

# Memory Allocation II

CSE 351 Spring 2020

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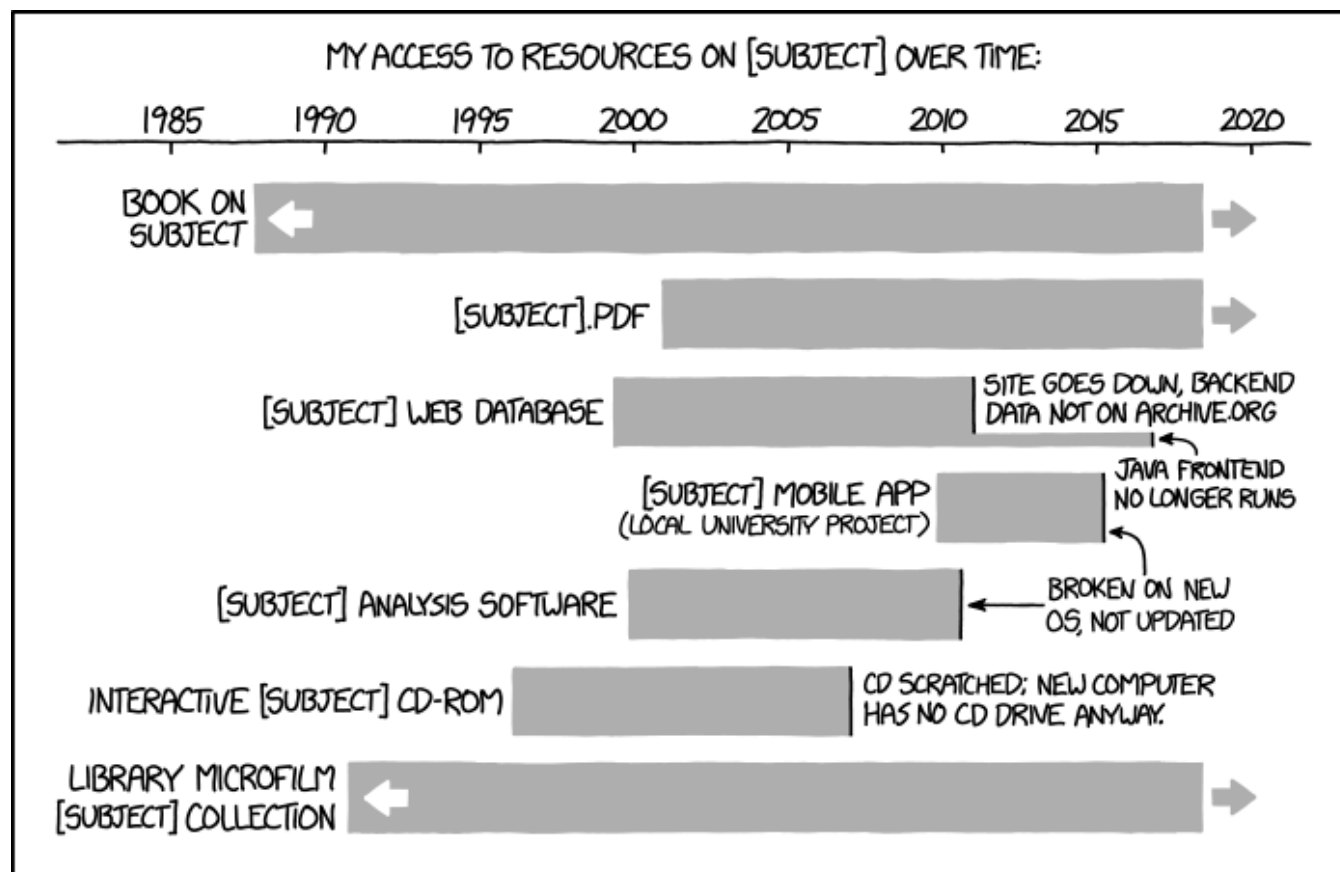
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IT'S UNSETTLING TO REALIZE HOW QUICKLY DIGITAL RESOURCES CAN DISAPPEAR WITHOUT ONGOING WORK TO MAINTAIN THEM.

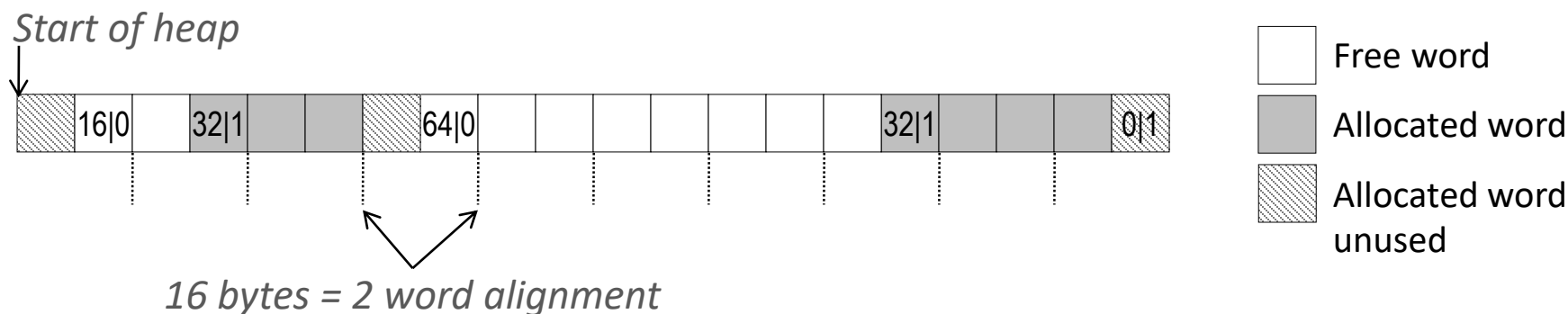
<http://xkcd.com/1909/>

# Administrivia

- ❖ Unit Summary #3 – due this Friday (5/29)
- ❖ Lab 5 (on Mem Alloc) due the last day of class (6/05)
  - The most significant amount of C programming you will do in this class – combines lots of topics from this class: pointers, bit manipulation, structs, examining memory
  - Understanding the concepts *first* and efficient *debugging* will save you lots of time
  - Light style grading
  - Can be submitted at most ONE day late. (Sun 6/07)
  - hw22 due Monday (6/01) – Do EARLY, will help with Lab 5
- ❖ **You must log on with your @uw google account to access!!**
  - **Google doc** for 11:30 Lecture: <https://tinyurl.com/351-05-27A>
  - **Google doc** for 2:30 Lecture: <https://tinyurl.com/351-05-27B>

# Implicit Free List Example

- ❖ Each block begins with header (size in bytes and allocated bit)
- ❖ Sequence of blocks in heap (`size|allocated`):  
16|0, 32|1, 64|0, 32|1



- ❖ 16-byte alignment for *payload*
  - May require initial padding (internal fragmentation)
  - Note `size`: padding is considered part of *previous* block
- ❖ Special one-word marker (0|1) marks end of list
  - Zero `size` is distinguishable from all other blocks

# Implicit List: Finding a Free Block

(*\*p*) gets the block header  
 (*\*p & 1*) extracts the allocated bit  
 (*\*p & -2*) extracts the size

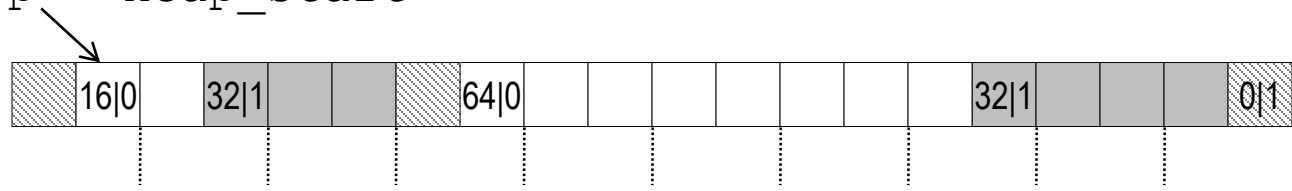
## ❖ *First fit*

- Search list from beginning, choose first free block that fits:

```
p = heap_start;
while ((p < end) && // not past end
      ((*p & 1) || // already allocated
       (*p <= len))) { // too small
    p = p + (*p & -2); // go to next block (UNSCALED +)
} // p points to selected block or end
```

- Can take time linear in total number of blocks
- In practice can cause “splinters” at beginning of list

p = heap\_start



Free word  
 Allocated word  
 Allocated word unused

# Implicit List: Finding a Free Block

## ❖ *Next fit*

- Like first-fit, but **search list starting where previous search finished**
- Should often be faster than first-fit: avoids re-scanning unhelpful blocks
- Some research suggests that fragmentation is worse

## ❖ *Best fit*

- Search the list, choose the **best** free block: large enough AND with fewest bytes left over
- Keeps fragments small—usually helps fragmentation
- Usually worse throughput

# Polling Question [Alloc II]

- ❖ Which allocation strategy and requests remove *external* fragmentation in this Heap? B3 was the last fulfilled request.

