

# Memory Allocation II

CSE 351 Autumn 2024

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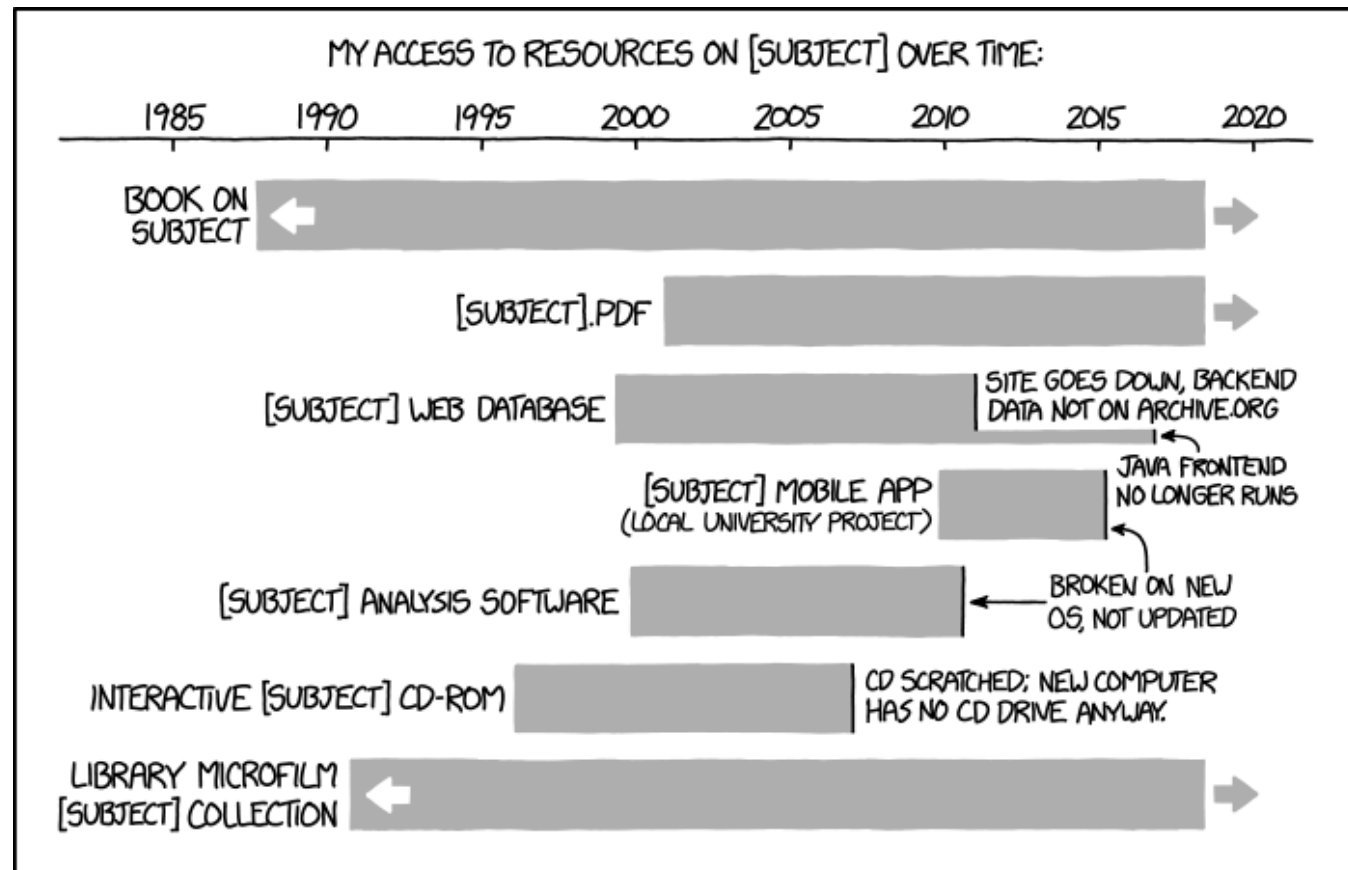
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IT'S UNSETTLING TO REALIZE HOW QUICKLY DIGITAL RESOURCES CAN DISAPPEAR WITHOUT ONGOING WORK TO MAINTAIN THEM.

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

# Relevant Course Information

- ❖ HW19 due tonight, Friday (11/15) @ 11:59 pm
  - Lab 4 preparation
- ❖ HW20 due Monday (11/18) @ 11:59 pm
- ❖ HW21 due Wednesday (11/20) @ 11:59 pm
- ❖ Lab 4 due Friday (11/22) @ 11:59 pm
  - Cache parameter puzzles and code optimizations

# Reading Review

## ❖ Terminology:

- Allocation strategies: first fit, next fit, best fit
- Allocating a block: splitting, minimum block size
- Freeing a block: coalescing
- Boundary tags: header and footer
- Explicit free list

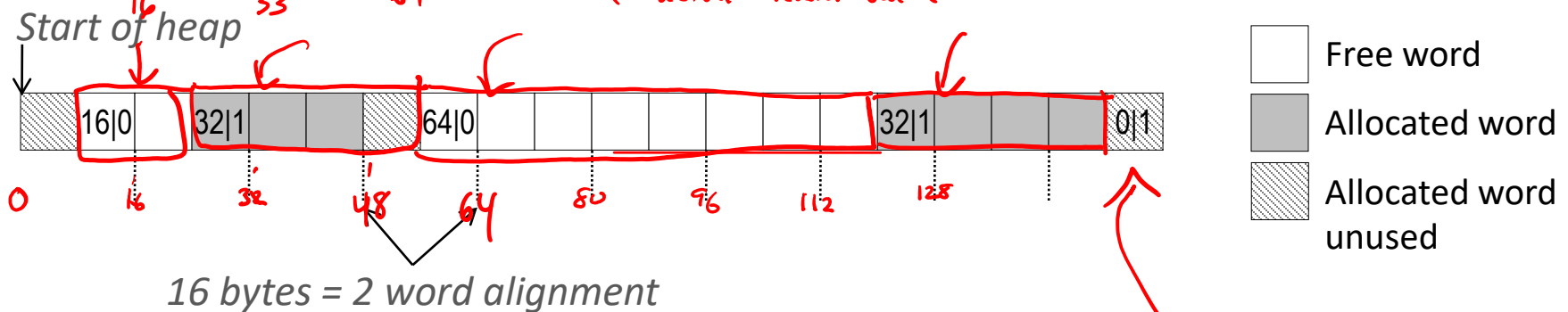
# Implicit Free List Example

□ = 8-byte word

- ❖ 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

← actual header data



- ❖ 16-byte alignment for *payload*
  - Address of payload must be a multiple of the alignment
  - 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:

```

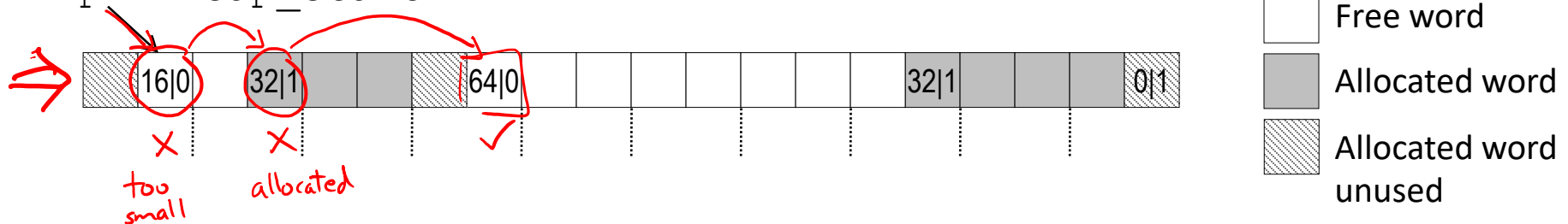
p = heap_start;
while ((p < end) &&           // not past end
      ((*p & 1) ||           // already allocated
      (*p <= len))) {        // too small
  p = p + (*p & -2);          // go to next block (UNSCALED +)
}                             // p points to selected block or end

```

*equivalent to pointer arithmetic with char\**  
*after loop exits*

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

p = heap\_start



# 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

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

■ Vote in Ed Lessons

(A) Best-fit:

`malloc(50), malloc(50)`

(B) First-fit:

