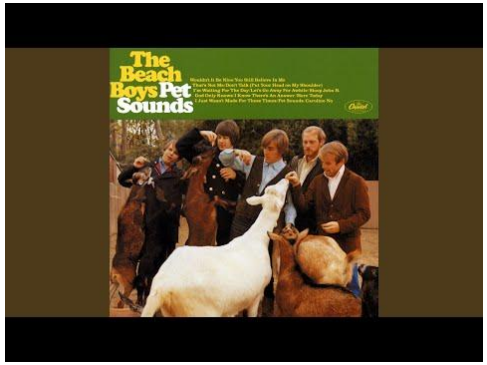
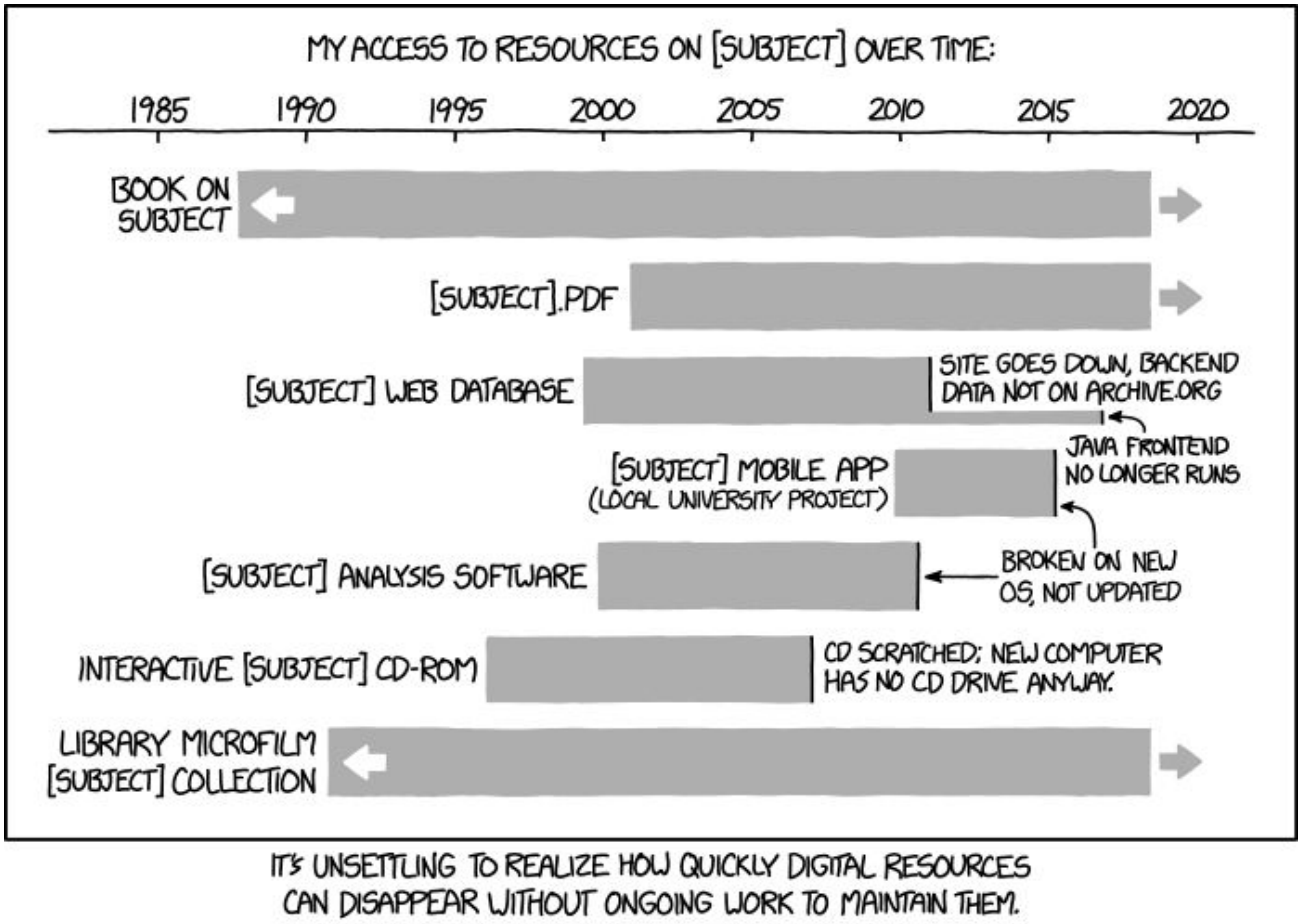
Memory Allocation II

CSE 351 Summer 2021

Instructor:
Mara Kirdani-Ryan

Teaching Assistants:
Kashish Aggarwal
Nick Durand
Colton Jobes
Tim Mandzyuk





http://xkcd.com/1909/

End of Quarter Approaching!

- You've done a ton of work and learning in a condensed schedule, be proud of that!
- End of the quarter can get hectic (especially in the summer) balancing final assignments, projects, exams
- **Please start Lab 5/Unit Summary 3 early**!
  - Also allows you to make use of office hours and the message board if you have questions or get stuck
  - Let us know how we can help, how we can accommodate! We'll do what we can.

Gentle Loving Reminders!

- hw20 due today!
  - This should be helpful for lab 5
- hw21 due Monday
- Lab 5 due Wednesday
  - You *could* use late days, but you still have a unit summary.
  - **Email us if you're using late days, so we can start grading ASAP**
- Unit Summary 3 due Friday
  - We'll have some time for in-class critique on Monday
  - Come prepared with something to share!
  - No late days! We need to grade!

Learning Objectives

Understanding this lecture means you can:

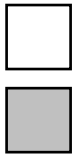
- Explain implicit free lists
- Motivate and explain coalescing of memory blocks, from the perspective of fragmentation
- Explain, and implement an explicit free list allocator (lab 5)

Looking Ahead!

- Lab 5 due Wednesday!
  - 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
  - Can be difficult to debug so please start early and use OH
  - Light style grading
  - hw20 will help get you started!
  - Email if you're using late days!

- Unit Summary 3 due last day of quarter (Friday 8/20)
  - ***No late days!***

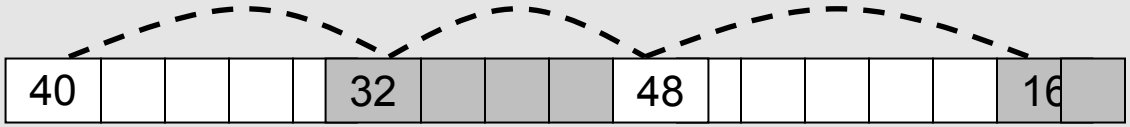
Tracking Free blocks



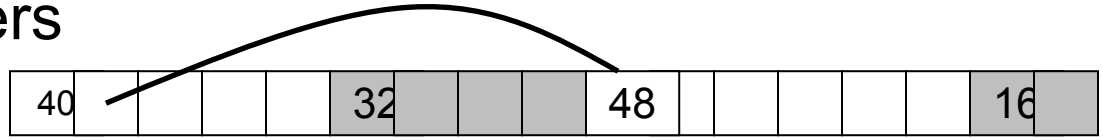
= 8-byte word (free)

= 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"

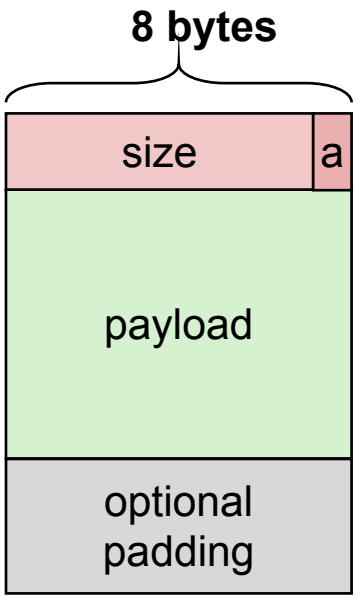
4) *Blocks sorted by size*
   - Can use a balanced binary tree (*e.g.* red-black tree) with pointers within each free block, and the length used as a key

Implicit Free Lists

e.g. with 8-byte alignment, possible values for size:
00001000 = 8 bytes
00010000 = 16 bytes
00011000 = 24 bytes
. . .

- For each block we need: **`size`, is-allocated?**
  - Could store using two words, but wasteful
- Standard trick
  - If blocks are aligned, some low-order bits of `size` are always 0
  - Use lowest bit as an allocated/free flag (fine as long as aligning to K>1)
  - When reading `size`, must remember to mask out this bit!

