Dynamic Memory Allocation

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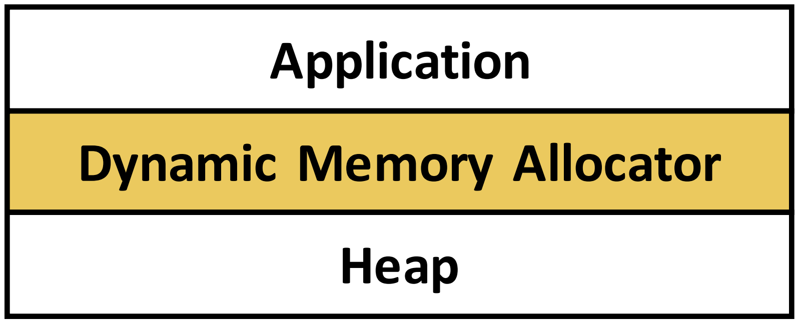
Note: these slides derive from those by Markus Püschel at CMU

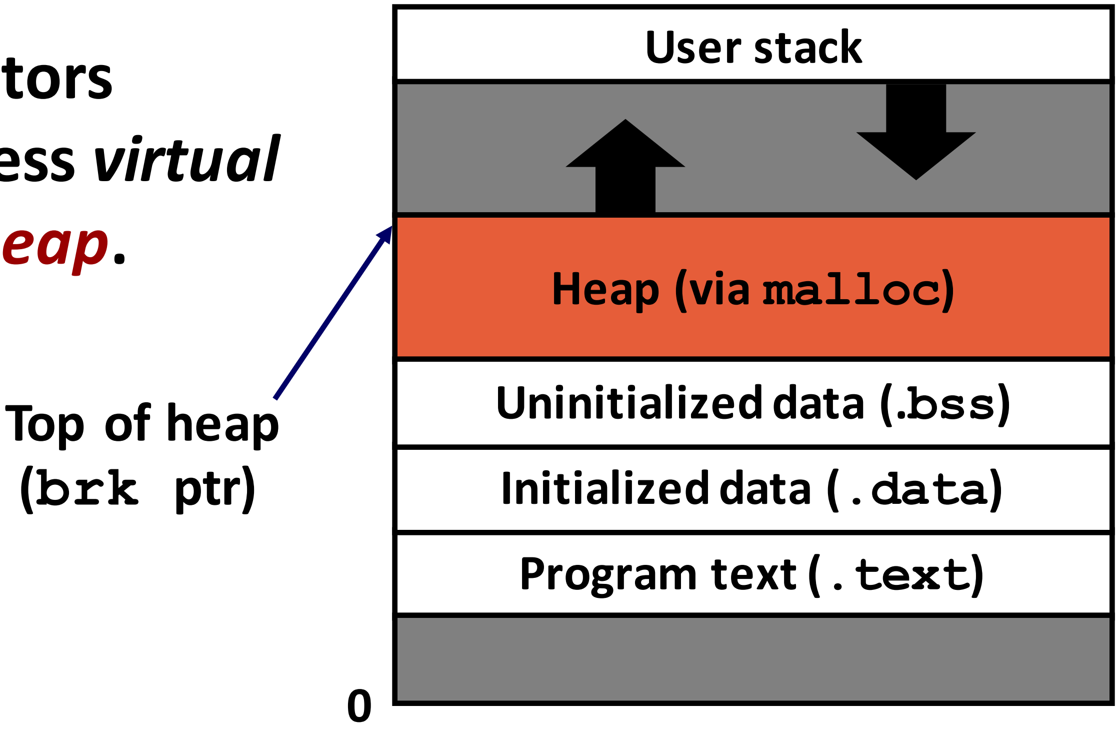
Today

- Basic concepts
- Implicit free lists
- Explicit free lists
- Segregated free lists

Dynamic Memory Allocation

- Programmers use ***dynamic memory allocators*** (like `malloc`) to acquire memory at run time.
  - For data structures whose size is only known at runtime
- Dynamic memory allocators manage an area of process *virtual memory* known as the ***heap***.





Dynamic Memory Allocation

- **Allocator maintains heap as collection of variable sized *blocks*, which are either *allocated* or *free***
- **Types of allocators**
  - ***Explicit allocator***: application allocates and frees
    - E.g., `malloc` and `free` in C
  - ***Implicit allocator:*** application allocates, but does not free
    - E.g. garbage collection in Java, ML, and Lisp

The `malloc` Package

`#include <stdlib.h>`

`void *malloc(size_t size)`

- Successful:
  - Returns a pointer to a memory block of at least **`size`** bytes (typically) aligned to 8-byte boundary
  - If **`size == 0`**, returns NULL
- Unsuccessful: returns NULL (0) and sets **`errno`**

`void free(void *p)`

- Returns the block pointed at by **`p`** to pool of available memory
- **`p`** must come from a previous call to **`malloc`** or **`realloc`**

Other functions

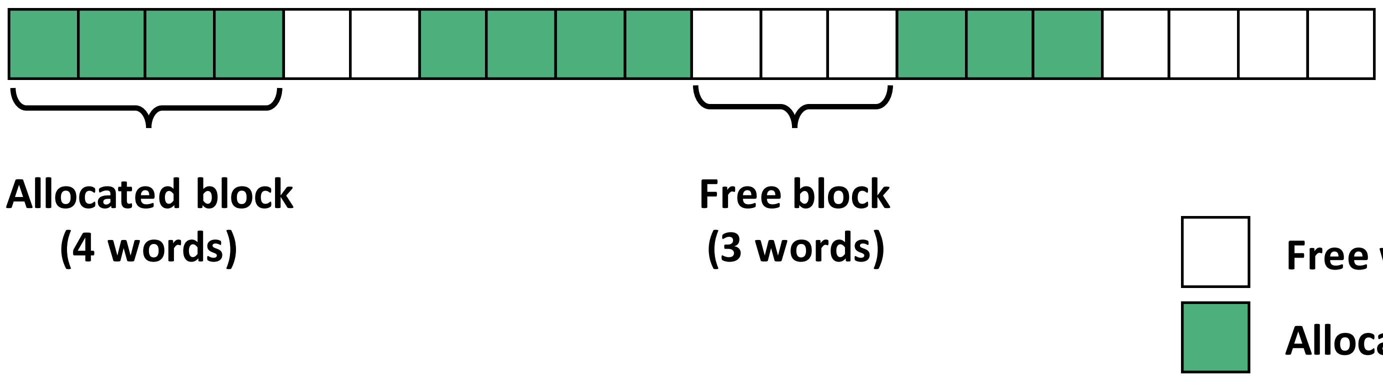
- **`calloc`:** initializes allocated block to zero
- **`realloc`:** changes size of a previously allocated block
- **`sbrk`:** used internally by allocators to grow or shrink heap

malloc Example

```
void foo(int n, int m) {
    int i, *p;

    /* Allocate a block of n ints */
    p = (int *) malloc(n * sizeof(int));
    if (p == NULL) {
        perror("malloc");
        exit(0);
    }

    /* Initialize allocated block */
    for (i=0; i<n; i++)
        p[i] = i;


    /* Return p to the heap */
    free(p);
}
```

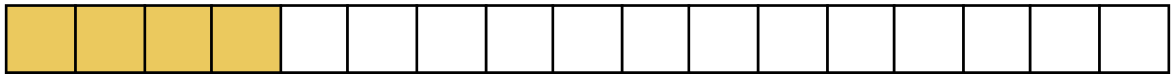
Assumptions Made in This Lecture

- Memory is word addressed
- Each word can hold a pointer

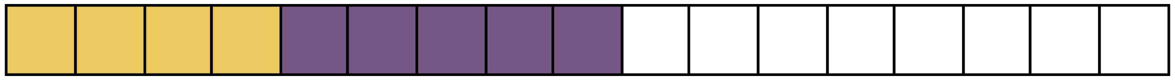


Allocation Example

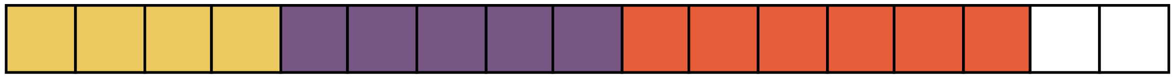
```
p1 = malloc(4)
```



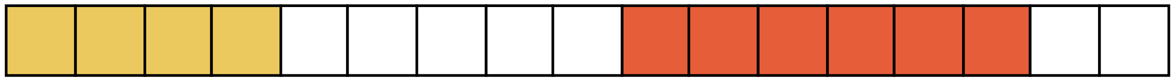
```
p2 = malloc(5)
```



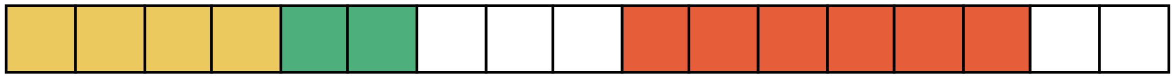
```
p3 = malloc(6)
```



```
free(p2)
```



```
p4 = malloc(2)
```



Constraints

- **Applications**
  - Can issue arbitrary sequence of **`malloc`** and **`free`** requests
  - **`free`** request must be to a **`malloc`**’d block

- **Allocators**
  - Can’t control number or size of allocated blocks
  - Must respond immediately to **`malloc`** requests
    - *i.e.*, can’t reorder or buffer requests
  - Must allocate blocks from free memory
    - *i.e.*, can only place allocated blocks in free memory
  - Must align blocks so they satisfy all alignment requirements
    - 8 byte alignment for GNU **`malloc`** (**`libc malloc`**) on Linux boxes
  - Can manipulate and modify only free memory
  - Can’t move the allocated blocks once they are **`malloc`**’d
    - *i.e.*, compaction is not allowed

Performance Goal #1: Throughput

- **Given some sequence of `malloc` and `free` requests:**
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$

- **Maximize Throughput:**
  - Number of completed requests per unit time
  - Example:
    - 5,000 **`malloc`** calls and 5,000 **`free`** calls in 10 seconds
    - Throughput is 1,000 operations/second

Performance Goal #2: Memory Utilization

- **Given some sequence of `malloc` and `free` requests:**
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$

