# Memory Allocation II

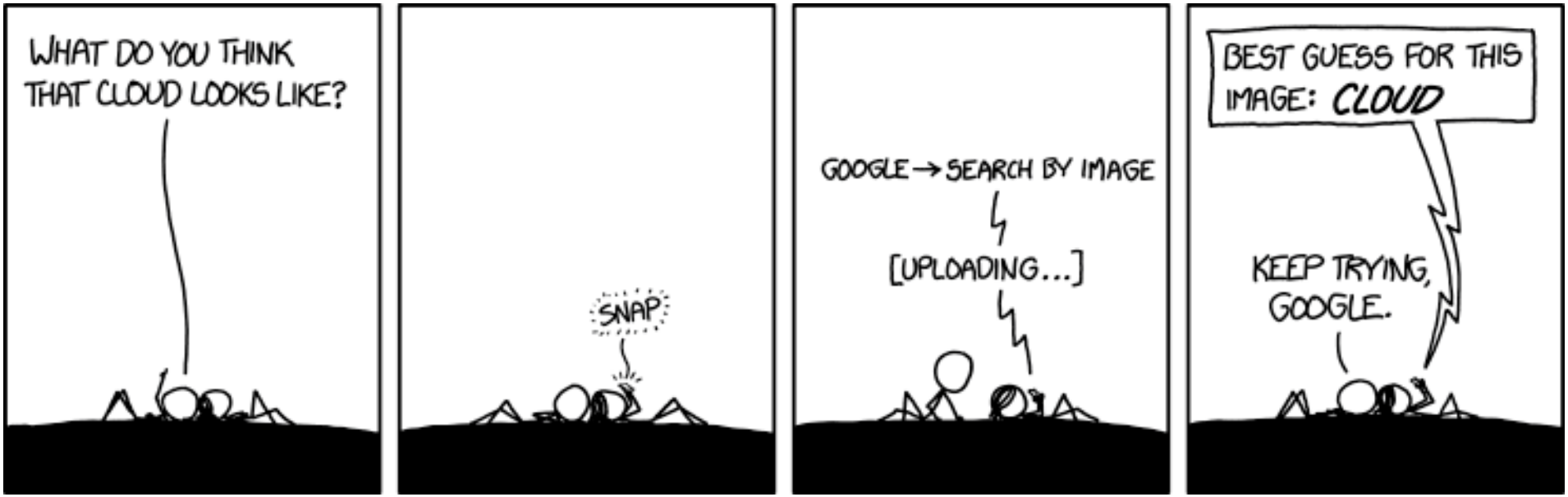
CSE 351 Autumn 2016

**Instructor:**

Justin Hsia

**Teaching Assistants:**

| | | | |
|---|---|---|---|
| Chris Ma | Hunter Zahn | John Kaltenbach | Kevin Bi |
| Sachin Mehta | Suraj Bhat | Thomas Neuman | Waylon Huang |
| Xi Liu | Yufang Sun | | |




http://xkcd.com/1444/

# Administrivia

- Homework 4 due Friday @ 11:45pm
- Lab 5 due Dec. 9 @ 11:45pm

- **Final Exam:** Tue, Dec. 13 @ 12:30pm in Kane 120
  - Combined for both lectures
  - Review Session: Sun, Dec. 11 @ 1:30pm in EEB 105
  - Cumulative (midterm clobber policy applies)
  - You get TWO double-sided handwritten 8.5×11" cheat sheets
    - Recommended that you reuse or remake your midterm cheat sheet

# Peer Instruction Question

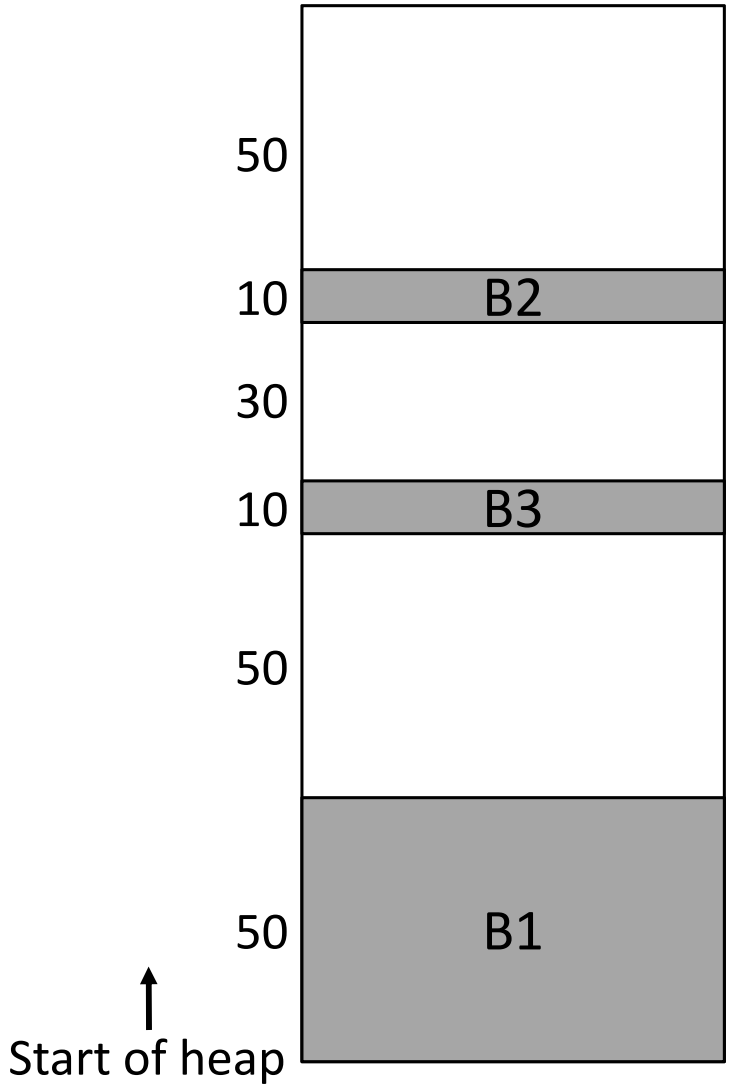
- Which allocation strategy and requests removes *external* fragmentation in this Heap? B3 was the last fulfilled request.
  - http://PollEv.com/justinh