Format of allocated and free blocks:



a = 1: allocated block
a = 0: free block

size: block size (in bytes)

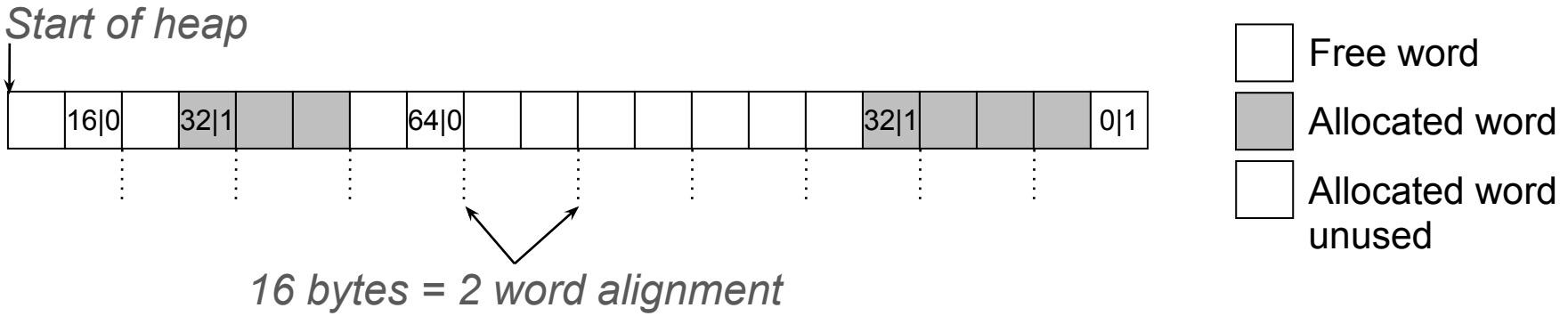
payload: application data (allocated blocks only)

Let X=header (first word)

```
x = size | a;
a = x & 1;
size = x & ~1;
```

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)
- Special one-word marker (0|1) marks end of list
  - Zero `size` is distinguishable from all other blocks

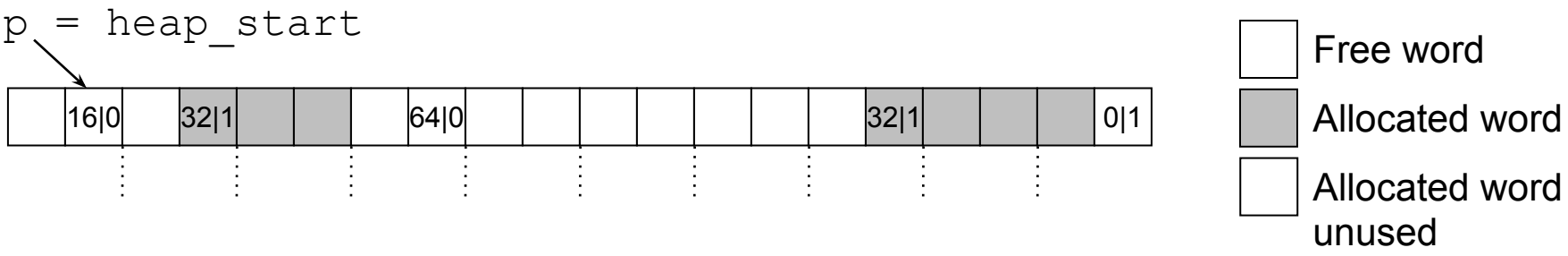
(*p) gets the block *header*
(*p & 1) extracts the `allocated` bit
(*p & -2) extracts the `size`

Finding a Free Block

- *First fit*
  - **Search list from beginning**, choose first free block

```
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

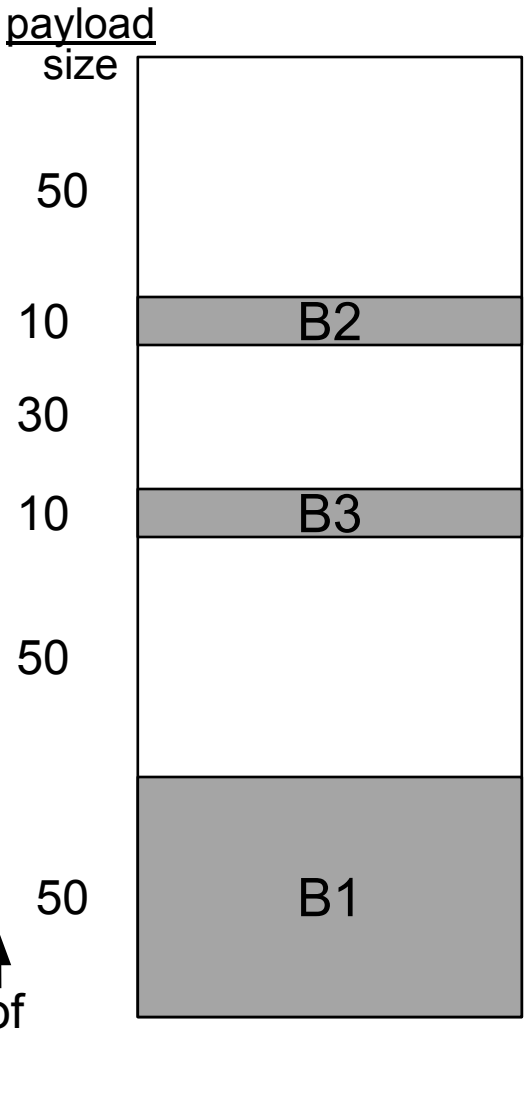


Implicit List: Finding a Free Block

- *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

Checking in!

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



🐶 **Best-fit:**
`malloc(50), malloc(50)`

🐈 **First-fit:**
`malloc(50), malloc(30)`

🐑 **Next-fit:**
`malloc(30), malloc(50)`

🦄 **Next-fit:**
`malloc(50), malloc(30)`

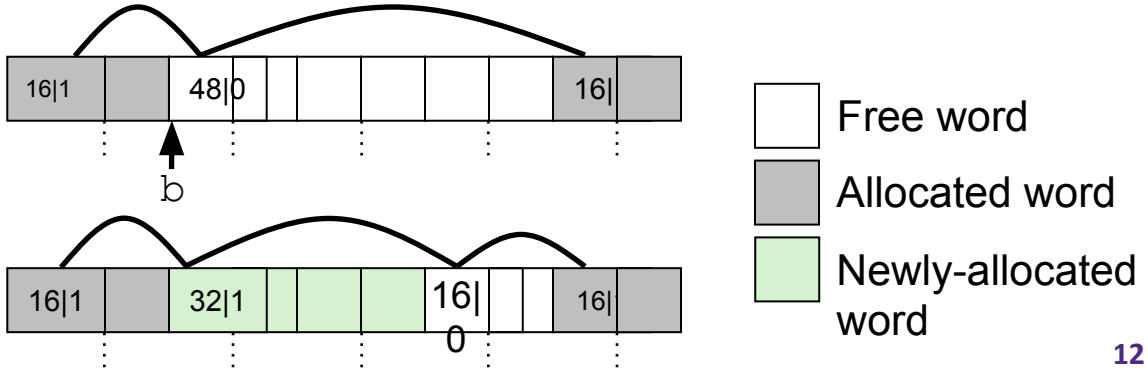
Implicit List: Allocating in a Free Block

- 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

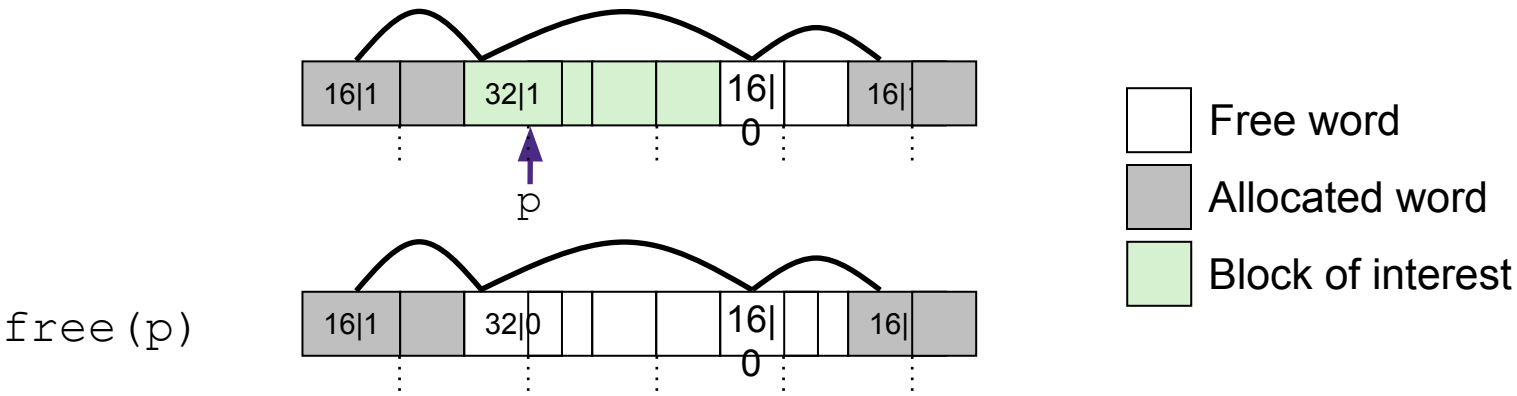
```
void split(ptr b, int bytes) {                  // bytes = desired block size
  int newsize = ((bytes+15) >> 4) << 4; // round up to multiple of 16
  int oldsize = *b;                             // why not mask out low bit?
  *b = newsize;                                 // initially unallocated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

