Operating Systems

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Ch7

Memory Management from a Programmer’s Perspective

Why we need memory management

- The running program code requires memory
  - Because the CPU needs to fetch the instructions from the memory for execution
- We must keep several processes in memory
  - Improve both CPU utilization and responsiveness
  - Multiprogramming

It is required to efficiently manage the memory

Topics in Ch7

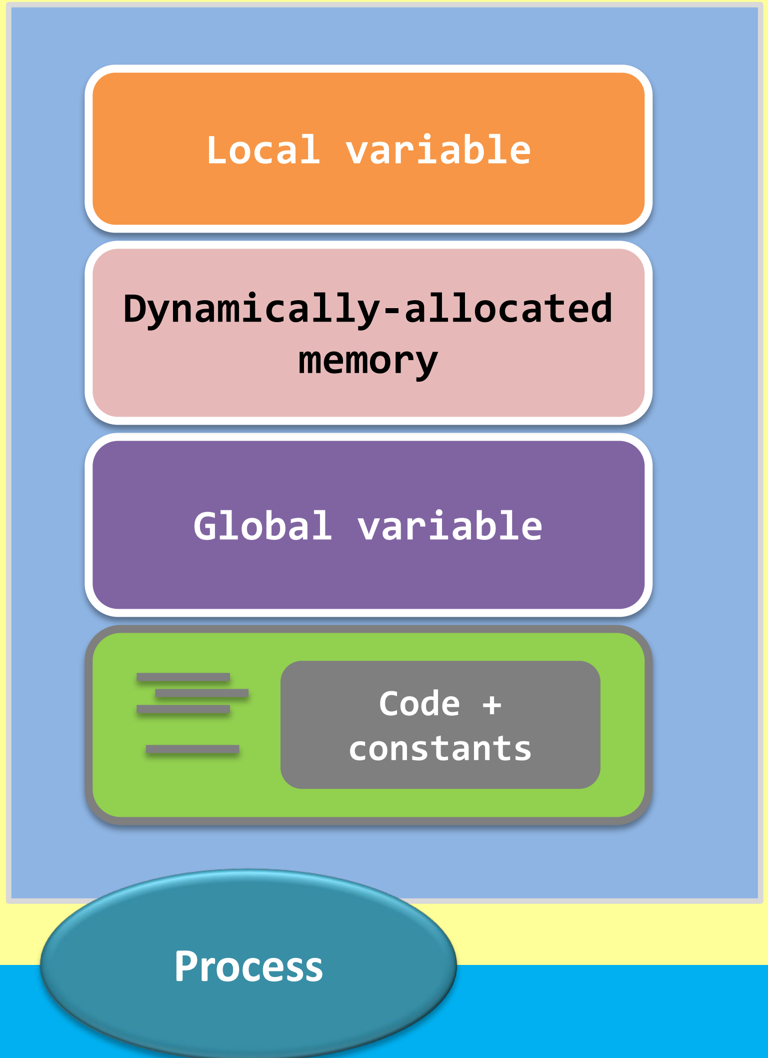
From a programmer's perspective: user-space memory management

What is the address space of a process?
How are the program code and data stored in memory?
How to allocate/free memory (malloc() + free())?
How much memory can be used in a program?
What are segmentation and segmentation fault?

From the kernel's perspective: How to manage the memory

What is virtual memory?
How to realize address mapping (paging)?
How to support very large programs (demand paging)?
How to do page replacement?
What is TLB?
What is memory-mapped file?

Part 1: User-space memory



Do you remember this?

- Content of a process (in user-space memory)

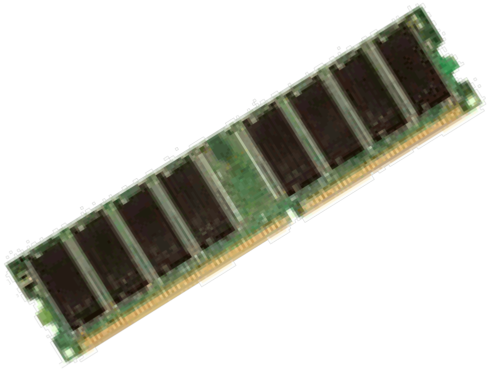
How does each part use the memory?

- From a programmer’s perspective

Let’s forget about the kernel for a moment. We are going to explore the **user-space memory** first.

User-space memory management

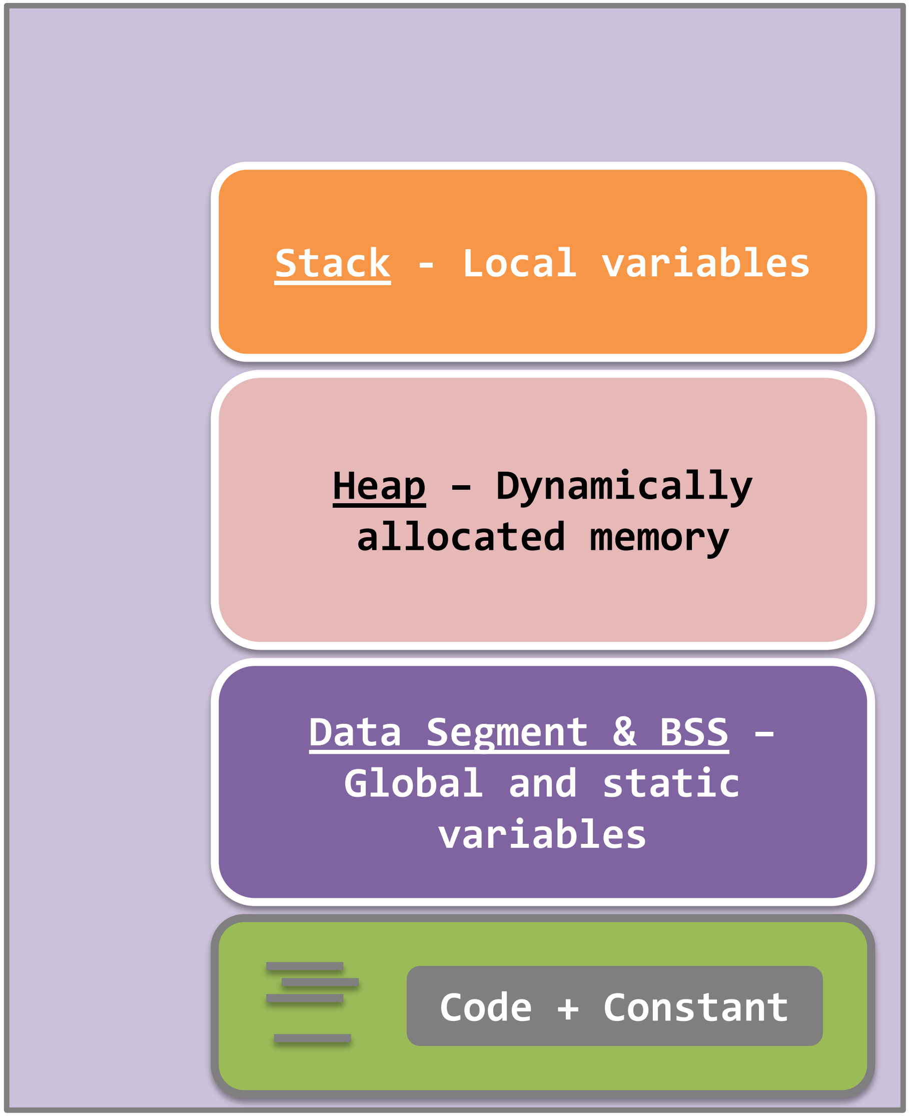
- **Address space;**
- Code & constants;
- Data segment;
- Stack;
- Heap;
- Segmentation fault;



Address space

How does a programmer look at the memory space?

- An array of bytes?
- Memory of a process is divided into segments
- This way of arranging memory is called **segmentation**

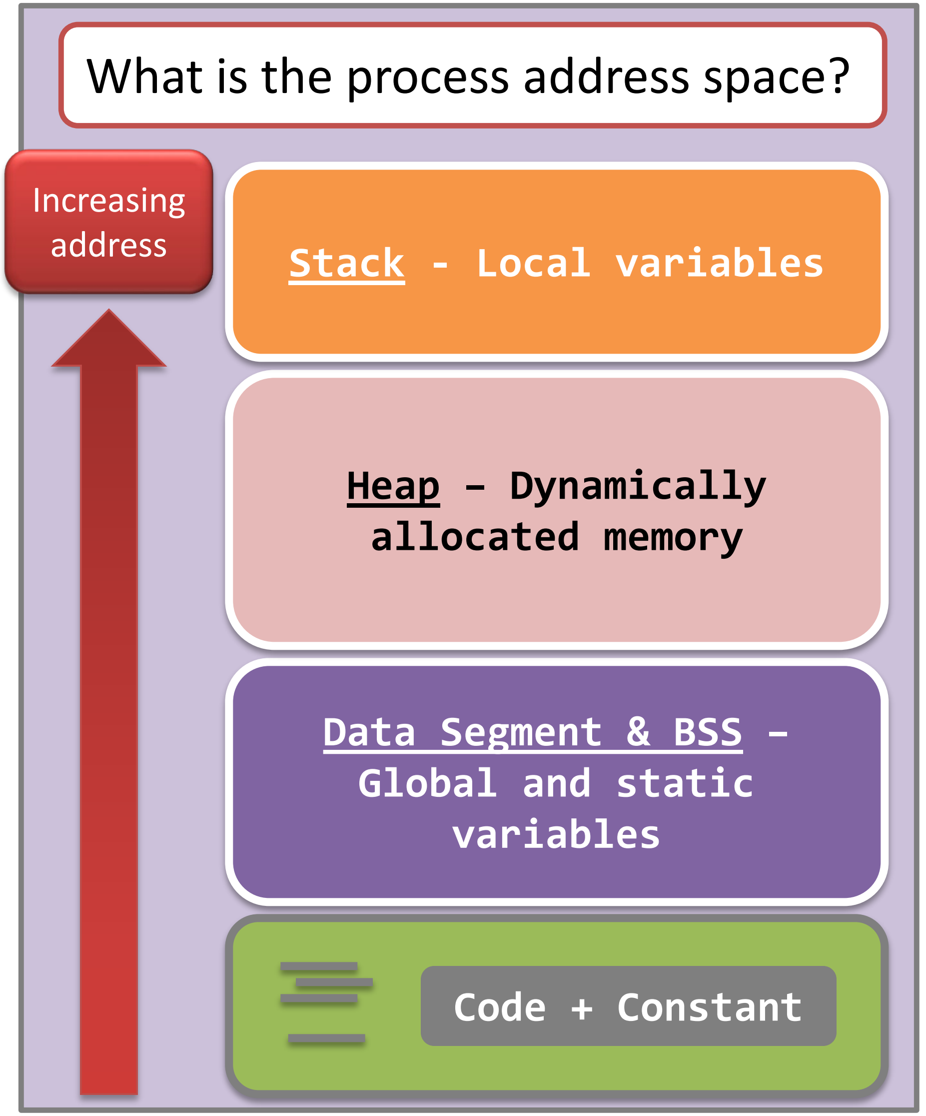


Address space

```c
int main(void) {
    int *malloc_ptr = malloc(4);
    char *constant_ptr = "hello";

    printf("Local variable  = %15p\n", &malloc_ptr);
    printf("malloc() space  = %15p\n", malloc_ptr);
    printf("Global variable = %15p\n", &global_int);
    printf("Code & constant = %15p\n", constant_ptr);

    return 0;
}
```

```
$ ./addr
Local variable  = 0xbfa8938c
malloc() space  =  0x915c008
Global variable =  0x804a020
Code & constant =  0x8048550
$ _
```

Note
The addresses are not necessarily the same in different processes



Address space

0xf = 1111 → 0xffffffff

1 '1' bit + 16 '0' bits → 0x100000000

0xffffffff = 0x100000000 - 1

= 2^32 - 1

= 4G - 1

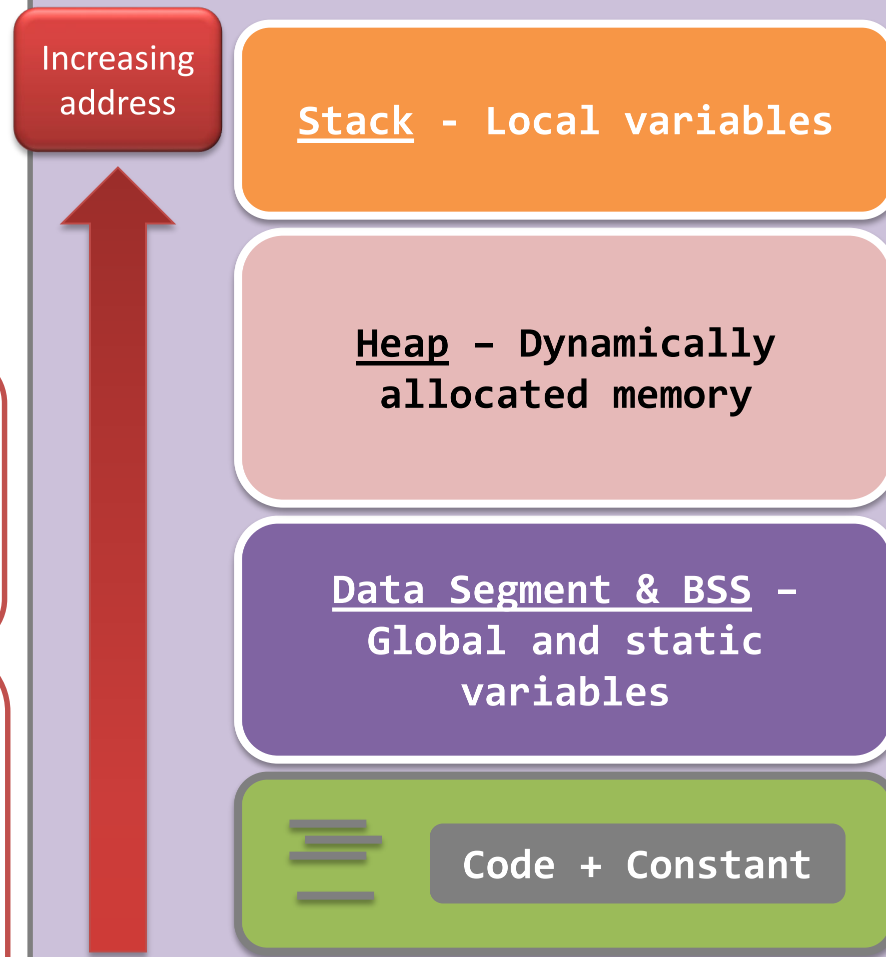
In a 32-bit system,

- One address maps to one byte.
- The maximum amount of memory in a process is **4GB**.

Note

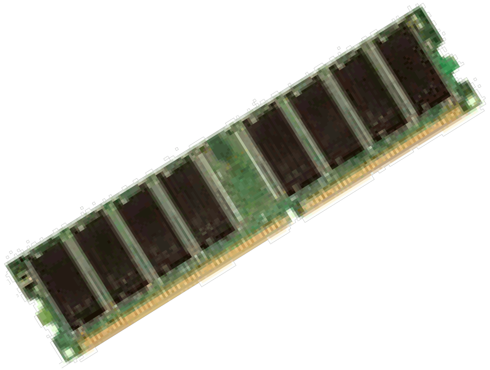
- This is the so called logical address space
- **Each process has its own address space**, and it can reside in any part of the physical memory

How large is the address space?



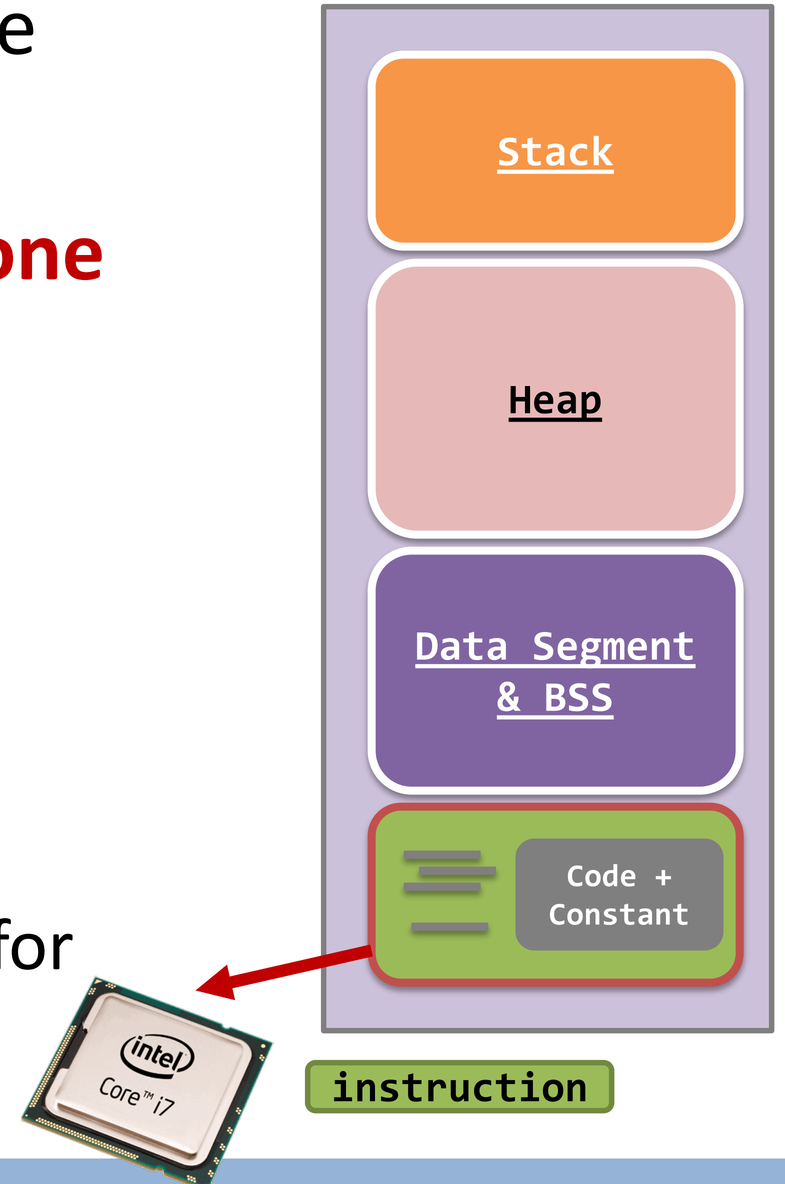
User-space memory management

- Address space;
- Code & constants;
- Data segment;
- Stack;
- Heap;
- Segmentation fault;



Program code & constants

- A program is an executable file
- A process is **not bounded to one program code**.
  - Remember **exec*()** family?
- The program code requires memory space because…
  - The CPU needs to fetch the instructions from the memory for execution.