- <http://pollev.com/rea>

(A) Best-fit:

`malloc(50), malloc(50)`

(B) First-fit:

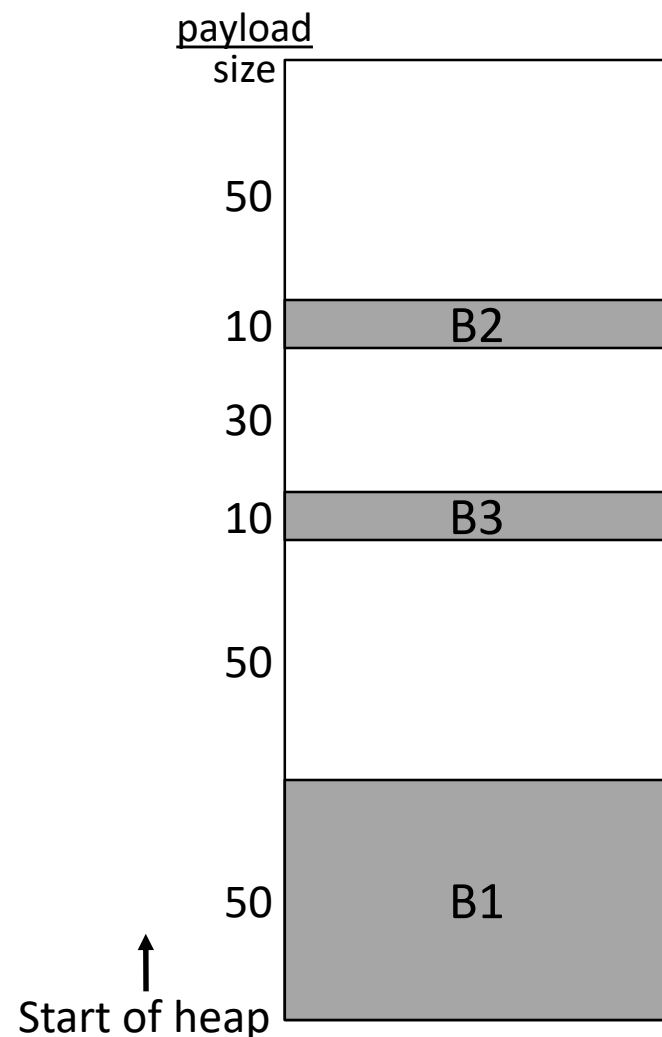
`malloc(50), malloc(30)`

(C) Next-fit:

`malloc(30), malloc(50)`

(D) Next-fit:

`malloc(50), malloc(30)`



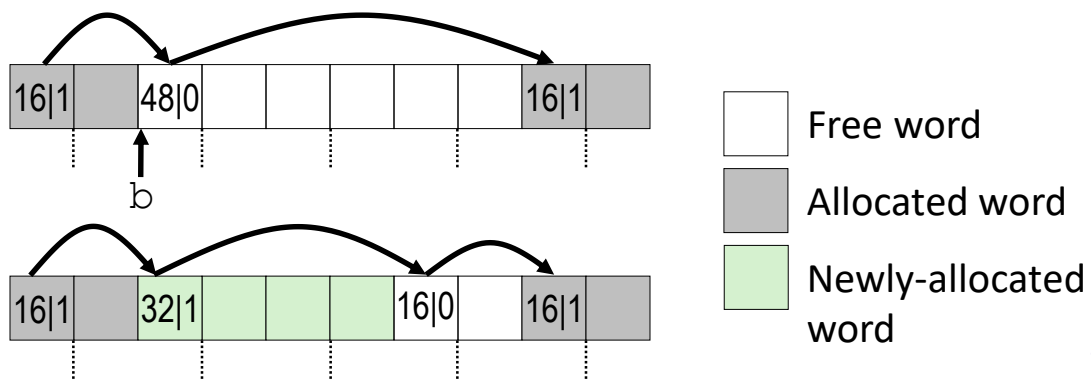
# Implicit List: Allocating in a Free Block

- ❖ Allocating in a free block: *splitting*
  - Since allocated space might be smaller than free space, we might want to split the block

Assume `ptr` points to a free block and has unscaled pointer arithmetic

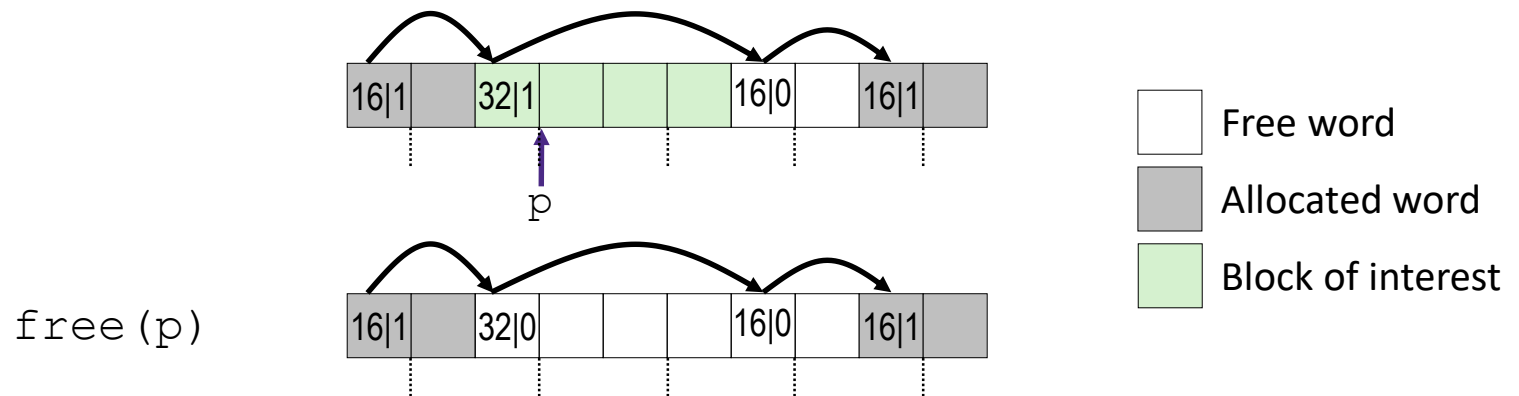
```
void split(ptr b, int bytes) { // bytes = desired block size
    int newsize = ((bytes+15) >> 4) << 4; // round up to multiple of 16
    int oldsize = *b; // why not mask out low bit?
    *b = newsize; // initially unallocated
    if (newsize < oldsize)
        *(b+newsize) = oldsize - newsize; // set length in remaining
} // part of block (UNSCALED +)
```

```
malloc(24):
    ptr b = find(24+8)
    split(b, 24+8)
    allocate(b)
```



# Implicit List: Freeing a Block

- ❖ Simplest implementation just clears “allocated” flag
  - `void free(ptr p) { *(p-WORD) &= -2; }`
  - But can lead to “false fragmentation”



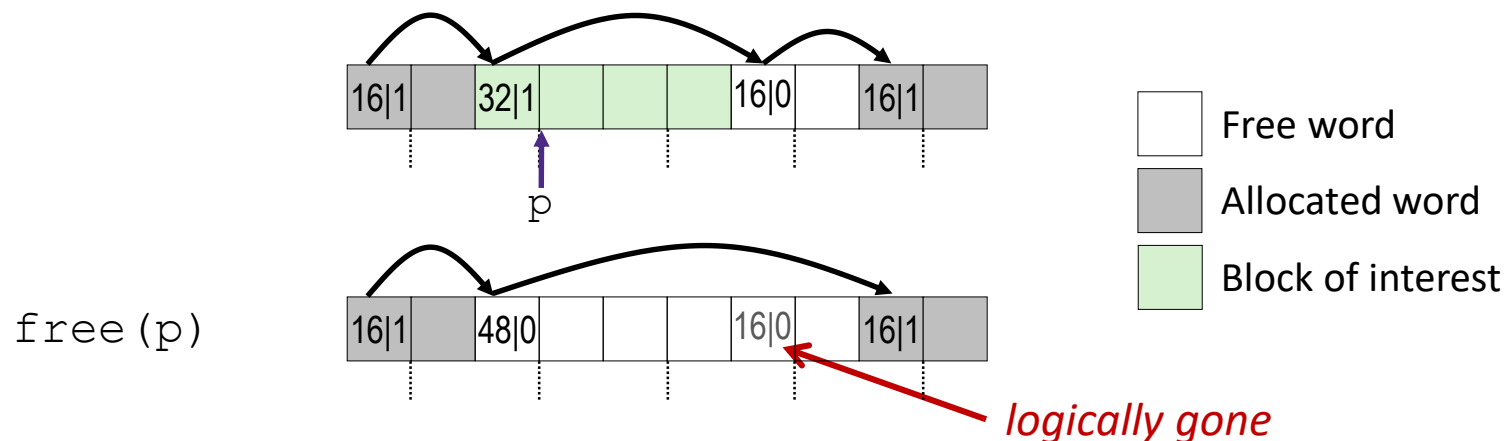
`malloc(40)`

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



# Implicit List: Coalescing with Next

- ❖ Join (*coalesce*) with next block if also free



```

void free(ptr p) {
    ptr b = p - WORD;
    *b &= -2;
    ptr next = b + *b;
    if ((*next & 1) == 0)
        *b += *next;
}