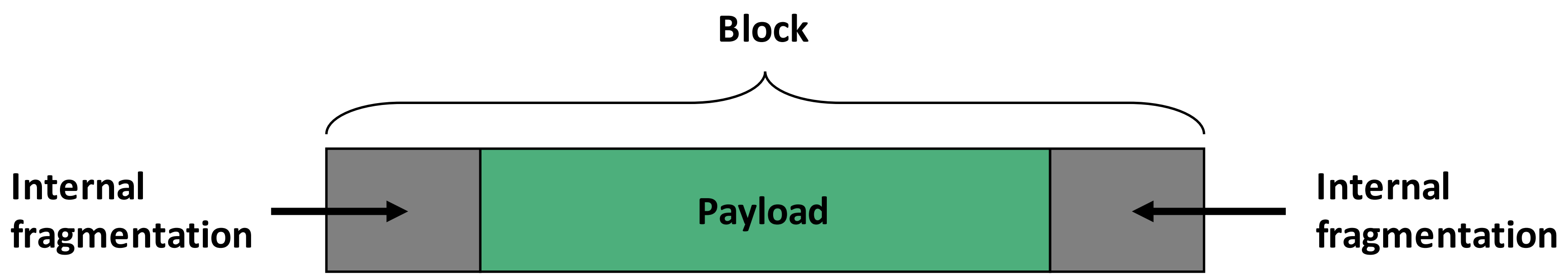
- **Maximize Memory Utilization:**
  - Extra constraint for 3410 version: the heap does not grow!
  - For a given task, how large a heap do you need to suceed
  - Poor memory utilization caused by *fragmentation*

Maximizing throughput and peak memory utilization = HARD

- These goals are often conflicting

Internal Fragmentation

- **For a given block, *internal fragmentation* occurs if payload (the amount requested by the application) is smaller than block size**



- **Caused by**
  - Overhead of maintaining heap data structures
  - Padding for alignment purposes
  - Explicit policy decisions
    (e.g., to return a big block to satisfy a small request)
- **Depends only on the pattern of *previous* requests**
  - Thus, easy to measure

External Fragmentation

- **Occurs when there is enough aggregate heap memory, but no single free block is large enough**

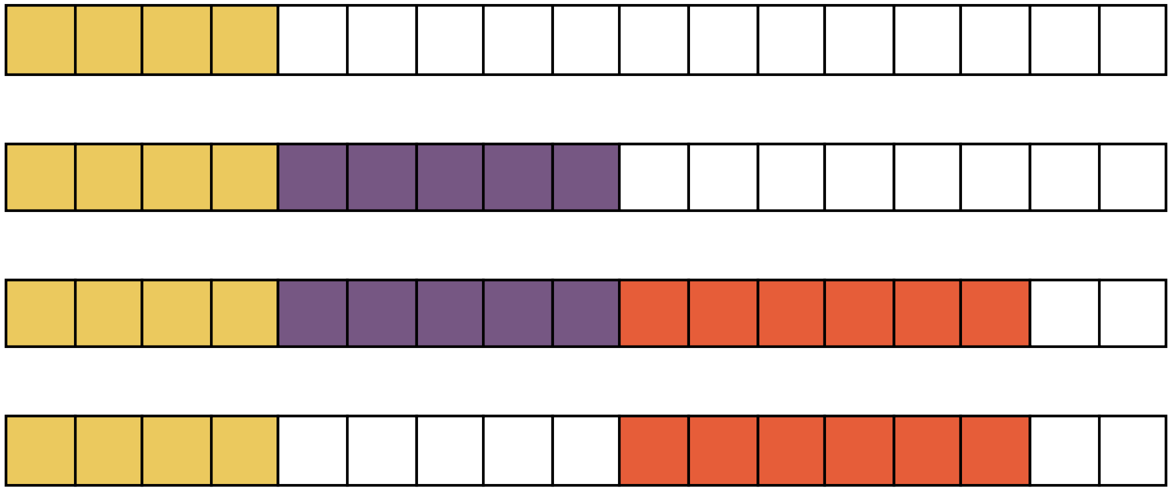
`p1 = malloc(4)`

`p2 = malloc(5)`

`p3 = malloc(6)`

`free(p2)`

`p4 = malloc(6)`



Oops! (what would happen now?)

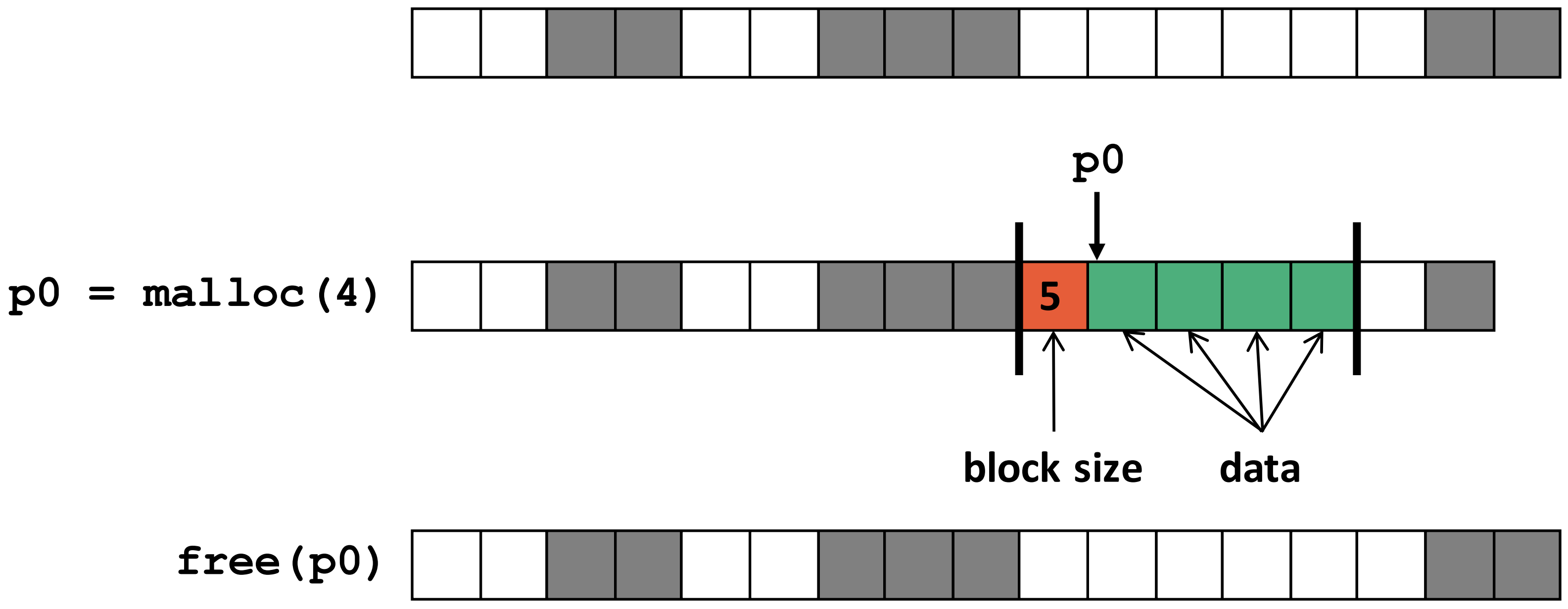
- **Depends on the pattern of future requests**
  - Thus, difficult to measure

Implementation Issues: the 5 Questions

1. Given just a pointer, how much memory do we free?
2. How do we keep track of the free blocks?
3. When allocating a structure that is smaller than the free block it is placed in, what do we do with the extra space?
4. How do we pick a block to use for allocation? (if a few work)
5. How do we reinsert freed block?

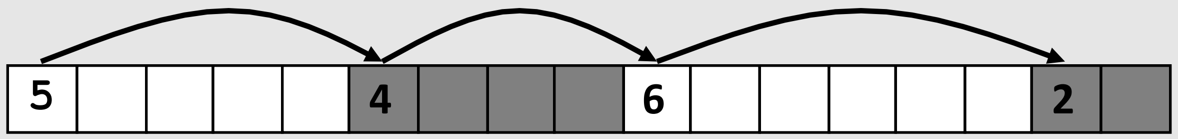
Q1: Knowing How Much to Free

- **Standard method**
  - Keep the length of a block in the word preceding the block.
    - This word is often called the ***header field*** or ***header***
  - Requires an extra word for every allocated block

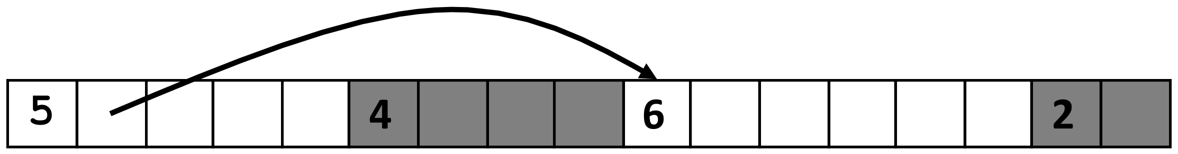


Q2: Keeping Track of Free Blocks

- Method 1: *Implicit list* using length—links all blocks



- Method 2: *Explicit list* among the free blocks using pointers



- Method 3: *Segregated free list*
  - Different free lists for different size classes

- Method 4: *Blocks sorted by size*
  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Today

- Basic concepts
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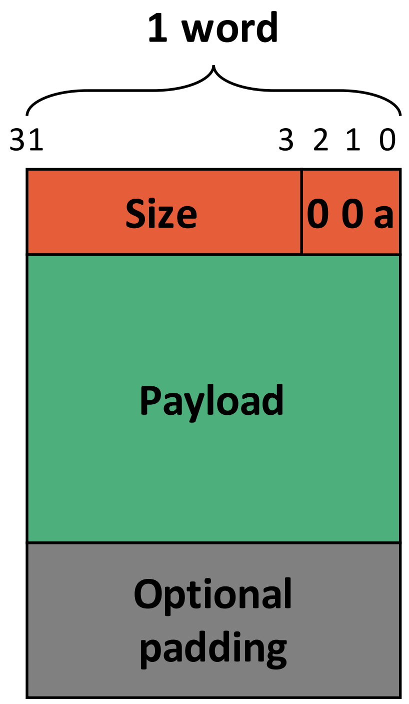
- Explicit free lists
- Segregated free lists

