# Dynamic Memory Allocation

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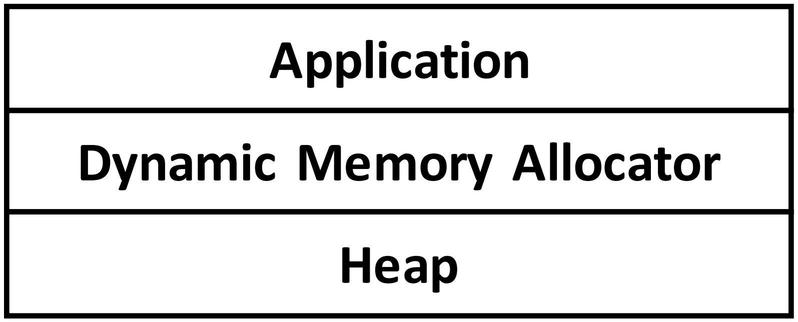
Note: these slides derive from those by Markus Püschel at CMU

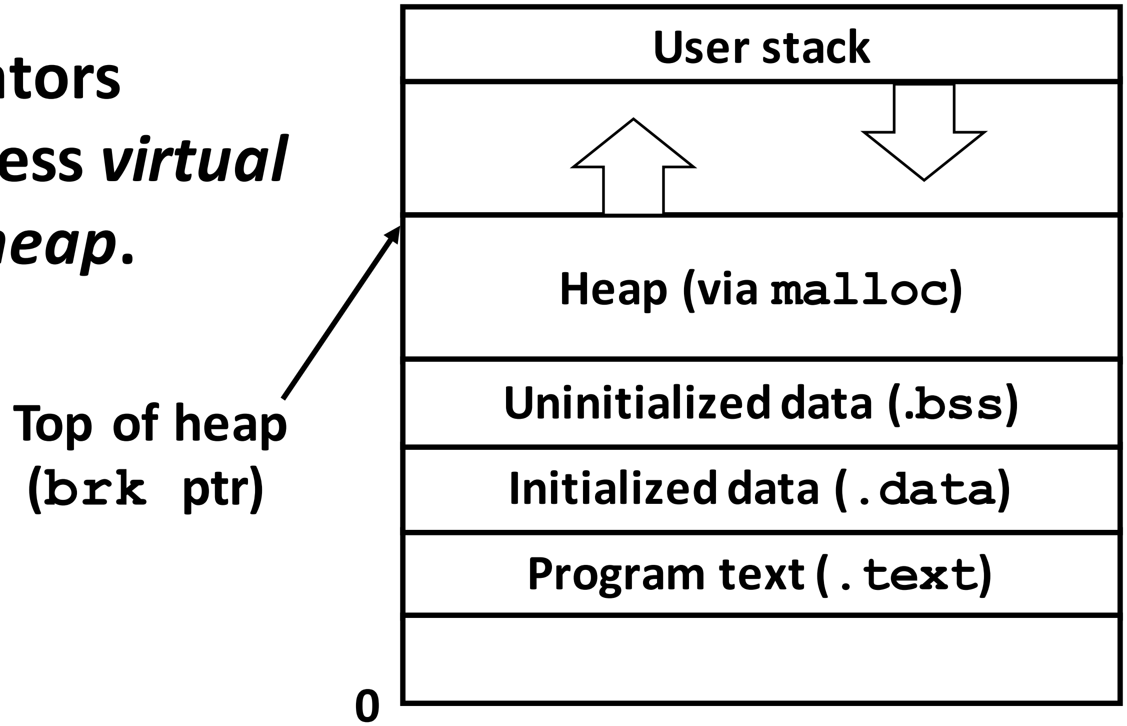
# Today

- 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**

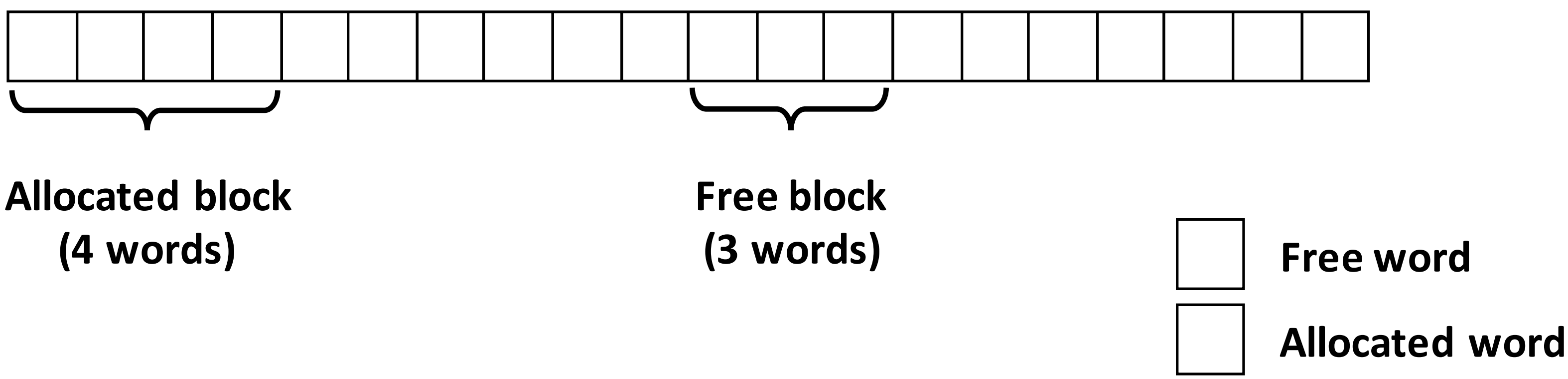
- **`calloc:`** initializes allocated block to zero
- **`realloc:`** changes size of a previously allocated block
- **`sbrk:`** used internally by allocators to grow or shrink heap

# `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);
}
```

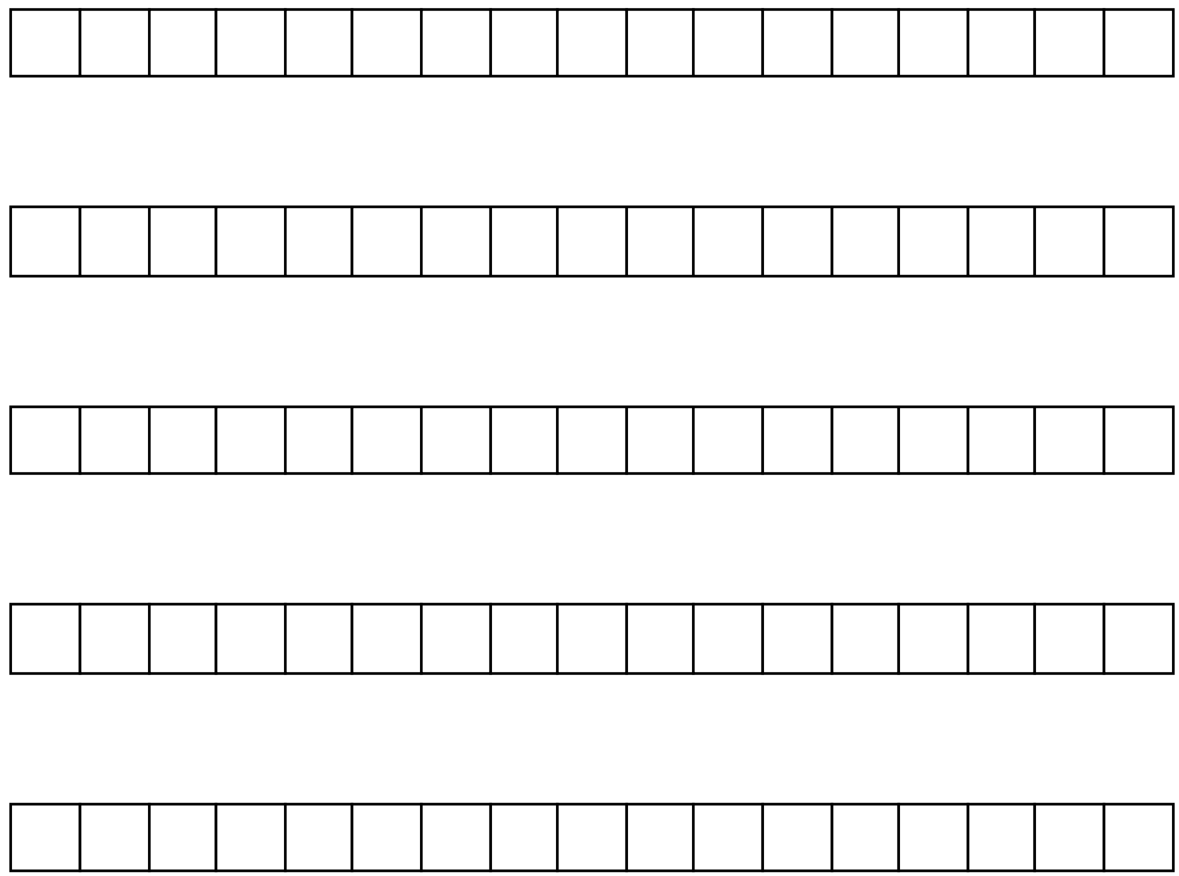
# Assumptions Made in This Lecture

- **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:**
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$

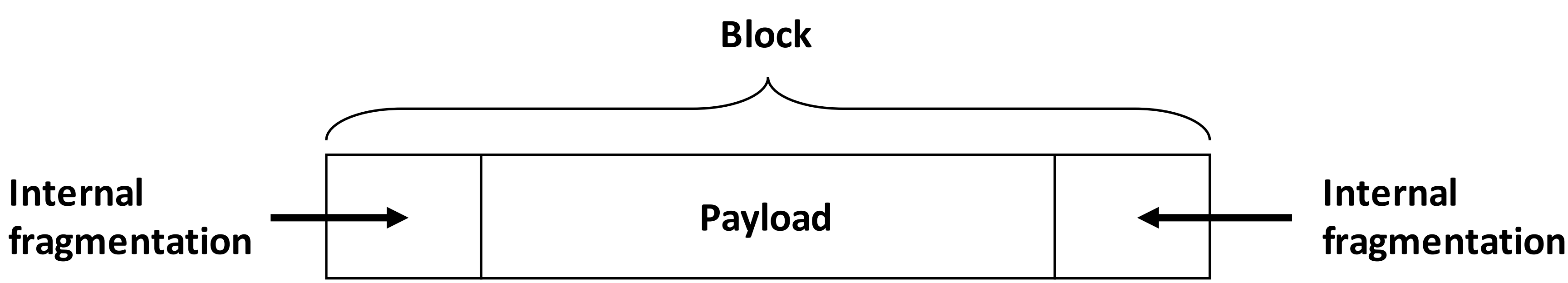
- **Maximize Memory Utilization:**
  - Extra constraint for 3410 version: the heap does not grow!