Program code & constants

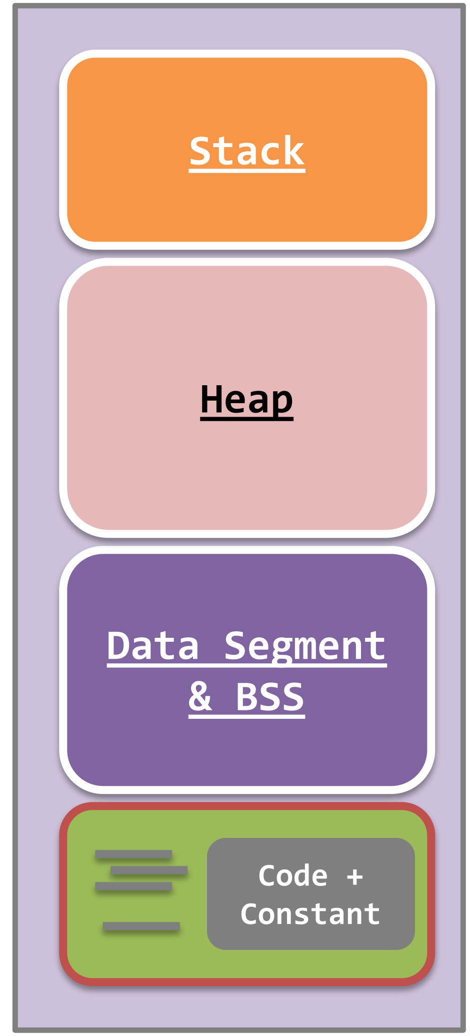
```
1   int main(void) {
2       char *string = "hello";
3       printf("\"hello\"       = %p\n", "hello");
4       printf("String pointer = %p\n", string);
5       string[4] = '\0';
6       printf("Go to %s\n", string);
7       return 0;
8   }
```

- **Question #1.** What are the printouts from Line 3 & 4?

```
"hello"        = 0x8048520
String pointer = 0x8048520
```

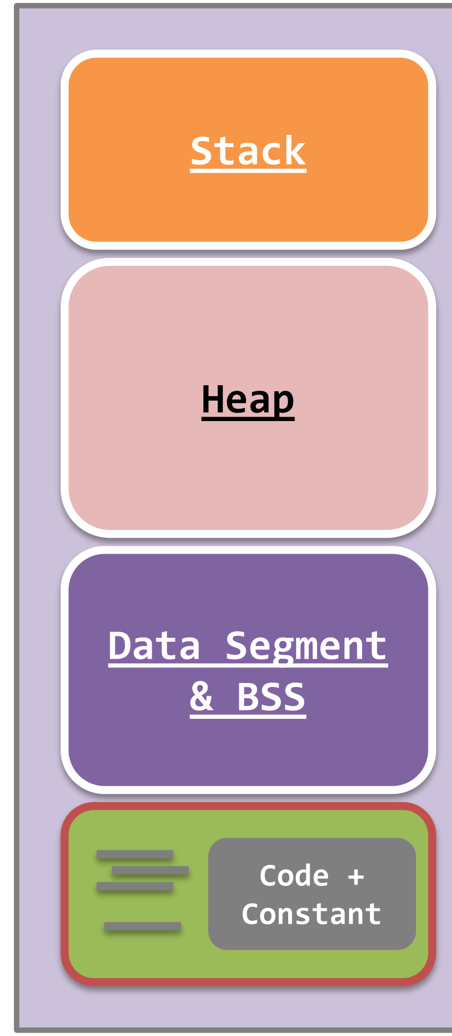
- **Question #2.** What is the printout from Line 6?

```
Segmentation fault
```



Program code & constants

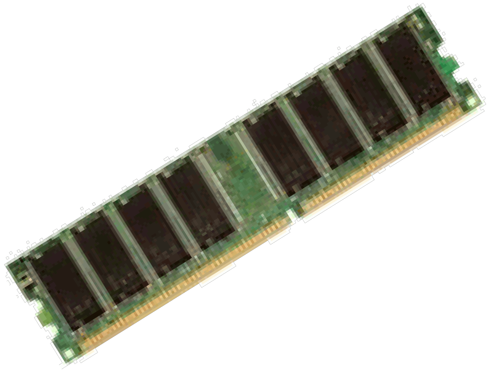
```
int main(void) {
    char *string = "hello";
    printf("\"hello\"       = %p\n", "hello");
    printf("String pointer = %p\n", string);
    string[4] = '\0';
    printf("Go to %s\n", string);
    return 0;
}
```



- Constants are stored in code segment.
  - Accessing of constants are done using addresses (or pointers).
- Codes and constants are both **read-only**.

User-space memory management

- Address space;
- Code & constants;
- **Data segment;**
- Stack;
- Heap;
- Segmentation fault;



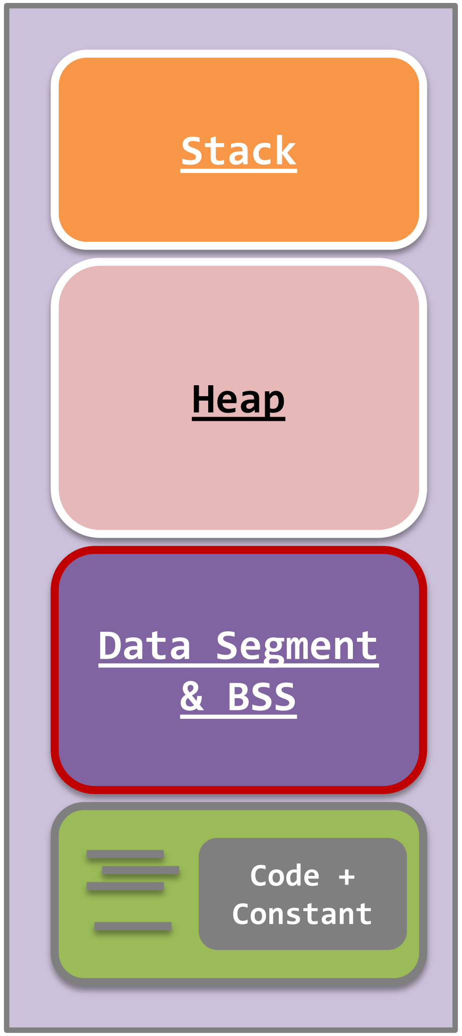
Data Segment & BSS – properties

```c
int global_int = 10;
int main(void) {
    int local_int = 10;
    static int static_int = 10;
    printf("local_int  addr = %p\n", &local_int );
    printf("static_int addr = %p\n", &static_int );
    printf("global_int addr = %p\n", &global_int );
    return 0;
}
```

```
$ ./global_vs_static
local_int  addr = 0xbf8bb8ac
static_int addr = 0x804a018
global_int addr = 0x804a014
$_
```

They are stored next to each other.

This implies that they are **in the same segment!**

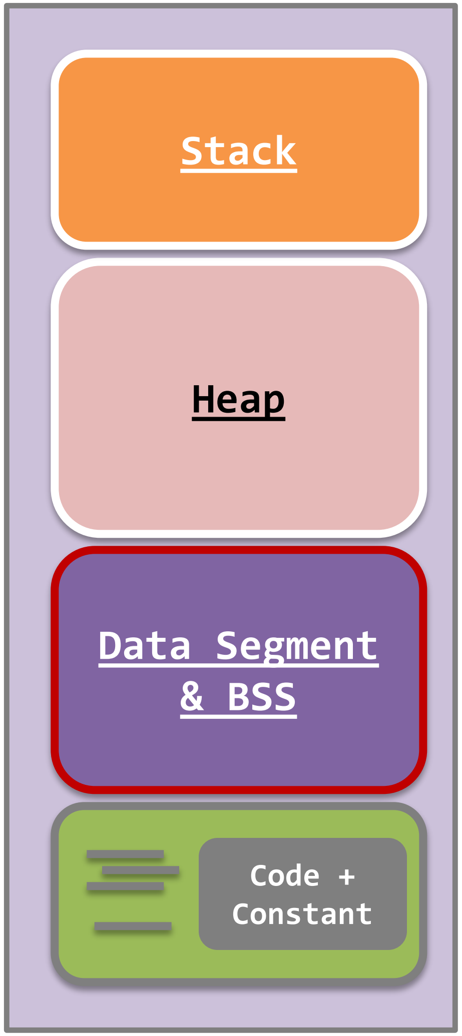


Note: A static variable is treated as the same as a global variable!

Data Segment & BSS – properties

- Data
  - Containing initialized global and static variables.

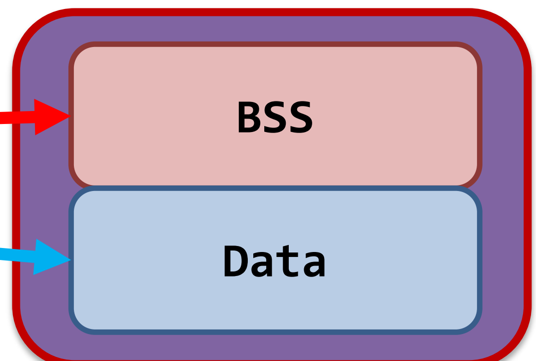
- BSS (**B**lock **S**tarted by **S**ymbol)
  - Containing uninitialized global and static variables.

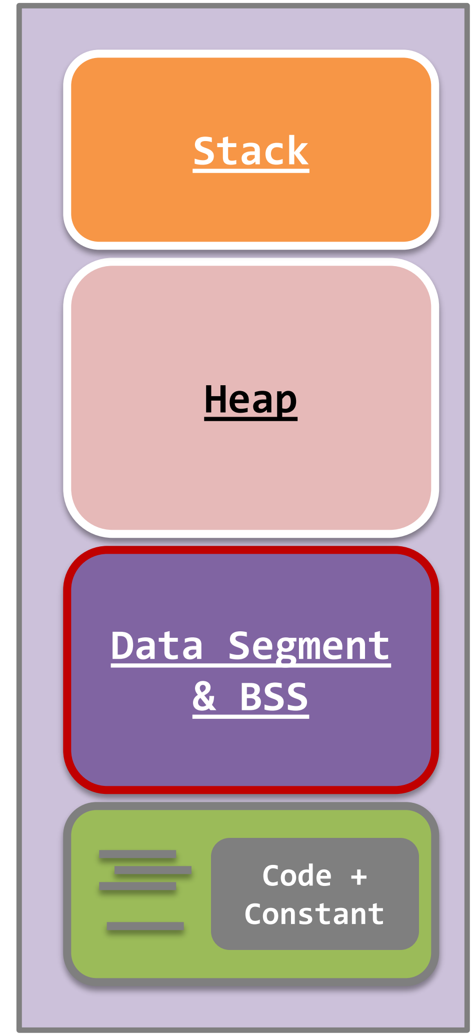


Data Segment & BSS – locations

```c
int global_bss;
int global_data = 10;
int main(void) {
        static int static_bss;
        static int static_data = 10;
        printf("global  bss = %p\n", &global_bss  );
        printf("static  bss = %p\n", &static_bss  );
        printf("global data = %p\n", &global_data );
        printf("static data = %p\n", &static_data );
}
```

```
$ ./data_vs_bss
global  bss = 0x804a028
static  bss = 0x804a024
global data = 0x804a014
static data = 0x804a018
$_
```





Data Segment & BSS – sizes

```
char a[1000000] = {10};

int main(void) {
    return 0;
}
```

Program: data_large.c

```
char a[100] = {10};

int main(void) {
    return 0;
}
```

Program: data_small.c

No optimization.

```
$ gcc -O0 -o data_large data_large.c
$ gcc -O0 -o data_small data_small.c

$ ls -l data_small    data_large
```

Guess! Which one is large?

What is the difference between data and BSS?

Data Segment & BSS – sizes

```
char a[1000000] = {10};

int main(void) {
    return 0;
}
```

Program: data_large.c

```
char a[100] = {10};

int main(void) {
    return 0;
}
```

Program: data_small.c

```
$ gcc -O0 -o data_large data_large.c
$ gcc -O0 -o data_small data_small.c

$ ls -l data_small   data_large
-rwxr-xr-x ... 1004816 ... data_large
-rwxr-xr-x ...    4916 ... data_small
$_
```

Wow!

The data segment has the required space **already allocated**.

Data Segment & BSS – sizes

```c
char a[1000000];

int main(void) {
    return 0;
}
```

Program: bss_large.c

```c
char a[100];

int main(void) {
    return 0;
}
```

Program: bss_small.c

```
$ gcc -O0 -o bss_large bss_large.c
$ gcc -O0 -o bss_small bss_small.c

$ ls -l bss_small   bss_large
-rwxr-xr-x ... 4775... bss_large
-rwxr-xr-x ... 4775... bss_small
$_
```

Same size!

To the program, BSS is just a bunch of symbols. **The space is not yet allocated**.

The space will be allocated to the process once it starts executing.

This is why BSS is called "*Block Started by Symbol*".

Data Segment & BSS – limits

How large is the data segment?

```
$ ulimit -a
  core file size    (blocks, -c) 0
  data seg size     (kbytes, -d) unlimited
  ......
$ _
```

In Linux, "**ulimit**" is a built-in command in "**/bin/bash**".

It sets or gets the system limitations in the current shell.

Does the "unlimited" mean that you can define a global array with large enough size?

Data Segment & BSS – limits

```
#define ONE_MEG (1024 * 1024)

char a[1024 * ONE_MEG];

int main(void) {
    memset(a, 0, sizeof(a));
    printf("1GB OK\n");
}
```

```
#define ONE_MEG (1024 * 1024)

char a[2048 * ONE_MEG];

int main(void) {
    memset(a, 0, sizeof(a));
    printf("2GB OK\n");
}
```

```
$ gcc -Wall -O0    global_2gb.c    -o global_2gb
global_2gb.c:6: warning: integer overflow in expression
global_2gb.c:6: error: size of array 'a' is negative
$ _
```

The size of an array is a 32-bit **signed integer**, no matter 32-bit or 64-bit systems. Therefore…

Data Segment & BSS – limits

```
#define ONE_MEG (1024 * 1024)

char a[1024 * ONE_MEG];
char b[1024 * ONE_MEG];
char c[1024 * ONE_MEG];
char d[1024 * ONE_MEG];

int main(void) {
    memset(a, 0, sizeof(a));
    printf("1GB OK\n");
    memset(b, 0, sizeof(b));
    printf("2GB OK\n");
    memset(c, 0, sizeof(c));
    printf("3GB OK\n");
    memset(d, 0, sizeof(d));
    printf("4GB OK\n");
}
```

Program: global_4gb.c

Segmentation fault
why?

On a **32-bit** Linux system, the user-space **addressing space is around 3GB**.

The kernel reserves 1GB addressing space.

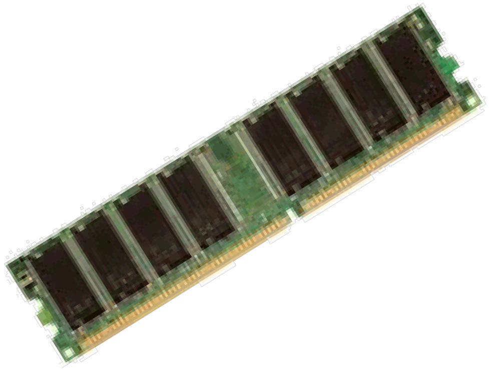
Data Segment & BSS – summary

- Remember, "**global variable == static variables**".
  - Only the **compiler cares** about the difference!

- Everything in a computer has a limit!
  - Different systems have different limits: 32-bit VS 64-bit.
  - Your job is to adapt to such limits.
  - On a **32-bit** Linux system, the user-space **addressing space is around 3GB**.

User-space memory management

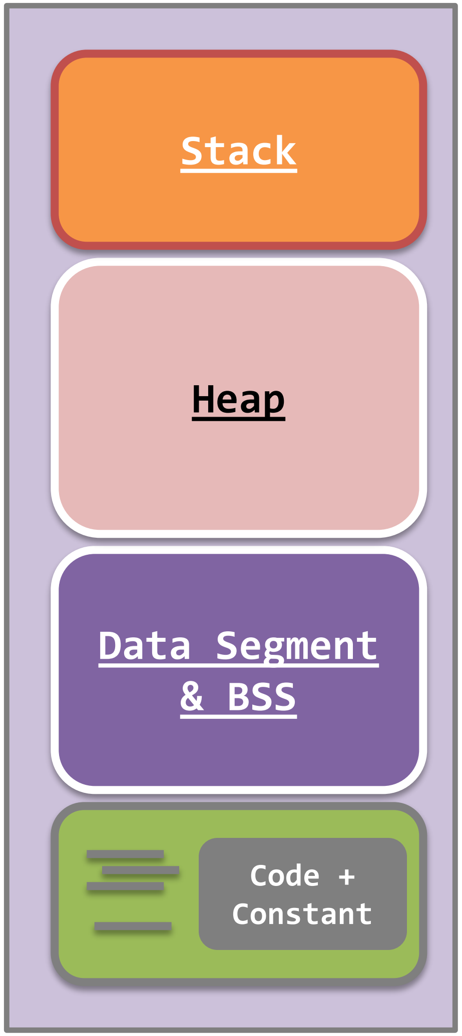
- Address space;
- Code & constants;
- Data segment;
- **Stack;**
- Heap;
- Segmentation fault;



Stack – properties

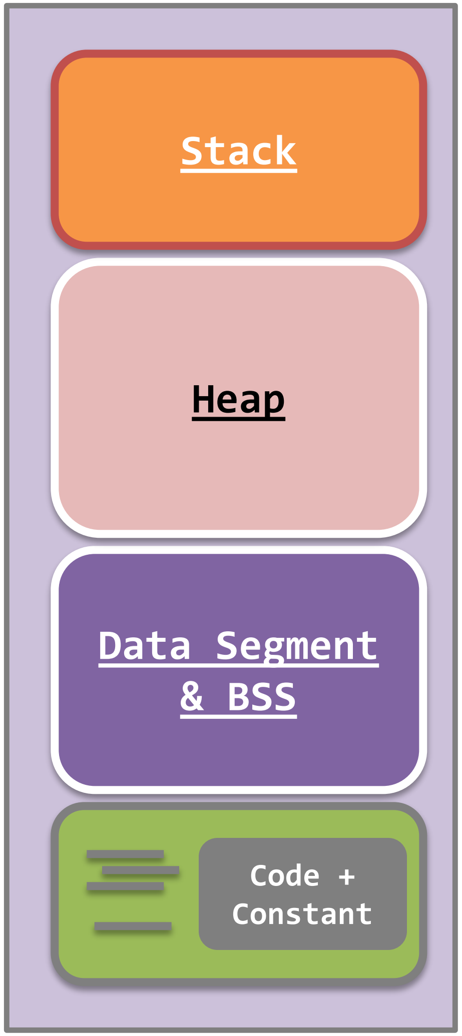
- The stack contains:
  - all the local variables,
  - all function parameters,
  - program arguments, and
  - environment variables.

How are the data stored and what is the size limit?