```

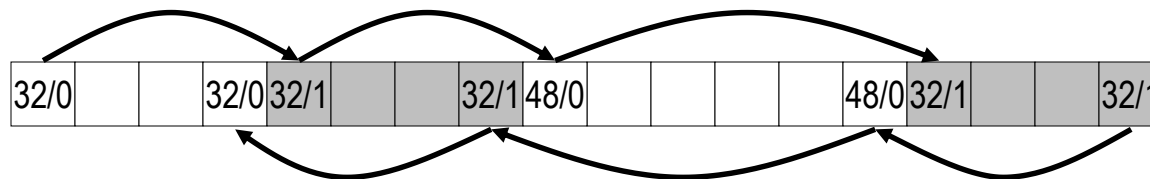
// p points to payload  
// b points to block header  
// clear allocated bit  
// find next block (UNSCALED +)  
// if next block is not allocated,  
// add its size to this block

- ❖ How do we coalesce with the *previous* block?

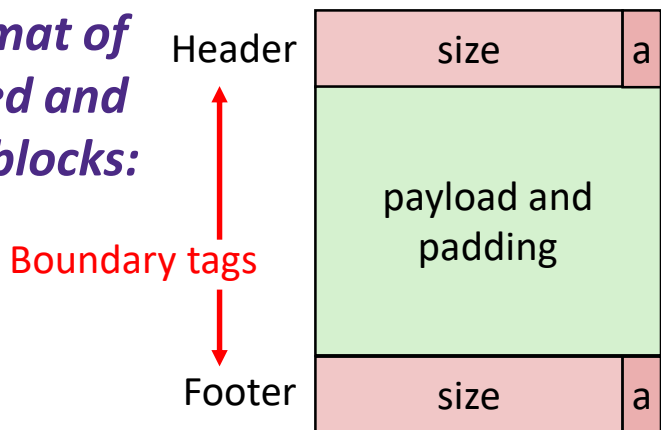
# Implicit List: Bidirectional Coalescing

❖ *Boundary tags* [Knuth73]

- Replicate header at “bottom” (end) of free blocks
- Allows us to traverse backwards, but requires extra space
- Important and general technique!



*Format of allocated and free blocks:*



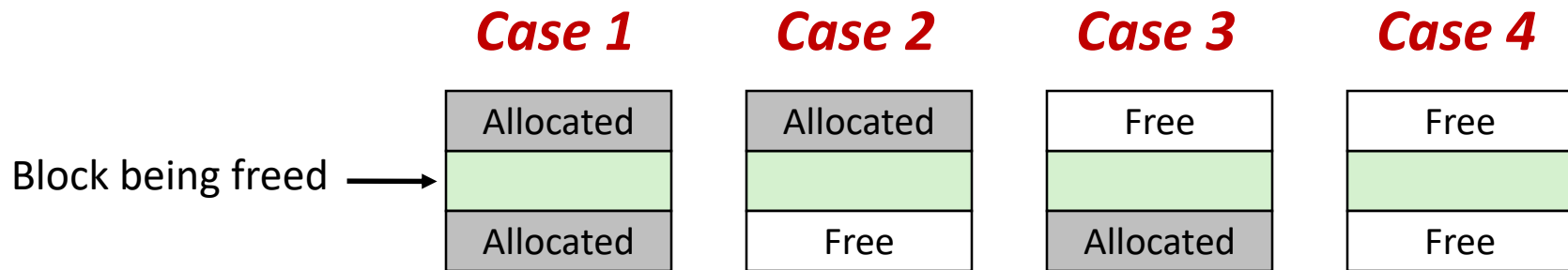
**a = 1:** allocated block

**a = 0:** free block

**size:** block size (in bytes)

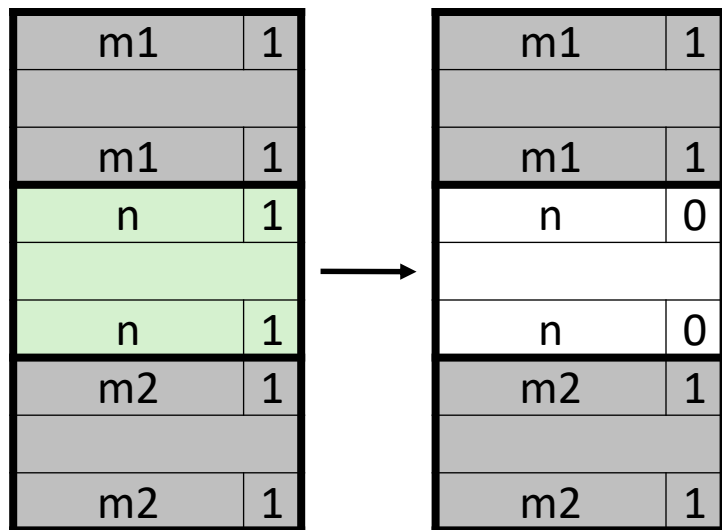
**payload:** application data (allocated blocks only)