  - For a given task, how large a heap do you need to suceed
  - Poor memory utilization caused by *fragmentation*

**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**



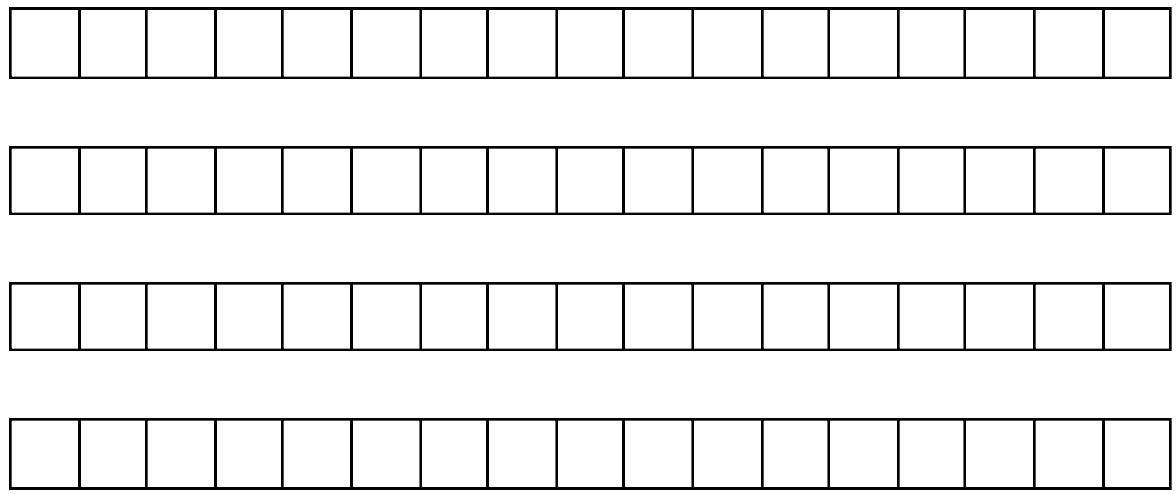

- **Caused by**
  - Overhead of maintaining heap data structures
  - Padding for alignment purposes
  - Explicit policy decisions
    (e.g., to return a big block to satisfy a small request)

- **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?

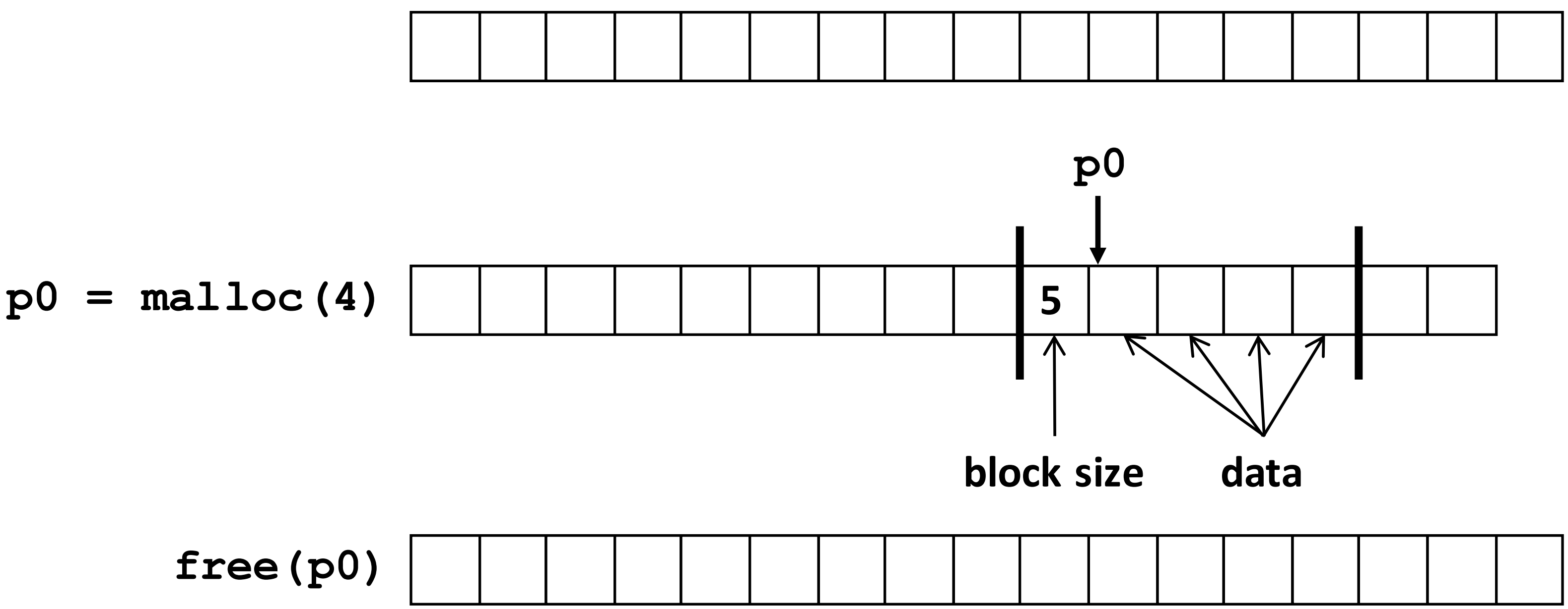
3. When allocating a structure that is smaller than the free block it is placed in, what do we do with the extra space?

4. How do we pick a block to use for allocation? (if a few work)