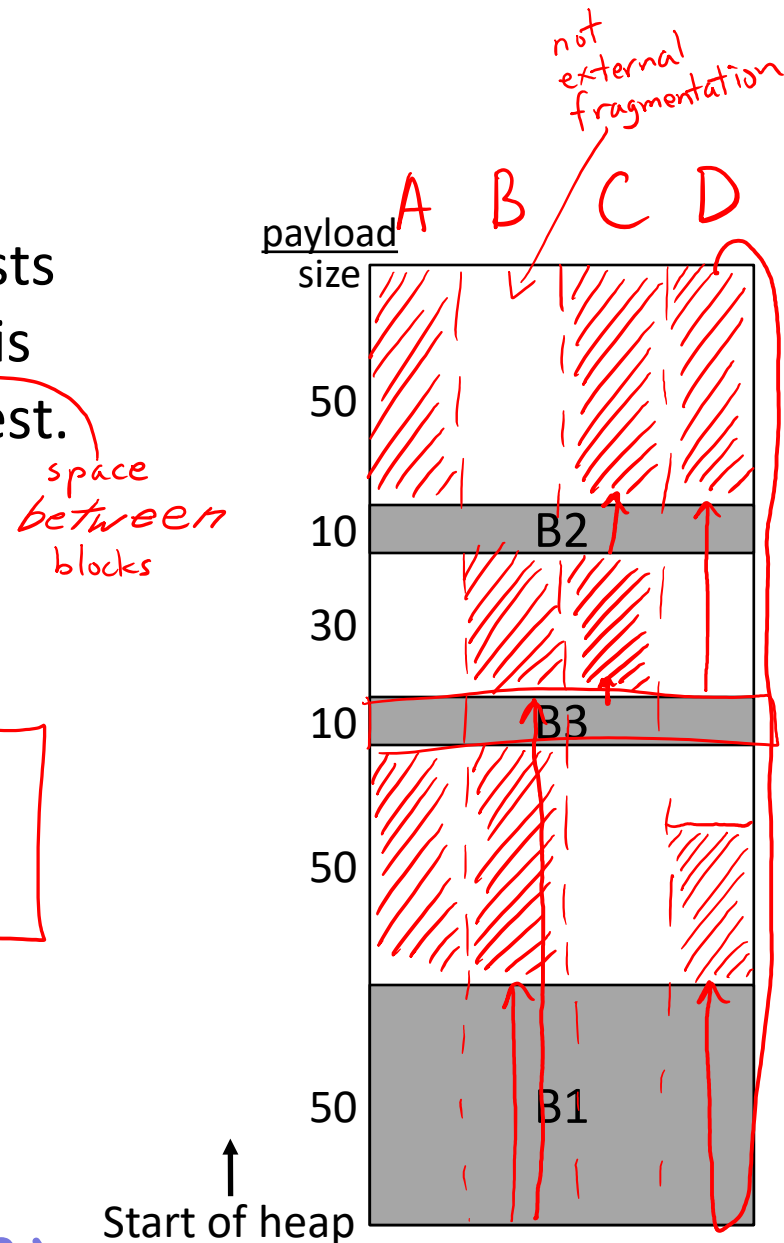
`malloc(50), malloc(30)`

(C) Next-fit:

`malloc(30), malloc(50)`

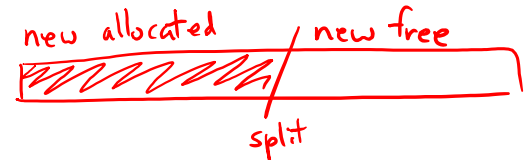
(D) Next-fit:

`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

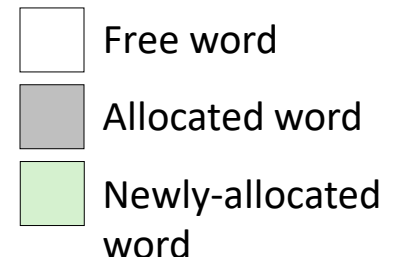
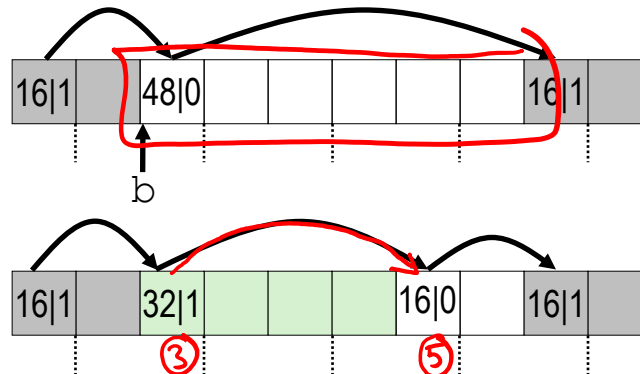
```

void split(ptr b, int bytes) {
  ① int newsize = ((bytes+15) >> 4) << 4; // bytes = desired block size
  ② int oldsize = *b; // round up to multiple of 16
  ③ *b = newsize; // why not mask out low bit?
  ④ if (newsize < oldsize) // initially unallocated
  ⑤ *(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)

↑ sets a=1

header

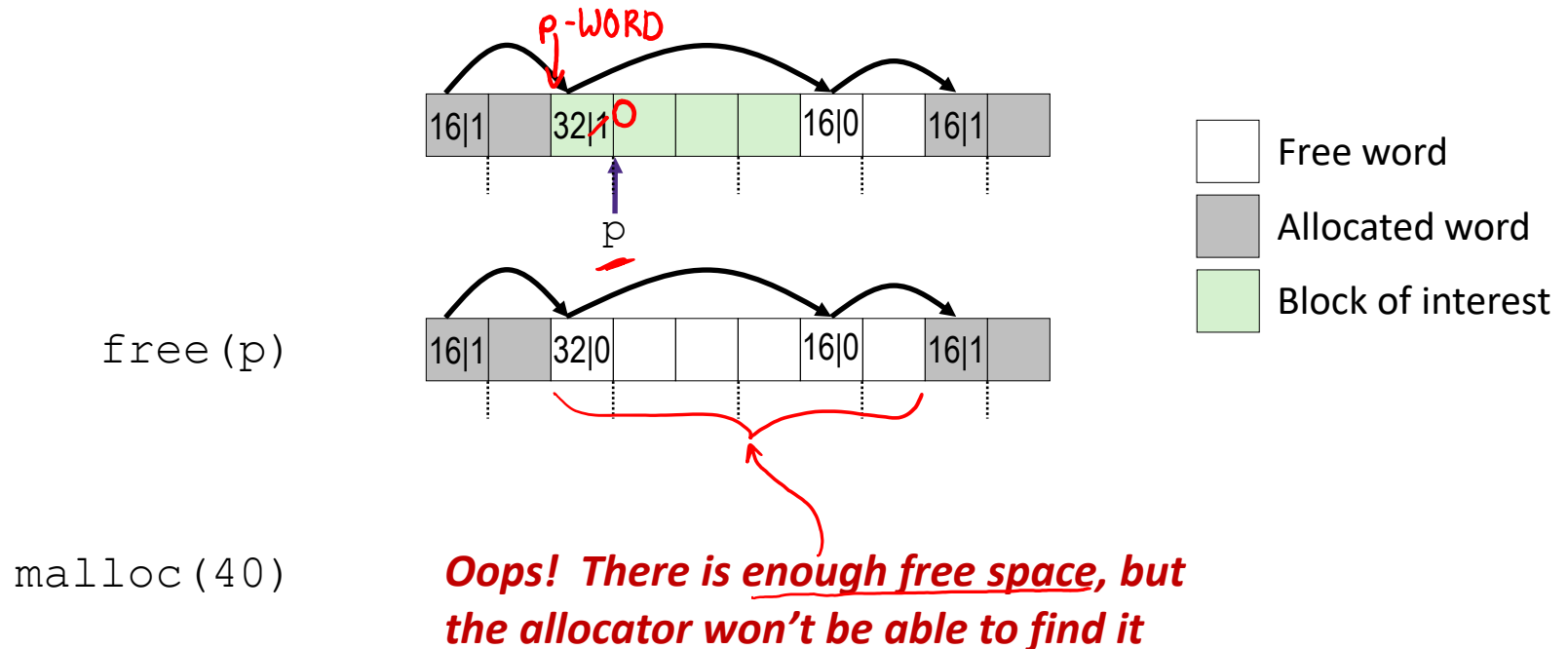




# Implicit List: Freeing a Block

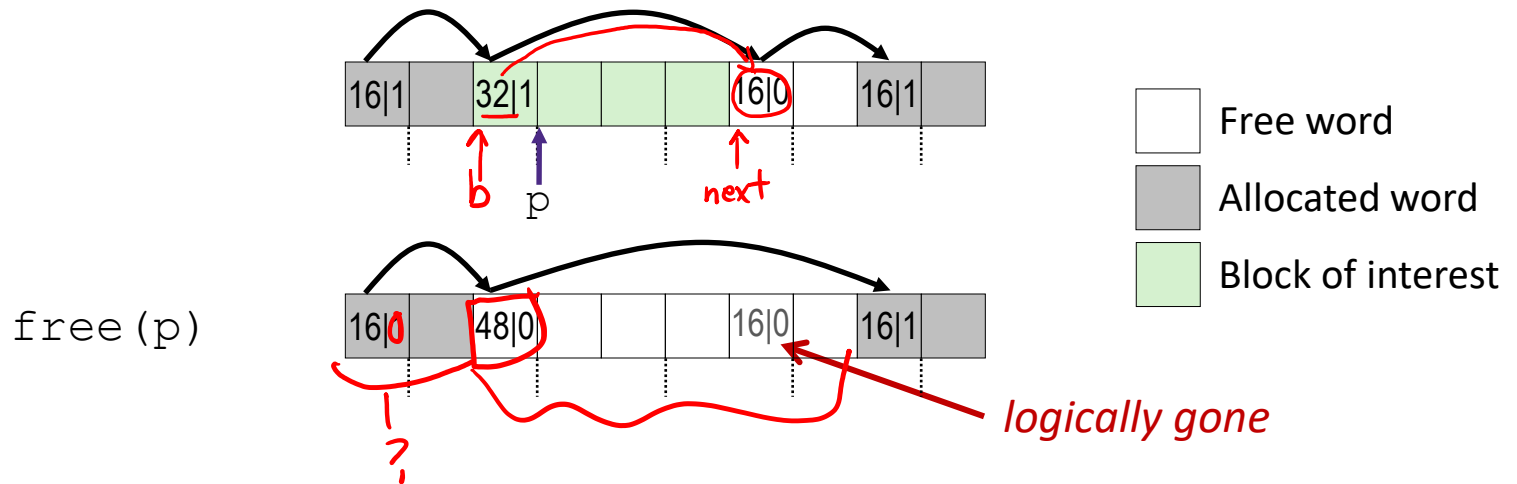
❖ Simplest implementation just clears “allocated” flag

- `void free(ptr p) { * (p-WORD) &= -2; }`
- But can lead to “false fragmentation”



# Implicit List: Coalescing with Next

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



