

# All of Bare Metal!

Processor and memory architecture

Peripherals: GPIO, timers, UART

Assembly language and machine code

From C to assembly language

Function calls and stack frames

Serial communication and strings

Modules and libraries: Building and linking

Memory management: Memory map & heap

# **Memory Management**

**Sections and memory map**

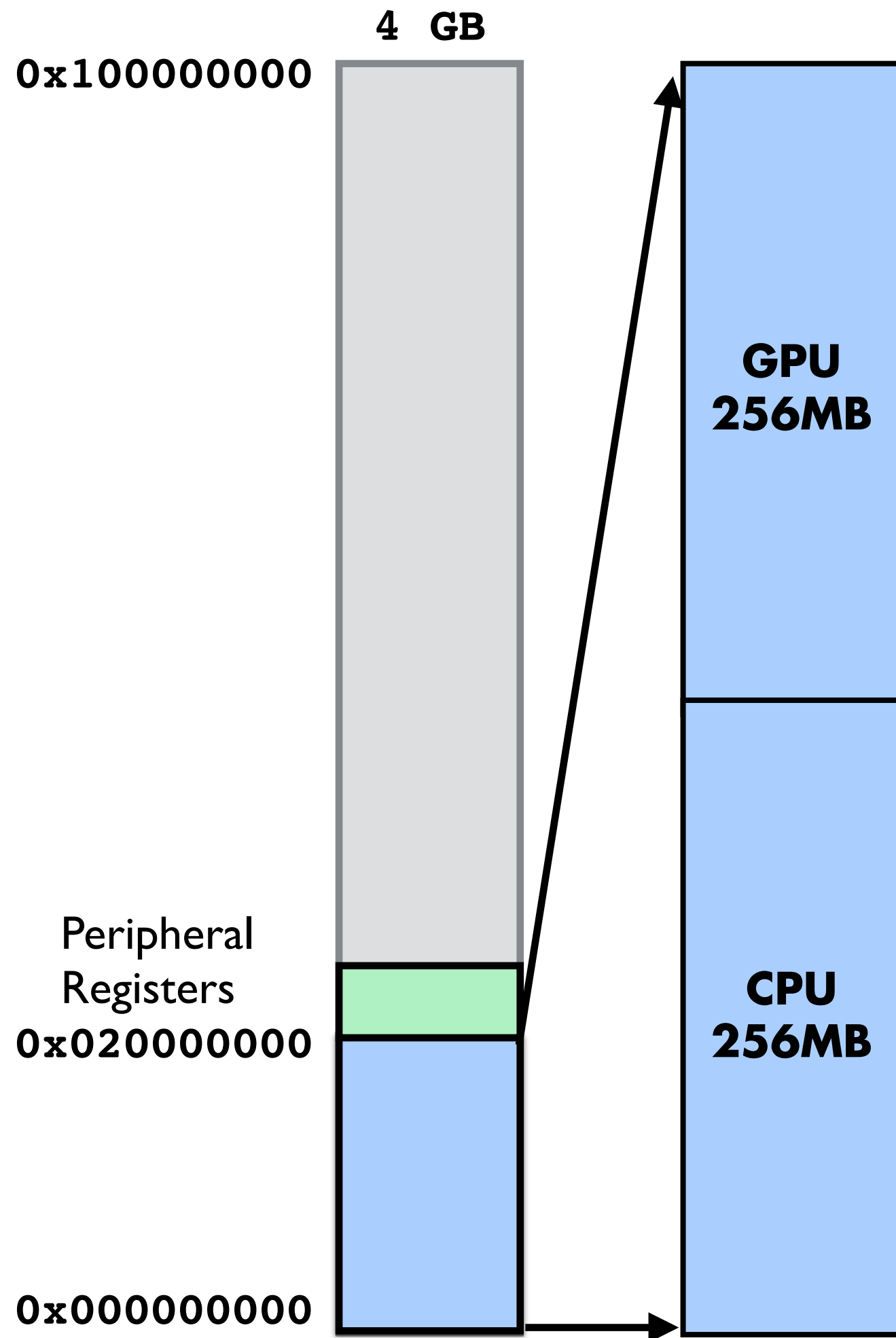