Method 1: Implicit List

- **For each block we need both size and allocation status**
  - Could store this information in two words: wasteful!
- **Standard trick**
  - If blocks are aligned, some low-order address bits are always 0
  - Instead of storing an always-0 bit, use it as a allocated/free flag
  - When reading size word, must mask out this bit

Format of allocated and free blocks

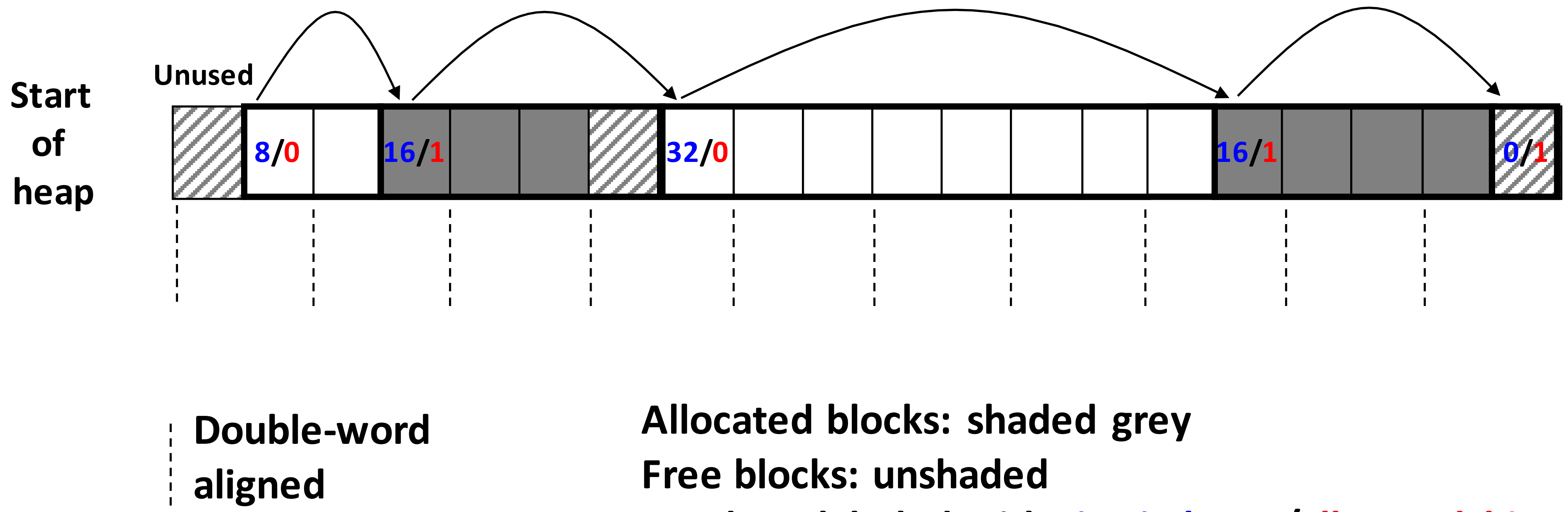


a = 1: Allocated block
a = 0: Free block

Size: block size

Payload: application data (allocated blocks only)

Detailed Implicit Free List Example



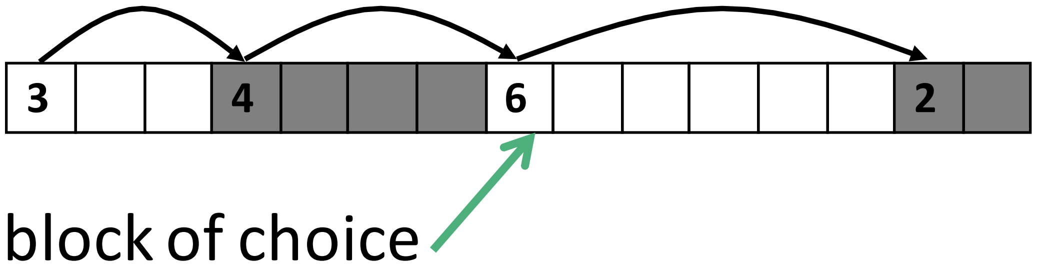
Allocated blocks: shaded grey
Free blocks: unshaded
Headers: labeled with size in bytes/allocated bit

Q4: Implicit List: Finding a Free Block

- **First fit:**
  - Search list from beginning, choose ***first*** free block that fits:
  - Linear time in total number of blocks (allocated and free)
  - Can cause "splinters" (of small free blocks) at beginning of list
- **Next fit:**
  - Like first fit, but search list starting where previous search finished
  - Often faster than first fit: avoids re-scanning unhelpful blocks
  - Some research suggests that fragmentation is worse
- **Best fit:**
  - Search list, choose the ***best*** free block: fits, with fewest bytes left over
  - Keeps fragments small—usually helps fragmentation
  - Typically runs slower than first fit

Q3: Implicit List: Allocating in Free Block

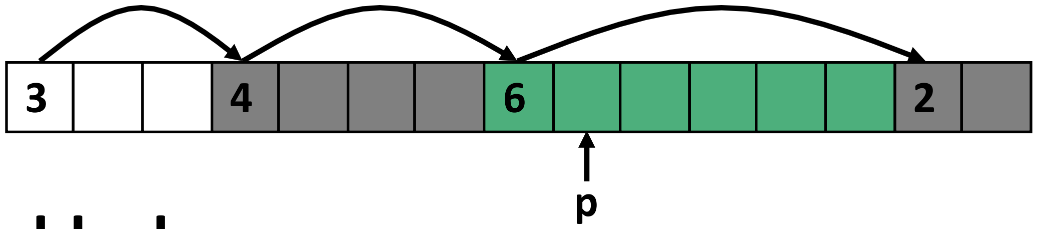
Suppose we need to allocate 3 words



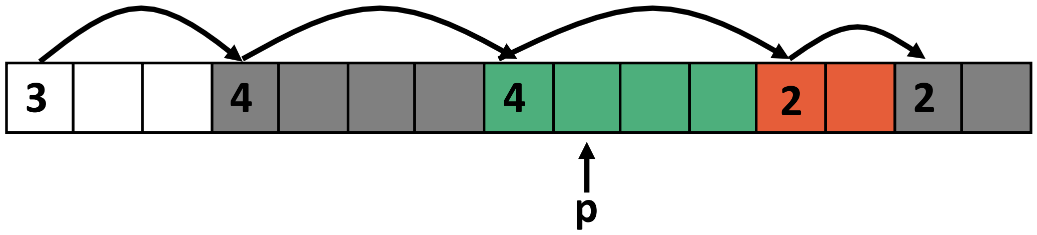
This is our free block of choice

Two options:

1. **Allocate the whole block (internal fragmentation!)**



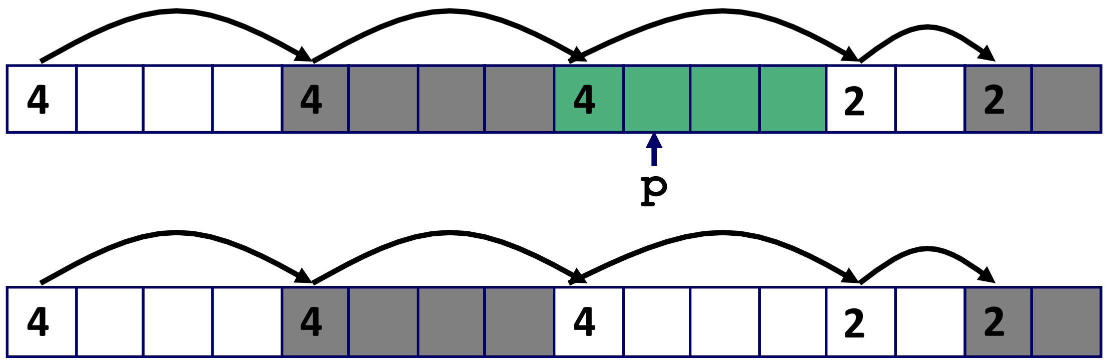
2. **Split the free block**



Q5: Implicit List: Freeing a Block

- **Simplest implementation: clear the "allocated" flag**
  - But can lead to "false fragmentation"

`free(p)`



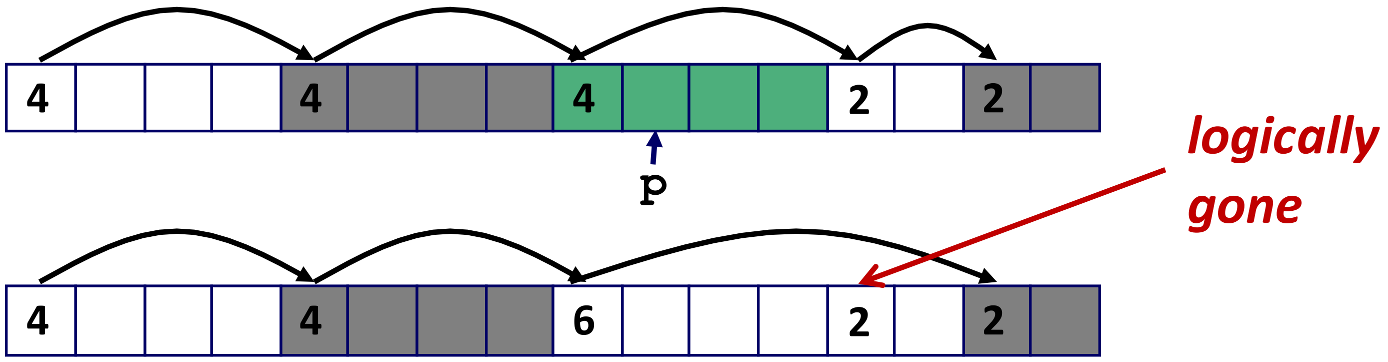
`malloc(5)` ***Oops!***

There is enough free space, but the allocator won't be able to find it

Implicit List: Coalescing

- **Join *(coalesce)* with next/previous blocks, if they are free**
  - Coalescing with next block

