Hack the Virtual Memory: malloc, the heap & the program break

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This is the fourth chapter in a series around virtual memory. The goal is to learn some CS basics, but in a different and more practical way.

If you missed the previous chapters, you should probably start there:

- Chapter 0: Hack The Virtual Memory: C strings & /proc
- Chapter 1: Hack The Virtual Memory: Python bytes
- Chapter 2: Hack The Virtual Memory: Drawing the VM diagram

The heap

In this chapter we will look at the heap and `malloc` in order to answer some of the questions we ended with at the end of the previous chapter:

- Why doesn't our allocated memory start at the very beginning of the heap (0x2050010 vs 02050000)? What are those first 16 bytes used for?
- Is the heap actually growing upwards?

Prerequisites

In order to fully understand this article, you will need to know:

- The basics of the C programming language (especially pointers)
- The very basics of the Linux filesystem and the shell
- We will also use the `/proc/[pid]/maps` file (see `man proc` or read our first article Hack The Virtual Memory, chapter 0: C strings & /proc)

Environment

All scripts and programs have been tested on the following system:

- Ubuntu
  - Linux ubuntu 4.4.0-31-generic #50~14.04.1-Ubuntu SMP Wed Jul 13 01:07:32 UTC 2016 x86_64 x86_64 x86_64 GNU/Linux

Tools used:

- gcc
  - gcc (Ubuntu 4.8.4-2ubuntu1~14.04.3) 4.8.4

- glibc 2.19 (see version.c if you need to check your glibc version)
- strace
    - strace — version 4.8

Everything we will write will be true for this system/environment, but may be different on another system

We will also go through the Linux source code. If you are on Ubuntu, you can download the sources of your current kernel by running this command:

```
apt-get source linux-image-$(uname -r)
```

`malloc`

`malloc` is the common function used to dynamically allocate memory. This memory is allocated on the "heap".
Note: `malloc` is not a system call.

From `man malloc`:

```
[...] allocate dynamic memory[...]
void *malloc(size_t size);
[...]
The malloc() function allocates size bytes and returns a pointer to the
```

No malloc, no [heap]

Let's look at memory regions of a process that does not call `malloc` (`0-main.c`).

```
#include <stdlib.h>
#include <stdio.h>

/**
 * main - do nothing
 *
 * Return: EXIT_FAILURE if something failed. Otherwise EXIT_SUCCESS
 */
int main(void)
{
    getchar();
    return (EXIT_SUCCESS);
}
```

```
julien@holberton:~/holberton/w/hackthevm3$ gcc -Wall -Wextra -pedantic -
julien@holberton:~/holberton/w/hackthevm3$ ./0
```

Quick reminder (1/3): the memory regions of a process are listed in the `/proc/[pid]/maps` file. As a result, we first need to know the PID of the process. That is done using the `ps` command; the second column of `ps aux` output will give us the PID of the process. Please read chapter 0 to learn more.

```
julien@holberton:/tmp$ ps aux | grep \ \./0$
julien     3638  0.0  0.0   4200   648 pts/9    S+   12:01   0:00 ./0
```

Quick reminder (2/3): from the above output, we can see that the PID of the process we want to look at is `3638`. As a result, the `maps` file will be found in the directory `/proc/3638`.

```
julien@holberton:/tmp$ cd /proc/3638
```

Quick reminder (3/3): The `maps` file contains the memory regions of the process. The format of each line in this file is:
address perms offset dev inode pathname

```
julien@holberton:/proc/3638$ cat maps
00400000-00401000 r-xp 00000000 08:01 174583
00600000-00601000 r--p 00000000 08:01 174583
00601000-00602000 rw-p 00001000 08:01 174583
7f38f87d7000-7f38f8991000 r-xp 00000000 08:01 136253
7f38f8991000-7f38f8b91000 ---p 001ba000 08:01 136253
7f38f8b91000-7f38f8b95000 r--p 001ba000 08:01 136253
7f38f8b95000-7f38f8b97000 rw-p 001be000 08:01 136253
7f38f8b97000-7f38f8b9c000 rw-p 00000000 00:00 0
7f38f8b9c000-7f38f8bbf000 r-xp 00000000 08:01 136229
7f38f8da3000-7f38f8da6000 rw-p 00000000 00:00 0
7f38f8dbb000-7f38f8dbe000 rw-p 00000000 00:00 0
7f38f8dbe000-7f38f8dbf000 r--p 00022000 08:01 136229
7f38f8dbf000-7f38f8dc0000 rw-p 00023000 08:01 136229
7f38f8dc0000-7f38f8dc1000 rw-p 00000000 00:00 0
7ffdd85c5000-7ffdd85e6000 rw-p 00000000 00:00 0
7ffdd85f2000-7ffdd85f4000 r--p 00000000 00:00 0
7ffdd85f4000-7ffdd85f6000 r-xp 00000000 00:00 0
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0
julien@holberton:/proc/3638$
```

Note: `hackthevm3` is a symbolic link to `hack_the_virtual_memory/03. The Heap/`

-> As we can see from the above maps file, there's no [heap] region allocated.

`malloc(x)`

Let's do the same but with a program that calls `malloc` (`1-main.c`):

```
#include <stdio.h>
#include <stdlib.h>

/**
 * main - 1 call to malloc
 *
 * Return: EXIT_FAILURE if something failed. Otherwise EXIT_SUCCESS
 */
int main(void)
{
    malloc(1);
    getchar();
    return (EXIT_SUCCESS);
}
```

```
julien@holberton:~/holberton/w/hackthevm3$ gcc -Wall -Wextra -pedantic -
julien@holberton:~/holberton/w/hackthevm3$ ./1
```

```
julien@holberton:/proc/3638$ ps aux | grep \ \./1$
julien     3718  0.0  0.0   4332   660 pts/9    S+   12:09   0:00 ./1
julien@holberton:/proc/3638$ cd /proc/3718
julien@holberton:/proc/3718$ cat maps
00400000-00401000 r-xp 00000000 08:01 176964
00600000-00601000 r--p 00000000 08:01 176964
00601000-00602000 rw-p 00001000 08:01 176964
01195000-011b6000 rw-p 00000000 00:00 0
...
julien@holberton:/proc/3718$
```

-> the [heap] is here.

