

CSC 252: Computer Organization

Spring 2019: Lecture 25

Instructor: Yuhao Zhu

Department of Computer Science
University of Rochester

Action Items:

- **Programming Assignment 6 is out**

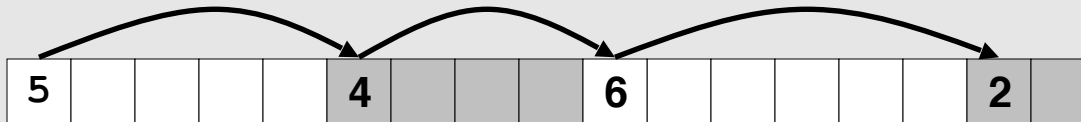
Announcement

- Programming Assignment 6 is out
 - Main assignment: 11:59pm, **Thursday, May 2.**

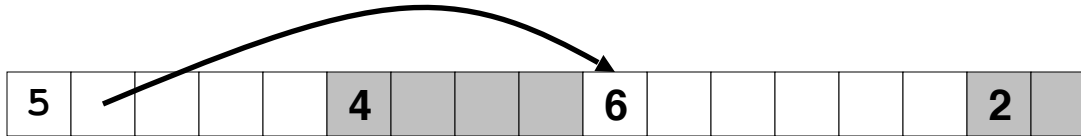
14	15	16	17	18	19	20
21	22	23	24	25	26	27
		Today				
28	29	30	May 1	2	3	4
				Due		

Keeping Track of Free Blocks

- Method 1: *Implicit list* using length—links all blocks



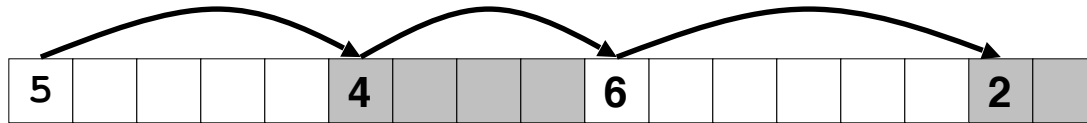
- Method 2: *Explicit list* among the free blocks using pointers



- Method 3: *Segregated free list*
 - Different free lists for different size classes

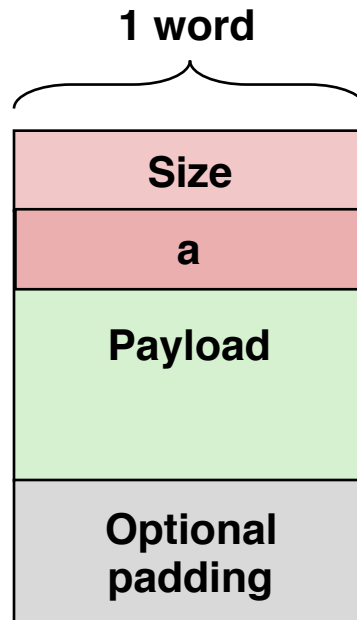
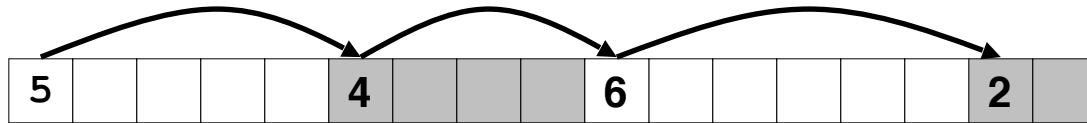
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a = 1: Allocated block