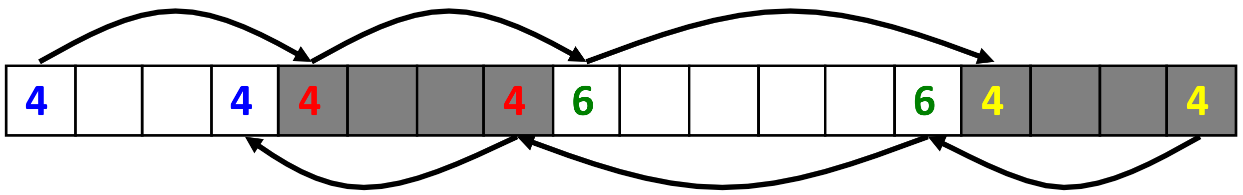
`free(p)`

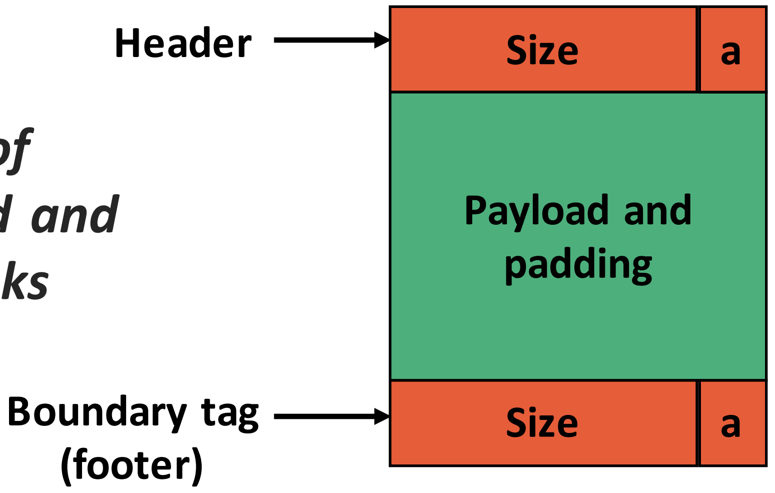


How do we coalesce with *previous* block?

Implicit List: Bidirectional Coalescing

- ***Boundary tags*** [Knuth73]
  - Replicate size/allocated word at "bottom" (end) of free blocks
  - Allows us to traverse the "list" backwards, but requires extra space
  - Important and general technique!





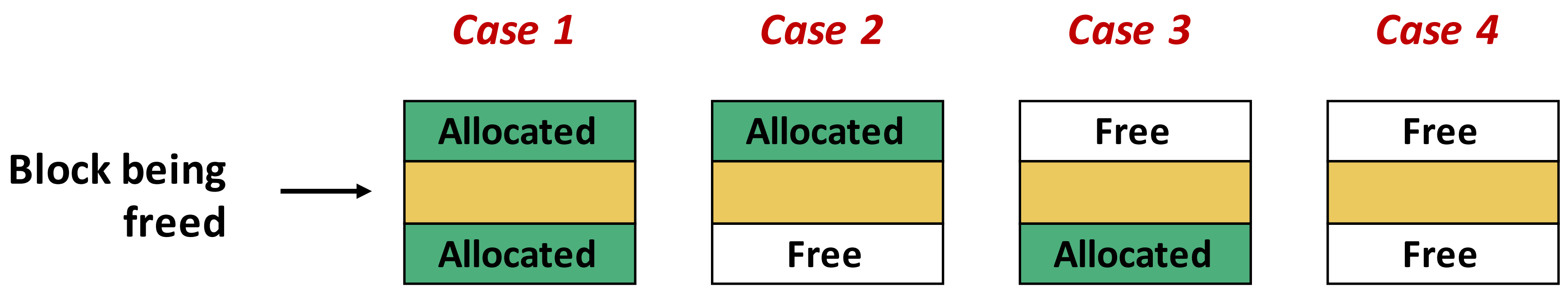
Format of allocated and free blocks

a = 1: Allocated block
a = 0: Free block

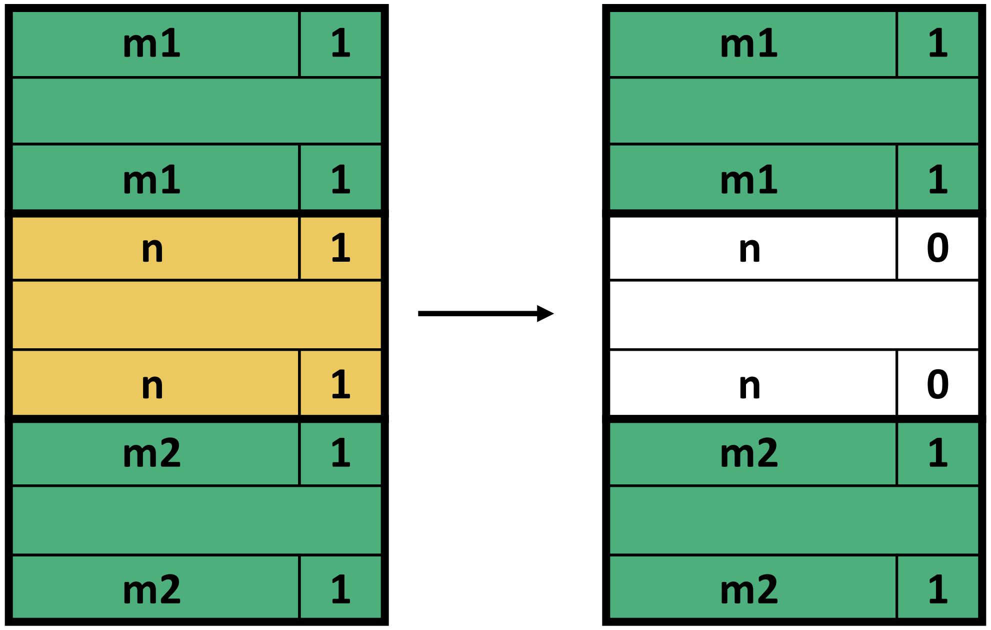
Size: Total block size

Payload: Application data (allocated blocks only)

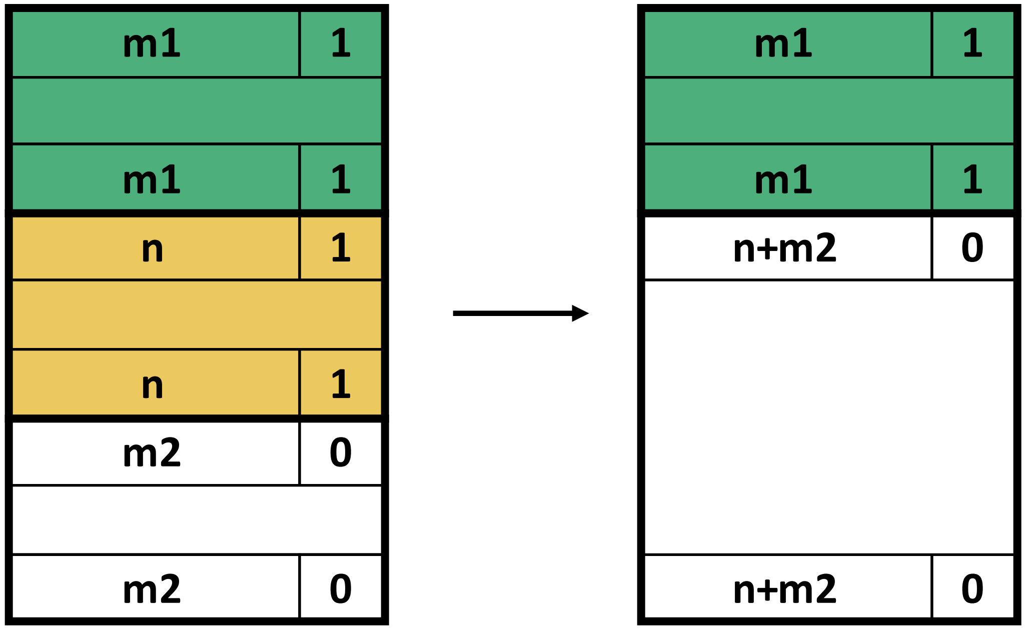
Constant Time Coalescing



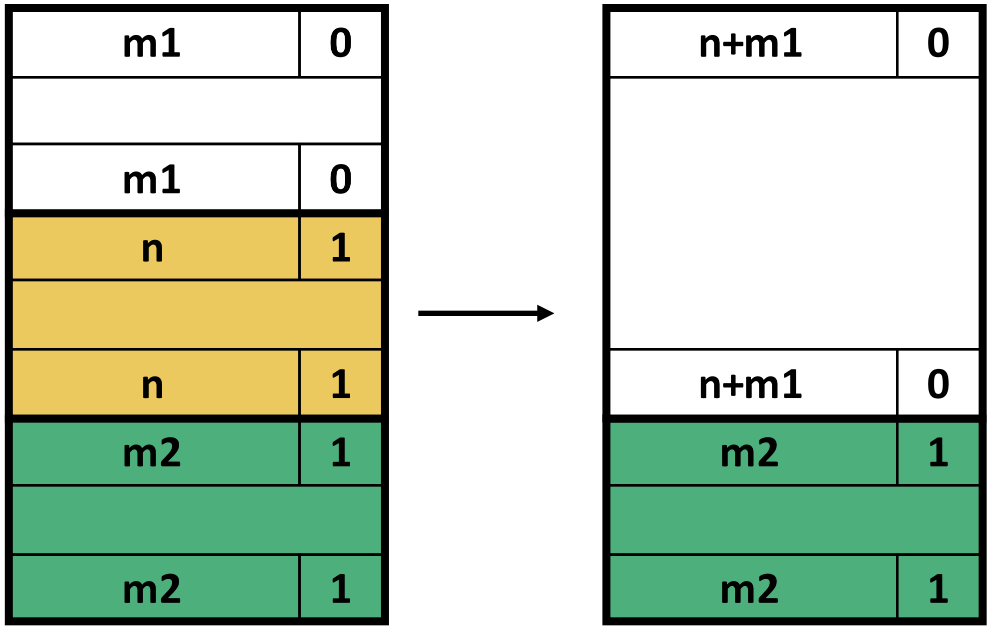
Constant Time Coalescing (Case 1)