Let's check the return value of `malloc` to make sure the returned address is in the heap region (`2-main.c`):

```
#include <stdio.h>
#include <stdlib.h>

/**
 * main - prints the malloc returned address
 *
 * Return: EXIT_FAILURE if something failed. Otherwise EXIT_SUCCESS
 */
int main(void)
{
    void *p;

    p = malloc(1);
    printf("%p\n", p);
    getchar();
    return (EXIT_SUCCESS);
}
```

```
julien@holberton:~/holberton/w/hackthevm3$ gcc -Wall -Wextra -pedantic -
julien@holberton:~/holberton/w/hackthevm3$ ./2
0x24d6010
```

```
julien@holberton:/proc/3718$ ps aux | grep \ \./2$
julien     3834  0.0  0.0   4336   676 pts/9    S+   12:48   0:00 ./2
julien@holberton:/proc/3718$ cd /proc/3834
julien@holberton:/proc/3834$ cat maps
```

```
00400000-00401000 r-xp 00000000 08:01 176966
00600000-00601000 r--p 00000000 08:01 176966
00601000-00602000 rw-p 00001000 08:01 176966
024d6000-024f7000 rw-p 00000000 00:00 0
...
julien@holberton:/proc/3834$
```

-> `024d6000` <`0x24d6010` < `024f7000`

The returned address is inside the heap region. And as we have seen in the previous chapter, the returned address does not start exactly at the beginning of the region; we'll see why later.

strace, brk and sbrk

`malloc` is a "regular" function (as opposed to a system call), so it must call some kind of syscall in order to manipulate the heap. Let's use `strace` to find out.

`strace` is a program used to trace system calls and signals. Any program will always use a few syscalls before your `main` function is executed. In order to know which syscalls are used by `malloc`, we will add a `write` syscall before and after the call to `malloc`(`3-main.c`).

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

/**
 * main - let's find out which syscall malloc is using
 *
 * Return: EXIT_FAILURE if something failed. Otherwise EXIT_SUCCESS
 */
int main(void)
{
    void *p;

    write(1, "BEFORE MALLOC\n", 14);
    p = malloc(1);
    write(1, "AFTER MALLOC\n", 13);
    printf("%p\n", p);
    getchar();
    return (EXIT_SUCCESS);
}
```

```
julien@holberton:~/holberton/w/hackthevm3$ gcc -Wall -Wextra -pedantic -
julien@holberton:~/holberton/w/hackthevm3$ strace ./3
execve("./3", ["./3"], [/* 61 vars */]) = 0
...
write(1, "BEFORE MALLOC\n", 14BEFORE MALLOC
)         = 14
brk(0)                                  = 0xe70000
brk(0xe91000)                           = 0xe91000
write(1, "AFTER MALLOC\n", 13AFTER MALLOC
)          = 13
...
read(0,
```

From the above listing we can focus on this:

```
brk(0)                                  = 0xe70000
brk(0xe91000)                           = 0xe91000
```

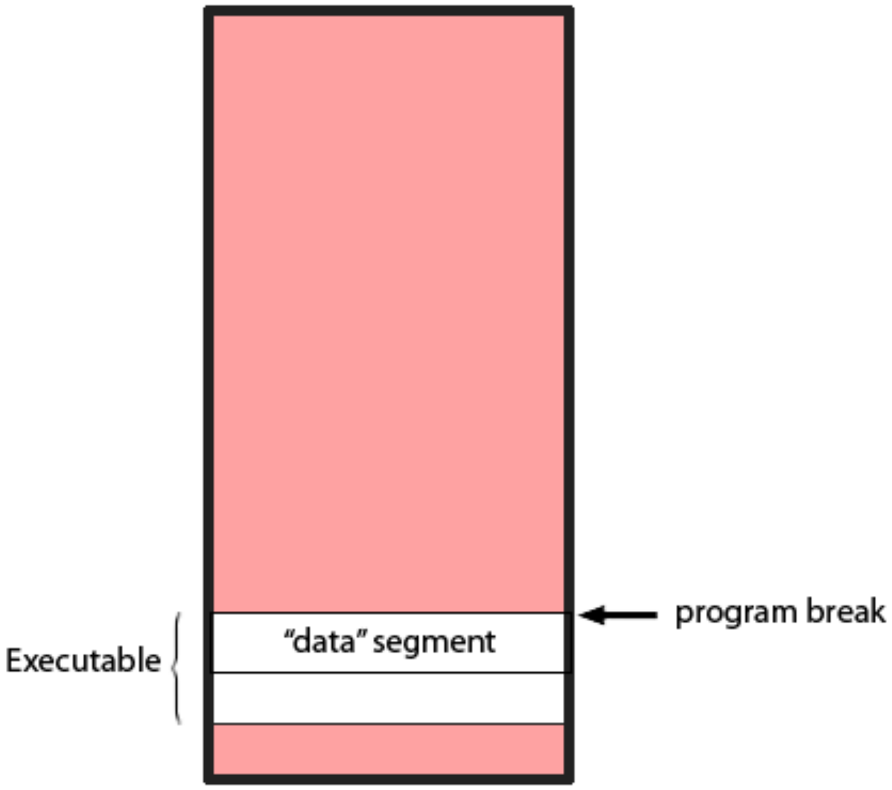
-> `malloc` is using the `brk` system call in order to manipulate the heap.

From `brk` man page (`man brk`), we can see what this system call is doing:

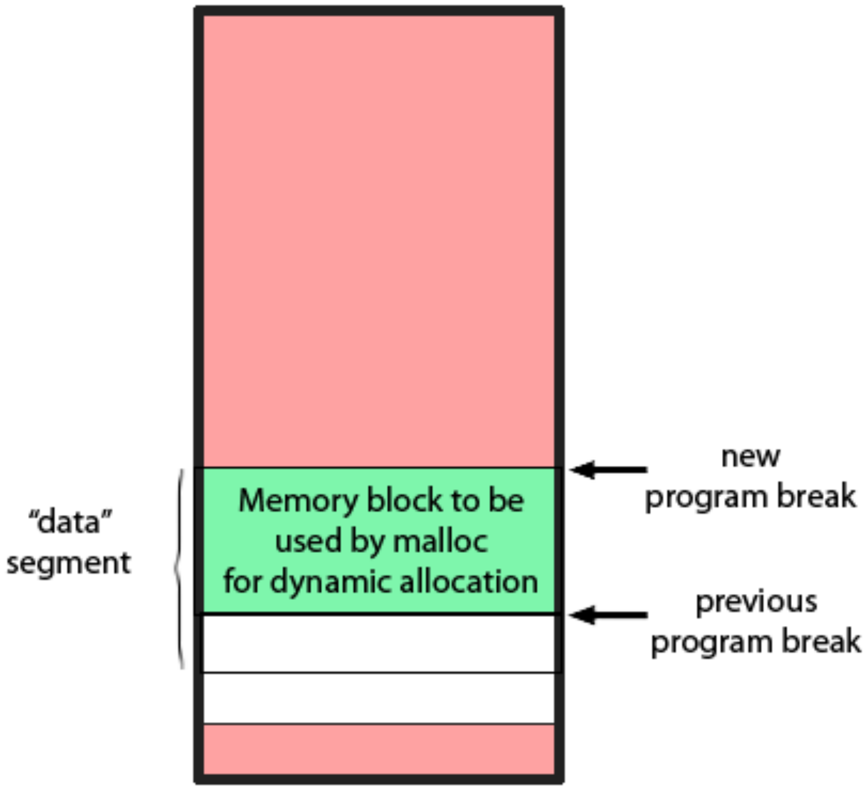
```
...
       int brk(void *addr);
       void *sbrk(intptr_t increment);
...
DESCRIPTION
       brk() and sbrk() change the location of the program  break,  whic
       the end of the process's data segment (i.e., the program break is
       location after the end of the uninitialized data segment).  Incre
       program  break has the effect of allocating memory to the process
       ing the break deallocates memory.