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

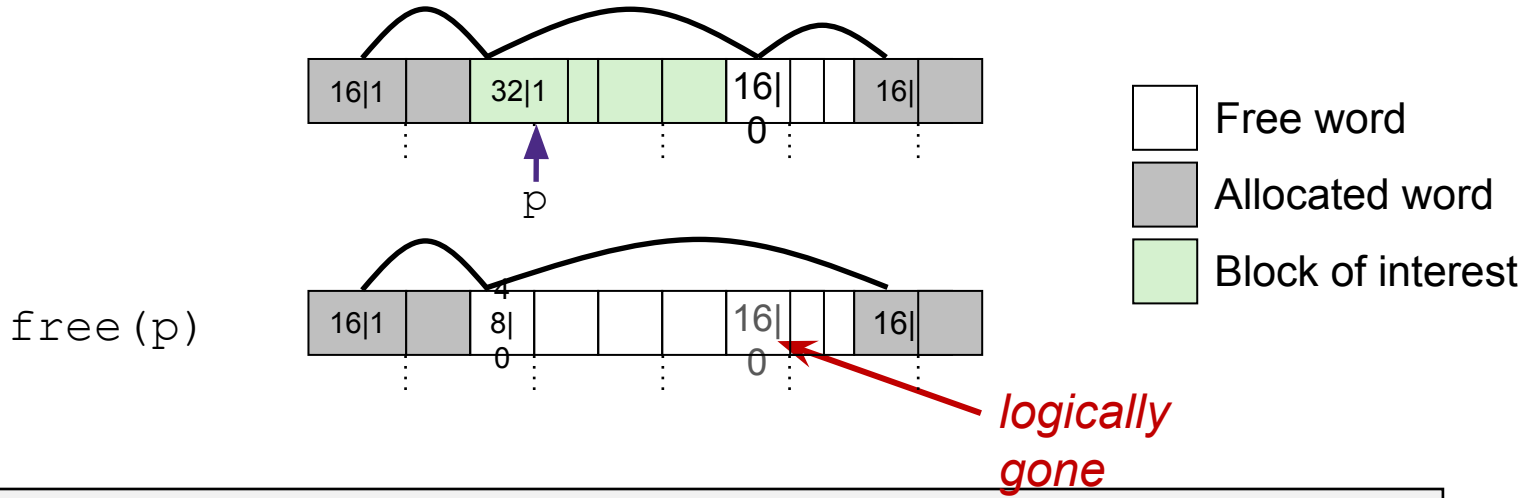


`malloc(40)`

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

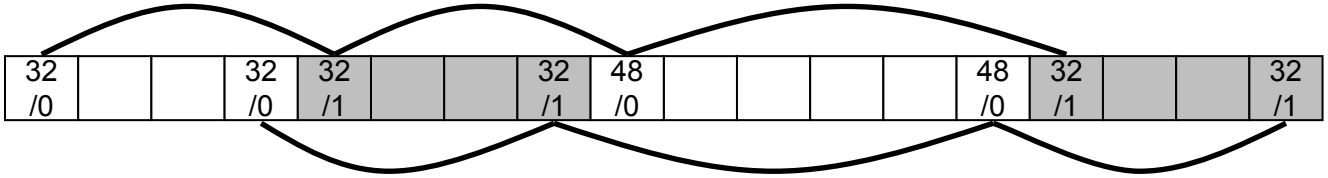



```
void free(ptr p) {          // p points to payload
    ptr b = p - WORD;        // b points to block header
    *b &= -2;                // clear allocated bit
    ptr next = b + *b;       // find next block (UNSCALED +)
    if ((*next & 1) == 0)    // if next block is not allocated,
      *b +=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

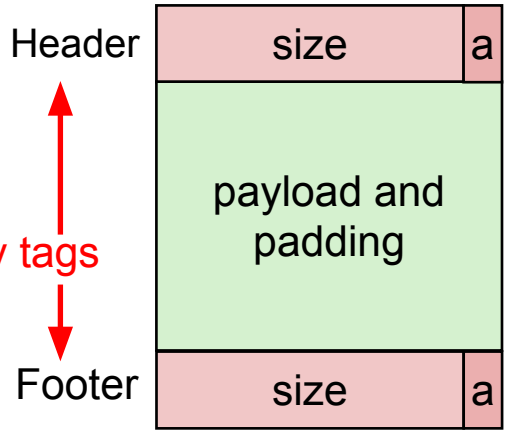
- How do we coalesce with the *previous* block?

Implicit List: Bidirectional Coalescing

- *Boundary tags* [Knuth73]
  - Replicate header at "bottom" (end) of free blocks
  - Allows backwards traversal, but requires extra space
  - Important and general technique!



Format of allocated and free blocks:



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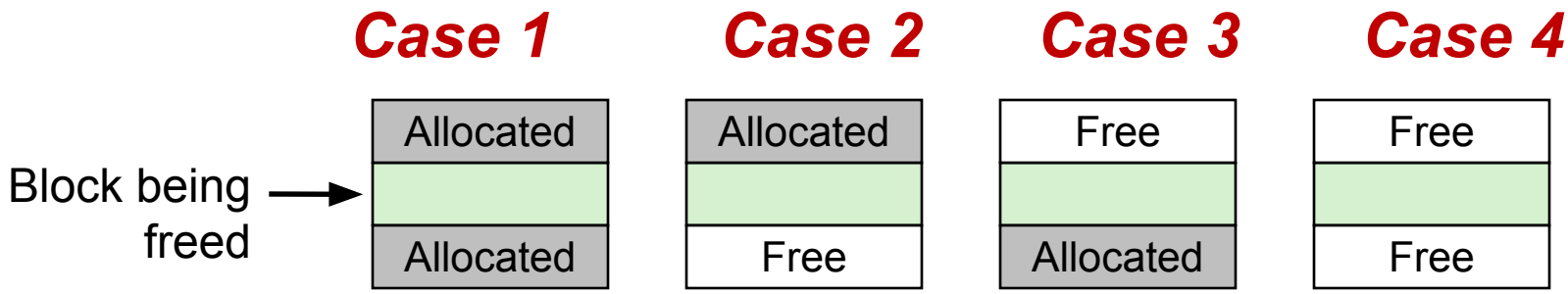