```

void free(ptr p) {
    ptr b = p - WORD; // p points to payload
    *b &= -2;         // b points to block header
    ptr next = b + *b; // clear allocated bit
    if ((*next & 1) == 0) // find next block (UNSCALED +)
        *b += *next;     // if next block is not allocated,
                        // add its size to this block
}

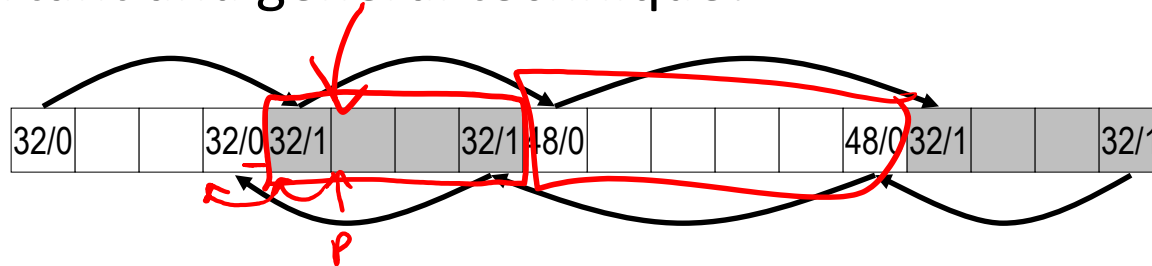
```

- ❖ How do we coalesce with the preceding block? *we can't currently*

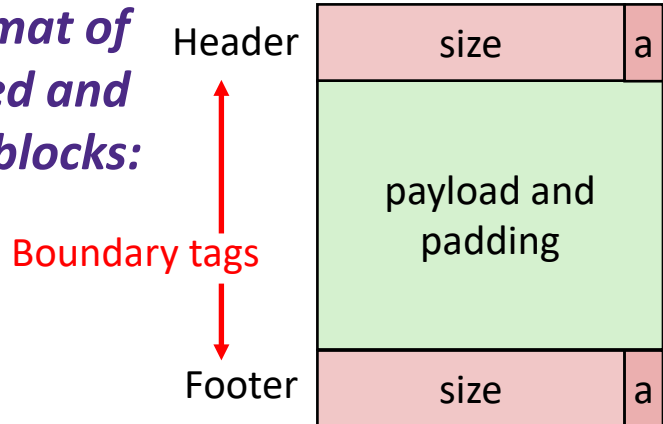
# Implicit List: Bidirectional Coalescing

## ❖ *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:*



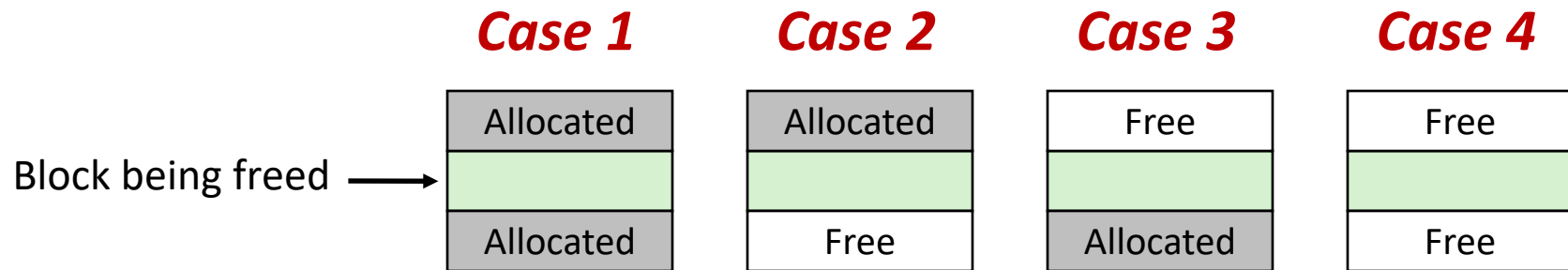
**a = 1:** allocated block

**a = 0:** free block

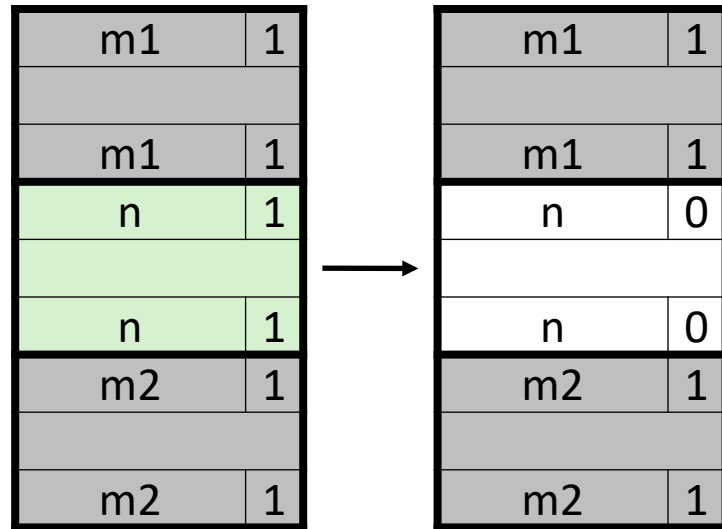
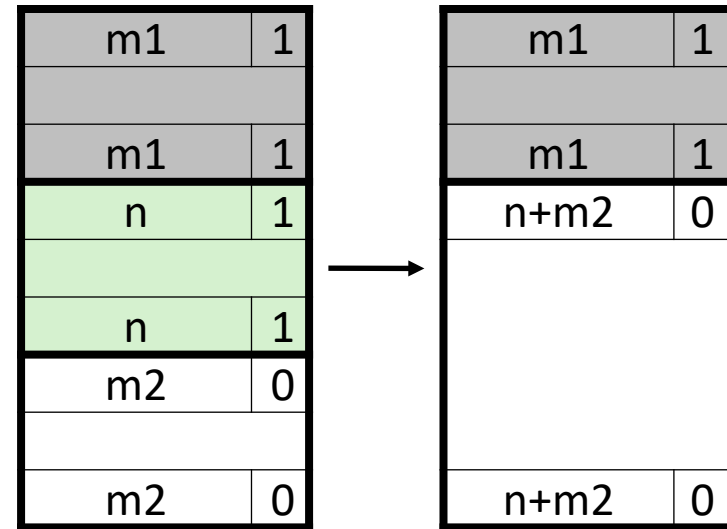
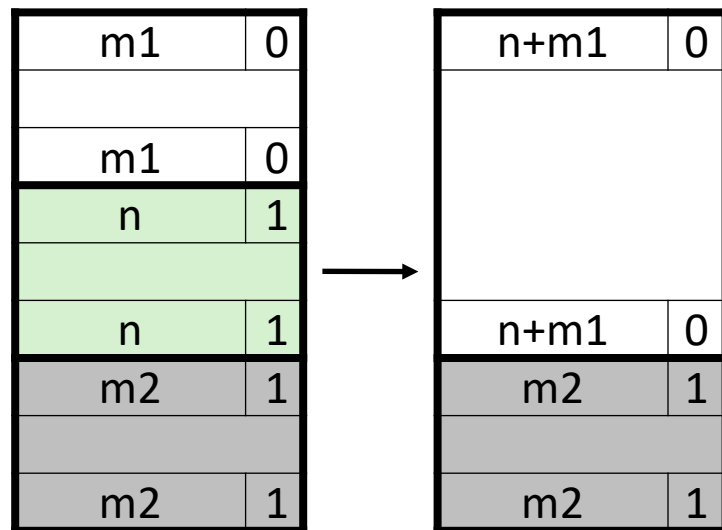
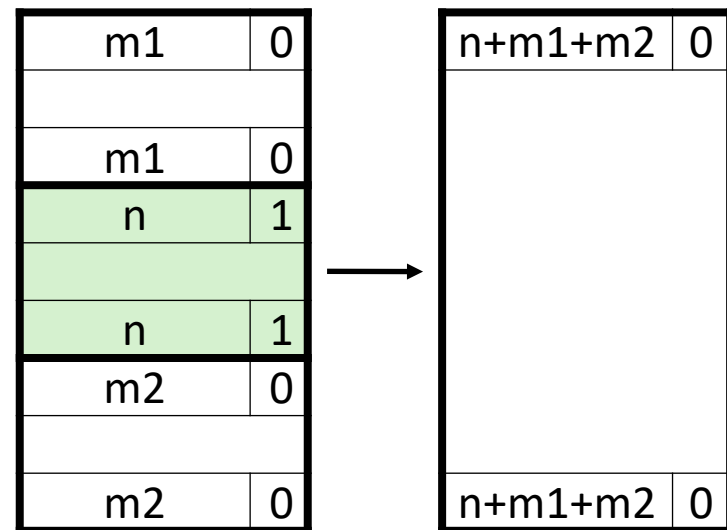
**size:** block size (in bytes)

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