       brk() sets the end of the data segment to the value specified by
       that  value  is  reasonable,  the system has enough memory, and t
       does not exceed its maximum data size (see setrlimit(2)).

       sbrk() increments the program's data space  by  increment  bytes.
       sbrk()  with  an increment of 0 can be used to find the current l
       the program break.
```

The program break is the address of the first location beyond the current end of the data region of the program in the virual memory.

THE VIRTUAL MEMORY



By increasing the value of the program break, via `brk` or `sbrk`, the function `malloc` creates a new space that can then be used by the process to dynamically allocate memory (using `malloc`).



So the heap is actually an extension of the data segment of the program.

The first call to `brk` (`brk(0)`) returns the current address of the program break to `malloc`. And the second call is the one that actually creates new memory (since `0xe91000` > `0xe70000`) by increasing the value of the program break. In the above example, the heap is now starting at `0xe70000` and ends at `0xe91000`. Let's double check with the `/proc/[PID]/maps` file:

```
julien@holberton:/proc/3855$ ps aux | grep \ \./3$
julien     4011  0.0  0.0   4748   708 pts/9    S+   13:04   0:00 strace
julien     4014  0.0  0.0   4336   644 pts/9    S+   13:04   0:00 ./3
julien@holberton:/proc/3855$ cd /proc/4014
julien@holberton:/proc/4014$ cat maps
```

```
00400000-00401000 r-xp 00000000 08:01 176967
00600000-00601000 r--p 00000000 08:01 176967
00601000-00602000 rw-p 00001000 08:01 176967
00e70000-00e91000 rw-p 00000000 00:00 0
...
julien@holberton:/proc/4014$
```

-> `00e70000-00e91000 rw-p 00000000 00:00 0 [heap]` matches the pointers returned back to `malloc` by `brk`.

That's great, but wait, why did`malloc` increment the heap by `00e91000` – `00e70000` = `0x21000` or `135168` bytes, when we only asked for only 1 byte?

Many mallocs

What will happen if we call `malloc` several times? (`4-main.c`)

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

/**
 * main - many calls to malloc
 *
 * Return: EXIT_FAILURE if something failed. Otherwise EXIT_SUCCESS
 */
int main(void)
{
    void *p;

    write(1, "BEFORE MALLOC #0\n", 17);
    p = malloc(1024);
    write(1, "AFTER MALLOC #0\n", 16);
    printf("%p\n", p);

    write(1, "BEFORE MALLOC #1\n", 17);
    p = malloc(1024);
    write(1, "AFTER MALLOC #1\n", 16);
    printf("%p\n", p);

    write(1, "BEFORE MALLOC #2\n", 17);
    p = malloc(1024);
    write(1, "AFTER MALLOC #2\n", 16);
    printf("%p\n", p);

    write(1, "BEFORE MALLOC #3\n", 17);
    p = malloc(1024);
    write(1, "AFTER MALLOC #3\n", 16);
    printf("%p\n", p);

    getchar();
    return (EXIT_SUCCESS);
}
```

```
julien@holberton:~/holberton/w/hackthevm3$ gcc -Wall -Wextra -pedantic -
julien@holberton:~/holberton/w/hackthevm3$ strace ./4
execve("./4", ["./4"], [/* 61 vars */]) = 0
...
write(1, "BEFORE MALLOC #0\n", 17BEFORE MALLOC #0
)      = 17
brk(0)                                  = 0x1314000
brk(0x1335000)                          = 0x1335000
write(1, "AFTER MALLOC #0\n", 16AFTER MALLOC #0
)       = 16
...
write(1, "0x1314010\n", 100x1314010
)              = 10
write(1, "BEFORE MALLOC #1\n", 17BEFORE MALLOC #1
)       = 17
write(1, "AFTER MALLOC #1\n", 16AFTER MALLOC #1
)        = 16
write(1, "0x1314420\n", 100x1314420
)              = 10
write(1, "BEFORE MALLOC #2\n", 17BEFORE MALLOC #2
)       = 17
write(1, "AFTER MALLOC #2\n", 16AFTER MALLOC #2
)        = 16
write(1, "0x1314830\n", 100x1314830
)              = 10
write(1, "BEFORE MALLOC #3\n", 17BEFORE MALLOC #3
)       = 17
write(1, "AFTER MALLOC #3\n", 16AFTER MALLOC #3
)        = 16
write(1, "0x1314c40\n", 100x1314c40
)              = 10
...
read(0,
```

-> `malloc` is NOT calling `brk` each time we call it.

The first time, `malloc` creates a new space (the heap) for the program (by increasing the program break location). The following times, `malloc` uses the same space to give our program "new" chunks of memory. Those "new" chunks of memory are part of the memory previously allocated using `brk`. This way, `malloc` doesn't have to use syscalls (`brk`) every time we call it, and thus it makes `malloc` – and our programs using `malloc` – faster. It also allows `malloc` and `free` to optimize the usage of the memory.