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

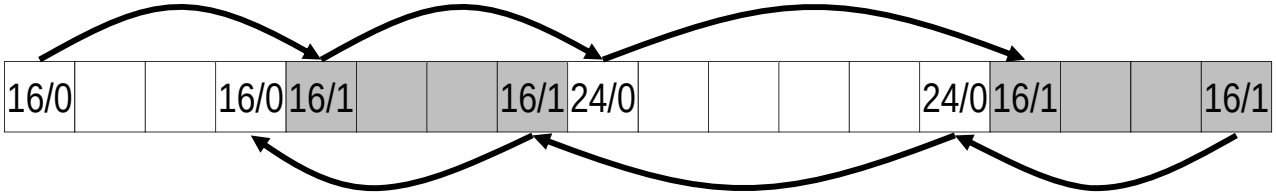
**(B) First-fit:**
`malloc(50), malloc(30)`

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

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

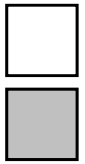


# Implicit Free List Review Questions

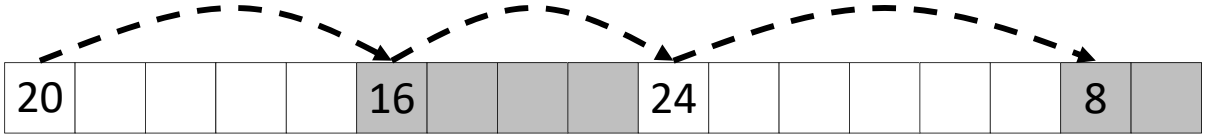



- What is the block header? What do we store and how?
- What are boundary tags and why do we need them?
- When we coalesce free blocks, how many neighboring blocks do we need to check on either side? Why is this?
- If I want to check the size of the $n$-th block forward from the current block, how many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

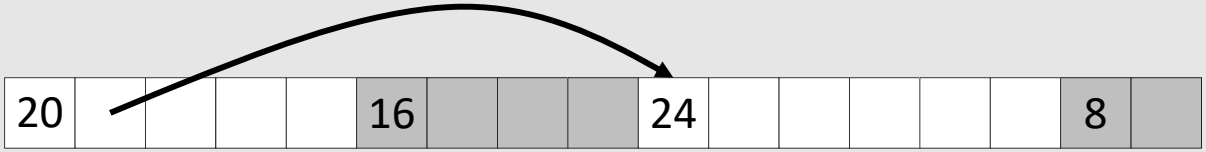
# Keeping Track of Free Blocks




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




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

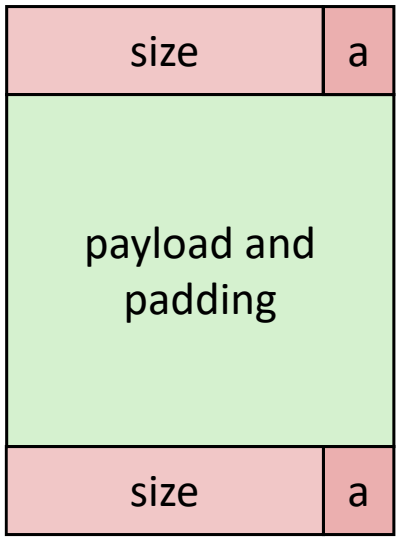



3) *Segregated free list*
   - Different free lists for different size "classes"

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

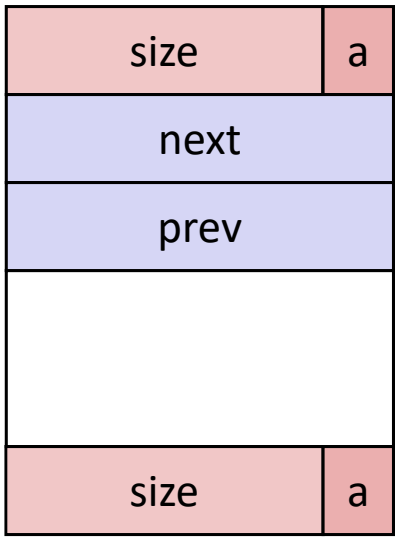
# Explicit Free Lists

**Allocated block:**




(same as implicit free list)

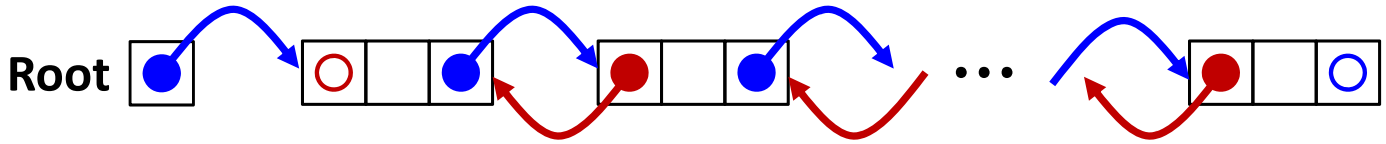
**Free block:**



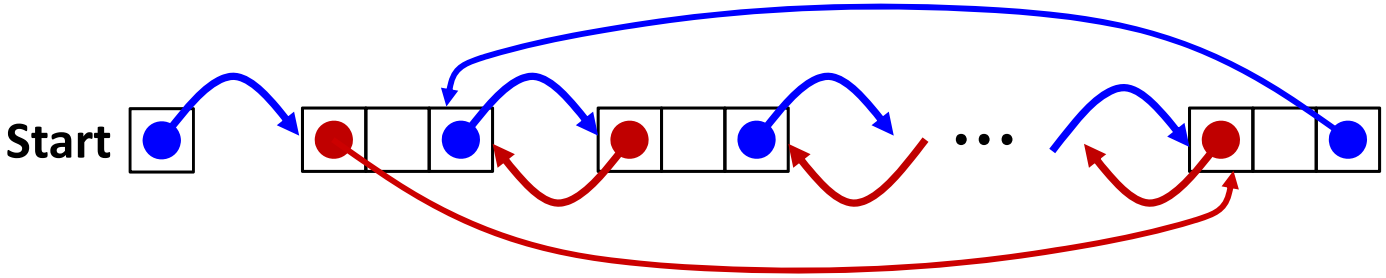

- Use list(s) of *free* blocks, rather than implicit list of *all* blocks
  - The "next" free block could be anywhere in the heap
    - So we need to store next/previous pointers, not just sizes
  - Since we only track free blocks, so we can use "payload" for pointers
  - Still need boundary tags (header/footer)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

