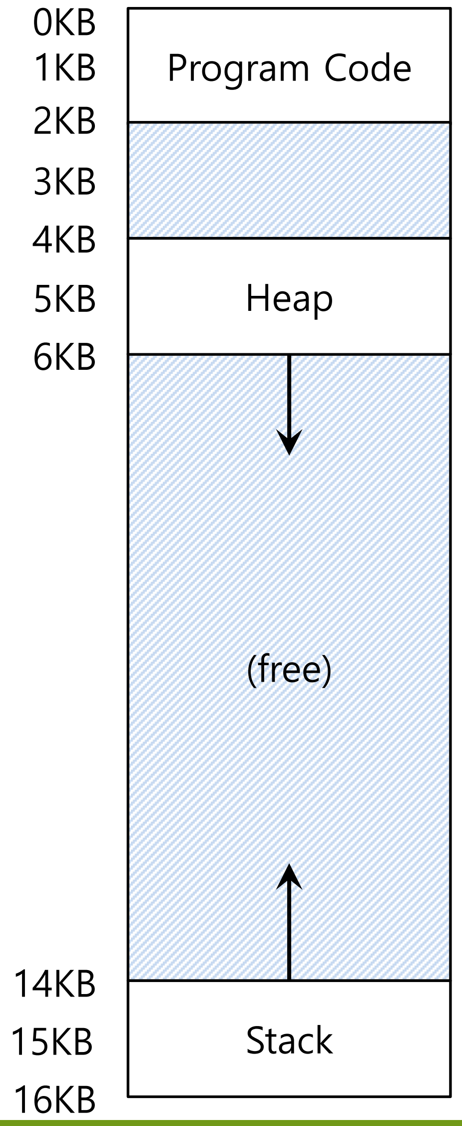
Memory Segmentation and Free-Space Management

Inefficiency of Base and Bound Approach

- Big chunk of “free” space
- “free” space takes up physical memory
- Hard to run when an address space does not fit into physical memory

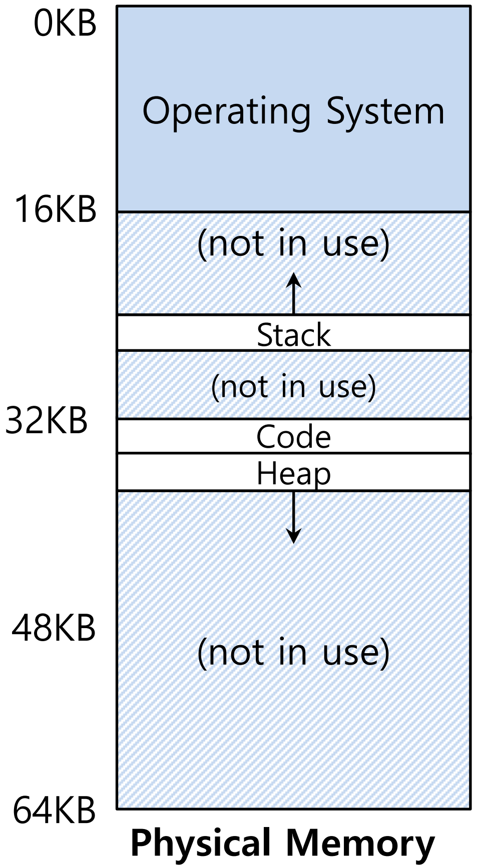


Segmentation

- Segment is just **a contiguous portion** of the address space of a particular length
  - Logically-different segment: code, stack, heap, and etc.

- Each segment can be **placed** in **different part of physical memory**
  - **Base** and **bounds** exist **per each segment**

Placing Segment In Physical Memory



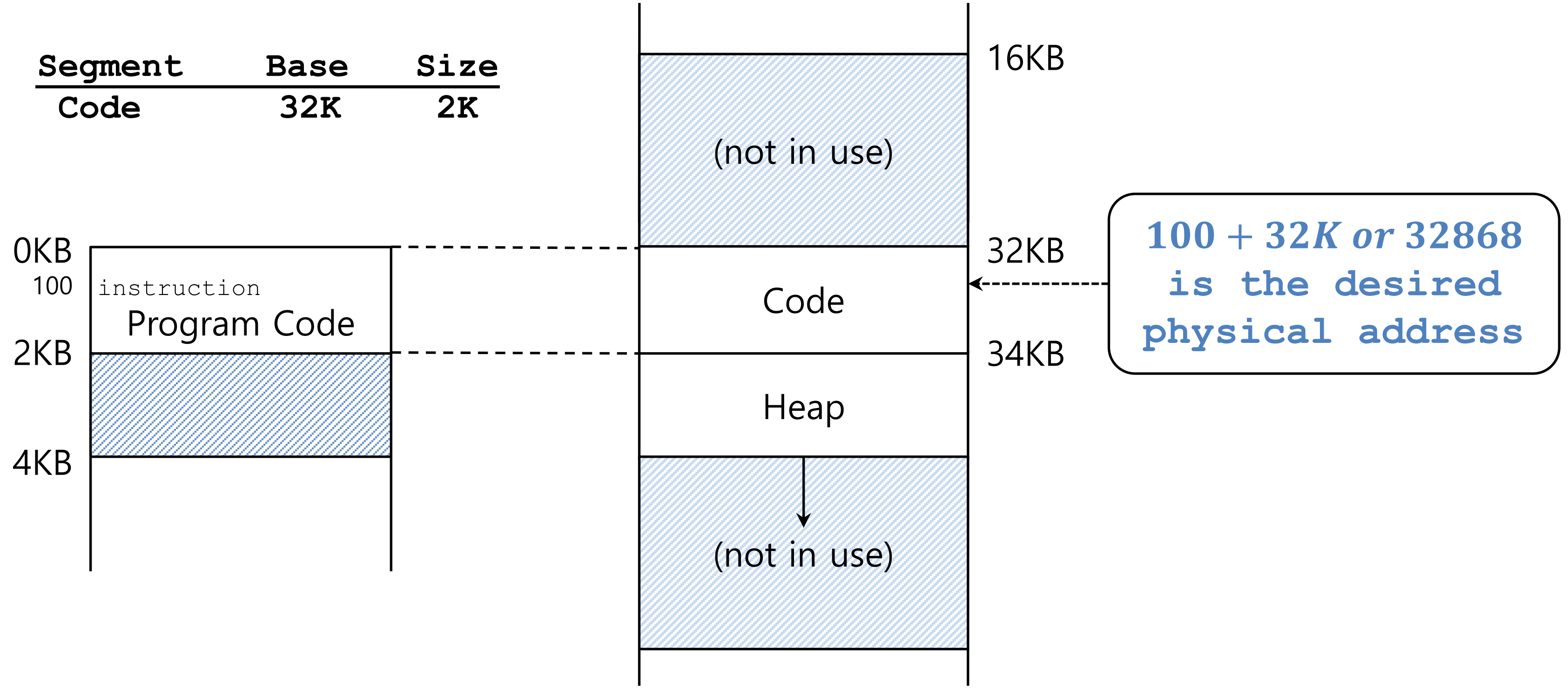
Segment	Base	Size
Code	32K	2K
Heap	34K	2K
Stack	28K	2K