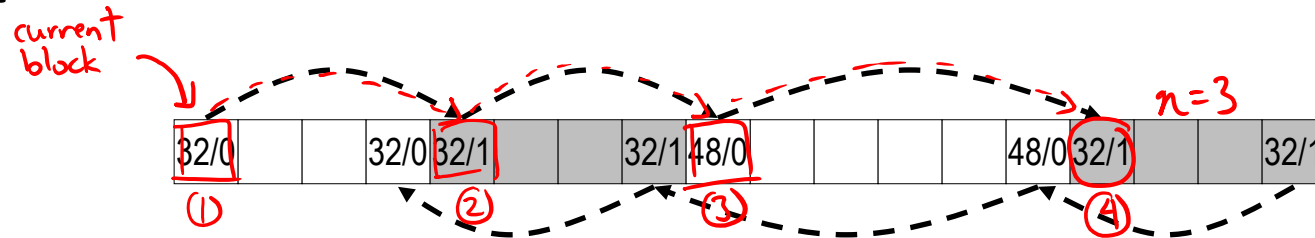
# Constant Time Coalescing



# 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?  
stores info about block      size of block, is-allocated?  

↑ lowest bit of header
- ❖ What are boundary tags and why do we need them?  
header and footer (same info)      so we can traverse list in either direction  
(particularly for coalescing)
- ❖ When we coalesce free blocks, how many neighboring blocks do we need to check on either side? Why is this?  
just 1 — adjacent free blocks should have already been coalesced
- ❖ If I want to check the size of the  $n$ -th block forward from the current block, how many memory accesses do I make?  
 $n+1$ : need to read current block's header as well as header of target block to get the size

# Keeping Track of Free Blocks

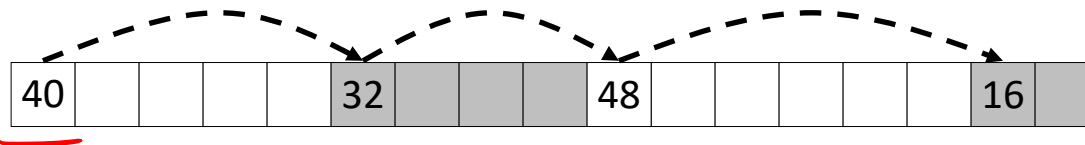


= 8-byte word (free)

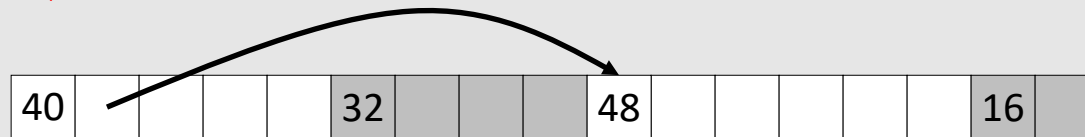