# Review: 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

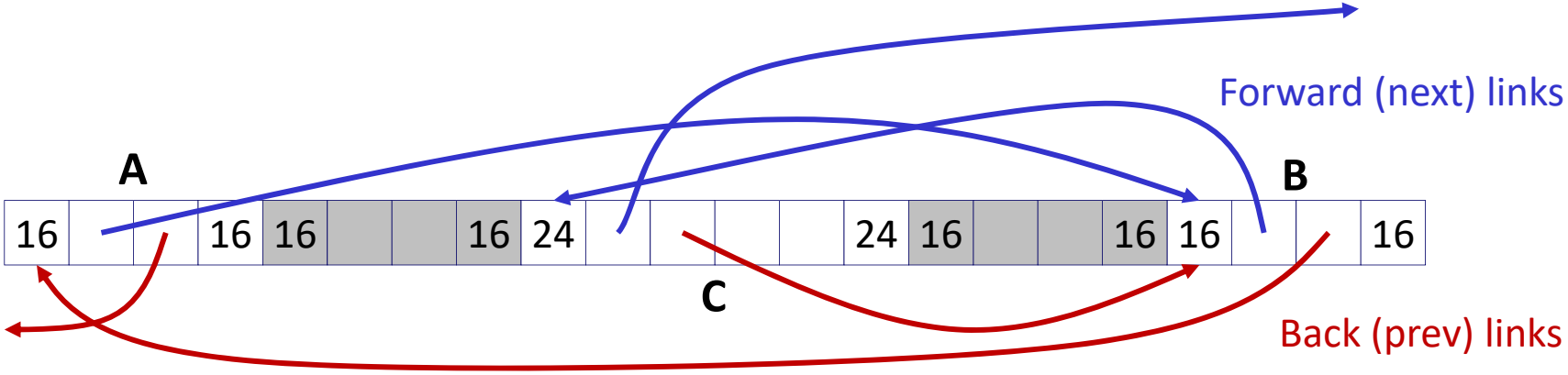



- **Circular**
  - Still have pointer to tell you which node to start with
  - No NULL pointers (term condition is back at starting point)
  - Good for next-fit, best-fit

