Memory Allocation II

CSE 351 Winter 2022

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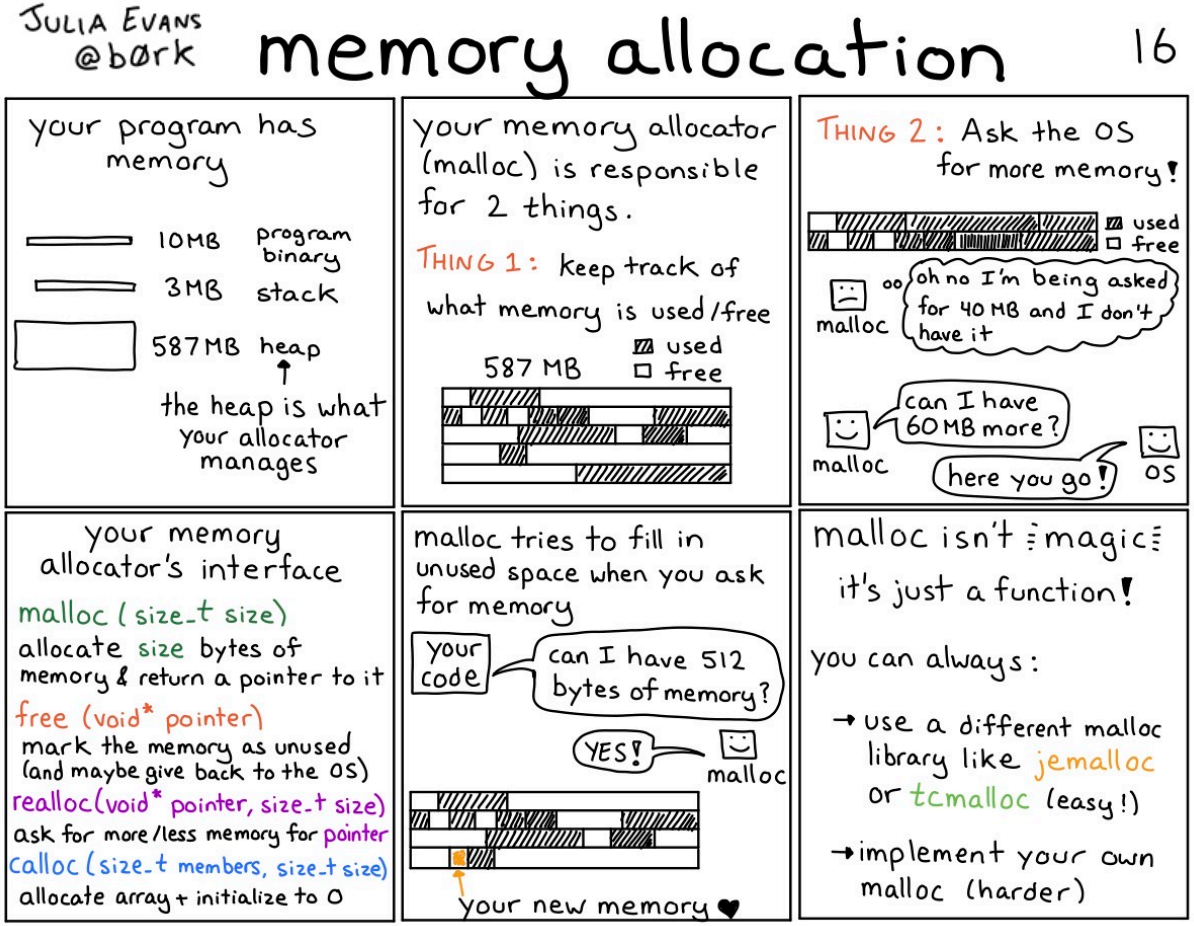


http://wizardzines.com/zines/bite-size-linux/

Relevant Course Material

- hw22 due tonight, hw23 due next Monday (3/7)
- Lab 5 due next Friday (3/11)
  - 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
  - A bit of style grading
- **Final exam**: March 15—17
  - Section 10 will be final review, plus a bit of VM
  - Final review session?

Reading Review

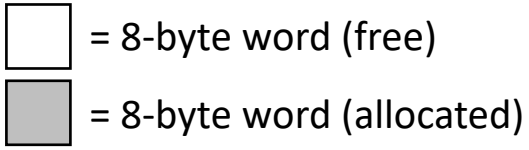
- Terminology:
  - Allocation strategies: first fit, next fit, best fit
  - Allocating a block: splitting, minimum block size
  - Freeing a block: coalescing
  - Boundary tags: header and footer
  - Explicit free list

- Questions from the Reading?

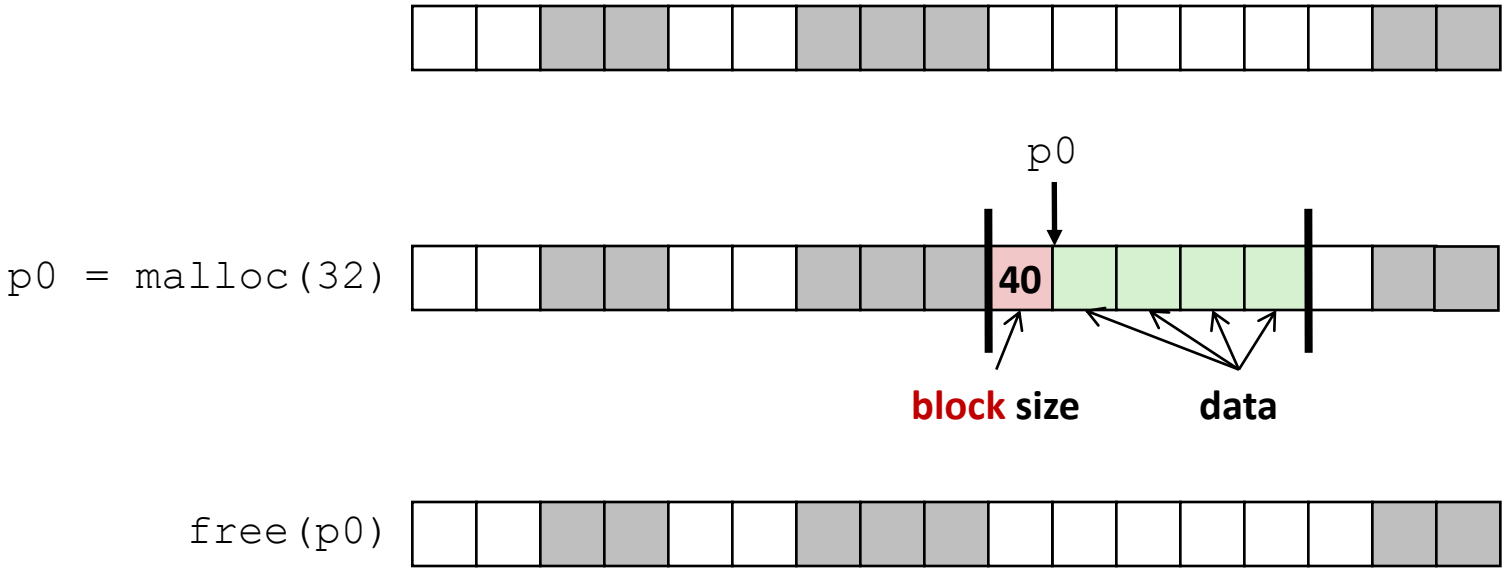
Implementation Issues

- How do we know how much memory to free given just a pointer?
- How do we keep track of the free blocks?
- How do we pick a block to use for allocation (when many might fit)?
- What do we do with the extra space when allocating a structure that is smaller than the free block it is placed in?
- How do we reinsert a freed block into the heap?