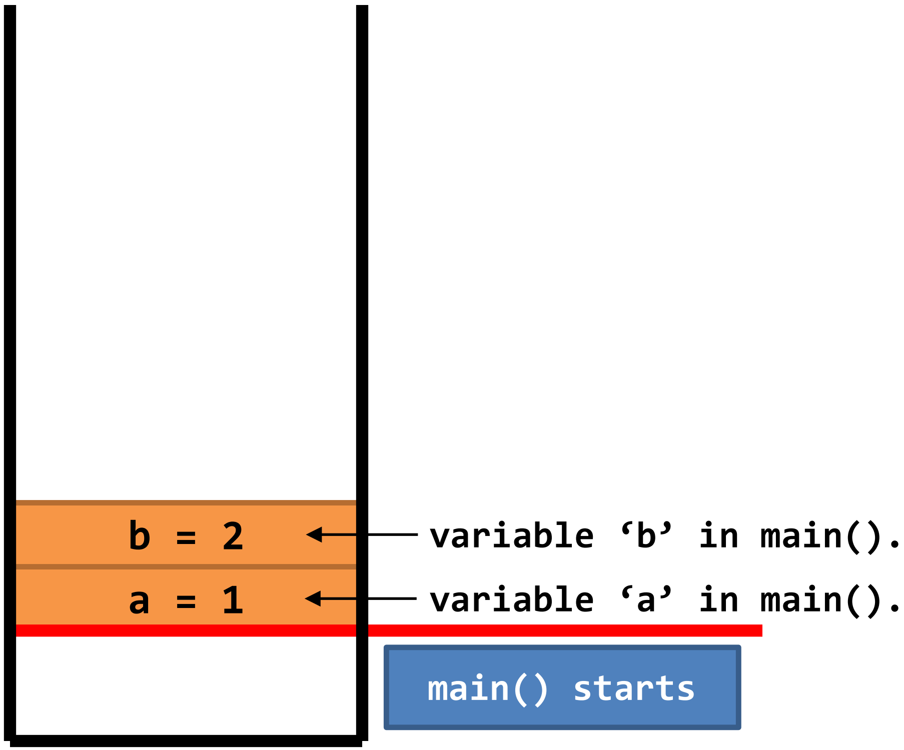
Stack – properties

- Stack: FILO
- When a function is called, the local variables are <u>allocated</u> in the stack.
- When a function returns, the local variables are <u>deallocated</u> from the stack.



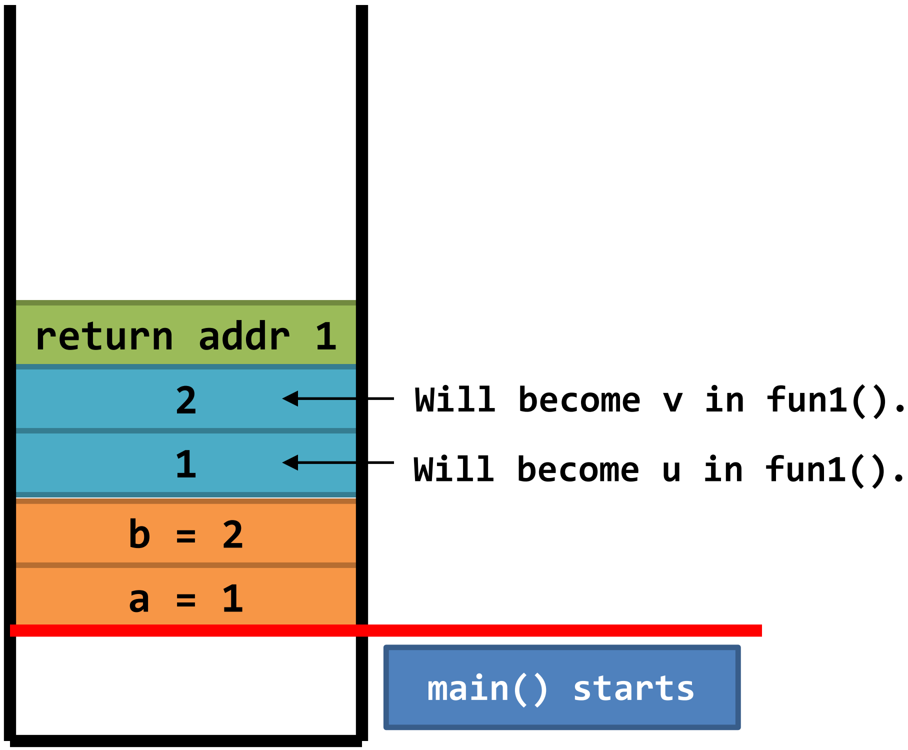
Stack – push & pop mechanisms

```
int fun2(int x, int y) {
    int c = 10;
    return (x + y + c);
}

int fun1(int u, int v) {
    return fun2(v, u);
}

int main(void) {
    int a = 1, b = 2;
    b = fun1(a, b);
    return 0;
}
```



Stack – push & pop mechanisms

Calling function "**fun1()**" starts.
It is the beginning of the call, and the CPU has not switched to **fun1()** yet.

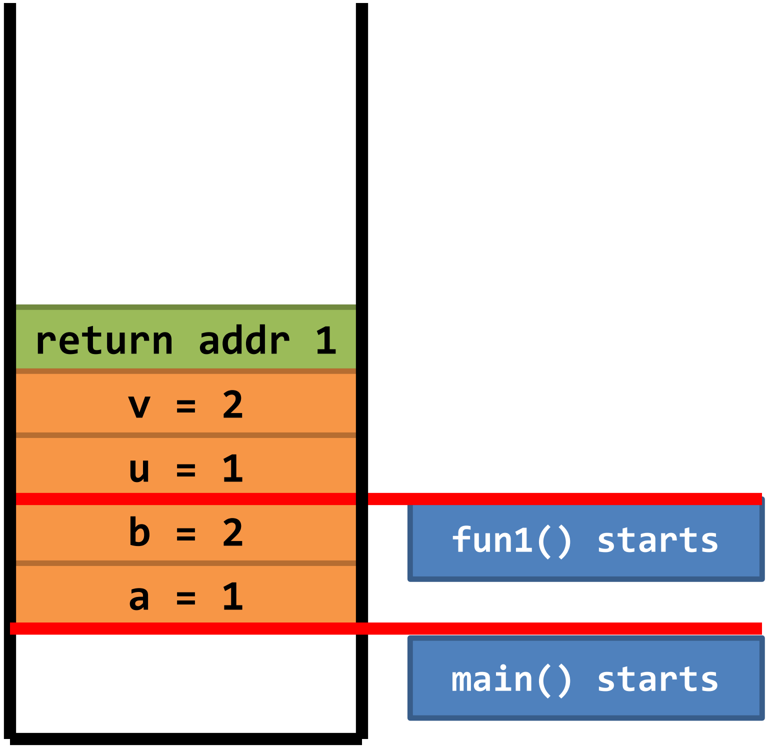



```
int fun2(int x, int y) {
    int c = 10;
    return (x + y + c);
}

int fun1(int u, int v) {
    return fun2(v, u);
}

int main(void) {
    int a = 1, b = 2;
    b = fun1(a, b);
    return 0;
}
```

"return addr 1" is approx. here.

Stack – push & pop mechanisms

Calling function “**fun1()**” takes place. The CPU has switched to **fun1()** .



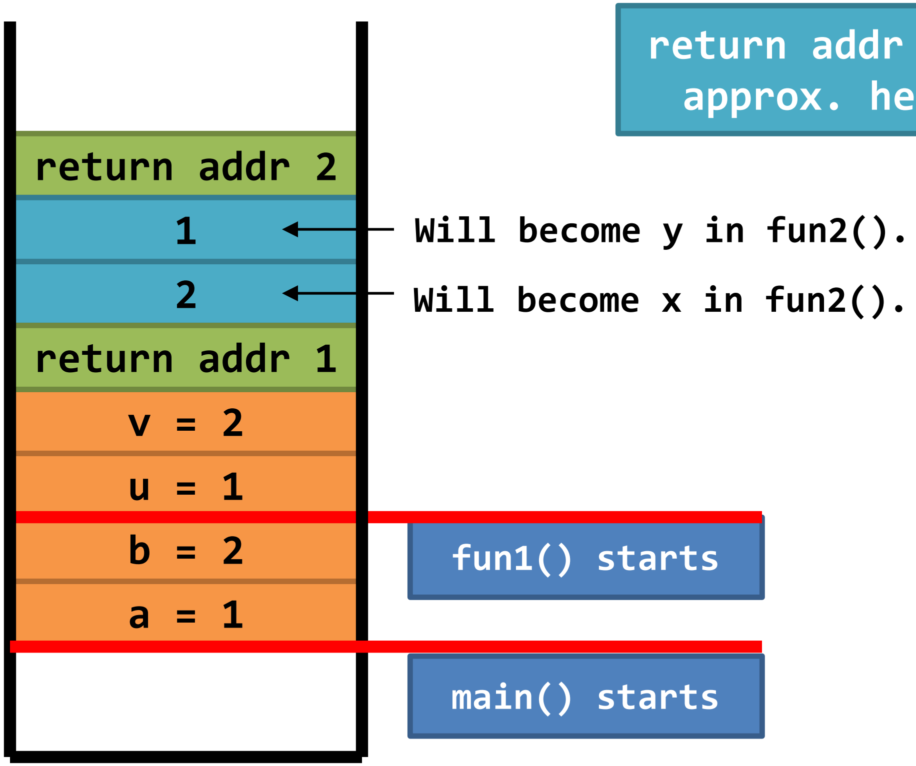

```
int fun2(int x, int y) {
    int c = 10;
    return (x + y + c);
}

int fun1(int u, int v) {
    return fun2(v, u);
}

int main(void) {
    int a = 1, b = 2;
    b = fun1(a, b);
    return 0;
}
```

Stack – push & pop mechanisms

Calling function "**fun2()**" starts.
It is the beginning of the call, and the CPU has not switched to **fun2()** yet.

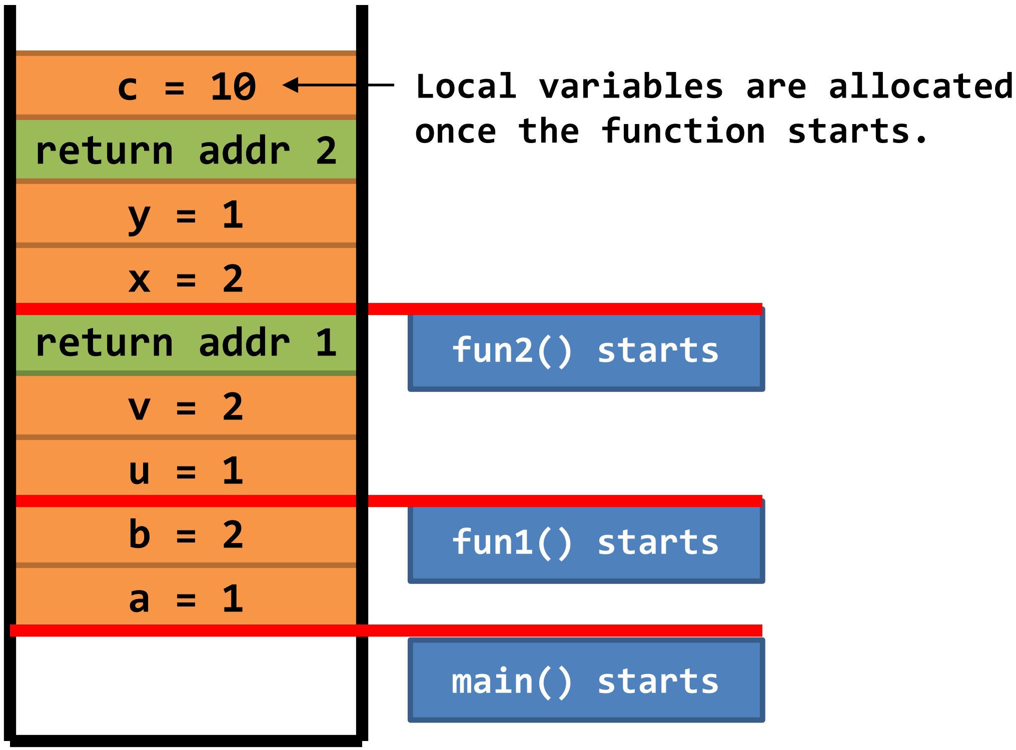
```c
int fun2(int x, int y) {
    int c = 10;
    return (x + y + c);
}

int fun1(int u, int v) {
    return fun2(v, u);
}

int main(void) {
    int a = 1, b = 2;
    b = fun1(a, b);
    return 0;
}
```

return addr 2 is approx. here.



Stack – push & pop mechanisms

Calling function "**fun2()**" takes place. The CPU has switched to **fun2()** .

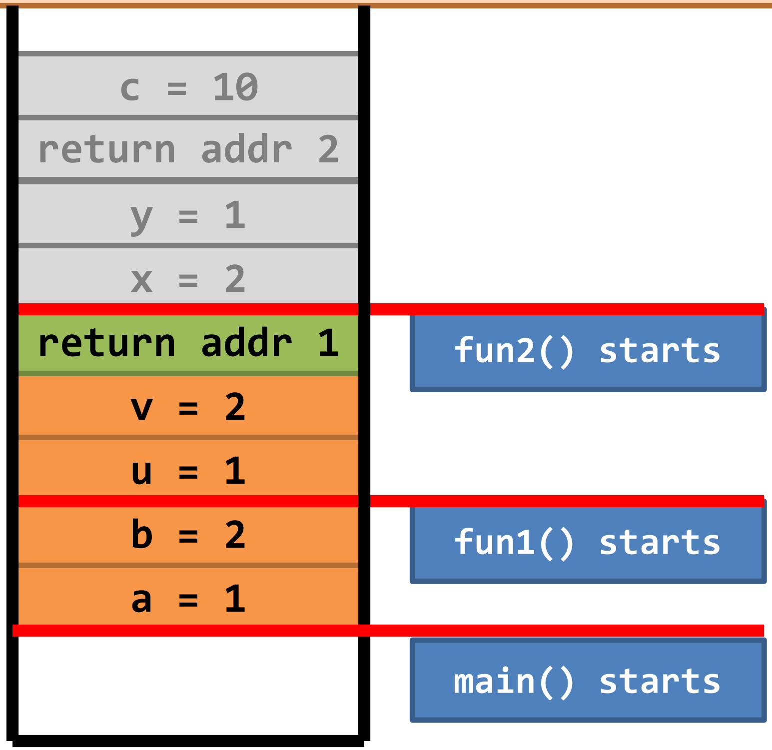



```
int fun2(int x, int y) {
    int c = 10;
    return (x + y + c);
}

int fun1(int u, int v) {
    return fun2(v, u);
}

int main(void) {
    int a = 1, b = 2;
    b = fun1(a, b);
    return 0;
}
```

Stack – push & pop mechanisms

"Return" takes place.

(1) Return value is written to the EAX register.
(2) Stack **shrinks**.
(3) CPU jumps back to **fun1()**.




```
int fun2(int x, int y) {
    int c = 10;
    return (x + y + c);
}

int fun1(int u, int v) {
    return fun2(v, u);
}

int main(void) {
    int a = 1, b = 2;
    b = fun1(a, b);
    return 0;
}
```

EAX: 13

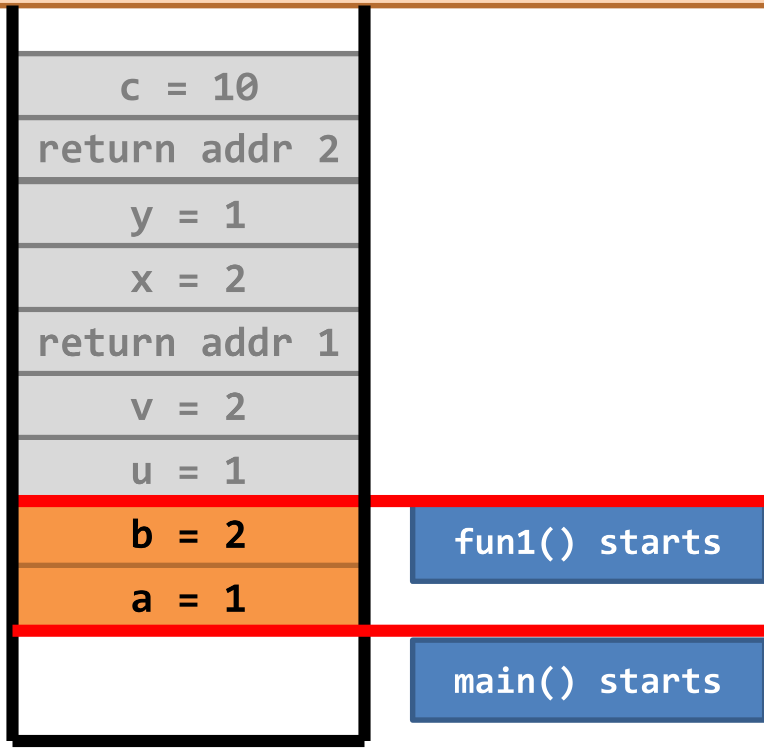
Stack – push & pop mechanisms

"Return" takes place.

(1) Return value is written to the EAX register.

(2) Stack **shrinks**.

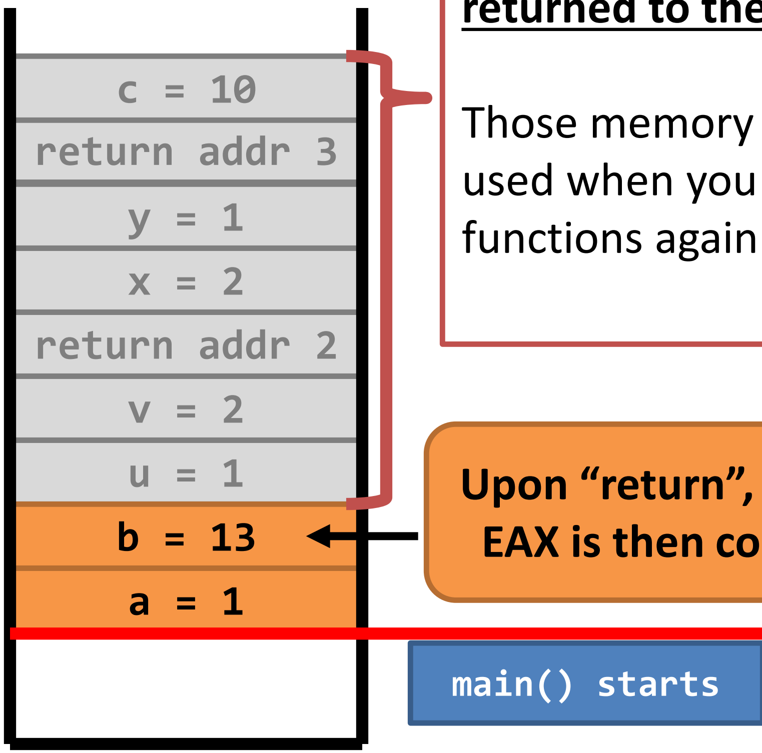
(3) CPU jumps back to **`main()`**.




```
int fun2(int x, int y) {
    int c = 10;
    return (x + y + c);
}

int fun1(int u, int v) {
    return fun2(v, u);
}

int main(void) {
    int a = 1, b = 2;
    b = fun1(a, b);
    ret    0;
}
```

EAX: 13

Stack – push & pop mechanisms



Those memory **<u>is NOT returned to the OS</u>**!!

