Memory Allocation II

CSE 351 Autumn 2021

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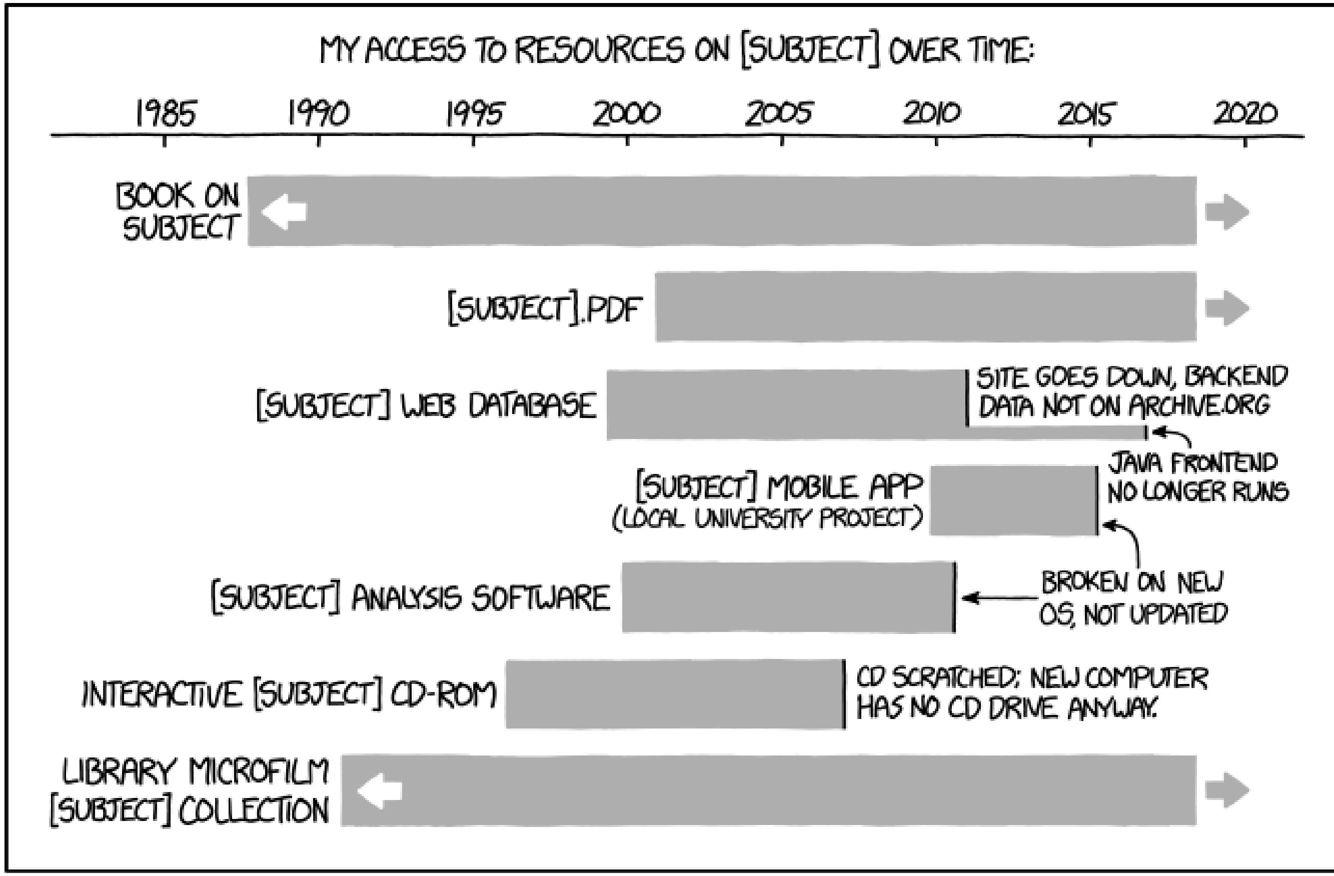


IT'S UNSETTLING TO REALIZE HOW QUICKLY DIGITAL RESOURCES CAN DISAPPEAR WITHOUT ONGOING WORK TO MAINTAIN THEM.

http://xkcd.com/1909/

Relevant Course Material

- hw25 due Friday, hw26 due next Wednesday (12/8)
- Lab 5 due next Friday (12/10)
  - 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
- **Final Exam:** 12/13-15
  - Final review section on 12/9, final review session on 12/11?

Reading Review

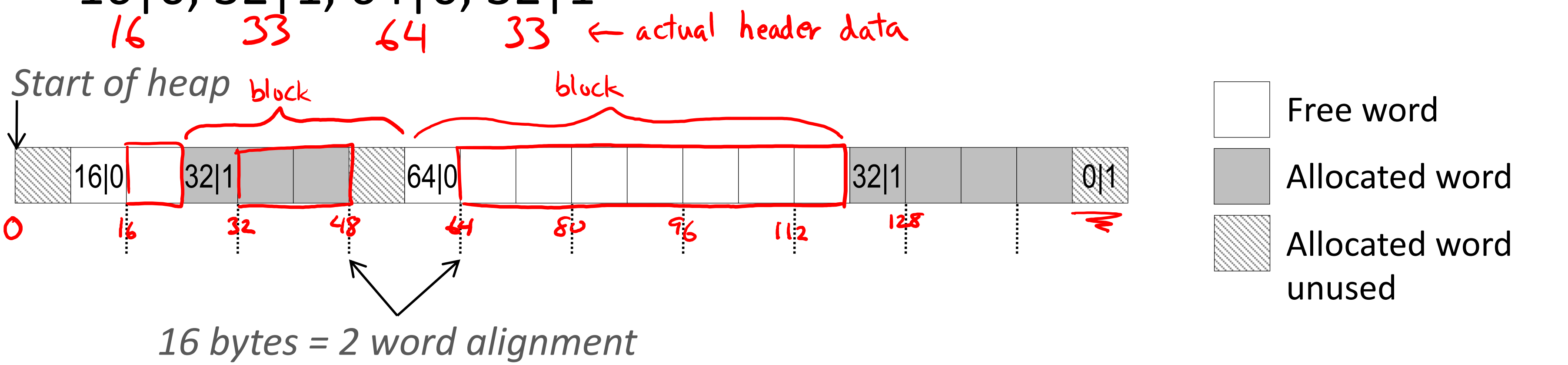
- Terminology:
  - Allocation strategies: first fit, next fit, best fit
  - Allocating a block: splitting, minimum block size
  - Freeing a block: coalescing
  - Boundary tags: header and footer
  - Explicit free list

- Questions from the Reading?

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



- 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

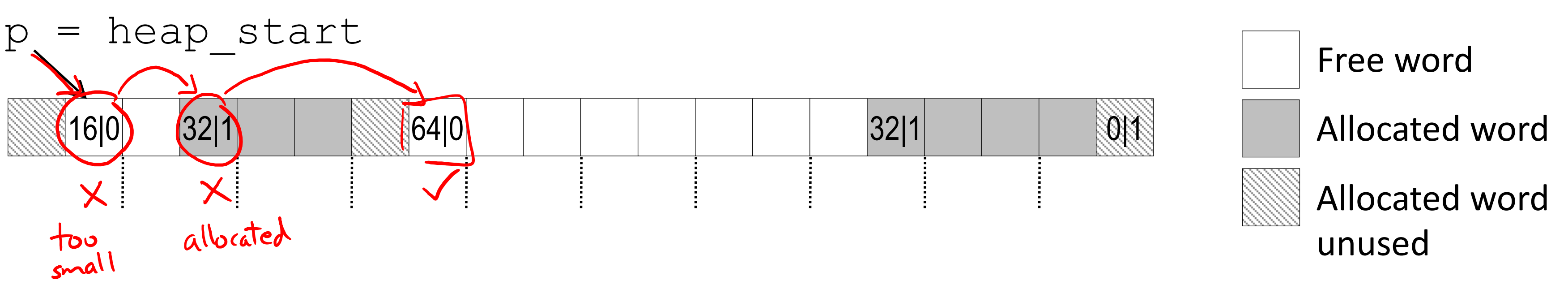
(*p) gets the block *header*
(*p & 1) extracts the `allocated` bit
(*p & -2) extracts the `size`