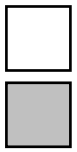
Knowing How Much to Free



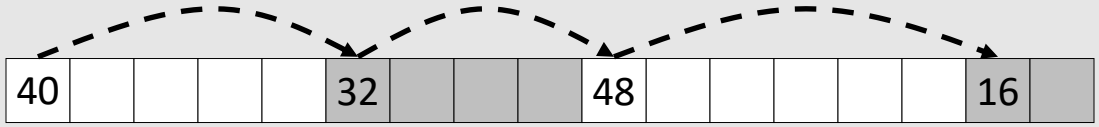
- Standard method
  - Keep the length of a block in the word preceding the data
    - This word is often called the ***header field*** or ***header***
  - Requires an extra word for every allocated block



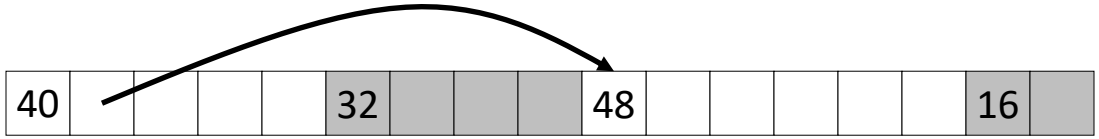
Keeping Track of Free Blocks



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"

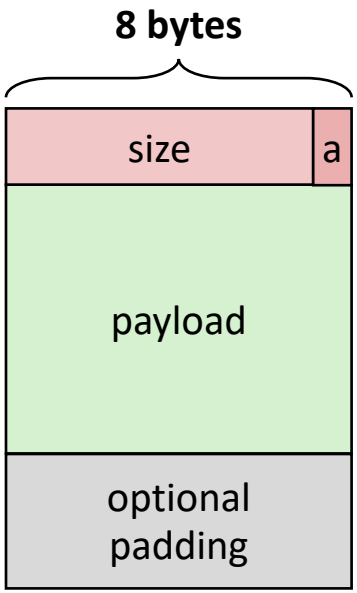
4) *Blocks sorted by size*
   - Can use a balanced binary tree (*e.g.*, red-black tree) with pointers within each free block, and the length used as a key

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
- Neat 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)

If `x` is first word (header):

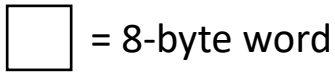
```
x = size | a;

a = x & 1;

size = x & ~1;
```

Header Questions

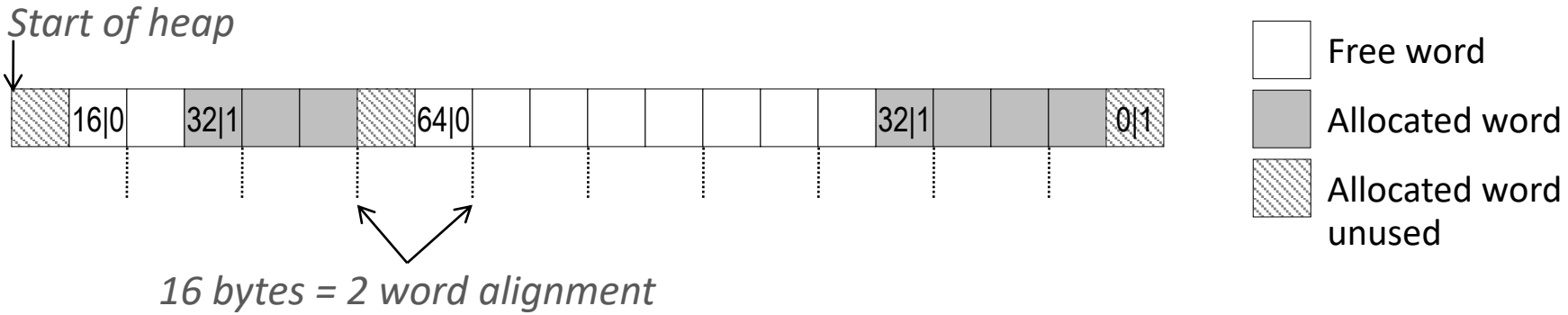
- How many "flags" can we fit in our header if our allocator uses 16-byte alignment?

- If we placed a new "flag" in the second least significant bit, write out a C expression that will extract this new flag from `header`.

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

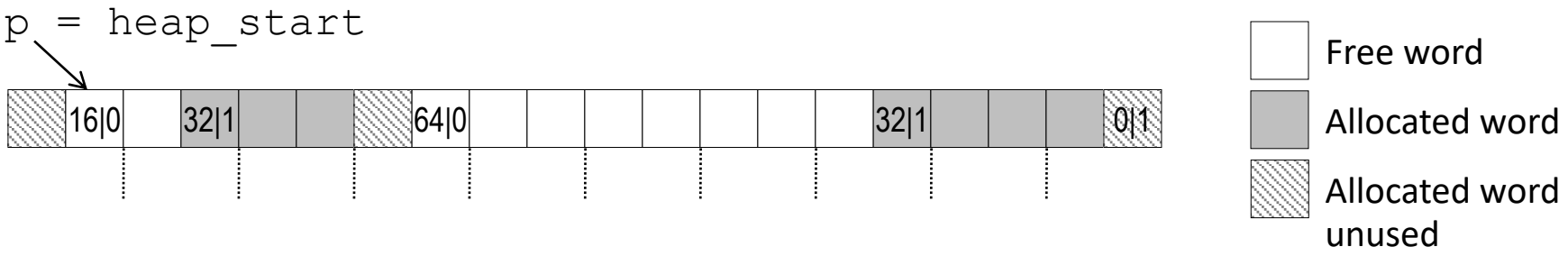
(*p) gets the block *header*
(*p & 1) extracts the `allocated` bit
(*p & -2) extracts the `size`

Implicit List: Finding a Free Block

- *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



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

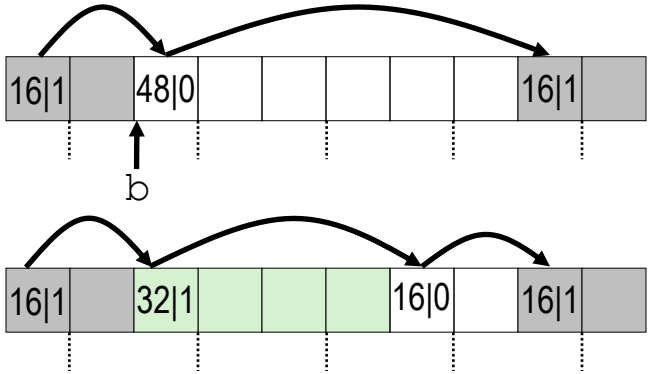
Implicit List: Allocating in a Free Block

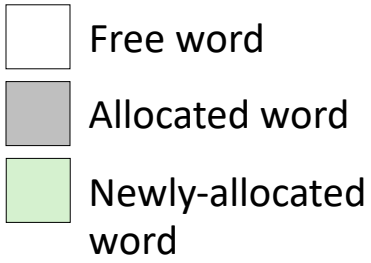
- Allocating in a free block: *splitting*
  - Since allocated space might be smaller than free space, we might want to split the block