size: block size (in bytes)

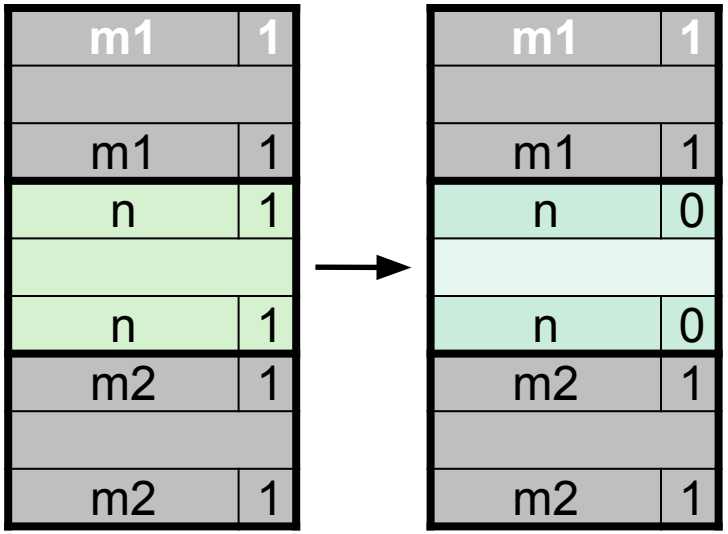
payload: application data (allocated blocks only)

Constant Time Coalescing

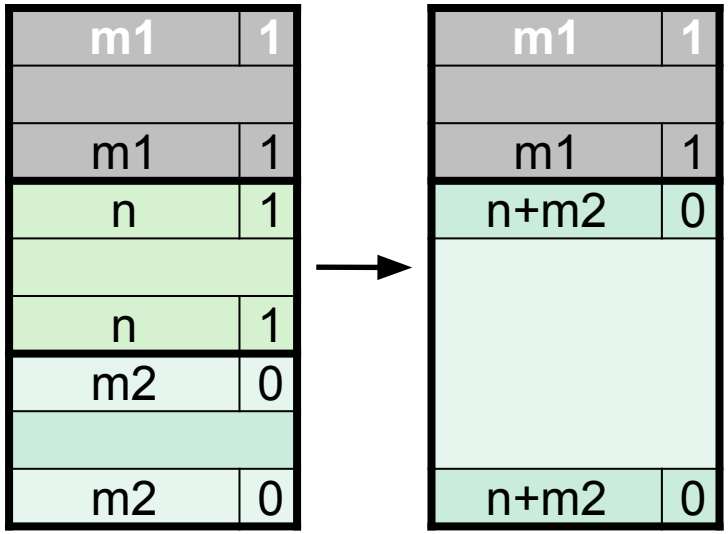


Constant Time Coalescing

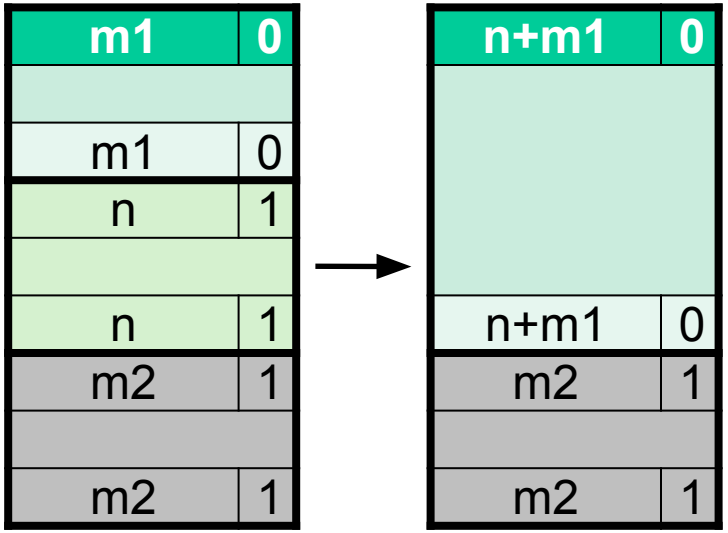
Case 1



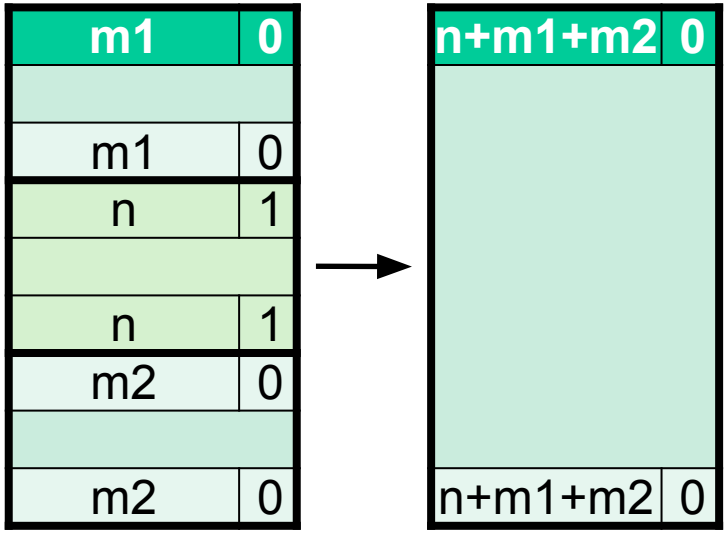
Case 2



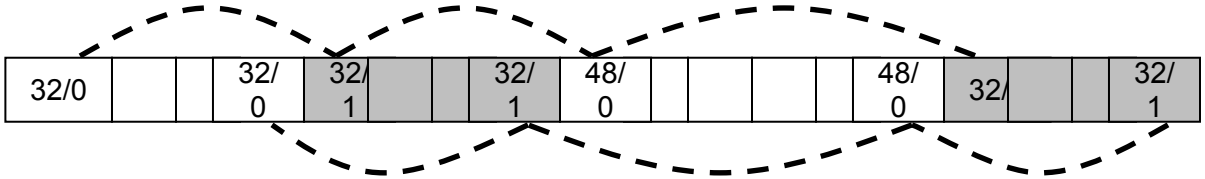
Case 3



Case 4



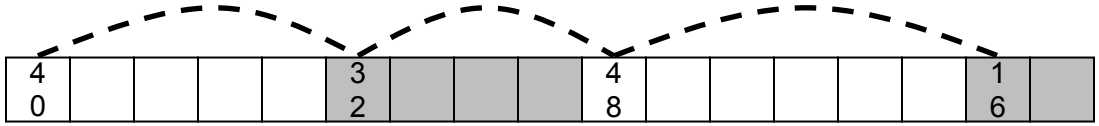
Implicit Free List Review Questions



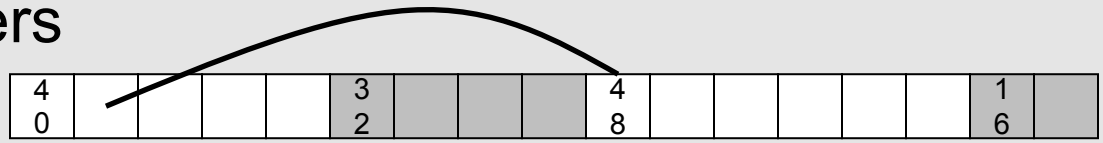
- What is the block header? What do we store and how?
- What are boundary tags and why do we need them?
- When we coalesce free blocks, how many neighboring blocks do we need to check on either side? Why is this?
- If I want to check the size of the n-th block forward from the current block, how many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

Keeping Track of Free Blocks

1) *Implicit free list* using length – links <u>all</u> blocks using math
   - No actual pointers, and must check each block if allocated or free