5. How do we reinsert freed block?

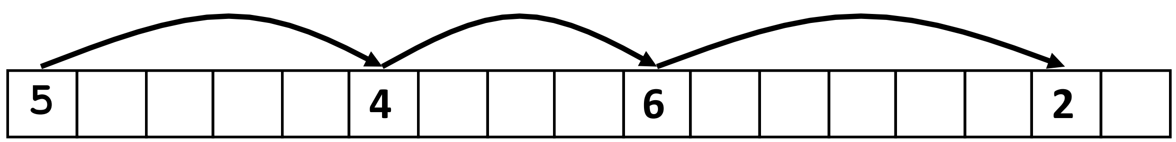
# Q1: Knowing How Much to Free

- **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

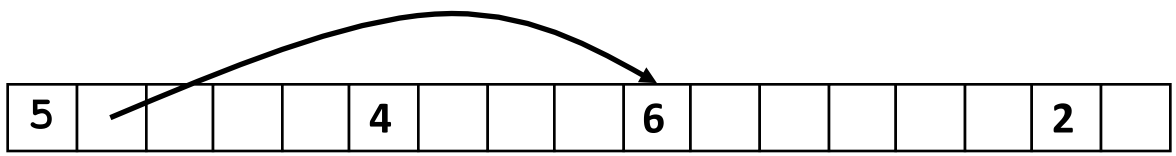


# Q2: Keeping Track of Free Blocks

- **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

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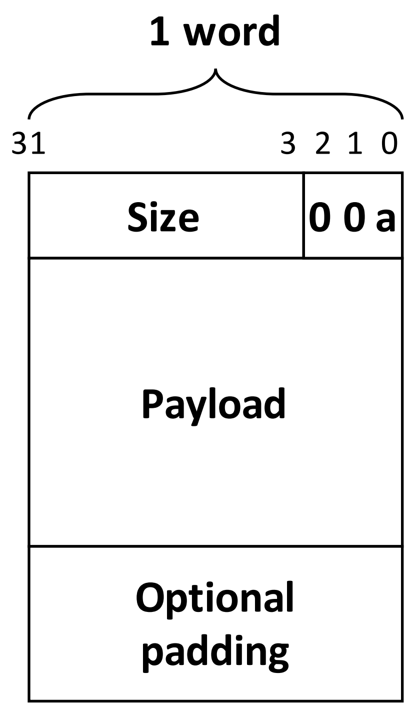
# Method 1: Implicit List

- **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***

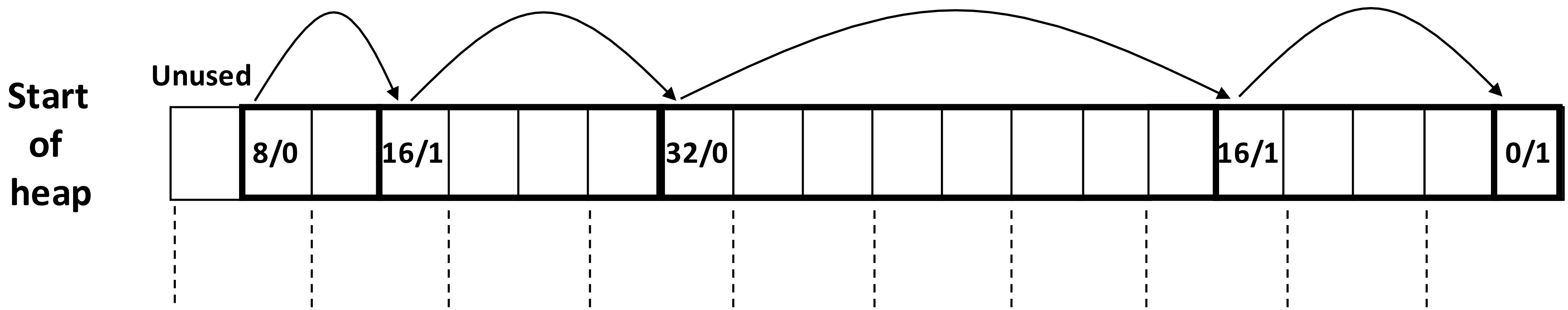



**a = 1: Allocated block**
**a = 0: Free block**

**Size: block size**

**Payload: application data (allocated blocks only)**

# Detailed Implicit Free List Example




Double-word aligned

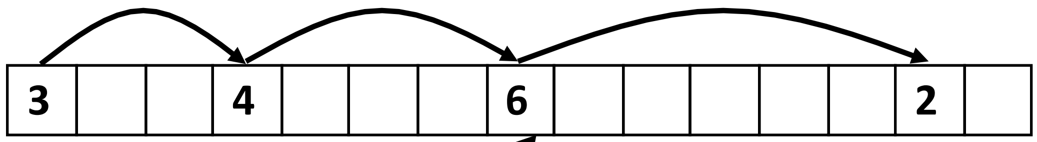
Allocated blocks: shaded grey
Free blocks: unshaded
Headers: labeled with size in bytes/allocated bit

# 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

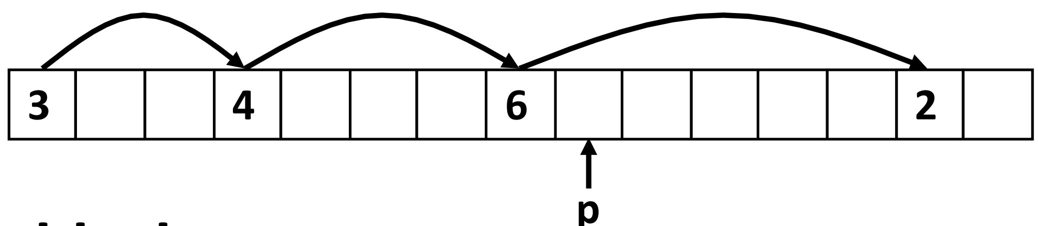
**Suppose we need to allocate 3 words**



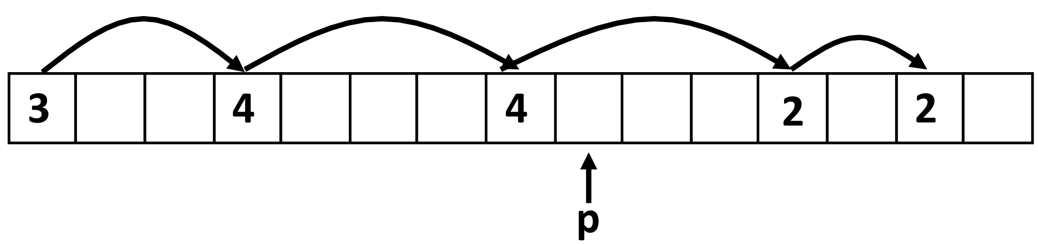

This is our free block of choice

**Two options:**

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

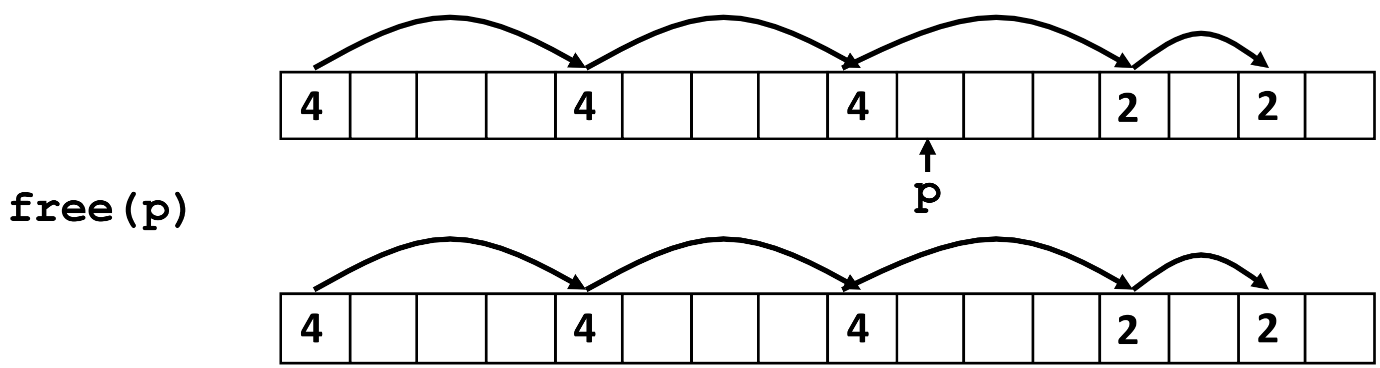



2. **Split the free block**



# Q5: Implicit List: Freeing a Block

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

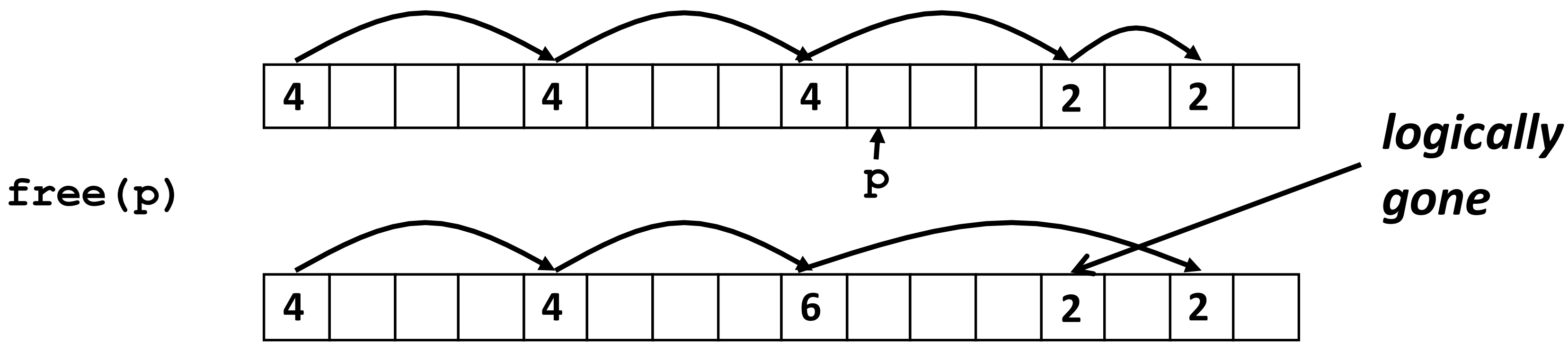



`malloc(5)` ***Oops!***

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

# Implicit List: Coalescing

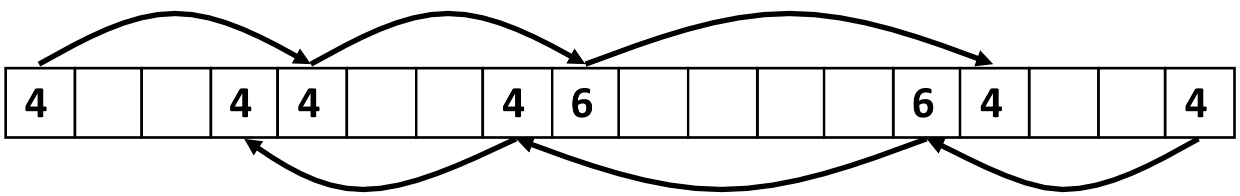
- **Join *(coalesce)* with next/previous blocks, if they are free**
  - Coalescing with next block



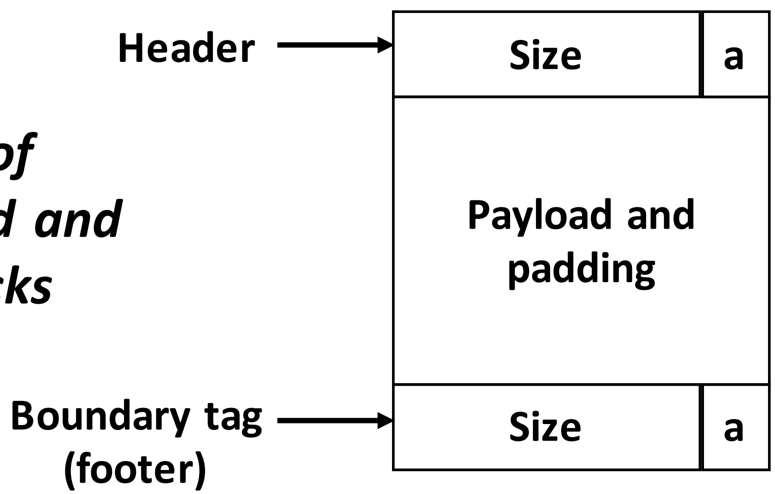

How do we coalesce with *previous* block?