Let's double check that we have only one heap, allocated by the first call to `brk`:

```
julien@holberton:/proc/4014$ ps aux | grep \ \./4$
julien     4169  0.0  0.0   4748   688 pts/9    S+   13:33   0:00 strace
julien     4172  0.0  0.0   4336   656 pts/9    S+   13:33   0:00 ./4
julien@holberton:/proc/4014$ cd /proc/4172
julien@holberton:/proc/4172$ cat maps
00400000-00401000 r-xp 00000000 08:01 176973
00600000-00601000 r--p 00000000 08:01 176973
00601000-00602000 rw-p 00001000 08:01 176973
01314000-01335000 rw-p 00000000 00:00 0
7f4a3f2c4000-7f4a3f47e000 r-xp 00000000 08:01 136253
7f4a3f47e000-7f4a3f67e000 ---p 001ba000 08:01 136253
7f4a3f67e000-7f4a3f682000 r--p 001ba000 08:01 136253
7f4a3f682000-7f4a3f684000 rw-p 001be000 08:01 136253
7f4a3f684000-7f4a3f689000 rw-p 00000000 00:00 0
7f4a3f689000-7f4a3f6ac000 r-xp 00000000 08:01 136229
7f4a3f890000-7f4a3f893000 rw-p 00000000 00:00 0
7f4a3f8a7000-7f4a3f8ab000 rw-p 00000000 00:00 0
7f4a3f8ab000-7f4a3f8ac000 r--p 00022000 08:01 136229
7f4a3f8ac000-7f4a3f8ad000 rw-p 00023000 08:01 136229
7f4a3f8ad000-7f4a3f8ae000 rw-p 00000000 00:00 0
7ffd1ba73000-7ffd1ba94000 rw-p 00000000 00:00 0
7ffd1bbed000-7ffd1bbef000 r--p 00000000 00:00 0
7ffd1bbef000-7ffd1bbf1000 r-xp 00000000 00:00 0
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0
julien@holberton:/proc/4172$
```

-> We have only one [heap] and the addresses match those returned by `sbrk`: `0x1314000` & `0x1335000`

Naive malloc

Based on the above, and assuming we won't ever need to free anything, we can now write our own (naive) version of `malloc`, that would move the program break each time it is called.

```
#include <stdlib.h>
#include <unistd.h>

/**
 * malloc - naive version of malloc: dynamically allocates memory on the
 * @size: number of bytes to allocate
 *
 * Return: the memory address newly allocated, or NULL on error
 *
 * Note: don't do this at home :)
 */
void *malloc(size_t size)
{
    void *previous_break;

    previous_break = sbrk(size);
    /* check for error */
    if (previous_break == (void *) -1)
    {
        /* on error malloc returns NULL */
        return (NULL);
    }
    return (previous_break);
}
```

The 0x10 lost bytes

If we look at the output of the previous program (`4-main.c`), we can see that the first memory address returned by `malloc` doesn't start at the beginning of the heap, but `0x10` bytes after: `0x1314010` vs `0x1314000`. Also, when we call `malloc(1024)` a second time, the address should be `0x1314010` (the returned value of the first call to `malloc`) + `1024` (or `0x400` in hexadecimal, since the first call to `malloc` was asking for `1024` bytes) = `0x1318010`. But the return value of the second call to `malloc` is `0x1314420`. We have lost `0x10` bytes again! Same goes for the subsequent calls.

Let's look at what we can find inside those "lost" `0x10`-byte memory spaces (`5-main.c`) and whether the memory loss stays constant:

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

/**
 * pmem - print mem
 * @p: memory address to start printing from
 * @bytes: number of bytes to print
 *
 * Return: nothing
 */
void pmem(void *p, unsigned int bytes)
{
    unsigned char *ptr;
    unsigned int i;

    ptr = (unsigned char *)p;
    for (i = 0; i < bytes; i++)
    {
        if (i != 0)
        {
            printf(" ");
        }
        printf("%02x", *(ptr + i));
    }
    printf("\n");
}

/**
 * main - the 0x10 lost bytes
 *
 * Return: EXIT_FAILURE if something failed. Otherwise EXIT_SUCCESS
 */
int main(void)
{
    void *p;
    int i;

    for (i = 0; i < 10; i++)
    {
        p = malloc(1024 * (i + 1));
        printf("%p\n", p);
        printf("bytes at %p:\n", (void *)((char *)p - 0x10));
        pmem((char *)p - 0x10, 0x10);
    }
    return (EXIT_SUCCESS);
}
```

```
julien@holberton:~/holberton/w/hackthevm3$ gcc -Wall -Wextra -pedantic -
julien@holberton:~/holberton/w/hackthevm3$ ./5
0x1fa8010
bytes at 0x1fa8000:
00 00 00 00 00 00 00 00 11 04 00 00 00 00 00 00
0x1fa8420
bytes at 0x1fa8410:
00 00 00 00 00 00 00 00 11 08 00 00 00 00 00 00
```