# Constant Time Coalescing

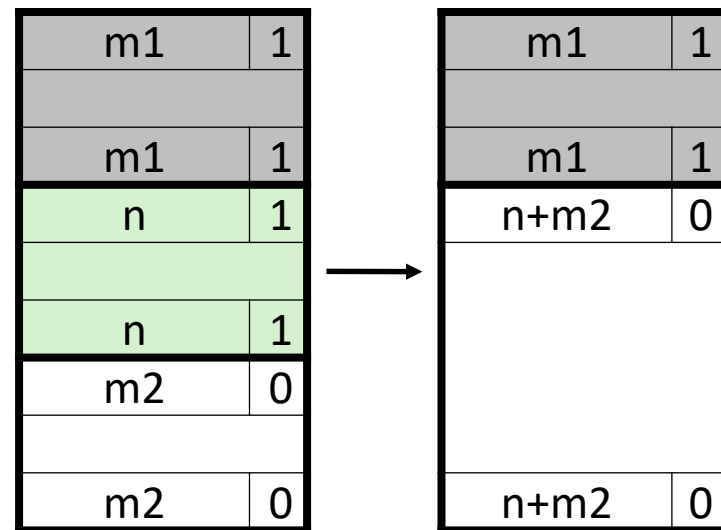


# Constant Time Coalescing

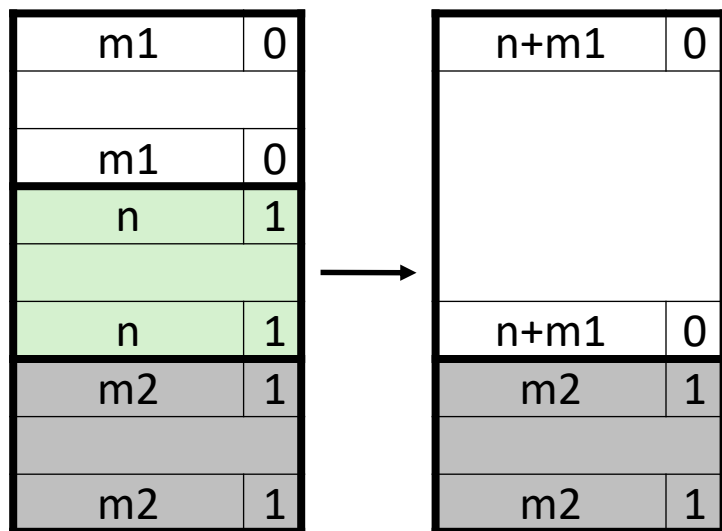
**Case 1**



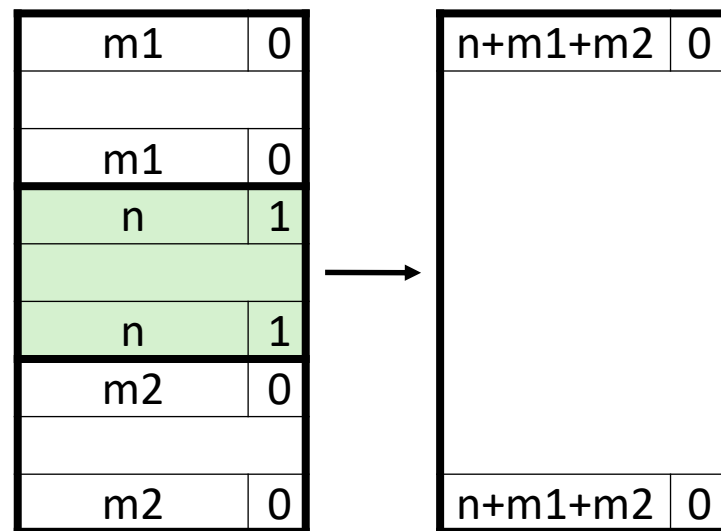
**Case 2**



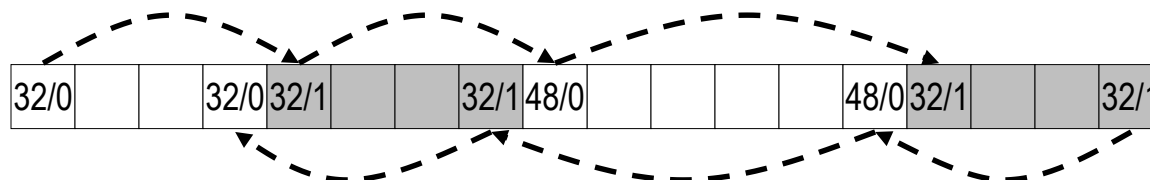
**Case 3**



**Case 4**

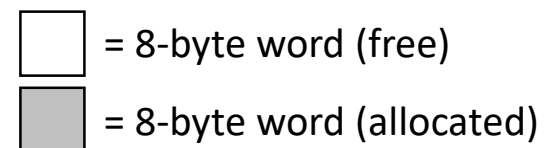


# Implicit Free List Review Questions



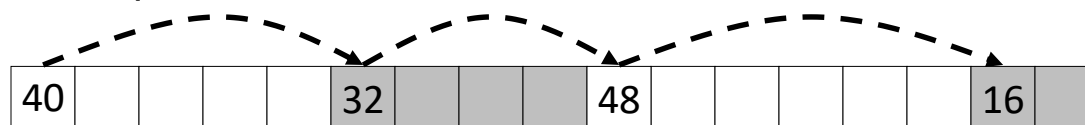
- ❖ What is the block header? What do we store and how?
- ❖ What are boundary tags and why do we need them?
- ❖ When we coalesce free blocks, how many neighboring blocks do we need to check on either side? Why is this?
- ❖ If I want to check the size of the  $n$ -th block forward from the current block, how many memory accesses do I make?

# Keeping Track of Free Blocks

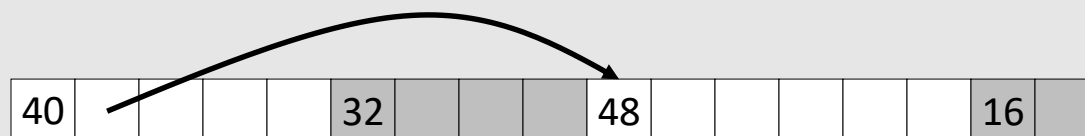


## 1) *Implicit free list* using length – links all blocks using math

- No actual pointers, and must check each block if allocated or free



## 2) *Explicit free list* among only the free blocks, using pointers



## 3) *Segregated free list*

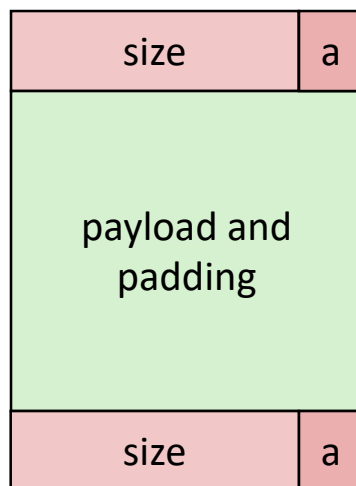
- Different free lists for different size “classes”

## 4) *Blocks sorted by size*

- Can use a balanced binary tree (e.g. red-black tree) with pointers within each free block, and the length used as a key

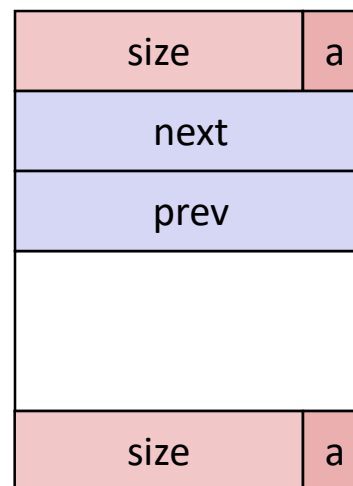
# Explicit Free Lists

Allocated block:



(same as implicit free list)

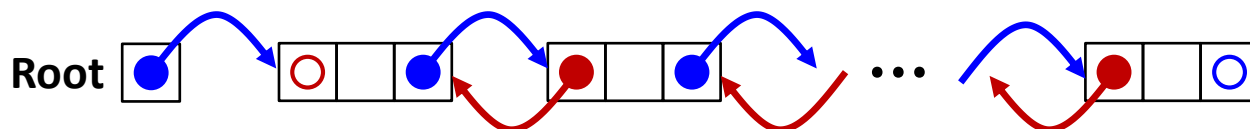
Free block:



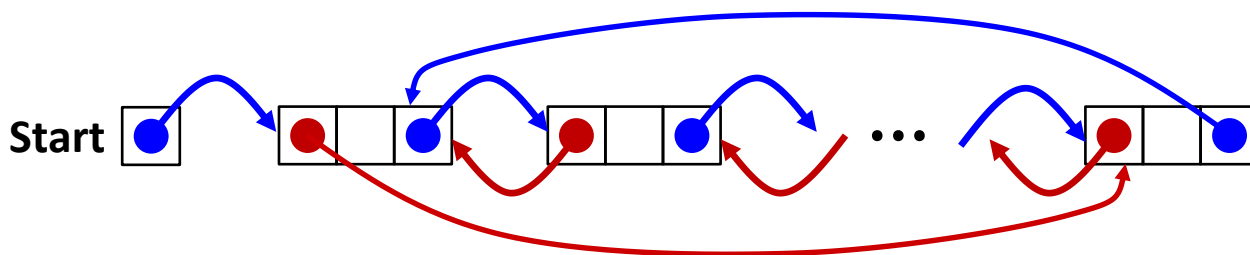
- ❖ Use list(s) of *free* blocks, rather than implicit list of *all* blocks
  - The “next” free block could be anywhere in the heap
    - So we need to store next/previous pointers, not just sizes
  - Since we only track free blocks, so we can use “payload” for pointers
  - Still need boundary tags (header/footer) for coalescing

# Doubly-Linked Lists

## ❖ Linear



- Needs head/root pointer
- First node prev pointer is `NULL`
- Last node next pointer is `NULL`
- Good for first-fit, best-fit



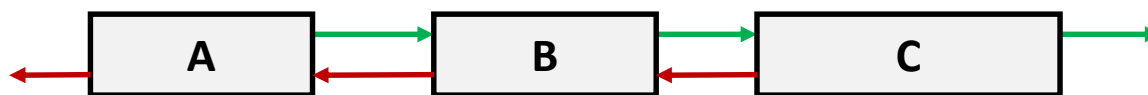
## ❖ Circular

- Still have pointer to tell you which node to start with
- No `NULL` pointers (term condition is back at starting point)
- Good for next-fit, best-fit