# Explicit Free Lists

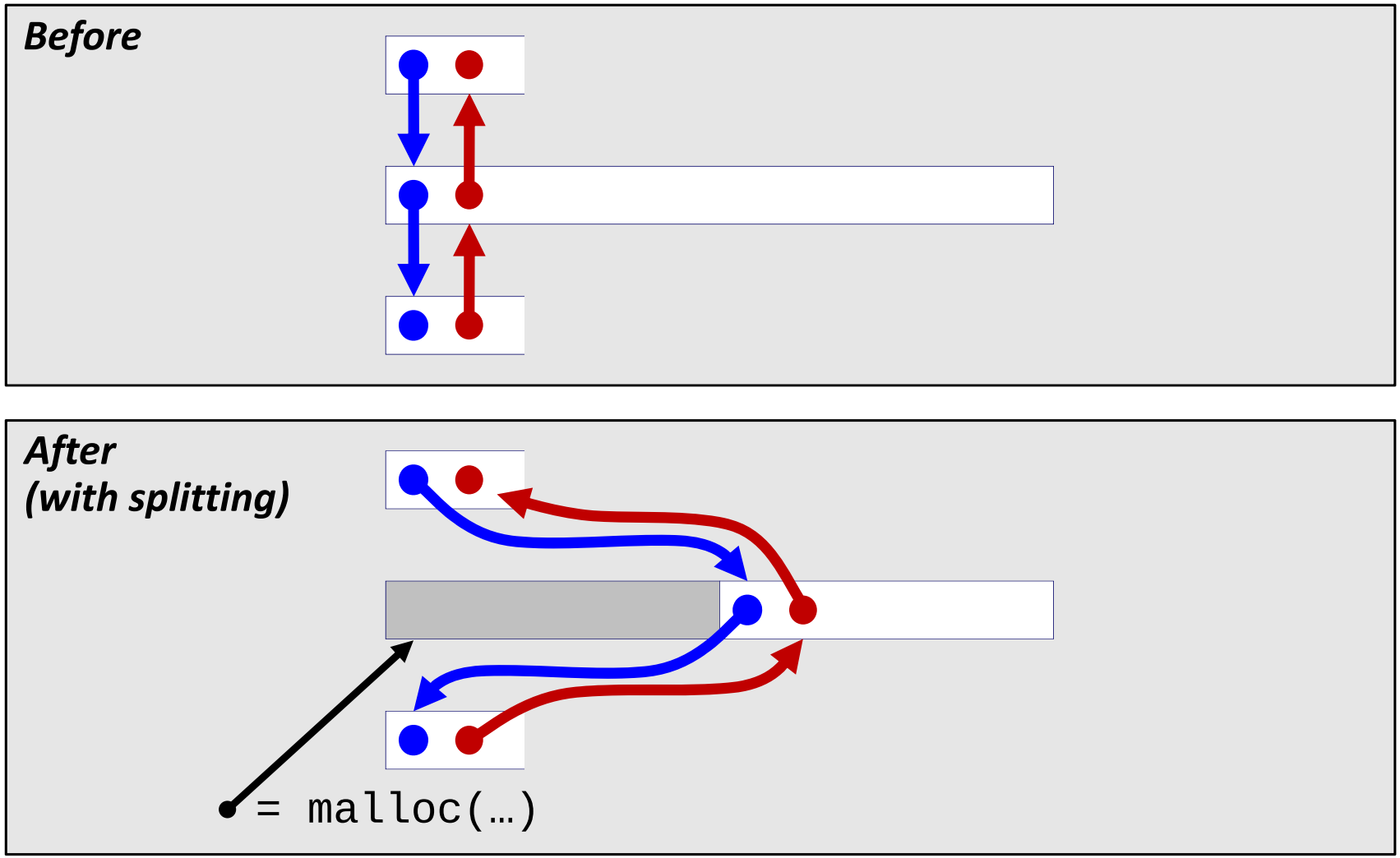
- **Logically:** doubly-linked list


- **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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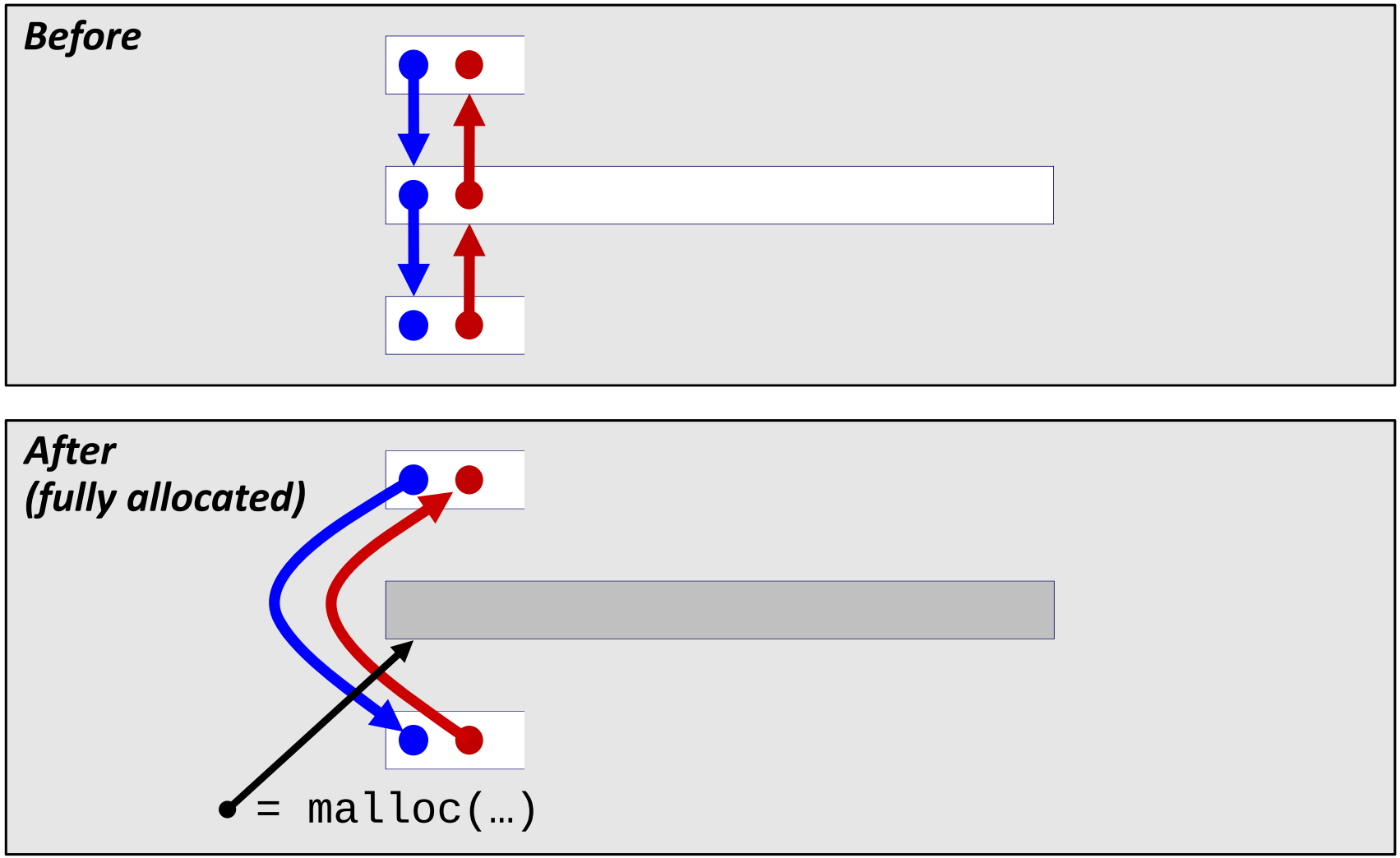
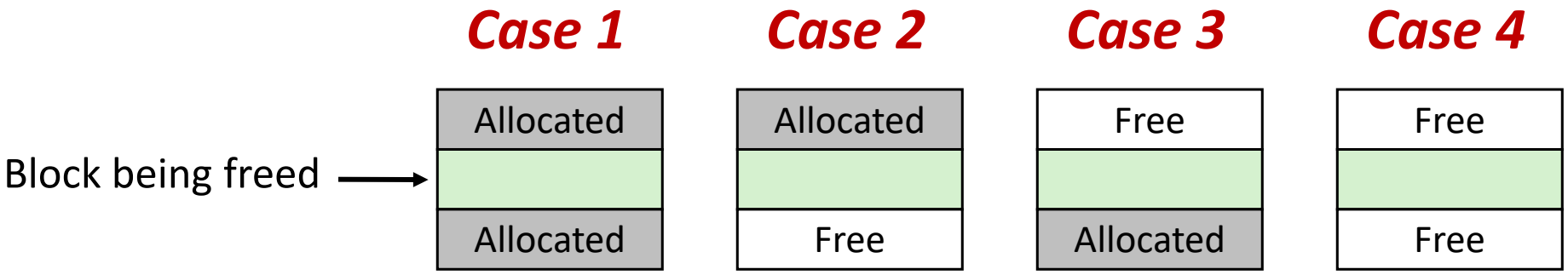