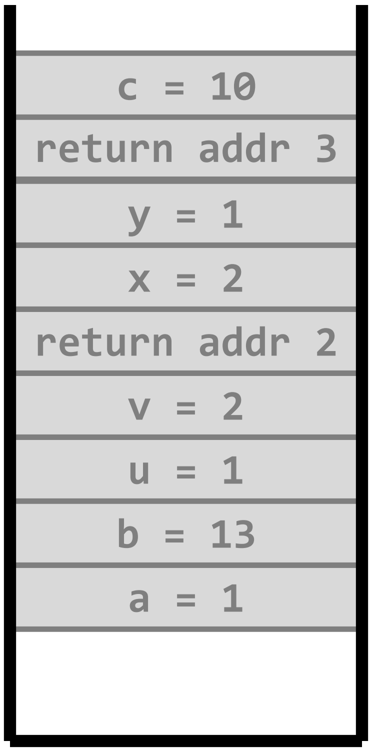
Those memory will be re-used when you call functions again.

Upon “return”, the value of EAX is then copied to “b”

```
int fun2(int x, int y) {
    int c = 10;
    return (x + y + c);
}

int fun1(int u, int v) {
    return fun2(v, u);
}

int main(void) {
    int a = 1, b = 2;
    b = fun1(a, b);
    return 0;
}
```

EAX: 13

Stack – push & pop mechanisms



Eventually, the main function reaches "**`return 0`**".

This takes the CPU pointing to the C library.

Inside the C library, we will eventually reach the system call **`exit()`**.

```
int fun2(int x, int y) {
    int c = 10;
    return (x + y + c);
}

int fun1(int u, int v) {
    return fun2(v, u);
}

int main(void) {
    int a = 1, b = 2;
    b = fun1(a, b);
    return 0;
}
```

EAX: 0

Stack – limits

```
$ ulimit -a
  core file size   (blocks, -c) 0
  data seg size    (kbytes, -d) unlimited
  ......
  stack size       (kbytes, -s) 8192
  ......
$ _
```

So, the limit is:
8192 x 1024 = 8MB.

Can you define a local array larger that the limit?

Segmentation fault

```
$ ulimit -a
  core file size   (blocks, -c) 0
  data seg size    (kbytes, -d) unlimited
  ......
  stack size       (kbytes, -s) 8192
  ......
$ ulimit -s 81920
```

Now, the limit is:
81920 x 1024 = 80MB.

Stack – summary

- What if it is a chain of endless recursive function calls?
- What will happen?
  - **Exception caught by the CPU!**
    - **Stack overflow exception!**
  - **Program terminated!**

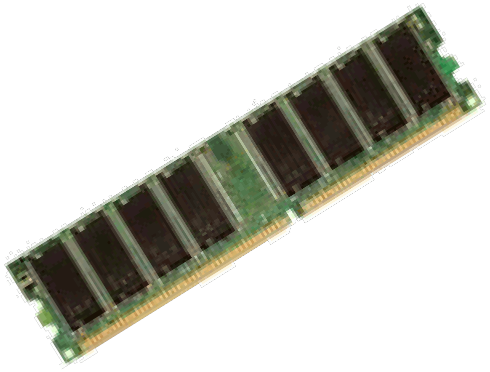
Stack – summary

- *"I really need to play with recursions."* Any workaround?
  - Minimize the number of arguments
  - Minimize the number of local variables
  - Minimize the number of calls
  - Use global variables

- Note: A function can ask the CPU **to read and to write anywhere in the stack**, **not just the "zone" belonging to the running function**!
  - Isn't it horrible (profitable and fun)?

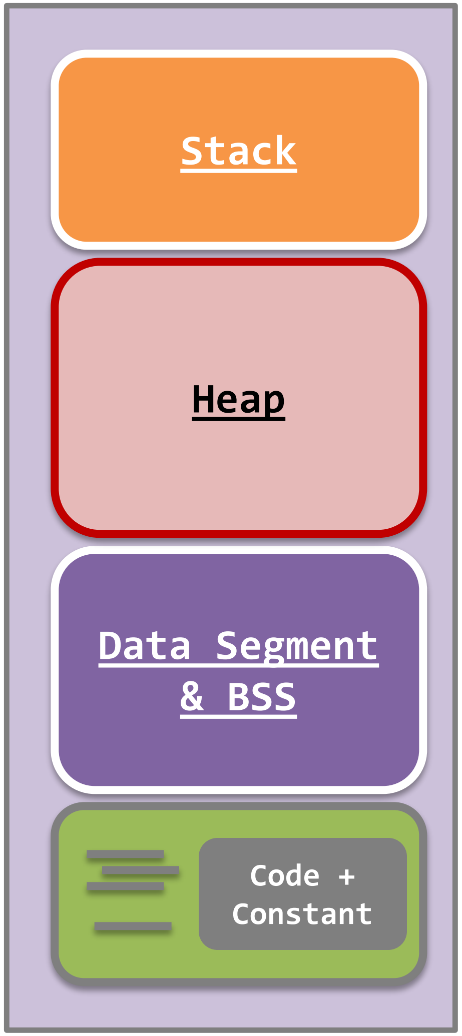
User-space memory management

- Address space;
- Code & constants;
- Data segment;
- Stack;
- **Heap;**
- Segmentation fault;



Dynamically allocated memory – properties

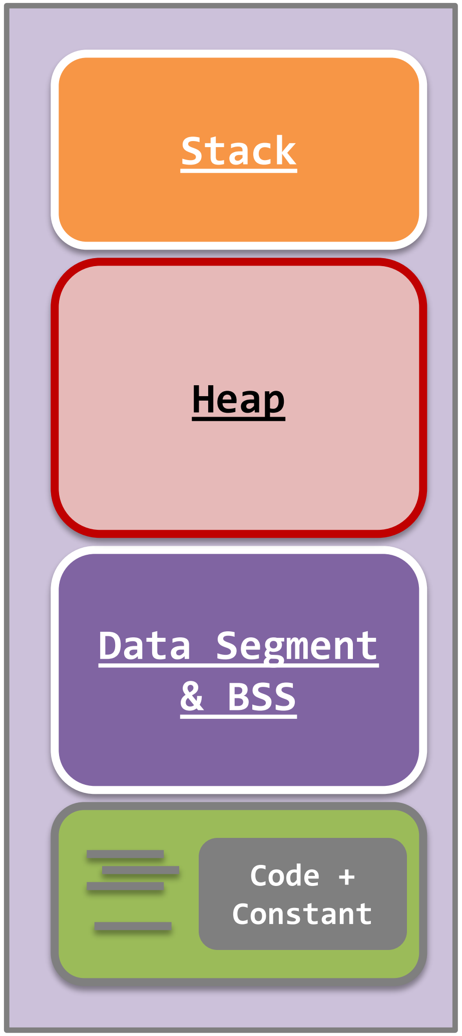
- Its name tells you its nature:
  - The dynamically allocated memory is called the **heap**.
    - Don't mix it up with the binary heap;
    - It has nothing to do with the binary heap.
  - **Dynamic**: not defined at compile time.
  - **Allocation**: only when you *ask for memory, you would be allocated the memory.*



Dynamically allocated memory – properties

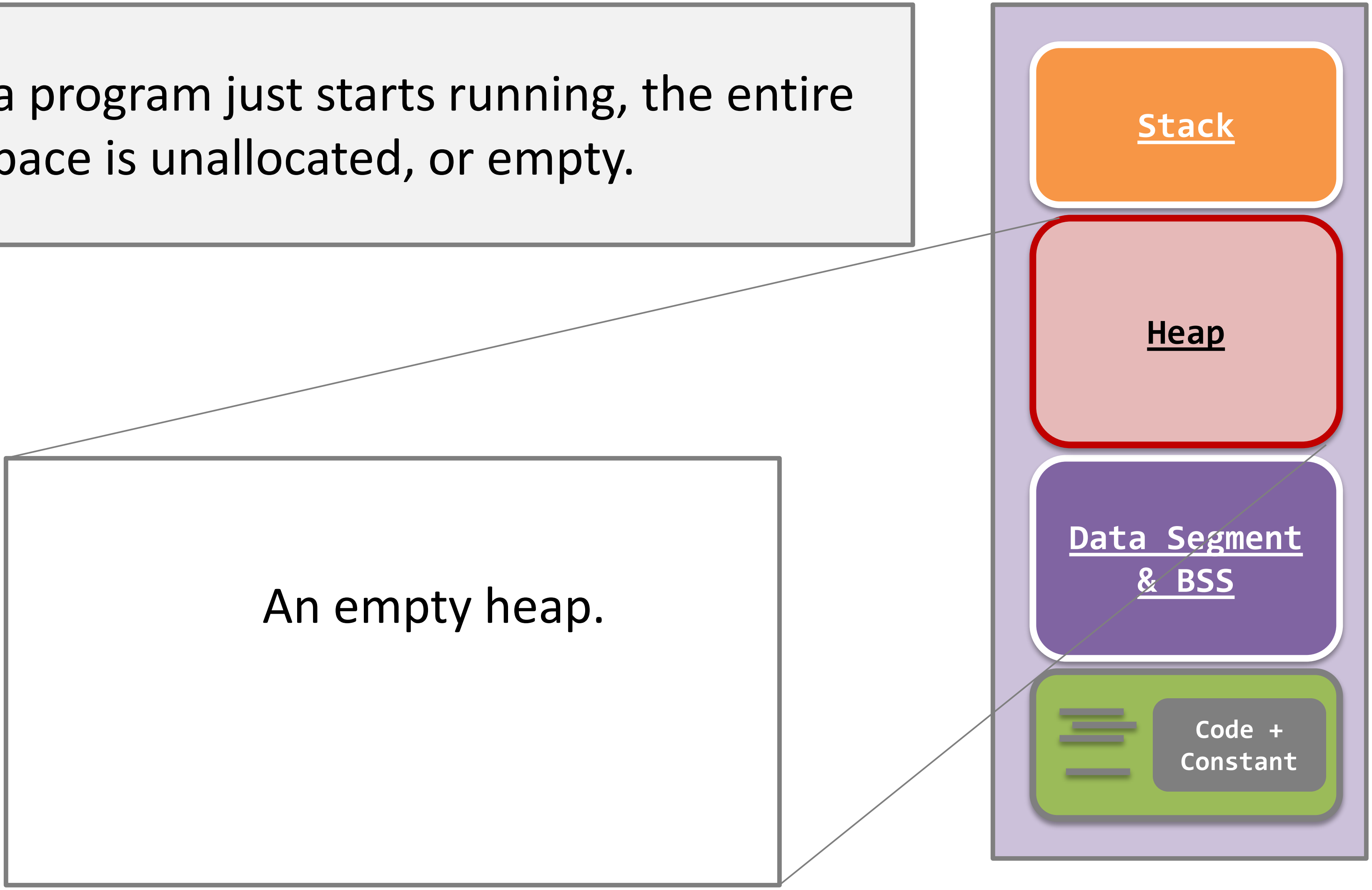
- Lecturers of a programming course would tell you the following:
  - *“**malloc()**” is a function that allocates memory for you.*
  - *“**free()**” is a function that gives up a piece of memory that is produced by previous “**malloc()**” call.*

- The lecturer of the OS course is **to define and to defy** what you know about the **`malloc()`** and **`free()`** library functions.



malloc()

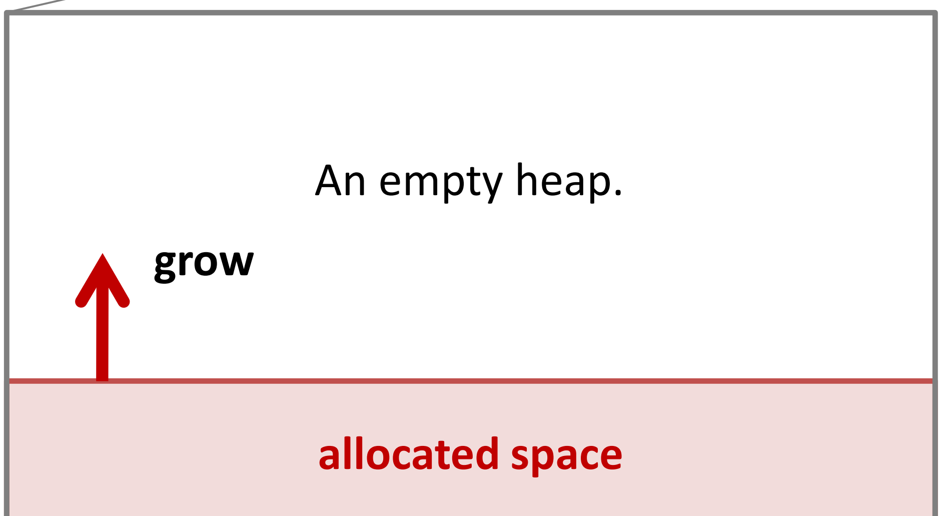
When a program just starts running, the entire heap space is unallocated, or empty.

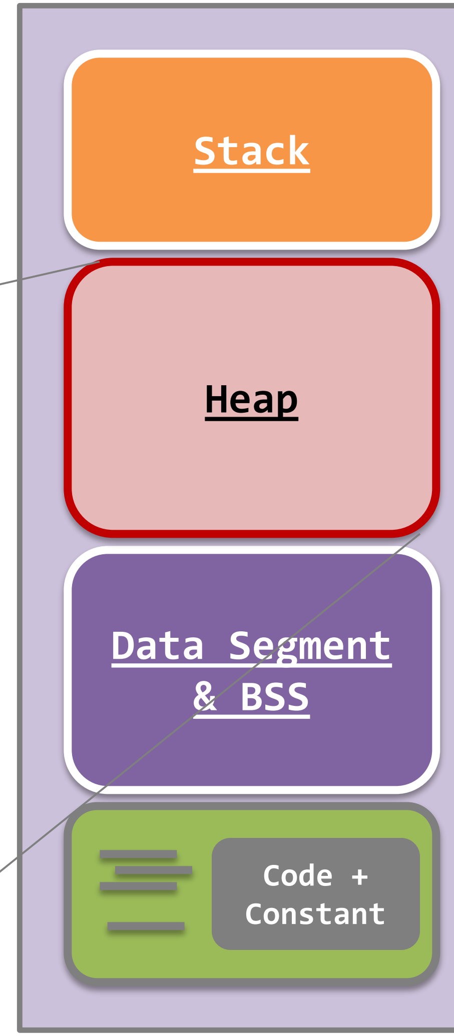


malloc()

When "**malloc()**" is called, the "**brk()**" system call is invoked accordingly.

"**brk()**" allocates the space required by "**malloc()**". But, it doesn't care how "**malloc()**" uses the space.



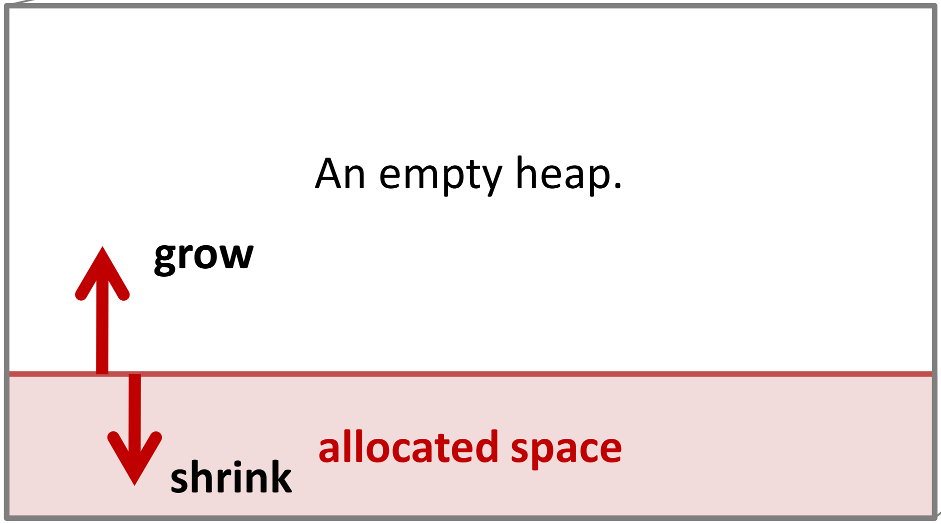


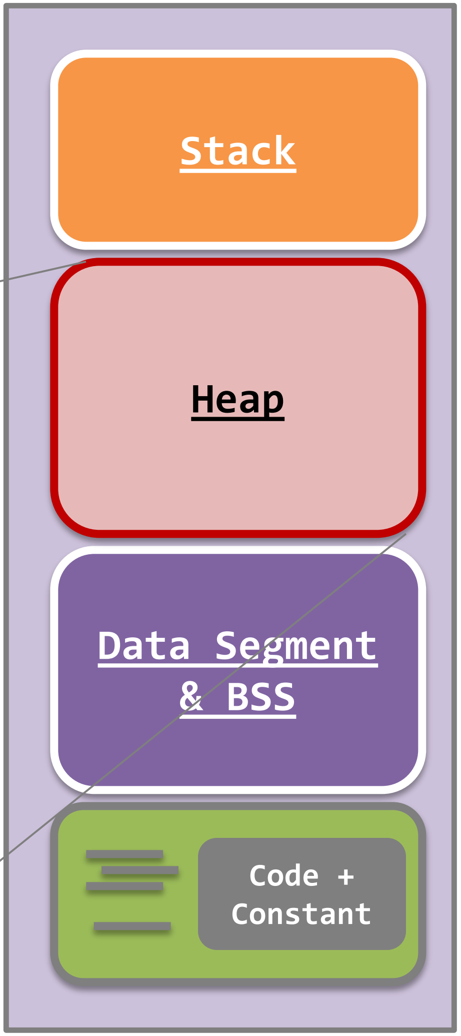
malloc()

The allocated space growing or shrinking depends on the further actions of the process. That means the "**brk()**" system call can **grow or shrink** the allocated area.

In **malloc()**, the library call just invoke **brk()** for growing the heap space.

The **free()** call may shrink the heap space.





malloc()

```
int main(void) {
  char *ptr1, *ptr2;
  ptr1 = (char *)malloc(16);
  ptr2 = (char *)malloc(16);

  printf("Distance between ptr1 an
         ptr2 - ptr1);
  return 0;
}
```

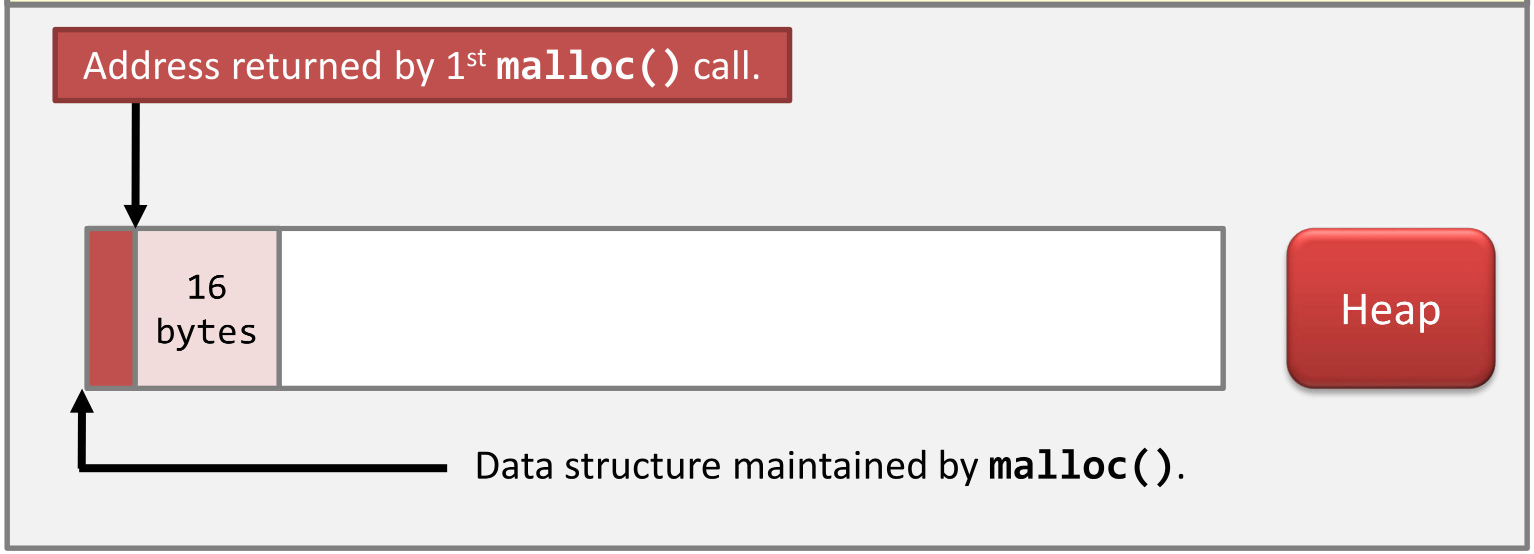
The return value of **malloc()** is of type "**void ***", which means it is just a memory address only, and can be of any data types.