- *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
```

equivalent to pointer arithmetic with char *
after loop exits

  - Can take time linear in total number of blocks O(n)
  - 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

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:

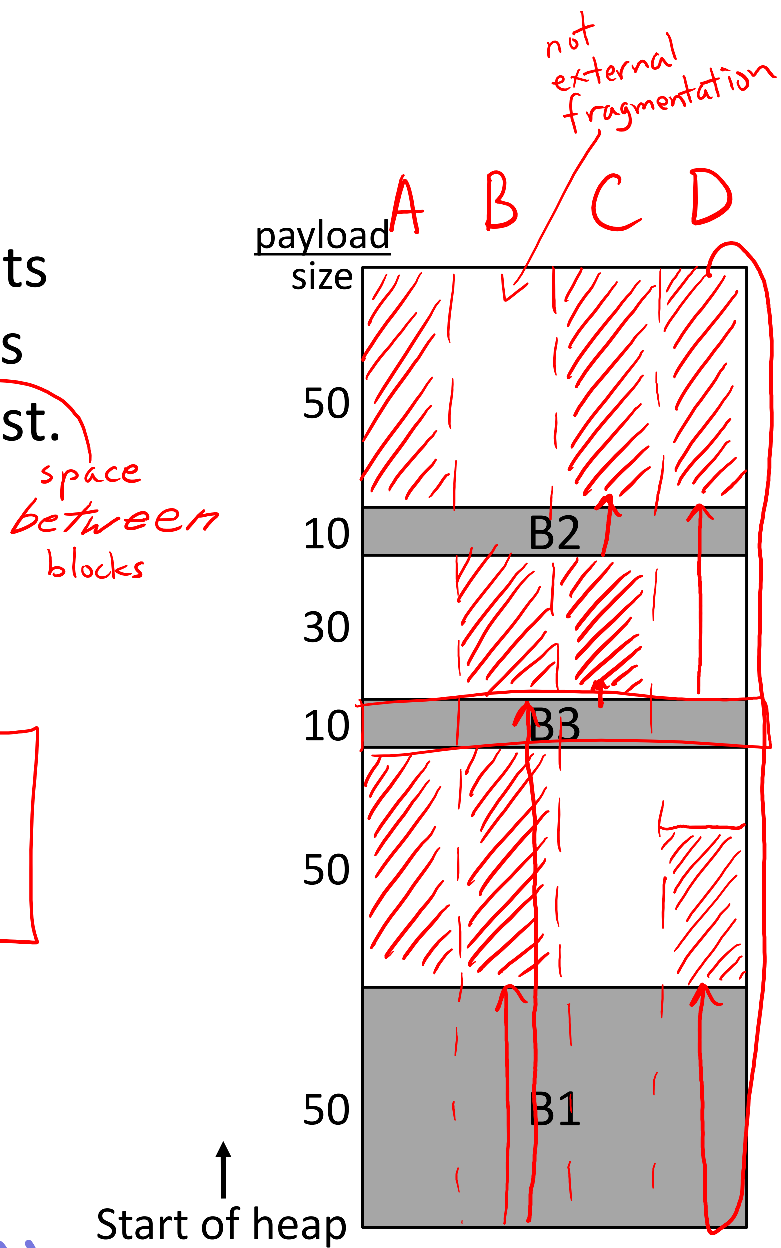
`malloc(50),malloc(30)`

(C) Next-fit:

`malloc(30),malloc(50)`

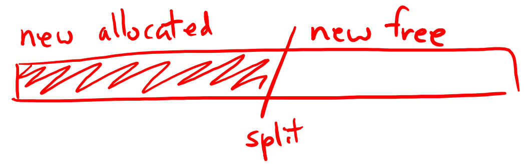
(D) Next-fit:

`malloc(50),malloc(30)`



Implicit List: Allocating in a Free Block

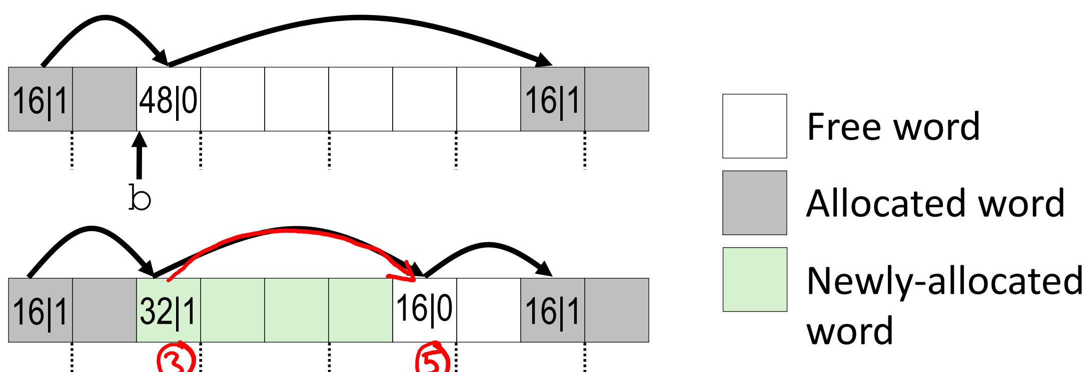
- Allocating in a free block: *splitting*
  - Since allocated space might be smaller than free space, we might want to split the block



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

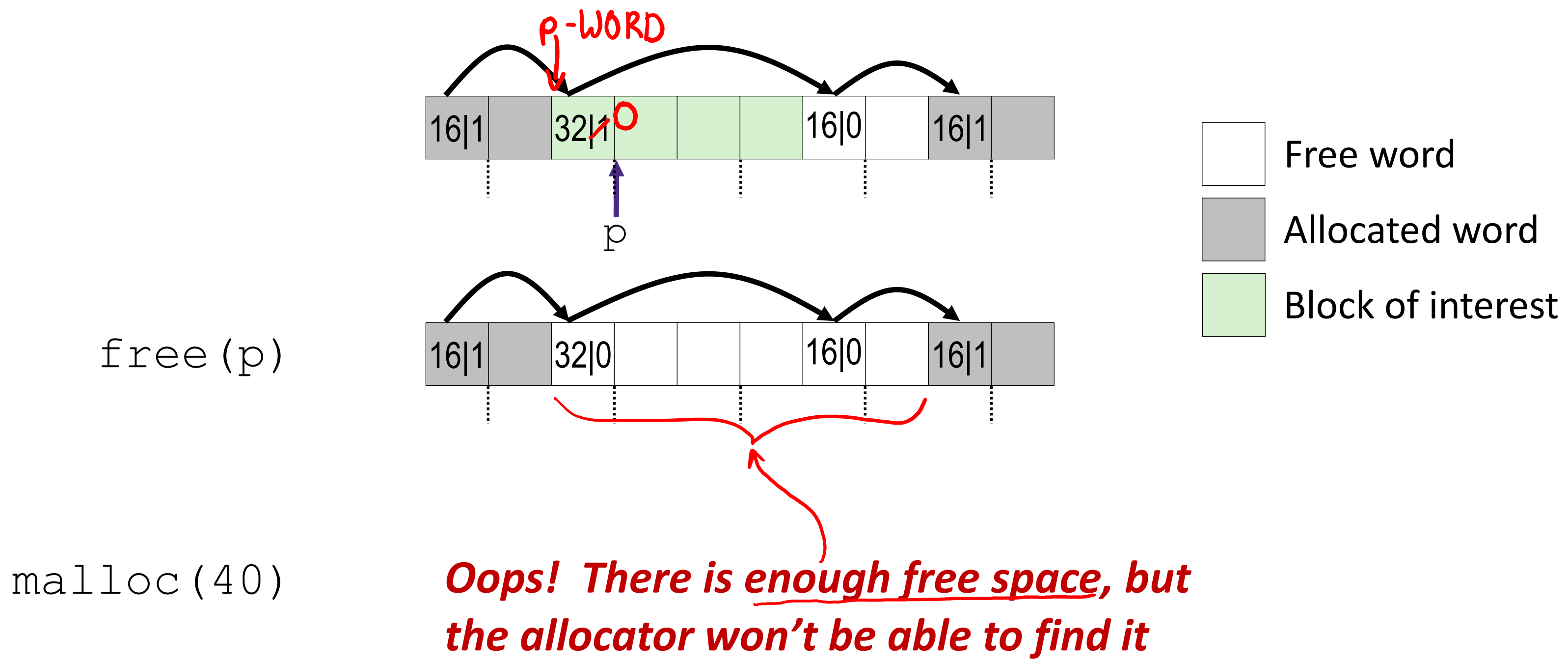
```
void split(ptr b, int bytes) {                // bytes = desired block size
  int newsize = ((bytes+15) >> 4) << 4;       // round up to multiple of 16
  int oldsize = *b;                           // why not mask out low bit?
  *b = newsize;                               // initially unallocated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