a = 0: Free block

Size: block size

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

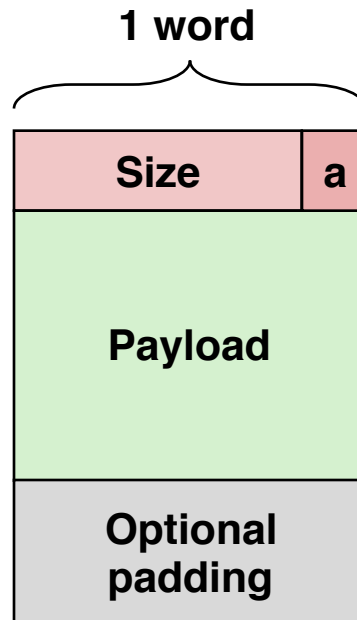
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- Standard trick
 - If blocks are aligned, some low-order address bits are always 0
 - Instead of storing an always-0 bit, use it as a allocated/free flag
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*Format of
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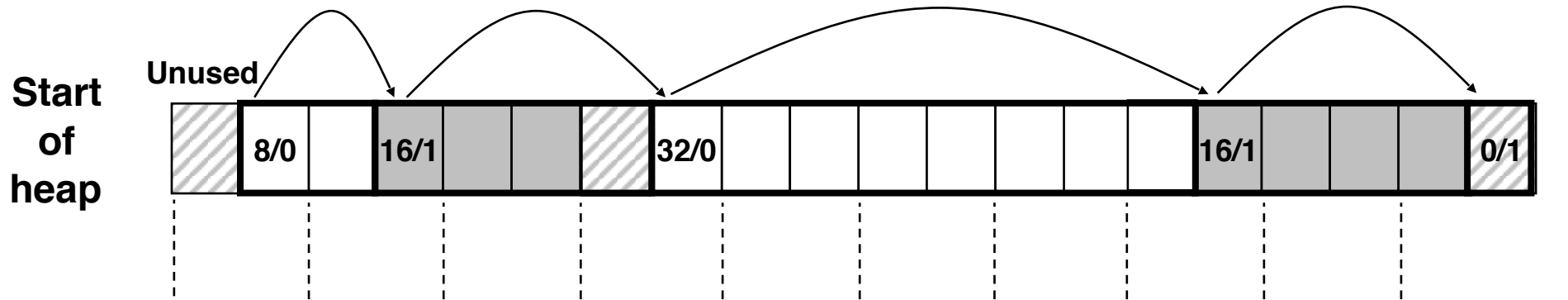
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Detailed Implicit Free List Example



Double-word
aligned

Allocated blocks: shaded

Free blocks: unshaded

Headers: labeled with size in bytes/allocated

Finding a Free Block

- **First fit:**
 - Search list from beginning, choose **first** free block that fits
 - Can take linear time in total number of blocks (allocated and free)
 - In practice it can cause “splinters” at beginning of list

Finding a Free Block

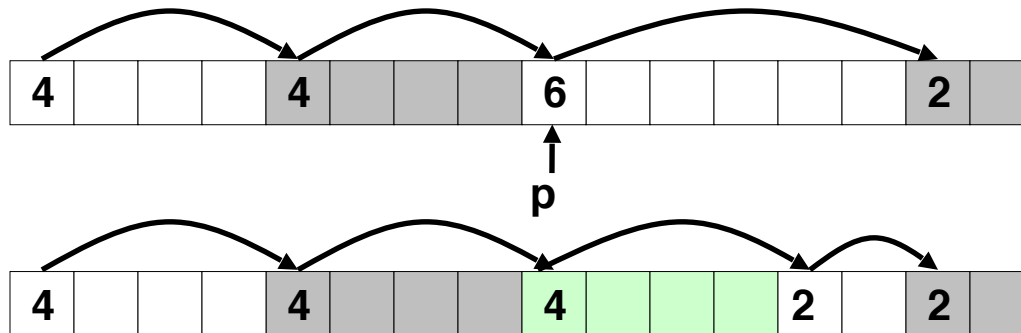
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 - Should often be faster than first fit: avoids re-scanning unhelpful blocks
 - Some research suggests that fragmentation is worse

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 - Some research suggests that fragmentation is worse
- **Best fit:**
 - Search the list, choose the **best** free block: fits, with fewest bytes left over
 - Keeps fragments small—usually improves memory utilization
 - Will typically run slower than first fit

Allocating in Free Block

- Allocated space might be smaller than free space
- We could simply leave the extra space there. Simple to implement but causes internal fragmentation
- Or we could **split** the block



```
void addblock(ptr p, int len) {
    int newsize = ((len + 1) >> 1) << 1; // round up to even
    int oldsize = *p & -2; // mask out low bit
    *p = newsize | 1; // set new length
    if (newsize < oldsize)
        *(p+newsize) = oldsize - newsize; // set length in remaining
} // part of block
```

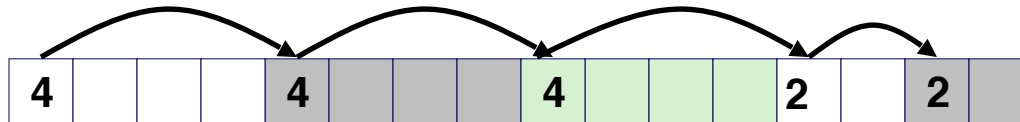
Freeing a Block

- Simplest implementation:

- Need only clear the “allocated” flag

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



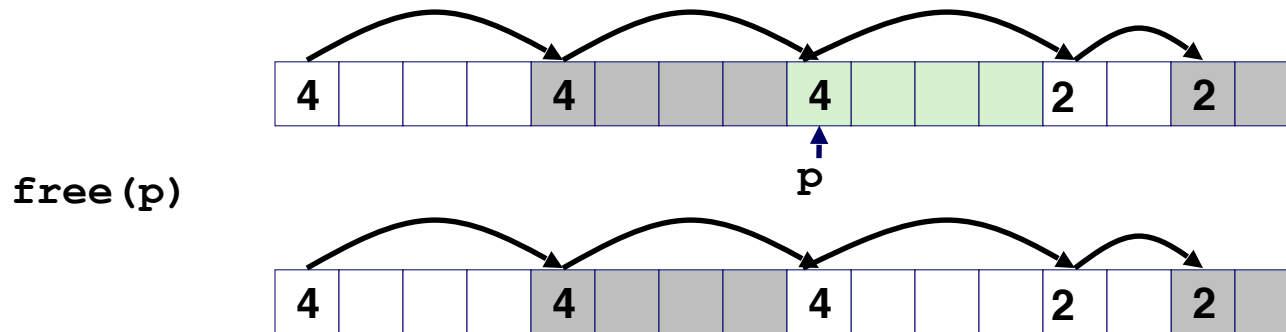
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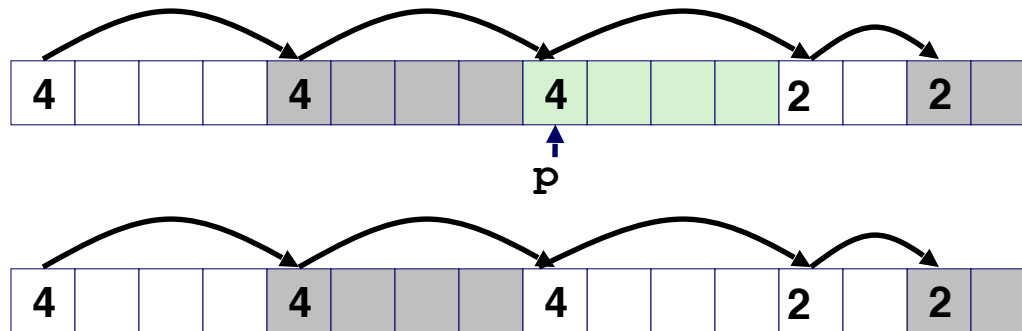
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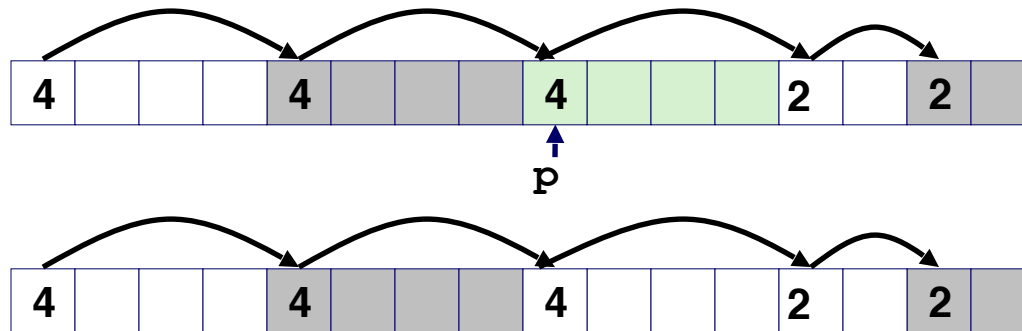
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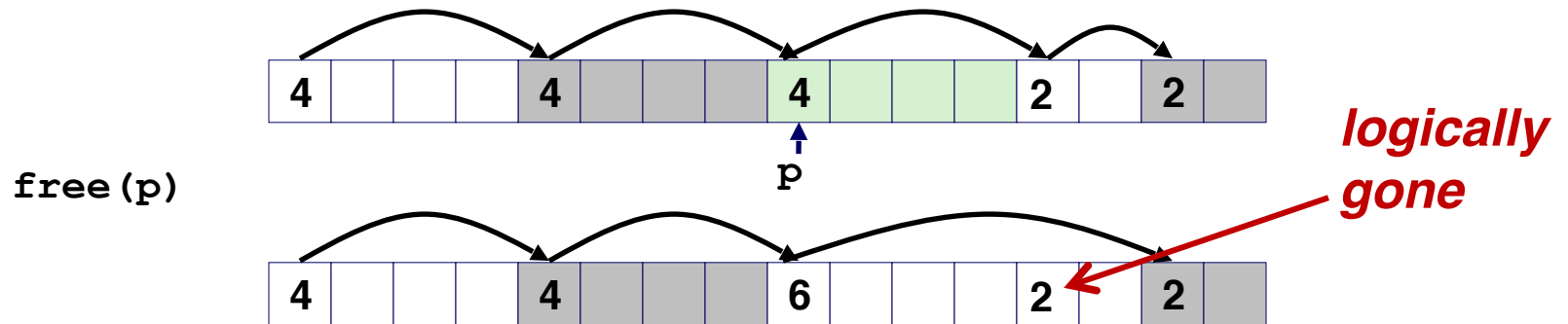