# 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***

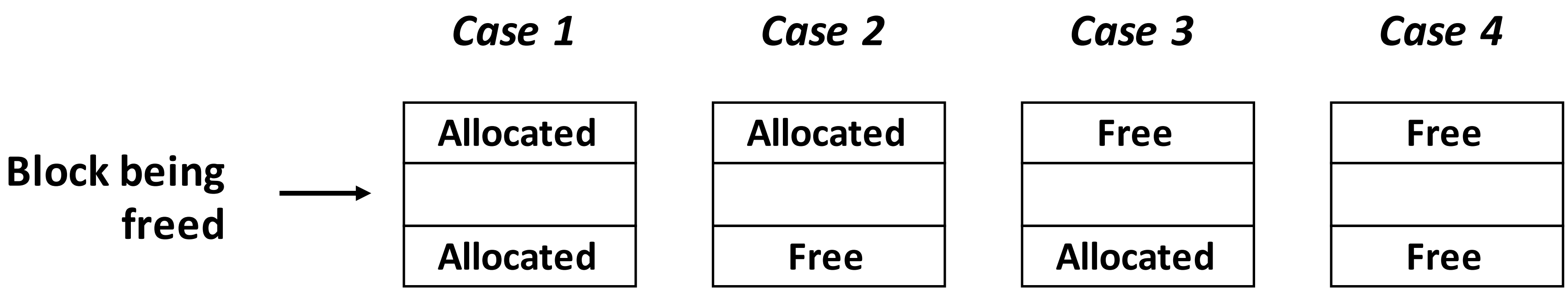



**a = 1: Allocated block**
**a = 0: Free block**

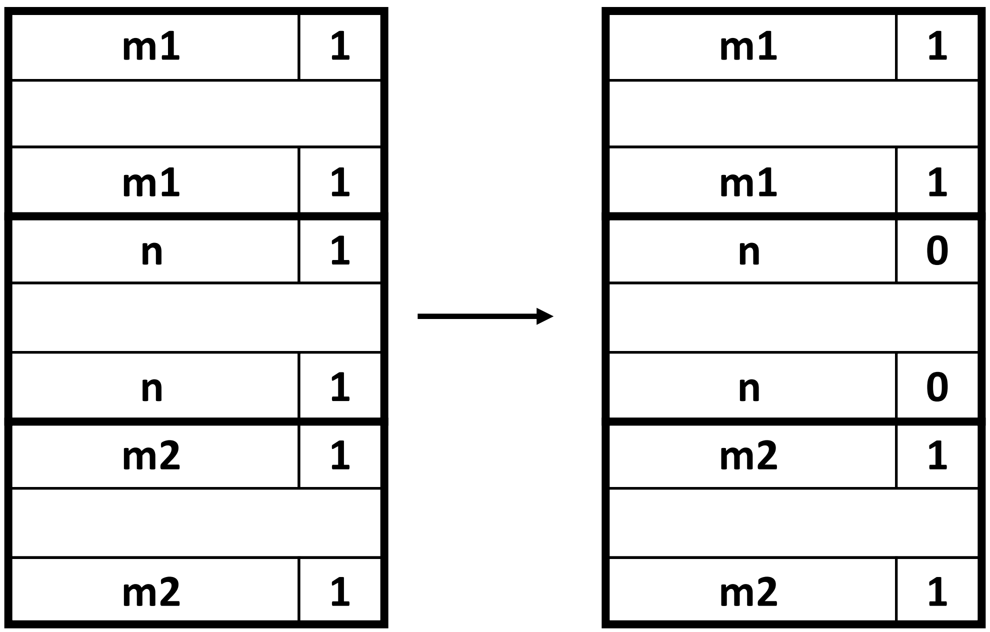
**Size: Total block size**

**Payload: Application data (allocated blocks only)**

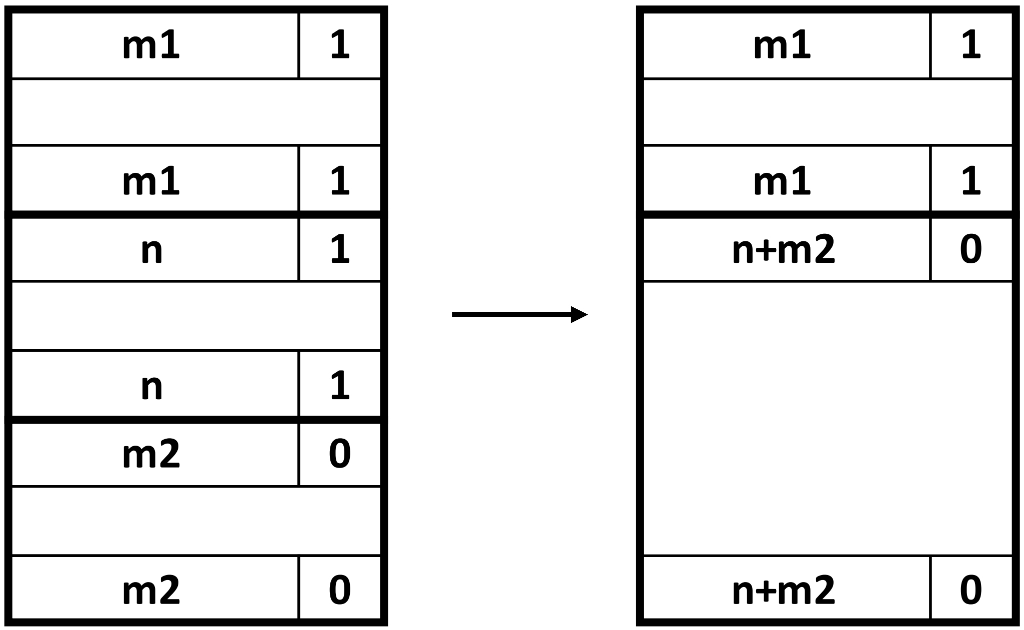
# Constant Time Coalescing



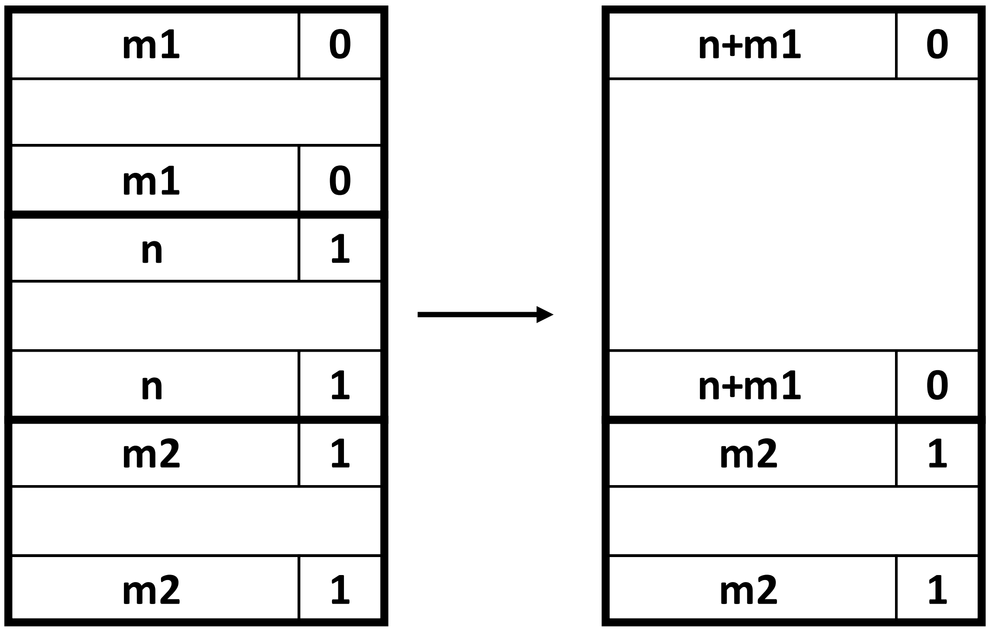
# Constant Time Coalescing (Case 1)



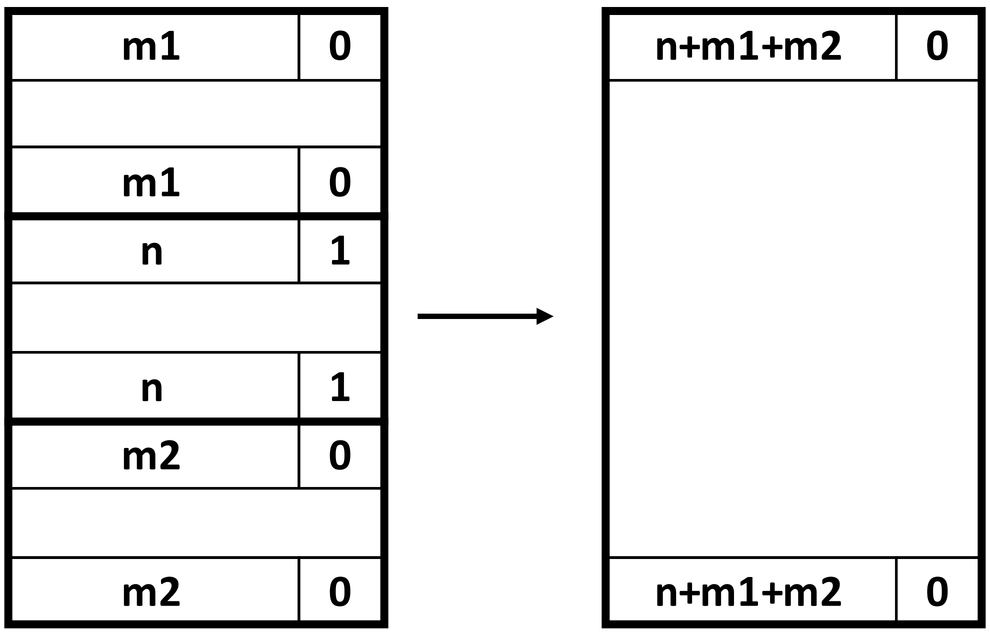
# Constant Time Coalescing (Case 2)



# 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
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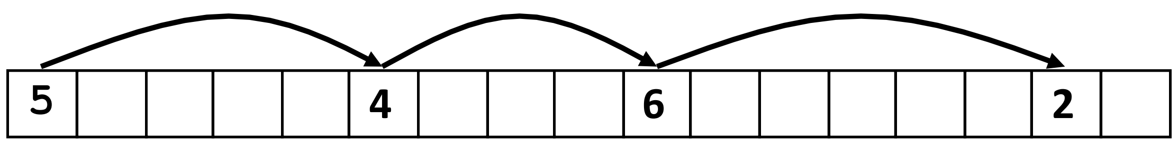
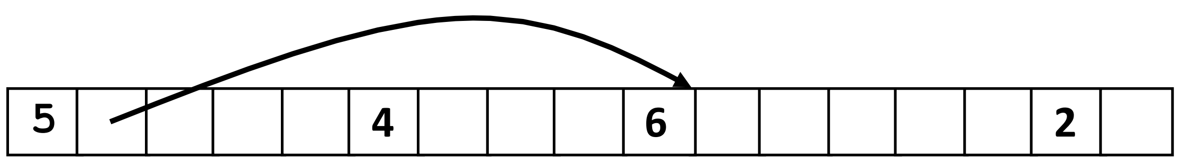