Address Translation on Segmentation

$$physical\ address = offset + base$$

- The `offset` of virtual address 100 is `100`
  - The code segment **starts at virtual address 0** in address space

Segment	Base	Size
Code	32K	2K

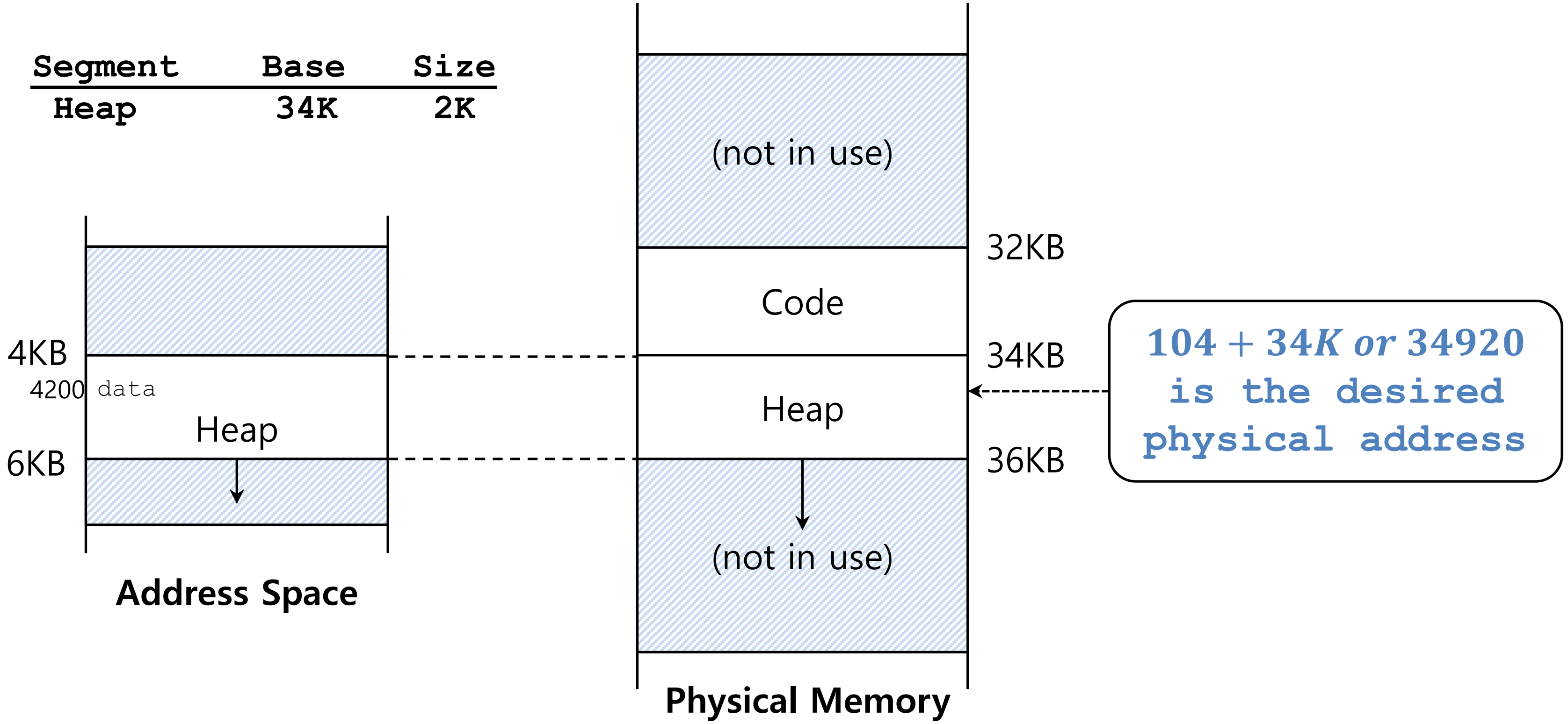


Address Translation on Segmentation

Virtual address + base is not the correct physical address

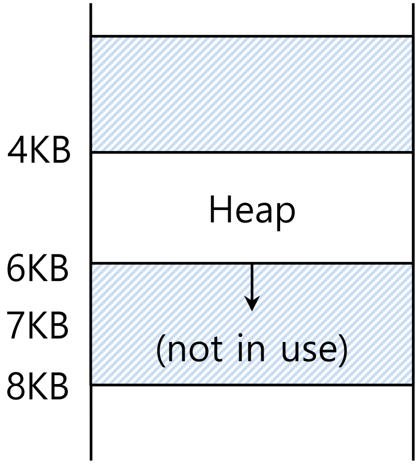
- The offset of virtual address 4200 is 104
  - The heap segment starts at virtual address 4096 in address space

Segment	Base	Size
Heap	34K	2K



Segmentation Fault or Violation

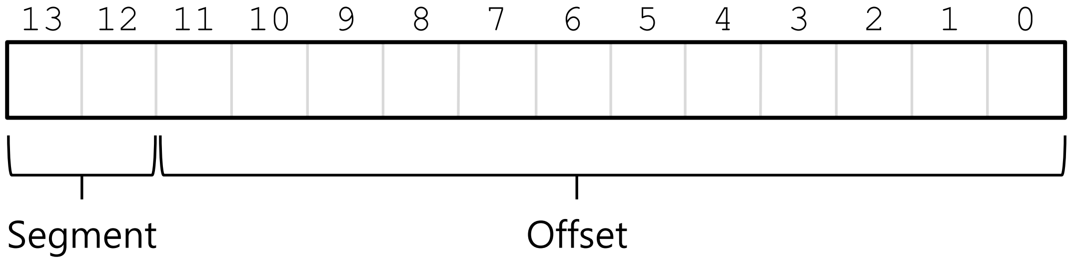
- If an **illegal address** such as 7KB which is beyond the end of heap is referenced, the OS occurs **segmentation fault**
  - The hardware detects that address is **out of bounds**



Address Space

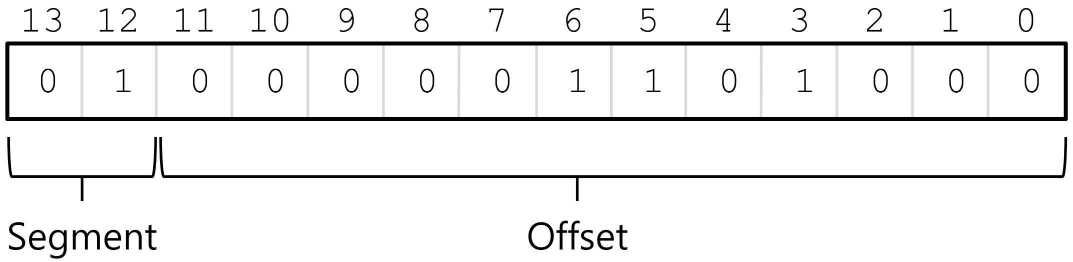
Referring to Segment

- **Explicit approach**
  - Chop up the address space into segments based on the **top few bits** of virtual address



- Example: virtual address 4200 (01000001101000)