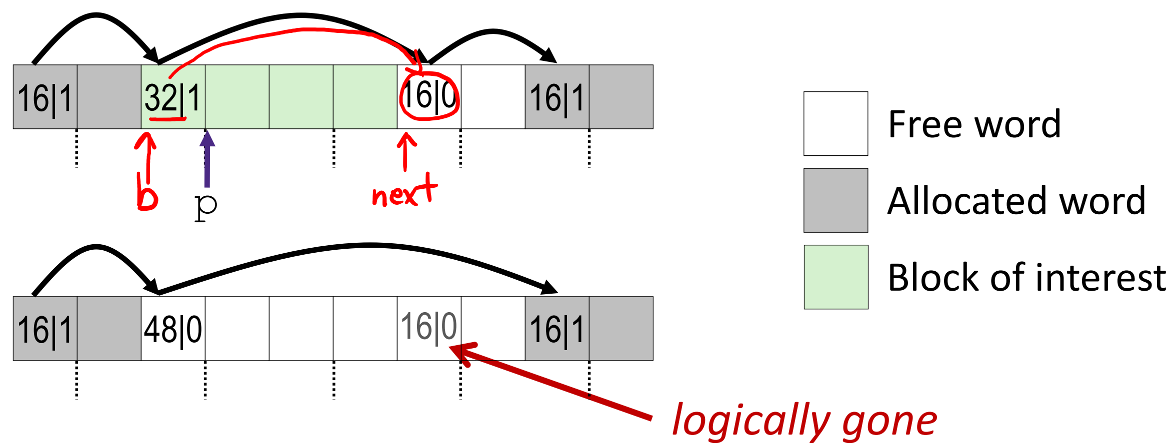
Implicit List: Freeing a Block

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



Implicit List: Coalescing with Next

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



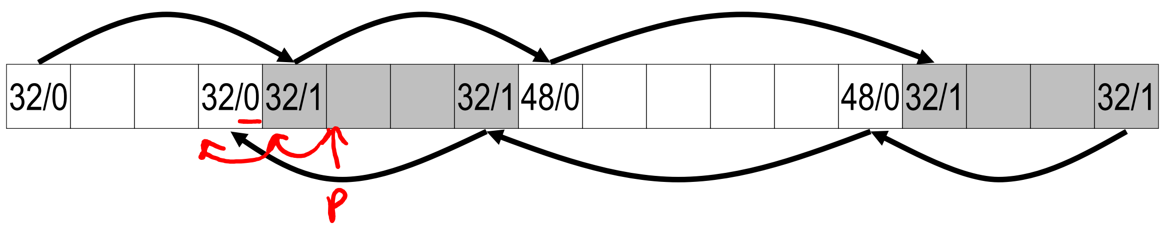
`free(p)`

```
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
}
```

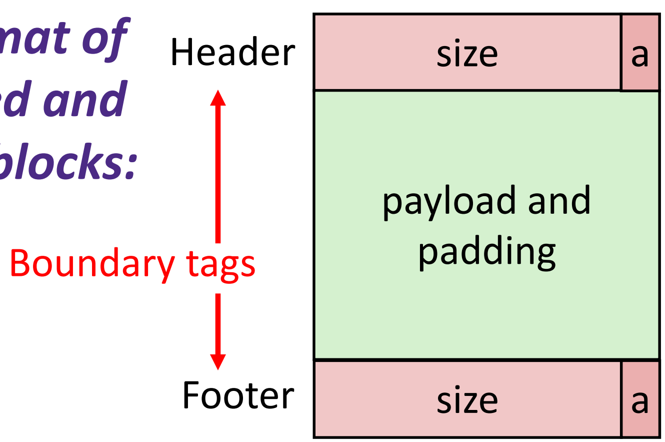
- How do we coalesce with the *preceding* block? we can't currently

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:

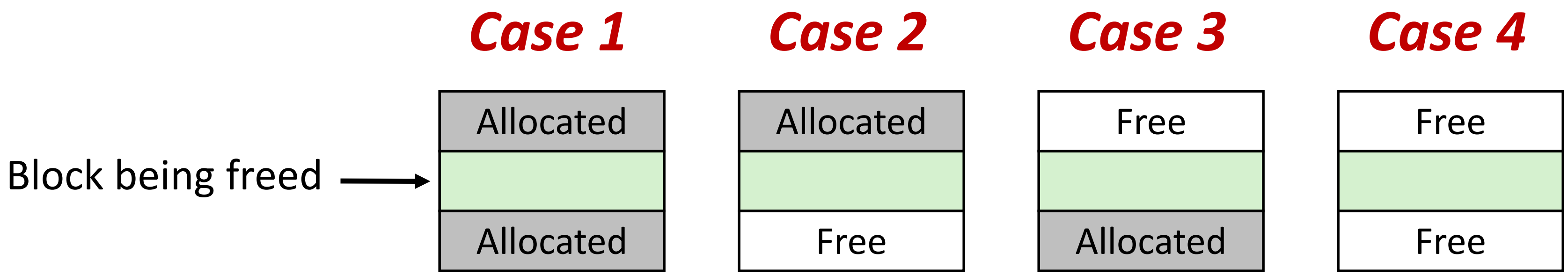


a = 1: allocated block
a = 0: free block

size: block size (in bytes)

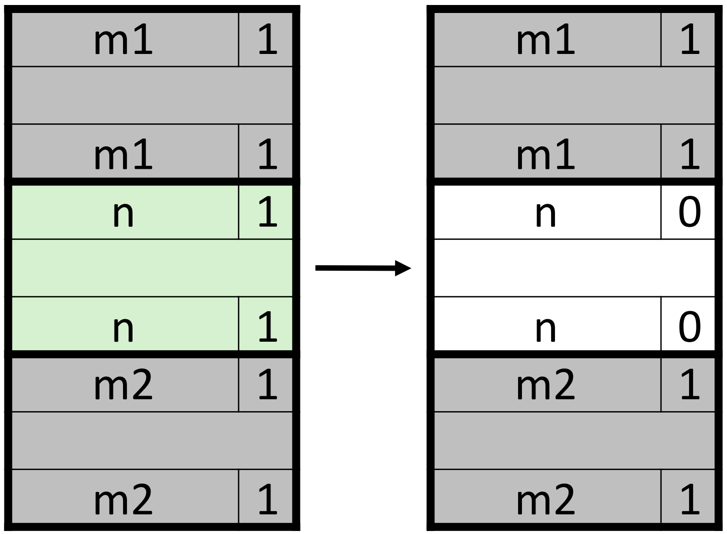
payload: application data (allocated blocks only)