2) *Explicit free list* among <u>only the free blocks</u>, using pointers

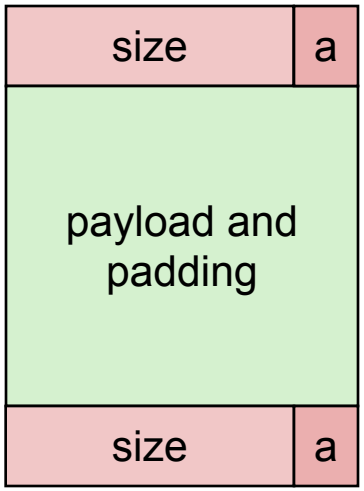


3) *Segregated free list*
   - Different free lists for different size "classes"

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

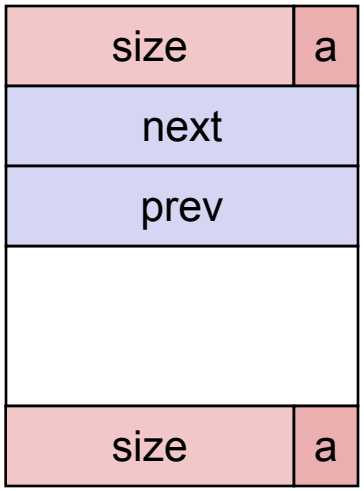
Explicit Free Lists

Allocated block:



(same as implicit free list)

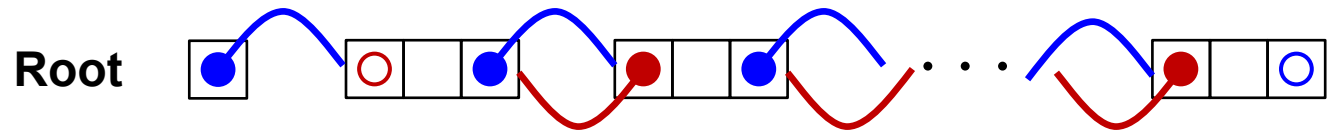
Free block:



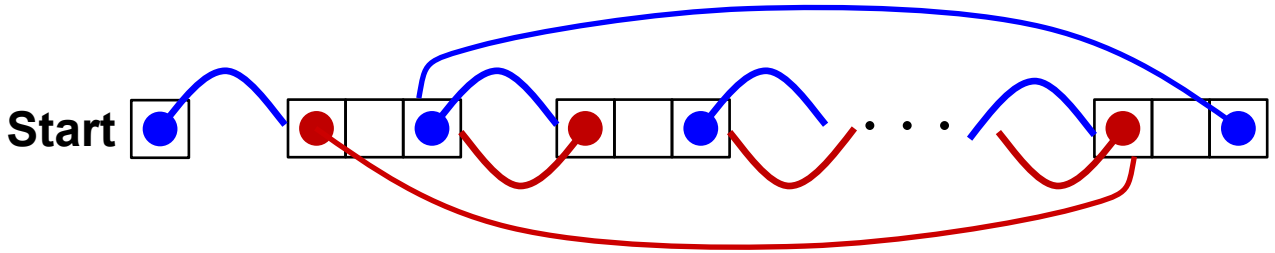
- Use list(s) of *free* blocks, instead of list of *all* blocks
  - The "next" free block could be anywhere in the heap
    - So we need to store next/previous pointers, not just sizes
  - Since we only track free blocks, so we can use "payload" for pointers
  - Still need boundary tags (header/footer)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

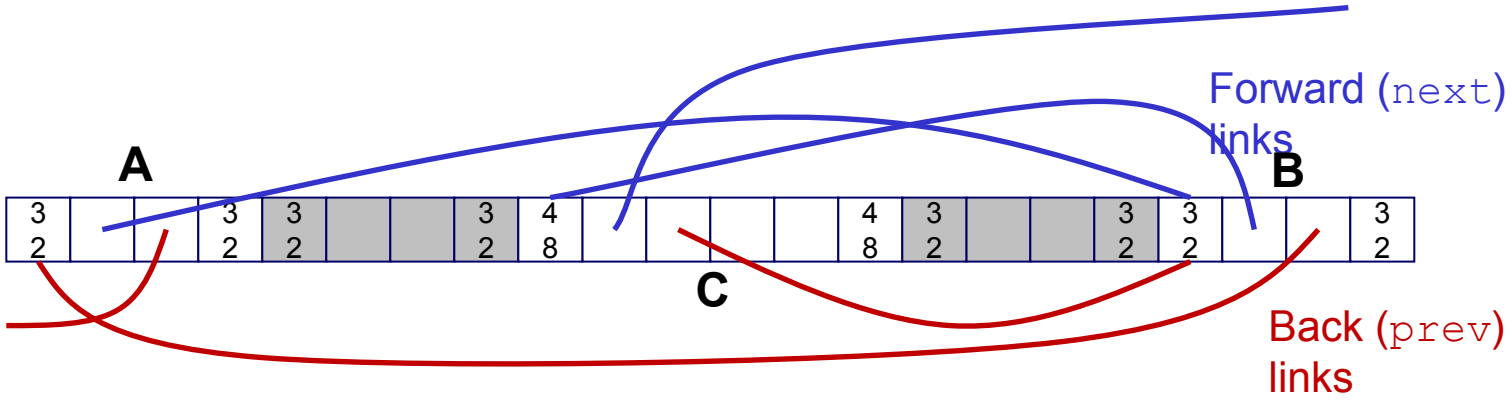


- **Circular**
  - Still have pointer to tell you which node to start with
  - No `NULL` pointers (term condition is back at starting point)