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)
```





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:

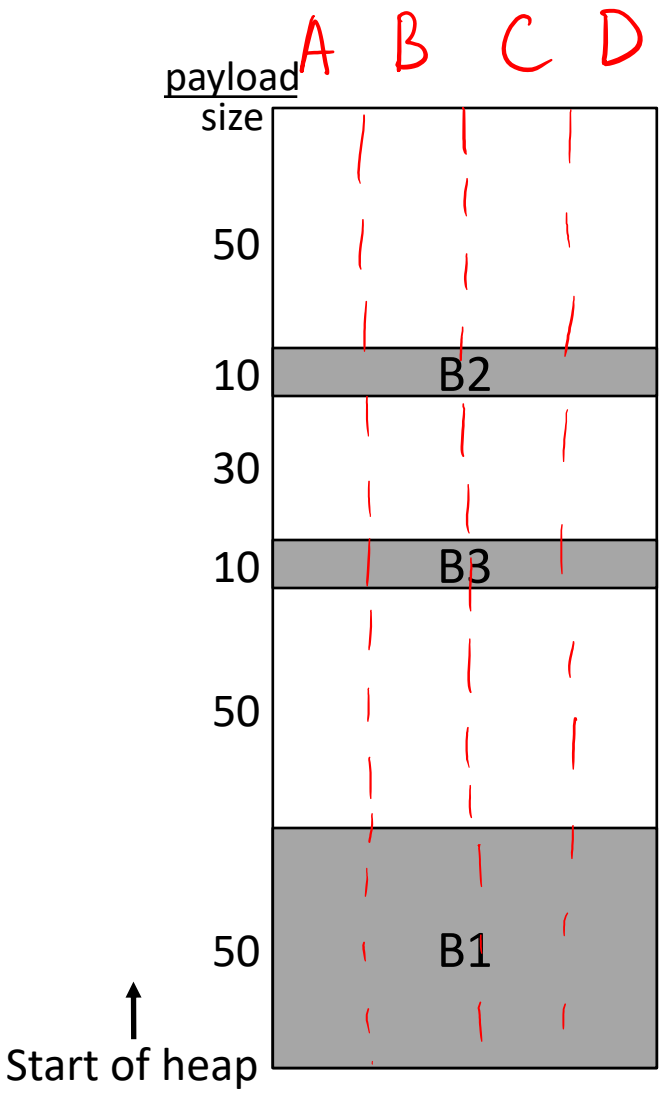
`malloc(50),malloc(30)`

(C) Next-fit:

`malloc(30),malloc(50)`

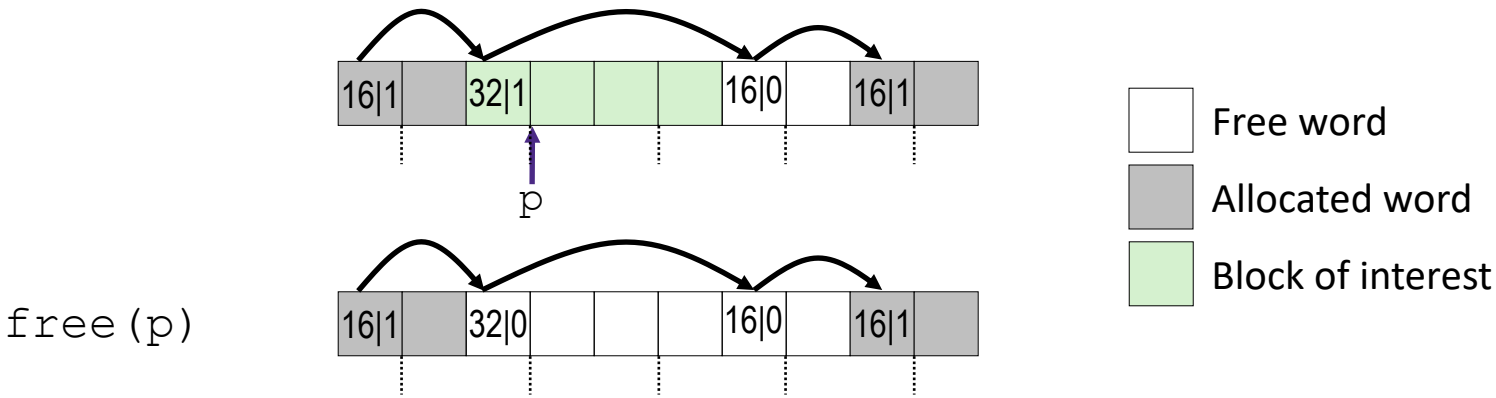
(D) Next-fit:

`malloc(50),malloc(30)`



Implicit List: Freeing a Block

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

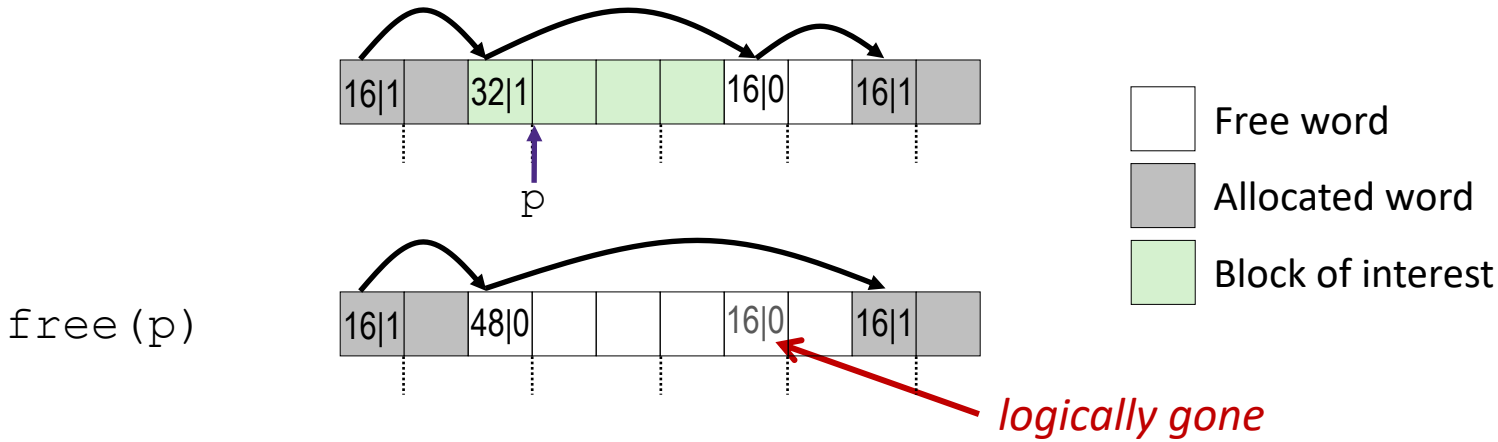


`malloc(40)`

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

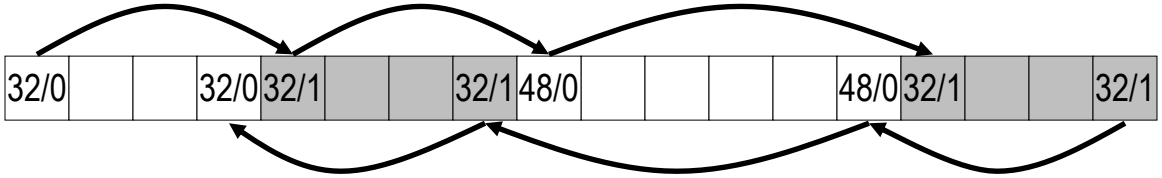



```
void free(ptr p) {          // p points to payload
    ptr b = p - WORD;       // b points to block header
    *b &= -2;               // clear allocated bit
    ptr next = b + *b;      // find next block (UNSCALED +)
    if ((*next & 1) == 0)   // if next block is not allocated,
      *b += *next;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

- How do we coalesce with the *preceding* 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 trade-off!



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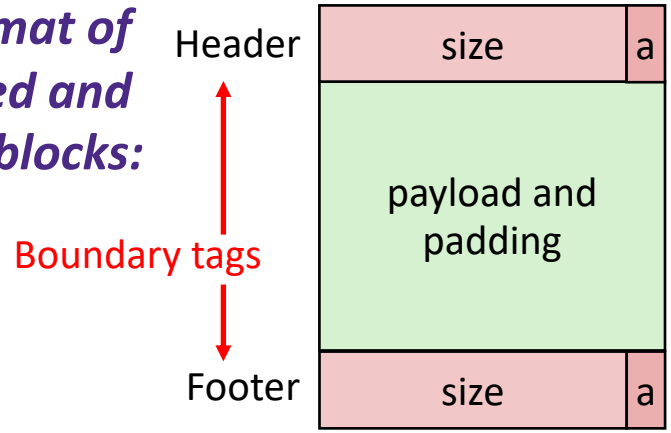

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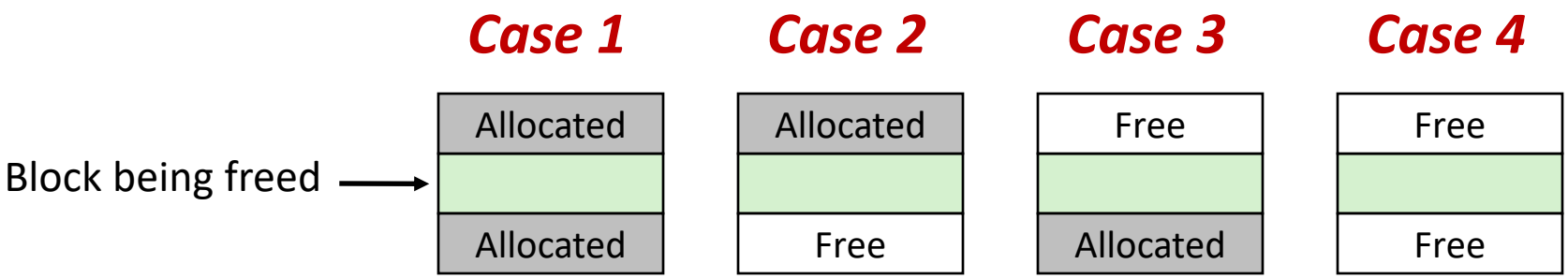
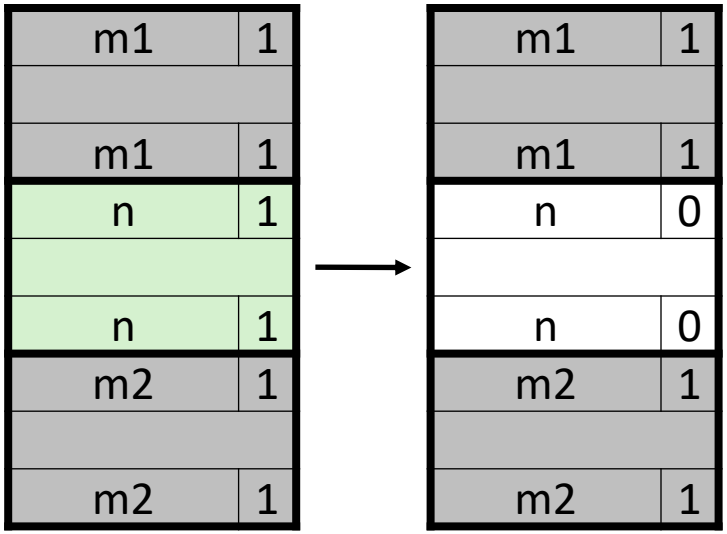
Constant Time Coalescing