Constant Time Coalescing

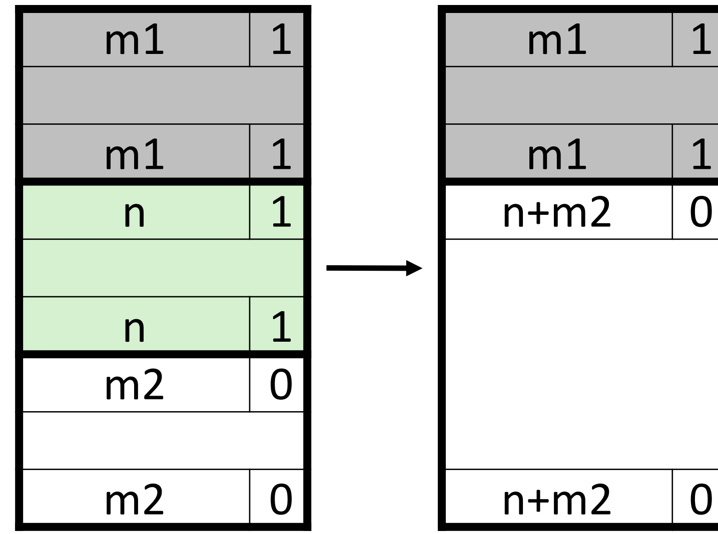


Constant Time Coalescing

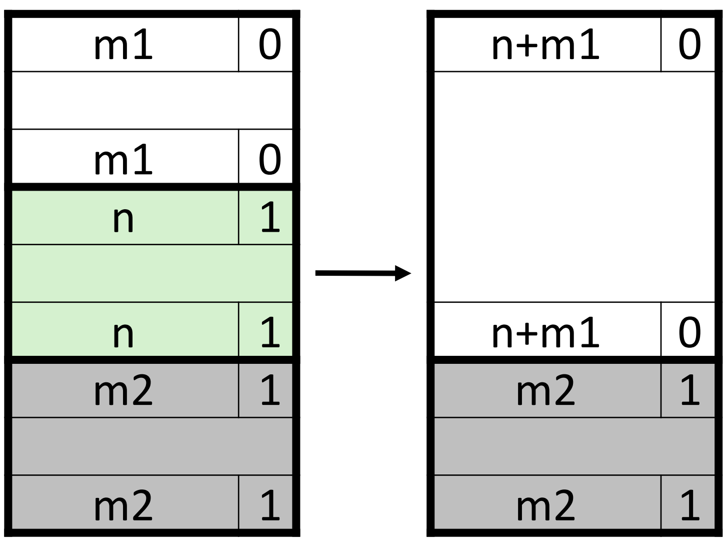
Case 1



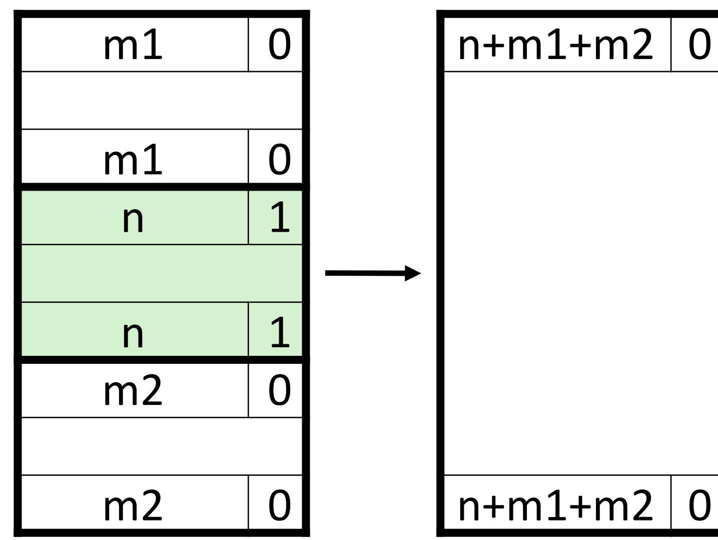
Case 2



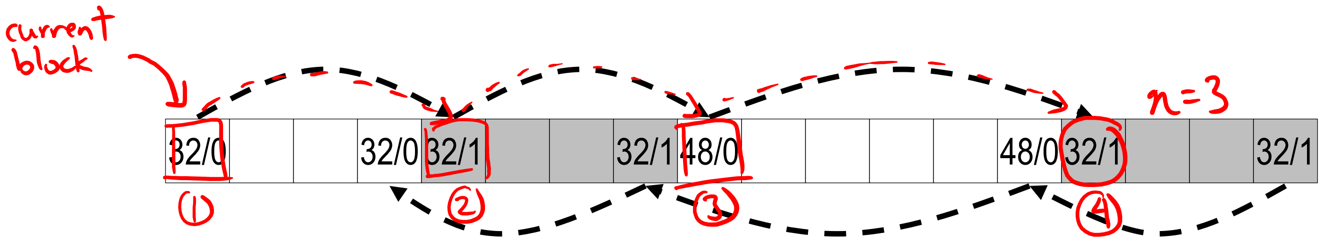
Case 3



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?

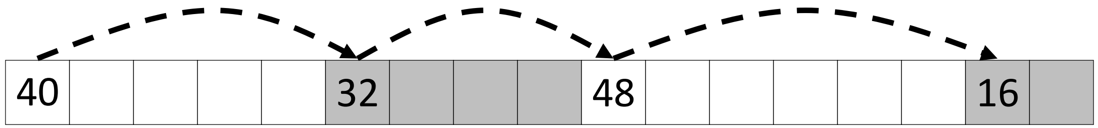
  n+1: need to read current block's header as well as header of target block to get the size

Keeping Track of Free Blocks

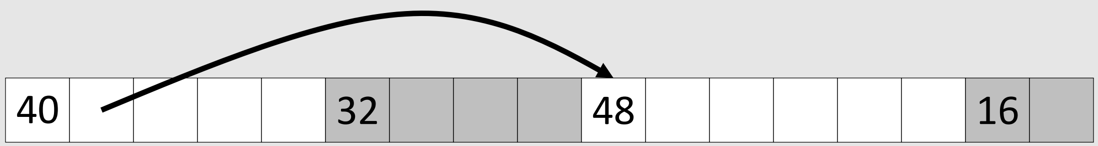
= 8-byte word (free)

= 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

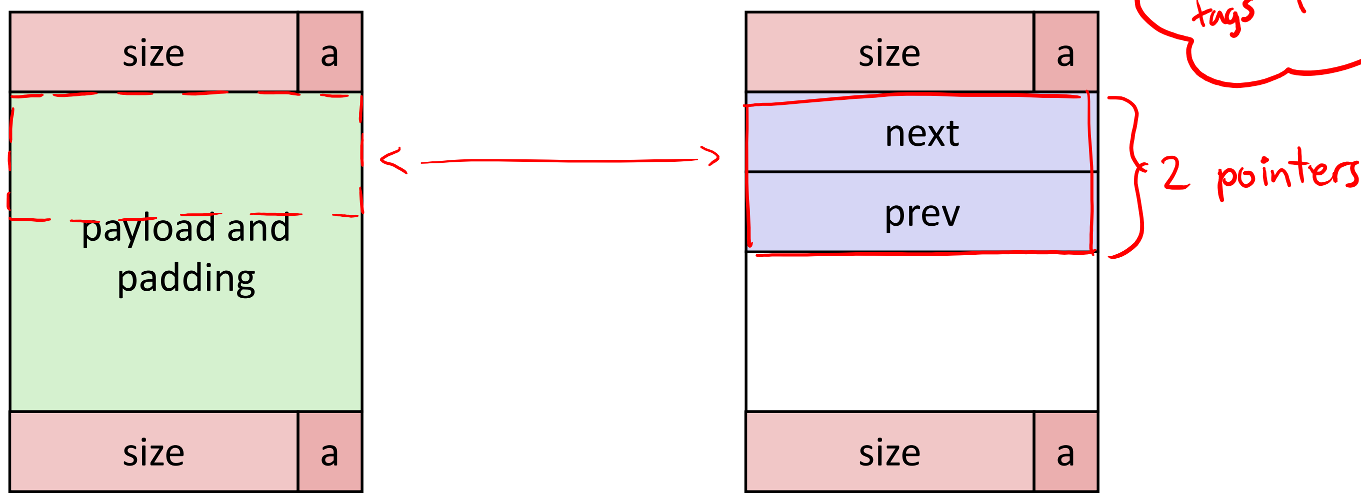


3) *Segregated free list*
   - Different free lists for different size "classes"

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: **Free block:**

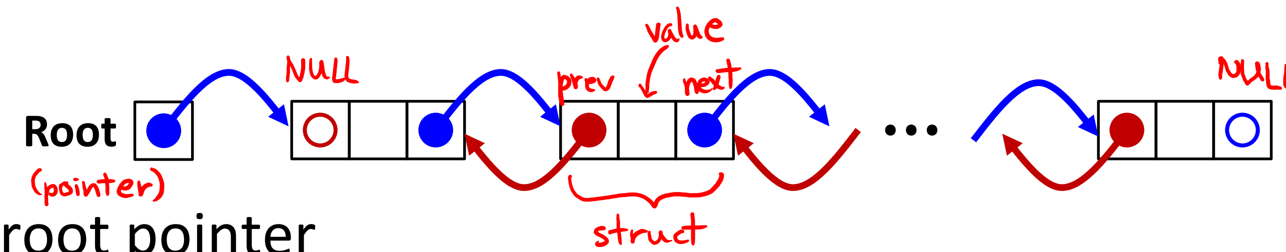


(same as implicit free list)

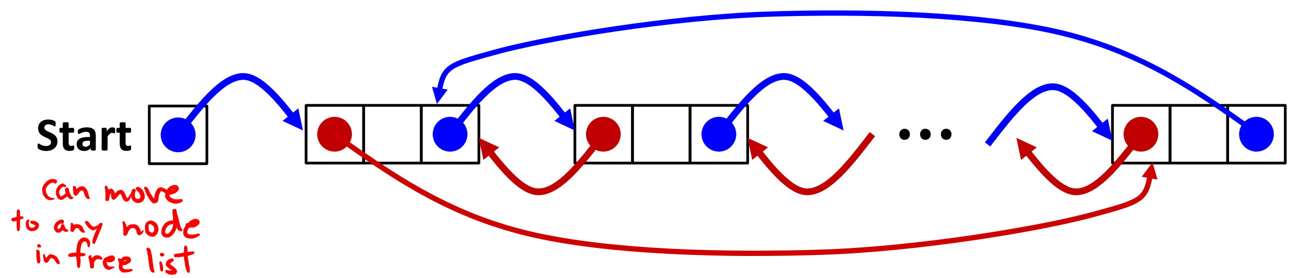
- Use list(s) of *free* blocks, rather than implicit list of *all* blocks
  - The "next" free block could be anywhere in the heap
    - So we need to store next/previous pointers, not just sizes
  - Since we only track free blocks, so we can use "payload" for pointers
  - Still need boundary tags (header/footer)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

