1 What do we need?

If we consider the problem outside of the programming context, we can infer what kind of information we need to solve our issues. Let’s take analogy: you own a field and partition it to rent portion of it. Clients ask for different length (you divide your field using only one dimension) which they expect to be continous. When they have finished they give you back their porpotion, so you can rent it again.

On one side of the field you have a road with a programmable car: you enter the distance between the begin of the field and the destination (the begining of your portion.) So we need to know where each portion begin (this the pointer returned by malloc) and when we are at a begining of a portion we need the address of the next one.

A solution is to put a sign at the begining of each where we indicate the address of the next one (and the size of the current one to avoid unecessary computing.) We also add a mark on free portion (we put that mark when the client give it back.) Now, when a client want a portion of a certain size we take the car and travel from sign to sign. When we find a portion marked as
free and wide enough we give it to the client and remove the mark from the sign. If we reach
the last portion (its sign have no next portion address) we simply go to the end of the portion
and add a new sign.

Now we can transpose this idea to the memory: we need extra-information at beginning of
each chunks indicating at least the size of the chunk, the address of the next one and whether
its free or not.

4.2 How to represent block information

So what we need is a small block at the beginning of each chunk containing the extra-information,
called meta-data. This block contains at least a pointer to the next chunk, a flag to mark free
chunks and the size of the data of the chunk. Of course, this block of information is before the
pointer returned by malloc.

![Heap’s Chunks Structures](image)

Figure 3: Heap’s Chunks Structures

Figure 3 presents an example of heap organisation with meta-data in front of the allocated
block. Each chunk of data is composed of a block of meta-data followed by the block of data.
The pointer returned by malloc is indicated in the lower part of the diagram, note that it points
on the data block, not on the complete chunk.

Now, how we translate this into C code? This look like a classic linked list (and this is a
linked list), so we write a type for linked list with the needed information inside member of the
list. The type definition is self describing and presents no surprise:

```c
typedef struct s_block *t_block;

struct s_block {
  size_t size;
  t_block next;
  int free;
};
```

Note the use of a typedef to simplify the use of the type. Since we will never use the type
without a pointer we include it in the typedef, this is in fact the good practice for linked list
since the list is the pointer, not the block (an empty list is a NULL pointer.)
It may seem a waste of space to use an int as a flag, but since struct are aligned by default, it won’t have changed anything, we will see later how we can shrink the size of metadata. Another point that we will see later is that malloc must return aligned address.

A frequent question at this point is: how can we create a struct without a working malloc? The answer is simple, you just need to know what really is a struct. In memory, a struct is simply the concatenation of its fields, so in our example a struct s_block is just 12 bytes (with 32 bit integer) the first four correspond to size, the next four to the pointer to next block and finally the last four are the integer free. When the compiler encounter an access to struct field (like s.free or p->free) it translate it to the base address of the struct plus the sum of the length of the previous field (so p->free is equivalent to *((char*)p+8) and s.free is equivalent to *((char*)&s+8).) All you have to do is to allocate enough space with sbrk for the chunk (so the size of the meta-data plus the size of the data block) and put the address of the old break in a variable of type t_block:

```c
/* Example of using t_block without malloc */
t_block b;
/* save the old break in b */
b = sbrk(0);
/* add the needed space */
sbrk(sizeof(struct s_block) + size);
/* ... */
```

5 A First Fit Malloc

In this section we will implement the classic first fit malloc. The first fit algorithm is quiet simple: we traverse the chunks list and stop when we find a free block with enough space for the requested allocation.

5.1 Aligned Pointers

It is often required that pointers be aligned to the integer size (which is also the pointer size.) In our case we will consider only 32 bit case. So, our pointer must be a multiple of 4 (32 bits = 4 bytes, of course.) Since our meta-data block is already aligned, the only thing we need is to align the size of the data block.

How do we do this? There are several ways, on of the more efficient is to add a preprocessor macro using arithmetic trick.