Such a memory address is the starting address of a piece of memory of 16 bytes ("16" is the request of **malloc()** call).

Heap

malloc()

```
int main(void) {
  char *ptr1, *ptr2;
  ptr1 = (char *)malloc(16);
  ptr2 = (char *)malloc(16);

  printf("Distance between ptr1 and ptr2: %d bytes\n",
         ptr2 – ptr1);
  return 0;
}
```



malloc()

```
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  ptr1 = (char *)malloc(16);
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  printf("Distance between ptr1 and ptr2: %d bytes\n",
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  return 0;
}
```
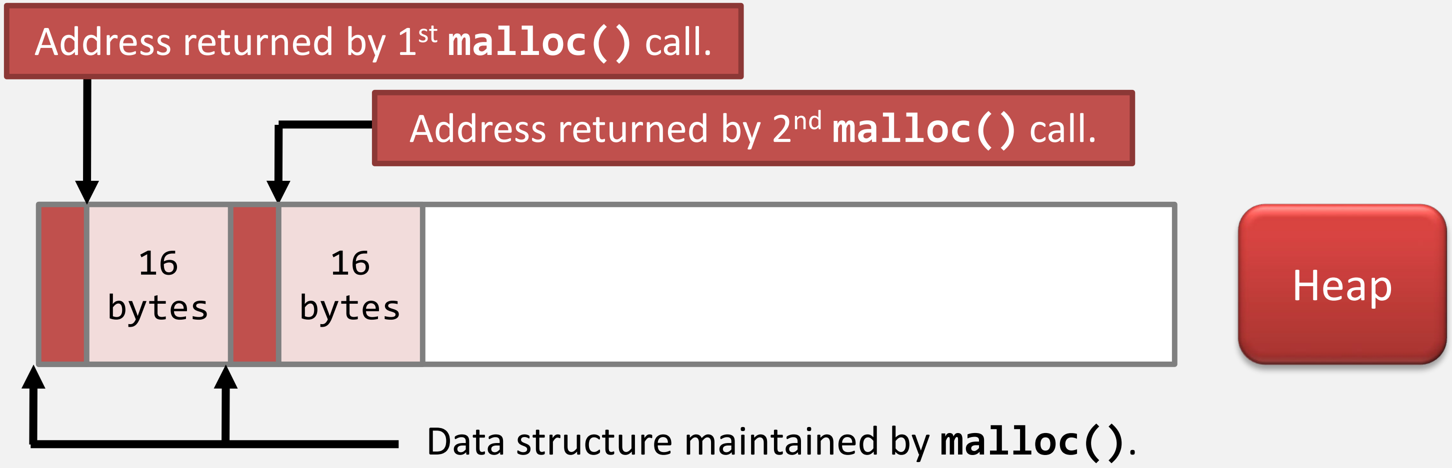
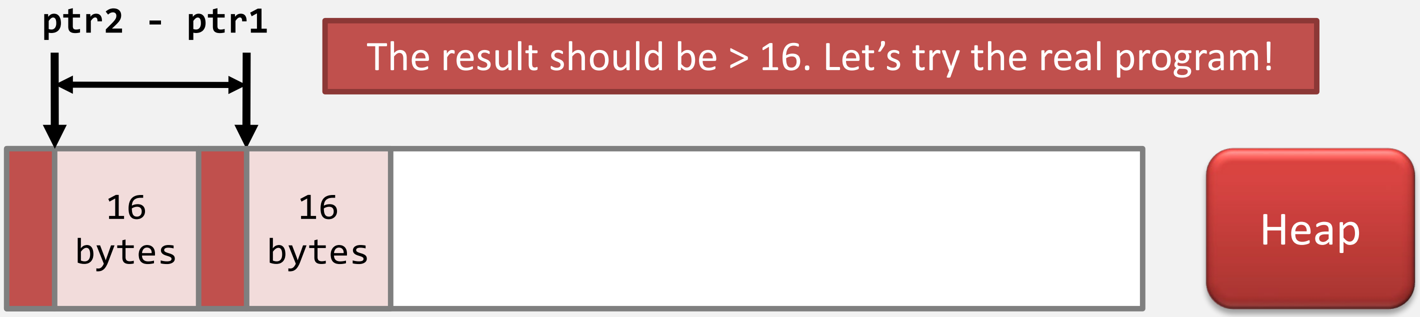



malloc()

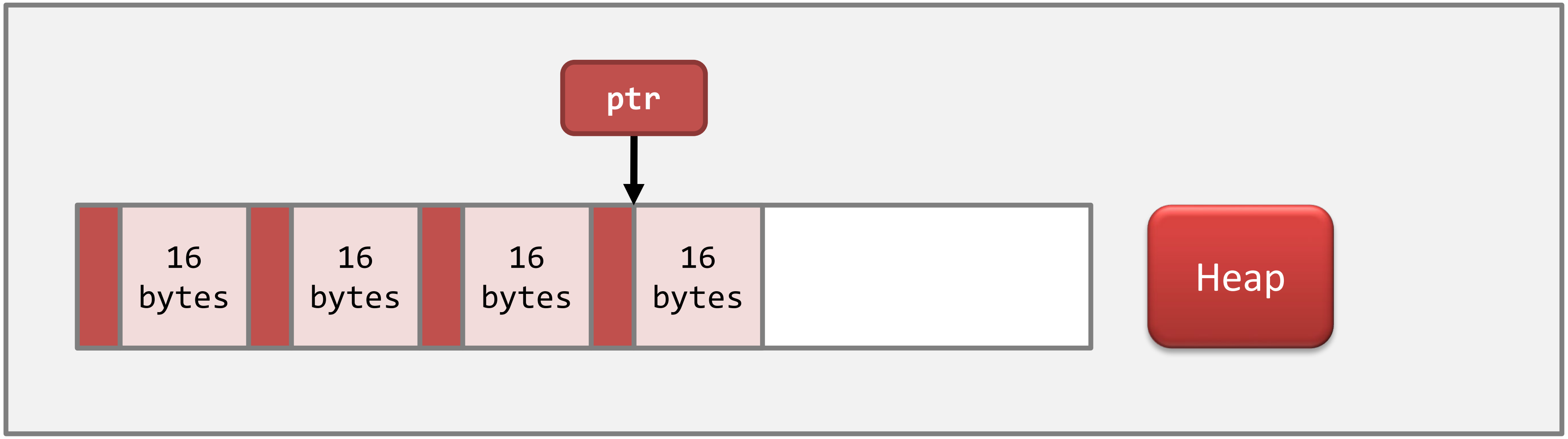
```
int main(void) {
  char *ptr1, *ptr2;
  ptr1 = malloc(16);
  ptr2 = malloc(16);

  printf("Distance between ptr1 and ptr2: %d bytes\n",
         ptr2 – ptr1);
  return 0;
}
```



The result should be > 16. Let’s try the real program!

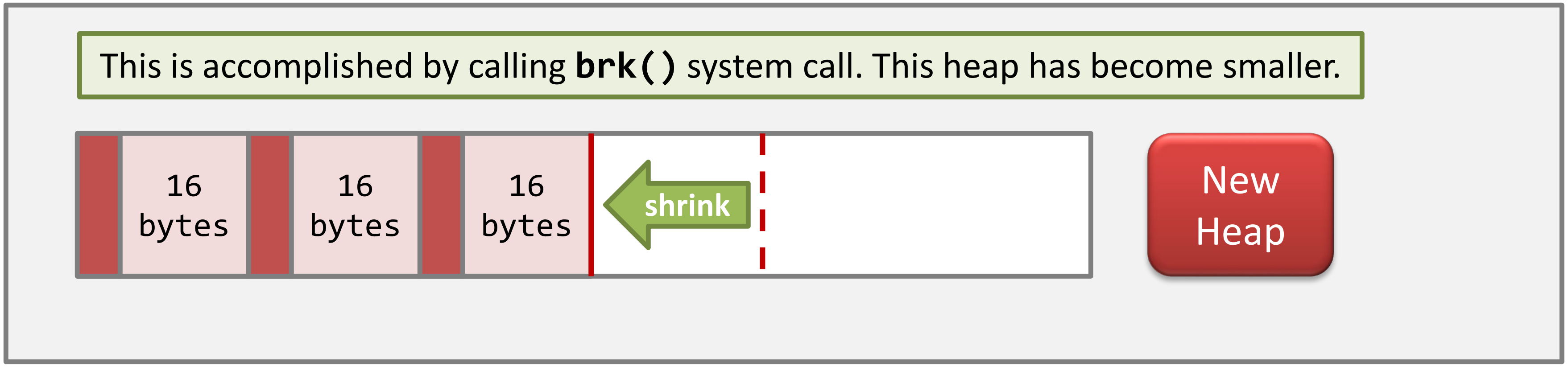
free()

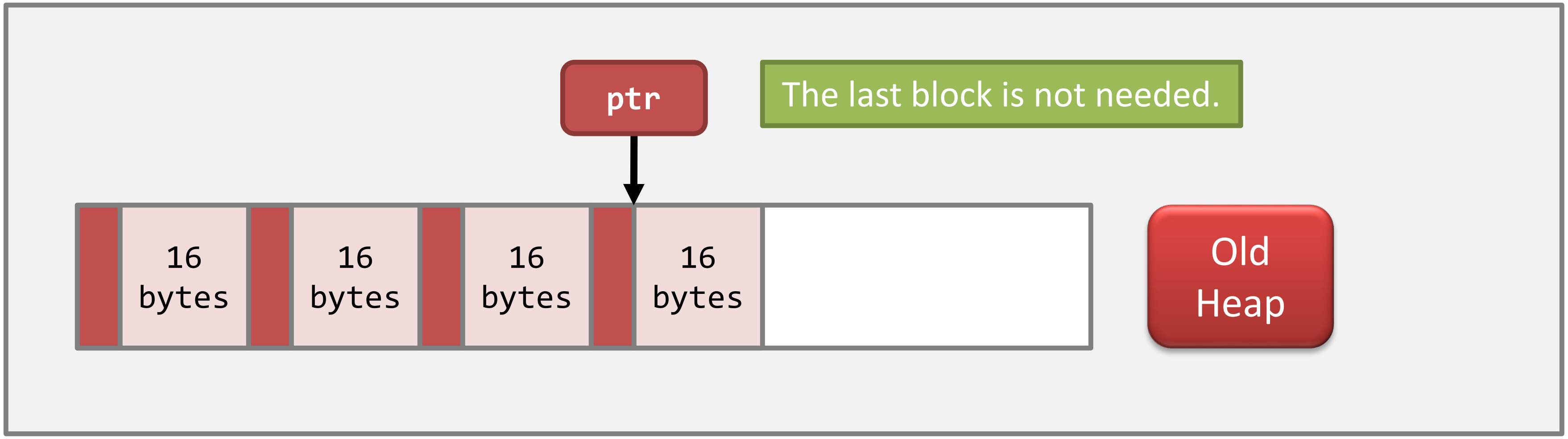
- "**free()**" *seems to* be the opposite to "**malloc()**":
  - It de-allocates any allocated memory.
  - When a program calls "**free(ptr)**", then the address "**ptr**" must be the start of a piece of memory obtained by a previous "**malloc()**" call.



`free()` – case #1

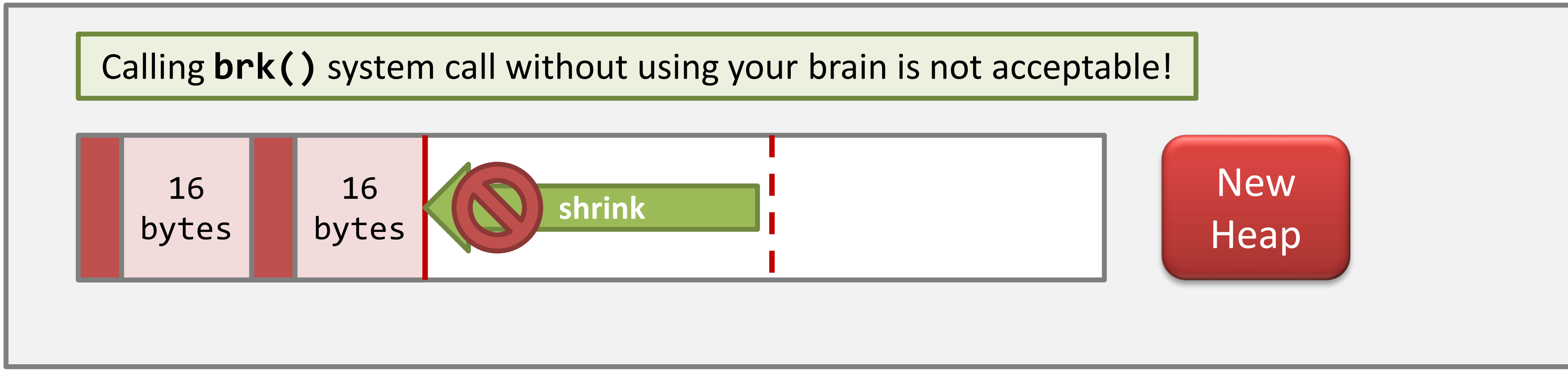
- Case #1: de-allocating the last block.

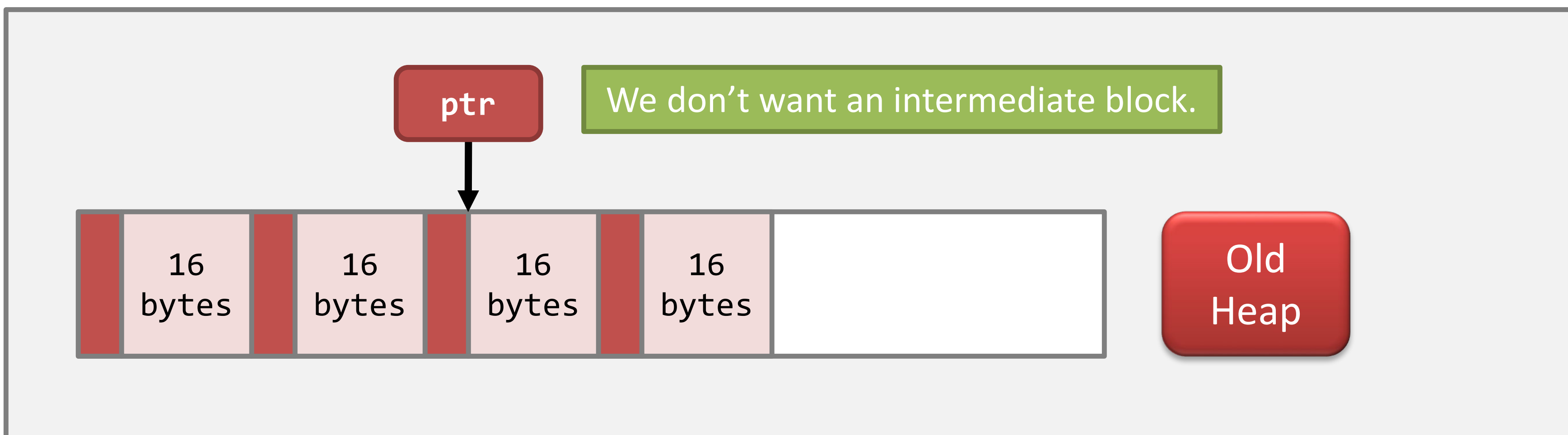




`free()` – case #2

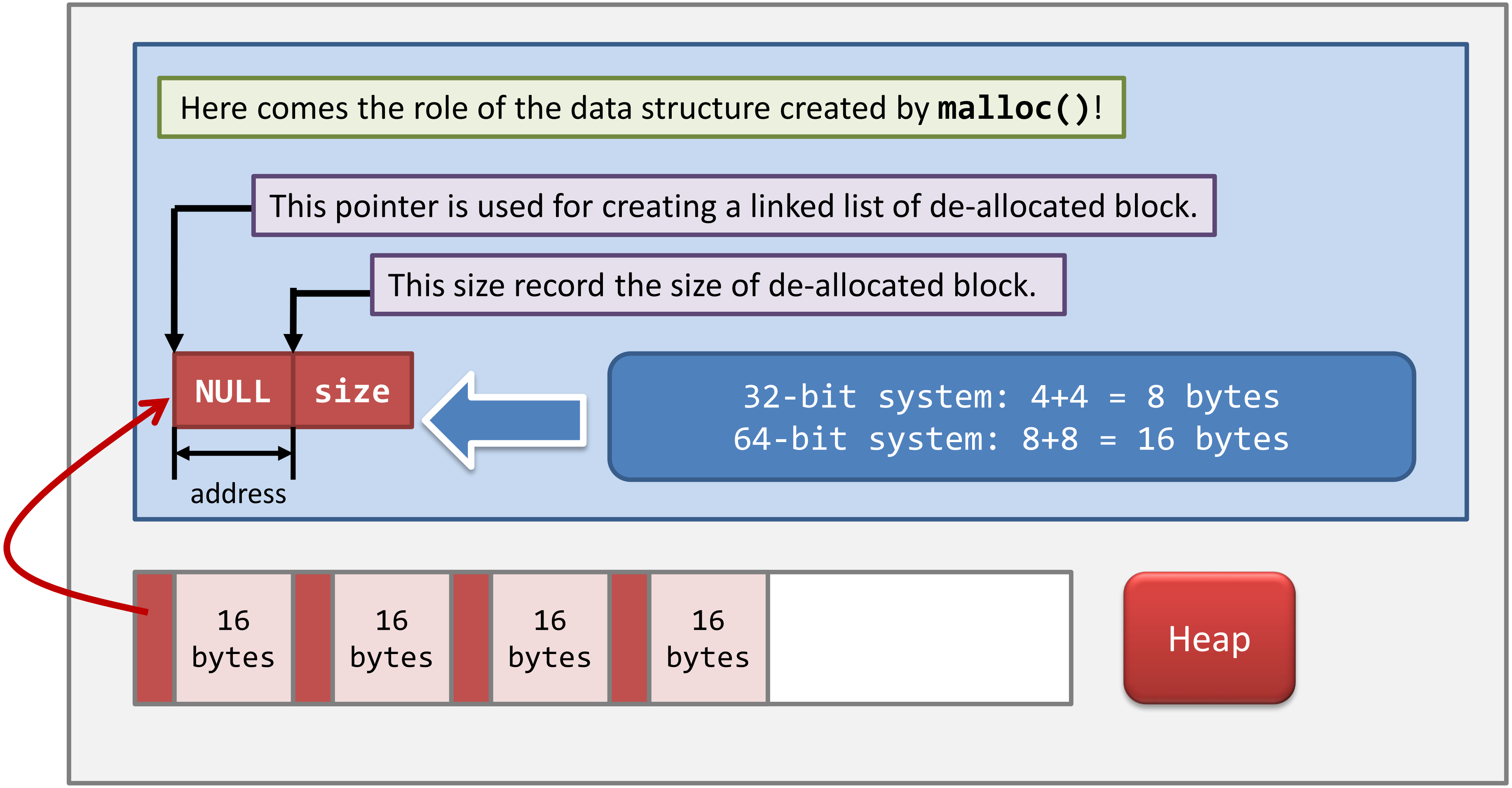
- Case #2: de-allocating an intermediate block.