Segment	bits
Code	00
Heap	01
Stack	10
-	11



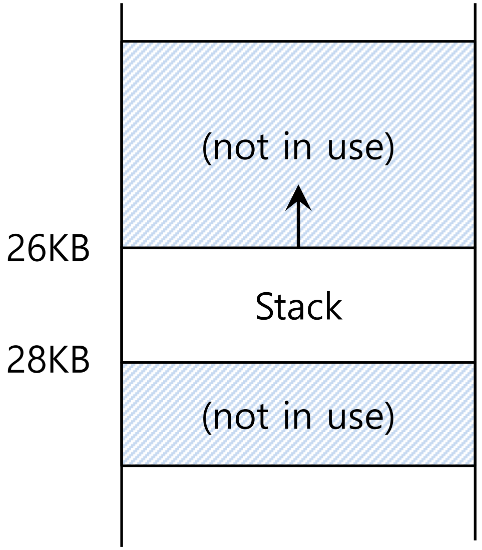
Referring to Segment

```
// get top 2 bits of 14-bit VA
Segment = (VirtualAddress & SEG_MASK) >> SEG_SHIFT
// now get offset
Offset = VirtualAddress & OFFSET_MASK
if (Offset >= Bounds[Segment])
    RaiseException(PROTECTION_FAULT)
else
    PhysAddr = Base[Segment] + Offset
    Register = AccessMemory(PhysAddr)
```

- SEG_MASK = 0x3000(11000000000000)
- SEG_SHIFT = 12
- OFFSET_MASK = 0xFFF (00111111111111)

Referring to Stack Segment

- Stack grows **backward**
- **Extra hardware support** is need
  - The hardware checks which way the segment grows
  - 1: positive direction, 0: negative direction



Physical Memory

Segment Register(with Negative-Growth Support)

Segment	Base	Size	Grows Positive?
Code	32K	2K	1
Heap	34K	2K	1
Stack	28K	2K	0

Support for Sharing

- Segment can be **shared between address** space
  - **Code sharing** is still in use in systems today
  - by extra hardware support
- Extra hardware support is need for form of **Protection bits**
  - **A few more bits** per segment to indicate **permissions** of **read,** write and **execute**

Segment Register Values(with Protection)

Segment	Base	Size	Grows Positive?	Protection
Code	32K	2K	1	Read-Execute
Heap	34K	2K	1	Read-Write
Stack	28K	2K	0	Read-Write

Fine-Grained and Coarse-Grained

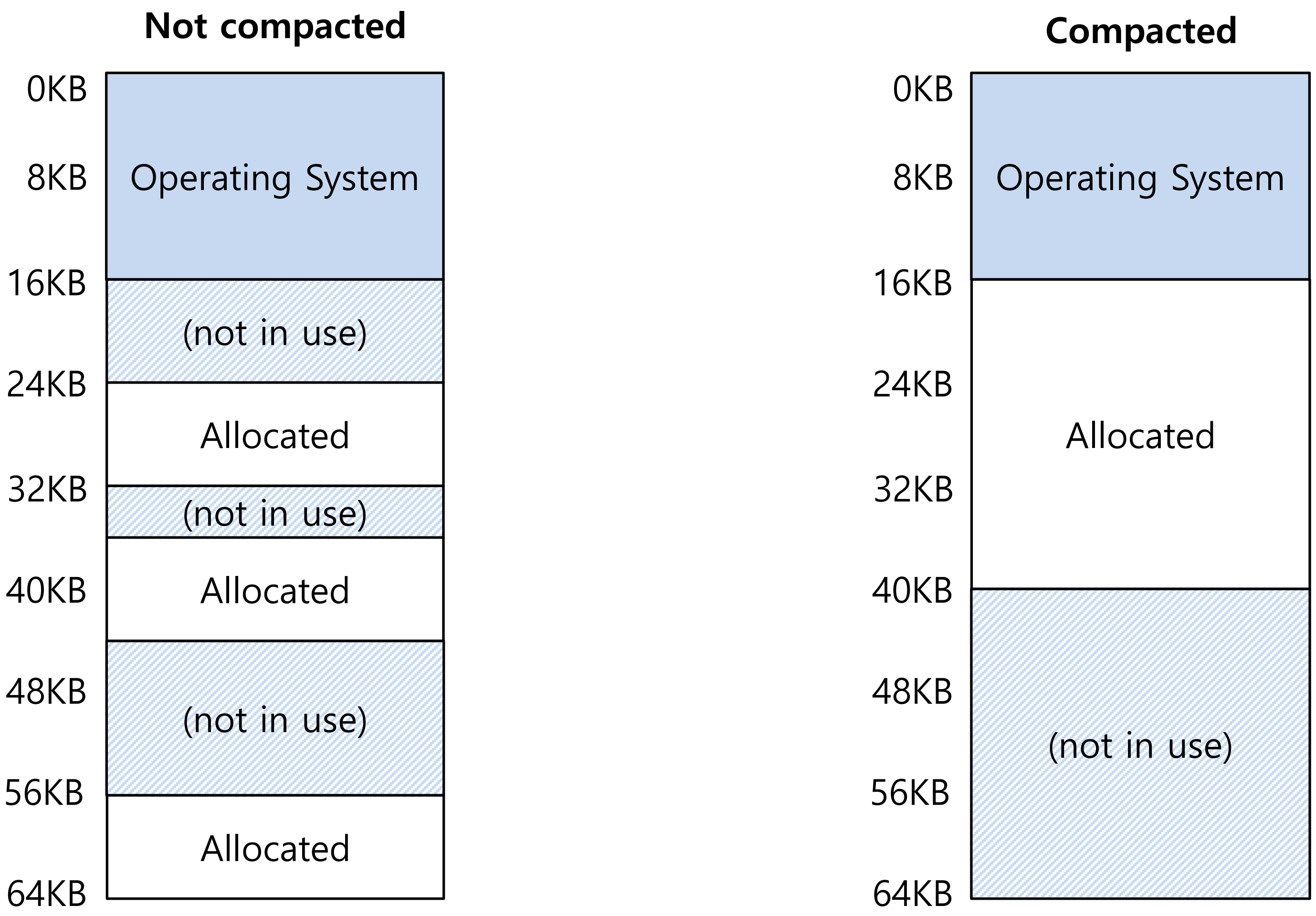
- **Coarse-Grained** means segmentation in a small number
  - e.g., code, heap, stack
- **Fine-Grained** segmentation allows **more flexibility** for address space in some early system
  - To support many segments, Hardware support with a **segment table** is required

OS support: Fragmentation

- **External Fragmentation**: little holes of **free space** in physical memory that make difficulty to allocate new segments
  - There is **24KB free**, but **not in one contiguous** segment
  - The OS **cannot** satisfy the **20KB request**