  - Good for next-fit, best-fit

Explicit Free Lists

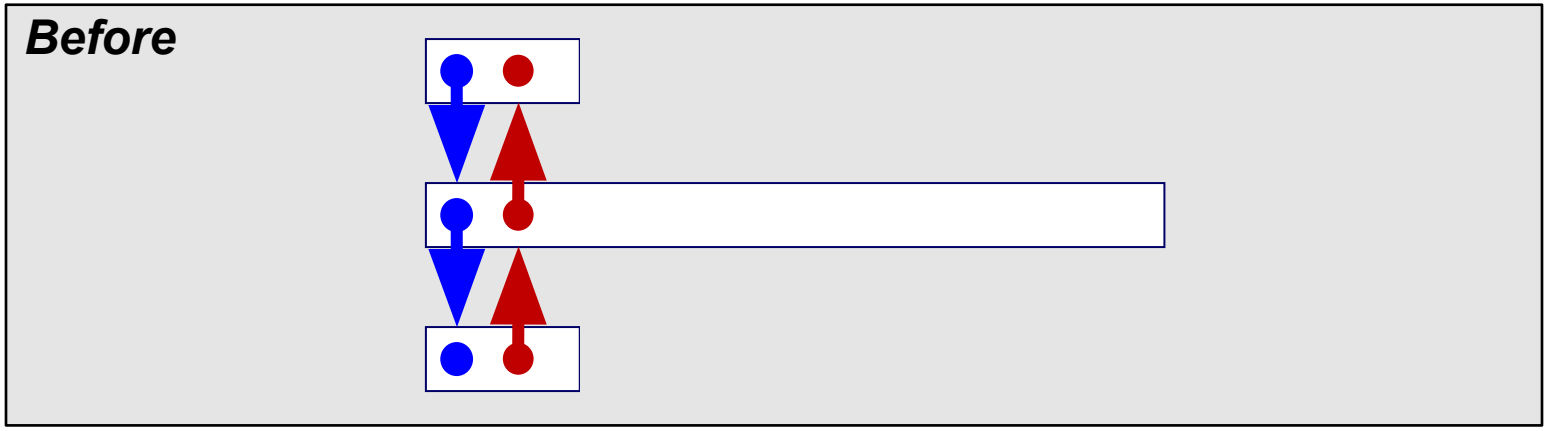
- **Logically:** doubly-linked list

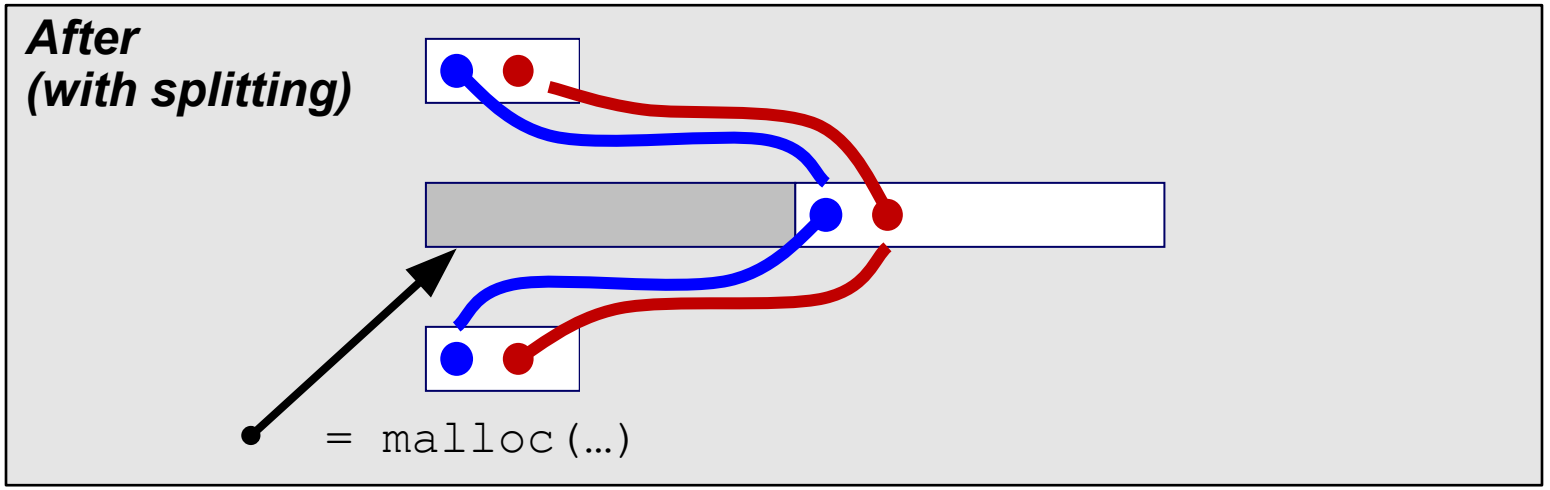
- **Physically:** blocks can be in any order



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).





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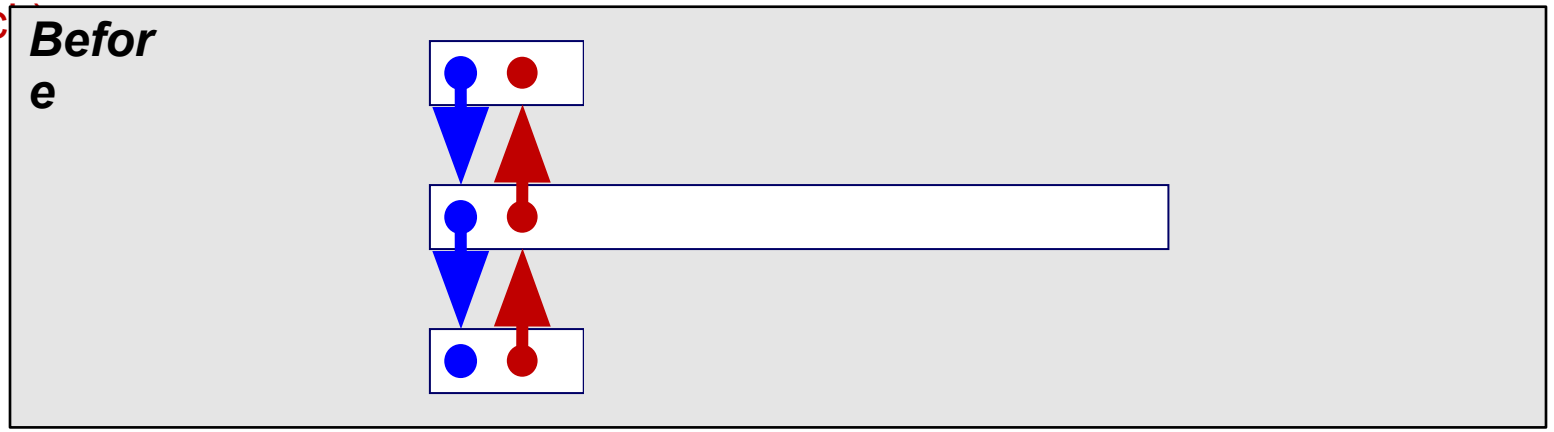
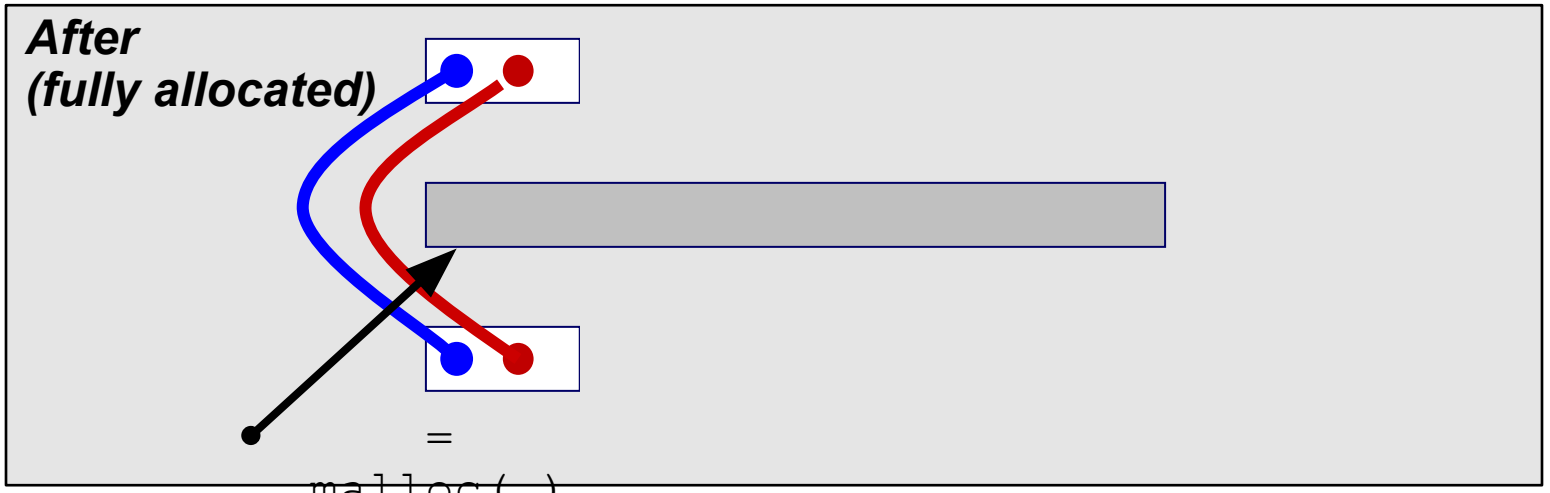




Freeing With Explicit Free Lists

- *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 head of the free list
    - Pro: simple and constant time
    - Con: fragmentation is worse than the alternative

Freeing With Explicit Free Lists

- *Insertion policy:* Where in the free list do you put the newly freed block?
  - **Address-ordered policy**
    - Insert freed blocks so that free list blocks are always in address order:

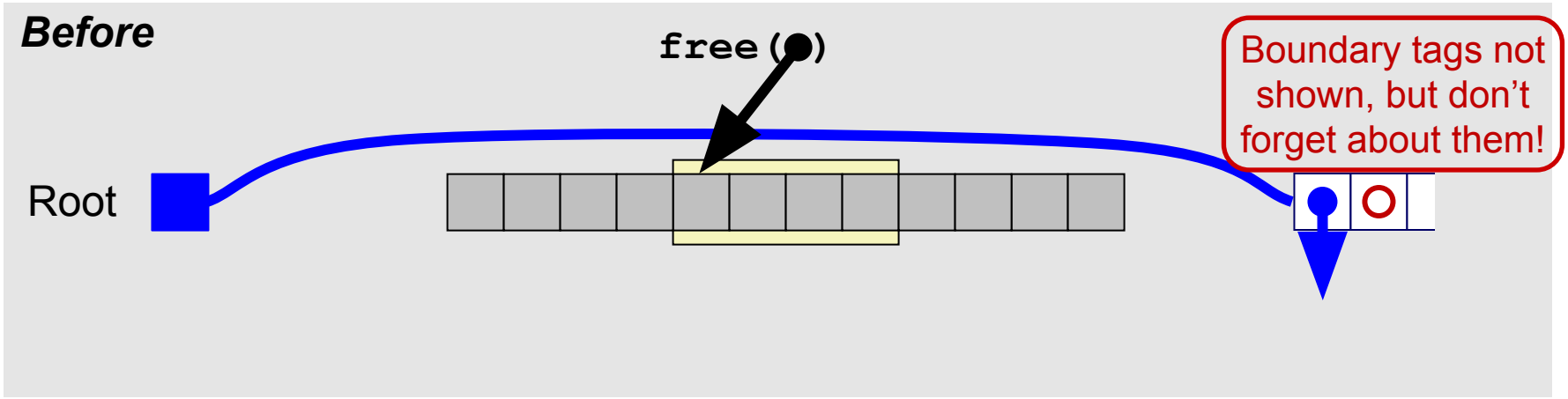
      address(previous) < address(current) < address(next)
    - Con: requires linear-time search