- Explicit free lists
- Segregated free lists

# Keeping Track of Free Blocks

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



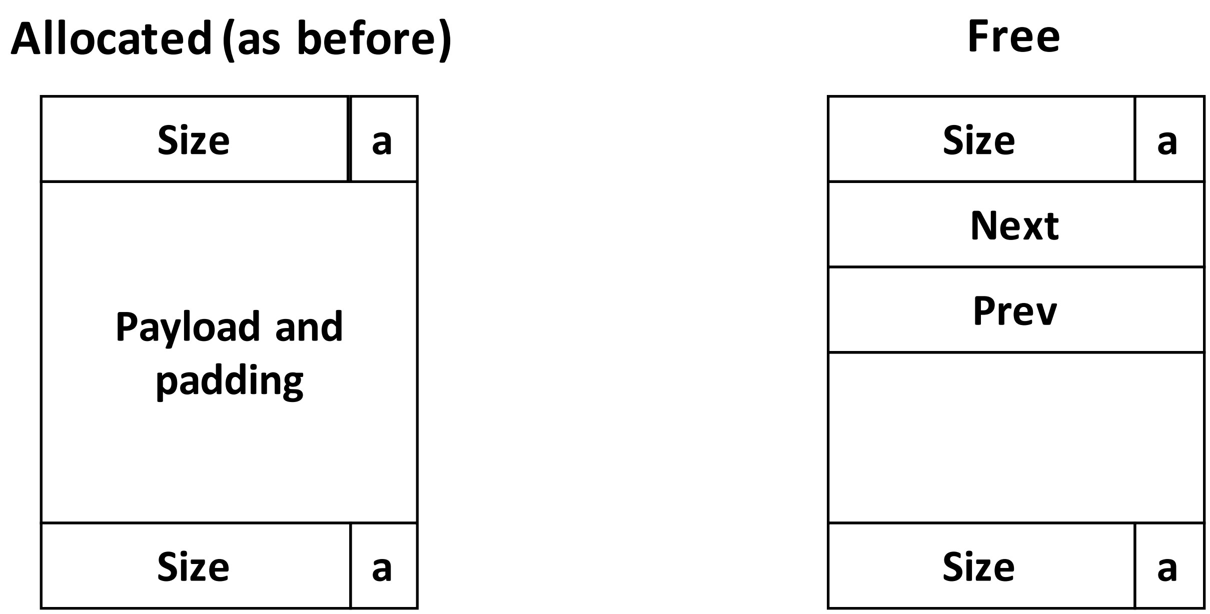

- **Method 2:** ***Explicit free list*** **among the free blocks using pointers**




- **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

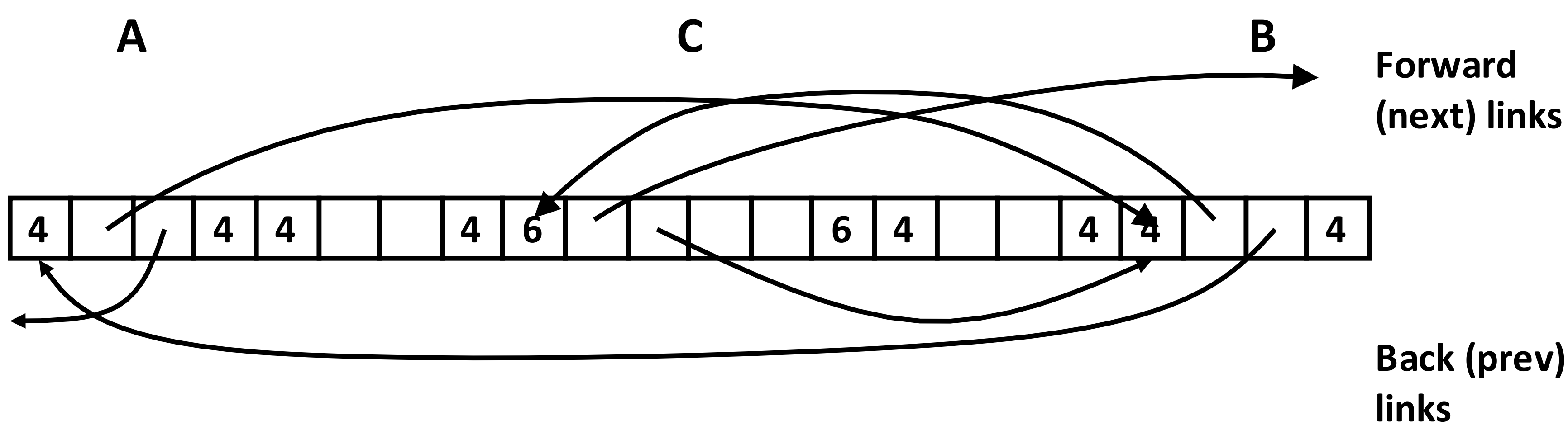



- **Maintain list(s) of *free* blocks, not *all* blocks**
  - "next" free block could be anywhere
    - need to store forward/back pointers, not just sizes
  - Still need boundary tags for coalescing
  - Tracking *free* blocks → can use payload area

# Explicit Free Lists

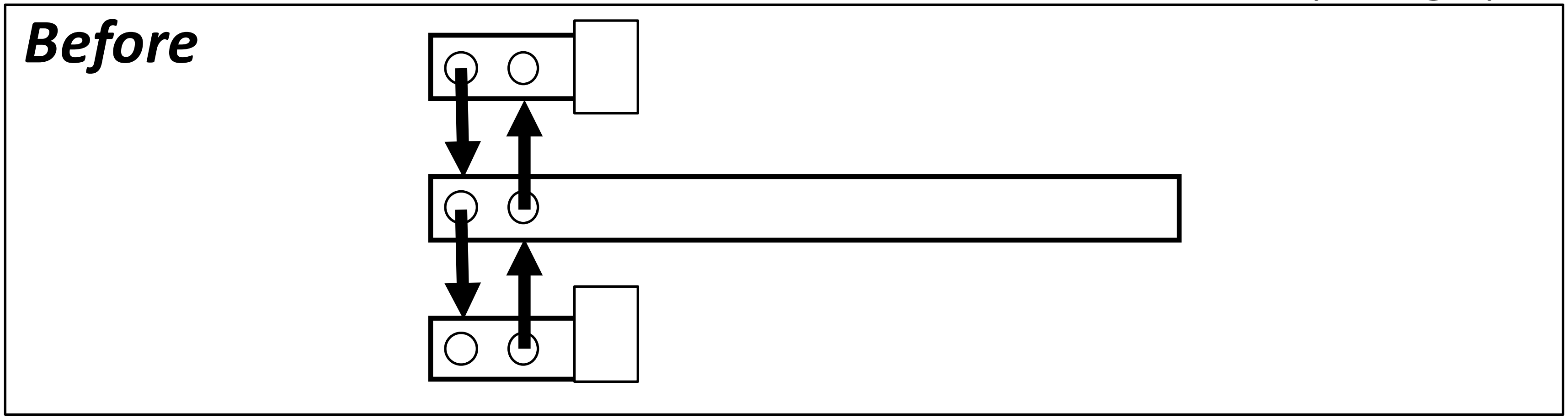
- **Logically:**