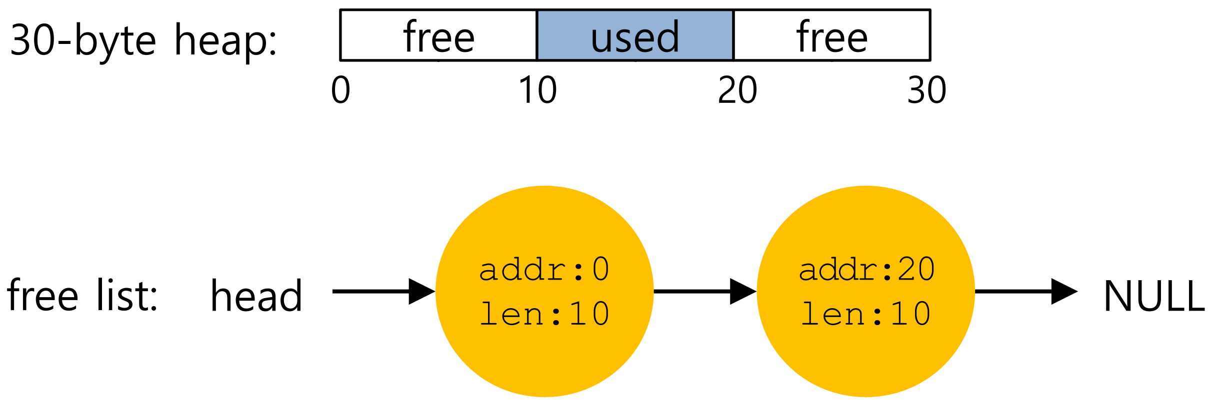
- **Compaction**: **rearranging** the exiting segments in physical memory
  - Compaction is **costly**
    - **Stop** running process
    - **Copy** data to somewhere
    - **Change** segment register value

Memory Compaction



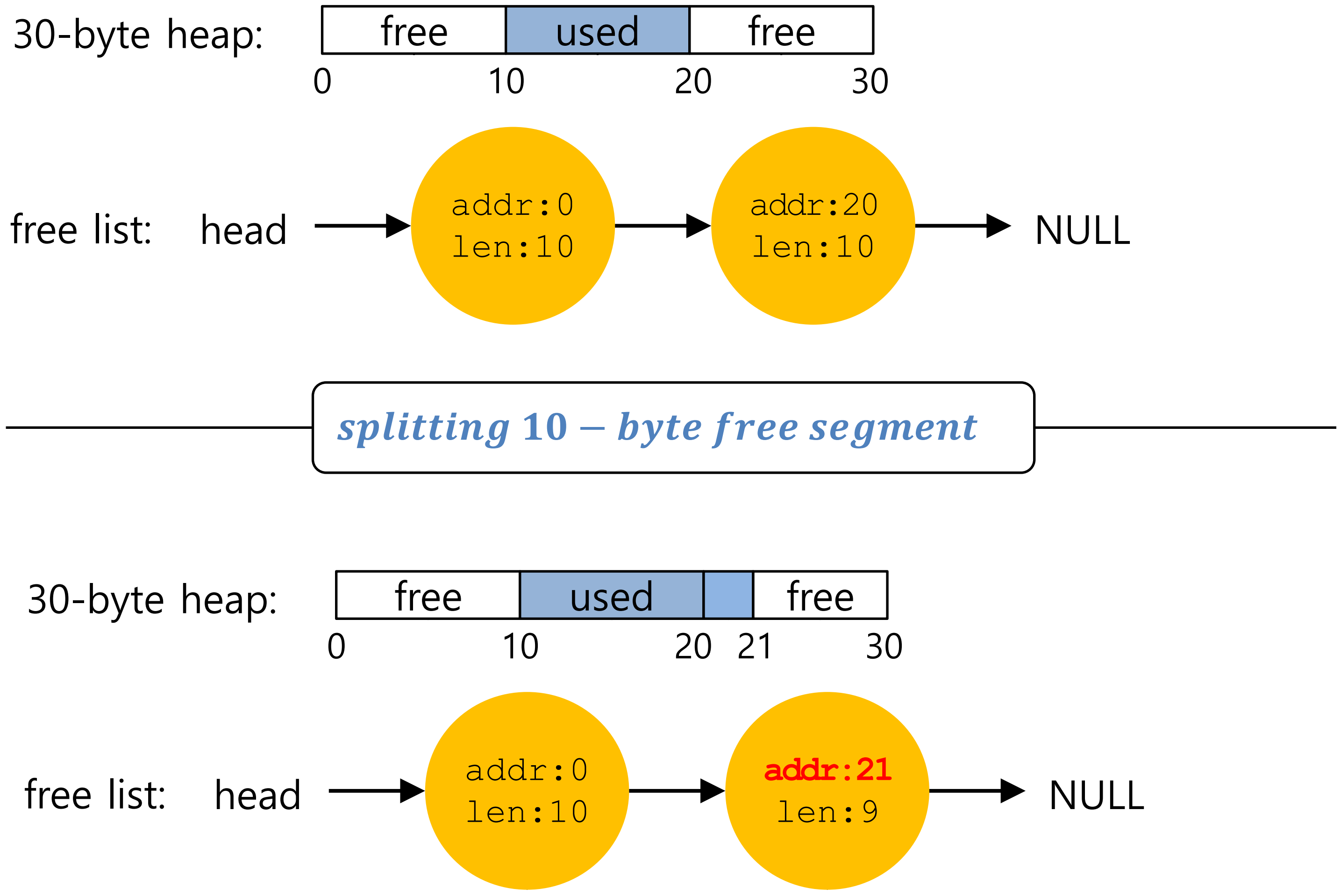
Splitting

- Finding a free chunk of memory that can satisfy the request and splitting it into two
  - When request for memory allocation is **smaller** than the size of free chunks