malloc(5) **Oops!**

There is enough free space, but the allocator won't be able to find it

Coalescing

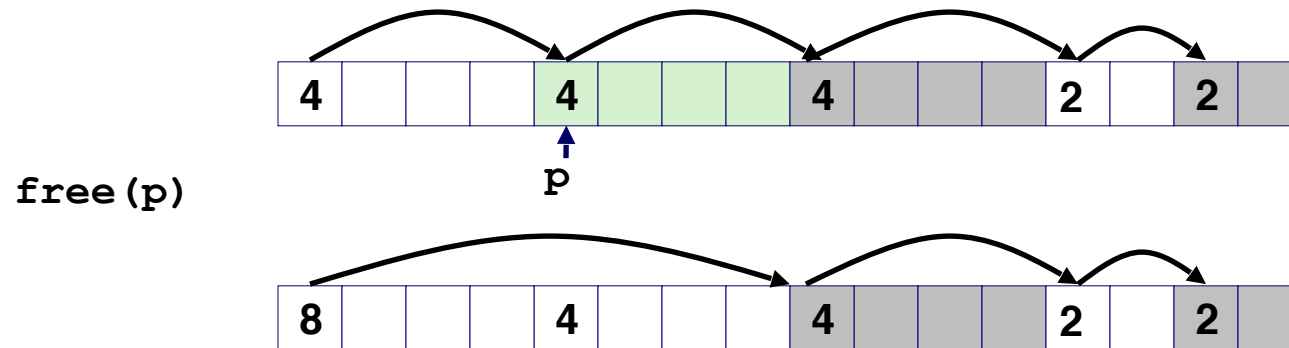
- Join (*coalesce*) with next/previous blocks, if they are free
 - Coalescing with next block



```
void free_block(ptr p) {  
    *p = *p & -2;           // clear allocated flag  
    next = p + *p;         // find next block  
    if ((*next & 1) == 0)  
        *p = *p + *next;   // add to this block if  
                            // not allocated  
}
```

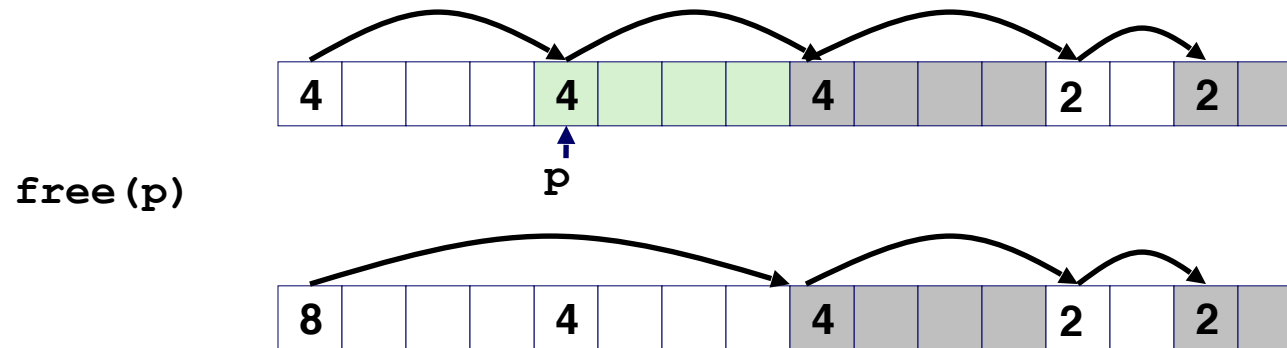
Coalescing

- How about now?