    - Pro: fragmentation is better than the alternative

Coalescing in Explicit Free Lists

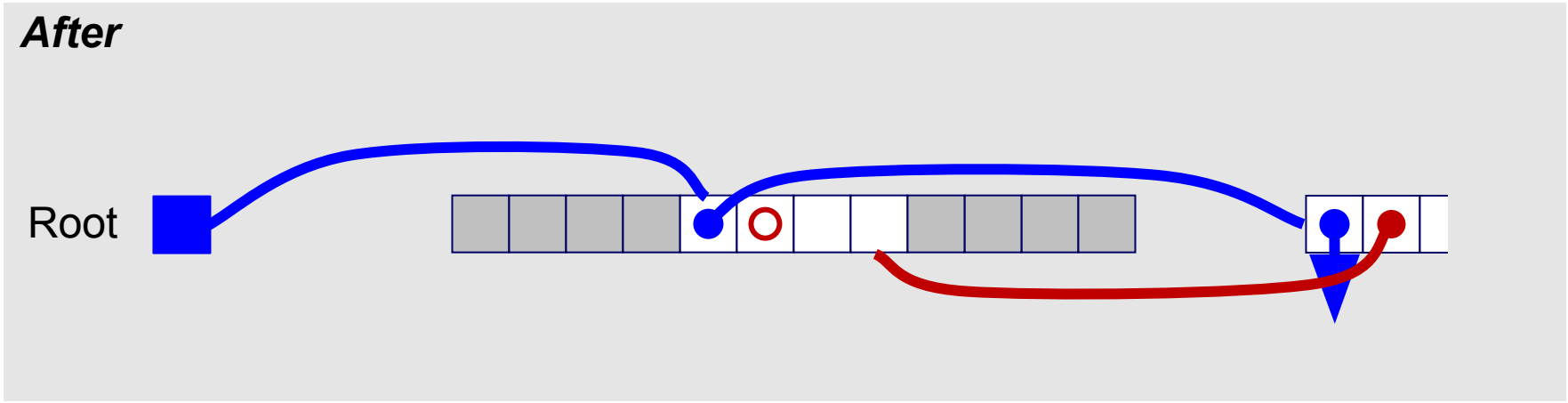
- Neighboring free blocks are *already part of the free list*
  1) Remove old block from free list
  2) Create new, larger coalesced block
  3) Add new block to free list (insertion policy)

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

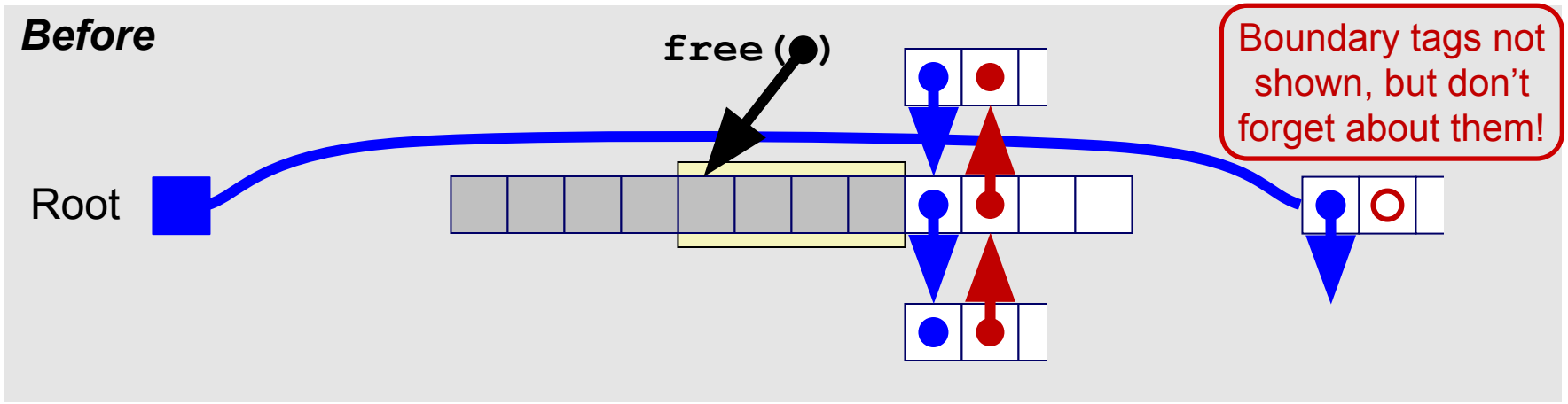
Freeing with LIFO Policy (Case 1)



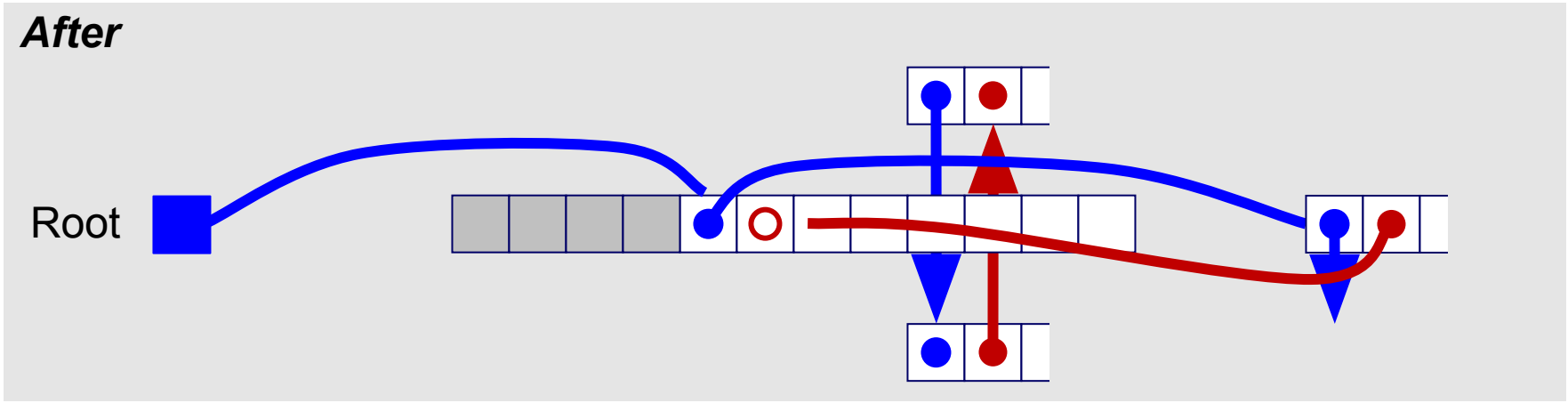
- Insert the freed block at the root of the list



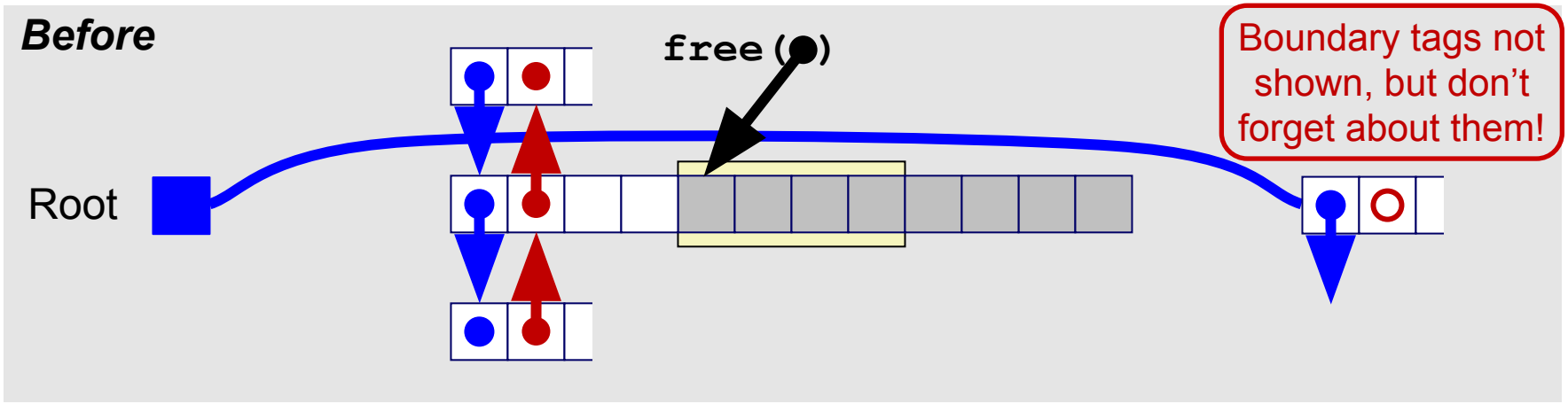
Freeing with LIFO Policy (Case 2)



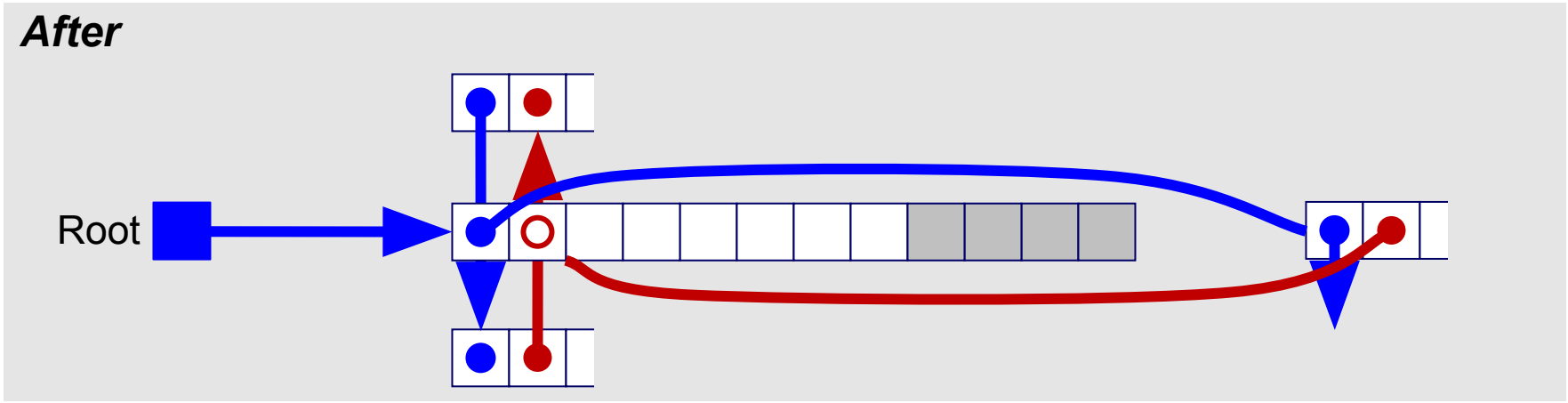
- Splice *successor* block out of list, coalesce both memory blocks, and insert the new block at the root of the list



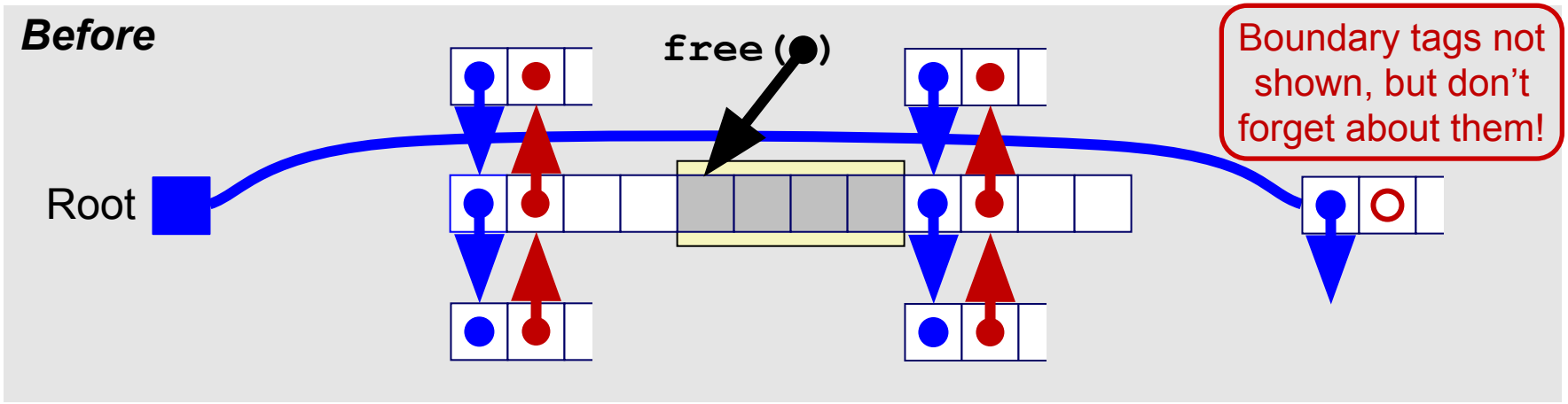
Freeing with LIFO Policy (Case 3)



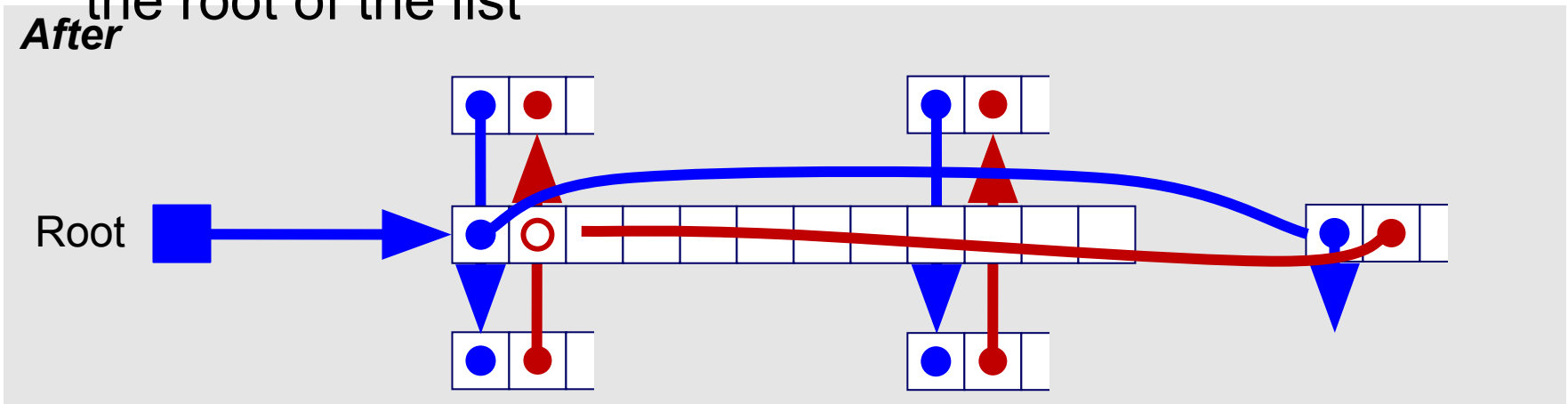
- Splice *predecessor* block out of list, coalesce memory blocks, and insert the new block at the root of the list