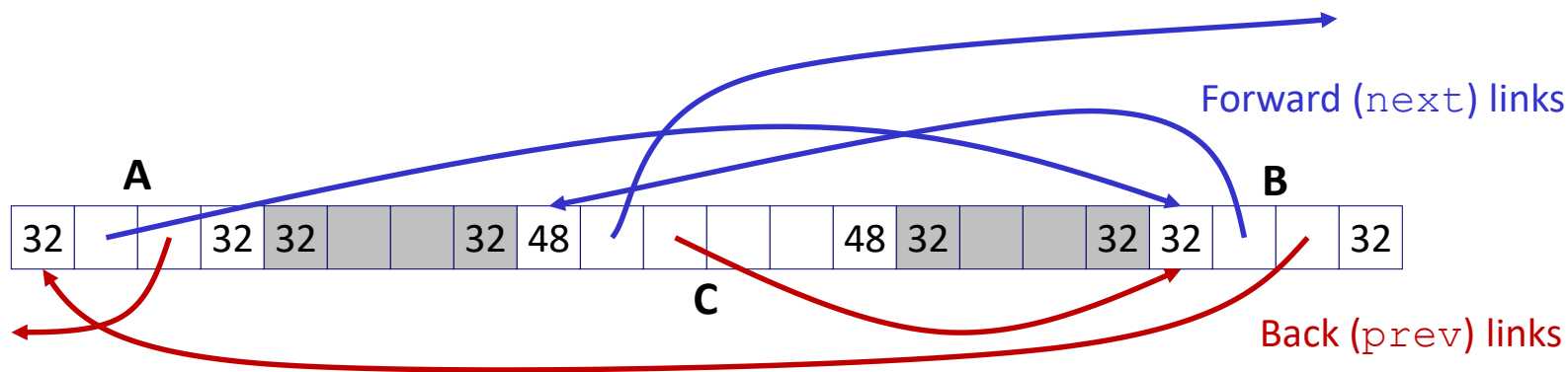


# Explicit Free Lists

- ❖ **Logically:** doubly-linked list

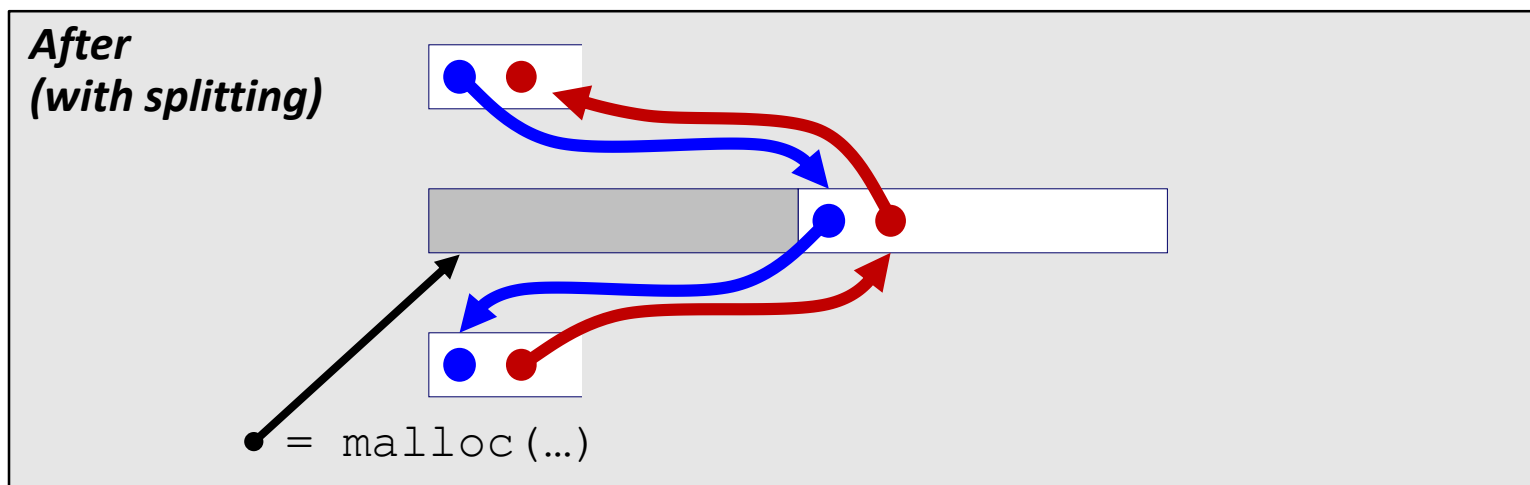
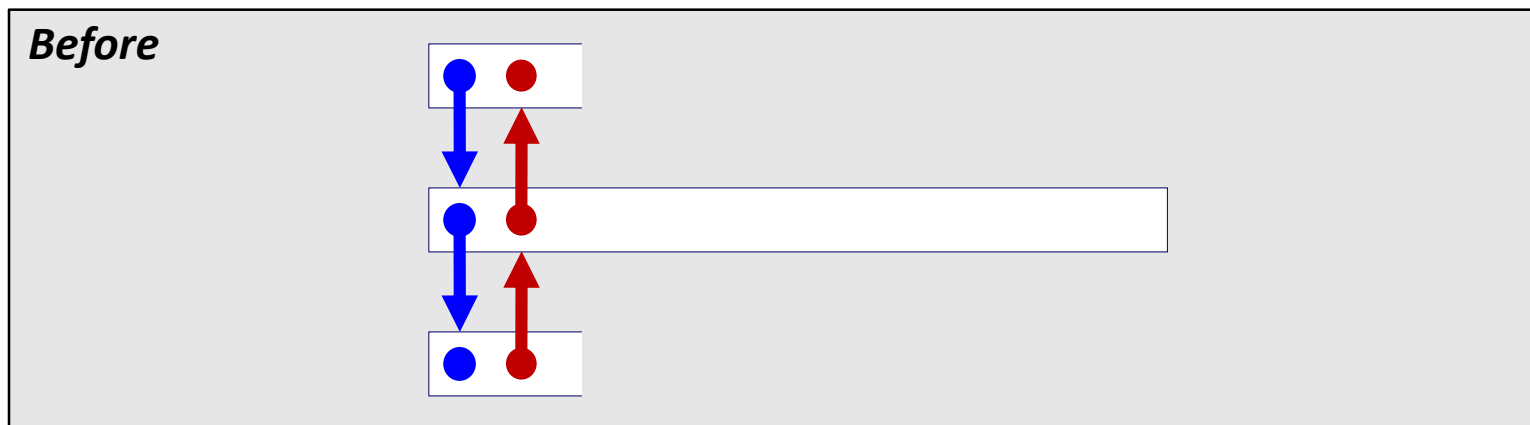


- ❖ **Physically:** blocks can be in any order



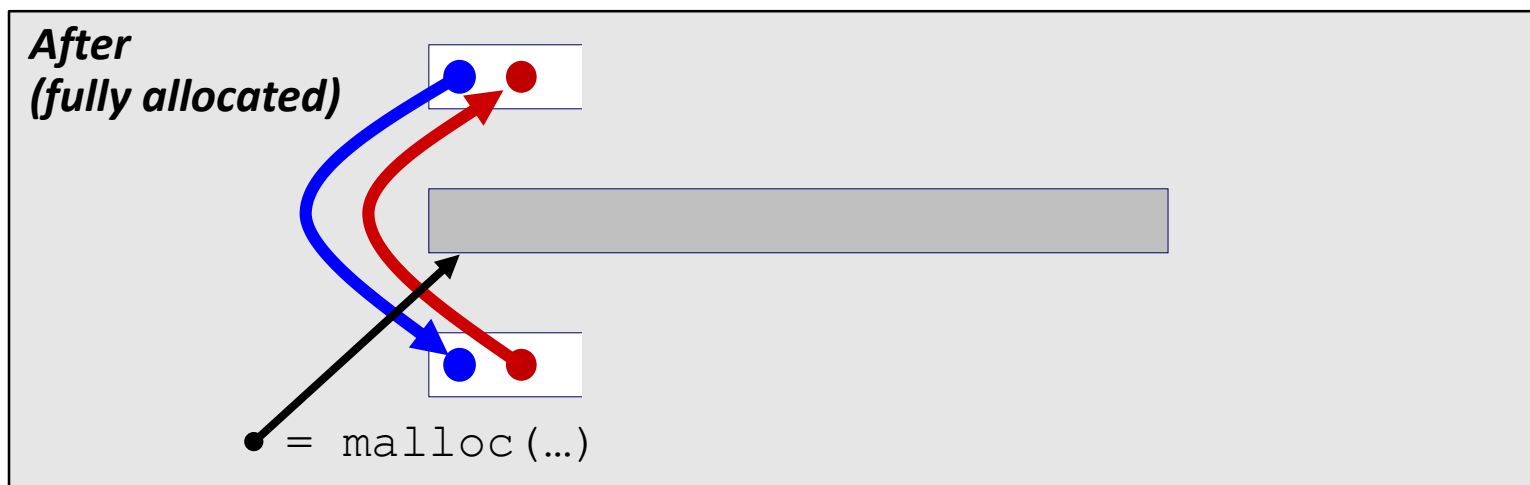
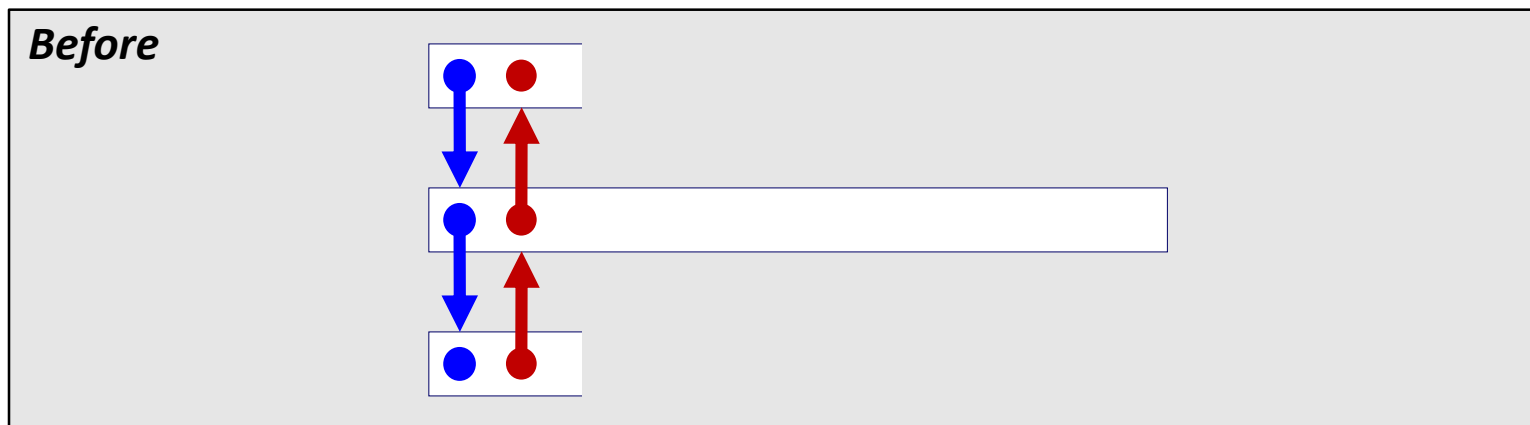
# Allocating From Explicit Free Lists