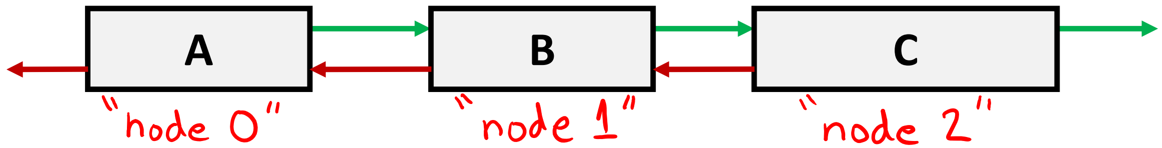


Circular

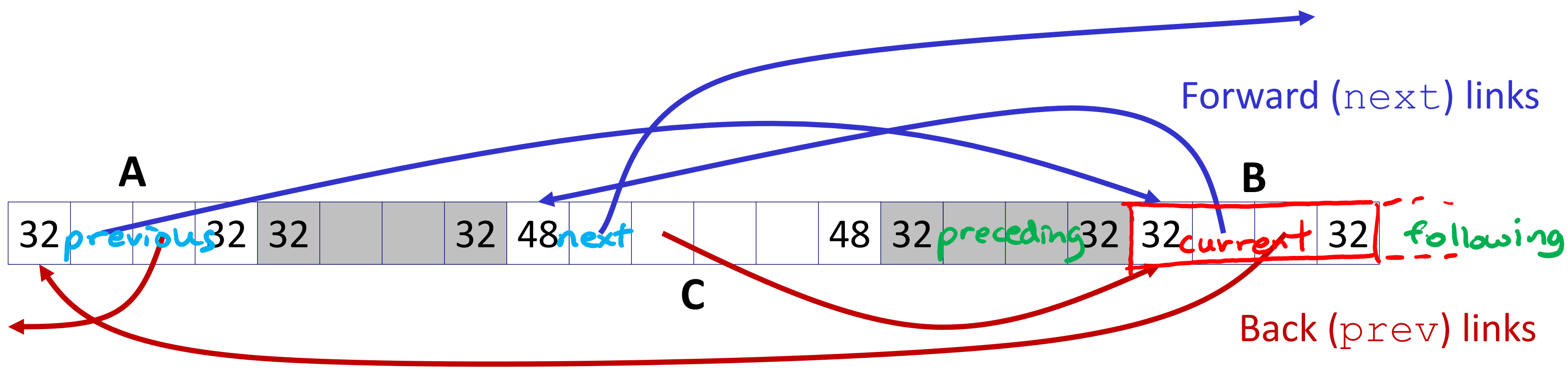
- Still have pointer to tell you which node to start with
- No NULL pointers (term condition is back at starting point)
- Good for next-fit, best-fit

Explicit Free Lists

- **Logically:** doubly-linked list



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

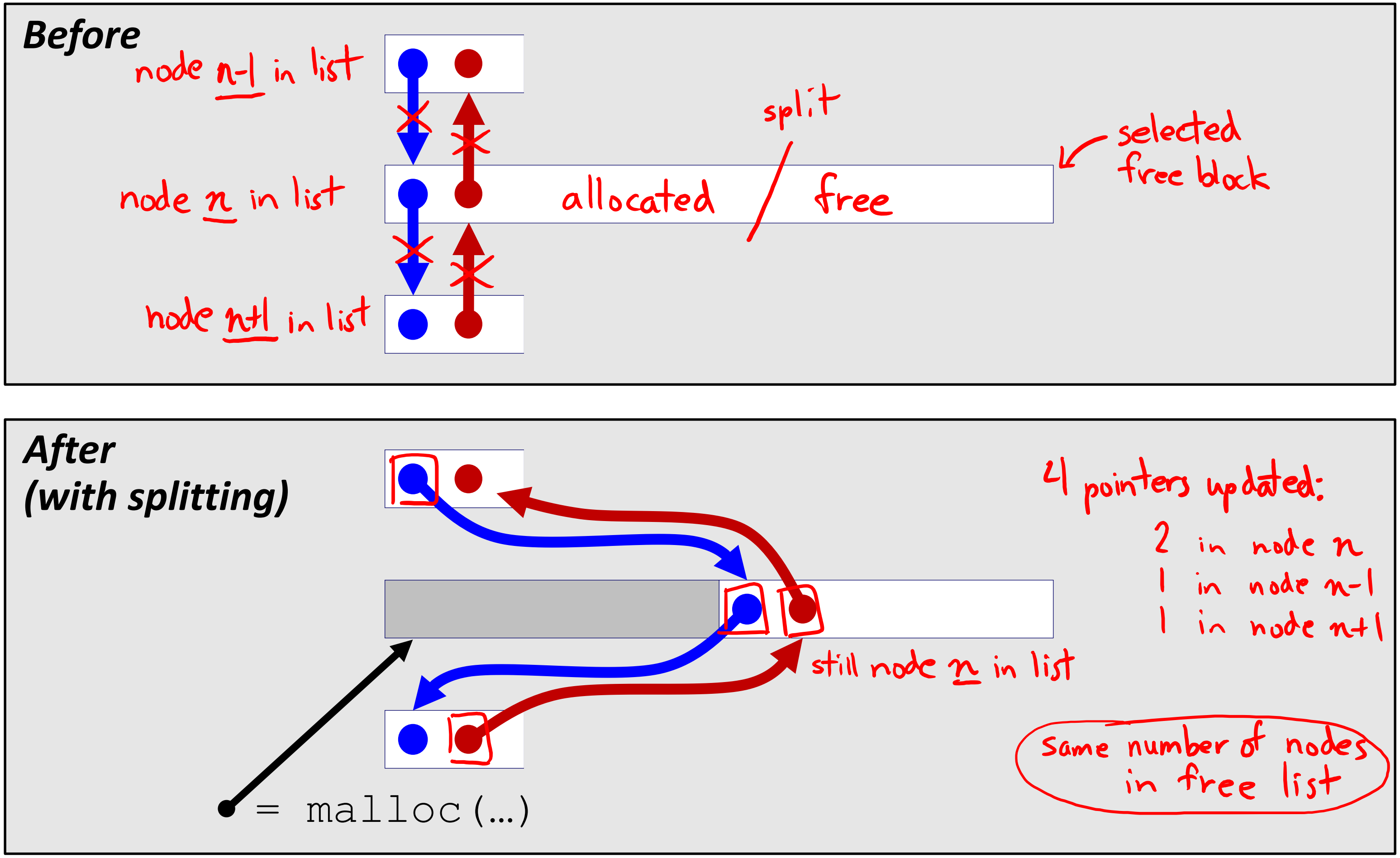


previous/next blocks are part of free list

preceding/following blocks are physical neighbors

Allocating From Explicit Free Lists

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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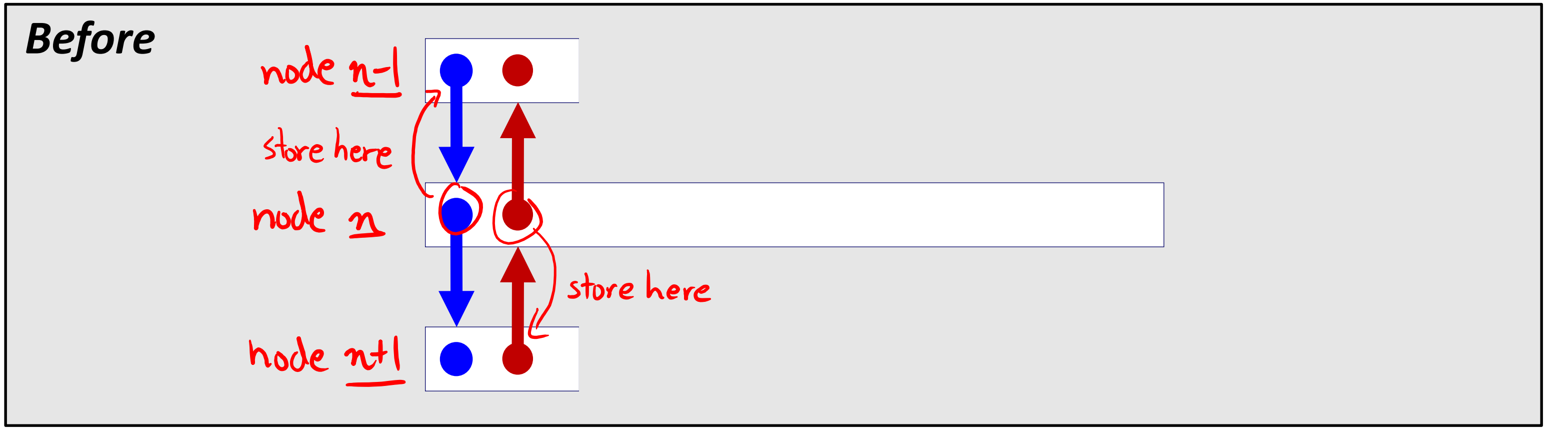
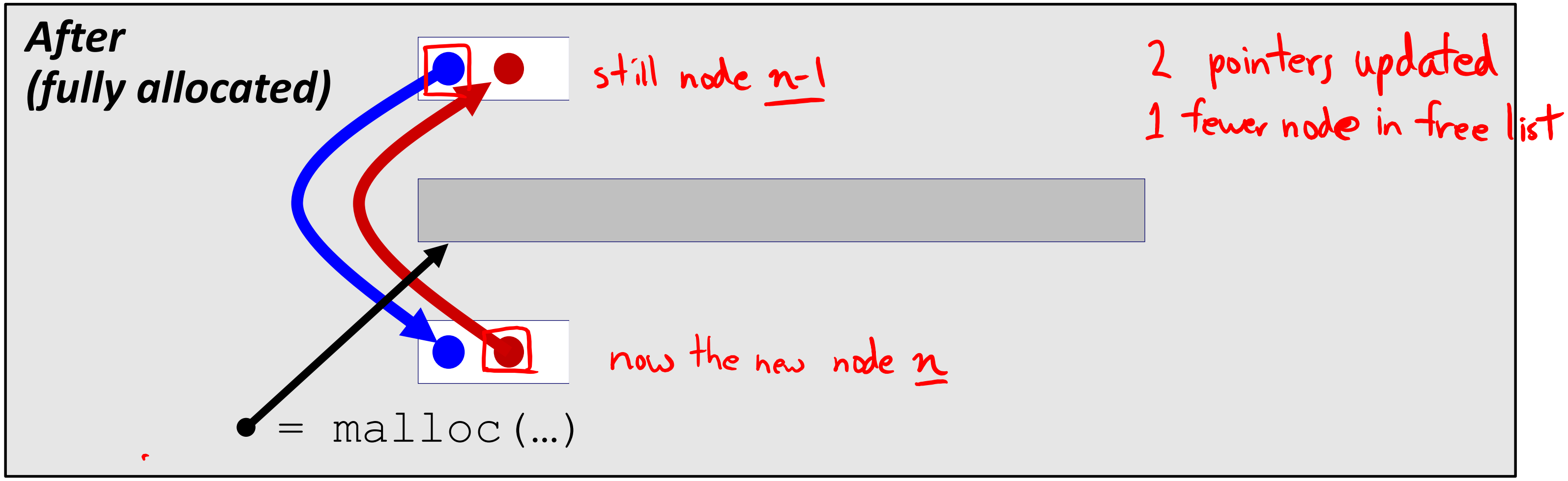