= 8-byte word (allocated)

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

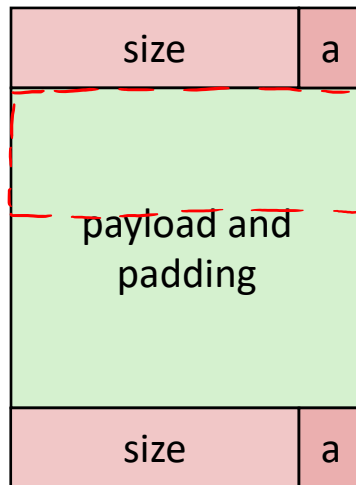
- Different free lists for different size “classes”

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

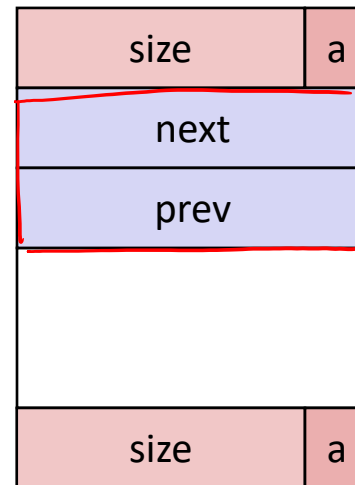
# Explicit Free Lists

Allocated block:



(same as implicit free list)

Free block:



minimum block size  
includes boundary  
tags & free list pointers

2 pointers

- ❖ 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

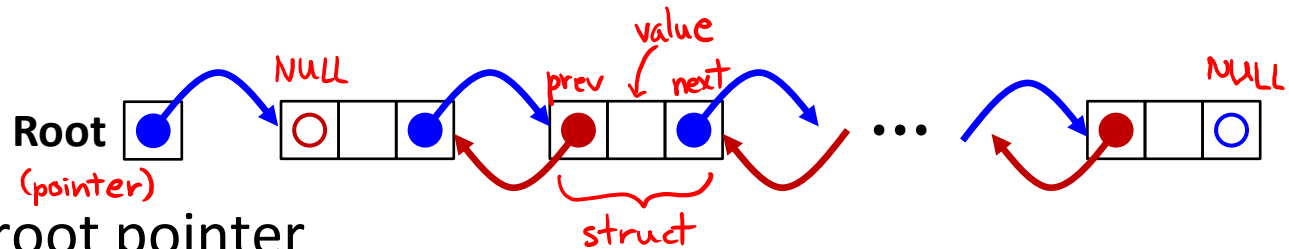


# Doubly-Linked Lists



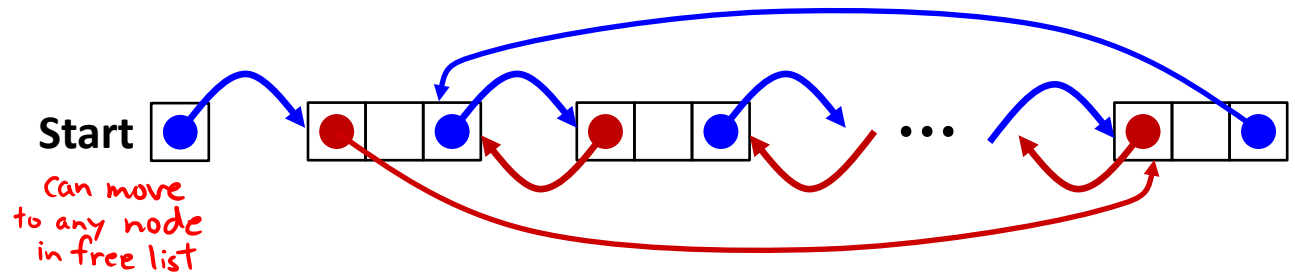
## Linear

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



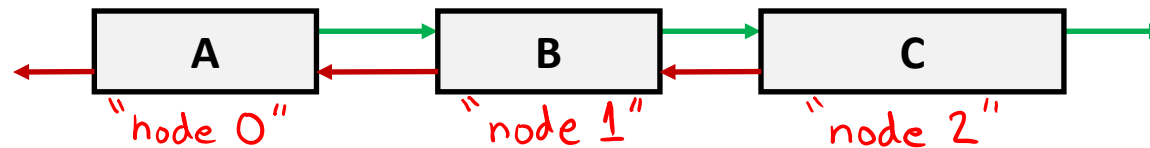
## ❖ Circular

- 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

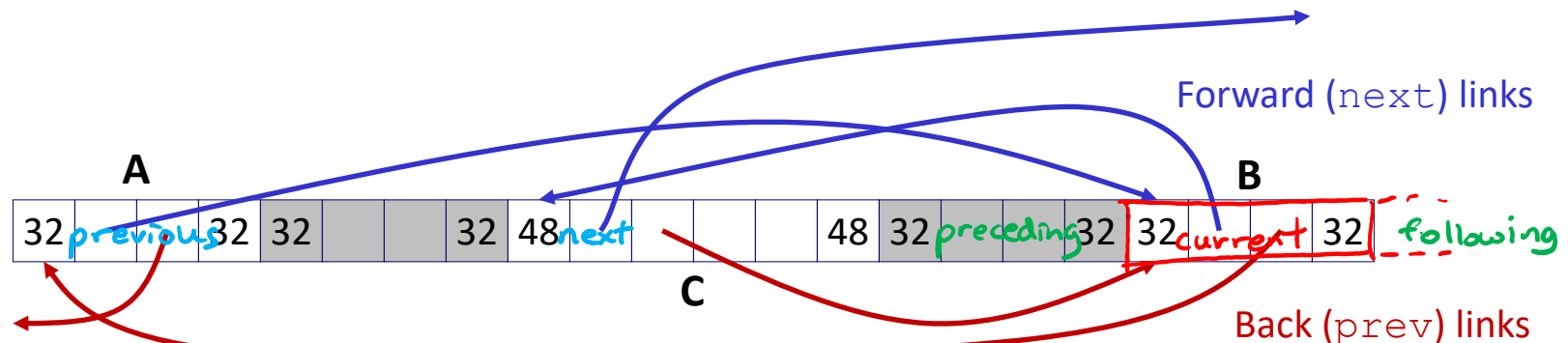


# Explicit Free Lists

- ❖ **Logically:** doubly-linked list



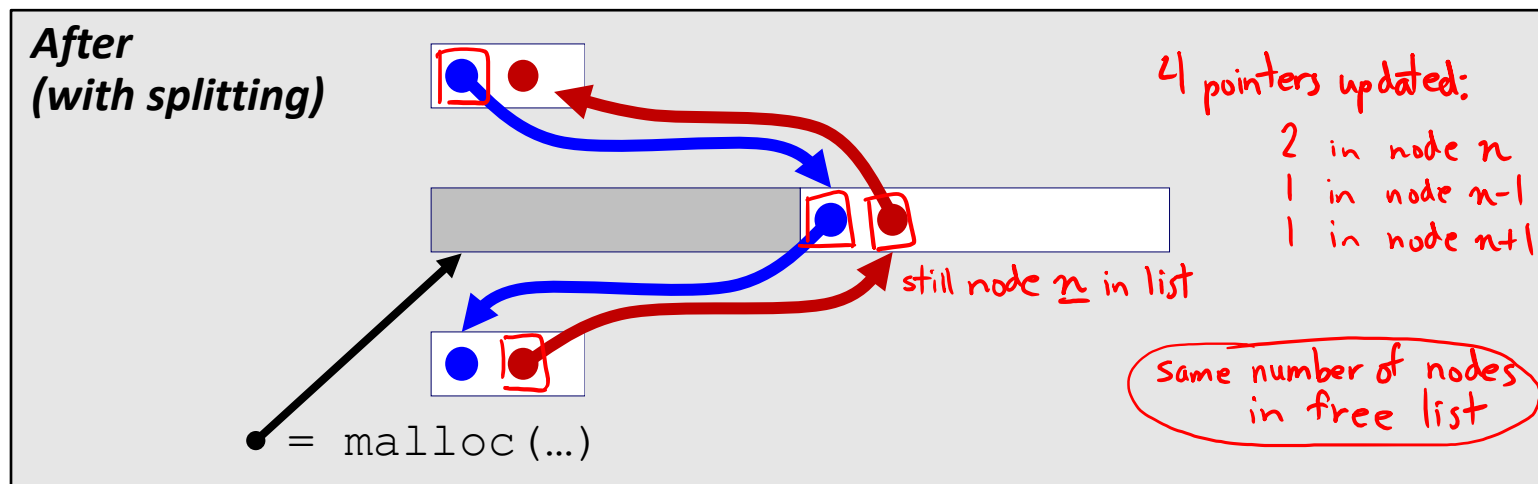