**Note:** These diagrams are not very specific about where inside a block a pointer points. In reality we would always point to one place (e.g. start/header of a block).



# Allocating From Explicit Free Lists

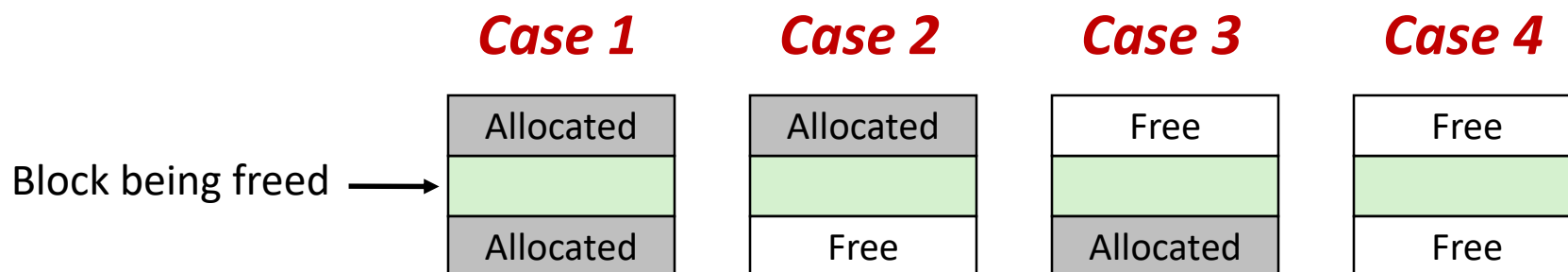
**Note:** These diagrams are not very specific about where inside a block a pointer points. In reality we would always point to one place (e.g. start/header of a block).



# Freeing With Explicit Free Lists

- ❖ *Insertion policy*: Where in the free list do you put the newly freed block?
  - **LIFO (last-in-first-out) policy**
    - Insert freed block at the beginning (head) of the free list
    - Pro: simple and constant time
    - Con: studies suggest fragmentation is worse than the alternative
  - **Address-ordered policy**
    - Insert freed blocks so that free list blocks are always in address order:  
 *$address(previous) < address(current) < address(next)$*
    - Con: requires linear-time search
    - Pro: studies suggest fragmentation is better than the alternative

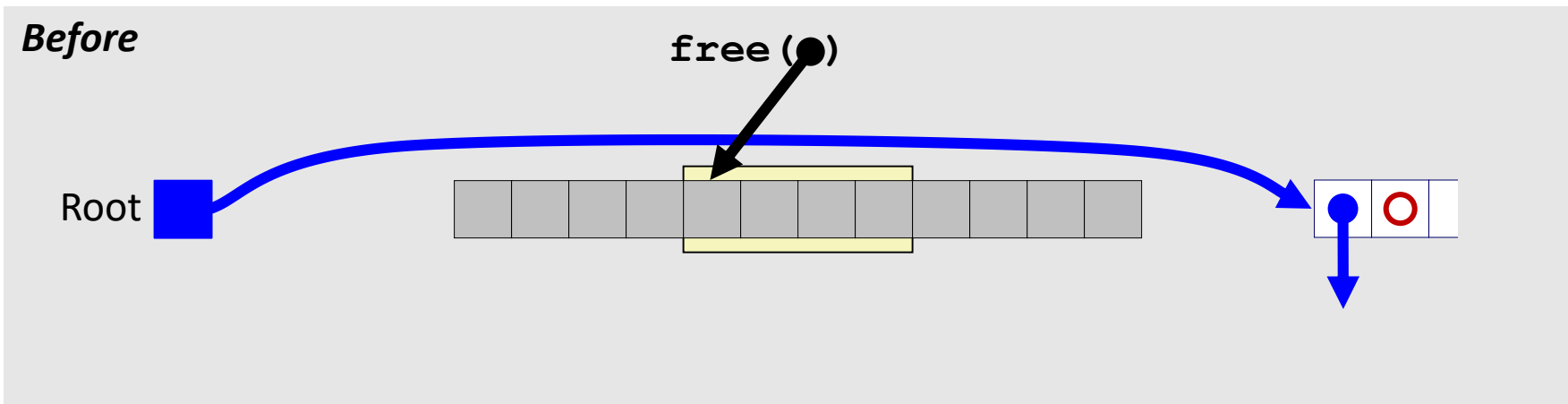
# Coalescing in Explicit Free Lists



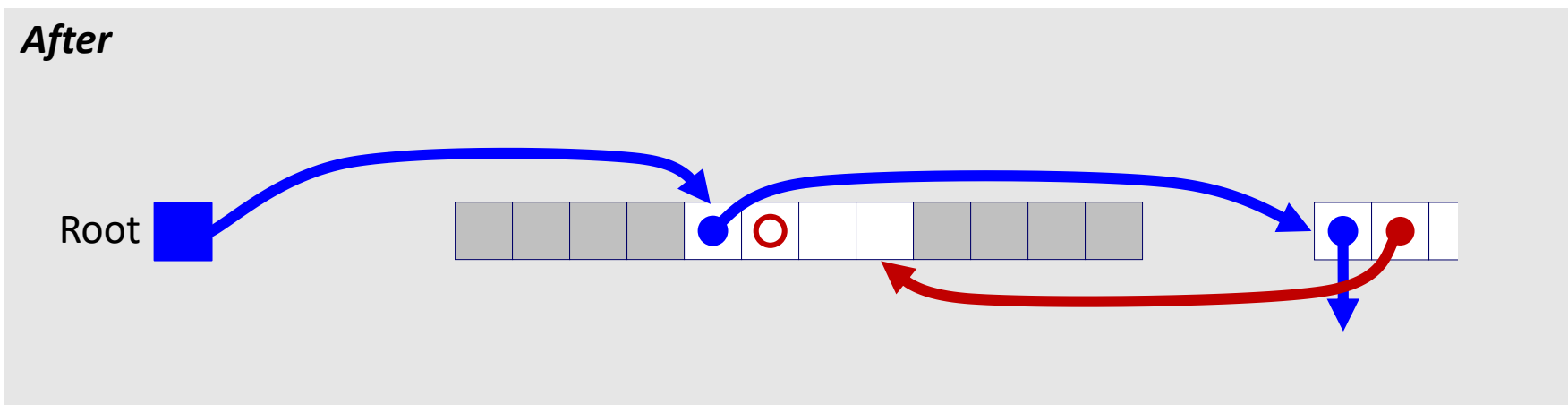
- ❖ Neighboring free blocks are *already part of the free list*
  - 1) Remove old block from free list
  - 2) Create new, larger coalesced block
  - 3) Add new block to free list (insertion policy)
- ❖ How do we tell if a neighboring block is free?

# Freeing with LIFO Policy (Case 1)

Boundary tags not shown, but don't forget about them!