# Freeing With Explicit Free Lists

- *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

# Coalescing in Explicit Free Lists

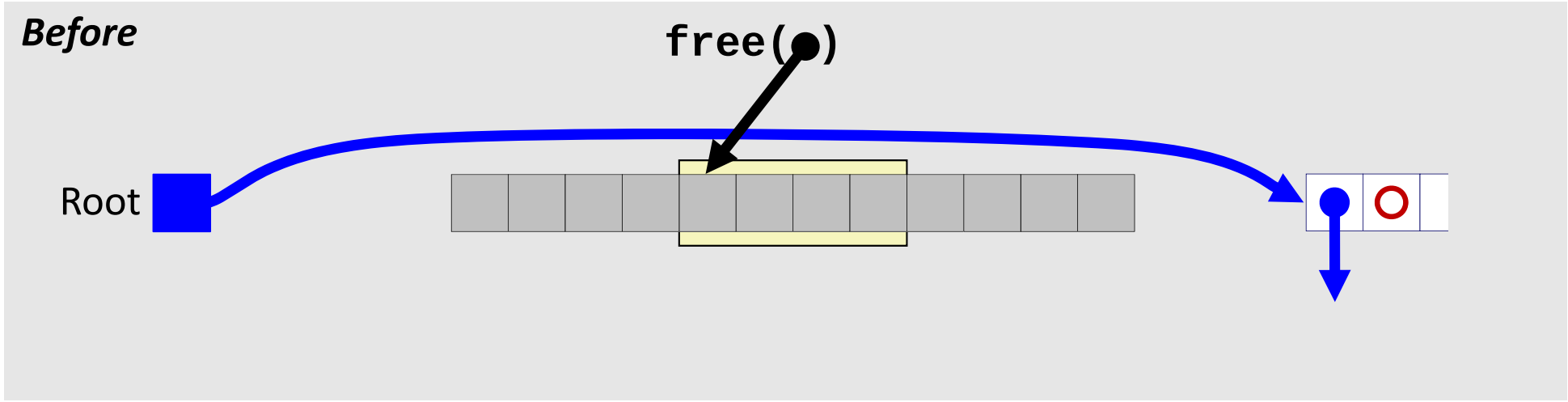



- Neighboring free blocks are *already part of the free list*
  1) Remove old block from free list
  2) Create new, larger coalesced block
  3) Add new block to free list (insertion policy)

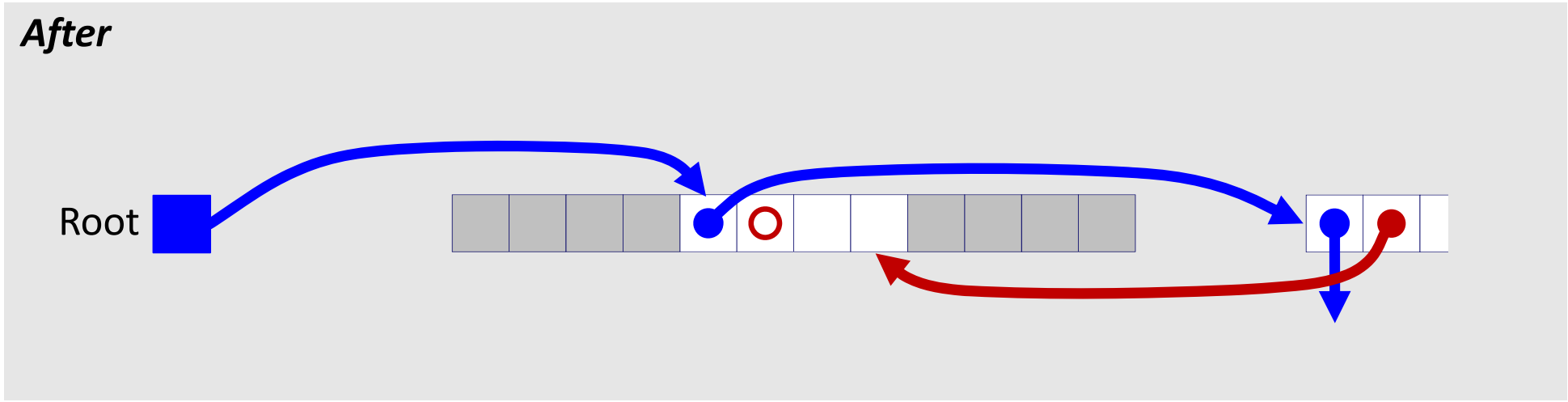
- How do we tell if a neighboring block if free?