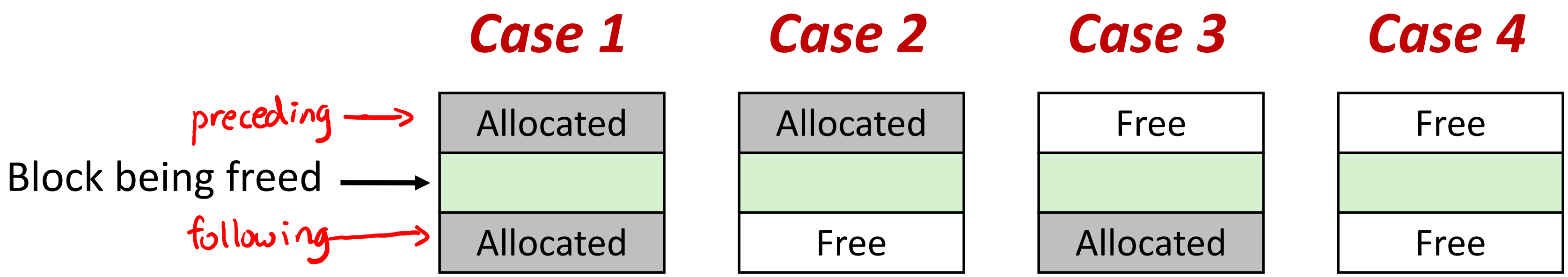


Freeing With Explicit Free Lists

- *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

Coalescing in Explicit Free Lists



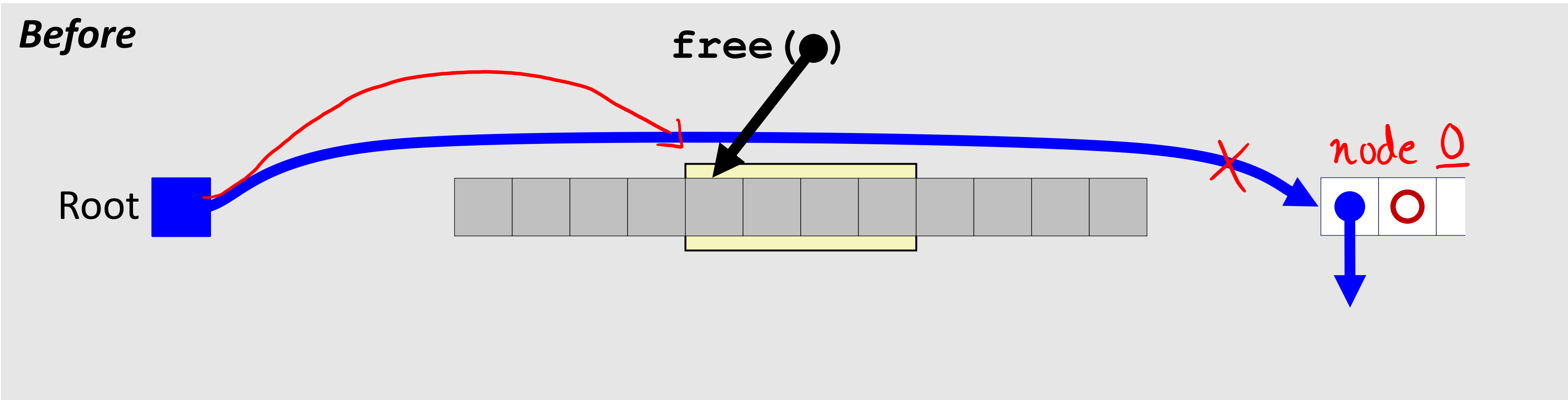
- Neighboring free blocks are *already part of the free list*
  1) Remove old block from free list
  2) Create new, larger coalesced block
  3) Add new block to free list (insertion policy)

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

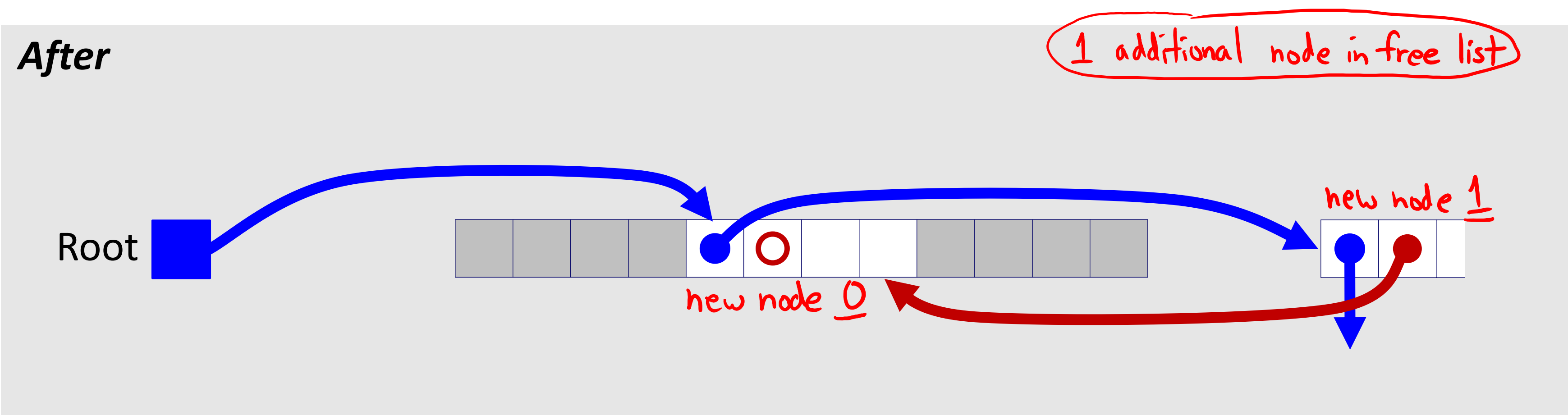
  can still use boundary tags (don't need to search free list). other implementations possible (see Lab5)

Freeing with LIFO Policy (Case 1)