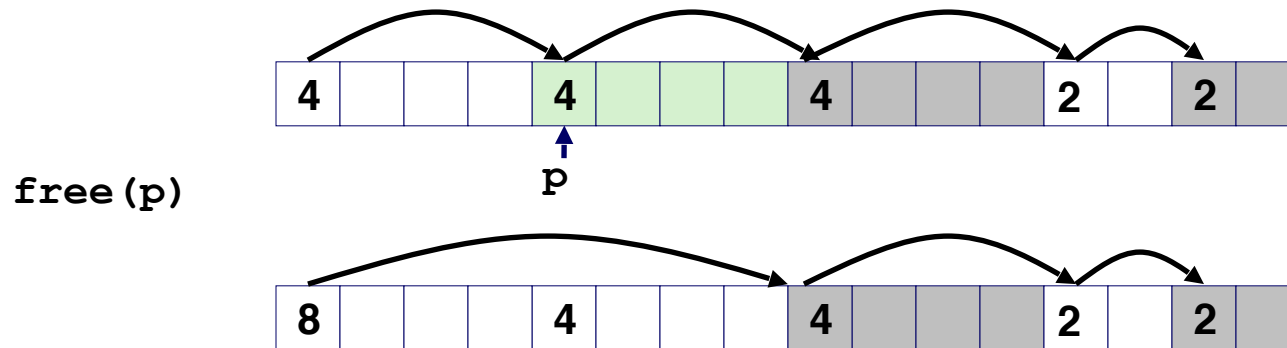
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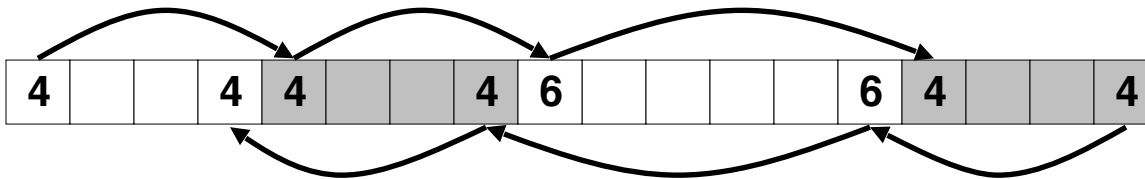
Coalescing

- How about now?
- How do we coalesce with previous block?
 - Linear time solution: scans from beginning



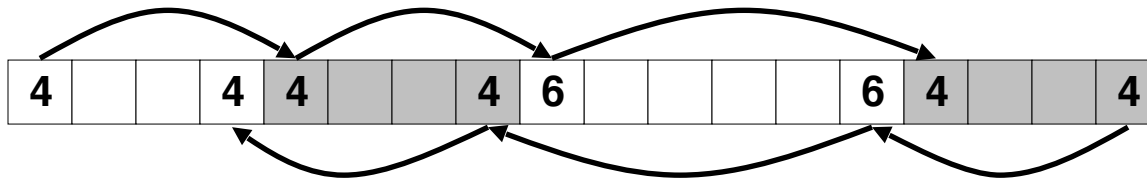
Bidirectional Coalescing (Constant Time)

- *Boundary tags* [Knuth73]
 - Replicate size/allocated word at “bottom” (end) of free blocks
 - Allows us to traverse the “list” backwards, but requires extra space
 - Important and general technique!