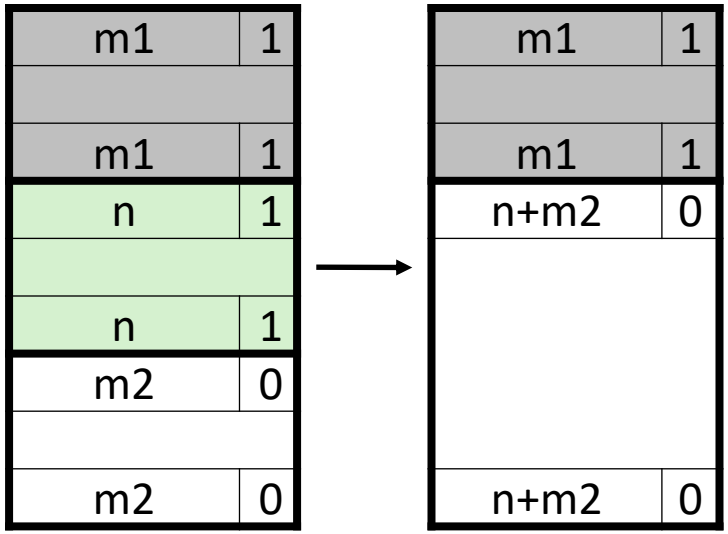


Constant Time Coalescing

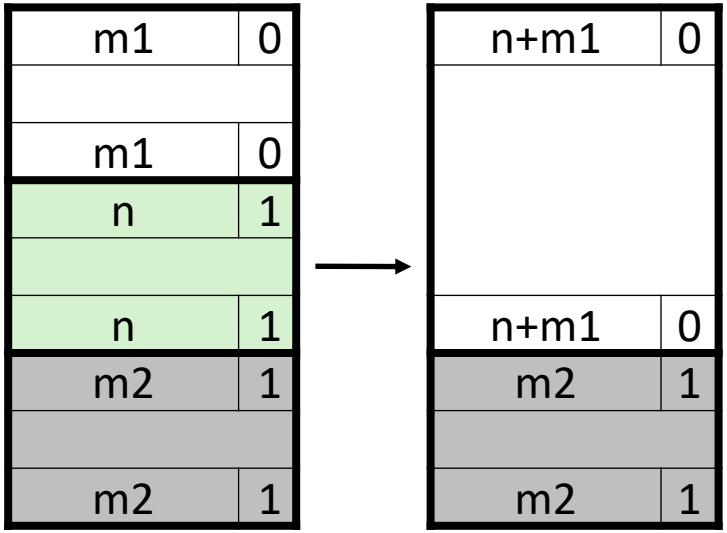
Case 1



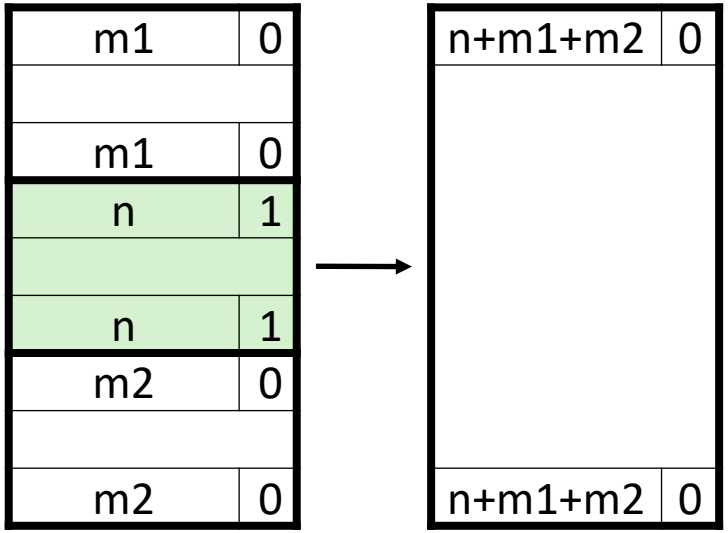
Case 2



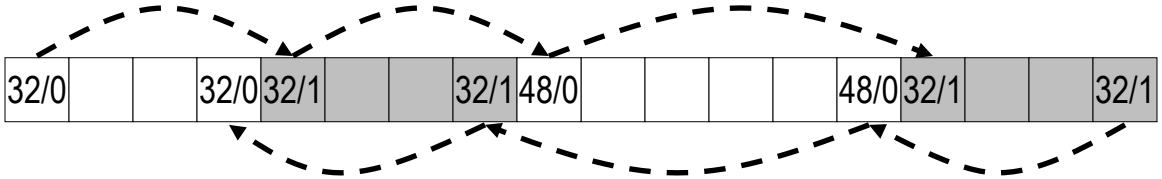
Case 3



Case 4

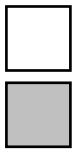


Implicit Free List Review Questions



- 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
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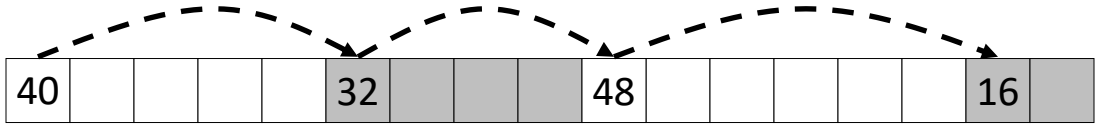

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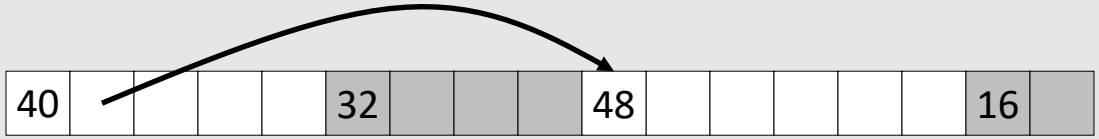
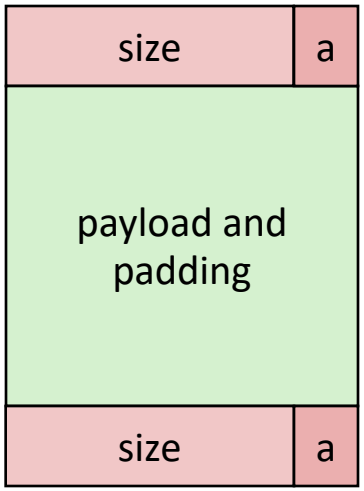


3) *Segregated free list*
   - Different free lists for different size "classes"

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

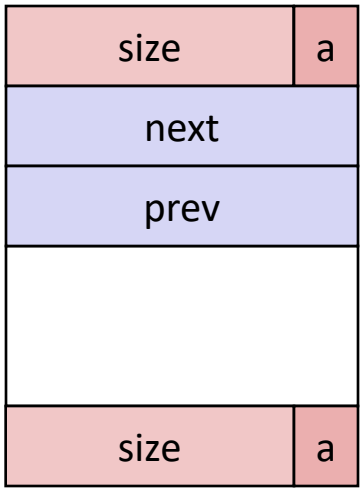
Explicit Free Lists

Allocated block:



(same as implicit free list)

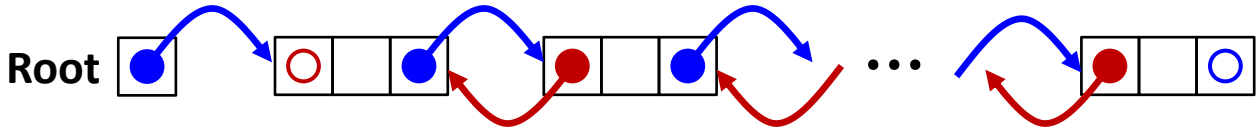
Free block:



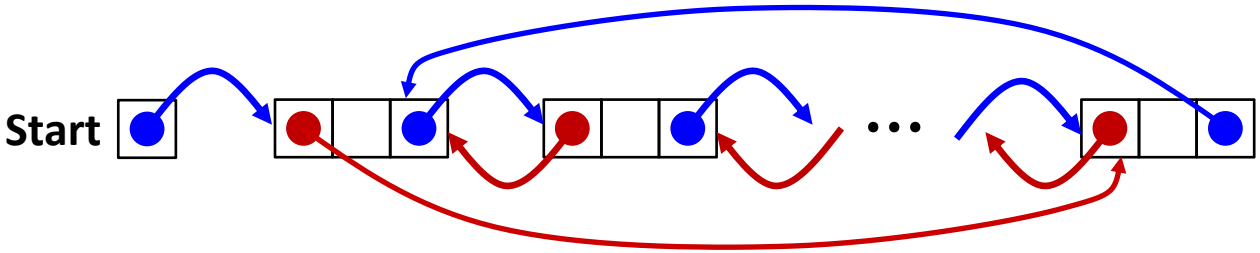
- Use list(s) of *free* blocks, rather than implicit list of *all* blocks
  - The "next" free block could be anywhere in the heap
    - So we need to store next/previous pointers, not just sizes
  - Since we only track free blocks, so we can use "payload" for pointers
  - Still need boundary tags (header/footer)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