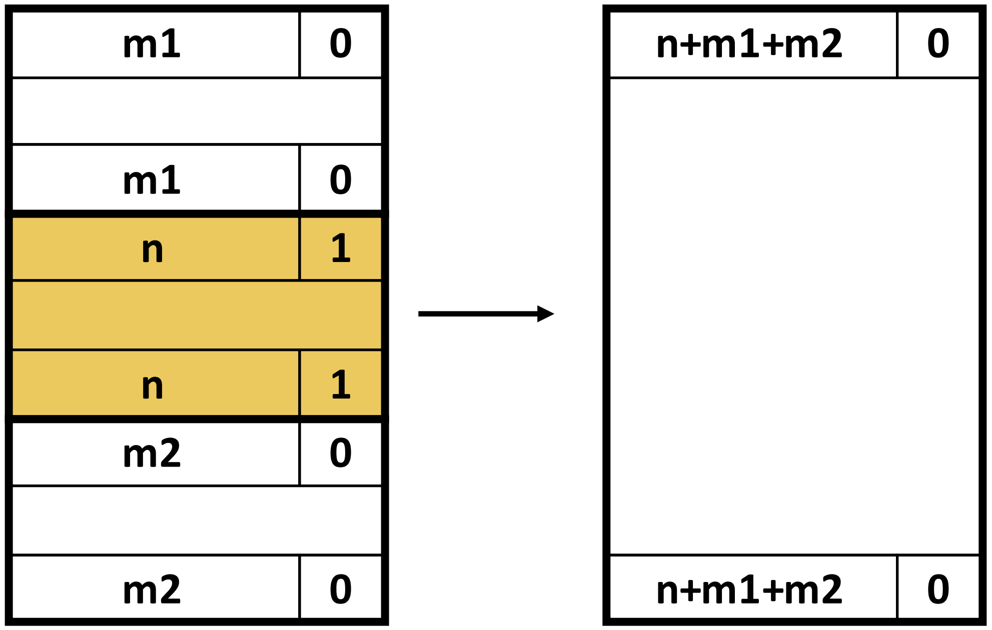
Constant Time Coalescing (Case 2)



Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)



Disadvantages of Boundary Tags

- **Internal fragmentation**

- **Can it be optimized?**
  - Which blocks need the footer tag?
  - What does that mean?

Summary of Key Allocator Policies

- **Placement policy:**
  - First-fit, next-fit, best-fit, etc.
  - Tradeoffs: throughput vs. fragmentation
  - ***Interesting observation***: segregated free lists (more later) approximate best fit placement policy without searching entire free list
- **Splitting policy:**
  - When do we go ahead and split free blocks?
  - How much internal fragmentation are we willing to tolerate?
- **Coalescing policy:**
  - ***Immediate coalescing:*** coalesce each time **`free`** is called
  - ***Deferred coalescing:*** improve performance by deferring until needed
    - Coalesce as you scan the free list for **`malloc`**
    - Coalesce when external fragmentation reaches some threshold

Implicit Lists: Summary

- **Implementation: very simple**
- **Allocate cost:**
  - linear time worst case
- **Free cost:**
  - constant time worst case
  - even with coalescing
- **Memory usage:**
  - will depend on placement policy (First-fit, next-fit or best-fit)

- **Not used in practice for `malloc/free` (too slow)**
  - used in many special purpose applications

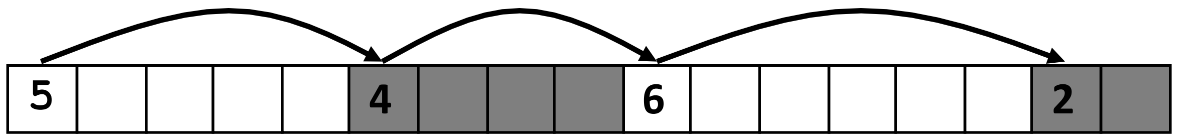
- **Concepts of splitting & coalescing are general to *all* allocators**

Today

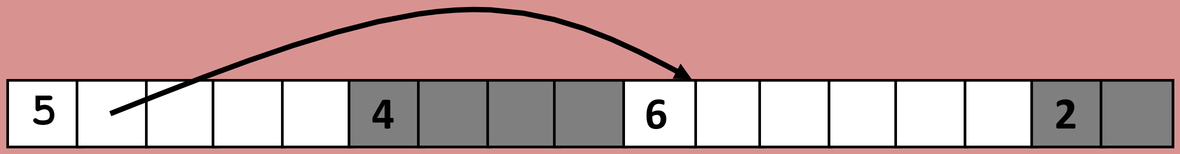
- Basic concepts
- Implicit free lists
- Explicit free lists
- Segregated free lists

Keeping Track of Free Blocks

- **Method 1:** ***Implicit free list*** **using length—links all blocks**



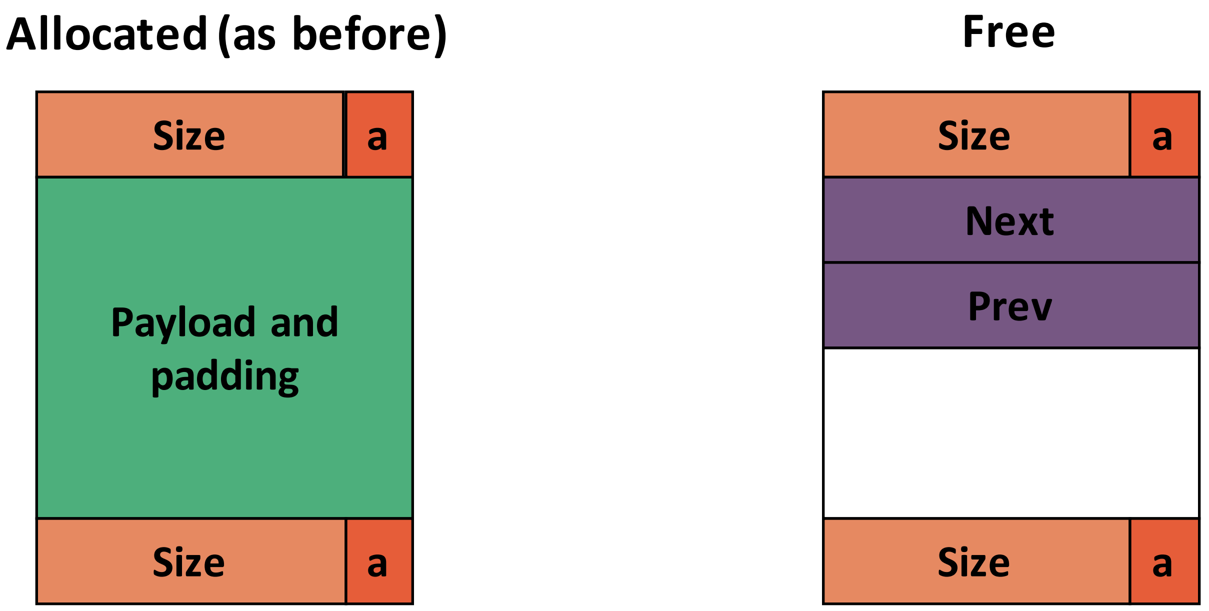
- **Method 2:** ***Explicit free list*** **among the free blocks using pointers**



- **Method 3:** ***Segregated free list***
  - Different free lists for different size classes

- **Method 4:** ***Blocks sorted by size***
  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

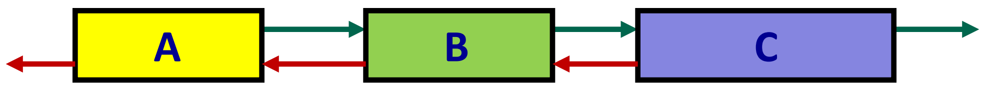
Explicit Free Lists



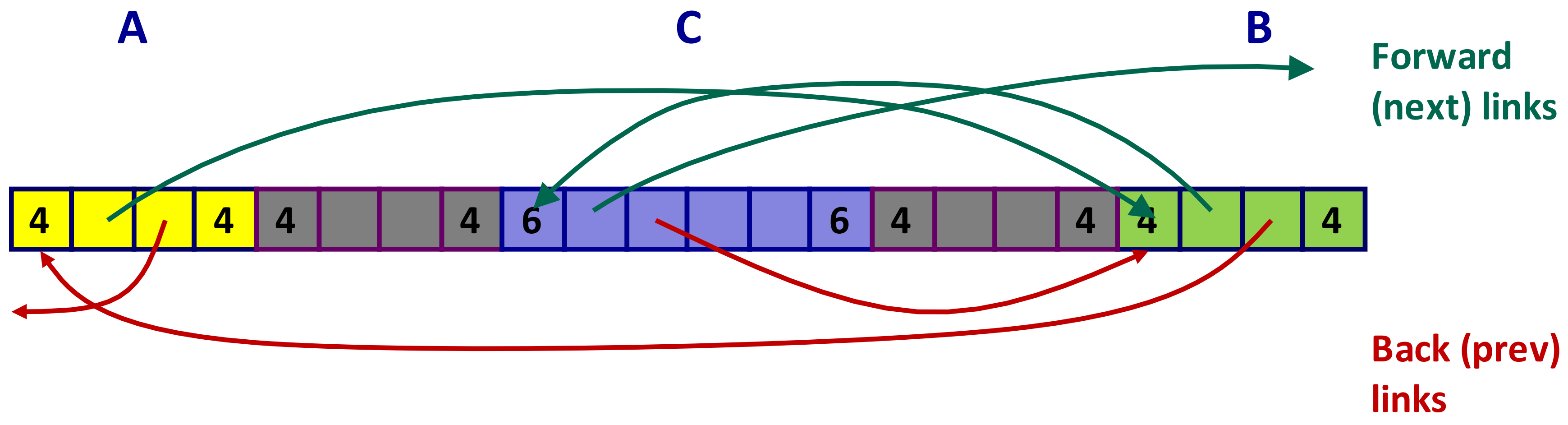
- **Maintain list(s) of *free* blocks, not *all* blocks**
  - "next" free block could be anywhere
    - need to store forward/back pointers, not just sizes
  - Still need boundary tags for coalescing
  - Tracking *free* blocks → can use payload area