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

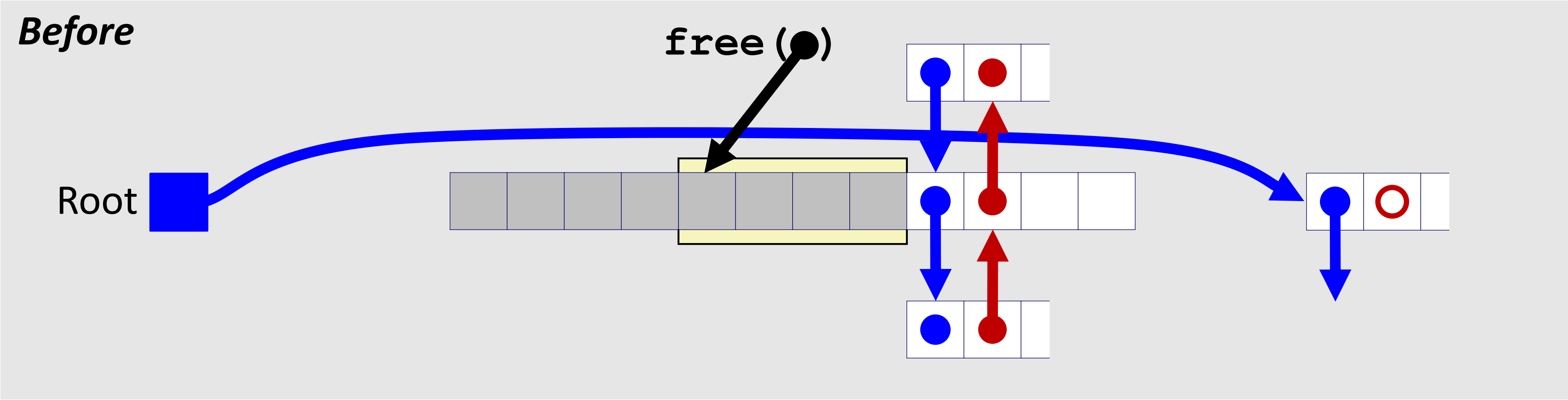


- Insert the freed block at the root of the list

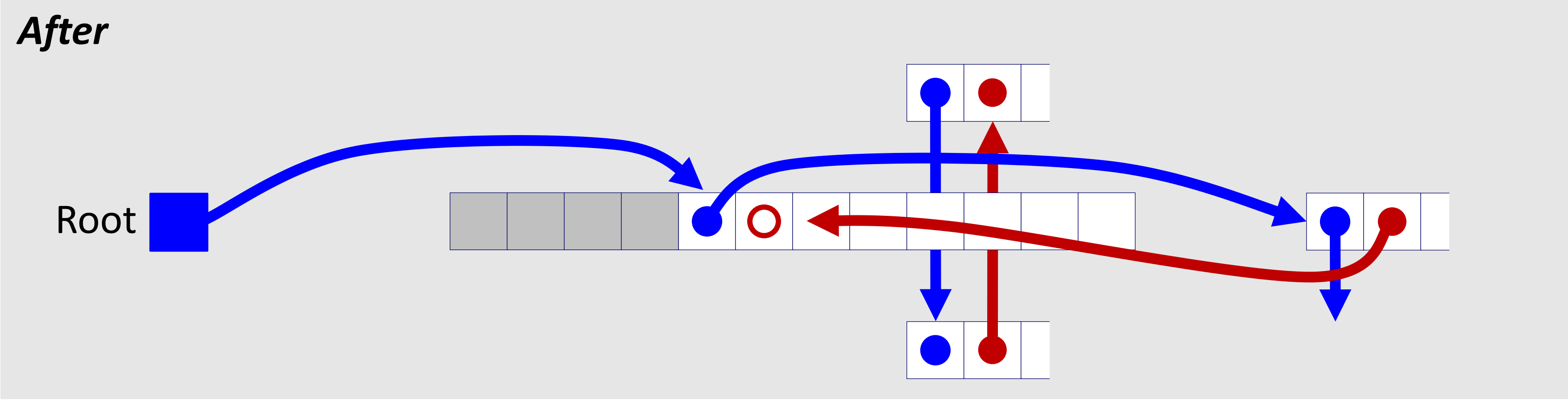


Freeing with LIFO Policy (Case 2)

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

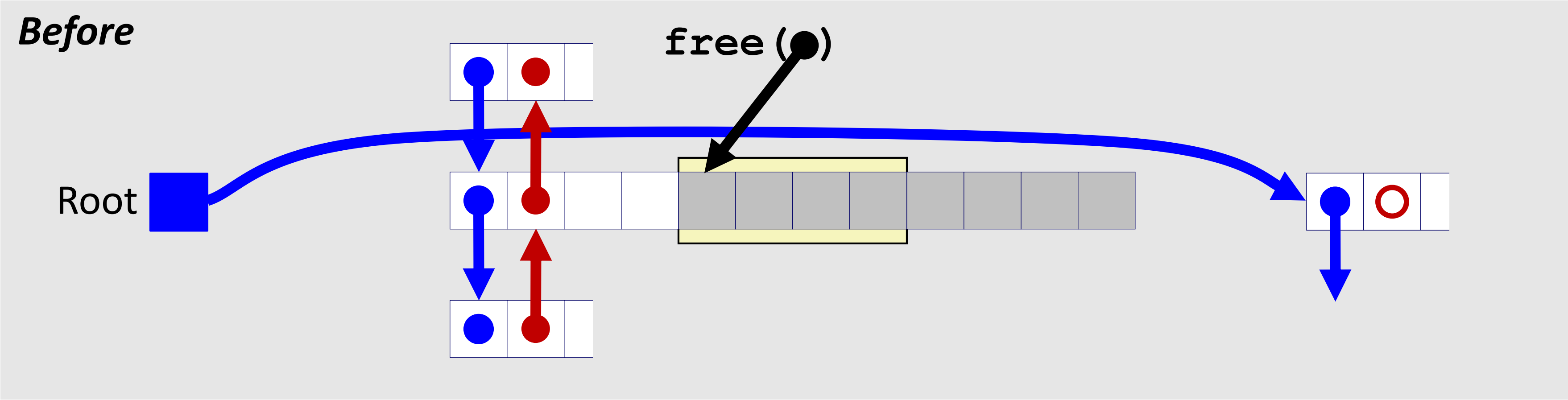


- Splice *following* block out of list, coalesce both memory blocks, and insert the new block at the root of the list

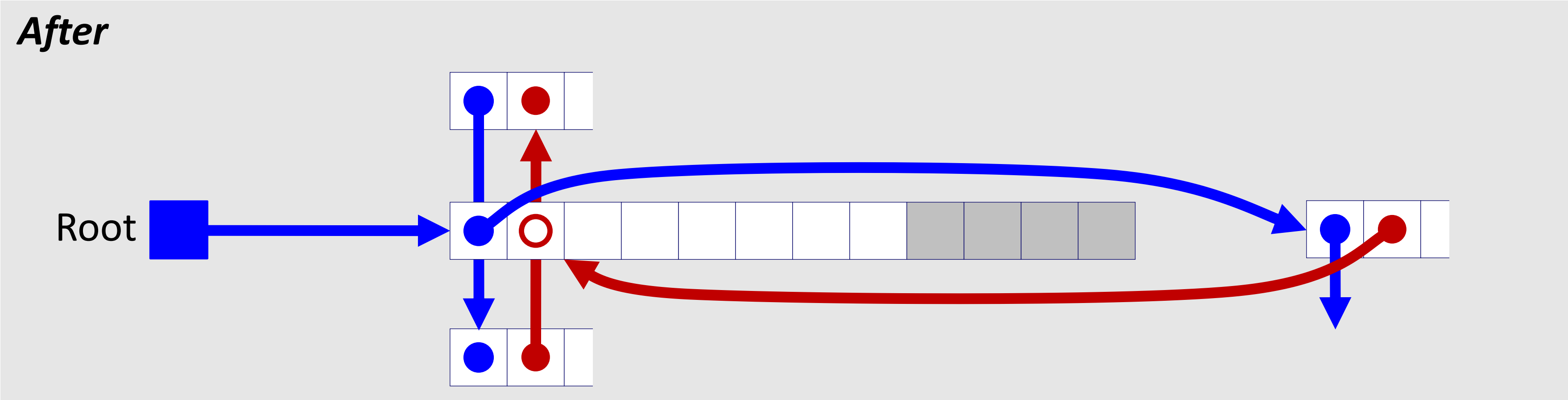


Freeing with LIFO Policy (Case 3)

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

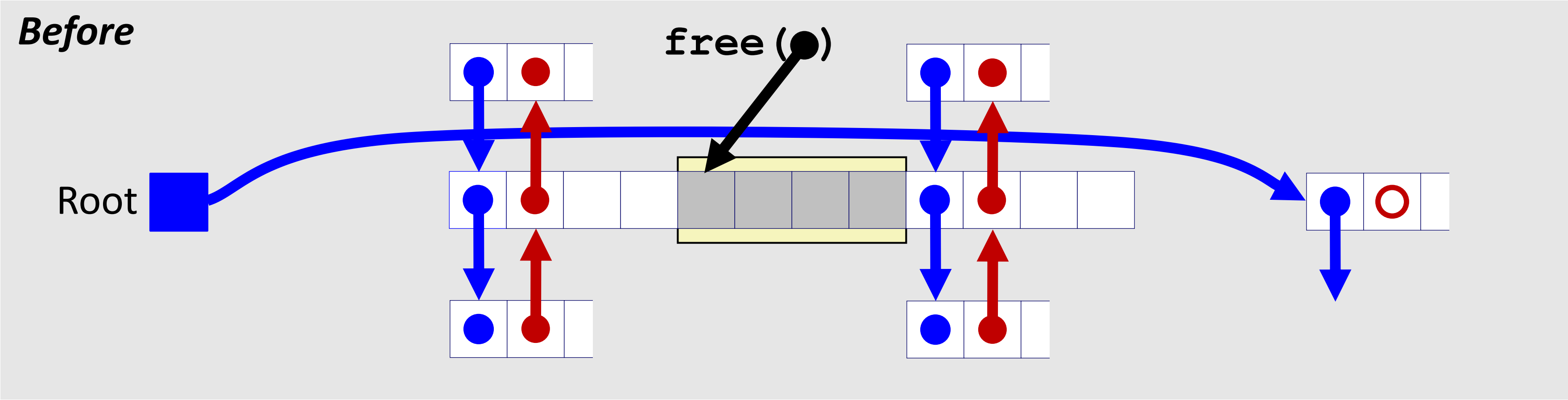


- Splice *preceding* block out of list, coalesce both memory blocks, and insert the new block at the root of the list