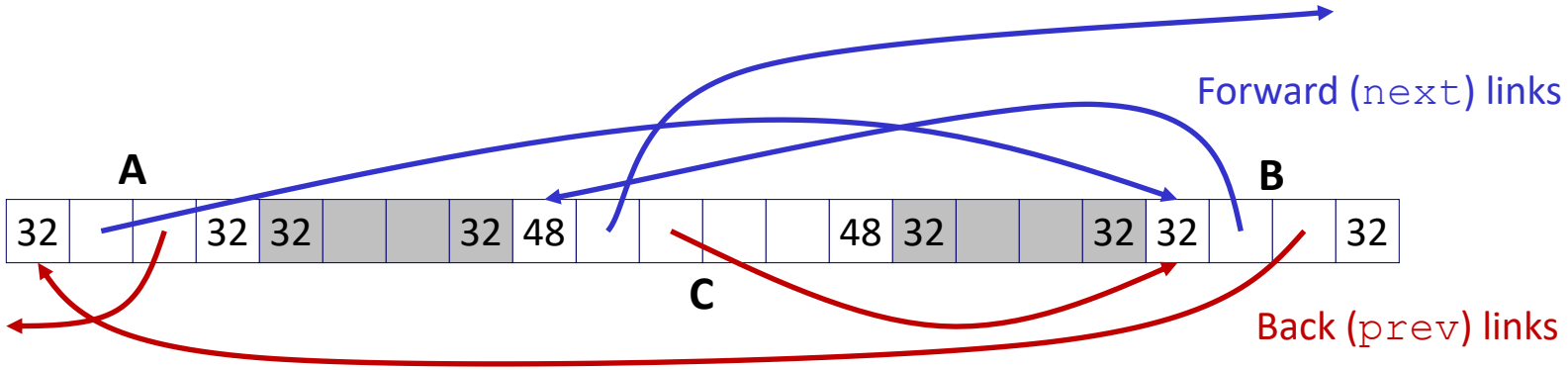


- **Circular**
  - Still have pointer to tell you which node to start with
  - No `NULL` pointers (term condition is back at starting point)
  - Good for next-fit, best-fit

Explicit Free Lists

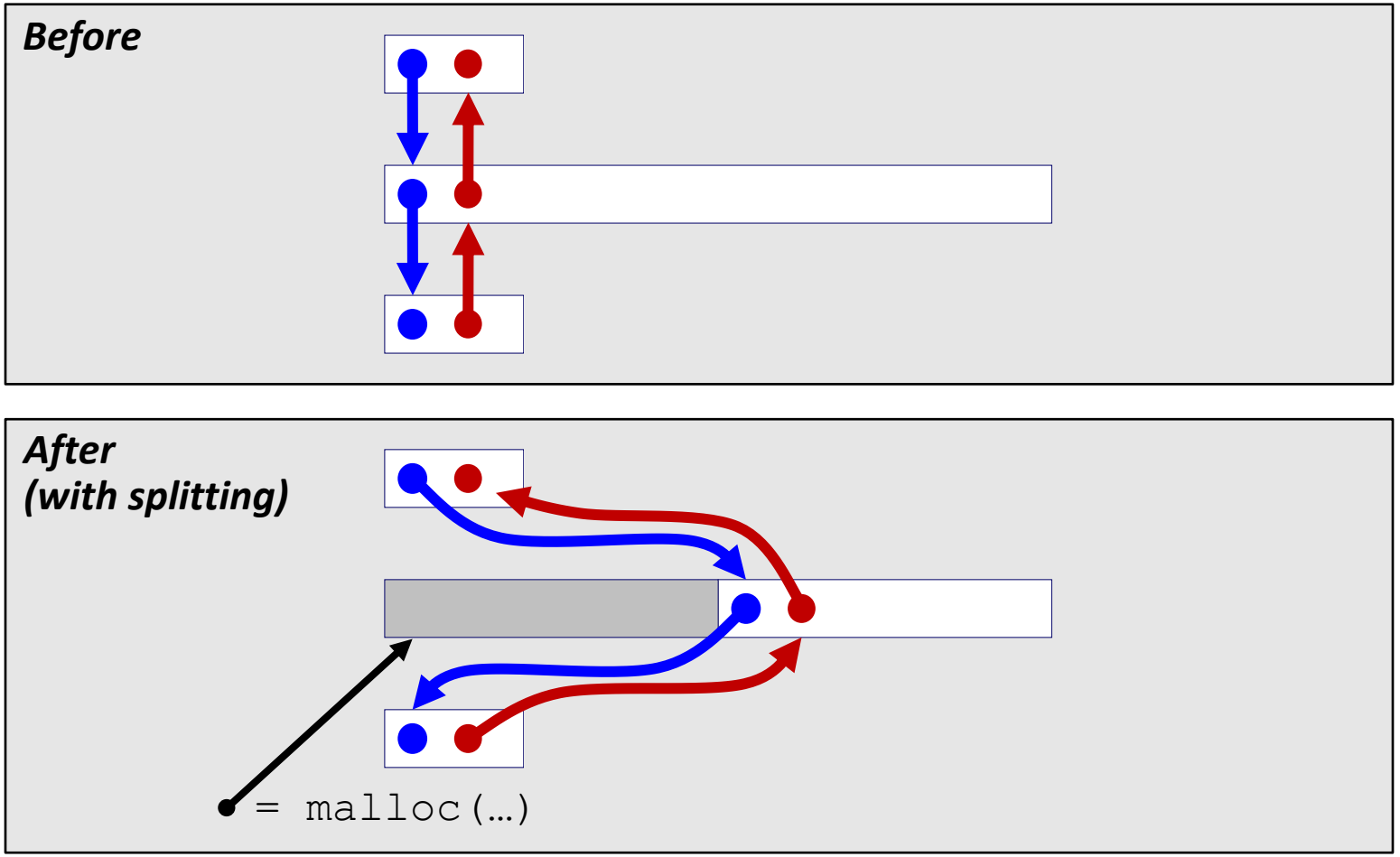
- **Logically:** doubly-linked list

- **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).