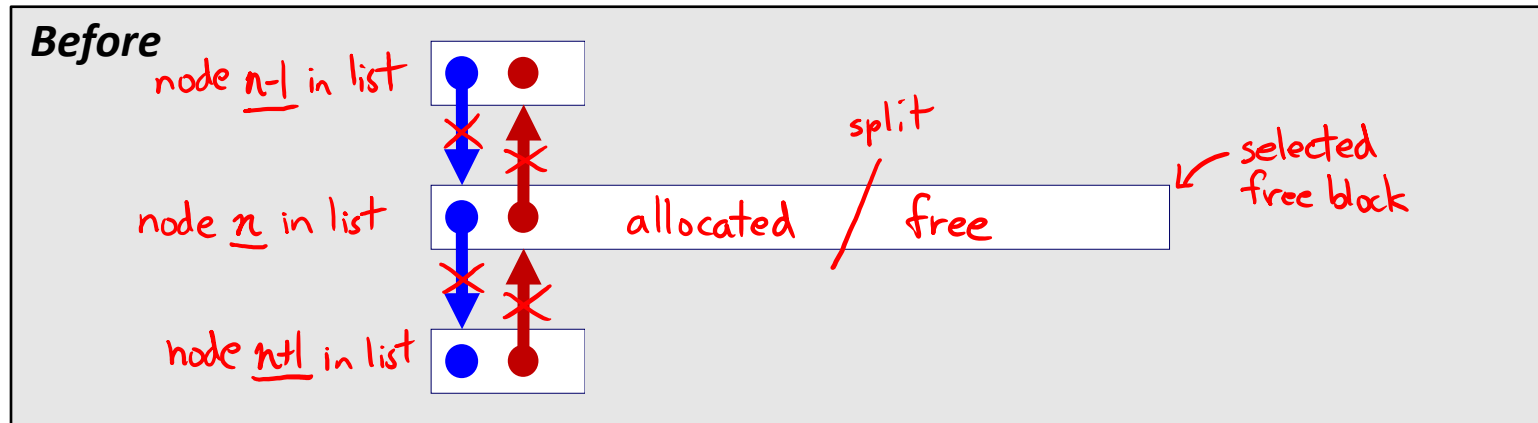
- ❖ **Physically:** blocks can be in any order



previous/next blocks are part of free list  
 preceding/following blocks are physical neighbors

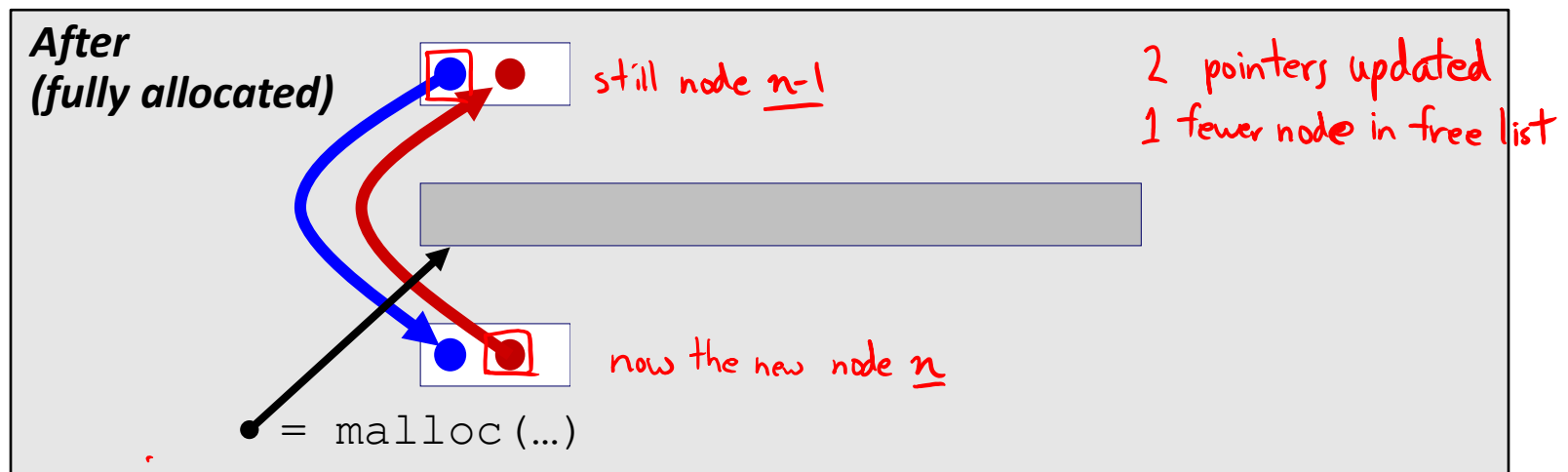
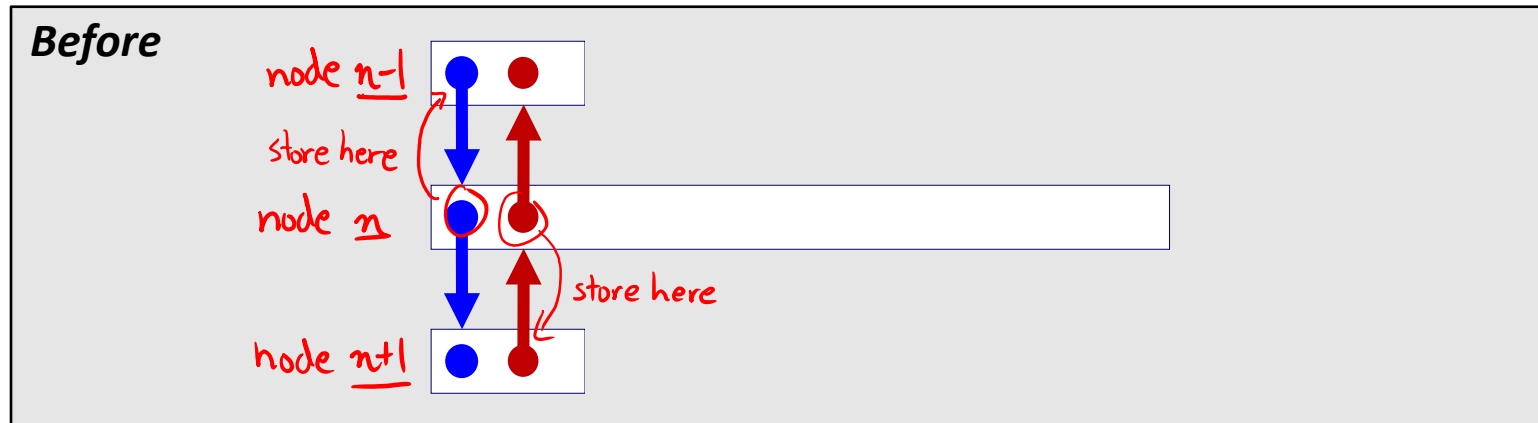
# Allocating From Explicit Free Lists (w. splitting)

**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 (w. full allocation)

**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?

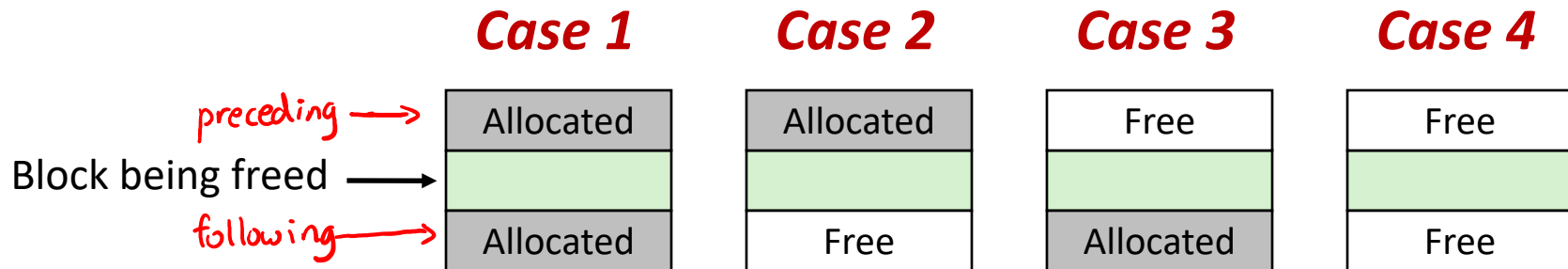
## ★ LIFO (last-in-first-out) policy

- 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)

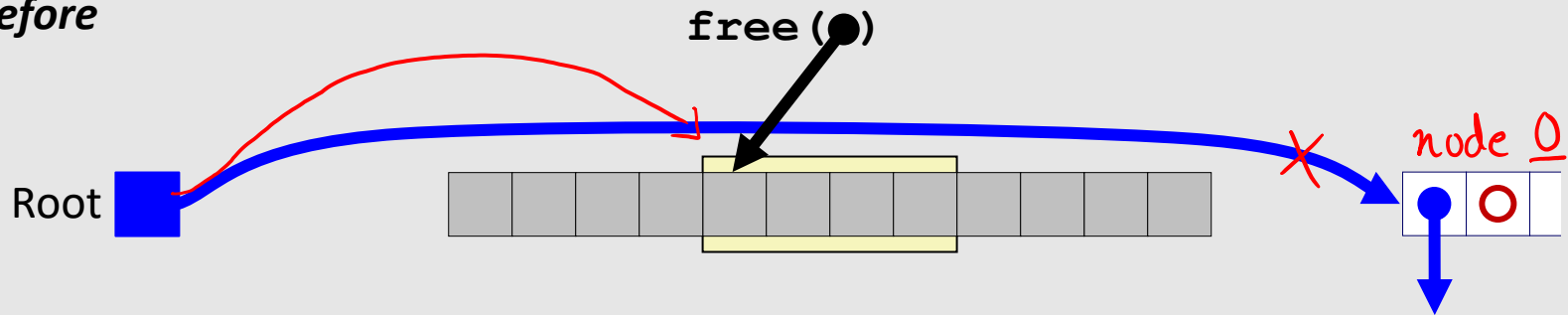
- ❖ How do we tell if a neighboring block is free?

can still use boundary tags (don't need to search free list). other implementations possible (see Lab5)

# Freeing with LIFO Policy (Case 1)

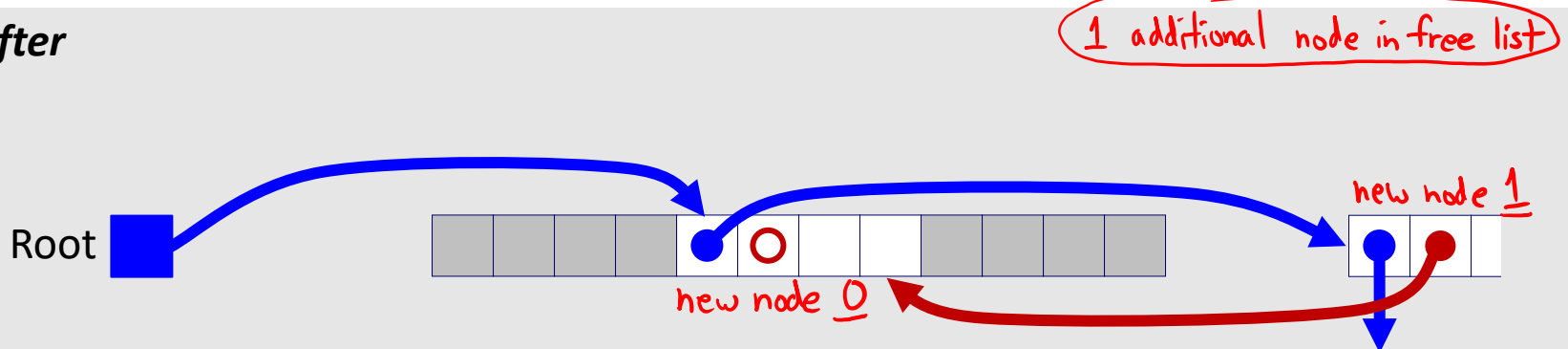
Boundary tags not shown, but don't forget about them!

Before