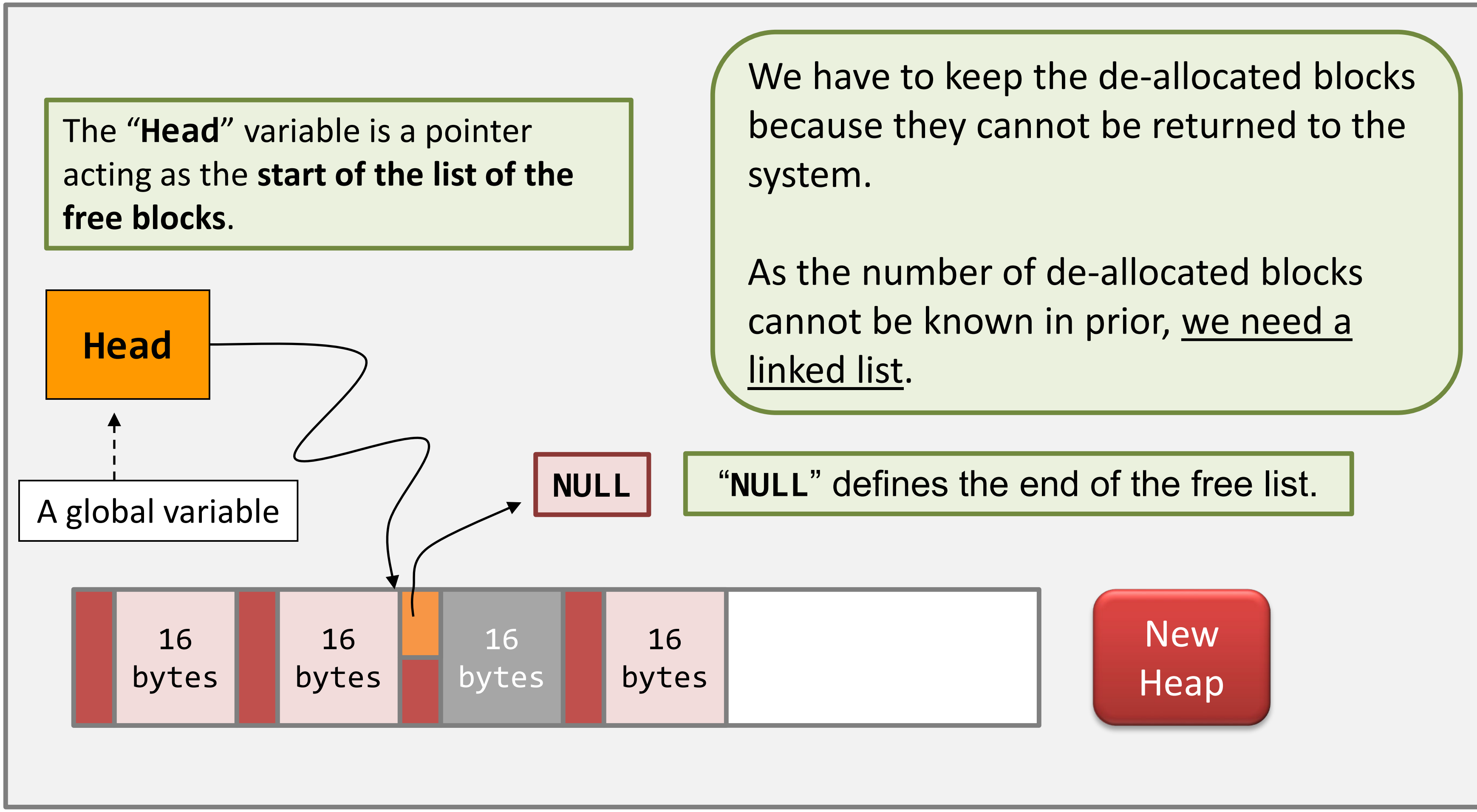
free() – case #2

- Case #2: de-allocating an intermediate block.



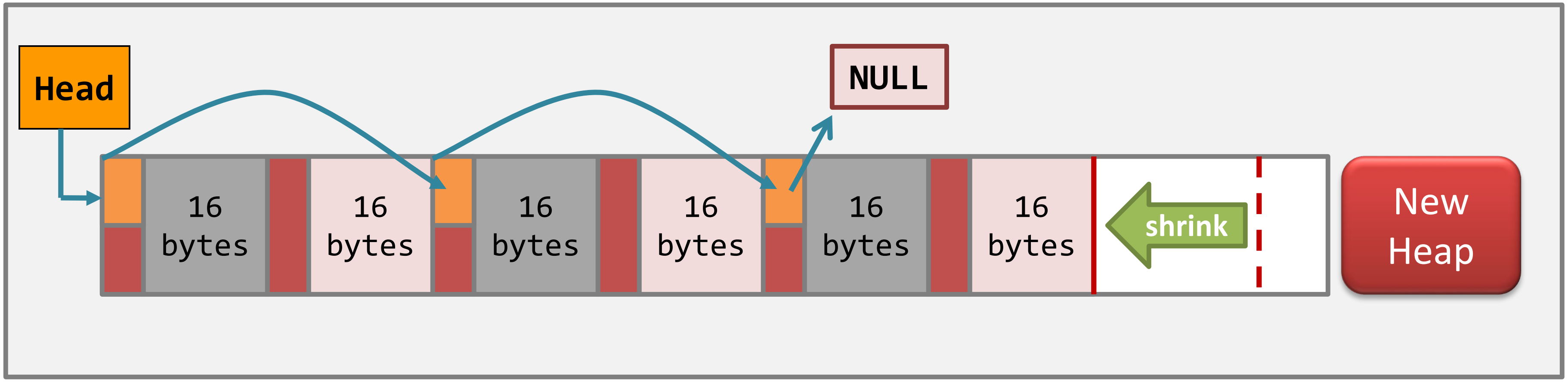
free() – case #2

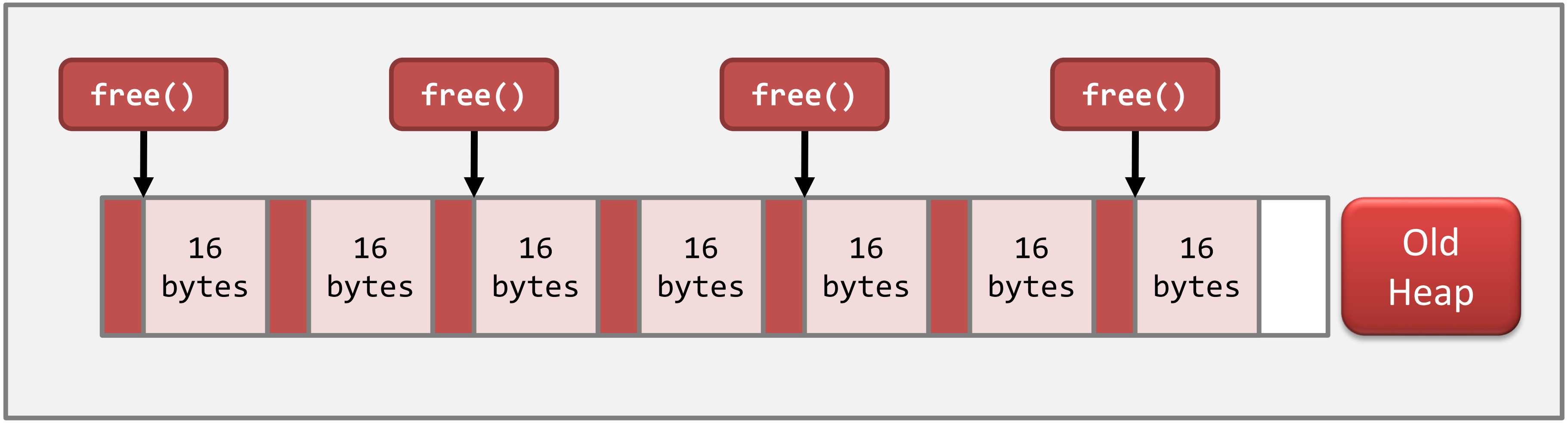
- Case #2: de-allocating an intermediate block.



free() – case #2

- Case #2: another example.

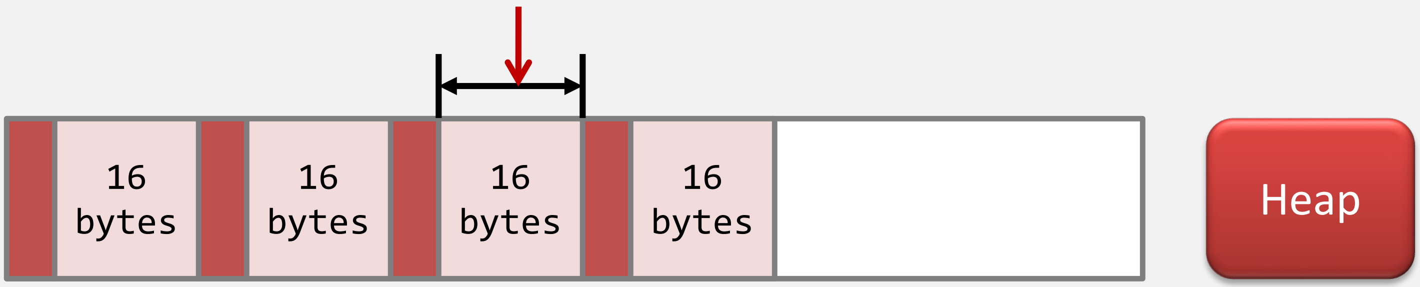




`free()` – cautions

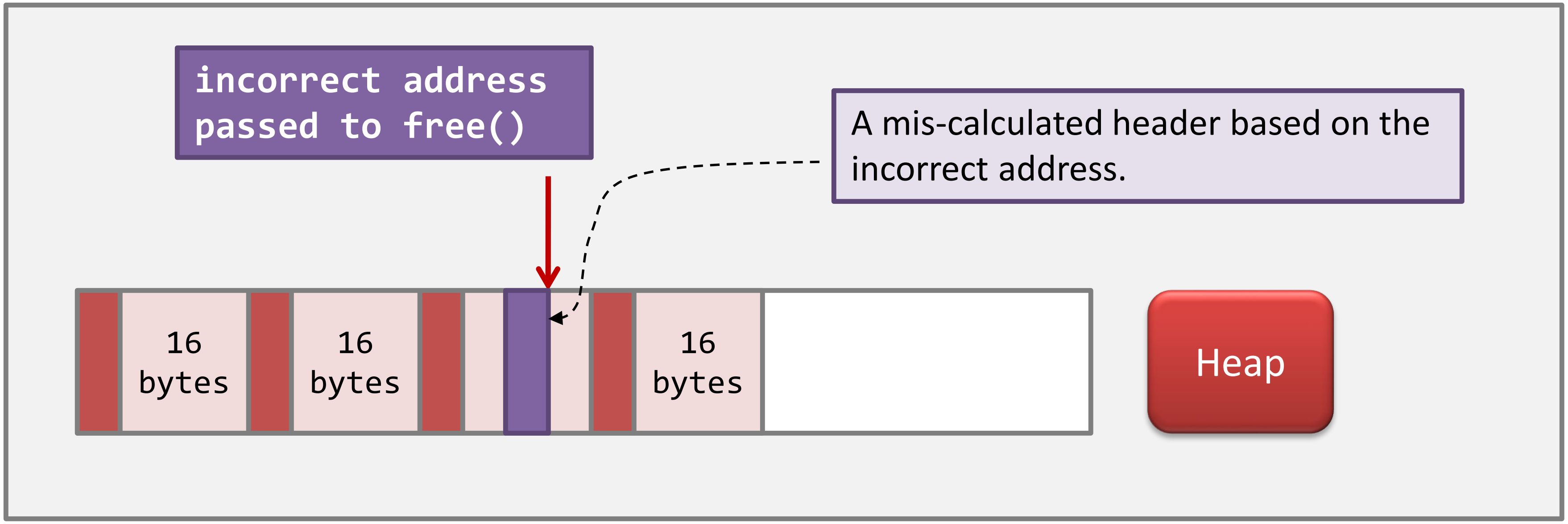
- The calling program is **assumed** to be carefully written.
  - After `malloc()` has been invoked, the program should read and write inside the requested area only.
  - Now, you know why you'd **have troubles** when you write data outside the allocated space.

You can only play within this zone. Please behave!
Note: be careful of the **consequences** of misbehaves…



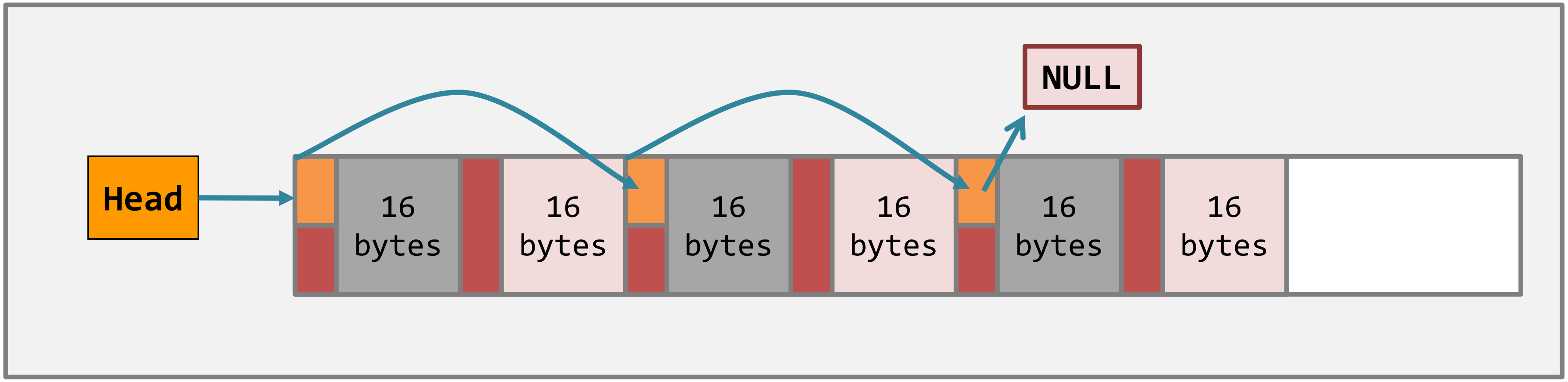
`free()` – cautions

- The calling program is **assumed** to be carefully written.
  - When **`free()`** is called, the program should provide **`free()`** with the correct address…
    - i.e., the address previously returned by a **`malloc()`** call.



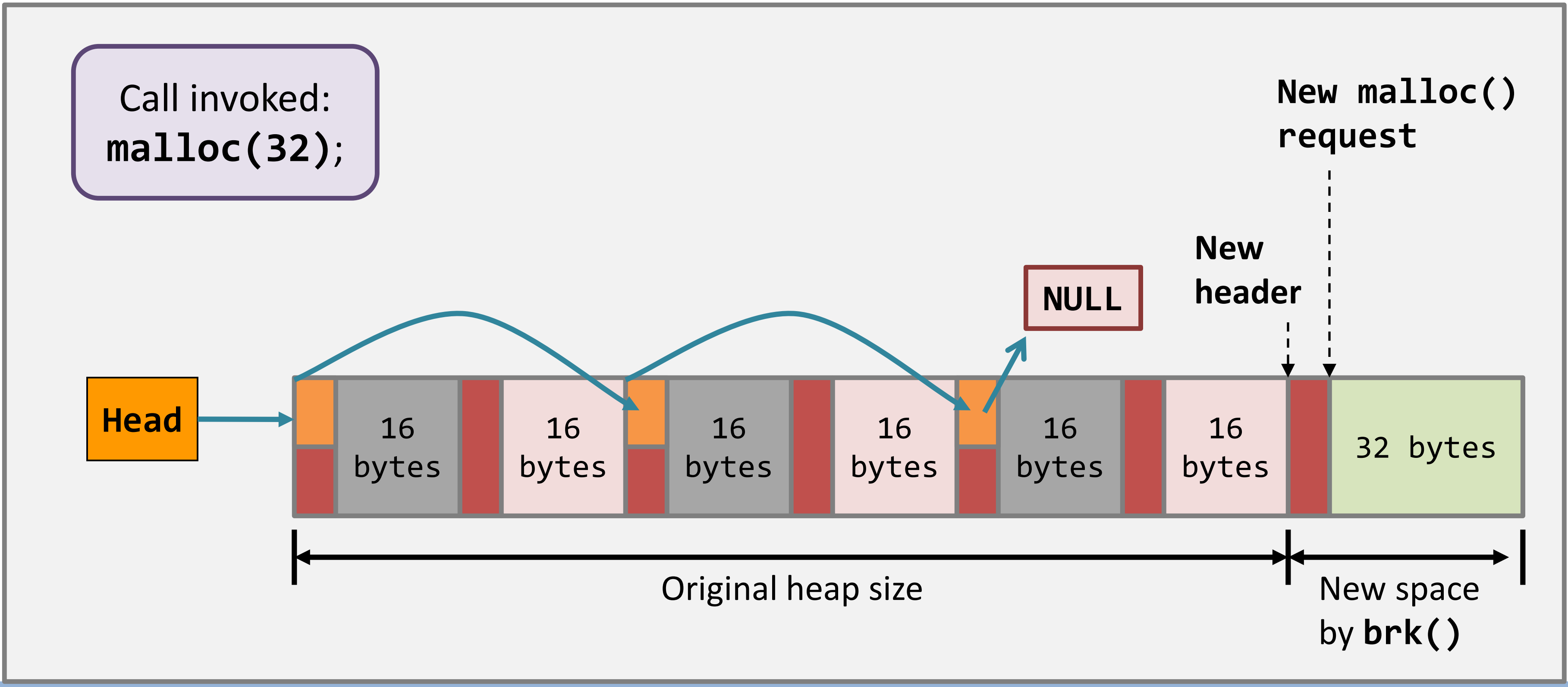
When **`malloc()`** meets free blocks…

- Problem: whether to use the free blocks or not?
  - *Is there any free block that is **large enough** to satisfy the need of the **`malloc()`** call?*