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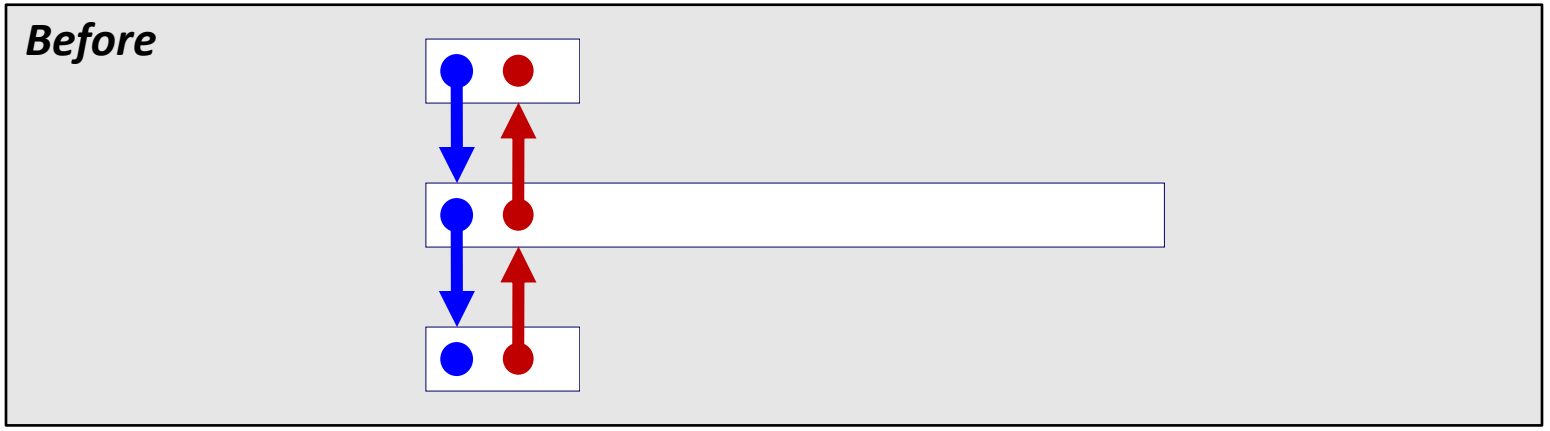
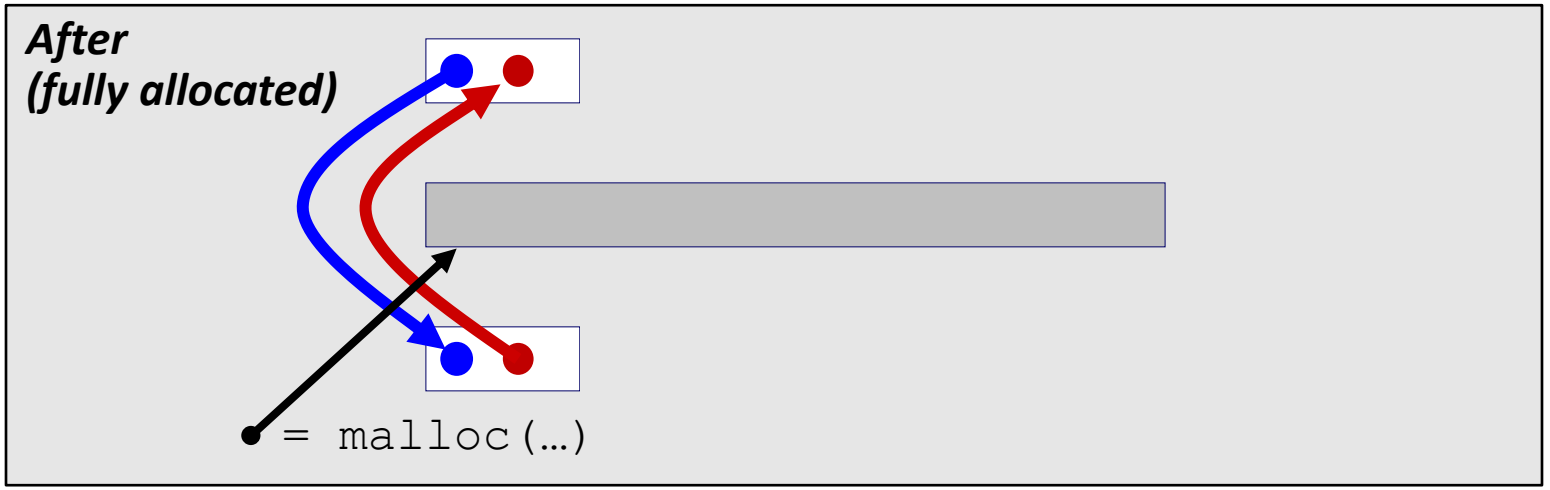


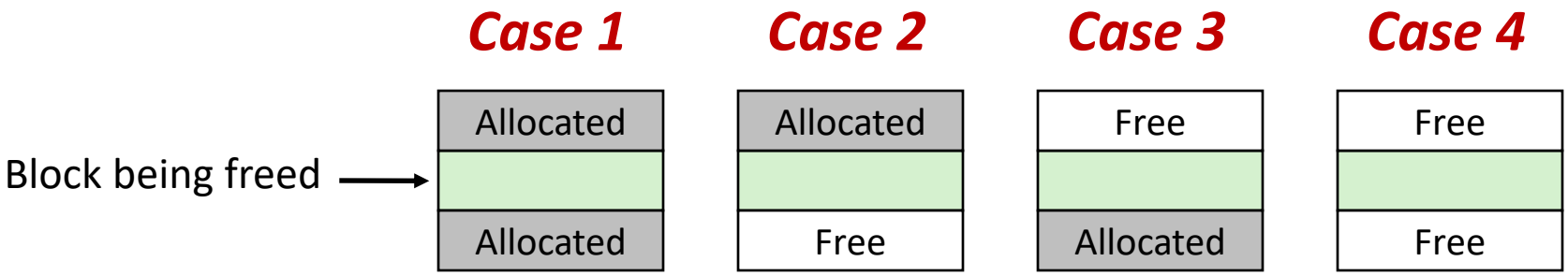


Freeing With Explicit Free Lists

- *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 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 (why?)

Coalescing in Explicit Free Lists



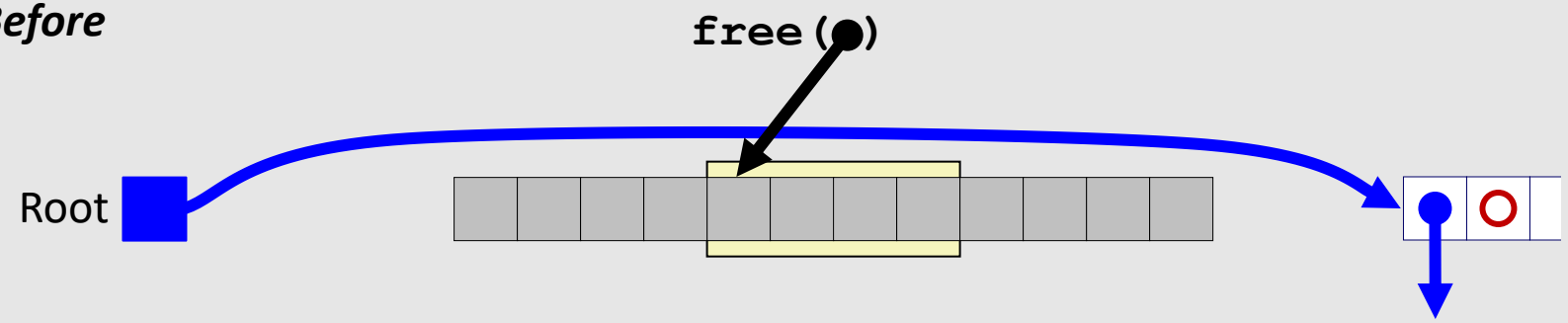
- Neighboring free blocks are *already part of the free list*
  1) Remove old block from free list
  2) Create new, larger coalesced block
  3) Add new block to free list (insertion policy)

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

Freeing with LIFO Policy (Case 1)

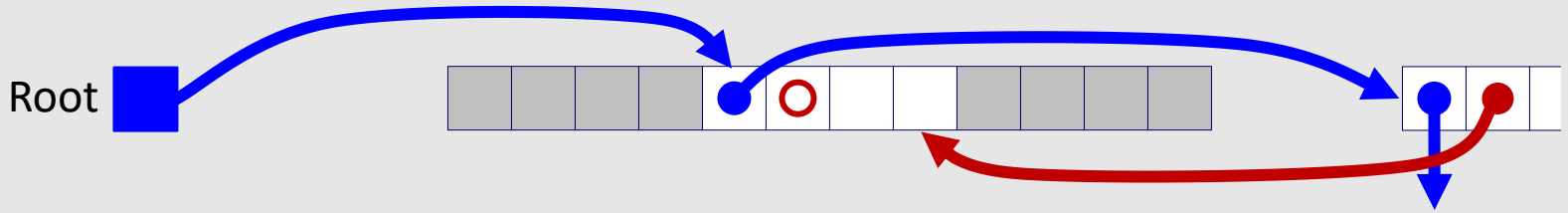
Boundary tags not shown, but don't forget about them!

Before



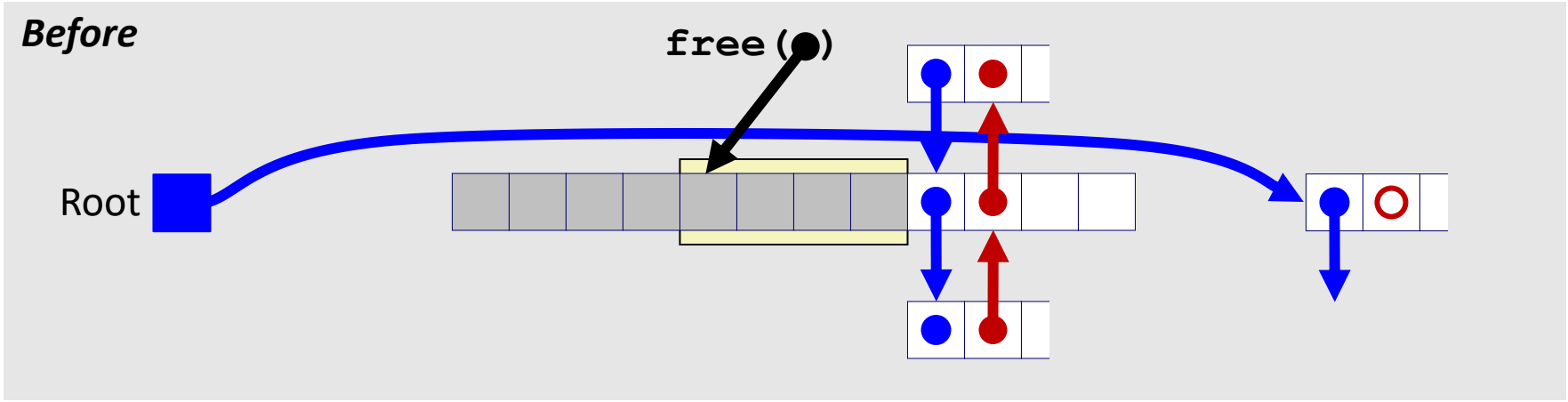
- Insert the freed block at the root of the list