- ❖ Insert the freed block at the root of the list

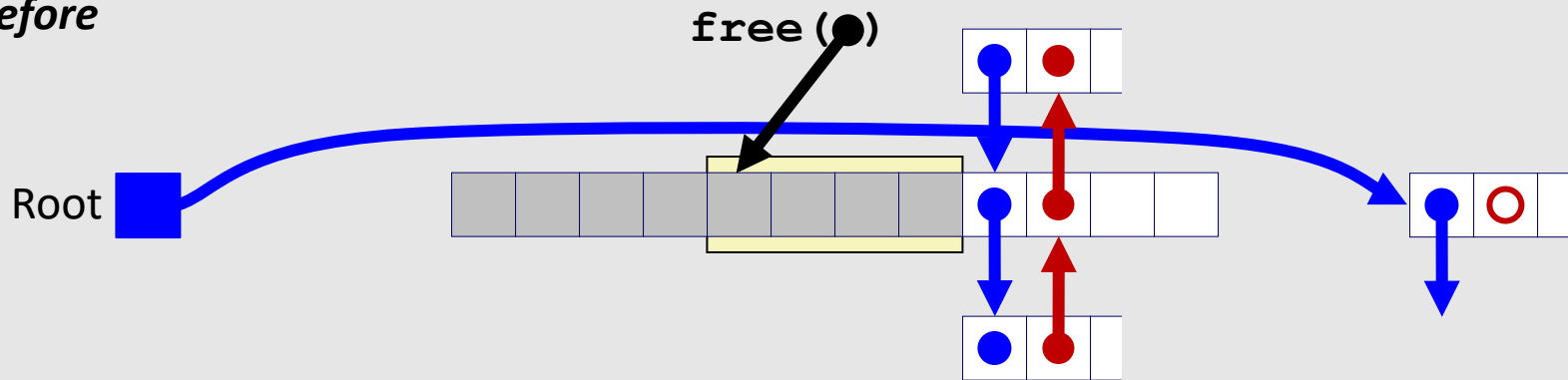
After



# Freeing with LIFO Policy (Case 2)

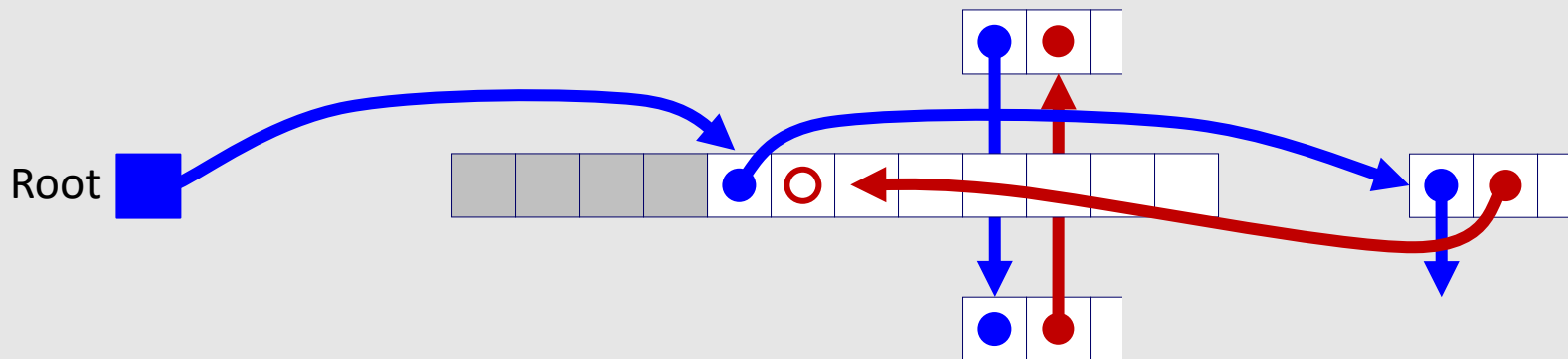
Boundary tags not shown, but don't forget about them!

Before



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

After

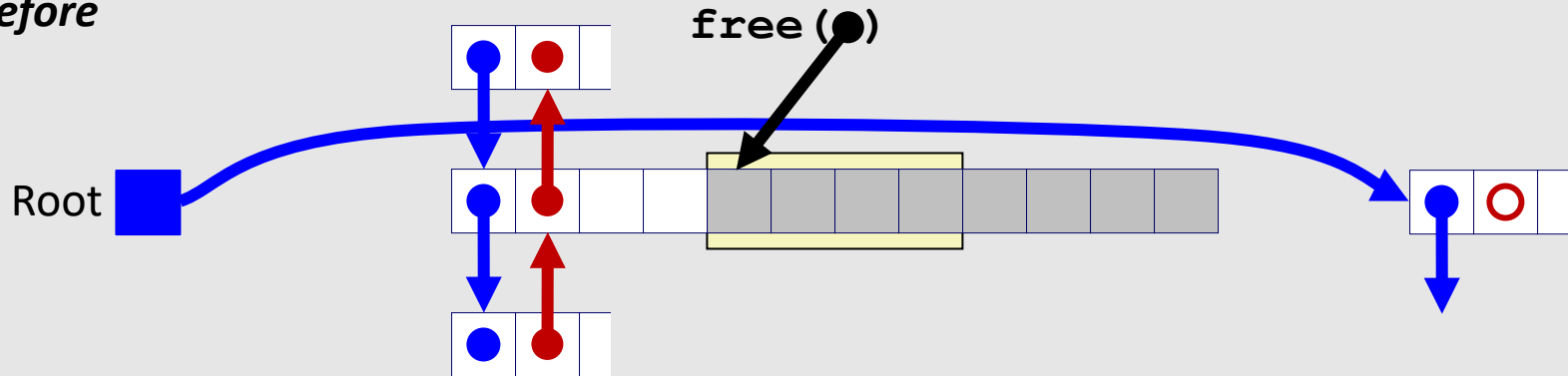




# Freeing with LIFO Policy (Case 3)

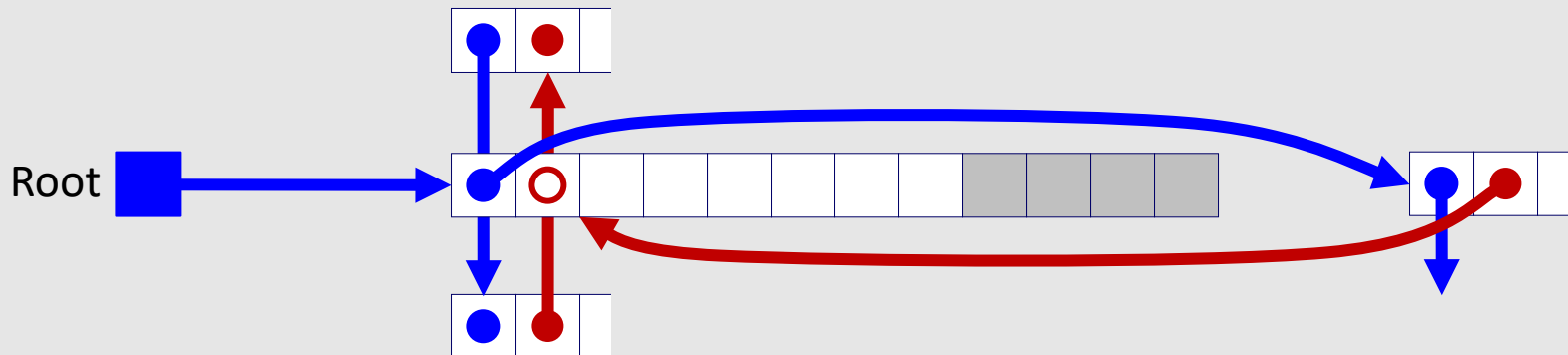
Boundary tags not shown, but don't forget about them!

Before



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

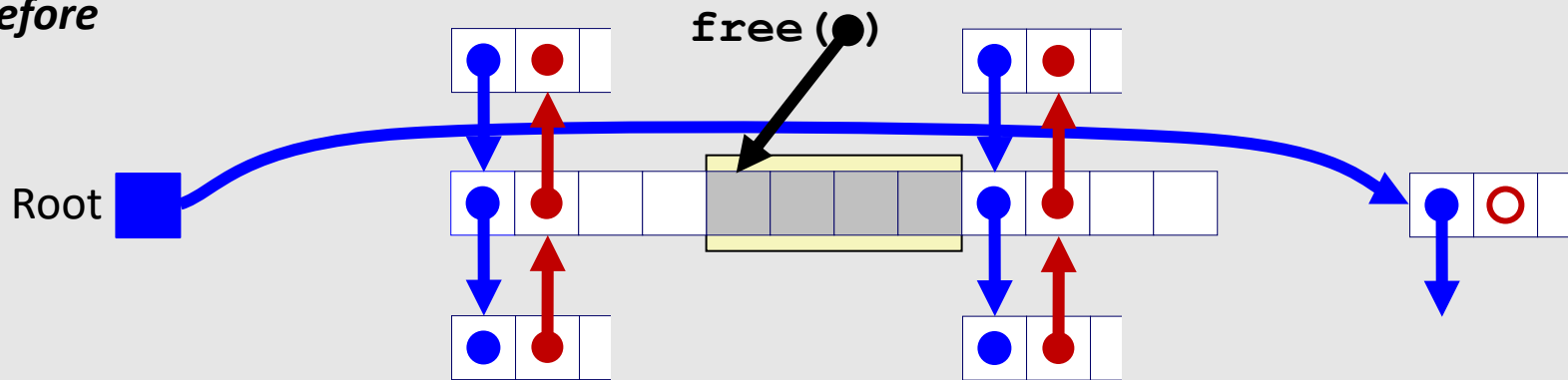
After



# Freeing with LIFO Policy (Case 4)

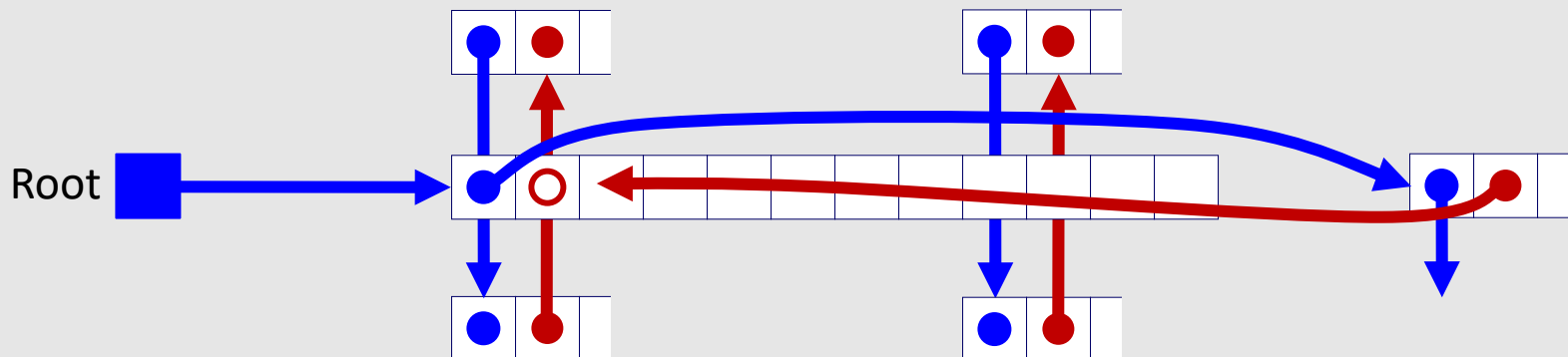
Boundary tags not shown, but don't forget about them!

Before



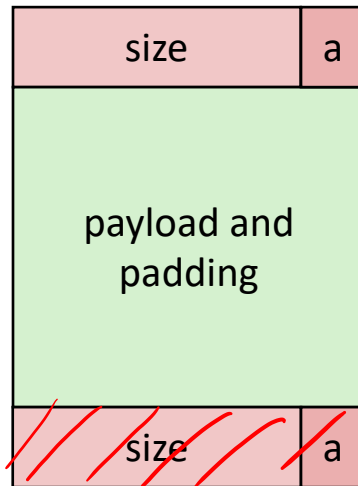
- ❖ Splice preceding and following blocks out of list, coalesce all 3 memory blocks, and insert the new block at the root of the list

After



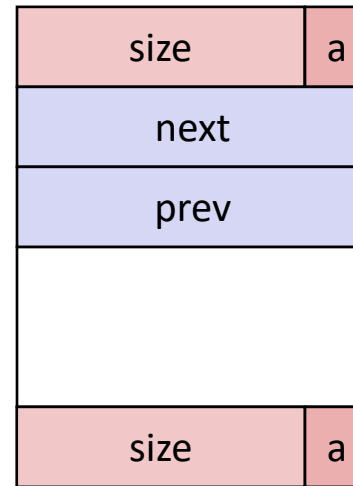