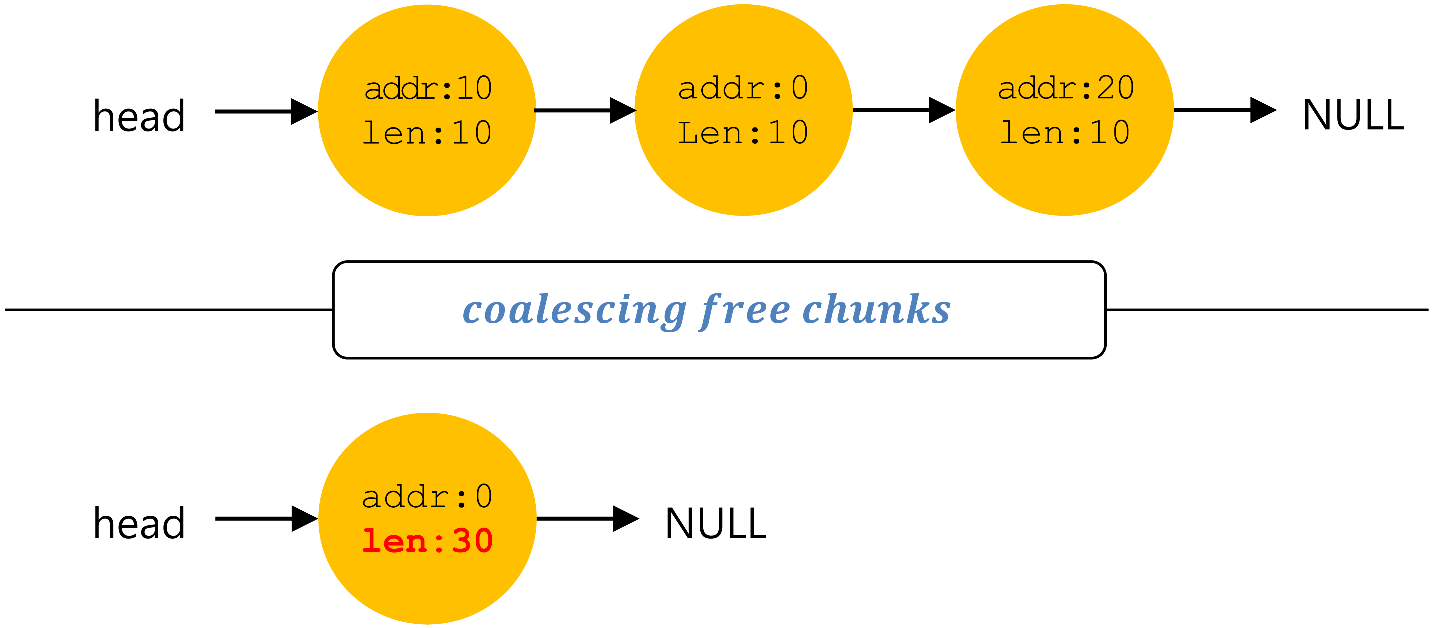
Splitting

- Two 10-bytes free segment with **1-byte request**



Coalescing

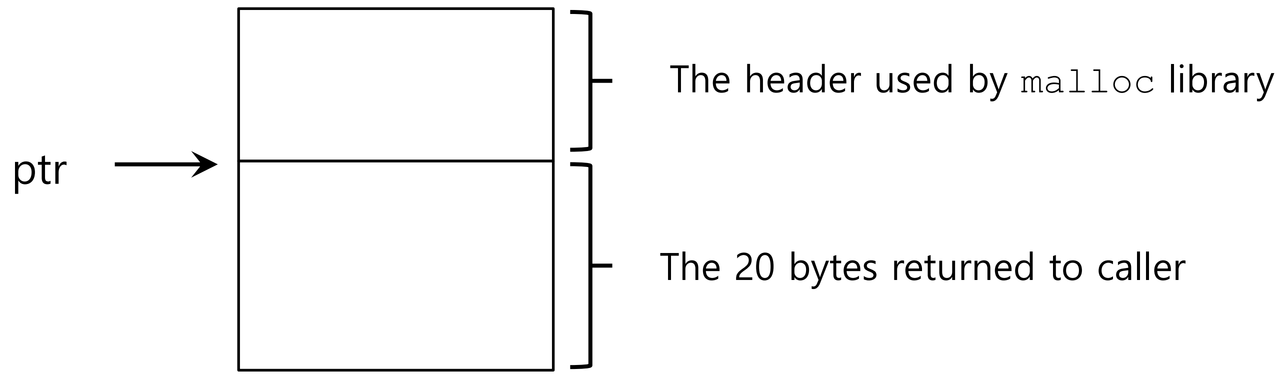
- If a user requests memory that is **bigger than free chunk size**, the list will **not find** such a free chunk
- Coalescing: **Merge** returning a free chunk with existing chunks into a large single free chunk if **addresses** of them are **nearby**



Tracking The Size of Allocated Regions

- The interface to free(void *ptr) does not take a size parameter
  - How does the library know the size of memory region that will be back into free list?
- Most allocators store extra information in a header block

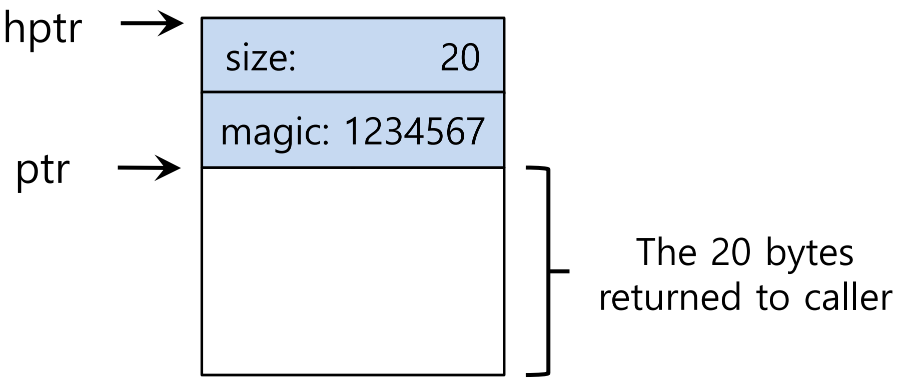
```
ptr = malloc(20);
```



An Allocated Region Plus Header

The Header of Allocated Memory Chunk

- The header minimally contains the size of the allocated memory region
- The header may also contain
  - Additional pointers to speed up deallocation
  - A magic number for integrity checking



Specific Contents Of The Header

```c
typedef struct __header_t {
        int size;
        int magic;
} header_t;
```

A Simple Header

The Header of Allocated Memory Chunk

- The size for free region is the size of the header plus the size of the space allocated to the user
- If a user request N bytes, the library searches for a free chunk of size N plus the size of the header

- Simple pointer arithmetic to find the header pointer

```
void free(void *ptr) {
        header_t *hptr = (void *)ptr - sizeof(header_t);
}
```

Embedding A Free List

- The memory-allocation library **initializes** the heap and **puts** the first element of **the free list** in the **free space**
  - The library **can't use** `malloc()` to build a list **within itself**

Embedding A Free List

- Description of a node of the list

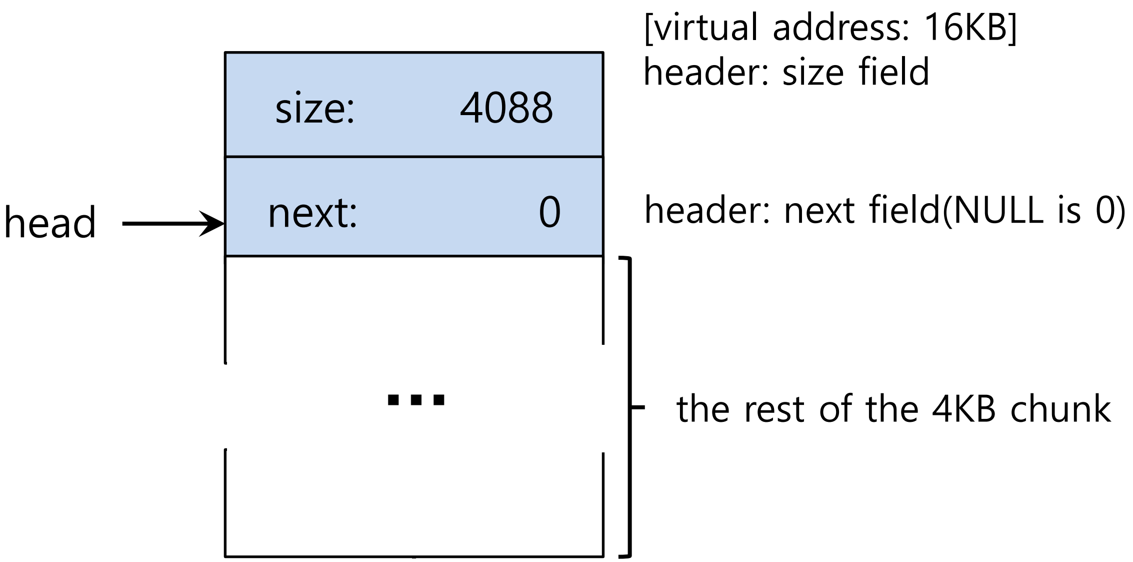
```
typedef struct __node_t {
        int size;
        struct __node_t *next;
} nodet_t;
```