After

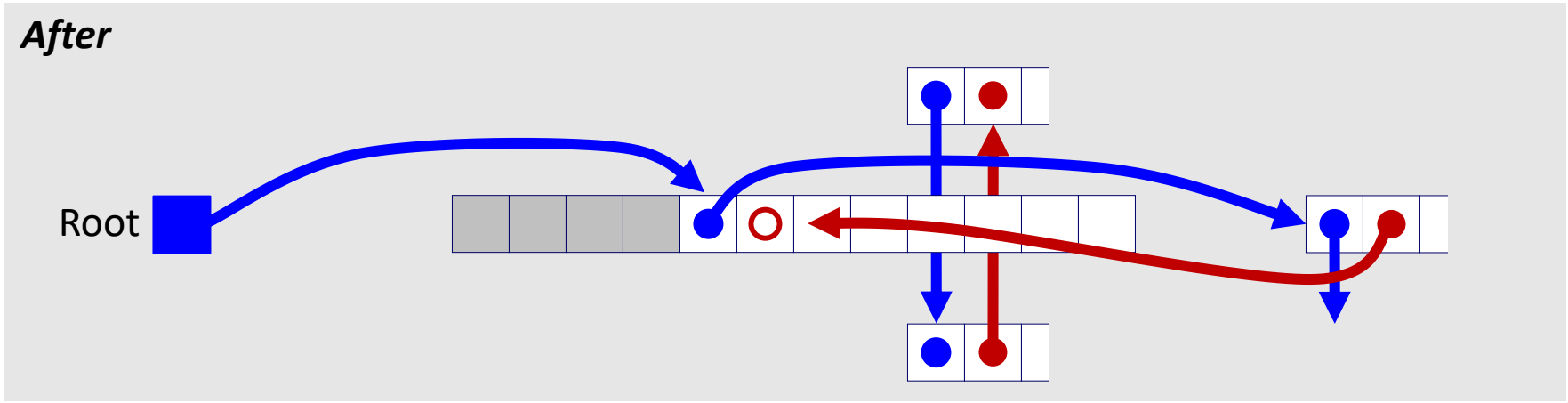


Freeing with LIFO Policy (Case 2)

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

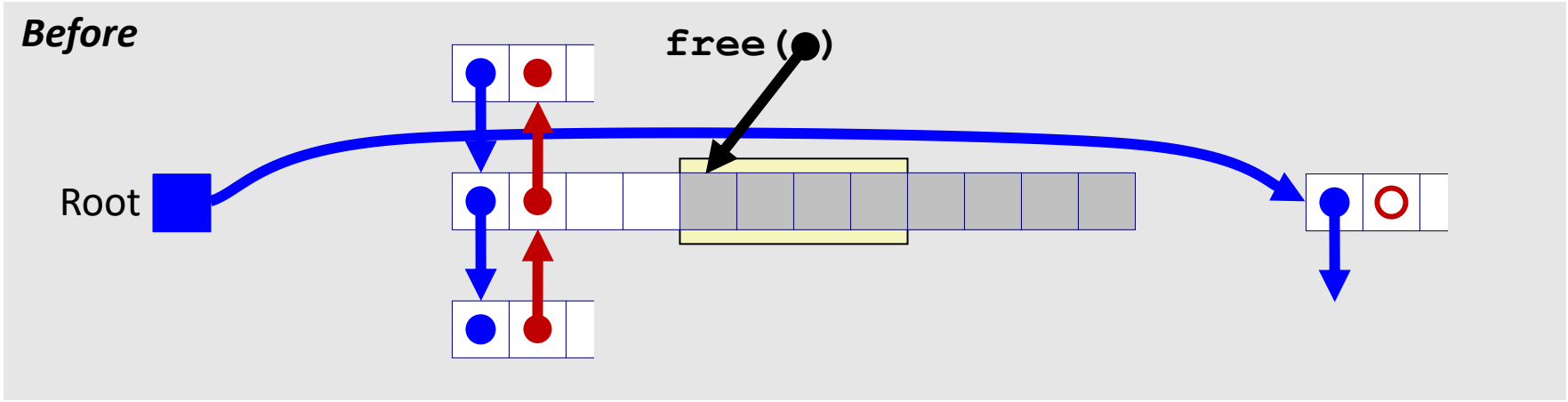


- Splice *following* block out of list, coalesce both memory blocks, and insert the new block at the root of the list

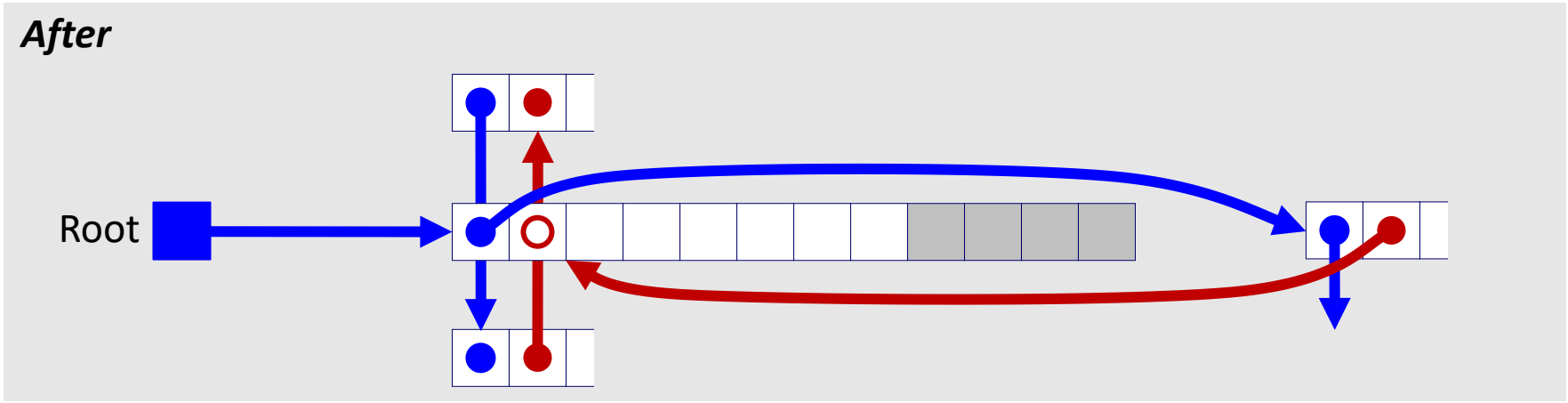


Freeing with LIFO Policy (Case 3)

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

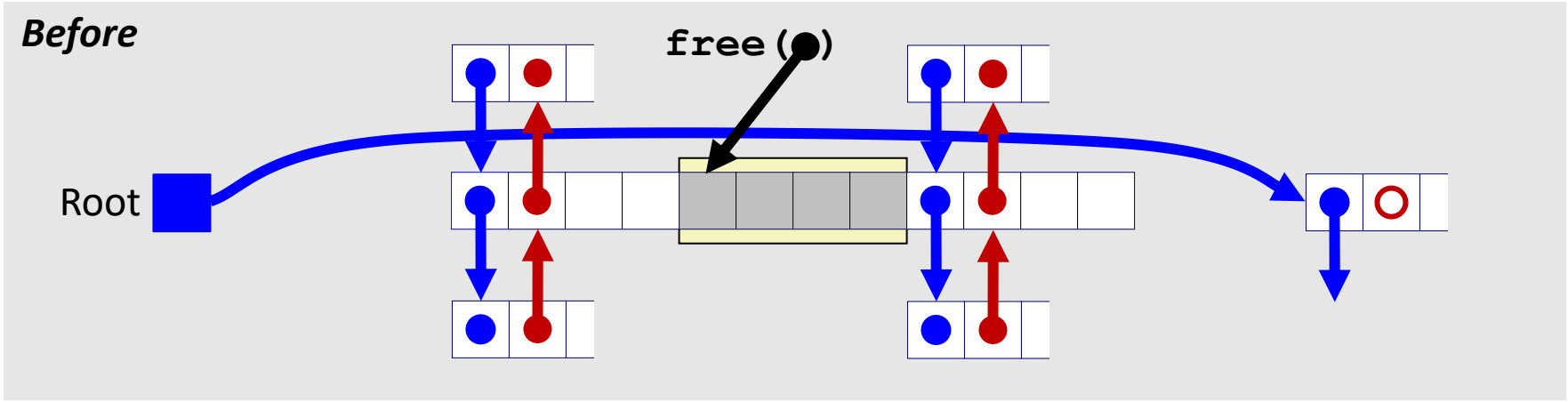


- Splice *preceding* block out of list, coalesce both memory blocks, and insert the new block at the root of the list