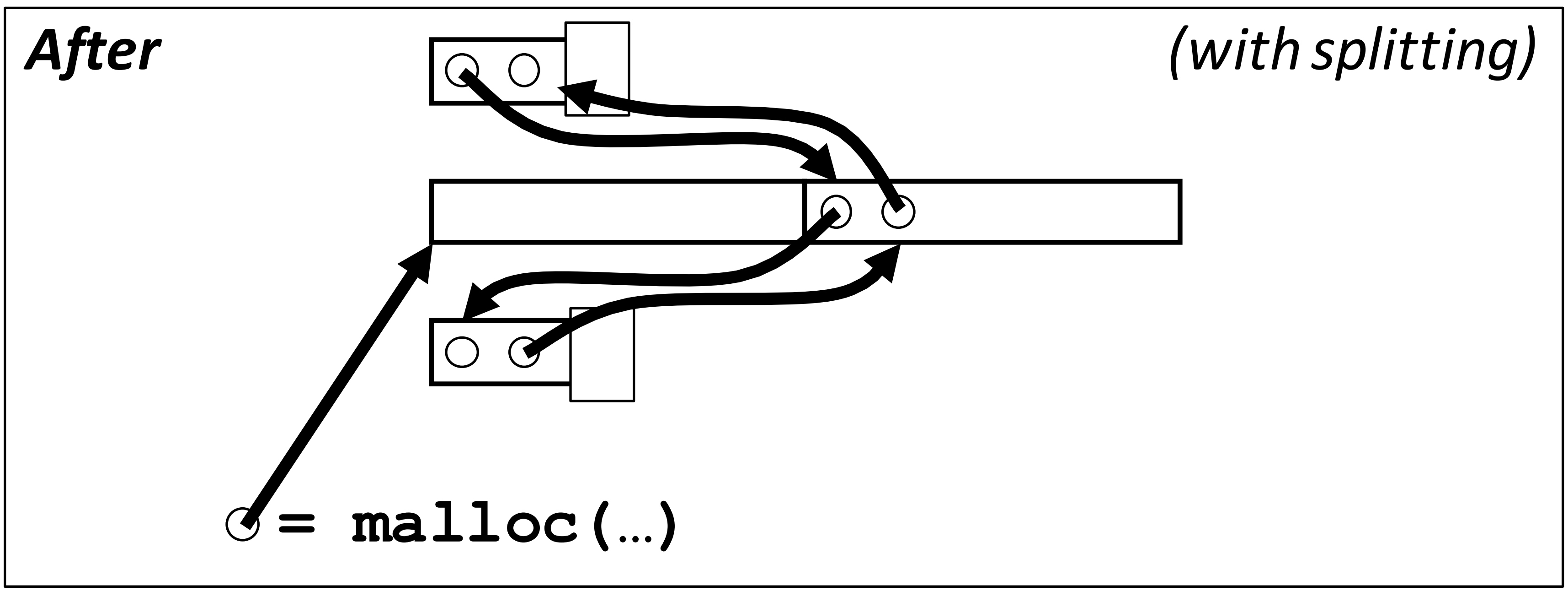

- **Physically: blocks can be in any order**



# Allocating From Explicit Free Lists

conceptual graphic



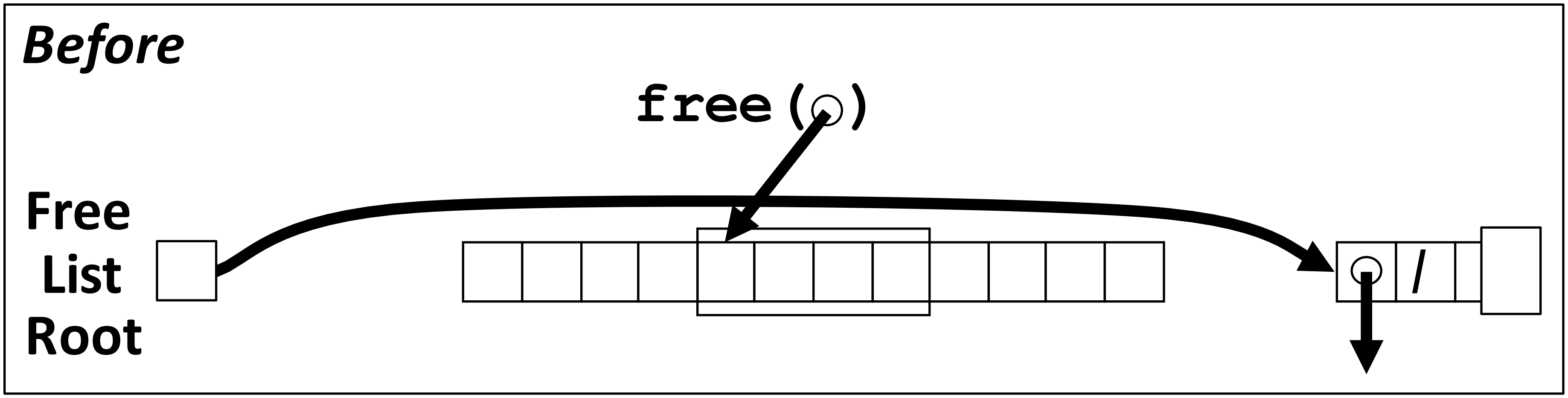



# Freeing With Explicit Free Lists

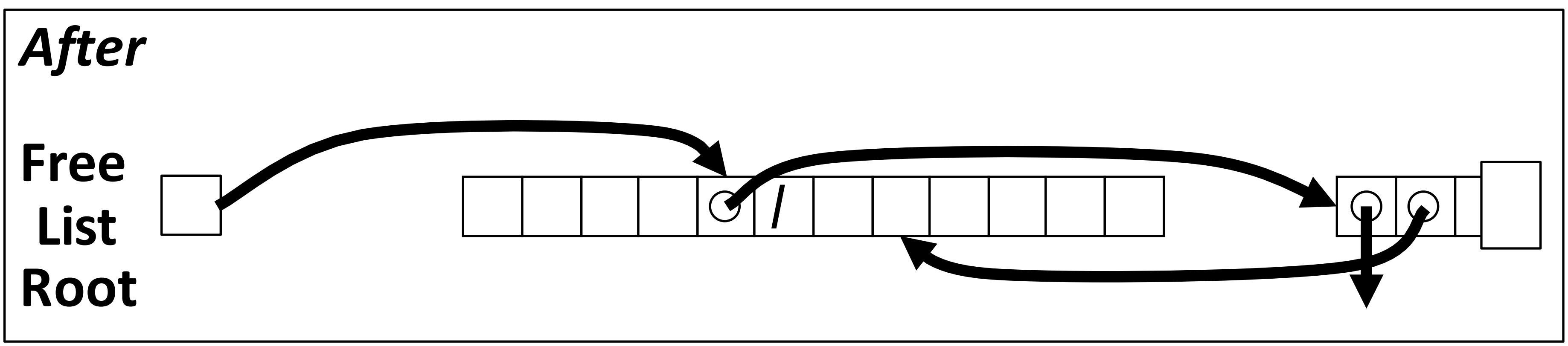
- ***Insertion policy*: Where do you put a newly freed block?**
  - **LIFO (last-in-first-out) policy**
    - Insert freed block at the beginning of the free list
    - ***Pro:*** simple and constant time
    - ***Con:*** studies suggest fragmentation worse than addr-ordered
  - **Address-ordered policy**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

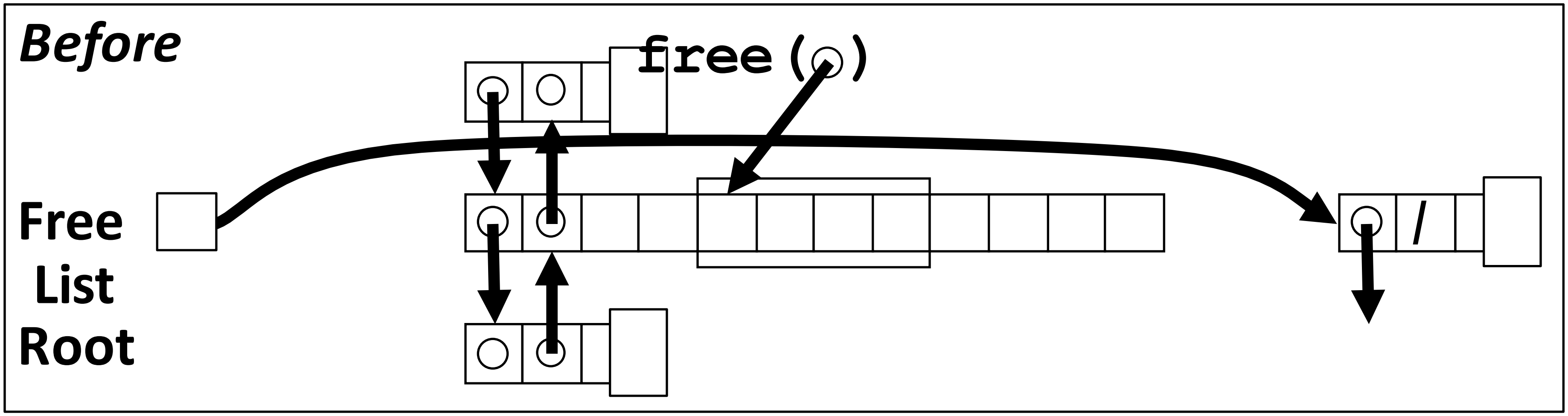