```
0x1fa8c30
bytes at 0x1fa8c20:
00 00 00 00 00 00 00 00 11 0c 00 00 00 00 00 00
0x1fa9840
bytes at 0x1fa9830:
00 00 00 00 00 00 00 00 11 10 00 00 00 00 00 00
0x1faa850
bytes at 0x1faa840:
00 00 00 00 00 00 00 00 11 14 00 00 00 00 00 00
0x1fabc60
bytes at 0x1fabc50:
00 00 00 00 00 00 00 00 11 18 00 00 00 00 00 00
0x1fad470
bytes at 0x1fad460:
00 00 00 00 00 00 00 00 11 1c 00 00 00 00 00 00
0x1faf080
bytes at 0x1faf070:
00 00 00 00 00 00 00 00 11 20 00 00 00 00 00 00
0x1fb1090
bytes at 0x1fb1080:
00 00 00 00 00 00 00 00 11 24 00 00 00 00 00 00
0x1fb34a0
bytes at 0x1fb3490:
00 00 00 00 00 00 00 00 11 28 00 00 00 00 00 00
julien@holberton:~/holberton/w/hackthevm3$
```

There is one clear pattern: the size of the malloc'ed memory chunk is always found in the preceding 0x10 bytes. For instance, the first `malloc` call is malloc'ing `1024` (`0x0400`) bytes and we can find `11 04 00 00 00 00 00 00` in the preceding `0x10` bytes. Those last bytes represent the number `0x 00 00 00 00 00 00 04 11` = `0x400` (1024) + `0x10` (the block size preceding those `1024` bytes + `1` (we'll talk about this "+1" later in this chapter). If we look at each `0x10` bytes preceding the addresses returned by `malloc`, they all contain the size of the chunk of memory asked to `malloc` + `0x10` + `1`.

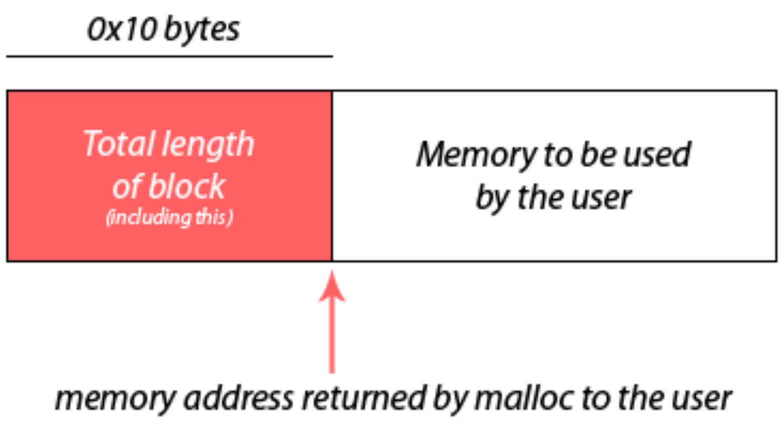
At this point, given what we said and saw earlier, we can probably guess that those 0x10 bytes are a sort of data structure used by `malloc` (and `free`) to deal with the heap. And indeed, even though we don't understand everything yet, we can already use this data structure to go from one malloc'ed chunk of memory to the other (`6-main.c`) as long as we have the address of the beginning of the heap (*and as long as we have never called `free`*):

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

/**
 * pmem - print mem
 * @p: memory address to start printing from
 * @bytes: number of bytes to print
 *
 * Return: nothing
 */
void pmem(void *p, unsigned int bytes)
{
    unsigned char *ptr;
    unsigned int i;

    ptr = (unsigned char *)p;
    for (i = 0; i < bytes; i++)
    {
        if (i != 0)
        {
            printf(" ");
        }
        printf("%02x", *(ptr + i));
    }
    printf("\n");
}

/**
 * main - using the 0x10 bytes to jump to next malloc'ed chunks
 *
 * Return: EXIT_FAILURE if something failed. Otherwise EXIT_SUCCESS
 */
int main(void)
{
    void *p;
    int i;
    void *heap_start;
    size_t size_of_the_block;

    heap_start = sbrk(0);
    write(1, "START\n", 6);
    for (i = 0; i < 10; i++)
    {
        p = malloc(1024 * (i + 1));
        *((int *)p) = i;
        printf("%p: [%i]\n", p, i);
    }
    p = heap_start;
    for (i = 0; i < 10; i++)
    {
        pmem(p, 0x10);
        size_of_the_block = *((size_t *)((char *)p + 8)) - 1;
        printf("%p: [%i] - size = %lu\n",
              (void *)((char *)p + 0x10),
              *((int *)((char *)p + 0x10)),
              size_of_the_block);
        p = (void *)((char *)p + size_of_the_block);
    }
    write(1, "END\n", 4);
    return (EXIT_SUCCESS);
}
```

```
julien@holberton:~/holberton/w/hackthevm3$ gcc -Wall -Wextra -pedantic -
julien@holberton:~/holberton/w/hackthevm3$ ./6
START
0x9e6010: [0]
0x9e6420: [1]
0x9e6c30: [2]
0x9e7840: [3]
0x9e8850: [4]
0x9e9c60: [5]
0x9eb470: [6]
0x9ed080: [7]
0x9ef090: [8]
0x9f14a0: [9]
00 00 00 00 00 00 00 00 11 04 00 00 00 00 00 00
0x9e6010: [0] - size = 1040
00 00 00 00 00 00 00 00 11 08 00 00 00 00 00 00
0x9e6420: [1] - size = 2064
00 00 00 00 00 00 00 00 11 0c 00 00 00 00 00 00
0x9e6c30: [2] - size = 3088
00 00 00 00 00 00 00 00 11 10 00 00 00 00 00 00
0x9e7840: [3] - size = 4112
00 00 00 00 00 00 00 00 11 14 00 00 00 00 00 00
0x9e8850: [4] - size = 5136
00 00 00 00 00 00 00 00 11 18 00 00 00 00 00 00
0x9e9c60: [5] - size = 6160
00 00 00 00 00 00 00 00 11 1c 00 00 00 00 00 00
0x9eb470: [6] - size = 7184
00 00 00 00 00 00 00 00 11 20 00 00 00 00 00 00
```

```
0x9ed080: [7] - size = 8208
00 00 00 00 00 00 00 00 11 24 00 00 00 00 00 00
0x9ef090: [8] - size = 9232
00 00 00 00 00 00 00 00 11 28 00 00 00 00 00 00
0x9f14a0: [9] - size = 10256
END
julien@holberton:~/holberton/w/hackthevm3$
```

One of our open questions from the previous chapter is now answered: `malloc` is using `0x10` additional bytes for each malloc'ed memory block to store the size of the block.


0x10 bytes
Total length of block (including this)
Memory to be used by the user
memory address returned by malloc to the user

This data will actually be used by `free` to save it to a list of available blocks for future calls to `malloc`.

But our study also raises a new question: what are the first 8 bytes of the 16 (`0x10` in hexadecimal) bytes used for? It seems to always be zero. Is it just padding?

RTFSC

At this stage, we probably want to check the source code of `malloc` to confirm what we just found (`malloc.c` from the glibc).

```
/*
      malloc_chunk details:

       (The following includes lightly edited explanations by Colin

       Chunks of memory are maintained using a `boundary tag' metho
       described in e.g., Knuth or Standish.  (See the paper by Pau
       Wilson ftp://ftp.cs.utexas.edu/pub/garbage/allocsrv.ps for a
       survey of such techniques.)  Sizes of free chunks are stored
       in the front of each chunk and at the end.  This makes
       consolidating fragmented chunks into bigger chunks very fast
       size fields also hold bits representing whether chunks are f
       in use.

       An allocated chunk looks like this:


       chunk-> +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
               |             Size of previous chunk, if unallocated
               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
               |             Size of chunk, in bytes
         mem-> +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
               |             User data starts here...
               .
               .             (malloc_usable_size() bytes)
               .
   nextchunk-> +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
               |             (size of chunk, but used for applicati
               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
               |             Size of next chunk, in bytes
               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-

       Where "chunk" is the front of the chunk for the purpose of m
       the malloc code, but "mem" is the pointer that is returned t
       user.  "Nextchunk" is the beginning of the next contiguous c
```

-> We were correct \o/. Right before the address returned by `malloc` to the user, we have two variables:

- Size of previous chunk, if unallocated: we never free'd any chunks so that is why it was always 0
- Size of chunk, in bytes

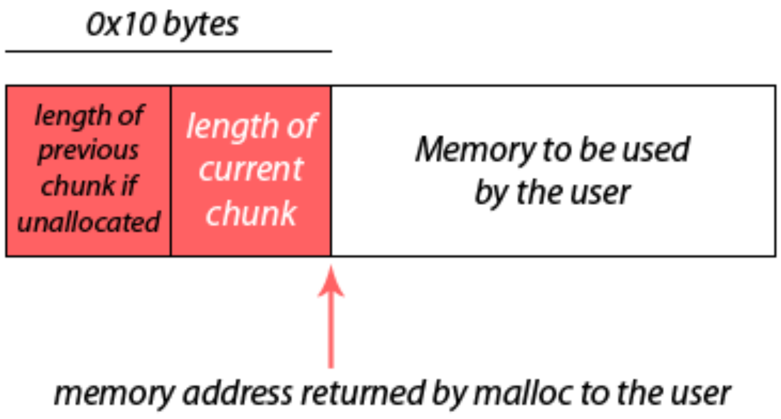
Let's free some chunks to confirm that the first 8 bytes are used the way the source code describes it (`7-main.c`):