**Initializing memory**

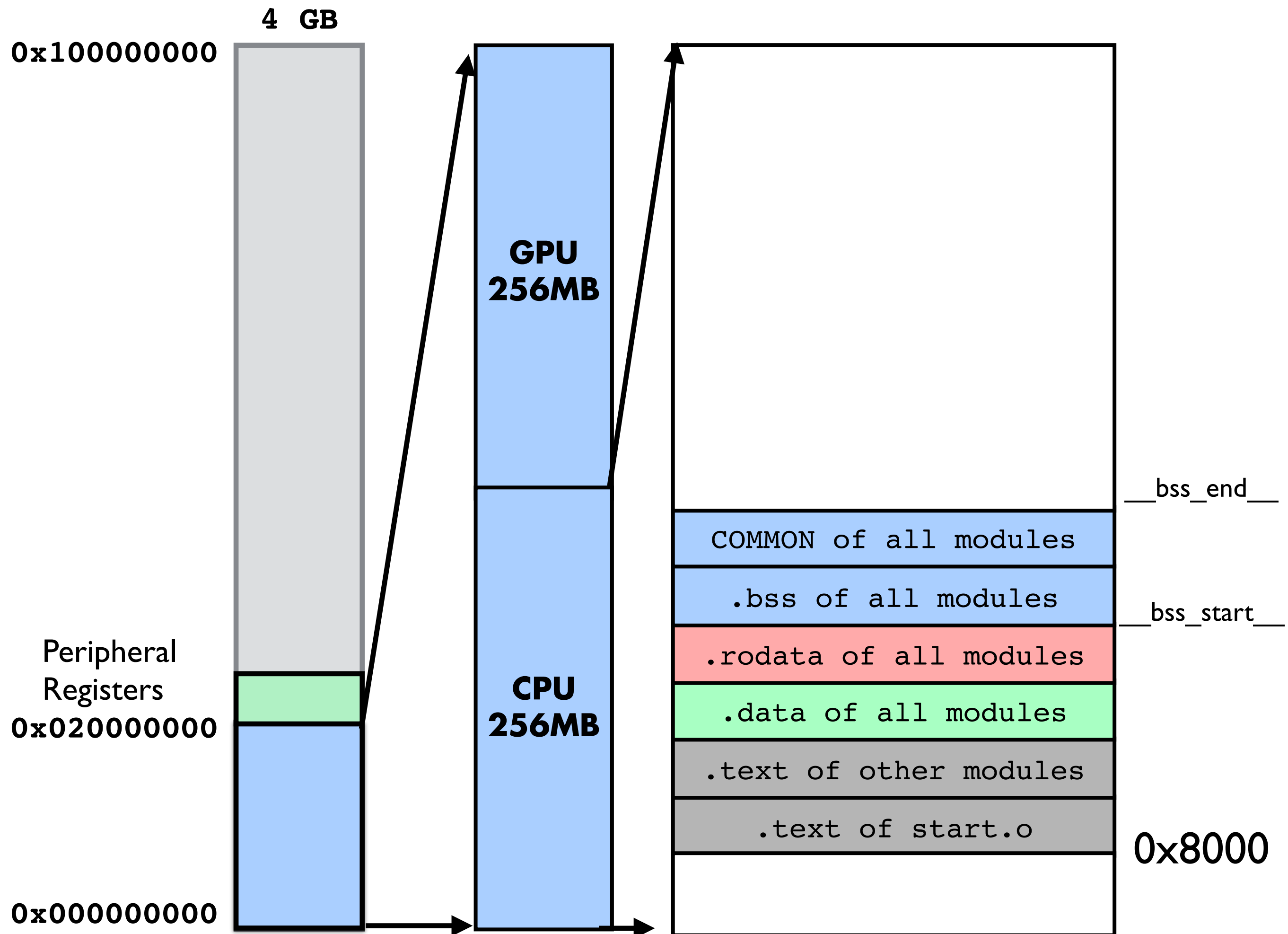
**Heap memory allocation**

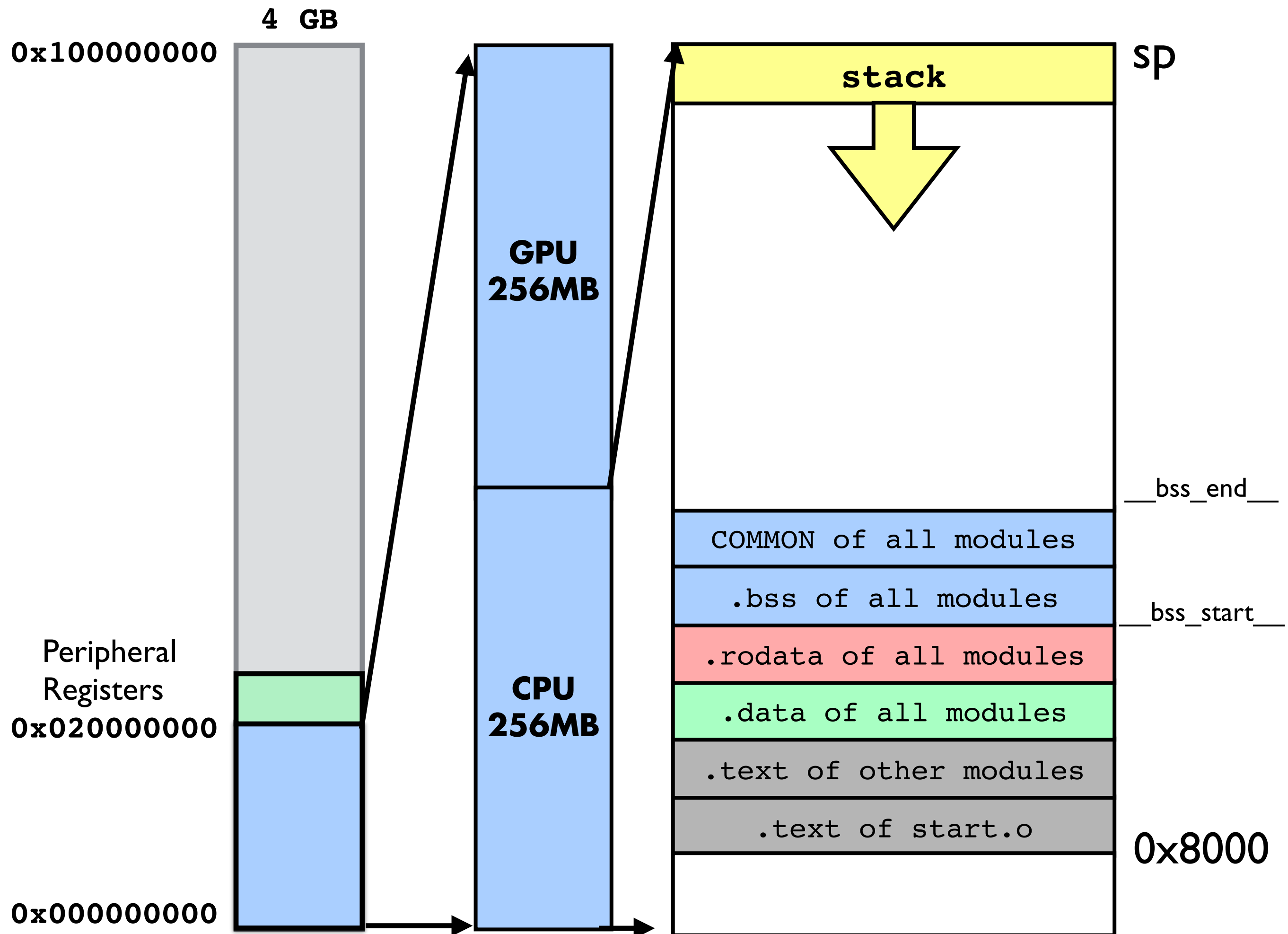
# **Memory Management**

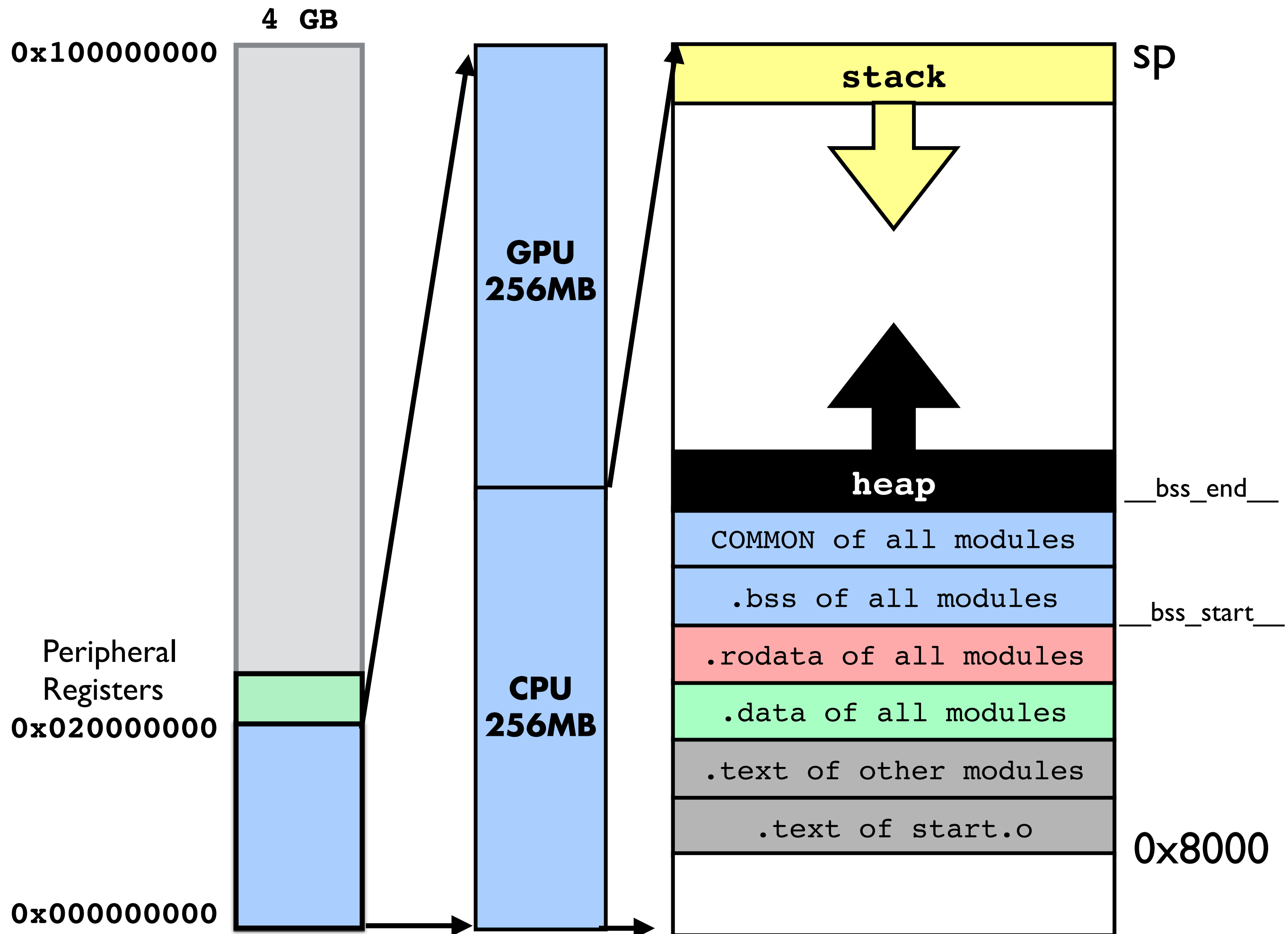
## **Heap memory allocation**











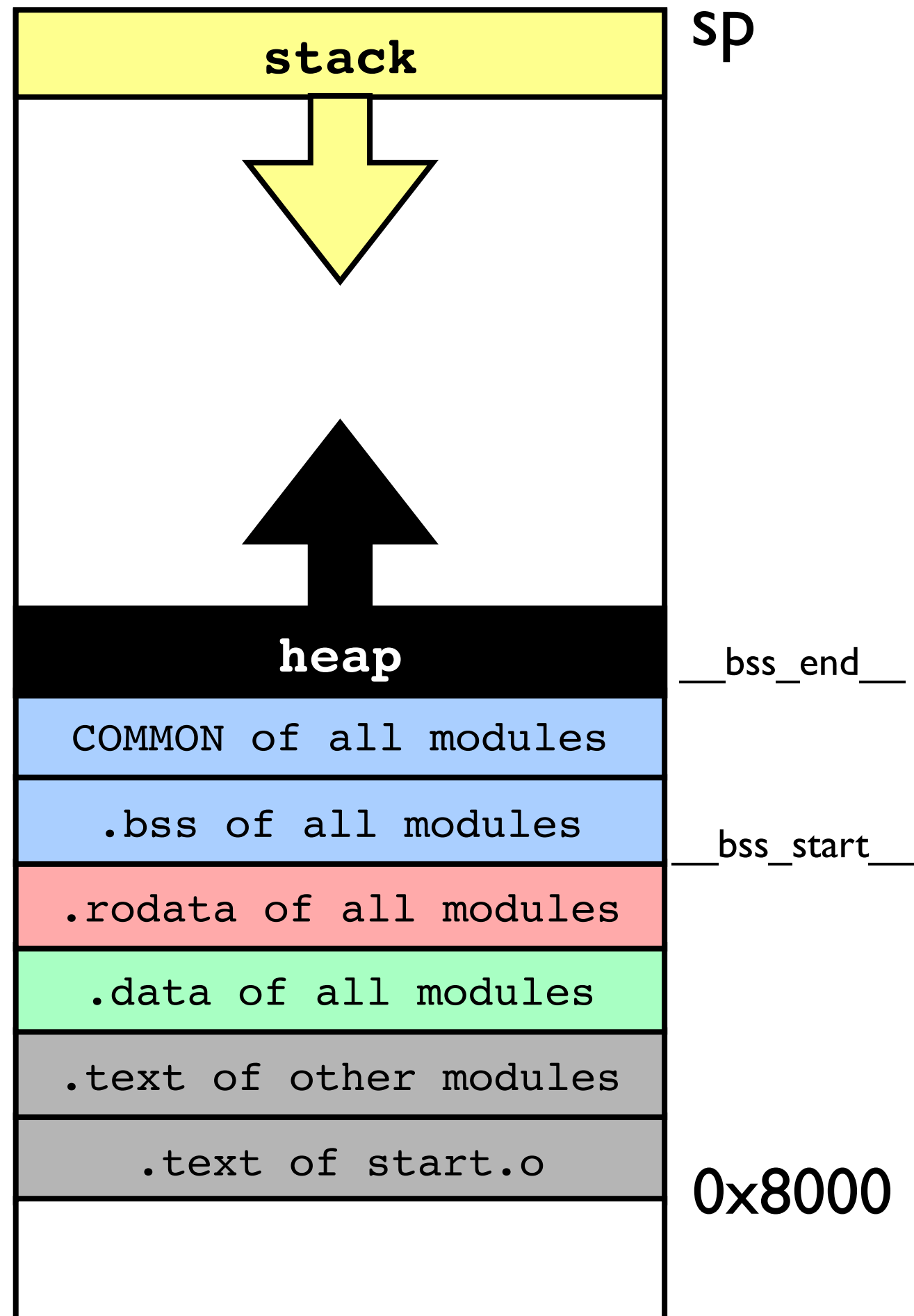


```
void f() {  
    int x;  
}
```

```
char* ptr = malloc(len);
```

global variables

code



# Heap Memory Allocation

# Memory Allocation

Compile-time vs. run-time memory allocation

Why run-time memory allocation?

1. Don't know the size of an array when compiling
2. Dynamic data structures such as strings, lists and trees

For example, you cannot return an array from a function, as it is on the stack...we must put it on the heap.