Freeing with LIFO Policy (Case 4)

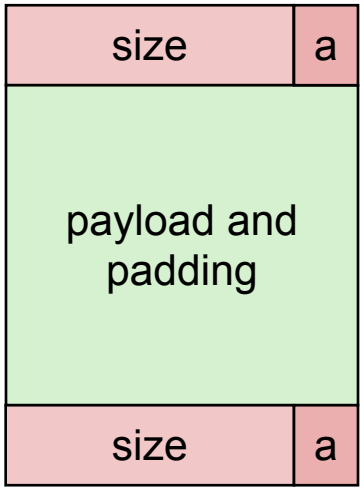


- Splice *predecessor* and *successor* blocks out of list, coalesce all 3 memory blocks, and insert the new block at the root of the list



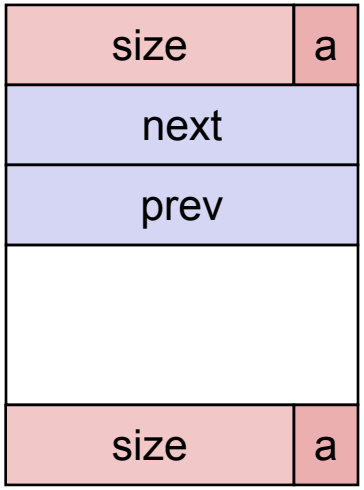
Do we always need the boundary tags?

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

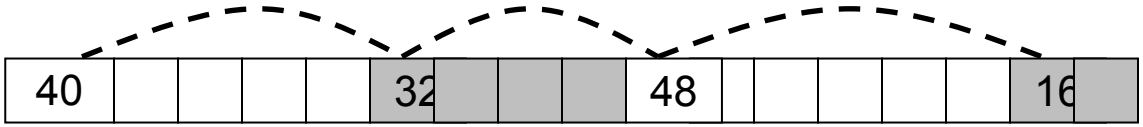
The following slides are about the **SegList Allocator**, for those curious. You will NOT be expected to know this material.

= 8-byte box (free)

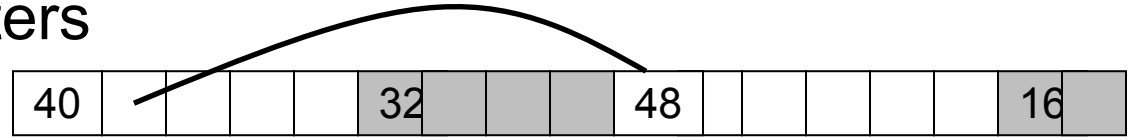
= 8-byte box (allocated)

Tracking Free Blocks

1) *Implicit free list* using length – links <u>all</u> blocks using math
   - No actual pointers, and must check each block if allocated or free



2) *Explicit free list* among <u>only the free blocks</u>, using pointers

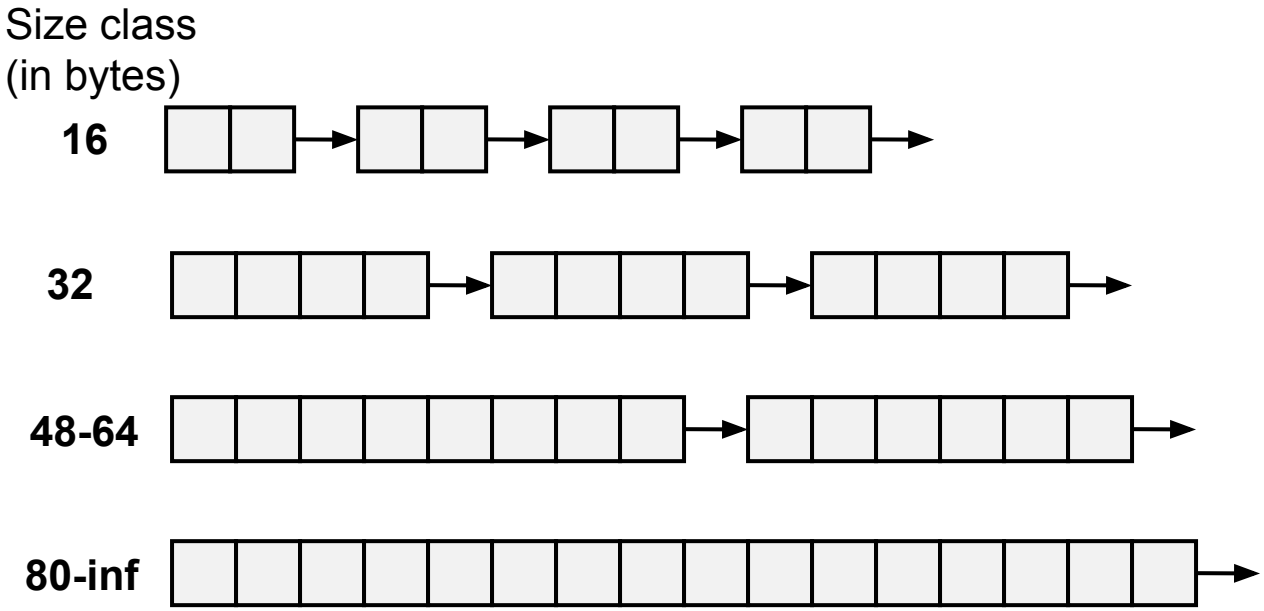


3) *Segregated free list*
   - Different free lists for different size "classes"

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