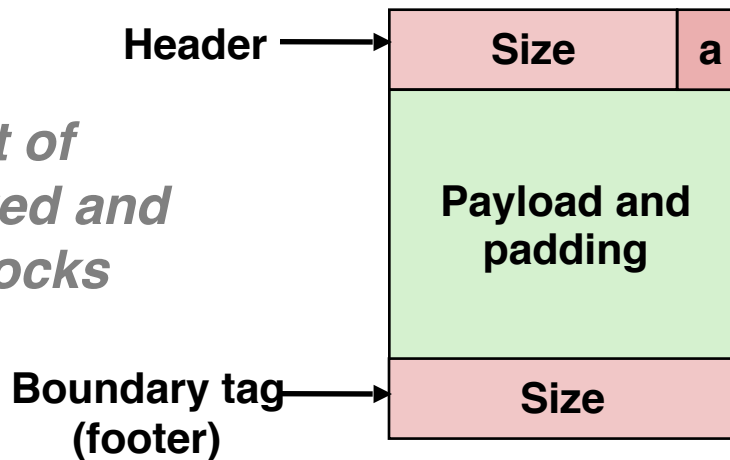


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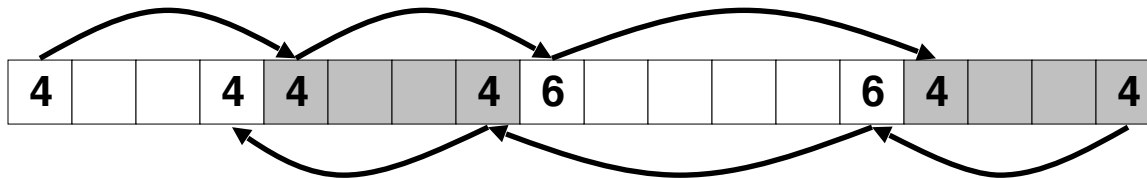
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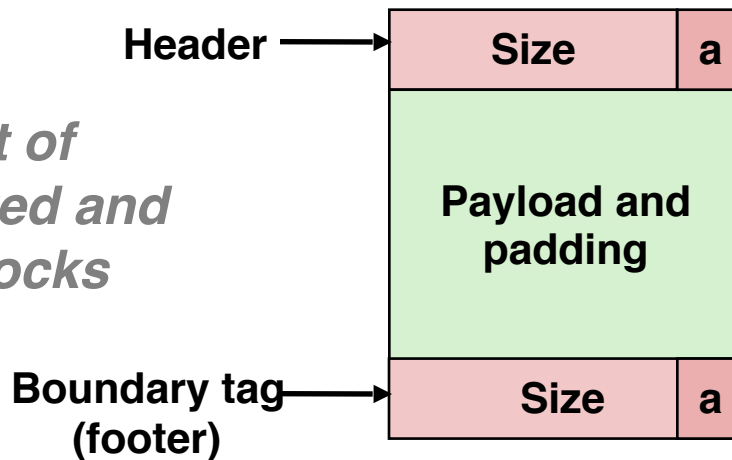
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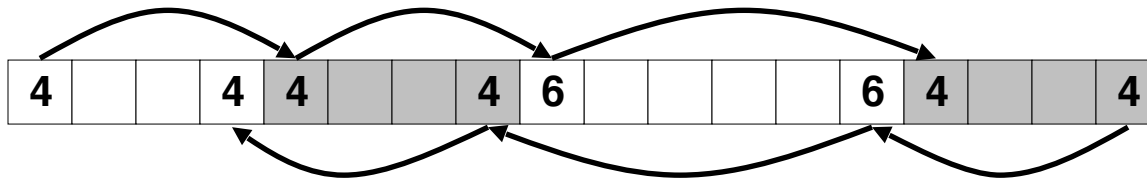
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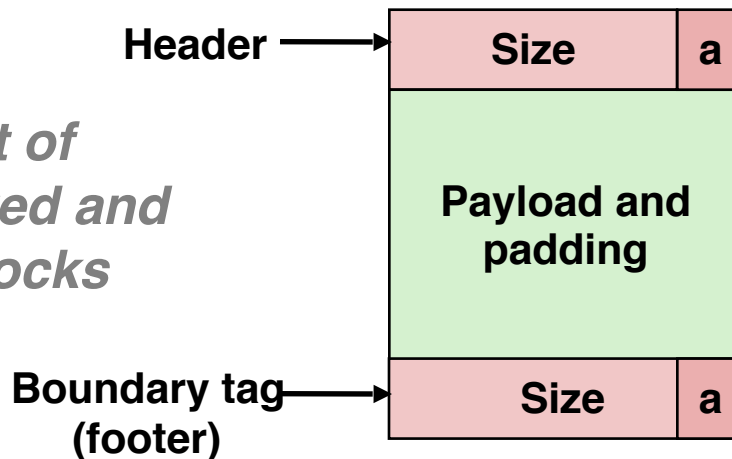
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 - Important and general technique!
- **Disadvantages?** (Think of small blocks...)



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Summary of Key Allocator Policies

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 - How much internal fragmentation are we willing to tolerate?

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 - First-fit, next-fit, best-fit, etc.
 - Trades off lower throughput for less fragmentation
- **Splitting policy:**
 - When do we split free blocks?
 - How much internal fragmentation are we willing to tolerate?
- **Coalescing policy:**
 - **Immediate coalescing:** coalesce each time `free` is called
 - **Deferred coalescing:** try to improve performance of `free` by deferring coalescing until needed. Examples:
 - Coalesce as you scan the free list for `malloc`
 - Coalesce when the amount of external fragmentation reaches some threshold

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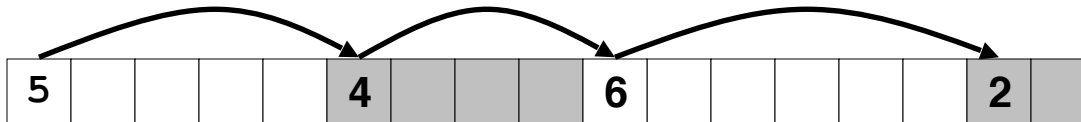
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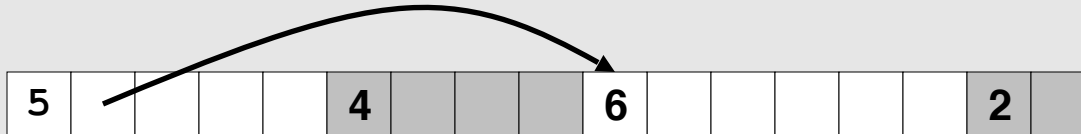
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 - First-fit, next-fit, or best-fit
- Not used in practice because of linear-time allocation
 - used in many special purpose applications
- However, the concepts of splitting and boundary tag coalescing are general to **all** allocators