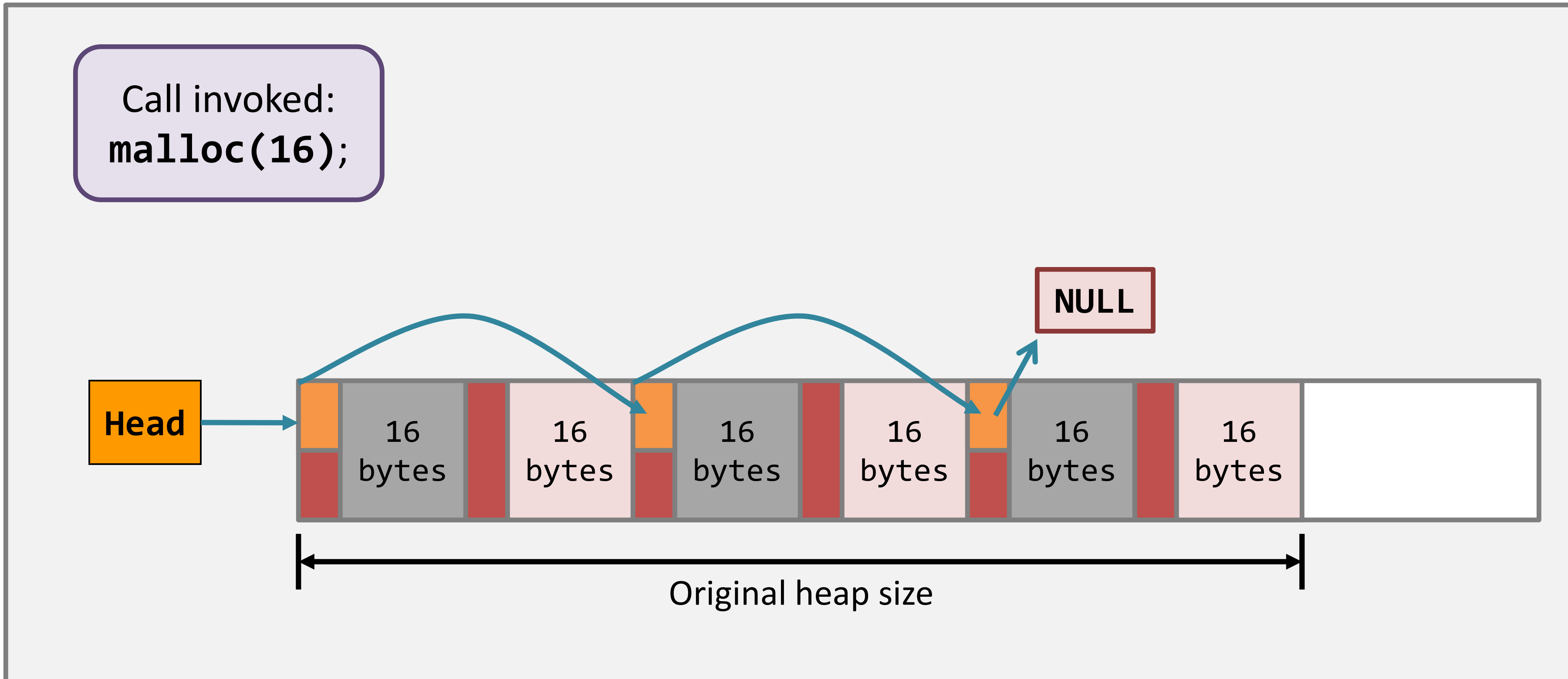
When **malloc()** meets free blocks…case #1

- Case #1: if there is **no suitable free block**…
  - then, the **malloc()** function should call **brk()** system call…in order to claim more heap space.



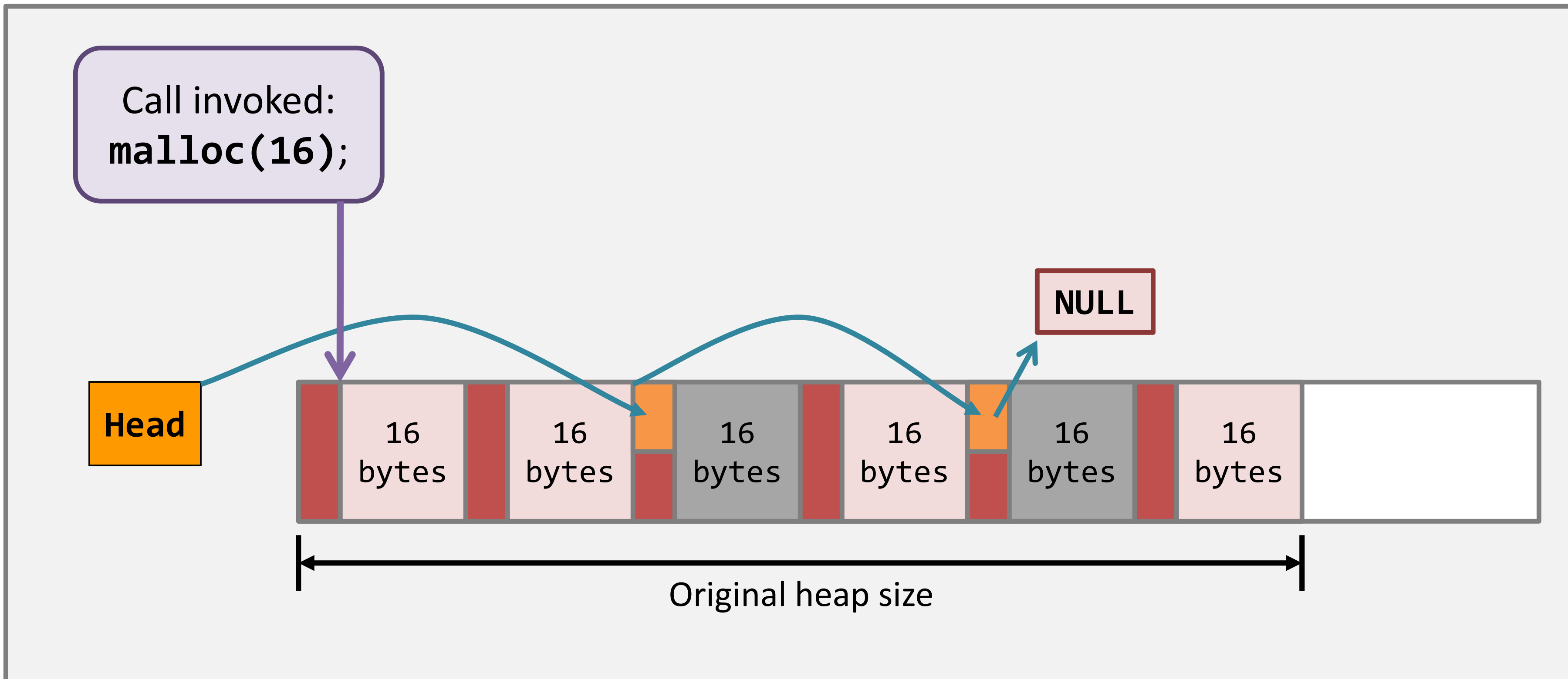
When `malloc()` meets free blocks…case #2

- Case #2: if there is a suitable free block



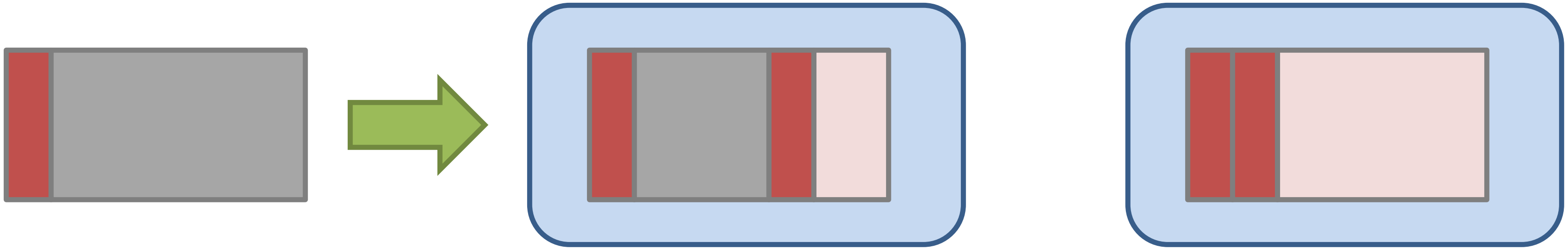
When `malloc()` meets free blocks…case #2

- Case #2: if there is a suitable free block
  - the `malloc()` function should reuse that free block.



When **malloc()** meets free blocks…

- There can be other cases:
  - A **malloc()** request that takes a partial block;
  - A **malloc()** request that takes a partial block, but leaving no space in the previously free block.



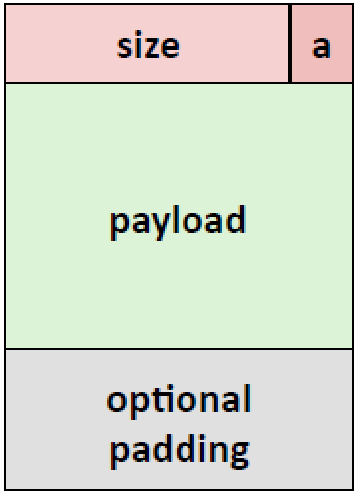
- We will skip those subtle cases…
  - It boils to implementation only...
  - You already have the **big picture** about **malloc()** and **free()**.

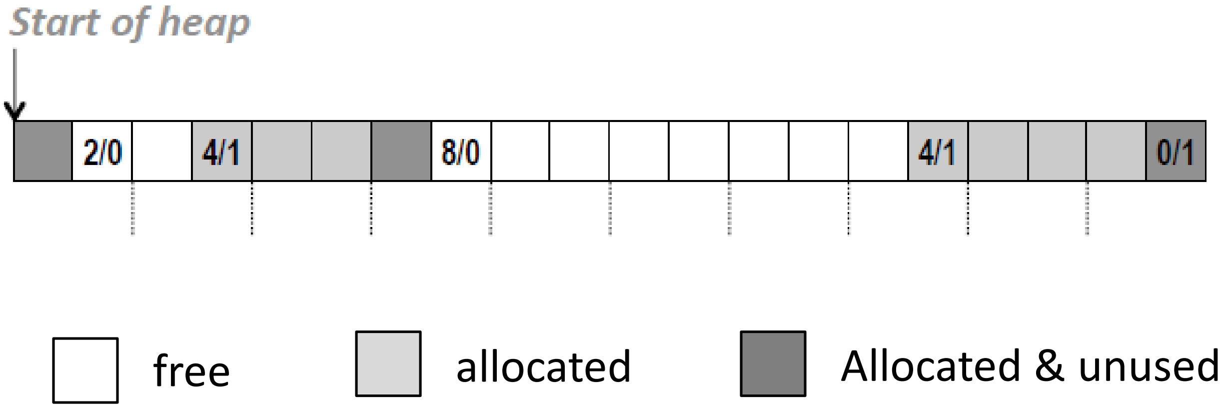
When `malloc()` meets free blocks…

- Now, let us look at some implementations…

Implicit free list

- Needs two information for each block
  - size & is_allocated

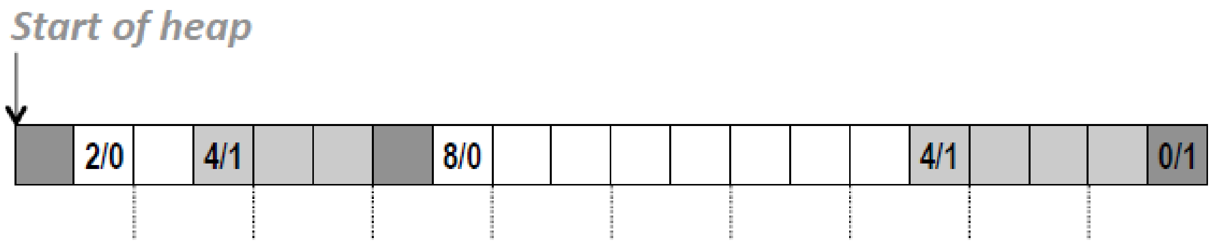




How about memory allocation and free?

Implicit free list

- **Contiguous Allocation**: May need linear time search



<u>First fit:</u> allocate the first hole that is big enough (fast)

<u>Next fit</u>: similar to first fit, but start where previous search finishes

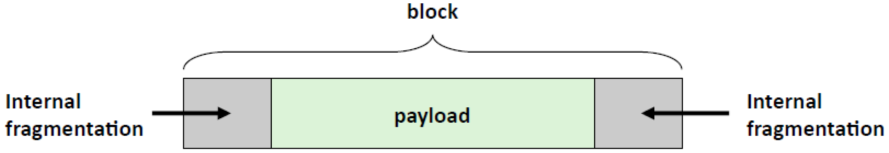
<u>Best fit:</u> allocate the smallest hole that is big enough (helps fragmentation, larger search time)

<u>Worst fit:</u> allocate the largest hole

– Allocate the whole block or splitting

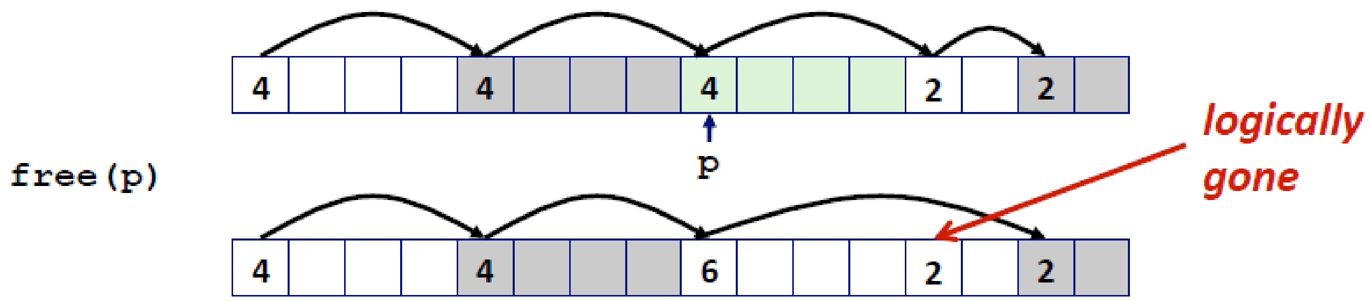
Fragmentation

- External fragmentation
  - The heap memory looks like a map with many holes
  - It is the source of inefficiency because of the **unavoidable search for suitable space**
  - Sol: Compaction (need to move data to merge free mem)
- Internal fragmentation
  - Payload is smaller than allocated block size

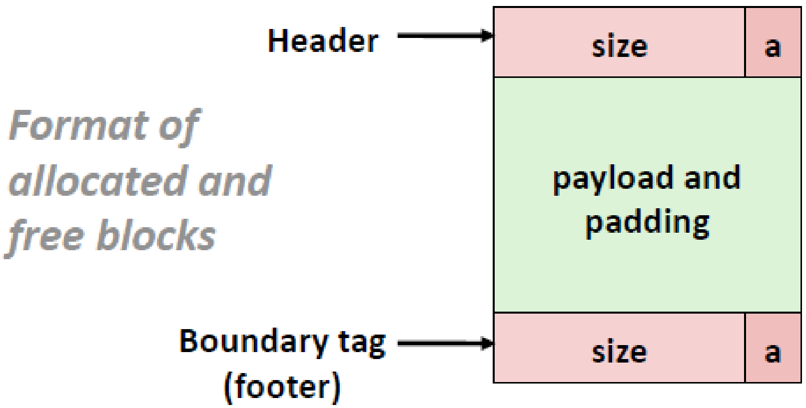


Implicit free list

- Free: Coalescing
  - Coalescing with next block: easy

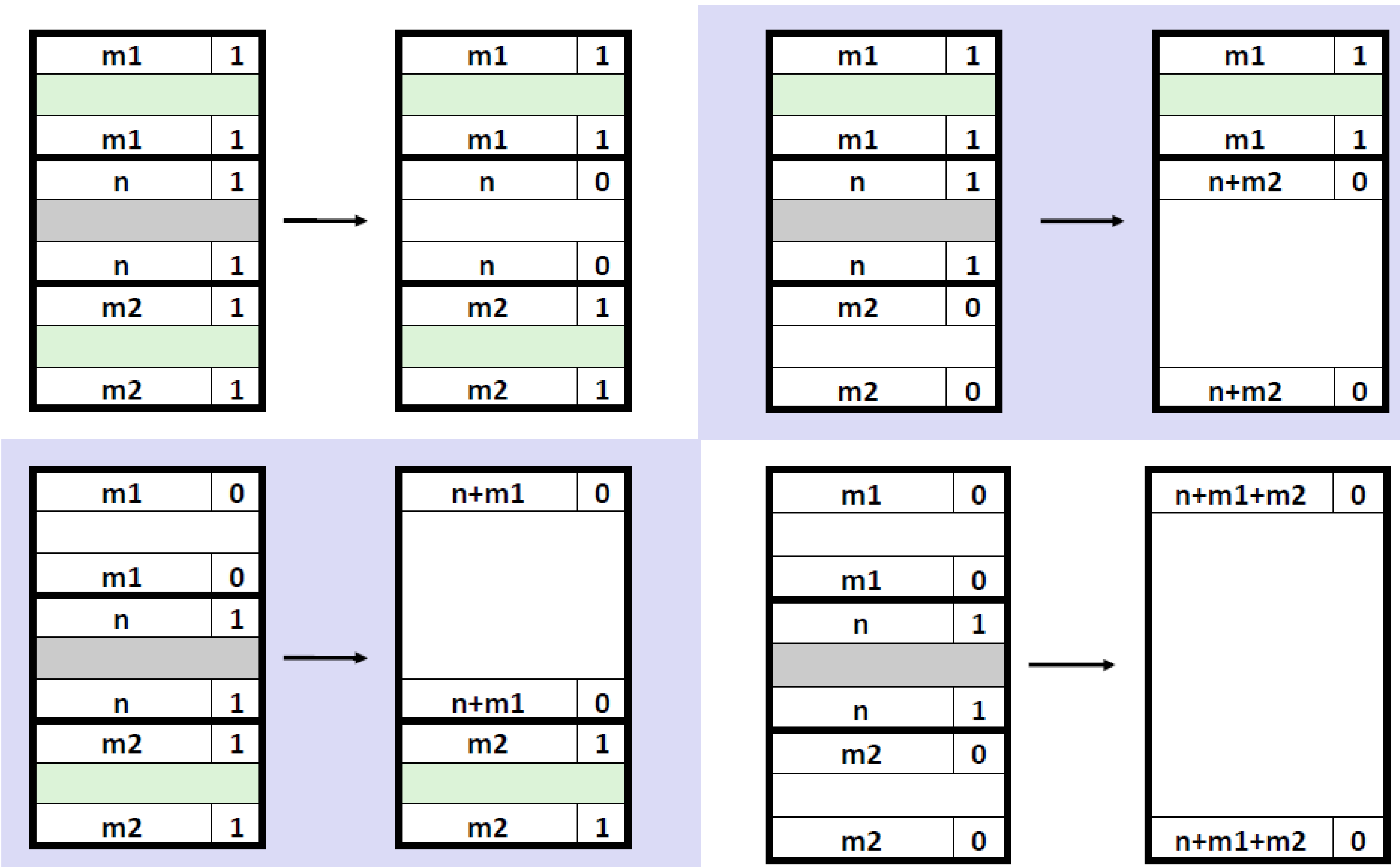


  - How about coalescing with previous block?
    - [Knuth 73] Add a boundary tag in the footer