# Why do we have both stack and heap allocation?

As we have discussed before, stack memory is limited and serves as a scratch-pad for functions, and it is continually being re-used by your functions. Stack memory isn't persistent, but because it is already allocated to your program, it is fast.

Heap memory takes more time to set up (you have to go through the heap allocator), but it is unlimited (for all intents and purposes), and persistent for the rest of your program.

# malloc, free, and realloc

`void *malloc(size_t size)`

Return pointer to memory block  $\geq$  requested size  
(failure returns `NULL` and sets `errno`)

`void free(void *p)`

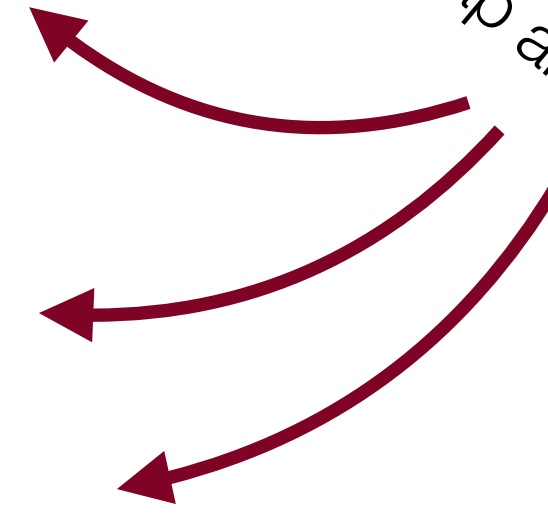
Recycle memory block  
`p` must be from previous `malloc`/`realloc` call

~~`void *realloc(void *p, size_t size)`~~

~~Changes size of block `p`, returns pointer to block (possibly same)  
Contents of new block unchanged up to min of old and new size  
If the new pointer isn't the same as the old pointer, the old block will  
have been free'd~~

~~realloc removed from spec (but you might want to know about it)~~

This is what your heap allocator is going to do!



# **Bump Memory Allocator**

**malloc.c**

# Allocator Requirements

The heap allocator must be able to service arbitrary sequence of `malloc()` and `free()` requests

`malloc` must return a pointer to contiguous memory that is equal to or greater than the requested size, or `NULL` if it can't satisfy the request.

The *payload* contents (this is the area that the pointer points to) are unspecified — they can be 0s or garbage.

If the client introduces an error, then the behavior is undefined

- If the client tries to free non-allocated memory, or tries to use free'd memory.

The heap allocator has some constraints:

It can't control the number, size, or lifetime of the allocated blocks.

It must respond immediately to each `malloc` request

I.e., it can't reorder or buffer `malloc` requests — the first request must be handled first.

It *can* defer, ignore, or reorder requests to `free`

# Allocator Requirements (continued)

Other heap allocator constraints:

The allocator must align blocks so they satisfy all alignment requirements

i.e., 8 byte alignment for `malloc` 32-bit ARM

The allocated payload must be maintained *as-is*

The allocator *cannot* move allocated blocks, such as to compact/coalesce free.

- Why not?

**All of the programs with allocated memory would have corrupted pointers!**

- The allocator *can* manipulate and modify free memory



# Allocator Goals

The allocator should first and foremost attempt to service `malloc` and `free` requests *quickly*.

Ideally, the requests should be handled in *constant time* and should not degrade to linear behavior (we will see that some implementations can do this, some cannot)

The allocator must try for a *tight space utilization*.

Remember, the allocator has a fixed block of memory to dole out smaller parts — it must try to allocate efficiently

The allocator should try to minimize *fragmentation*.

It should try to group allocated blocks together.

There should be a small overhead relative to the payload (we will see what this mean soon!)

# Allocator Goals (continued)

It is desirable for a heap allocator to have the following properties:

## Good locality

- Blocks are allocated close in time are located close in space
- "Similar" blocks are allocated close in space

## Robust

- Client errors should be recognized
  - What is required to detect and report them?

## Ease of implementation and maintenance

- Having `*(void **)` all over the place makes for hard-to-maintain code. Instead, use structs, and typedef when appropriate.
- The code is necessarily complex, but the more efforts you put into writing clean code, the more you will be rewarded by easier-to-maintain code.

# Tracing the Heap (possible implementation)

```
void *a, *b, *c, *d, *e;
```

```
a = malloc(16);
```

```
b = malloc(8);
```

```
c = malloc(24);
```

```
d = malloc(16);
```

```
free(a);
```

```
free(c);
```

```
e = malloc(8);
```

```
b = realloc(b, 24);
```

```
e = realloc(e, 24);
```

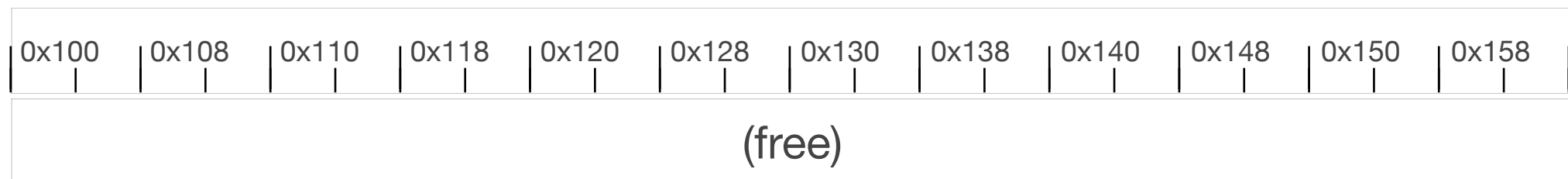
```
void *f = malloc(24);
```

← All allocated on the stack:

	Address	Value
e	0xfffffe820	<b>0x0</b>
d	0xfffffe818	<b>0xabcd</b> e
c	0xfffffe810	<b>0xf0123</b>
b	0xfffffe808	<b>0x0</b>
a	0xfffffe800	<b>0xbeef</b>

heap

← 96 bytes →



# Tracing the Heap (possible implementation)

```
void *a, *b, *c, *d, *e;
```

```
a = malloc(16);
```

```
b = malloc(8);
```

```
c = malloc(24);
```

```
d = malloc(16);
```

```
free(a);
```

```
free(c);
```

```
e = malloc(8);
```

```
b = realloc(b, 24);
```

```
e = realloc(e, 24);
```

```
void *f = malloc(24);
```

← All allocated on the stack:

	Address	Value
e	0xfffffe820	<b>0x0</b>
d	0xfffffe818	<b>0xabcd</b> e
c	0xfffffe810	<b>0xf0123</b>
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a	0xfffffe800	<b>0xbeef</b>

heap

96 bytes



Each  
section  
represents  
4 bytes

# Tracing the Heap (possible implementation)

```
void *a, *b, *c, *d, *e;
```

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a = malloc(16);
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b = malloc(8);
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c = malloc(24);
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```
d = malloc(16);
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b = realloc(b, 24);
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e = realloc(e, 24);
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```
void *f = malloc(24);
```

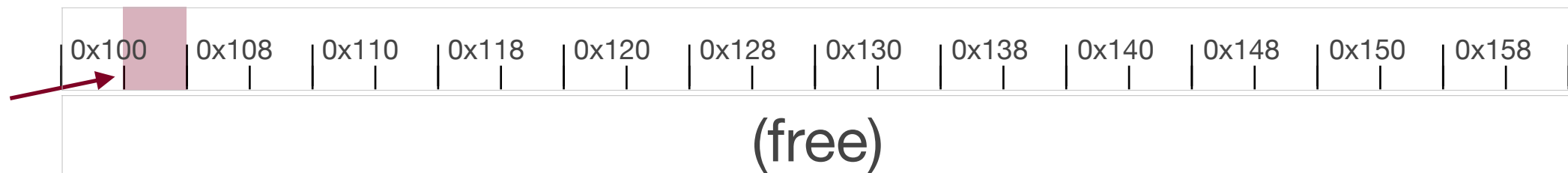
All allocated on the stack:

	Address	Value
e	0xfffffe820	<b>0x0</b>
d	0xfffffe818	<b>0xabcd</b> <b>e</b>
c	0xfffffe810	<b>0xf0123</b>
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b = realloc(b, 24);
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```

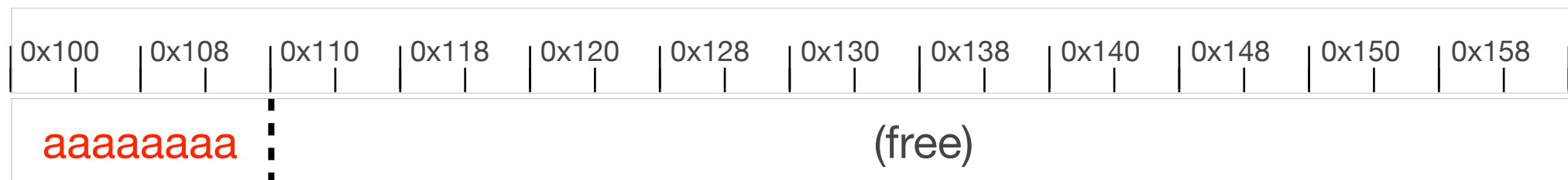
```
void *f = malloc(24);
```

← All allocated on the stack:

	Address	Value
e	0xfffffe820	<b>0x0</b>
d	0xfffffe818	<b>0xabcde</b>
c	0xfffffe810	<b>0xf0123</b>
b	0xfffffe808	<b>0x0</b>
a	0xfffffe800	<b>0x100</b>

heap

96 bytes



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```
void *a, *b, *c, *d, *e;
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a = malloc(16);
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d = malloc(16);
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free(a);
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e = malloc(8);
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```
b = realloc(b, 24);
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e = realloc(e, 24);
```

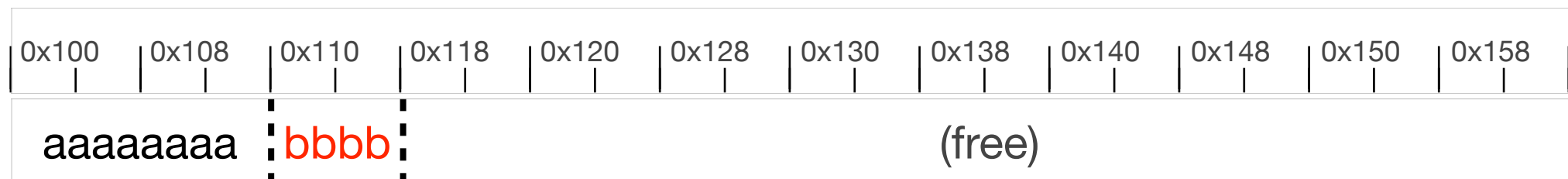
```
void *f = malloc(24);
```

← All allocated on the stack:

	Address	Value
e	0xfffffe820	<b>0x0</b>
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heap

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```
d = malloc(16);
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```
free(a);
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```
free(c);
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```
b = realloc(b, 24);
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e = realloc(e, 24);
```

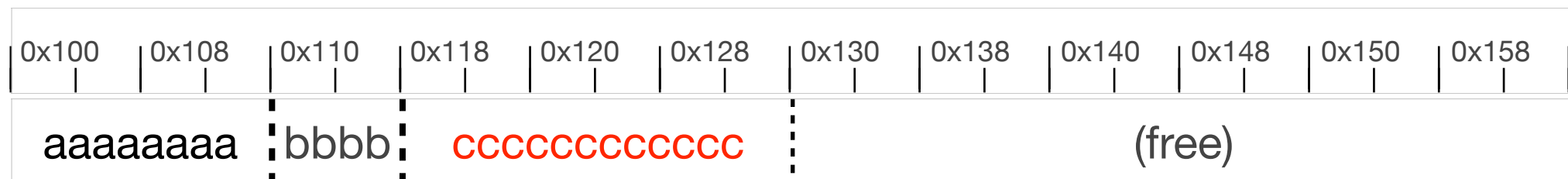
```
void *f = malloc(24);
```

← All allocated on the stack:

	Address	Value
e	0xfffffe820	<b>0x0</b>
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c	0xfffffe810	<b>0x118</b>
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heap

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d = malloc(16);
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free(a);
```

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free(c);
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e = malloc(8);
```

```
b = realloc(b, 24);
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```
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```

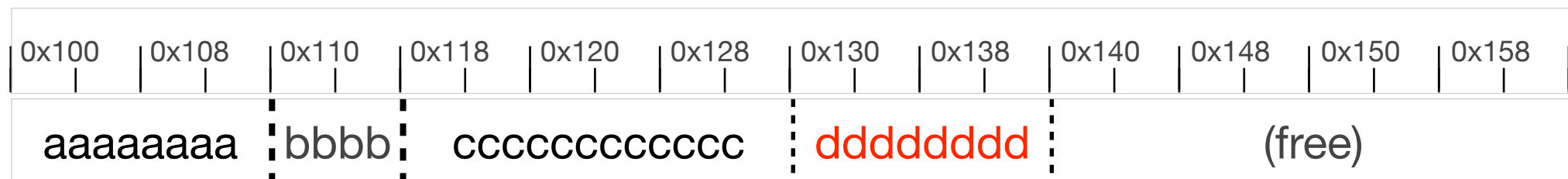
```
void *f = malloc(24);
```

← All allocated on the stack:

	Address	Value
e	0xfffffe820	<b>0x0</b>
d	0xfffffe818	<b>0x130</b>
c	0xfffffe810	<b>0x118</b>
b	0xfffffe808	<b>0x110</b>
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```
d = malloc(16);
```

```
free(a);
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free(c);
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b = realloc(b, 24);
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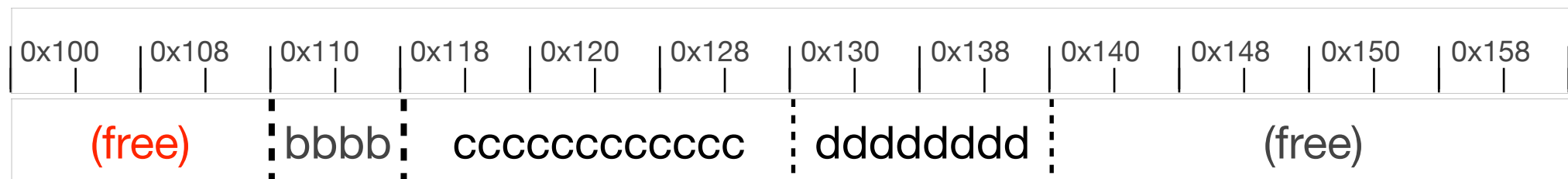
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```

```
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free(c);
```

```
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```
b = realloc(b, 24);
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```

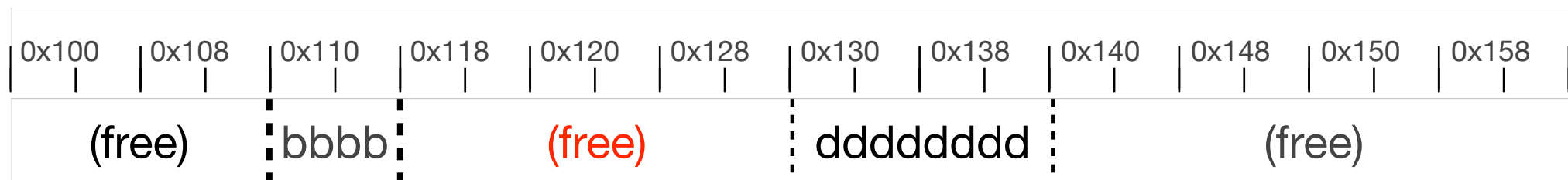
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heap

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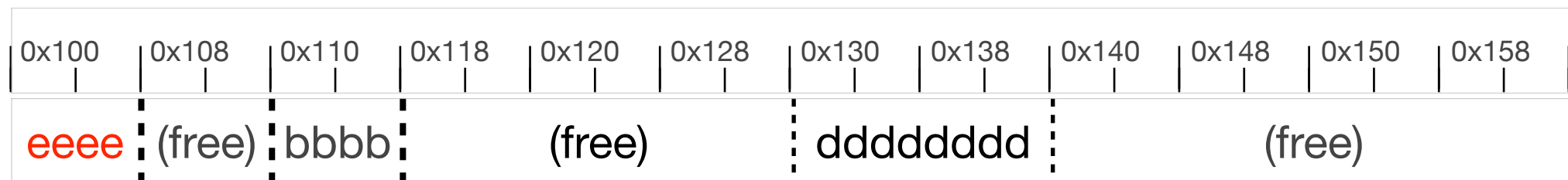
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void *f = malloc(24);
```

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	Address	Value
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heap

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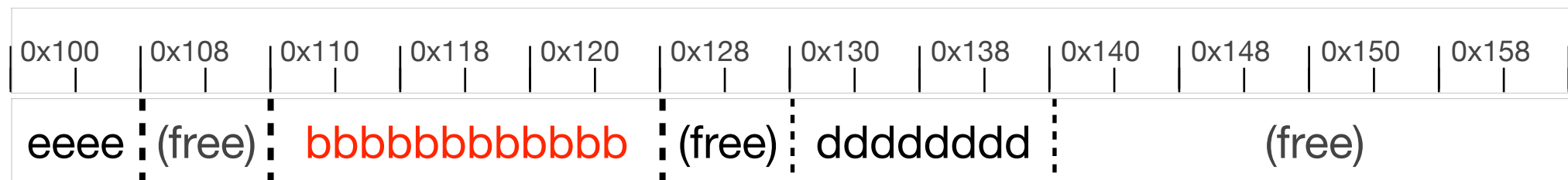
```
void *f = malloc(24);
```

← All allocated on the stack:

	Address	Value
e	0xffffe820	<b>0x100</b>
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heap

96 bytes



# Tracing the Heap (possible implementation)

```
void *a, *b, *c, *d, *e;
```

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a = malloc(16);
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```
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```

```
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```
free(c);
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```

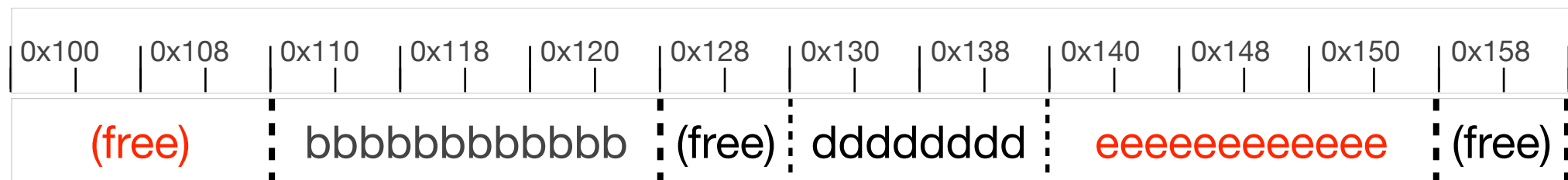
```
void *f = malloc(24);
```

← All allocated on the stack:

	Address	Value
e	0xffffe820	<b>0x140</b>
d	0xffffe818	<b>0x130</b>
c	0xffffe810	<b>0x118</b>
b	0xffffe808	<b>0x110</b>
a	0xffffe800	<b>0x100</b>

heap

96 bytes



# Tracing the Heap (possible implementation)