- Building heap and putting a free list
  - Assume that the heap is built vi mmap() system call

```
// mmap() returns a pointer to a chunk of free space
node_t *head = mmap(NULL, 4096, PROT_READ|PROT_WRITE,
                    MAP_ANON|MAP_PRIVATE, -1, 0);
head->size = 4096 - sizeof(node_t);
head->next = NULL;
```

A Heap With One Free Chunk

```
// mmap() returns a pointer to a chunk of free space
node_t *head = mmap(NULL, 4096, PROT_READ|PROT_WRITE,
                    MAP_ANON|MAP_PRIVATE, -1, 0);
head->size = 4096 - sizeof(node_t);
head->next = NULL;
```



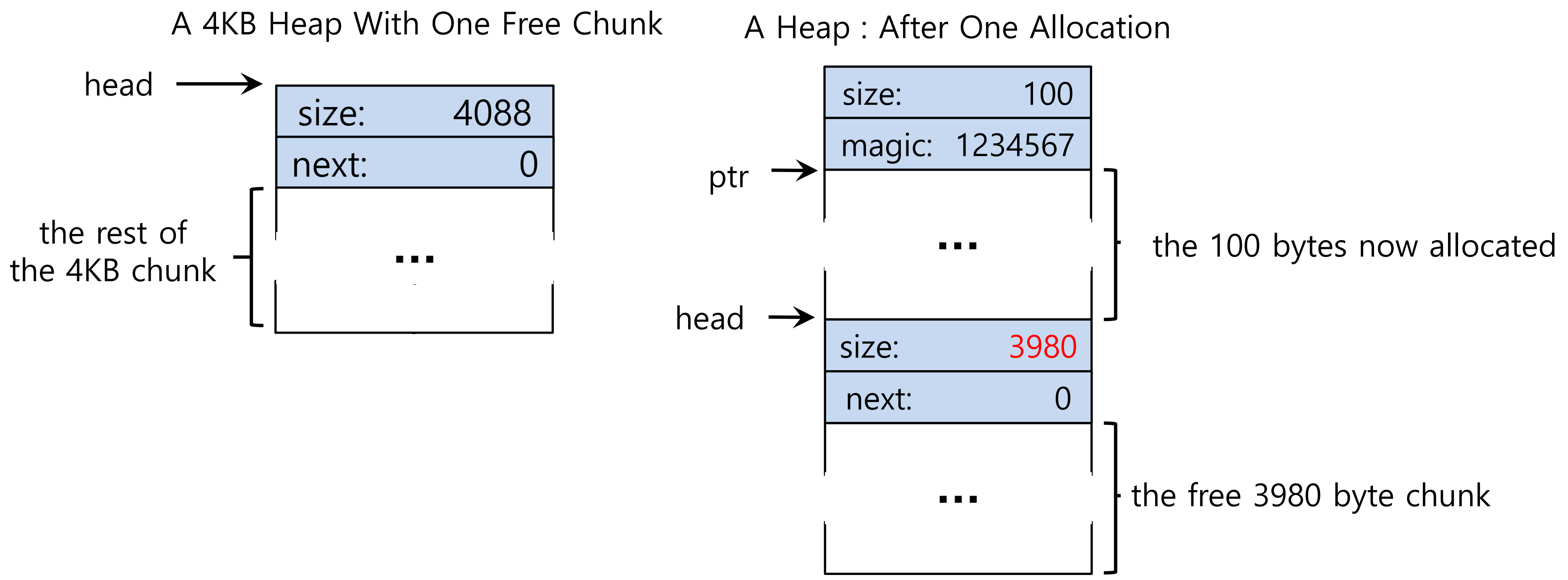
Embedding A Free List: Allocation

- If a chunk of memory is requested, the library will first find a chunk that is large enough to accommodate the request

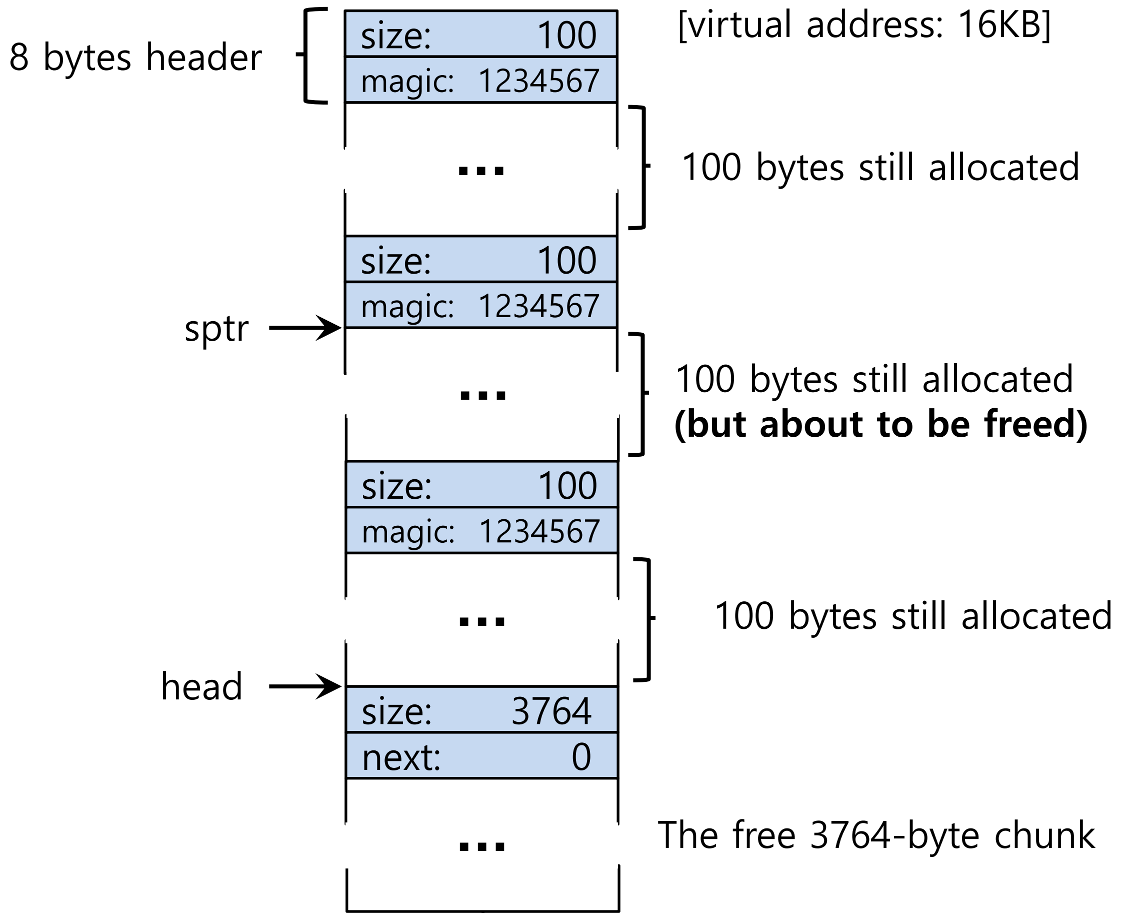
- The library will
  - Split the large free chunk into two
    - One for the request and the remaining free chunk
  - Shrink the size of free chunk in the list