Explicit Free Lists

- Logically:

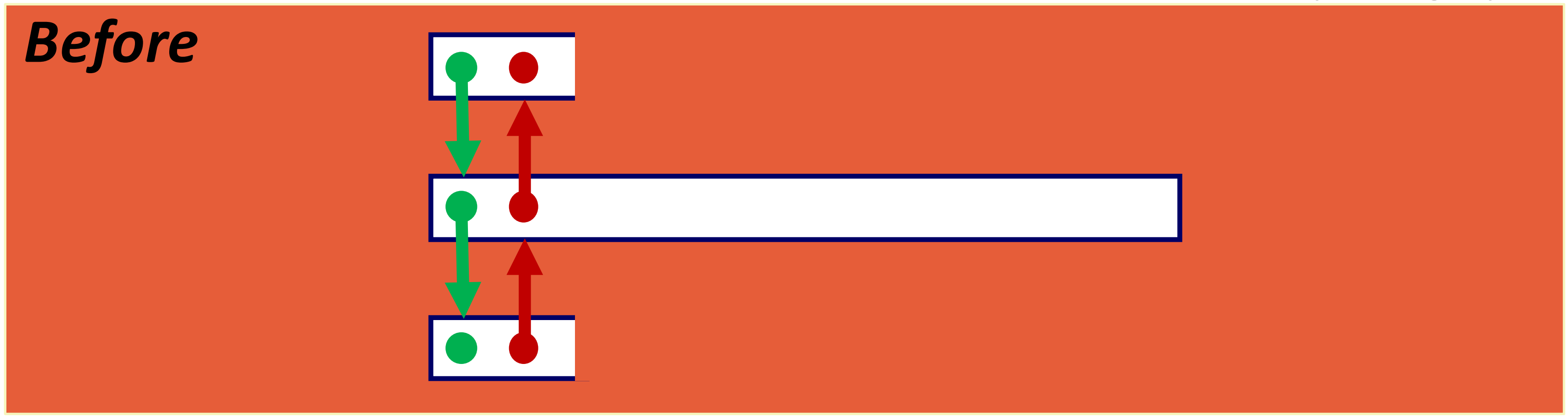


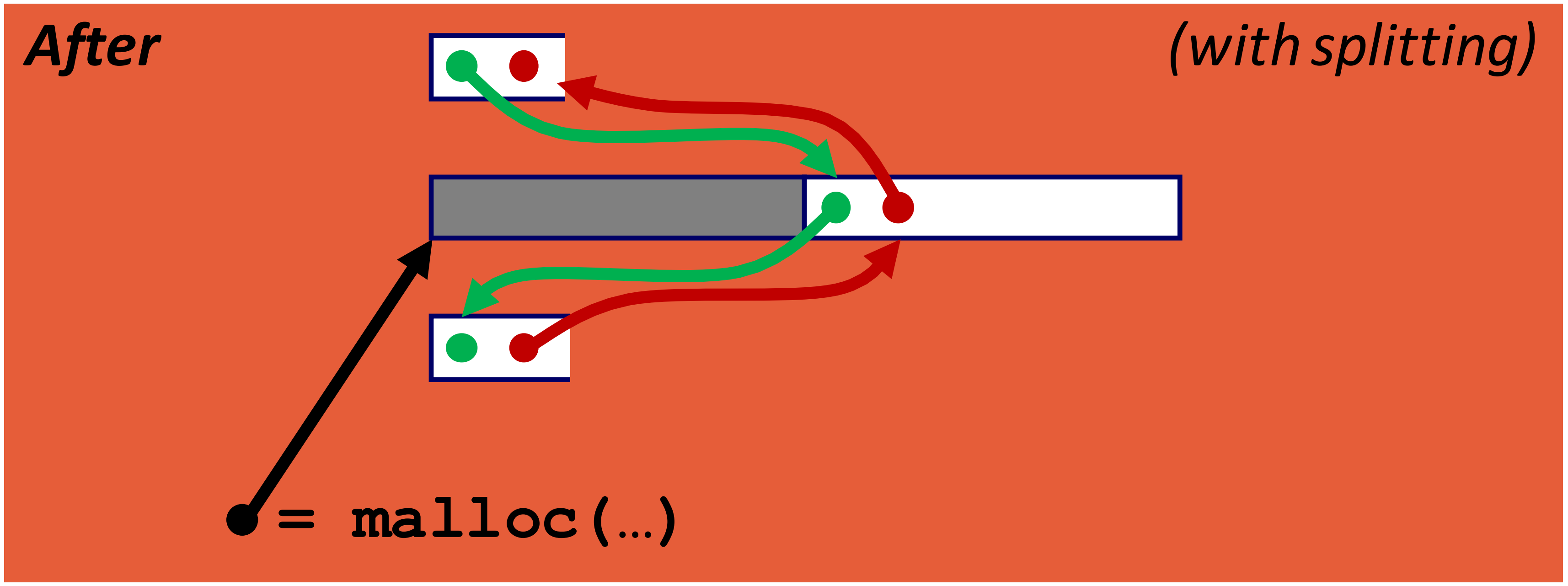
- Physically: blocks can be in any order



Allocating From Explicit Free Lists

conceptual graphic





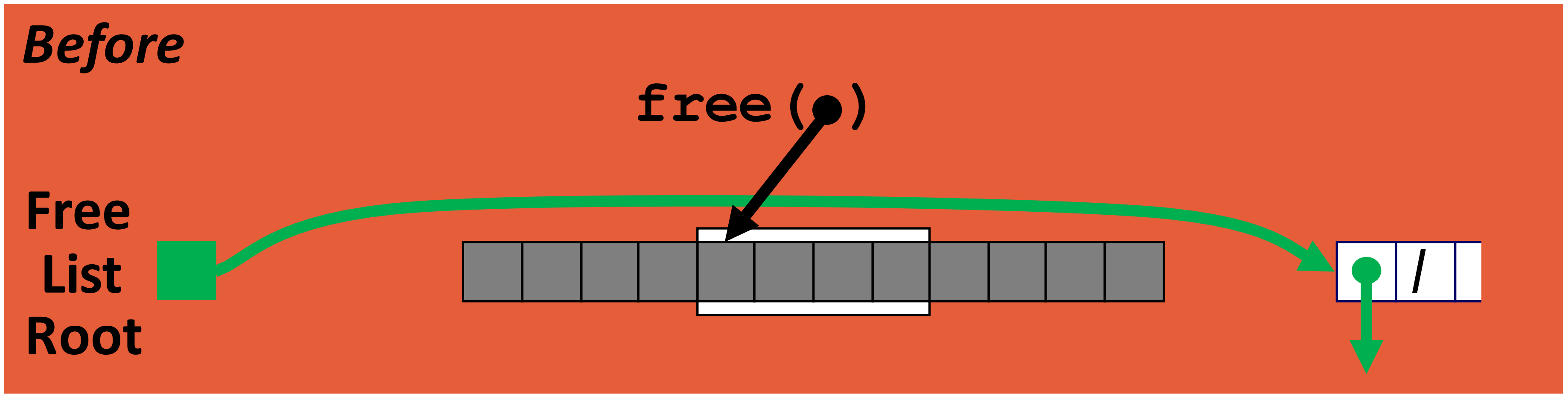
Freeing With Explicit Free Lists

- ***Insertion policy*: Where do you put a newly freed block?**
  - **LIFO (last-in-first-out) policy**
    - Insert freed block at the beginning of the free list
    - ***Pro:*** simple and constant time
    - ***Con:*** studies suggest fragmentation worse than addr-ordered
  - **Address-ordered policy**
    - Insert freed blocks so free list blocks always in address order:

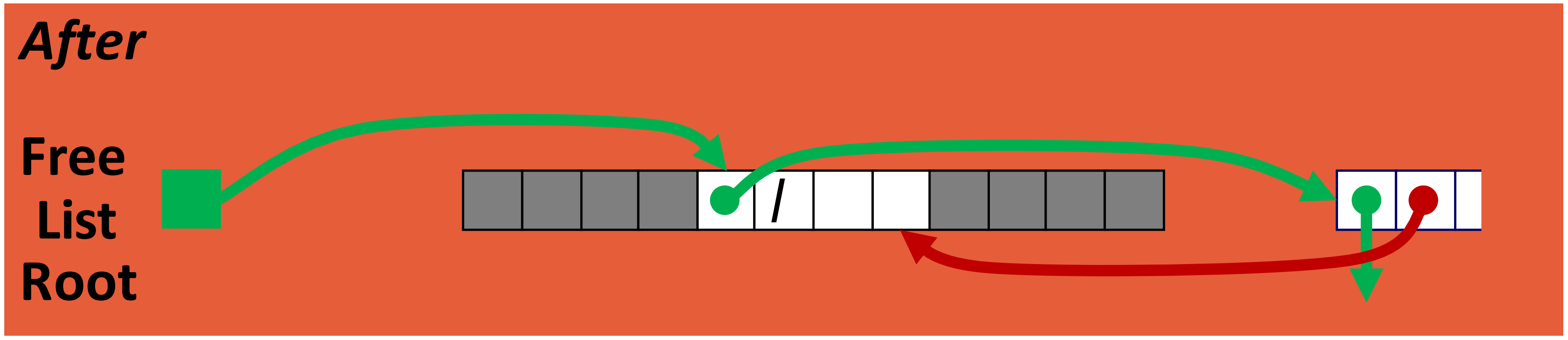
      addr(prev) < addr(curr) < addr(next)
    - ***Con:*** requires search
    - ***Pro:*** studies suggest fragmentation is lower than LIFO