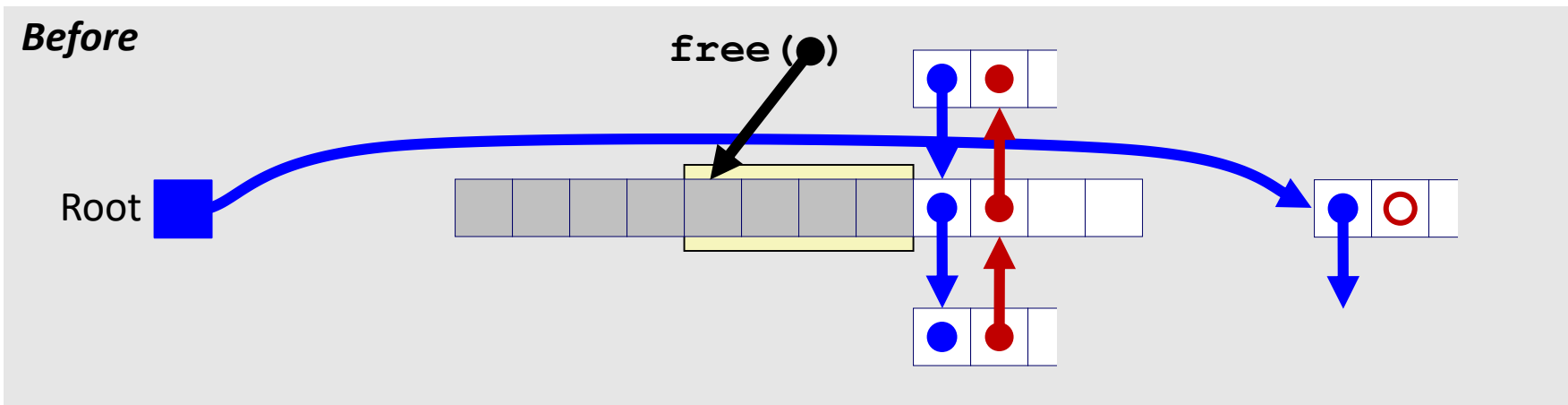


❖ Insert the freed block at the root of the list

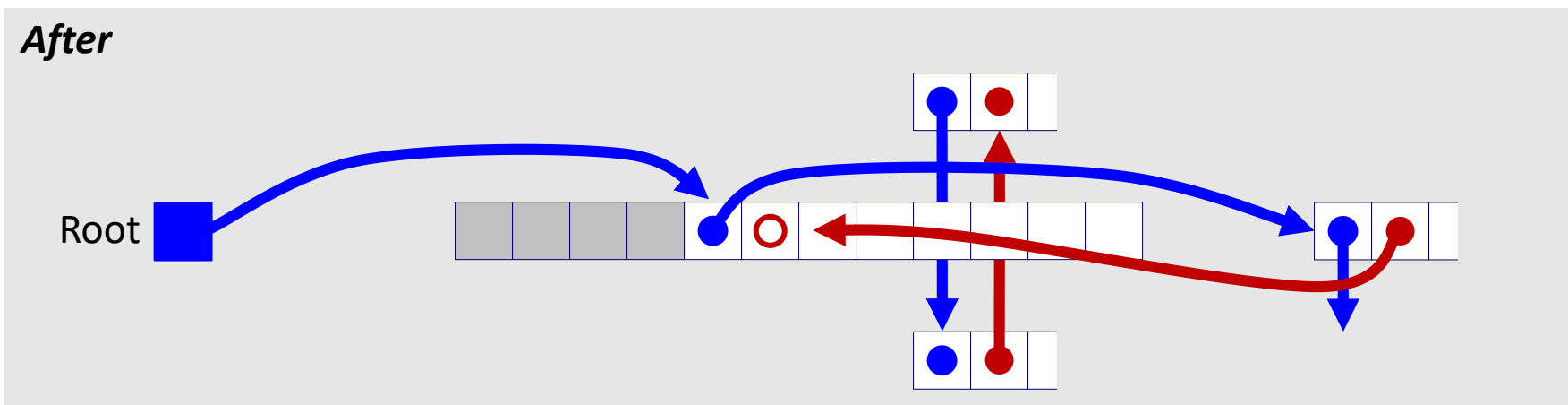


# Freeing with LIFO Policy (Case 2)

Boundary tags not shown, but don't forget about them!

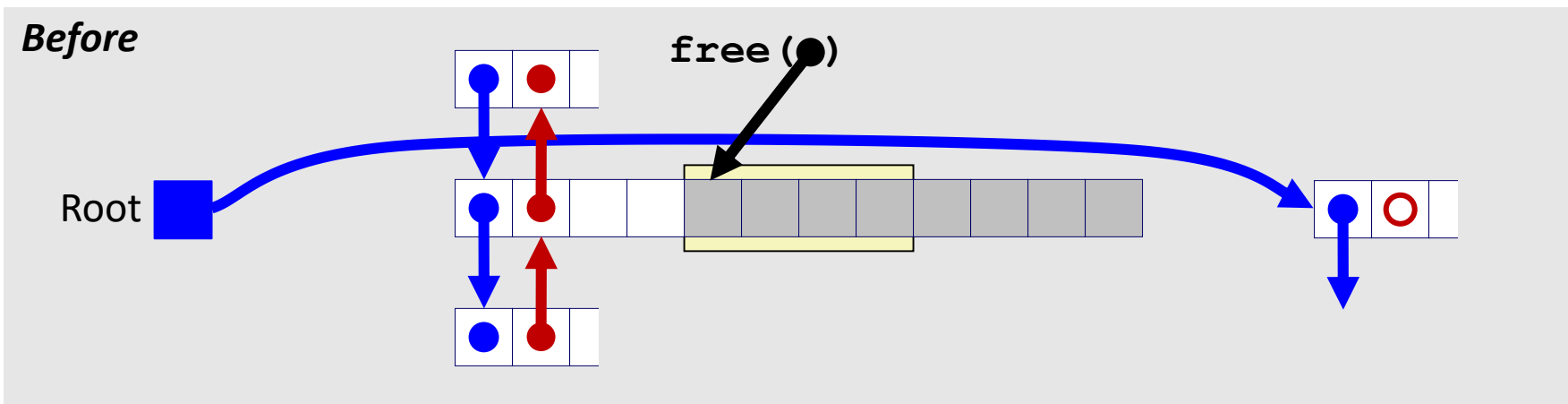


- ❖ Splice successor block out of list, coalesce both memory blocks, and insert the new block at the root of the list

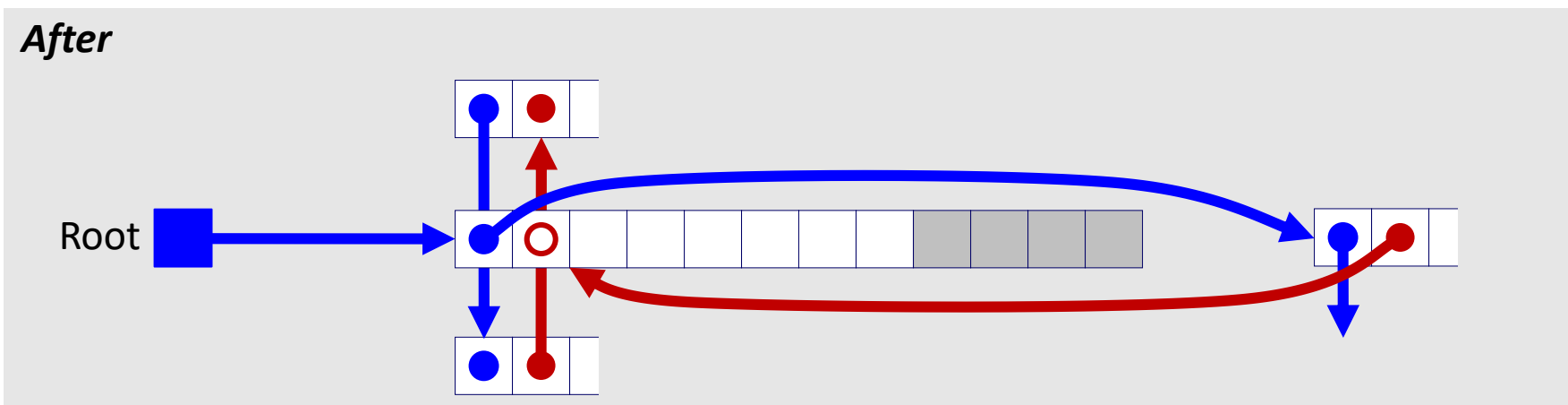


# Freeing with LIFO Policy (Case 3)

Boundary tags not shown, but don't forget about them!