Embedding A Free List: Allocation

- Example: a request for 100 bytes by ptr = malloc(100)
  - Allocating 108 bytes out of the existing one free chunk
  - shrinking the one free chunk to 3980(4088 minus 108)



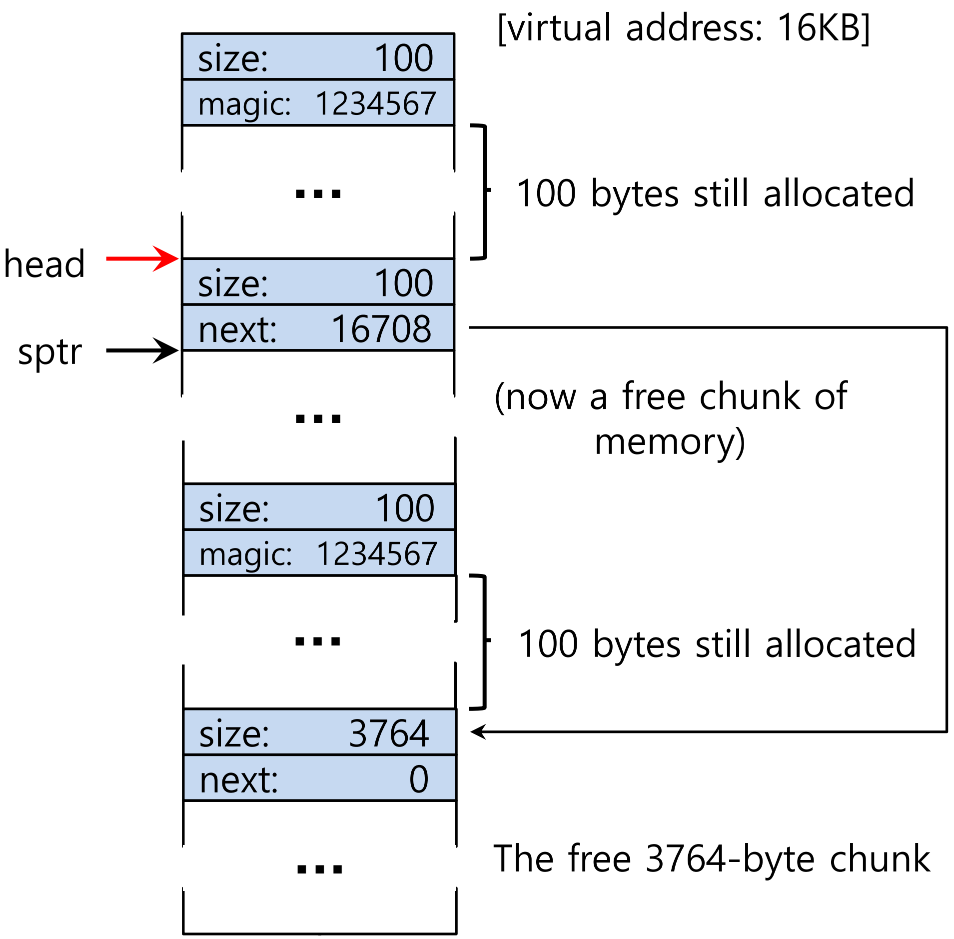
Free Space With Chunks Allocated



Free Space With Three Chunks Allocated

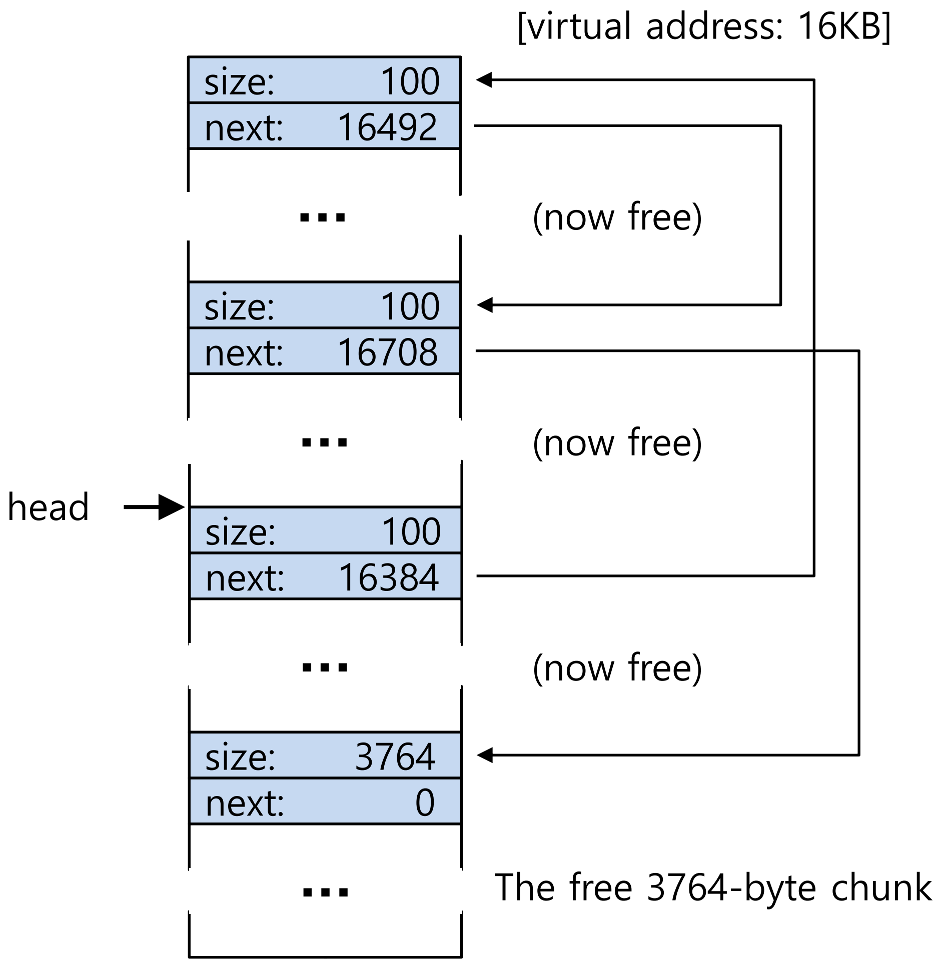
Free Space With `free()`

- Example: `free(sptr)`
  - The 100 bytes chunks is **back into** the free list
  - The free list will **start** with **a small chunk**
    - The list header will point the small chunk