First, the arithmetic trick: given any positive integer dividing (integer division) it by four and then multiplying it by four again results in the nearest smaller multiple of four, thus to obtain the nearest greater multiple of four we only need to add four to it. This is quiet simple, but it don’t work with an integer multiple of four, since it results with the next multiple of four. But, let’s play with arithmetic again, let x be an integer such that x = 4 × p + q with 0 ≤ q ≤ 3, then if x is a multiple of four, q = 0 and x - 1 = 4 × (p - 1) + 3, so (x - 1)/4 × 4 + 4 = 4 × p = x. If x is not a multiple of four, then q > 0 and x - 1 = 4 × p + (q - 1) and 0 ≤ q - 1 ≤ 2, so (x - 1)/4 × 4 + 4 = 4 × p + 4 = x/4 × 4 + 4. And thus, we have our formula since (x - 1)/4 × 4 + 4 always results to the nearest greater or equal multiple of four.
So, how do we do that in C? First, note that dividing and multiplying by four can be express using right and left bit-shift (>> and << in C) which are faster than simple multiplication. So our formula can be write in C like that: \(((x-1)>>2)<<2)+4\), to have a proper macro we need some extra parenthesis: \(((((x)-1)>>2)<<2)+4\). And now we can write our macro:

```c
#define align4(x) (((((x)-1)>>2)<<2)+4)
```

### 5.2 Finding a chunk: the First Fit Algorithm

Finding a free sufficiently wide chunk is quite simple: We begin at the base address of the heap (saved somehow in our code, we will see that later) test the current chunk, if it fit our need we just return its address, otherwise we continue to the next chunk until we find a fitting one or the end of the head. The only trick is to keep the last visited chunk, so the malloc function can easily extends the end of the heap if we found no fitting chunk. The function returns a fitting chunk, or NULL if none where found. After the execution, the argument last points to the last visited chunk.

### 5.3 Extending the heap

Now, we won’t always have a fitting chunk, and sometimes (especially at the begining of the program using our malloc) we need to extends the heap. This is quite simple: we move the break and initialize a new block, of course we need to update the next field of the last block on the heap.

In later development we will need to do some trick with the size of struct a_block, so we define a macro holding the size of meta-data block, for now it is define as:

### 5.4 Spliting blocks

You may have notice that we use the first available block regardless of its size (provide that it’s wide enough.) If we do that we will loose a lot of space (think of it: you ask for 2 bytes and find a block of 256 bytes.) A first solution is to split blocks: when a chunk is wide enough to held the asked size plus a new chunk (at least BLOCK_SIZE + 4), we insert a new chunk in the list.
Our algorithm.

First, if the requested size is 0, first we can not use the malloc function. If the requested size is not 0, we have to do some pointer arithmetic, to prevent errors, we will use a little trick to be sure that all our operations are done with one byte precision (remember p+1 depends on the type pointed to by p.)

We just add another field to struct a block of type characters array. Arrays in structure are simply put there: the array lies directly in the whole memory block of the structure at the point where the field is defined, thus for us, the array’s pointer indicate the end of the meta-data. C forbid zero length array, so we define a one byte long array and this why we need to specify a macro for the size of struct a block.

Note that this extension does not require any modification to extend_heap since the new field will not be used directly.

Now the function split_block: this function cut the block passed in argument to make data block of the wanted size. As for previous function s is already alined. The Figure 4 on the preceding page shows what is done here.

5.5 The malloc function

Now, we can do our malloc function. It is mostly a wrapper around previous functions. We have to aligne the required size, test if we are the first called malloc or not and every thing else have already been told.

First, remember in Section 5.2 on page 8 the function find_block use a global variable base. This variable is defined as follow:

It is a void pointer and it is NULL initialized. The first thing our malloc does is to test base, if it NULL then this the first time we’re called, otherwise we start the previously described algorithm.

Our malloc follow these lines:

- First align the requested size;
- If base is initialized:
  - Search for a free chunk wide enough;
  - If we found a chunk:
    * Try to split the block (the difference between the requested size and the size of the block is enough to store the meta-data and a minimal block (4 bytes;)
    * Mark the chunk as used (b->free=0;)

Figure 4: Splitting blocks
– Otherwise: we extend the heap.
  Note the use of the last: find_block put the pointer to the last visited chunk in
  last, so we can access it during the extension without traversing the whole list
  again.

  • Otherwise: we extended the heap (which is empty at that point.)
  Note that our function extend_heap works here with last=NULL.

  Note also that each time we fail, we silently returns NULL as expected by the specification
  of malloc. The Listing 1 presents the code.

6 calloc, free and realloc

6.1 calloc
calloc(3) is quite straightforward:

  • First do the malloc with right size (product of the two operands);
• Put 0 on any bytes in the block.

We just play a little trick: the data block size in the chunk is always a multiple of 4, so iterate by 4 bytes steps. For this, we just use our new pointer as an unsigned integer array. The code is straightforward (see listing 2.)