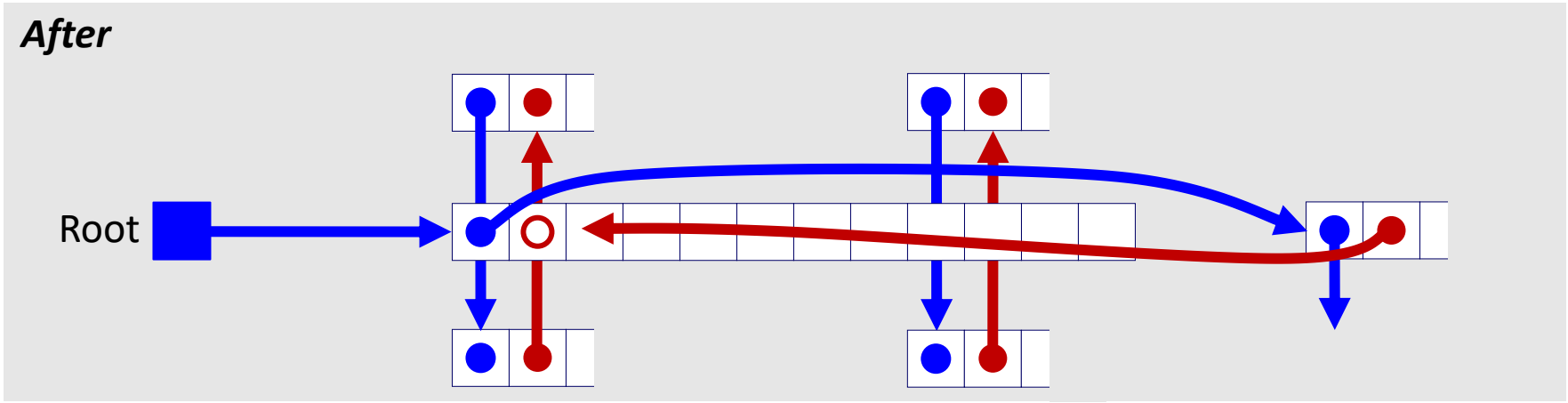


Freeing with LIFO Policy (Case 4)

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

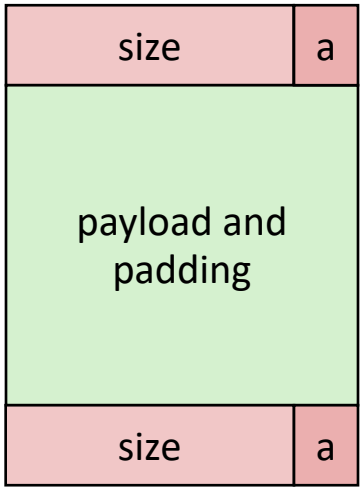


- Splice *preceding* and *following* blocks out of list, coalesce all 3 memory blocks, and insert the new block at the root of the list



Do we always need the boundary tags?

Allocated block:



(same as implicit free list)

Free block:

- Lab 5 suggests no…

Lab 5 Hints

- Struct pointers can be used to access field values, even if no struct instances have been created – just reinterpreting the data in memory
- Pay attention to boundary tag data
  - Size value + 2 tag bits – when do these need to be updated and do they have the correct values?
  - The `examine_heap` function follows the implicit free list searching algorithm – don't take its output as "truth"
- Learn to use and interpret the trace files for testing!!!
- A special heap block marks the end of the heap

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

Allocation Policy Tradeoffs

- Data structure of blocks on lists
  - Implicit (free/allocated), explicit (free), segregated (many free lists) – others possible!
- Placement policy: first-fit, next-fit, best-fit
  - Throughput vs. amount of fragmentation
- When do we split free blocks?
  - How much internal fragmentation are we willing to tolerate?

More Info on Allocators

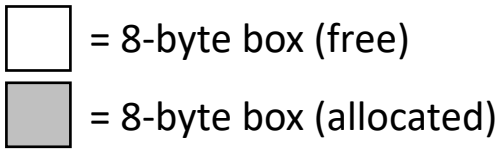
- D. Knuth, "*The Art of Computer Programming*", 2nd edition, Addison Wesley, 1973
  - The classic reference on dynamic storage allocation

- 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)

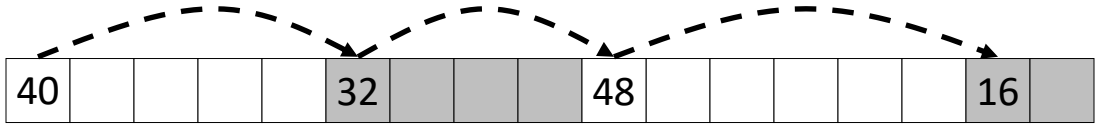
BONUS SLIDES

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

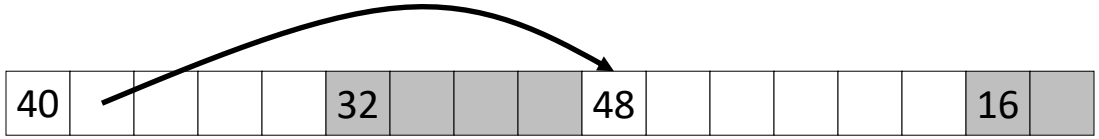
Keeping Track of Free Blocks



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

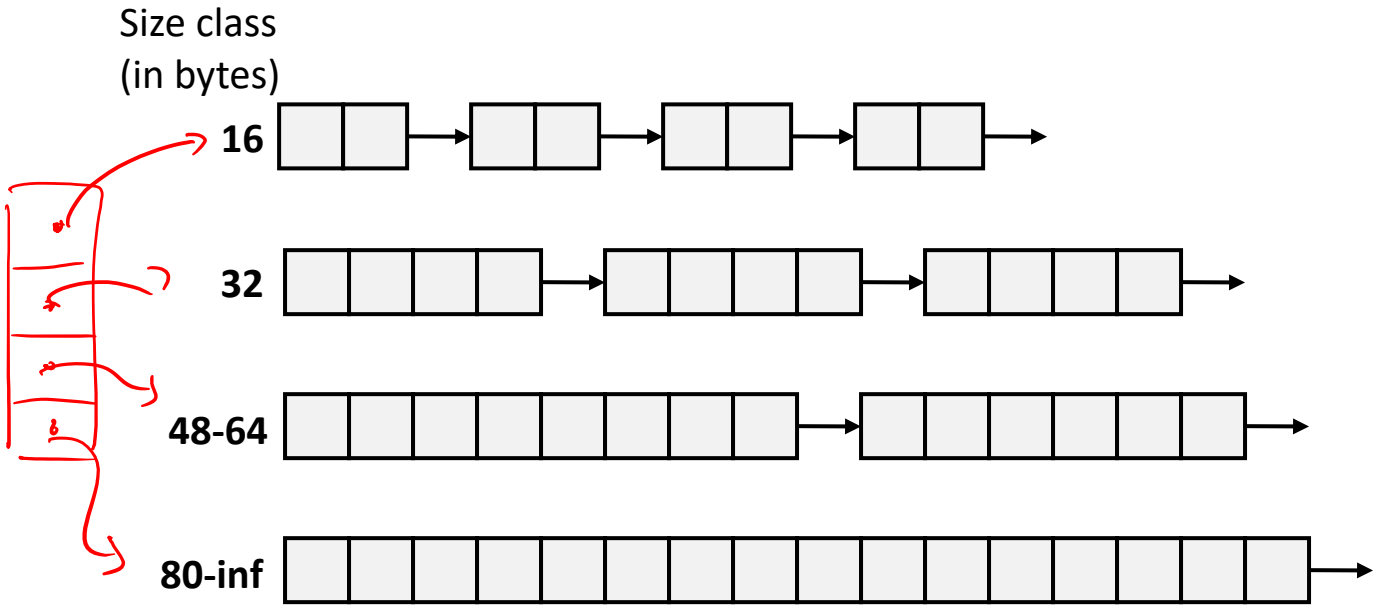


3) *Segregated free list*
   - Different free lists for different size "classes"

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