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

/**
 * pmem - print mem
 * @p: memory address to start printing from
 * @bytes: number of bytes to print
 *
 * Return: nothing
 */
void pmem(void *p, unsigned int bytes)
{
    unsigned char *ptr;
    unsigned int i;

    ptr = (unsigned char *)p;
    for (i = 0; i < bytes; i++)
    {
        if (i != 0)
        {
            printf(" ");
        }
        printf("%02x", *(ptr + i));
    }
    printf("\n");
}

/**
 * main - confirm the source code
 *
 * Return: EXIT_FAILURE if something failed. Otherwise EXIT_SUCCESS
 */
int main(void)
{
    void *p;
    int i;
    size_t size_of_the_chunk;
    size_t size_of_the_previous_chunk;
    void *chunks[10];

    for (i = 0; i < 10; i++)
    {
        p = malloc(1024 * (i + 1));
        chunks[i] = (void *)((char *)p - 0x10);
        printf("%p\n", p);
    }
    free((char *)(chunks[3]) + 0x10);
    free((char *)(chunks[7]) + 0x10);
    for (i = 0; i < 10; i++)
    {
        p = chunks[i];
        printf("chunks[%d]: ", i);
        pmem(p, 0x10);
        size_of_the_chunk = *((size_t *)((char *)p + 8)) - 1;
        size_of_the_previous_chunk = *((size_t *)((char *)p));
        printf("chunks[%d]: %p, size = %li, prev = %li\n",
              i, p, size_of_the_chunk, size_of_the_previous_chunk);
    }
    return (EXIT_SUCCESS);
}
```

```
julien@holberton:~/holberton/w/hackthevm3$ gcc -Wall -Wextra -pedantic -
julien@holberton:~/holberton/w/hackthevm3$ ./7
0x1536010
0x1536420
0x1536c30
0x1537840
0x1538850
0x1539c60
0x153b470
0x153d080
0x153f090
0x15414a0
chunks[0]: 00 00 00 00 00 00 00 00 11 04 00 00 00 00 00 00
chunks[0]: 0x1536000, size = 1040, prev = 0
chunks[1]: 00 00 00 00 00 00 00 00 11 08 00 00 00 00 00 00
chunks[1]: 0x1536410, size = 2064, prev = 0
chunks[2]: 00 00 00 00 00 00 00 00 11 0c 00 00 00 00 00 00
chunks[2]: 0x1536c20, size = 3088, prev = 0
chunks[3]: 00 00 00 00 00 00 00 00 11 10 00 00 00 00 00 00
chunks[3]: 0x1537830, size = 4112, prev = 0
chunks[4]: 10 10 00 00 00 00 00 00 10 14 00 00 00 00 00 00
chunks[4]: 0x1538840, size = 5135, prev = 4112
chunks[5]: 00 00 00 00 00 00 00 00 11 18 00 00 00 00 00 00
chunks[5]: 0x1539c50, size = 6160, prev = 0
chunks[6]: 00 00 00 00 00 00 00 00 11 1c 00 00 00 00 00 00
```

```
chunks[6]: 0x153b460, size = 7184, prev = 0
chunks[7]: 00 00 00 00 00 00 00 00 11 20 00 00 00 00 00 00
chunks[7]: 0x153d070, size = 8208, prev = 0
chunks[8]: 10 20 00 00 00 00 00 00 10 24 00 00 00 00 00 00
chunks[8]: 0x153f080, size = 9231, prev = 8208
chunks[9]: 00 00 00 00 00 00 00 00 11 28 00 00 00 00 00 00
chunks[9]: 0x1541490, size = 10256, prev = 0
julien@holberton:~/holberton/w/hackthevm3$
```

As we can see from the above listing, when the previous chunk has been free'd, the malloc chunk's first 8 bytes contain the size of the previous unallocated chunk. So the correct representation of a malloc chunk is the following:


0x10 bytes
length of previous chunk if unallocated
length of current chunk
Memory to be used by the user
memory address returned by malloc to the user

Also, it seems that the first bit of the next 8 bytes (containing the size of the current chunk) serves as a flag to check if the previous chunk is used (`1`) or not (`0`). So the correct updated version of our program should be written this way (`8-main.c`):

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

/**
 * pmem - print mem
 * @p: memory address to start printing from
 * @bytes: number of bytes to print
 *
 * Return: nothing
 */
void pmem(void *p, unsigned int bytes)
{
    unsigned char *ptr;
    unsigned int i;

    ptr = (unsigned char *)p;
    for (i = 0; i < bytes; i++)
    {
        if (i != 0)
        {
            printf(" ");
        }
        printf("%02x", *(ptr + i));
    }
    printf("\n");
}

/**
 * main - updating with correct checks
 *
 * Return: EXIT_FAILURE if something failed. Otherwise EXIT_SUCCESS
 */
int main(void)
```

```
{
    void *p;
    int i;
    size_t size_of_the_chunk;
    size_t size_of_the_previous_chunk;
    void *chunks[10];
    char prev_used;

    for (i = 0; i < 10; i++)
    {
        p = malloc(1024 * (i + 1));
        chunks[i] = (void *)((char *)p - 0x10);
    }
    free((char *)(chunks[3]) + 0x10);
    free((char *)(chunks[7]) + 0x10);
    for (i = 0; i < 10; i++)
    {
        p = chunks[i];
        printf("chunks[%d]: ", i);
        pmem(p, 0x10);
        size_of_the_chunk = *((size_t *)((char *)p + 8));
        prev_used = size_of_the_chunk & 1;
        size_of_the_chunk -= prev_used;
        size_of_the_previous_chunk = *((size_t *)((char *)p));
        printf("chunks[%d]: %p, size = %li, prev (%s) = %li\n",
              i, p, size_of_the_chunk,
              (prev_used? "allocated": "unallocated"), size_of_the_previ
    }
    return (EXIT_SUCCESS);
}
```

```
julien@holberton:~/holberton/w/hackthevm3$ gcc -Wall -Wextra -pedantic -
julien@holberton:~/holberton/w/hackthevm3$ ./8
chunks[0]: 00 00 00 00 00 00 00 00 11 04 00 00 00 00 00 00
```

```
chunks[0]: 0x1031000, size = 1040, prev (allocated) = 0
chunks[1]: 00 00 00 00 00 00 00 00 11 08 00 00 00 00 00 00
chunks[1]: 0x1031410, size = 2064, prev (allocated) = 0
chunks[2]: 00 00 00 00 00 00 00 00 11 0c 00 00 00 00 00 00
chunks[2]: 0x1031c20, size = 3088, prev (allocated) = 0
chunks[3]: 00 00 00 00 00 00 00 00 11 10 00 00 00 00 00 00
chunks[3]: 0x1032830, size = 4112, prev (allocated) = 0
chunks[4]: 10 10 00 00 00 00 00 00 10 14 00 00 00 00 00 00
chunks[4]: 0x1033840, size = 5136, prev (unallocated) = 4112
chunks[5]: 00 00 00 00 00 00 00 00 11 18 00 00 00 00 00 00
chunks[5]: 0x1034c50, size = 6160, prev (allocated) = 0
chunks[6]: 00 00 00 00 00 00 00 00 11 1c 00 00 00 00 00 00
chunks[6]: 0x1036460, size = 7184, prev (allocated) = 0
chunks[7]: 00 00 00 00 00 00 00 00 11 20 00 00 00 00 00 00
chunks[7]: 0x1038070, size = 8208, prev (allocated) = 0
chunks[8]: 10 20 00 00 00 00 00 00 10 24 00 00 00 00 00 00
chunks[8]: 0x103a080, size = 9232, prev (unallocated) = 8208
chunks[9]: 00 00 00 00 00 00 00 00 11 28 00 00 00 00 00 00
chunks[9]: 0x103c490, size = 10256, prev (allocated) = 0
julien@holberton:~/holberton/w/hackthevm3$
```