Freeing With a LIFO Policy (Case 1)

conceptual graphic

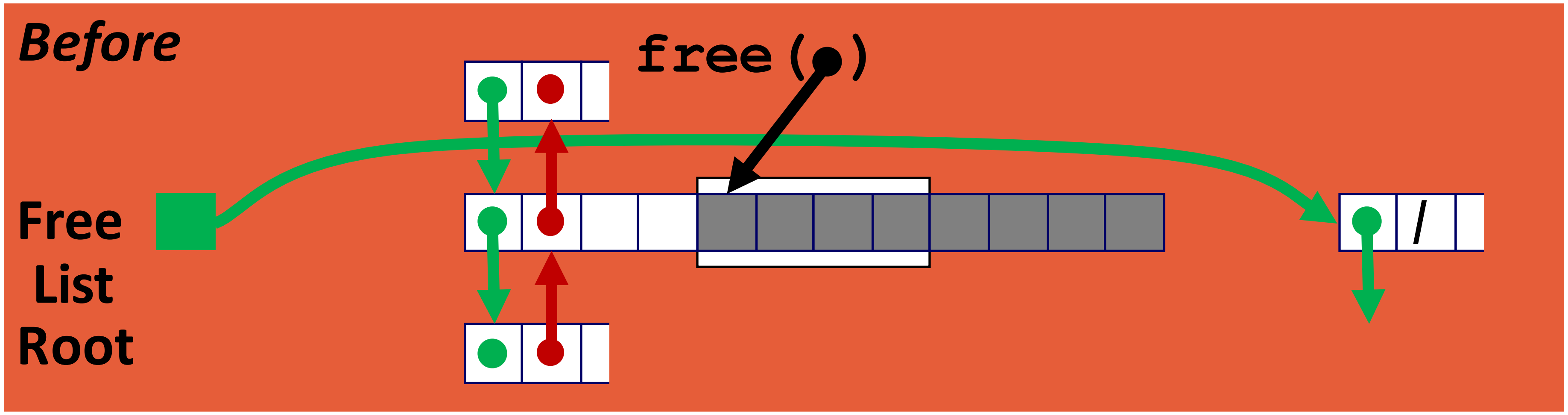


- Insert the freed block at the root of the list

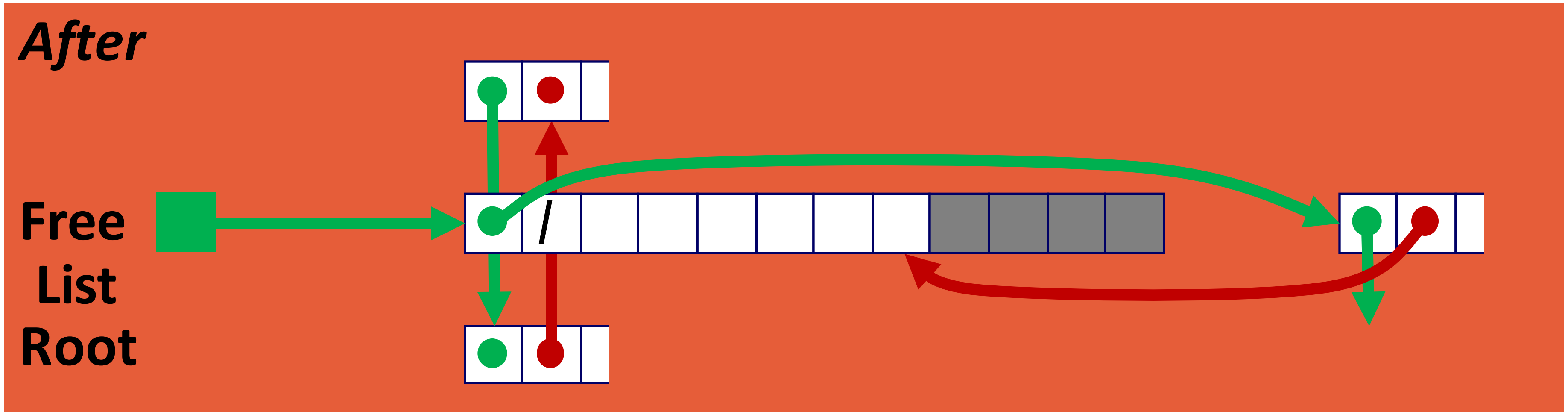


Freeing With a LIFO Policy (Case 2)

conceptual graphic

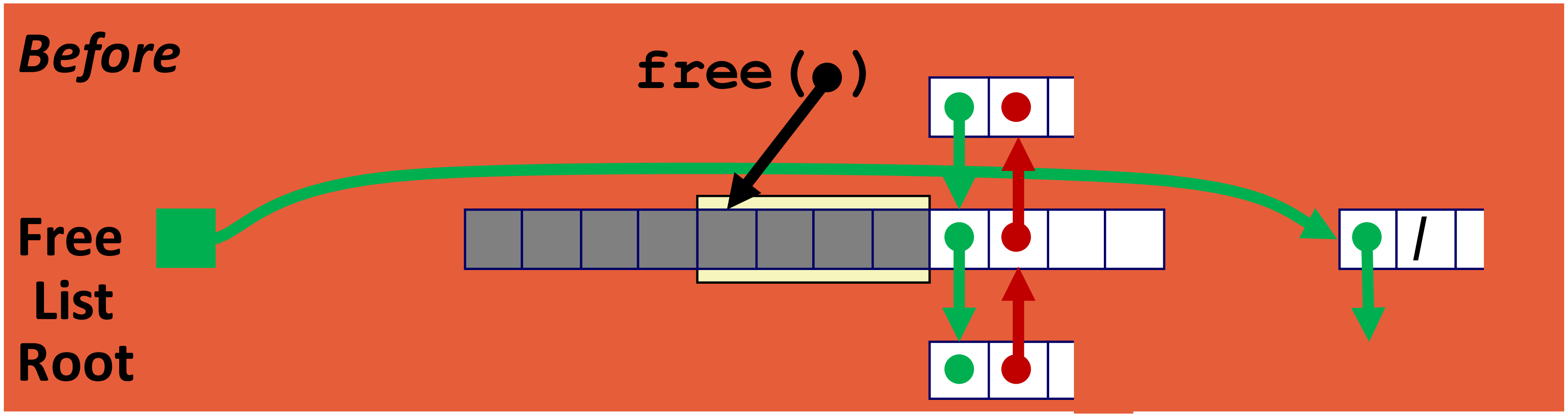


- Splice out predecessor block, coalesce both memory blocks, and insert the new block at the root of the list

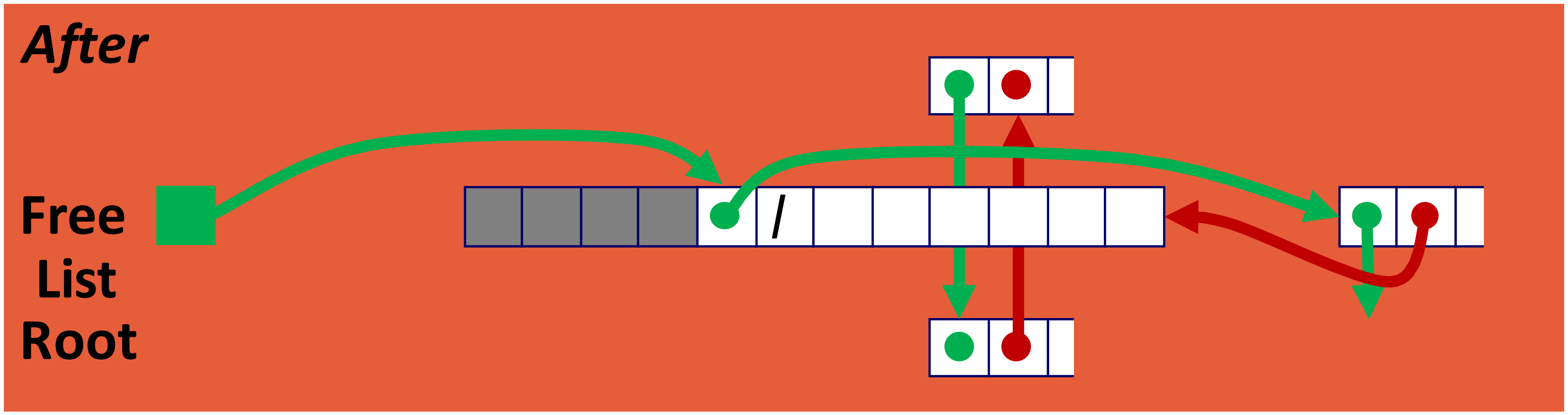


Freeing With a LIFO Policy (Case 3)

conceptual graphic

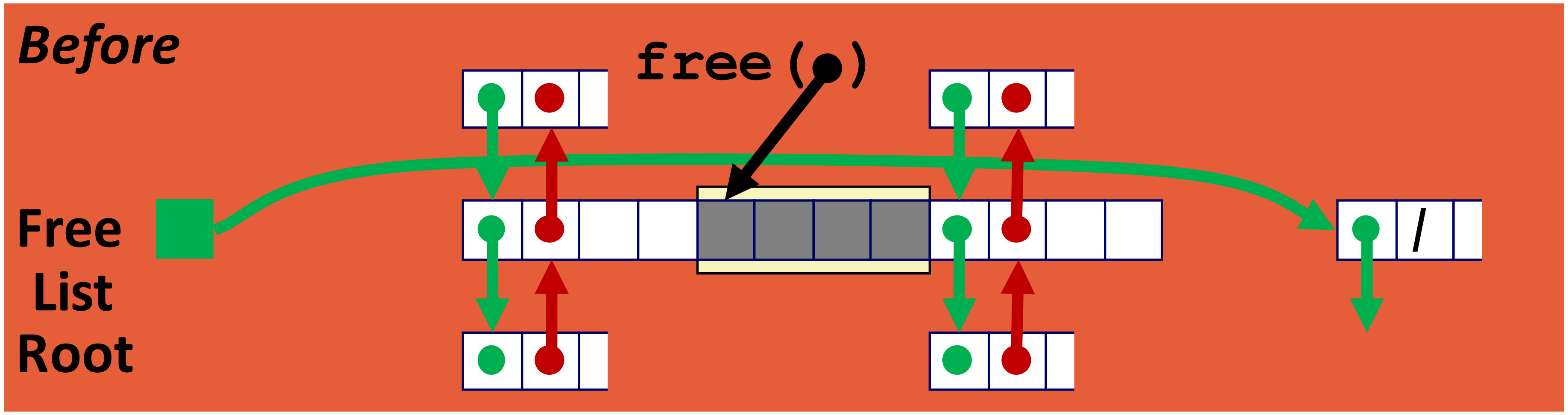


- Splice out successor block, coalesce both memory blocks and insert the new block at the root of the list