Implicit free list

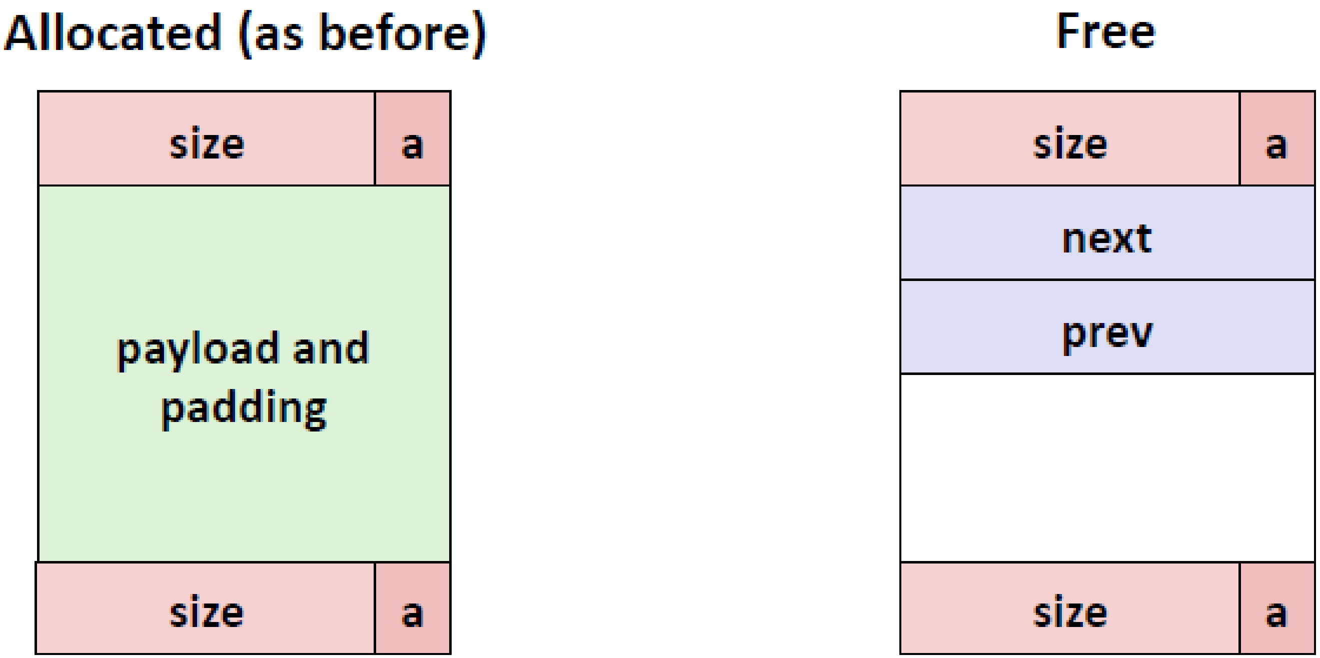
- Constant time coalescing w/ boundary tag (4 cases)



Implicit free list: summary

- May not be used in practical malloc() and free() implementations
  - High memory allocation cost
- Some ideas are still useful and important
  - Splitting available blocks
  - Boundary tag

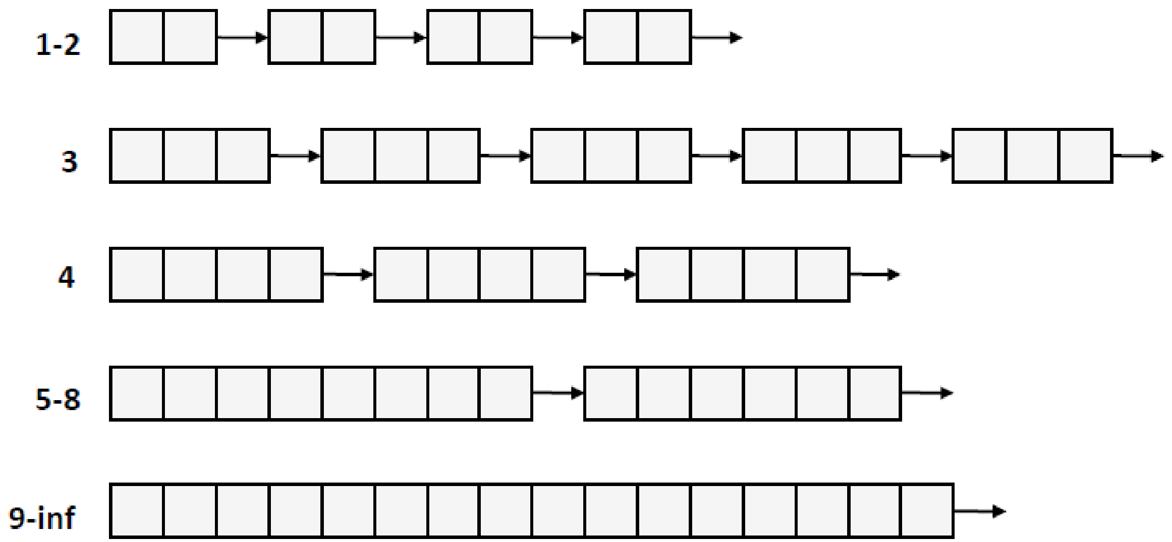
Explicit free list



- Track only free blocks (LIFO or address-ordered)
- Block splitting is useful in allocation
- Boundary tag is still useful in coalescing

Segregated free list

- Segregated free list (分离空闲链表)
  - Different free lists for different size classes

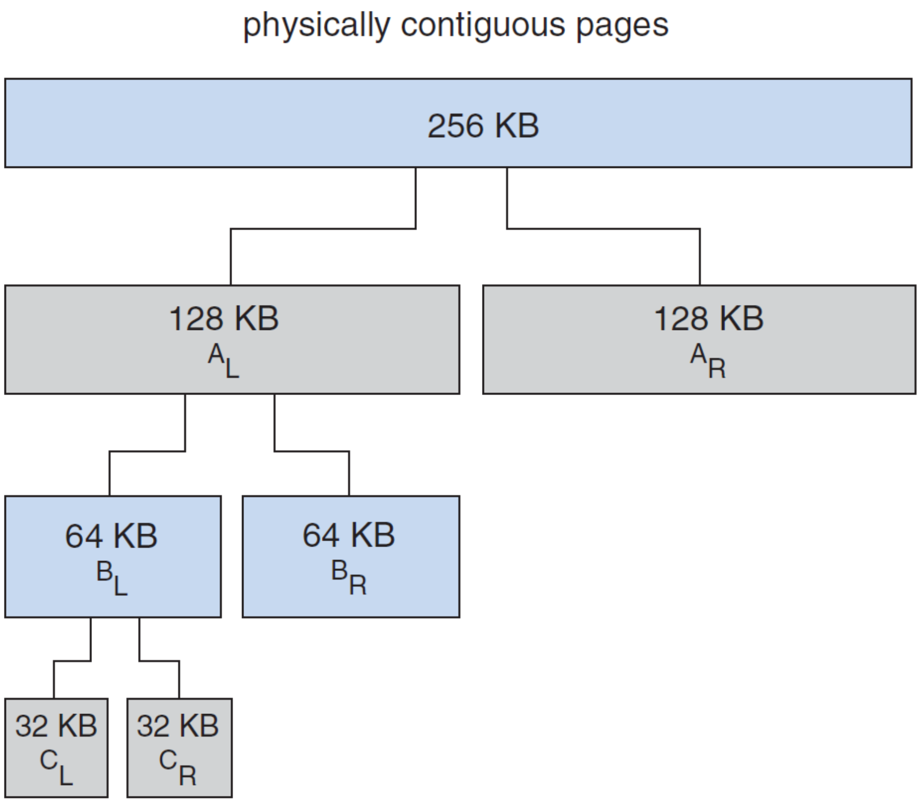


  - Allocation
    - Search appropriate list (larger size)
    - Found and split
    - Not found: search next

Approximates best -fit

Segregated free list

- Special example
  - Buddy system (power-of-two block size)



Issues raised by malloc() and free()

- The kernel knows how much memory should be given to the heap.
  - When you call **`brk()`**, the kernel **tries** to find the memory for you.

- Then…one natural question…
  - Is it possible to **run out of memory** **(OOM)**?

Out of memory?

- Try this!

```
#define ONE_MEG  1024 * 1024

int main(void) {
    void *ptr;
    int counter = 0;

    while(1) {
        ptr = malloc(ONE_MEG);
        if(!ptr)
            break;
        counter++;
        printf("Allocated %d MB\n", counter);
    }

    return 0;
}
```

Is it safe to run this program on a <u>32-bit machine</u>?

What is the output?

```
Allocated 3052 MB
Allocated 3053 MB
Allocated 3054 MB
Allocated 3055 MB
linux2:/uac/rshr/ykli>
```

Out of memory?

- On 32-bit Linux, why does the OOM generator stop at around 3055MB?

- Still remember what we said when we are talking about data segment?
  - Every 32-bit Linux system has an addressable memory space of 4G-1 bytes.
  - The kernel reserves 1GB addressing space.

Out of memory?

- Try this! Yet another OOM Generator!

```
#define ONE_MEG  1024 * 1024
char global[1024 * ONE_MEG];
int main(void) {
    void *ptr;
    int counter = 0;
    char local[8000 * 1024];
    while(1) {
        ptr = malloc(ONE_MEG);
        if(!ptr)
            break;
        counter++;
        printf("Allocated %d MB\n", counter);
    }

    return 0;
}
```

Yet, what is the output?

```
Allocated 3044 MB
Allocated 3045 MB
Allocated 3046 MB
Allocated 3047 MB
linux2:/uac/rshr/ykli>
```

Real OOM!

Explanation is in Part 2.

```
#define ONE_MEG  1024 * 1024

int main(void) {
    void *ptr;
    int counter = 0;

    while(1) {
        ptr = malloc(ONE_MEG);
        if(!ptr)
            break;
        memset(ptr, 0, ONE_MEG);
        counter++;
        printf("Allocated %d MB\n", counter);
    }

    return 0;
}
```

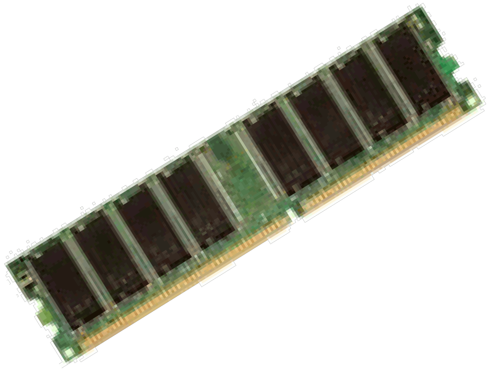
Warning #1. Don't run this program on any department's machines.

Warning #2. Don't run this program when you have important tasks running at the same time.

Lazy allocation
That is why previous programs run very fast.

User-space memory management

- Address space;
- Code & constants;
- Data segment;
- Stack;
- Heap;
- **Segmentation fault;**



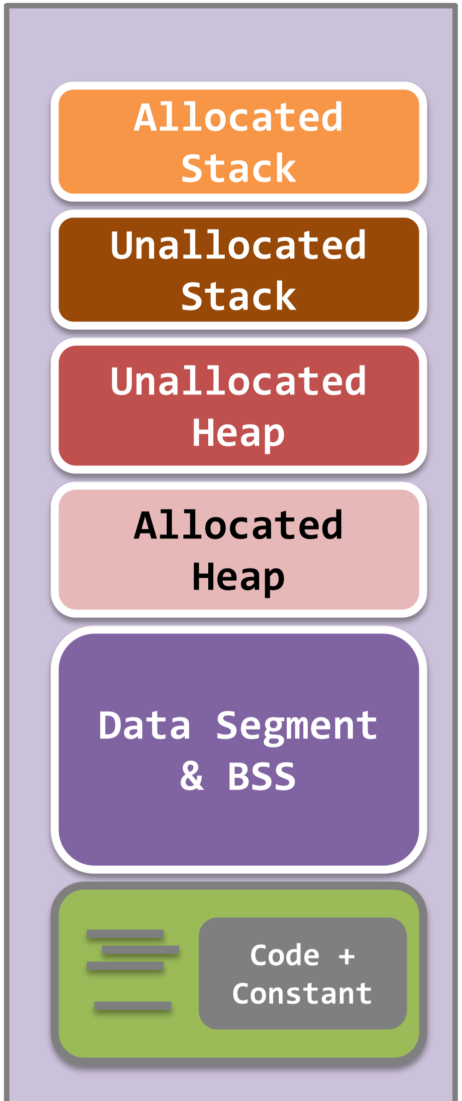
What is segmentation fault?

- Someone must have told you:

  – When you are accessing a piece of memory that is not allowed to be accessed, then the OS returns you an error called – segmentation fault.

- As a matter of fact, **how many ways** are there to generate a segmentation fault?

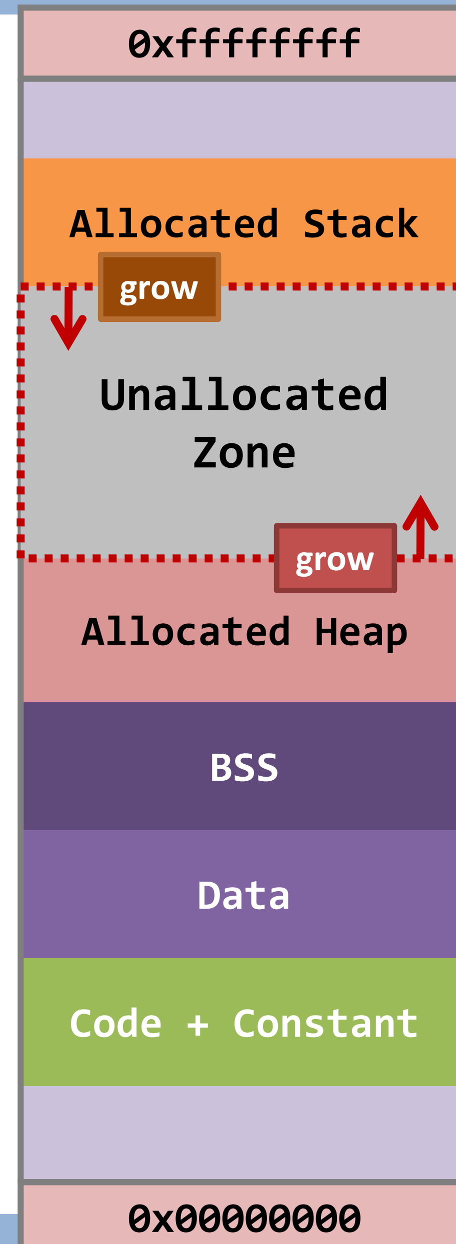
What is segmentation fault?



From illustration to reality…

Forget about the illustration, the memory in a process is separated into **segments**.

So, when you visit a segment in an illegal way, then…**segmentation fault**.



How to “segmentation fault”?

Read	0xffffffff	Write
YES	Unusable	YES
NO	Allocated Stack	NO
YES	Unallocated Zone	YES
NO	Allocated Heap	NO
NO	BSS	NO
NO	Data	NO
NO	Code + Constant	YES
YES	Unusable	YES
	0x00000000	

How to "segmentation fault"?

Read	0xffffffff	Write
YES	Unusable	YES
NO	Allocated Stack	NO
YES	Unallocated Zone	YES
NO	Allocated Heap	NO
NO	BSS	NO
NO	Data	NO
NO	Code + Constant	YES
YES	Unusable	YES
	0x00000000	

Now, we can understand:

```
char *ptr = NULL;
char c = *ptr;
```

will generates

Segmentation fault

NULL = 0x00000000

*ptr is reading

Summary of segmentation fault

- When you have a **so-called address** (maybe it is just a random sequence of 4 bytes), one of the following cases happens:

See if you have luck…

	Read-only segments	Allocated segments	Unused or unallocated segments
Reading	No problem	No problem	**Segmentation fault**
Writing	**Segmentation fault**	No problem	**Segmentation fault**

Summary of segmentation fault

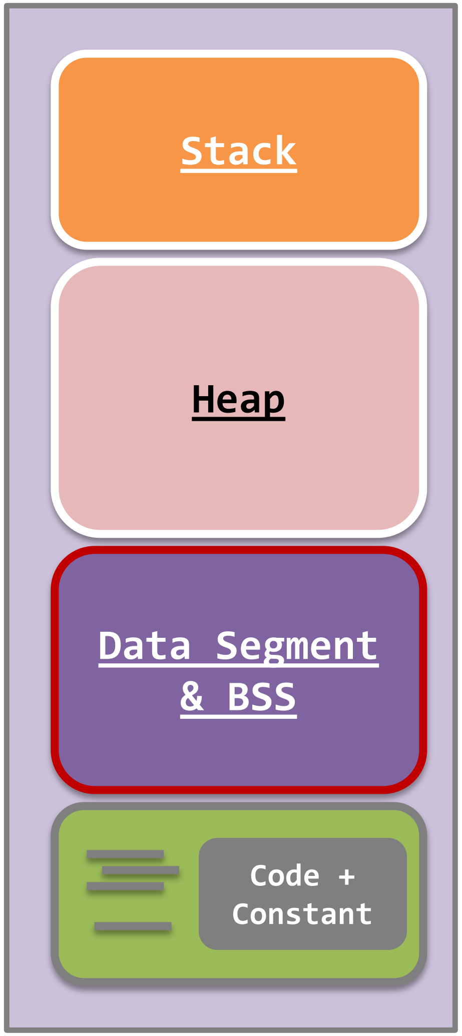
- Now, you know what is a segmentation fault, and the cause is always **carelessness**!
  - Now, you know why "**`free()`**" sometimes give you segmentation fault…
    - because **you corrupt the list of free blocks**!
  - Now, you know why "**`malloc()`**"-ing a space that is smaller than required is ok…
    - because **you are overwriting the neighboring blocks**!

Summary of part 1

- Memory of a process is divided into segments (**segmentation**):
  - codes and constants;
  - global and static variables;
  - allocated memory (or heap);
  - local variables (or stack);

- When you access a memory that is not allowed, then the OS returns you **segmentation fault**

- **Every process' segments are independent and distinct.**



Summary of part 1

- The dynamically allocated memory is not as simple as you learned before.
  - Allocating large memory blocks is not efficient; instead, **allocating small memory blocks** can make use of the **holes** in the heap memory efficiently.
  - Keep calling **malloc()** without calling **free()** is dangerous…
    - because there is no garbage collector in C or the OS…
    - **OOM error awaits you!**

End of part 1