# Freeing with LIFO Policy (Case 1)

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

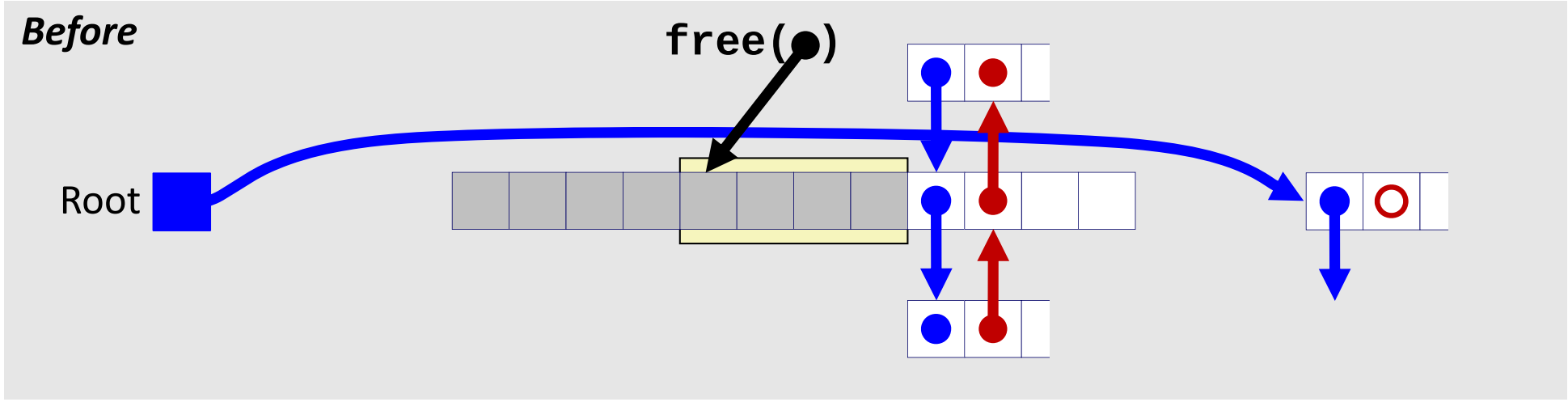



- Insert the freed block at the root of the list

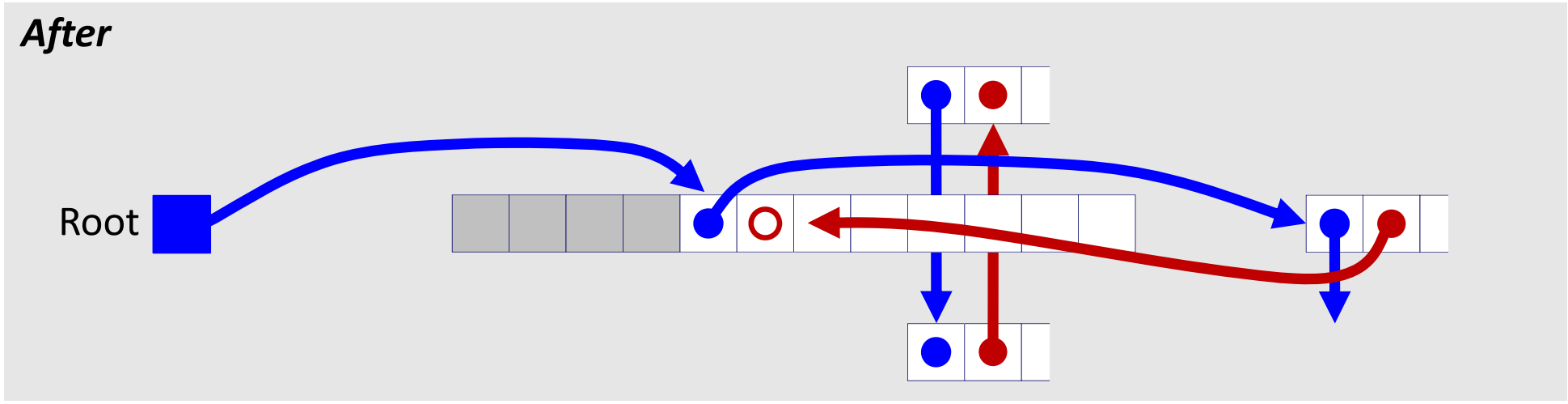


# Freeing with LIFO Policy (Case 2)

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

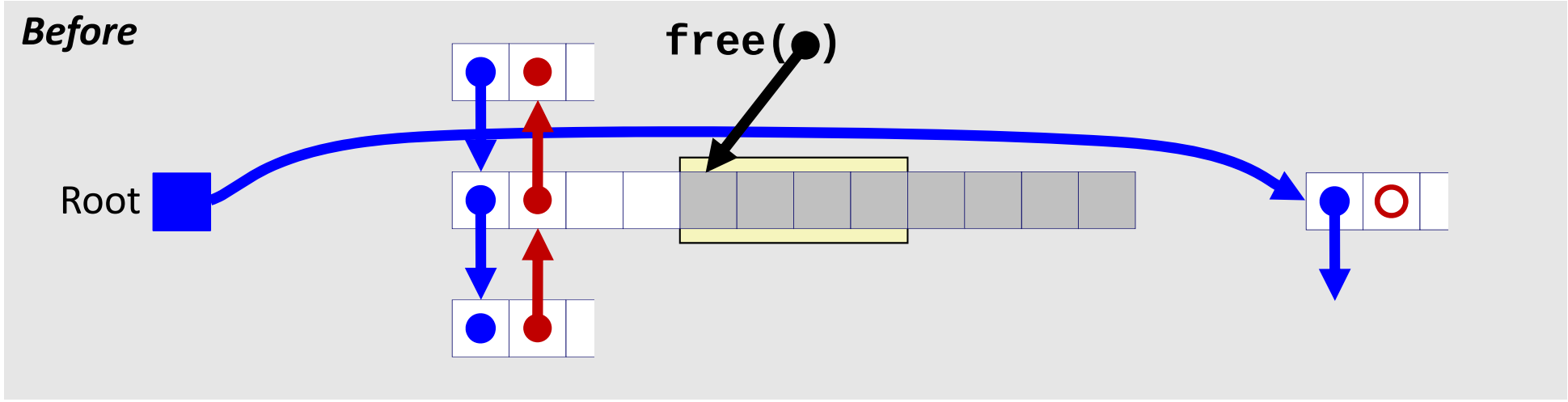



- Splice *successor* block out of list, coalesce both memory blocks, and insert the new block at the root of the list