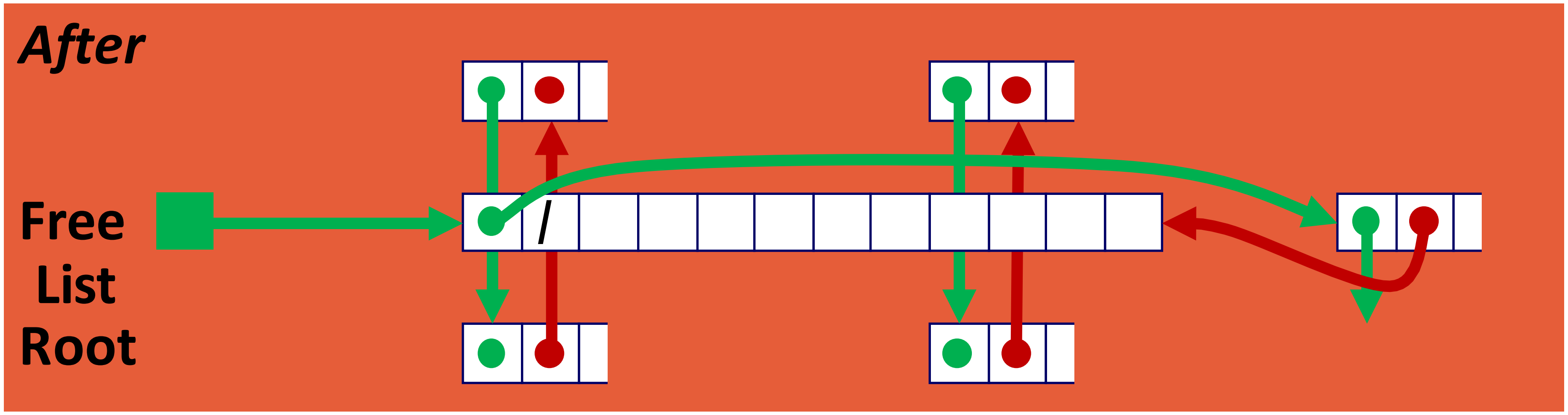


Freeing With a LIFO Policy (Case 4)

conceptual graphic



- Splice out predecessor and successor blocks, coalesce all 3 memory blocks and insert the new block at the root of the list



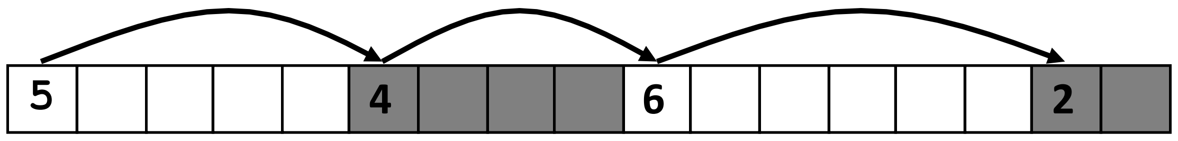
Explicit List Summary

- **Comparison to implicit list:**
  - Allocate: linear in number of ***free*** blocks (instead of ***all*** blocks)
    - ***Much faster*** when most of the memory is full
  - more complicated allocate/free (needs to splice blocks in/out of list)
  - extra space for the links (2 extra words needed for each block)
    - Does this increase internal fragmentation?

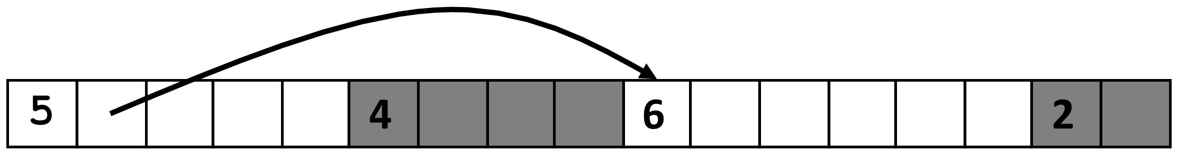
- **Most common use of linked lists is in conjunction with segregated free lists**
  - Keep multiple linked lists of different size classes, or possibly for different types of objects

Keeping Track of Free Blocks

- **Method 1: *Implicit list* using length—links all blocks**



- **Method 2: *Explicit list* among the free blocks using pointers**



- **Method 3: *Segregated free list***
  - Different free lists for different size classes

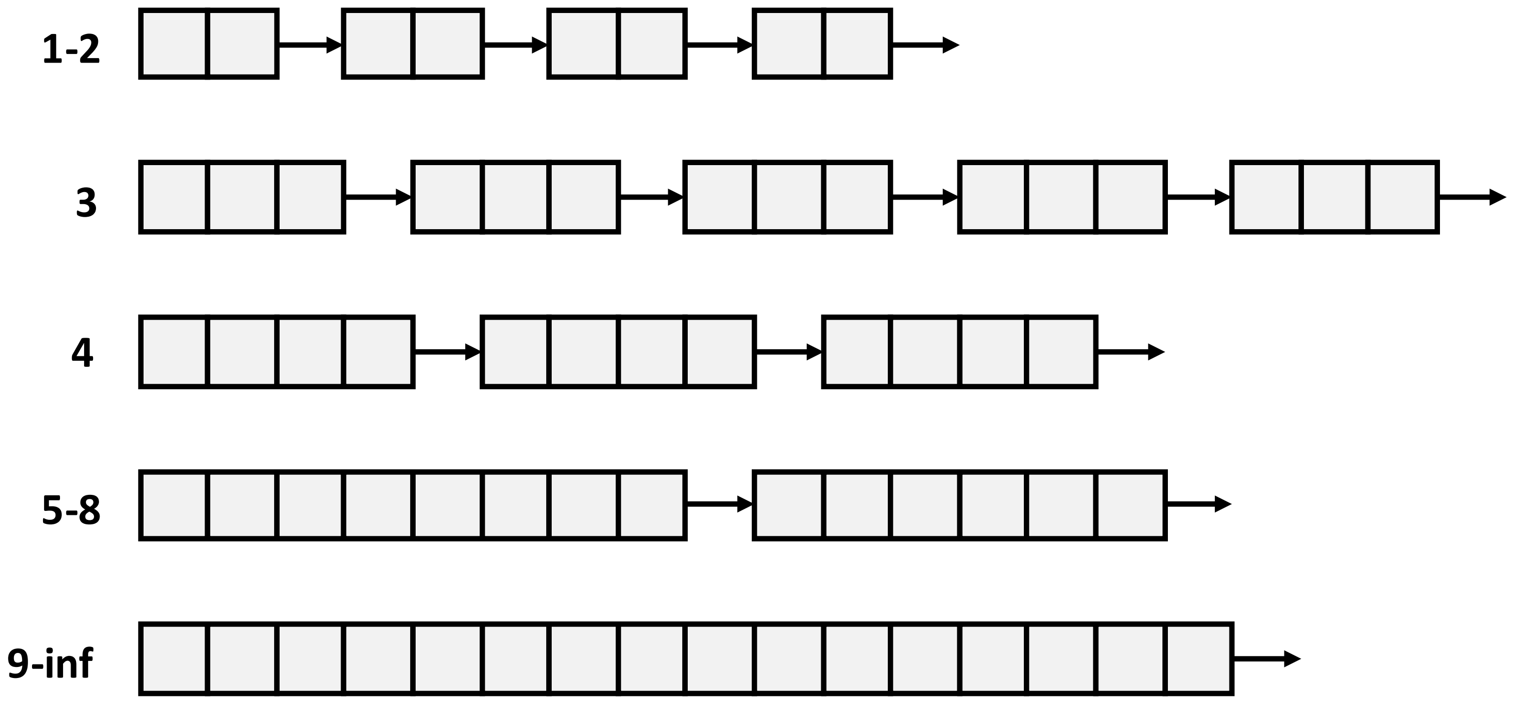
- **Method 4: *Blocks sorted by size***
  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Today

- Basic concepts
- Implicit free lists
- Explicit free lists
- Segregated free lists

Segregated List (Seglist) Allocators

- Each *size class* of blocks has its own free list



- Often have separate classes for each small size
- For larger sizes: One class for each two-power size

Seglist Allocator

- **Given an array of free lists, each one for some size class**

- **To allocate a block of size *n*:**
  - Search appropriate free list for block of size $m > n$
  - If found: split block, optionally place fragment on appropriate list
  - If no block is found, try next larger class
  - Repeat until block is found

- **If no block found:**
  - Real World:
    - Request additional heap memory from OS (using **`sbrk()`**)
    - Allocate block of *n* bytes from new memory
    - Place remainder as a single free block in largest size class
  - CS 3410, Project 4:
    - Return NULL

Seglist Allocator (cont.)

- **To free a block:**
  - Coalesce and place on appropriate list (optional)

- **Advantages of seglist allocators**
  - Higher throughput
    - log time for power-of-two size classes
  - Better memory utilization
    - First-fit search of segregated free list approximates a best-fit search of entire heap
    - Extreme case: giving each block its own size class is equivalent to best-fit

More Info on Allocators

- **Bryant & O'Hallaron, "Computer Systems: A Programmer's Perspective" Sections 9.9-9.13**
  - A great book about System Software

- **D. Knuth, "*The Art of Computer Programming*", 2nd edition, Addison Wesley, 1973**
  - The classic reference on dynamic storage allocation

- **Wilson et al, "*Dynamic Storage Allocation: A Survey and Critical Review*", Proc. 1995 Int'l Workshop on Memory Management, Kinross, Scotland, Sept, 1995.**
  - Comprehensive survey
  - Available from CS:APP student site (csapp.cs.cmu.edu)