- Insert the freed block at the root of the list

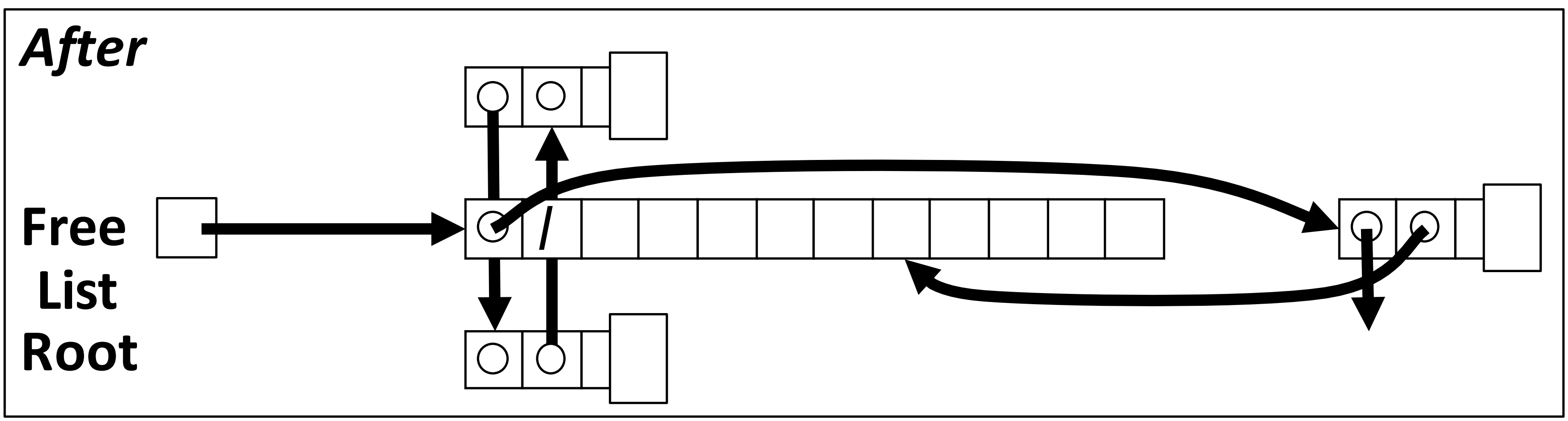


# Freeing With a LIFO Policy (Case 2)

conceptual graphic

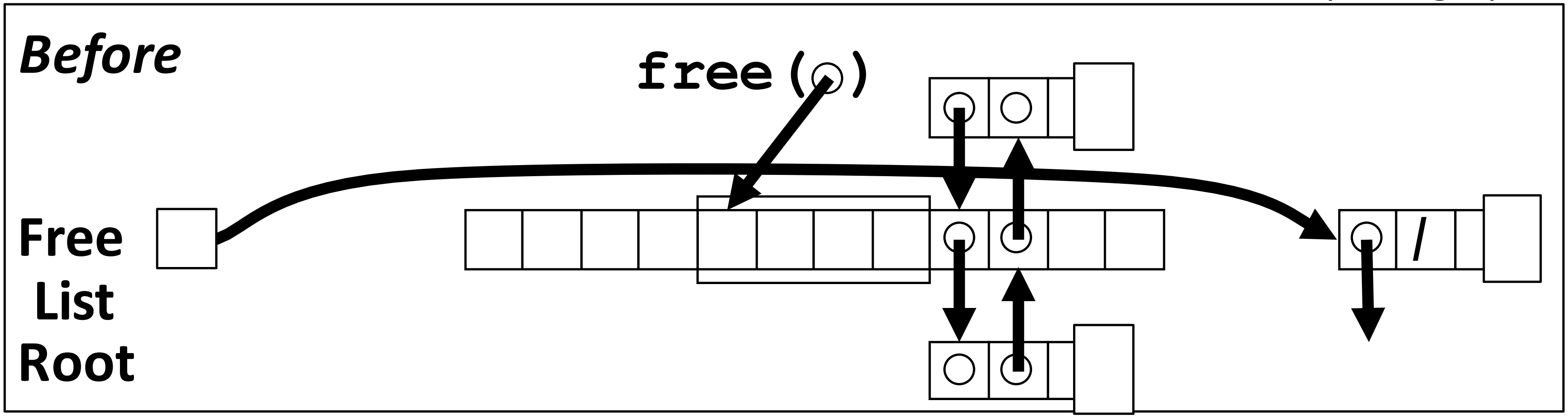



- Splice out predecessor block, coalesce both memory blocks, and insert the new block at the root of the list

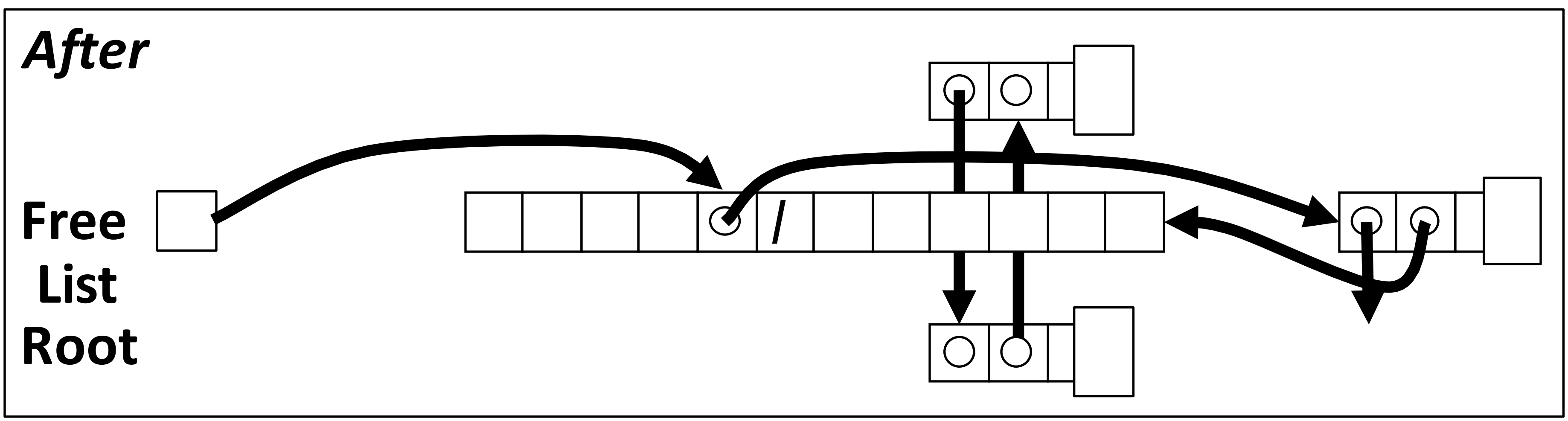


# Freeing With a LIFO Policy (Case 3)

conceptual graphic

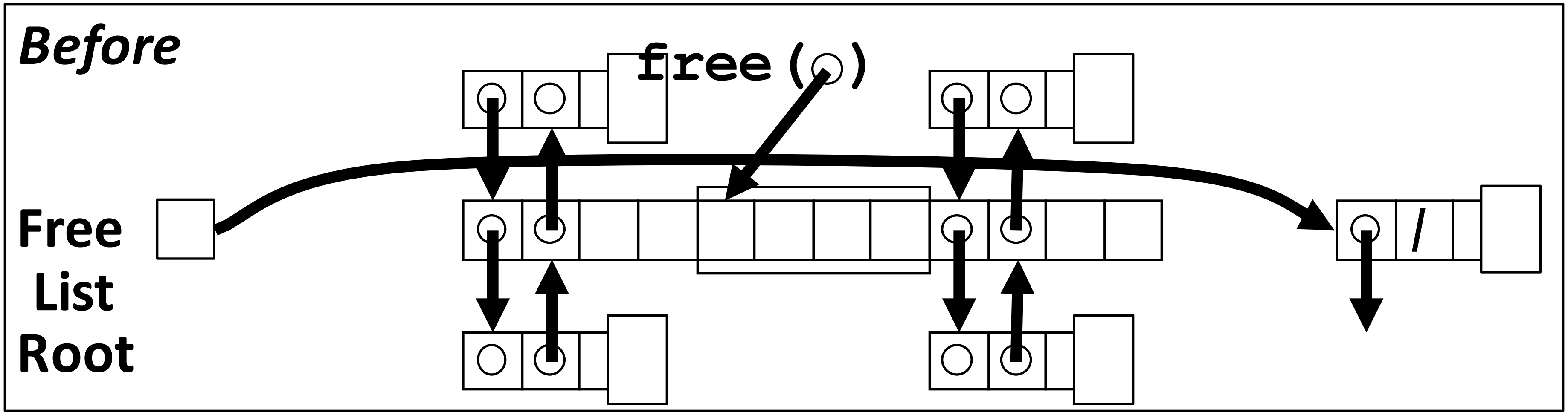



- **Splice out successor block, coalesce both memory blocks and insert the new block at the root of the list**

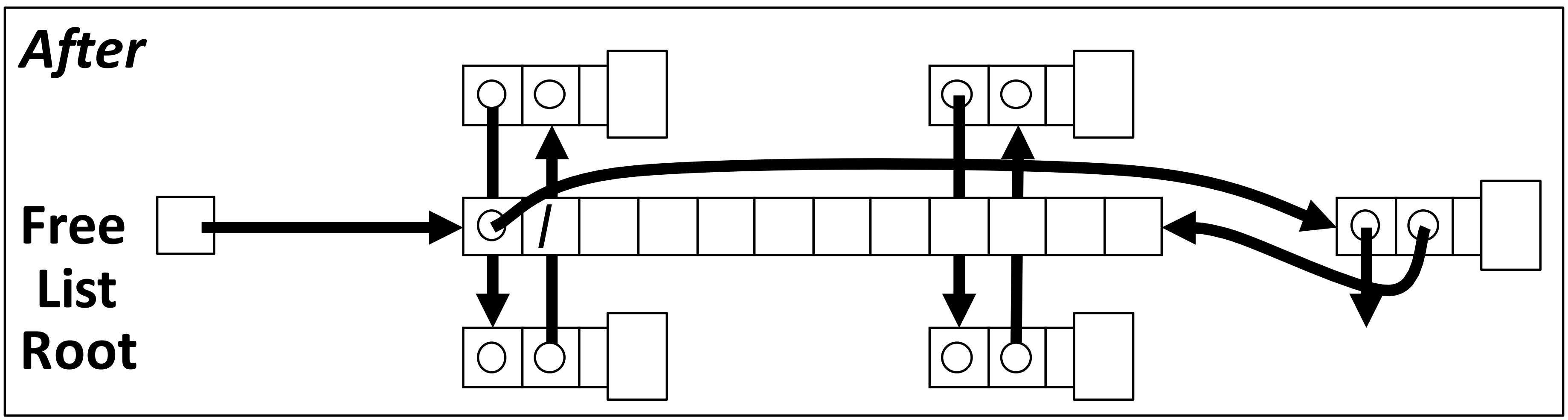


# Freeing With a LIFO Policy (Case 4)

conceptual graphic




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