6.2 free

A quick implementation of free(3) can be quiet simple, but this does not mean that it is convenient. We have two issues: find the chunk to be freed and avoiding space fragmentation.

6.2.1 Fragmentation: the malloc illness

A major issue of malloc is fragmentation: after several use of malloc and free, we end with a heap divided in many chunks individually to small to satisfy big malloc while the whole free space would have been sufficient. This issue is known as the space fragmentation problem. While we cannot go against the extra-fragmentation due to our algorithm without changing it, some other sources of fragmentation can be avoided.

When we select a free chunk wider enough to hold the requested allocation and another chunk, we split the current chunk. While this offer a better usage of the memory (the new chunk is free for further reservation) it introduces more fragmentation.

A solution to eliminate some fragmentation is to fusion free chunks. When we free a chunk, and its neighbors are also free, we can fusion them in one bigger chunk. All we have to do is to test the next and previous chunks. But, how to find the previous block? We have several solitions:

• search from the begin, particulary slow (especially if we already do a search for the freed chunk)

• if we already do a search for the current chunk, we could keep a pointer on the last visited chunk (as for find_block)

• Double link our list.
We choose the last solution, it’s simpler and let’s us do some trick to find the target chunk. So, we modify (again) our struct s_block, but since we have another pending modification (see the next section) we will present the modification later.

So, all we have to do now is the fusion. We first write a simple fusion function which fusion a chunk and its successor. Fusionning with the predecessor will just be a test and a call with the right chunk. In the code we use our new field prev for the predecessor.

Fusion is straightforward: if the next chunk is free, we sum the sizes of the current chunk and the next one, plus the meta-data size. Then, the we make next field point to the successor of our successor and if this successor exists we update its predecessor.

6.2.2 Finding the right chunk

The other free’s issue is to find, efficiently, the correct chunk with only the pointer returned by malloc. In fact, there are several issues here:

- Validating the input pointer (is it really a malloc’ed pointer?)
- Finding the meta-data pointer

We can eliminate most of invalid pointers by a quick range test: if the pointer is outside the heap, it can not be a valid pointer. The remaining cases are related to the last case. How can we be sure that a pointer was obtained by malloc?

A solution is to have some magic number inside the block structure. And better than a magic number, we could use the pointer itself. I explain: say we have field ptr pointing to the field data, if b->ptr == b->data, then b is probably (very probably) a valid block. So, here is the extended structure and functions that verify and access the block corresponding to a given pointer:

6.2.3 The free function

free is now straightforward: we verify the pointer and get the corresponding chunk, we mark it free and fusion it if possible. We also try to release memory if we’re at the end of the heap.

Releasing memory, is quite simple: if we are at the end of the heap, we just have to put the break at the chunk position with a simple call to brk(2).

the listing 3 on the following page presents our implementation, it follows this structure:

- If the pointer is valid:
  - we get the block address
  - we mark it free
  - if the previous exists and is free, we step backward in the block list and fusion the two blocks.
  - we also try fusion with then next block
  - if we’re the last block we release memory.
  - if there’s no more block, we go back the original state (set base to NULL.)

- If the pointer is not valid, we silently do nothing.
6.3 Resizing chunks with realloc

The `realloc(3)` function is almost as straightforward as `calloc(3)`. Basically, we only need a memory copy operation. We won’t use the provided `memcpy`, since we can do better (size are available in blocks and are aligned.)

The copy is straightforward:
A very naive (but working) `realloc`, just follow this algorithm:

- Allocate a new bloc of the given size using `malloc`;
- Copy data from the old one to the new one;
- Free the old block;
- Return the new pointer.

Of course, we want something a little bit more efficient: we don’t want a new allocation if we have enough room where we are. The different cases are thus:
• If the size doesn’t change, or the extra-available size (do to alignment constraint, or if the remaining size was to small to split) is sufficient, we do nothing;

• If we shrink the block, we try a split;

• If the next block is free and provide enough space, we fusion and try to split if necessary.

The listing 4 on the next page presents our implementation. Don’t forget, that the call `realloc(NULL, s)` is valid and should be replaced by `malloc(s)`. 
6.3.1 FreeBSD’s reallocf

FreeBSD provides another realloc function: reallocf(3) which free the given pointer in any case (even if the reallocation fails.) This just a call to realloc and a free if we get a NULL pointer. The listing 5 presents the code.