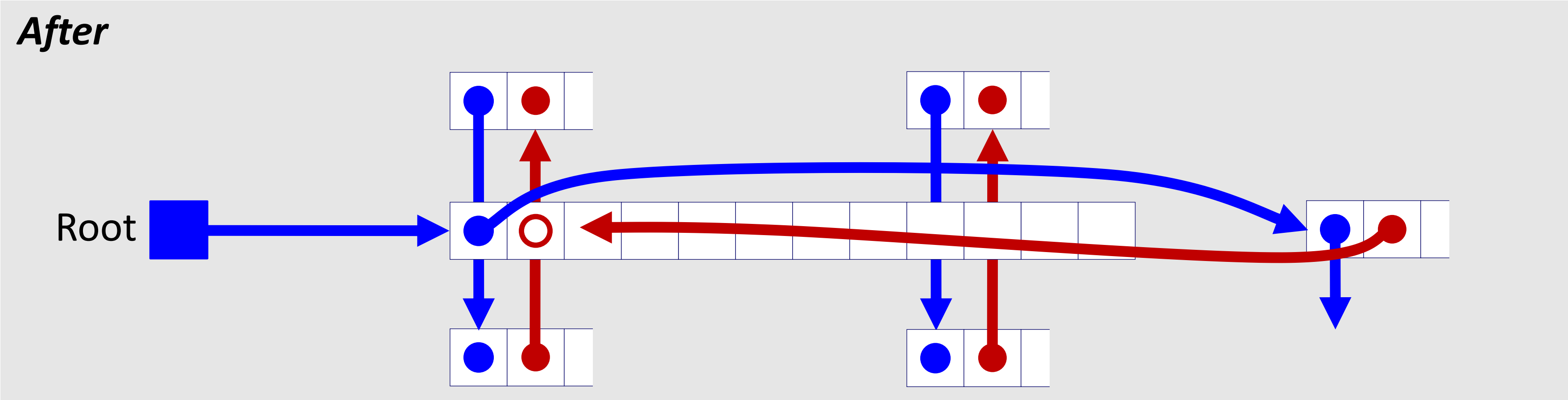


Freeing with LIFO Policy (Case 4)

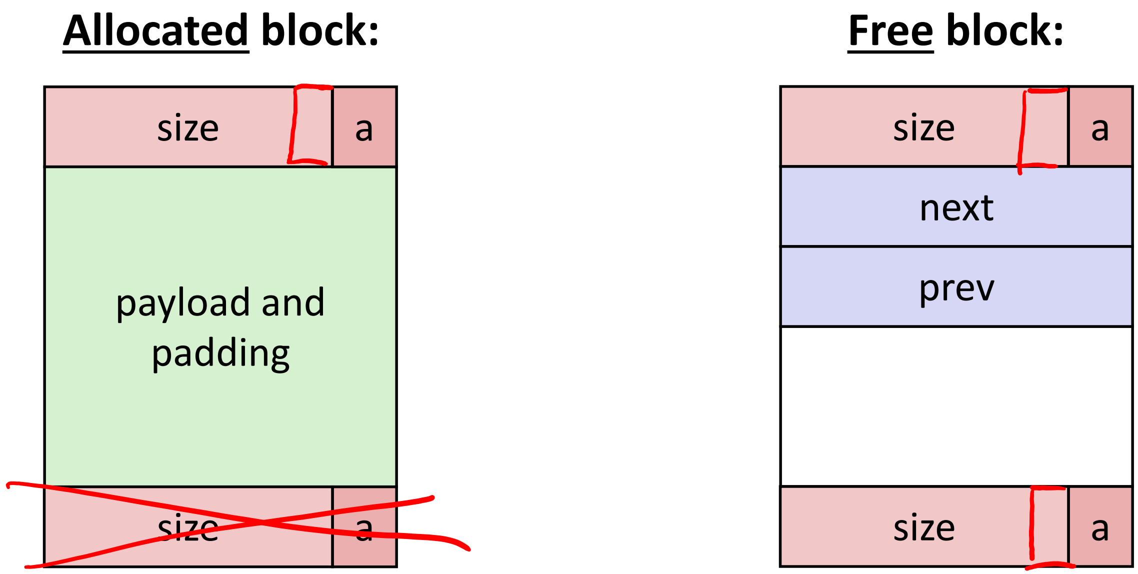
Boundary tags not shown, but don't forget about them!



- 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?



(same as implicit free list)

- Lab 5 suggests no…

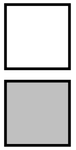
Explicit List Summary

- 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

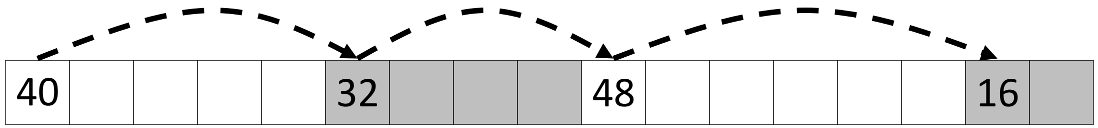
BONUS SLIDES

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

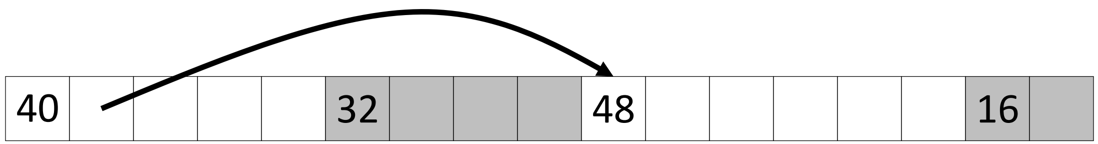
Keeping Track of Free Blocks



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

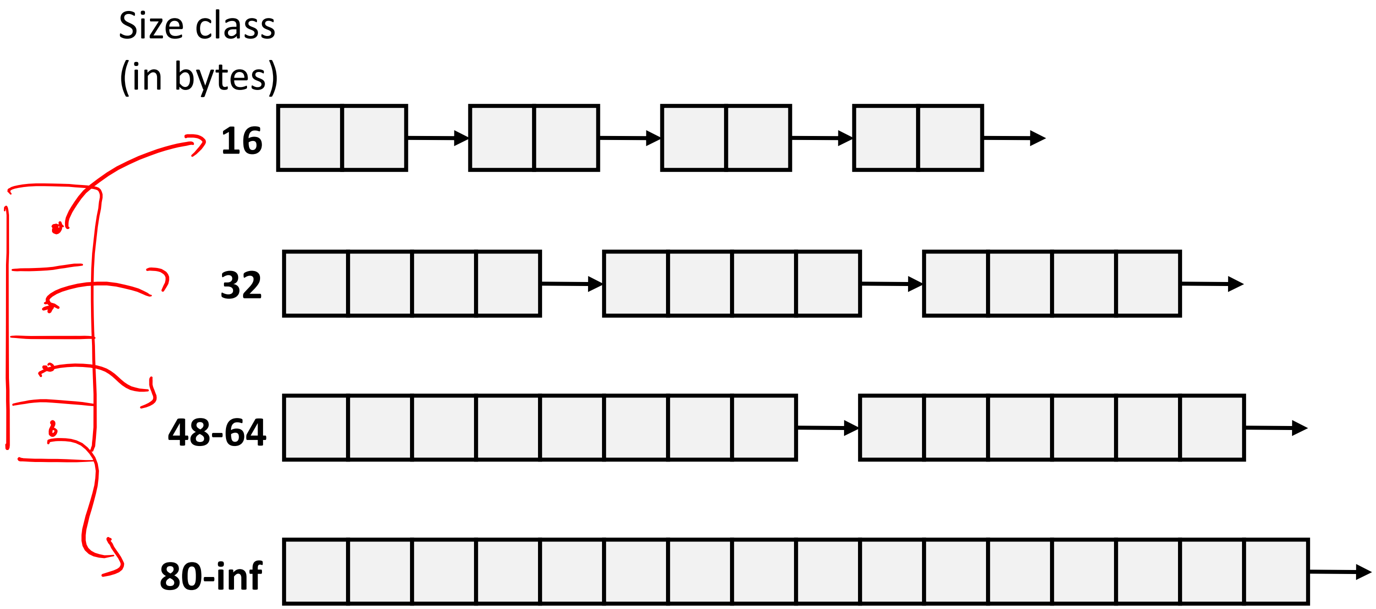


3) *Segregated free list*
   - Different free lists for different size "classes"

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