# Do we always need the boundary tags?

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

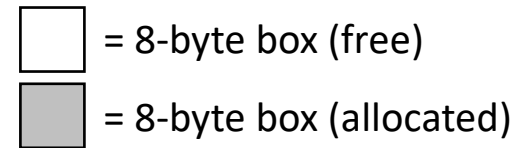
## ❖ Most common use of explicit lists is in conjunction with *segregated free lists*

- Keep multiple linked lists of different size classes, or possibly for different types of objects

# BONUS SLIDES

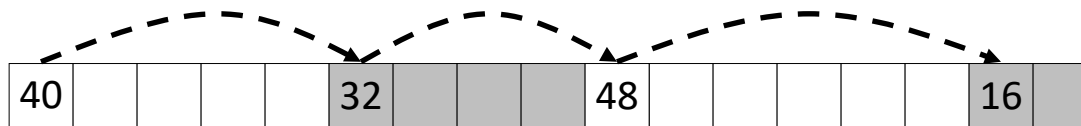
The following slides are about the **SegList Allocator**, for those curious. You will NOT be expected to know this material.

# Keeping Track of Free Blocks

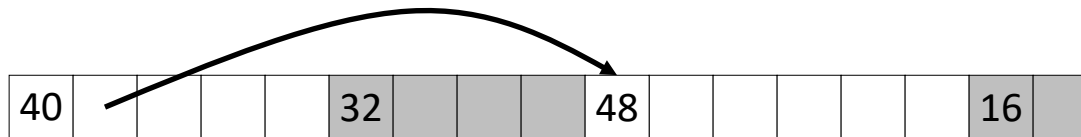


## 1) *Implicit free list* using length – links all blocks using math

- 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*

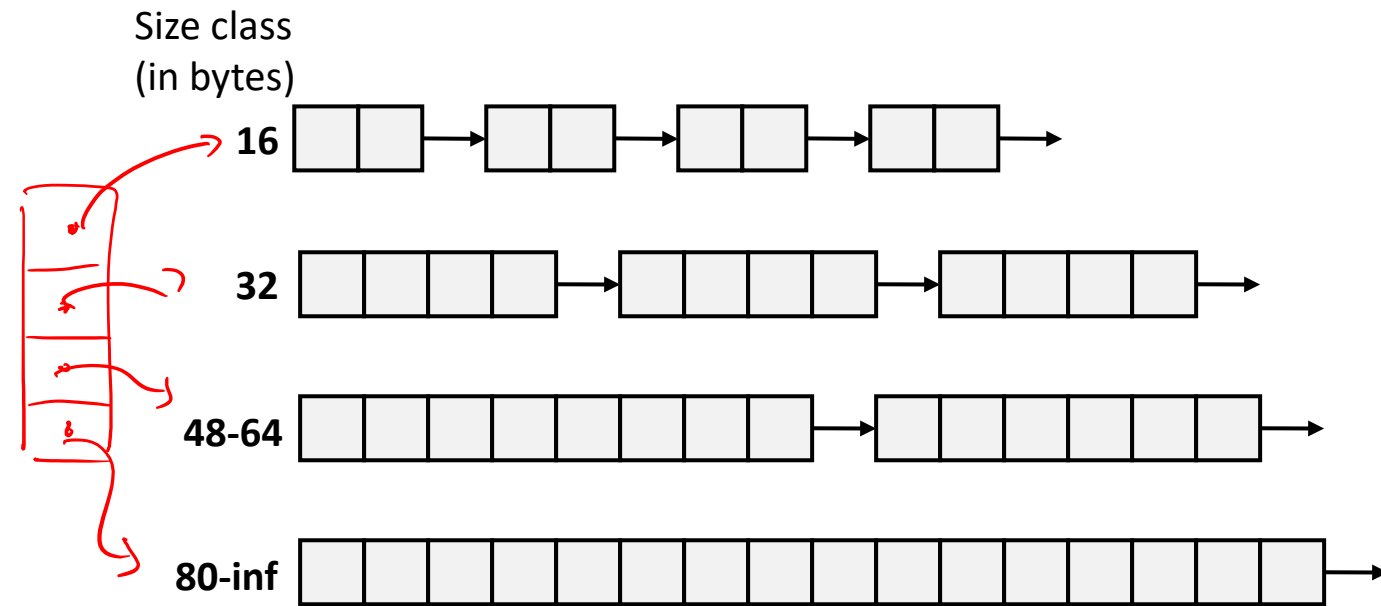
- Different free lists for different size “classes”

## 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



- ❖ 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