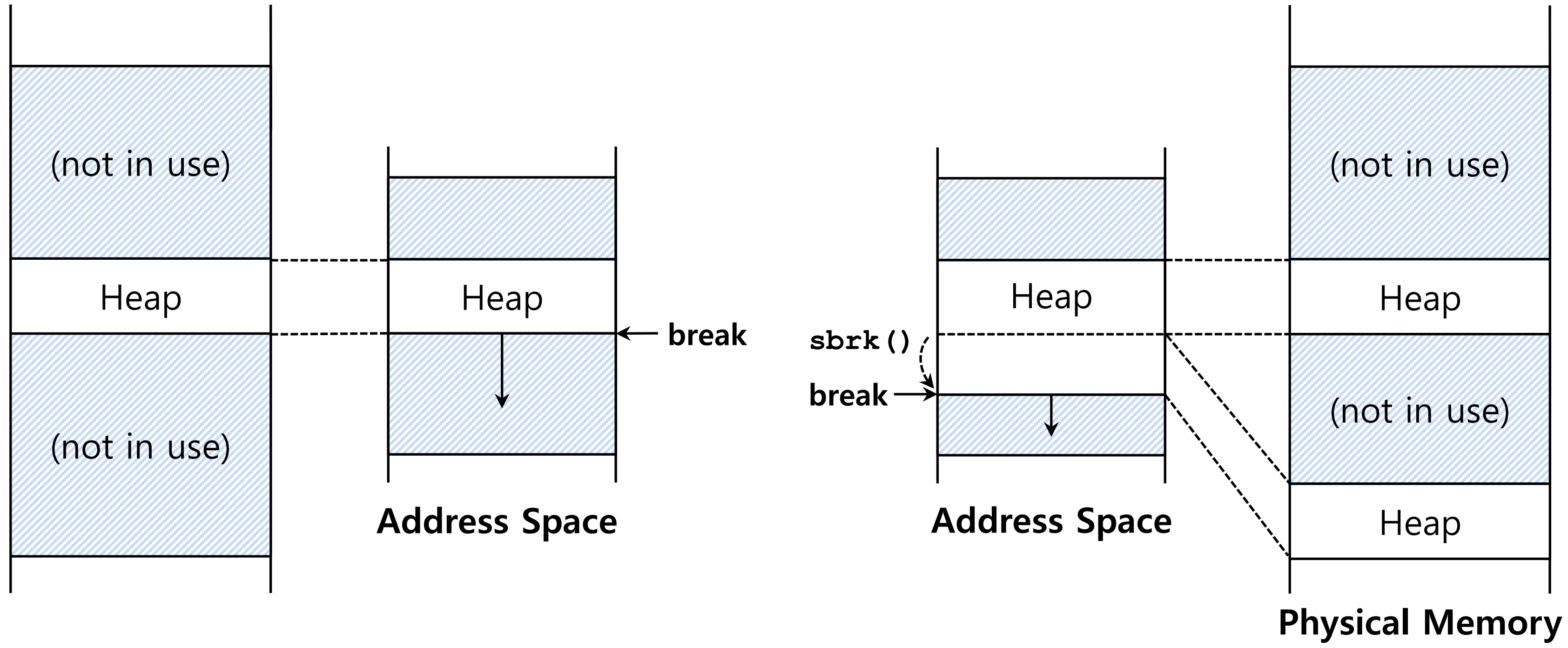
Free Space With Freed Chunks

- Let's assume that the last two in-use chunks are freed
- **External Fragmentation** occurs
  - **Coalescing** is needed in the list



Growing The Heap

- Most allocators **start** with **a small-sized heap** and then **request more** memory from the OS when they run out
  - e.g., `sbrk()`, `brk()` in most UNIX systems



Managing Free Space: Basic Strategies

- Best Fit:
  - Finding free chunks that are **big or bigger than the request**
  - Returning the **one of smallest** in the chunks **in the group** of candidates

- Worst Fit:
  - Finding the **largest free chunks** and allocation the amount of the request
  - **Keeping the remaining chunk** on the free list

Managing Free Space: Basic Strategies

- First Fit:
  - Finding the **first chunk** that is **big enough** for the request
  - Returning the requested amount and remaining the rest of the chunk

- Next Fit:
  - Finding the first chunk that is big enough for the request
  - Searching at **where one was looking** at instead of the begging of the list

Examples of Basic Strategies

- Allocation Request Size 15

head → 10 → 30 → 20 → NULL

- Result of Best-fit

head → 10 → 30 → 5 → NULL

- Result of Worst-fit

head → 10 → 15 → 20 → NULL

Other Approaches: Segregated List

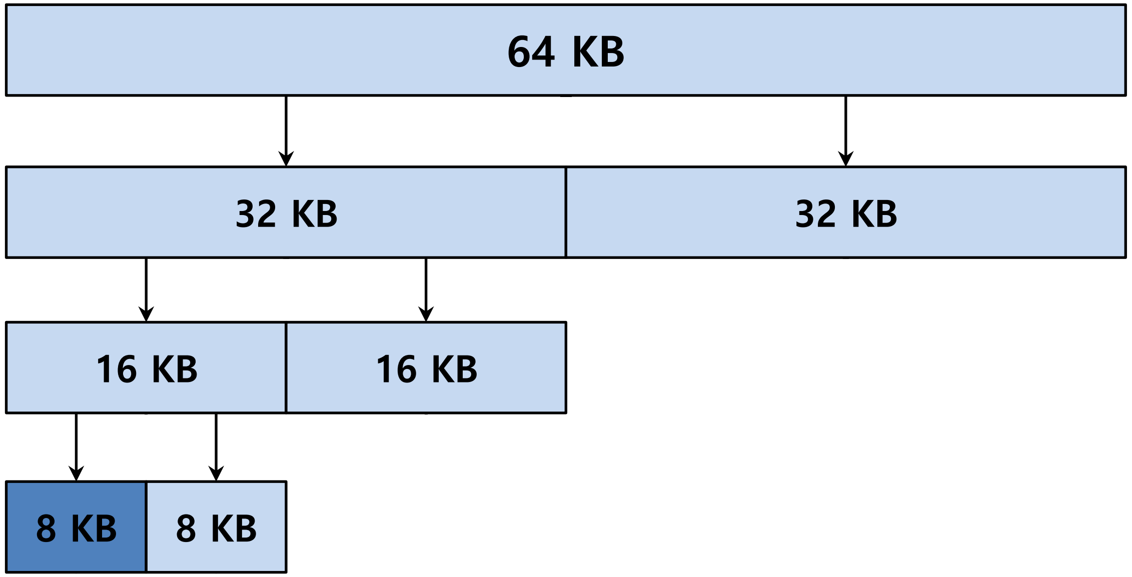
- Segregated List:
  - Keeping free chunks in different size in a separate list for the size of popular request
  - New Complication:
    - **How much** memory should dedicate to **the pool of memory** that serves **specialized requests** of a given size?
  - **Slab allocator** handles this issue

Other Approaches: Segregated List

- Slab Allocator
  - Allocate a number of object caches
    - The objects are likely to be requested frequently
    - e.g., locks, file-system inodes, etc
  - **Request some memory** from a more general memory allocator when **a given cache is running low** on free space

Other Approaches: Buddy Allocation

- Binary Buddy Allocation
  - The allocator **divides free space** by two **until a block** that is big enough to accommodate the request is **found**



64KB free space for 7KB request

Other Approaches: Buddy Allocation

- Buddy allocation can suffer from **internal fragmentation**

- Buddy system makes **coalescing** simple
  - **Coalescing** two blocks into the next level of blocks