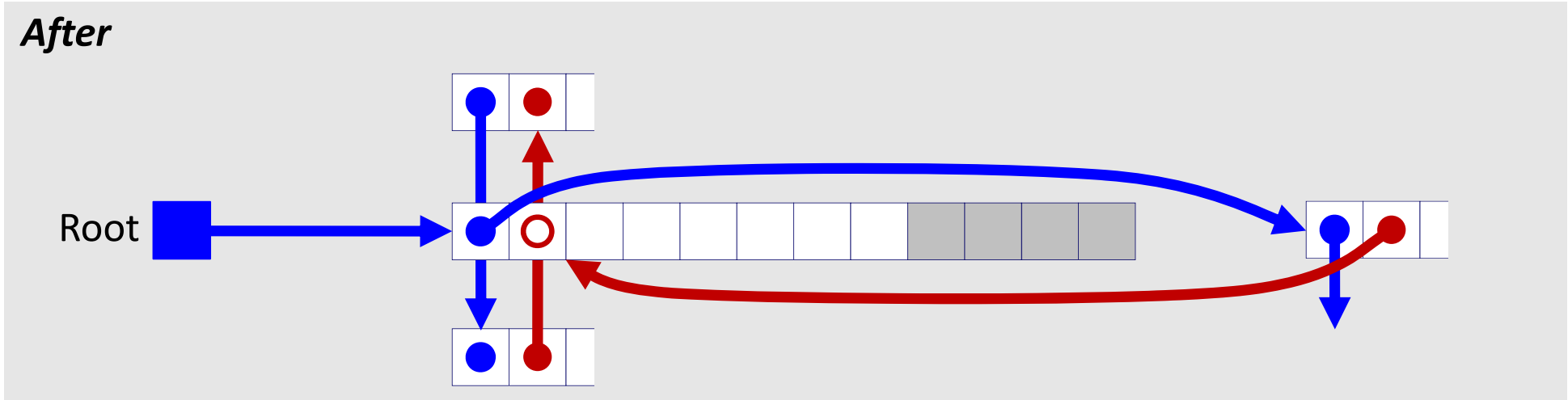


# Freeing with LIFO Policy (Case 3)

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

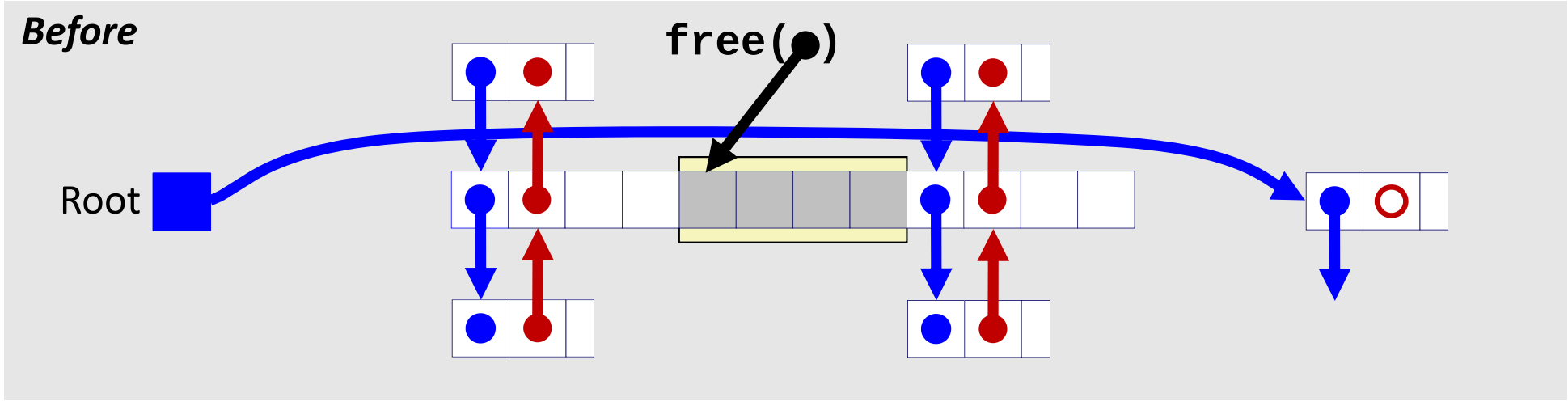



- Splice *predecessor* block out of list, coalesce both memory blocks, and insert the new block at the root of the list

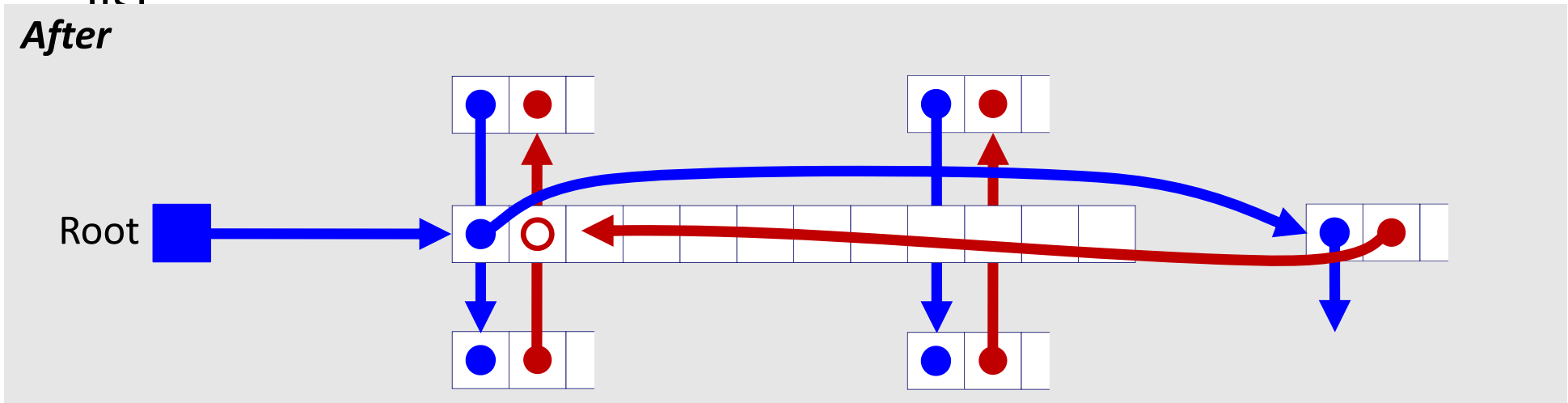


# Freeing with LIFO Policy (Case 4)

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

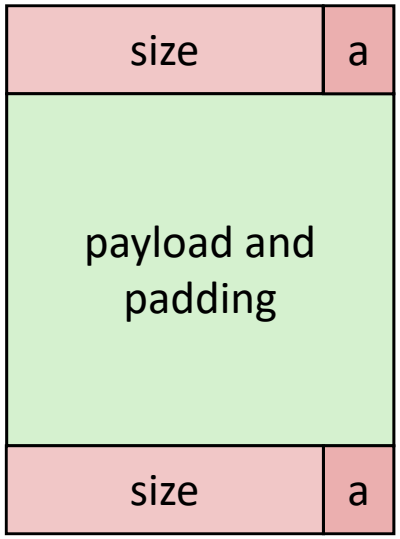



- Splice *predecessor* and *successor* blocks out of list, coalesce all 3 memory blocks, and insert the new block at the root of the list



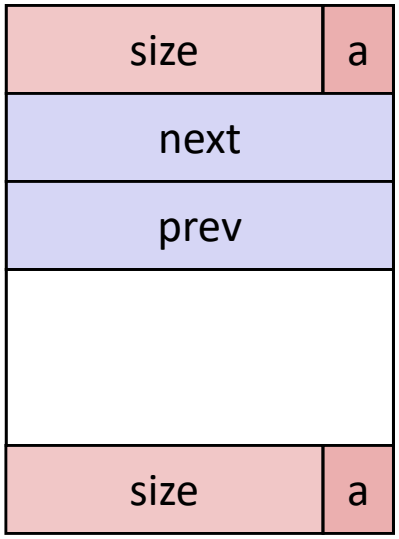
# Do we always need the boundary tag?