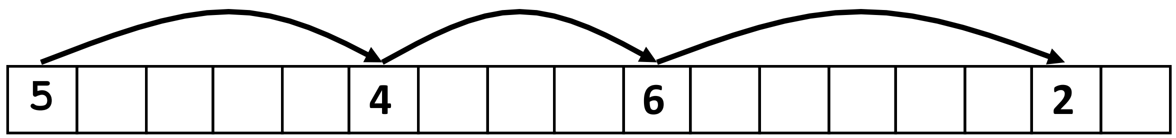
# Explicit List Summary

- **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?

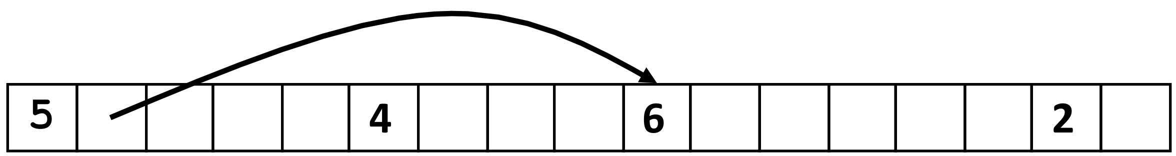
- **Most common use of linked lists is in conjunction with segregated free lists**
  - Keep multiple linked lists of different size classes, or possibly for different types of objects

# 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***
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- Method 4: ***Blocks sorted by size***
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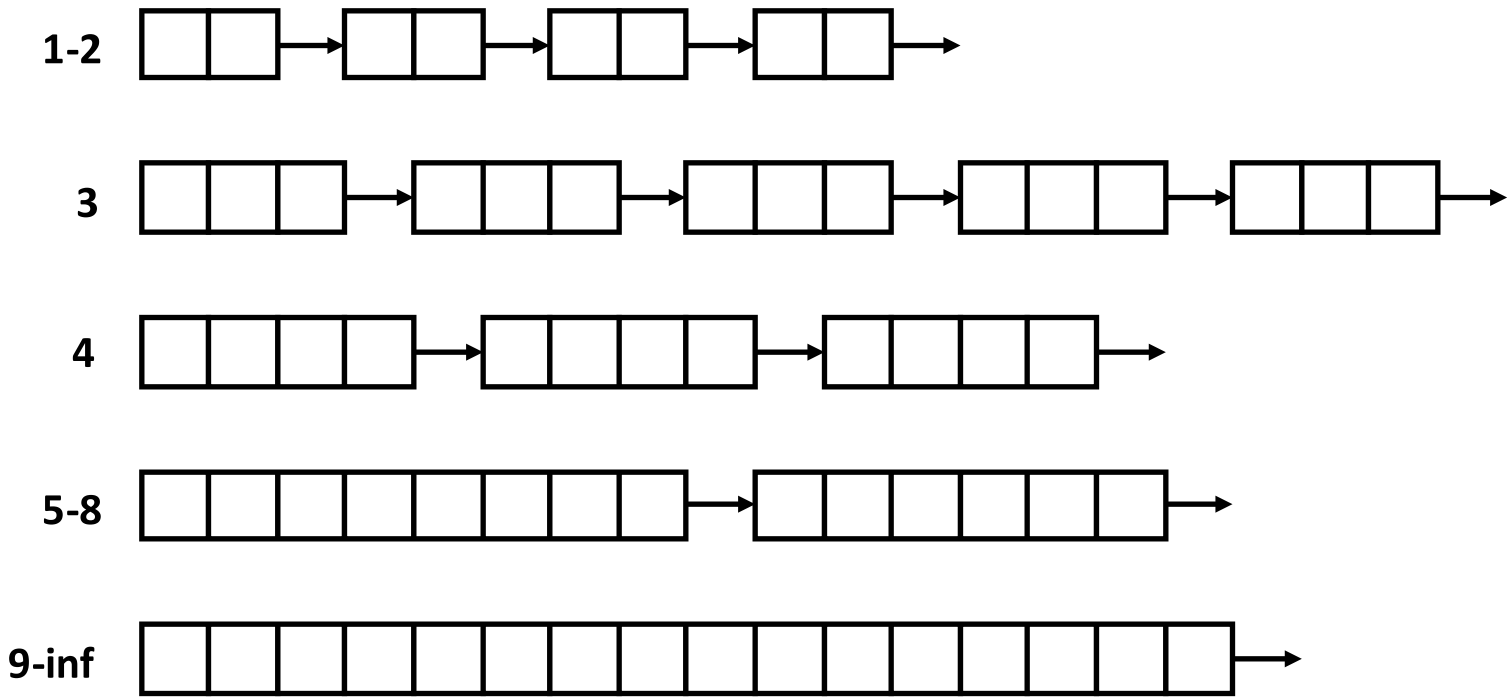
# Segregated List (Seglist) Allocators

- 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)