```
void *a, *b, *c, *d, *e;
a = malloc(16);
b = malloc(8);
c = malloc(24);
d = malloc(16);
free(a);
free(c);
e = malloc(8);
b = realloc(b, 24);
e = realloc(e, 24);
void *f = malloc(24);
```

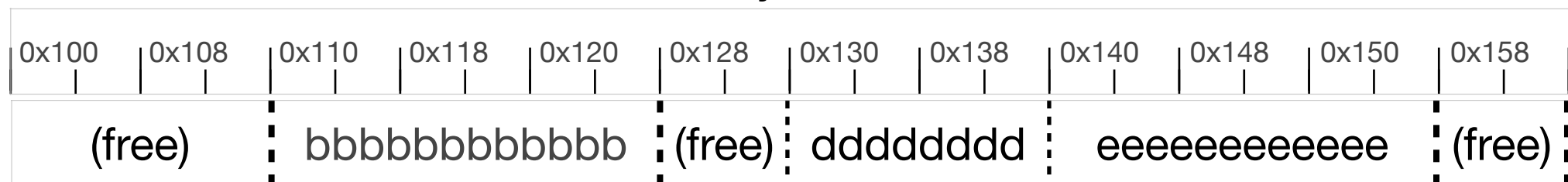
Returns NULL

← All allocated on the stack:

	Address	Value
e	0xfffffe820	<b>0x140</b>
d	0xfffffe818	<b>0x130</b>
c	0xfffffe810	<b>0x118</b>
b	0xfffffe808	<b>0x110</b>
a	0xfffffe800	<b>0x100</b>
f	0xfffffe7f0	<b>0x0</b>

heap

96 bytes



## API

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

```
void free( void *pointer );
```

```
// Note that void* is a generic pointer
```

```
// Note that size_t is for sizes
```



# What is this `void *` business, anyway?

This is an area that I like to call "the wild west" of pointers. We are going to discuss the `void *` pointer, which is a pointer that has an unspecified pointee type. In other words, it is a pointer, but does not have a width associated with the underlying data based on some type.

You can pass `void *` pointers to and from functions, and you can assign them values with the `&` operator. E.g.,

```
int arr[] = {2,4,6,8,10};  
void *arr_p1 = arr;  
int *arr_p2 = arr_p1;
```

# Generic Pointers

You **cannot** dereference a `void *` pointer, nor can you use pointer arithmetic with it. E.g.,

```
int arr[] = {2,4,6,8,10};  
  
void *arr_p1 = arr;  
  
arr_p1++; // gives compiler warning about incrementing void *  
  
printf("%d\n", arr_p1[0]); // warns, but also causes compiler error  
                           // because you cannot dereference void *
```

# Generic Pointers

Why would we ever want a type where we *lose* information?

Sometimes, a function needs to be *generic* so it can deal with any type. We have seen this with `realloc` and `free`:

```
void free(void *ptr);
```

It would not be very nice if we had to have a different `free` function for every type of pointer!


# Generic Pointers

What if you wanted to write a program to swap the first and last element in an `int` array? You might write something like this:

```
void swap_ends_int(int *arr, size_t nelems)
{
    int tmp = *arr;
    *arr = *(arr + nelems - 1);
    *(arr + nelems - 1) = tmp;
}

void main(void)
{
    int i_array[] = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) /
                      sizeof(i_array[0]);
    swap_ends_int(i_array, i_nelems);
}
```

Address	Value
0x7fffe4	55
0x7fffe0	18
0x7fffdc	-12
0x7fffd8	23



Great! But what if you also wanted to swap the first and last element in a `short` array?

# Generic Pointers

Great! But what if you also wanted to swap the first and last element in a `short` array?

```
void swap_ends_int(int *arr, size_t nelems)
{
    int tmp = *arr;
    *arr = *(arr + nelems - 1);
    *(arr + nelems - 1) = tmp;
}

void swap_ends_short(short *arr, size_t nelems)
{
    short tmp = *arr;
    *arr = *(arr + nelems - 1);
    *(arr + nelems - 1) = tmp;
}

void main(void)
{
    int i_array[] = {10,40,80,20,-30,50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);
    swap_ends_int(i_array,i_nelems);

    short s_array[] = {100, 400, 800, 200, -300, 500};
    size_t s_nelems = sizeof(s_array) / sizeof(s_array[0]);
    swap_ends_short(s_array, s_nelems);
}
```

Bummer. We have to write a function that is virtually identical, with the only difference being that we handle the type of the array elements differently.

In other words, the type system is getting in the way! We would like to write a single `swap_ends` function that handles *any* array, but the type system foils us.

# Generic Pointers

`void *` to the rescue! In this case, the pointer type gives us information about the size of the elements being pointed to (either 4-bytes for `int`, or 8-bytes for `long`, in the previous example).

By using `void *` and *explicitly including the width of the type*, we can write a function that can take any type as the elements to swap:

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

We can copy bytes using **`memmove`**!

We must pass the width of the elements in the array because the `void *` pointer doesn't carry that information.

# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

Let's look at this function in more detail. First, we have a `void *` pointer passed in as the array.

# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

Next, we create a **char** array to hold the bytes. Remember: **char** is the only 1-byte type we have, and using a **char** array is how we can create

an array that is exactly the number of bytes we want. We will use this almost every time we use **void \*** pointers, so get used to it!

(we could also use **malloc** if we wanted to, but it isn't really necessary here, as the array works just fine. Regardless, we would still use a **char \*** pointer)



# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

We copy the bytes with `memmove`.

# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

This part takes some time to get used to!

Notice that we need a pointer to the element that we are trying to copy into. We already said that we cannot do pointer arithmetic on a `void *` pointer, so we first cast the pointer to

`char *`, and then manually calculate the pointer arithmetic to get us to the correct location. In this case, because we want the last element in the array, the calculation is:

$$(\text{char } *)\text{arr} + (\text{nelems} - 1) * \text{width}$$

# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

In other words, what is the location of the 42?

`(char *)arr + (nelems - 1) * width`

`0x7fffd8 + (5 * 4) == 0x7fffec`

**nelems**

6

**width**

4

**arr**

0x7fffd8

Address	Value
0x7fffec	42
0x7fffe8	-5
0x7fffe4	14
0x7fffe0	7
0x7fffdc	2
0x7fffd8	8



A key point to understand is that the pointer arithmetic increases by exactly 20 because of the `char *` cast, which means that `+1` equals 1 byte.

# Generic Pointers

Very often, we will need to find the  $i^{\text{th}}$  element in an array. You should become familiar with the following idiom:

```
for (size_t i=0; i < nelems; i++) {  
    // get ith element  
    void *ith = (char *)arr + i * width;  
}
```

nelems

6

width

4

arr

0x7fffd8

Address	Value
0x7fffec	42
0x7fffe8	-5
0x7fffe4	14
0x7fffe0	7
0x7fffdc	2
0x7fffd8	8

# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

void main(void)
{
    int i_array[] = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    short s_array[] = {100, 400, 800, 200, -300, 500};
    size_t s_nelems = sizeof(s_array) / sizeof(s_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(s_array, s_nelems, sizeof(s_array[0]));
    ...
}
```

Let's walk through this example.

First, we create an `int` array, then we find its size.

# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

void main(void)
{
    int i_array[] = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    short s_array[] = {100, 400, 800, 200, -300, 500};
    size_t s_nelems = sizeof(s_array) / sizeof(s_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(s_array, s_nelems, sizeof(s_array[0]));
    ...
}
```

Let's walk through this example.

First, we create an `int` array, then we find its size.

Next, we create a short array, then we find its size.

# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

void main(void)
{
    int i_array[] = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    short s_array[] = {100, 400, 800, 200, -300, 500};
    size_t s_nelems = sizeof(s_array) / sizeof(s_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(s_array, s_nelems, sizeof(s_array[0]));
    ...
}
```

Let's walk through this example.

First, we create an `int` array, then we find its size.

Next, we create a long array, then we find its size.

Then, we call `swap_ends` on the `int` array.

Note that we pass in the width, which is 4:  
`sizeof(i_array[0])`

# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

void main(void)
{
    int i_array[] = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    short s_array[] = {100, 400, 800, 200, -300, 500};
    size_t s_nelems = sizeof(s_array) / sizeof(s_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(s_array, s_nelems, sizeof(s_array[0]));
    ...
}
```

Create a char array to hold the width of the element we want to swap.

At this point, all information about the int array is gone, so we just have to rely on the **width** argument.



# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

void main(void)
{
    int i_array[] = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    short s_array[] = {100, 400, 800, 200, -300, 500};
    size_t s_nelems = sizeof(s_array) / sizeof(s_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(s_array, s_nelems, sizeof(s_array[0]));
    ...
}
```

Move 4 bytes from the first element in the array to `tmp`.

# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

void main(void)
{
    int i_array[] = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    short s_array[] = {100, 400, 800, 200, -300, 500};
    size_t s_nelems = sizeof(s_array) / sizeof(s_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(s_array, s_nelems, sizeof(s_array[0]));
    ...
}
```

Move 4 bytes from the last element in the array to the first element.

# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

void main(void)
{
    int i_array[] = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    short s_array[] = {100, 400, 800, 200, -300, 500};
    size_t s_nelems = sizeof(s_array) / sizeof(s_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(s_array, s_nelems, sizeof(s_array[0]));
    ...
}
```

Move 4 bytes from  
tmp to the last  
position in the  
array.

# Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

void main(void)
{
    int i_array[] = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    short s_array[] = {100, 400, 800, 200, -300, 500};
    size_t s_nelems = sizeof(s_array) / sizeof(s_array[0]);

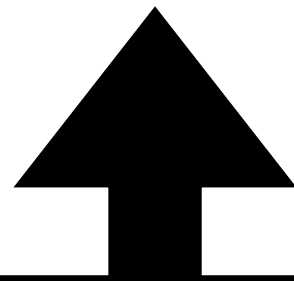
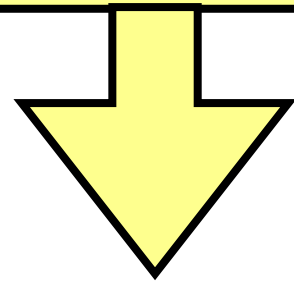
    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(s_array, s_nelems, sizeof(s_array[0]));
    ...
}
```

Repeat the process for the short array, which will pass in a `width` of 2:

```
sizeof(l_array[0]);
```

sp

stack



\_\_bss\_end\_\_

heap

\_\_bss\_start\_\_

COMMON of all modules

.bss of all modules

.rodata of all modules

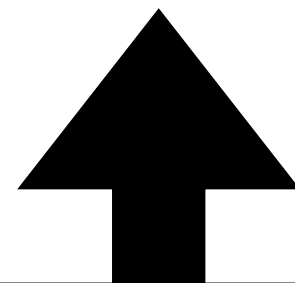
.data of all modules

.text of other modules

.text of start.o

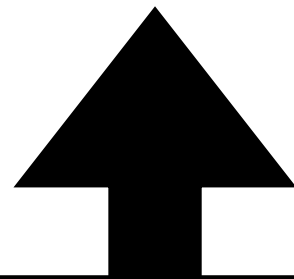
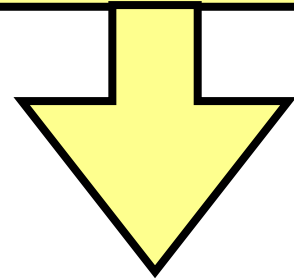
0x8000

\_\_bss\_end\_\_



sp

stack



```
char* ptr = malloc(10240);
```

\_\_bss\_end\_\_

heap

\_\_bss\_start\_\_

COMMON of all modules

.bss of all modules

.rodata of all modules

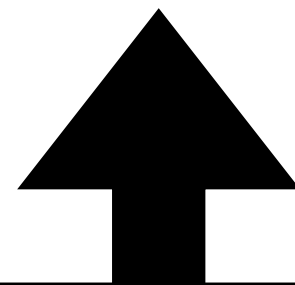
.data of all modules

.text of other modules

.text of start.o

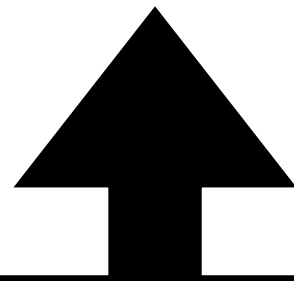
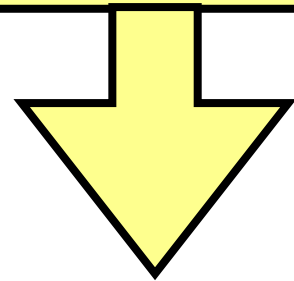
0x8000

\_\_bss\_end\_\_



sp

stack



```
char* ptr = malloc(10240);
```

\_\_bss\_end\_\_

heap

\_\_bss\_start\_\_

COMMON of all modules

.bss of all modules

.rodata of all modules

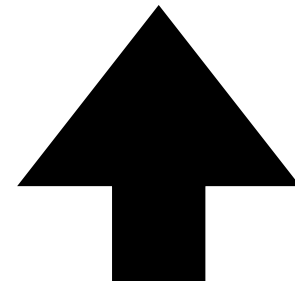
.data of all modules

.text of other modules

.text of start.o

0x8000

top



10240 +  $\delta$

\_\_bss\_end\_\_



# Questions

What happens if you forget to free a pointer after you are done using it?

Can you refer to a pointer after it has been freed?

What is stored in the memory that you malloc?

Calling free with a pointer that you didn't malloc?

Can you free the same pointer twice?

Wouldn't it be nice to not have to worry about freeing memory?



# Variable Size malloc/free

just malloc is easy



malloc with free is hard



- free returns blocks that can be re-allocated
- malloc should search to see if there is a block of sufficient size. Which block should it choose (best-fit, first-fit, largest)?
- malloc may use only some of the block. It splits the block into two sub-blocks of smaller sizes
- splitting blocks causes fragmentation

Buddy allocators, slab allocators, lots of approaches