**Allocated block:**




(same as implicit free list)

**Free block:**

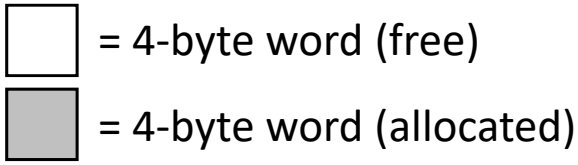



- Lab 5 suggests no…

# 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

# Keeping Track of Free Blocks

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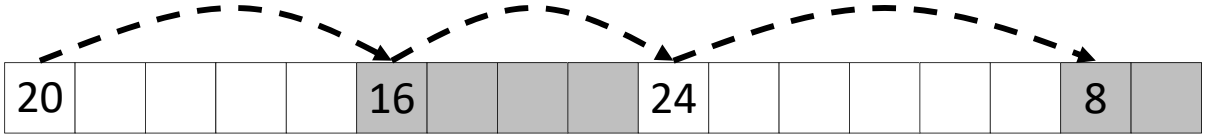


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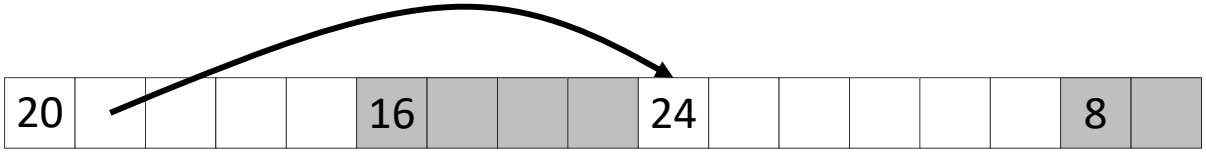
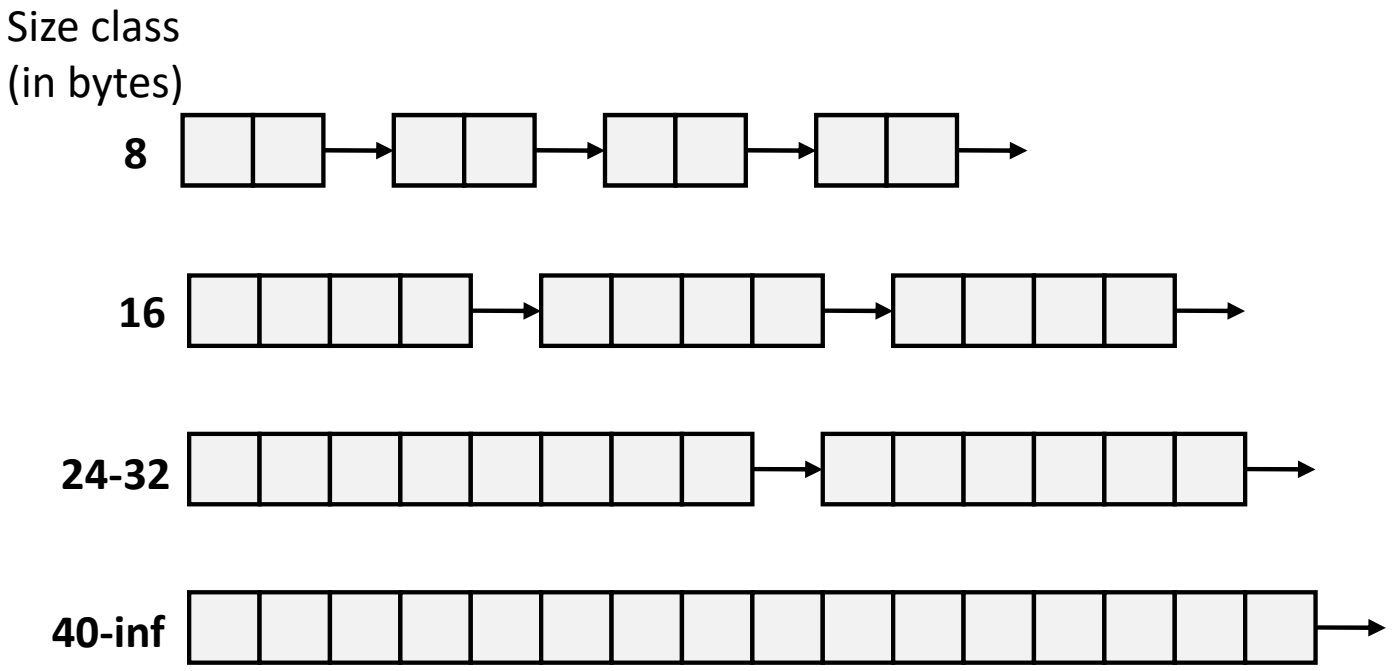



3) *Segregated free list*
   - Different free lists for different size "classes"

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

# 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

# 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?
- When do we coalesce free blocks?
  - **Immediate coalescing:** Every time `free` is called
  - **Deferred coalescing:** Defer coalescing until needed
    - e.g. when scanning free list for `malloc` or when external fragmentation reaches some threshold

# 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)

# Wouldn't it be nice…

- If we never had to free memory?
- Do you free objects in Java?
  - Reminder: *implicit* allocator

# Garbage Collection (GC)
## (Automatic Memory Management)

- *Garbage collection:* automatic reclamation of heap-allocated storage – application never explicitly frees memory

```
void foo() {
    int* p = (int*) malloc(128);
    return;  /* p block is now garbage! */
}
```

- Common in implementations of functional languages, scripting languages, and modern object oriented languages:
  - Lisp, Racket, Erlang, ML, Haskell, Scala, Java, C#, Perl, Ruby, Python, Lua, JavaScript, Dart, Mathematica, MATLAB, many more…

- Variants ("conservative" garbage collectors) exist for C and C++
  - However, cannot necessarily collect all garbage

# Garbage Collection

- How does the memory allocator know when memory can be freed?
  - In general, we cannot know what is going to be used in the future since it depends on conditionals
  - But, we can tell that certain blocks cannot be used if they are *unreachable* (via pointers in registers/stack/globals)

- Memory allocator needs to know what is a pointer and what is not – how can it do this?
  - Sometimes with help from the compiler