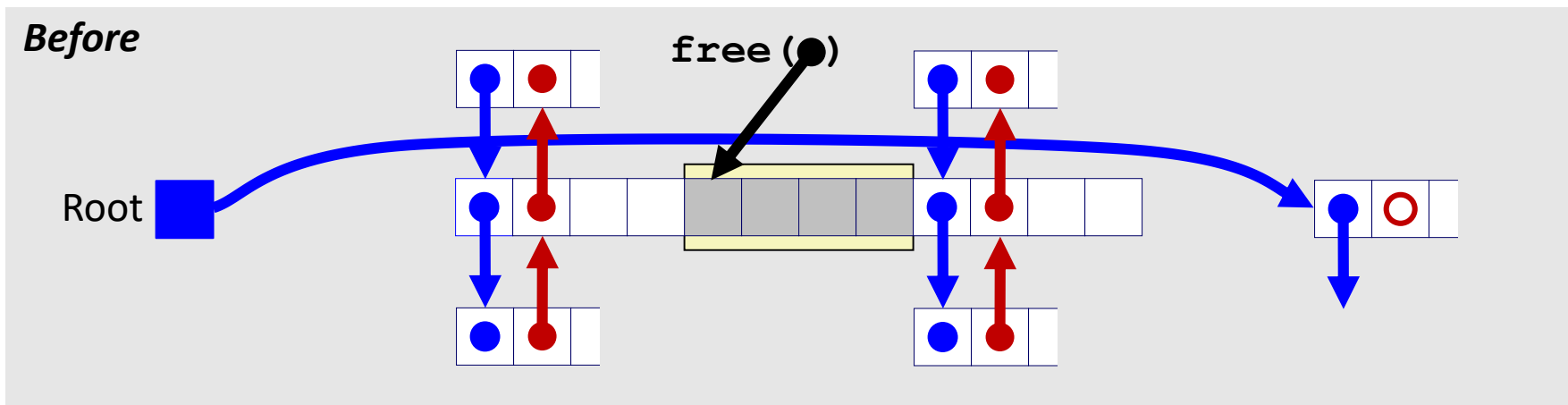
- ❖ Splice predecessor block out of list, coalesce both memory blocks, and insert the new block at the root of the list



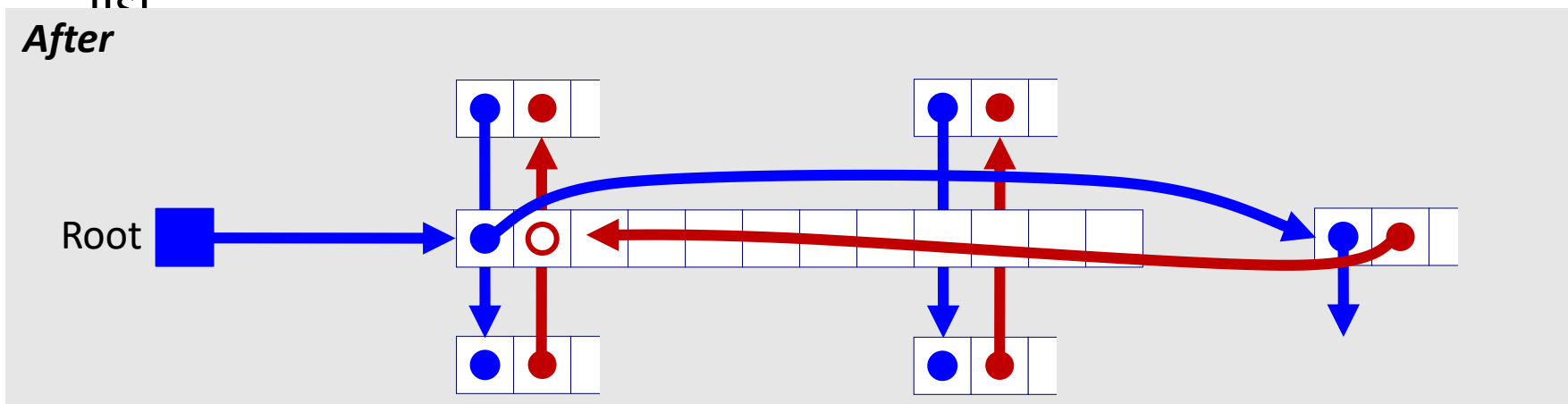


# Freeing with LIFO Policy (Case 4)

Boundary tags not shown, but don't forget about them!

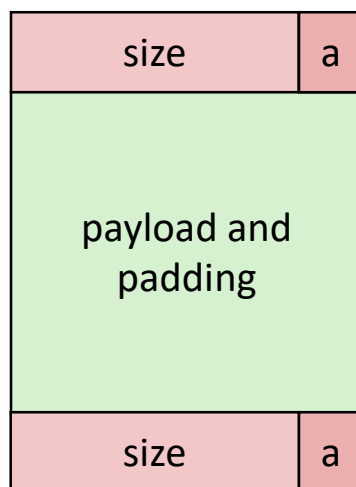


- ❖ Splice predecessor and successor blocks out of list, coalesce all 3 memory blocks, and insert the new block at the root of the list



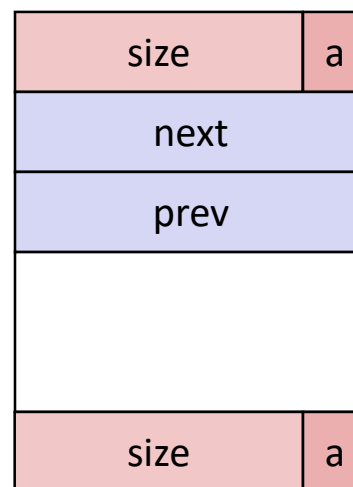
# Do we always need the boundary tags?

Allocated block:



(same as implicit free list)

Free block:



❖ Lab 5 suggests no...

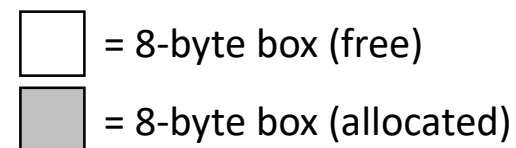
# Explicit List Summary

- ❖ Comparison with implicit list:
  - Block allocation is linear time in number of *free* blocks instead of *all* blocks
    - *Much faster* when most of the memory is full
  - Slightly more complicated allocate and free since we need to splice blocks in and out of the list
  - Some extra space for the links (2 extra pointers needed for each free block)
    - Increases minimum block size, leading to more internal fragmentation
- ❖ Most common use of explicit lists is in conjunction with *segregated free lists*
  - Keep multiple linked lists of different size classes, or possibly for different types of objects

# BONUS SLIDES

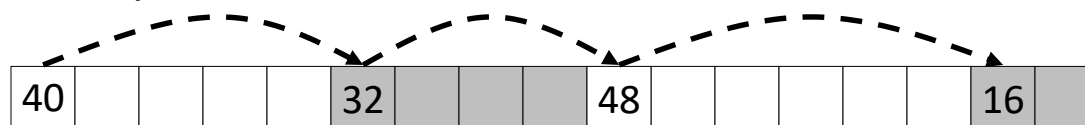
The following slides are about the **SegList Allocator**, for those curious. You will NOT be expected to know this material.

# Keeping Track of Free Blocks

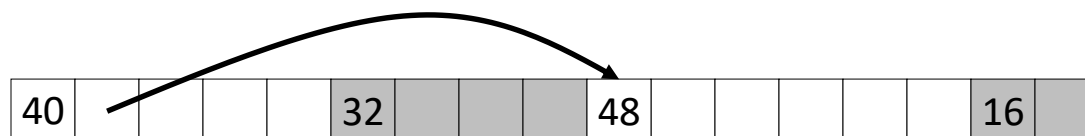


1) *Implicit free list* using length – links all blocks using math

- No actual pointers, and must check each block if allocated or free



2) *Explicit free list* among only the free blocks, using pointers



3) *Segregated free list*

- Different free lists for different size “classes”

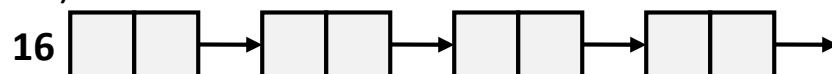
4) *Blocks sorted by size*

- Can use a balanced binary tree (e.g. red-black tree) with pointers within each free block, and the length used as a key

# Segregated List (SegList) Allocators

- ❖ Each *size class* of blocks has its own free list
- ❖ Organized as an array of free lists

Size class  
(in bytes)



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

# SegList Allocator

- ❖ Have an array of free lists for various size classes
  
- ❖ To allocate a block of size  $n$ :
  - Search appropriate free list for block of size  $m \geq n$
  - If an appropriate block is found:
    - [Optional] Split block and place free fragment on appropriate list
  - If no block is found, try the next larger class
    - Repeat until block is found
  
- ❖ If no block is found:
  - Request additional heap memory from OS (using `sbrk`)
  - Place remainder of additional heap memory as a single free block in appropriate size class

# SegList Allocator

- ❖ Have an array of free lists for various size classes
- ❖ To free a block:
  - Mark block as free
  - Coalesce (if needed)
  - Place on appropriate class list



# SegList Advantages

- ❖ Higher throughput
  - Search is log time for power-of-two size classes
- ❖ Better memory utilization
  - First-fit search of seglist approximates a best-fit search of entire heap
  - *Extreme case*: Giving every block its own size class is no worse than best-fit search of an explicit list
  - Don't need to use space for block size for the fixed-size classes