Is the heap actually growing upwards?

The last question left unanswered is: “Is the heap actually growing upwards?”. From the `brk` man page, it seems so:

```
DESCRIPTION
       brk() and sbrk() change the location of the program break, which
       process's  data  segment  (i.e., the program break is the first l
       the uninitialized data segment).  Increasing the program break ha
       ing memory to the process; decreasing the break deallocates memor
```

Let's check! (`9-main.c`)

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

/**
 * main - moving the program break
 *
 * Return: EXIT_FAILURE if something failed. Otherwise EXIT_SUCCESS
 */
int main(void)
{
    int i;

    write(1, "START\n", 6);
    malloc(1);
    getchar();
    write(1, "LOOP\n", 5);
    for (i = 0; i < 0x25000 / 1024; i++)
    {
        malloc(1024);
    }
    write(1, "END\n", 4);
    getchar();
    return (EXIT_SUCCESS);
}
```

Now let's confirm this assumption with strace:

```
julien@holberton:~/holberton/w/hackthevm3$ strace ./9
execve("./9", ["./9"], [/* 61 vars */]) = 0
...
```

```
write(1, "START\n", 6START
)                  = 6
brk(0)                                    = 0x1fd8000
brk(0x1ff9000)                            = 0x1ff9000
...
write(1, "LOOP\n", 5LOOP
)                   = 5
brk(0x201a000)                            = 0x201a000
write(1, "END\n", 4END
)                    = 4
...
julien@holberton:~/holberton/w/hackthevm3$
```

clearly, `malloc` made only two calls to `brk` to increase the allocated space on the heap. And the second call is using a higher memory address argument (`0x201a000` > `0x1ff9000`). The second syscall was triggered when the space on the heap was too small to host all the malloc calls.

Let's double check with `/proc`.

```
julien@holberton:~/holberton/w/hackthevm3$ gcc -Wall -Wextra -pedantic -
julien@holberton:~/holberton/w/hackthevm3$ ./9
START



julien@holberton:/proc/7855$ ps aux | grep \ \./9$
julien     7972  0.0  0.0   4332   684 pts/9    S+   19:08   0:00 ./9
julien@holberton:/proc/7855$ cd /proc/7972
julien@holberton:/proc/7972$ cat maps
...
00901000-00922000 rw-p 00000000 00:00 0
...
julien@holberton:/proc/7972$
```

-> `00901000-00922000 rw-p 00000000 00:00 0 [heap]`
Let’s hit Enter and look at the [heap] again:

```
LOOP
END
```

```
julien@holberton:/proc/7972$ cat maps
...
00901000-00943000 rw-p 00000000 00:00 0
...
julien@holberton:/proc/7972$
```

-> `00901000-00943000 rw-p 00000000 00:00 0 [heap]`
The beginning of the heap is still the same, but the size has increased upwards from `00922000` to `00943000`.

The Address Space Layout Randomisation (ASLR)

You may have noticed something “strange” in the `/proc/pid/maps` listing above, that we want to study:

The program break is the address of the first location beyond the current end of the data region – so the address of the first location beyond the executable in the virtual memory. As a consequence, the heap should start right after the end of the executable in memory. As you can see in all above listing, it is NOT the case. The only thing that is true is that the heap is always the next memory region after the executable, which makes sense since the heap is actually part of the data segment of the executable itself. Also, if we look even closer, the memory gap size between the executable and the heap is never the same:

Format of the following lines: [PID of the above `maps` listings]: address of the beginning of the [heap] – address of the end of the executable = memory gap size

- [3718]: 01195000 – 00602000 = b93000
- [3834]: 024d6000 – 00602000 = 1ed4000
- [4014]: 00e70000 – 00602000 = 86e000
- [4172]: 01314000 – 00602000 = d12000
- [7972]: 00901000 – 00602000 = 2ff000

It seems that this gap size is random, and indeed, it is. If we look at the ELF binary loader source code (`fs/binfmt_elf.c`) we can find this:

```
        if ((current->flags & PF_RANDOMIZE) && (randomize_va_space > 1))
                current->mm->brk = current->mm->start_brk =
                        arch_randomize_brk(current->mm);
#ifdef compat_brk_randomized
                current->brk_randomized = 1;
#endif
        }
```

where `current->mm->brk` is the address of the program break. The `arch_randomize_brk` function can be found in the `arch/x86/kernel/process.c` file:

```
unsigned long arch_randomize_brk(struct mm_struct *mm)
{
        unsigned long range_end = mm->brk + 0x02000000;
        return randomize_range(mm->brk, range_end, 0) ? : mm->brk;
}
```

The `randomize_range` returns a start address such that:

```
    [...... <range> .....]
  start                  end
```

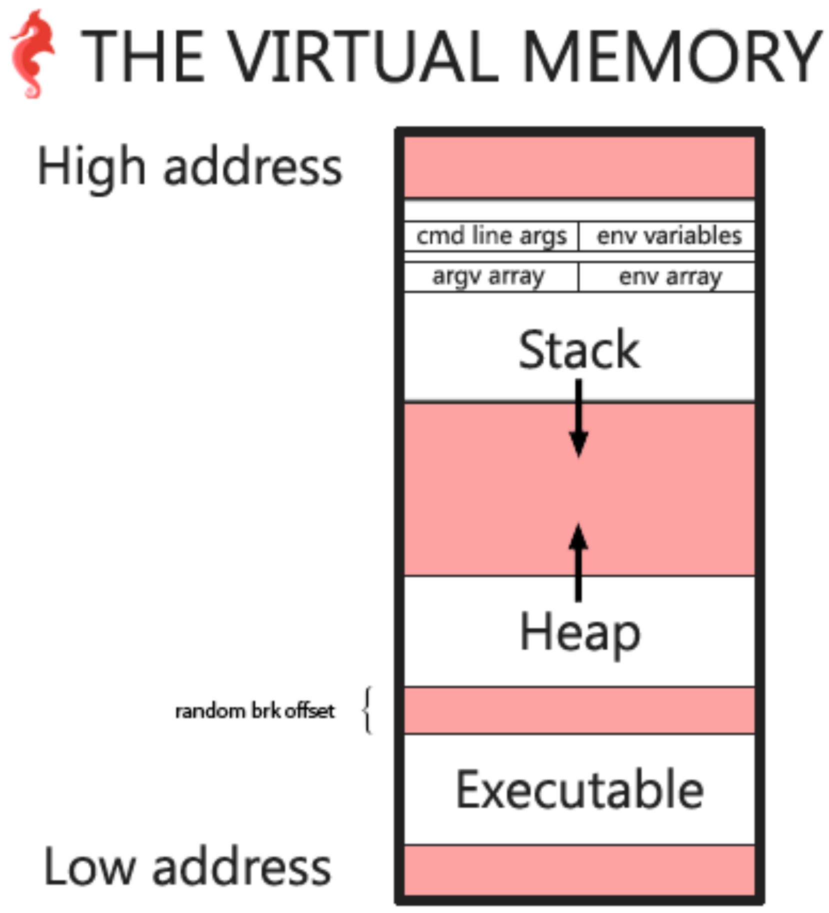
Source code of the `randomize_range` function (`drivers/char/random.c`):

```
/*
 * randomize_range() returns a start address such that
 *
 *    [...... <range> .....]
 *  start                  end
 *
 * a <range> with size "len" starting at the return value is inside in t
 * area defined by [start, end], but is otherwise randomized.
 */
unsigned long
randomize_range(unsigned long start, unsigned long end, unsigned long le
{
        unsigned long range = end - len - start;

        if (end <= start + len)
                return 0;
        return PAGE_ALIGN(get_random_int() % range + start);
}
```

As a result, the offset between the data section of the executable and the program break initial position when the process runs can have a size of anywhere between `0` and `0x02000000`. This randomization is known as Address Space Layout Randomisation (ASLR). ASLR is a computer security technique involved in preventing exploitation of memory corruption vulnerabilities. In order to prevent an attacker from jumping to, for example, a particular exploited function in memory, ASLR randomly arranges the address space positions of key data areas of a process, including the positions of the heap and the stack.

The updated VM diagram

With all the above in mind, we can now update our VM diagram:



`malloc(0)`

Did you ever wonder what was happening when we call `malloc` with a size of `0`? Let's check! (`10-main.c`)

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

/**
 * pmem - print mem
 * @p: memory address to start printing from
 * @bytes: number of bytes to print
 *
 * Return: nothing
 */
void pmem(void *p, unsigned int bytes)
{
    unsigned char *ptr;
    unsigned int i;

    ptr = (unsigned char *)p;
    for (i = 0; i < bytes; i++)
    {
        if (i != 0)
        {
            printf(" ");
        }
        printf("%02x", *(ptr + i));
    }
    printf("\n");
}

/**
 * main - moving the program break
 *
 * Return: EXIT_FAILURE if something failed. Otherwise EXIT_SUCCESS
 */
int main(void)
{
    void *p;
    size_t size_of_the_chunk;
    char prev_used;

    p = malloc(0);
    printf("%p\n", p);
    pmem((char *)p - 0x10, 0x10);
    size_of_the_chunk = *((size_t *)((char *)p - 8));
    prev_used = size_of_the_chunk & 1;
    size_of_the_chunk -= prev_used;
    printf("chunk size = %li bytes\n", size_of_the_chunk);
    return (EXIT_SUCCESS);
}
```

```
julien@holberton:~/holberton/w/hackthevm3$ gcc -Wall -Wextra -pedantic -
julien@holberton:~/holberton/w/hackthevm3$ ./10
0xd08010
00 00 00 00 00 00 00 00 21 00 00 00 00 00 00 00
chunk size = 32 bytes
julien@holberton:~/holberton/w/hackthevm3$
```

-> `malloc(0)` is actually using 32 bytes, including the first `0x10` bytes.

Again, note that this will not always be the case. From the man page (`man malloc`):

```
NULL may also be returned by a successful call to malloc() with a size o
```

Outro

We have learned a couple of things about malloc and the heap. But there is actually more than `brk` and `sbrk`. You can try malloc'ing a big chunk of memory, `strace` it, and look at `/proc` to learn more before we cover it in a next chapter ?

Also, studying how `free` works in coordination with `malloc` is something we haven't covered yet. If you want to look at it, you will find part of the answer to why the minimum chunk size is `32` (when we ask `malloc` for `0` bytes) vs `16` (`0x10` in hexadecimal) or `0`.

As usual, to be continued! Let me know if you have something you would like me to cover in the next chapter.

Questions? Feedback?

If you have questions or feedback don't hesitate to ping us on Twitter at @holbertonschool or @julienbarbier42.
Haters, please send your comments to `/dev/null`.

Happy Hacking!

Thank you for reading!

As always, no-one is perfect (except Chuck of course), so don't hesitate to contribute or send me your comments if you find anything I missed.

Files

This repo contains the source code (`naive_malloc.c`, `version.c` & "X-main.c` files) for programs created in this tutorial.

Read more about the virtual memory

Follow @holbertonschool or @julienbarbier42 on Twitter to get the next chapters!

- Chapter 0: Hack The Virtual Memory: C strings & /proc
- Chapter 1: Hack The Virtual Memory: Python bytes
- Chapter 2: Hack The Virtual Memory: Drawing the VM diagram
- Chapter 3: Hack the Virtual Memory: malloc, the heap & the program break

Many thanks to Tim, Anne and Ian for proof-reading! ?