Keeping Track of Free Blocks

- Method 1: *Implicit list* using length—links all blocks



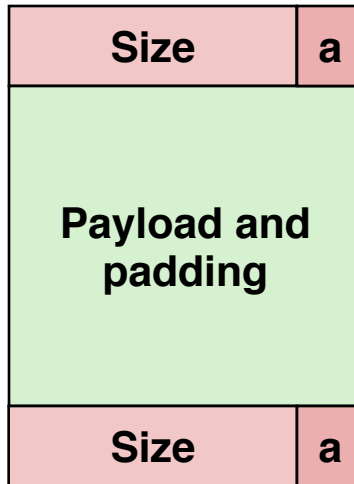
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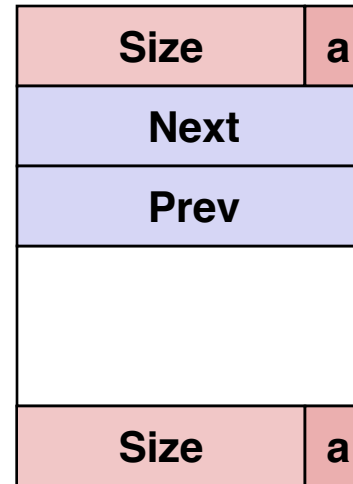
- Method 3: *Segregated free list*
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Explicit Free Lists

Allocated (as before)



Free



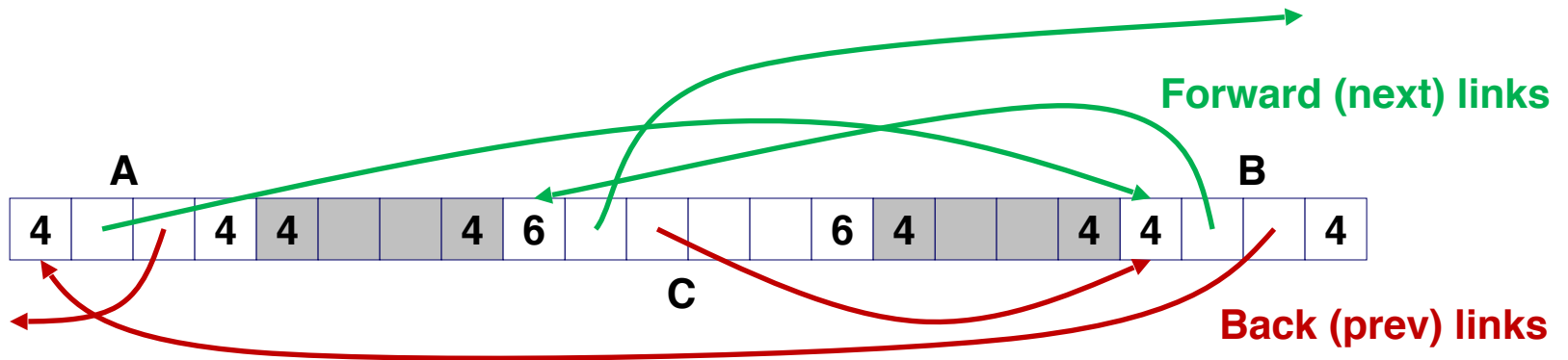
- Maintain list(s) of *free* blocks, not *all* blocks
 - The “next” free block could be anywhere
 - So we need to store forward/back pointers, not just sizes
 - Still need boundary tags for coalescing
 - Luckily we track only free blocks, so we can use payload area

Explicit Free Lists

- Logically:

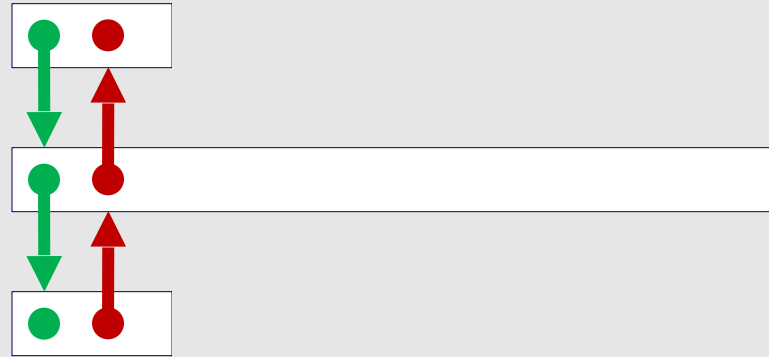


- Physically: blocks can be in any order



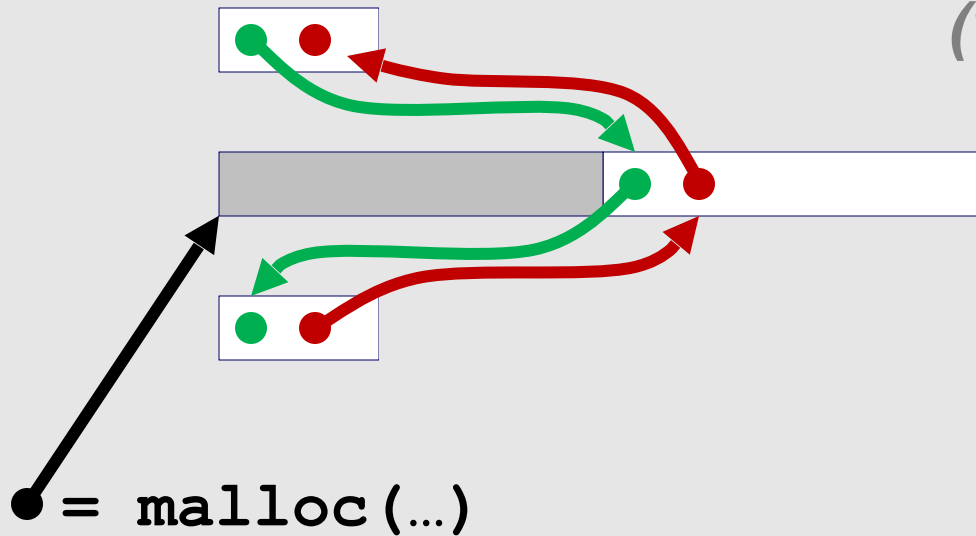
Allocating From Explicit Free Lists

Before



conceptual graphic

After



(with splitting)

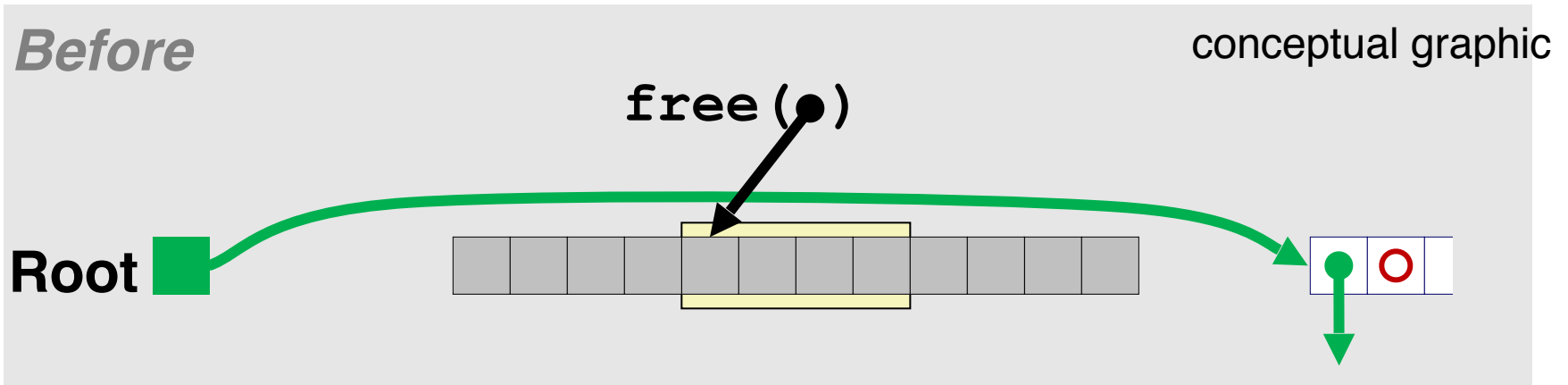
● = `malloc(...)`

Freeing With Explicit Free Lists

- *Insertion policy*: Where in the free list do you put a newly freed block?
- LIFO (last-in-first-out) policy
 - Insert freed block at the beginning of the free list
 - *Pro*: simple and constant time
 - *Con*: studies suggest fragmentation is worse than address ordered
- Address-ordered policy
 - Insert freed blocks so that free list blocks are always in address order:
$$addr(prev) < addr(curr) < addr(next)$$
 - *Con*: requires search
 - *Pro*: studies suggest fragmentation is lower than LIFO

Freeing With a LIFO Policy (Case 1)

- Insert the freed block at the root of the list

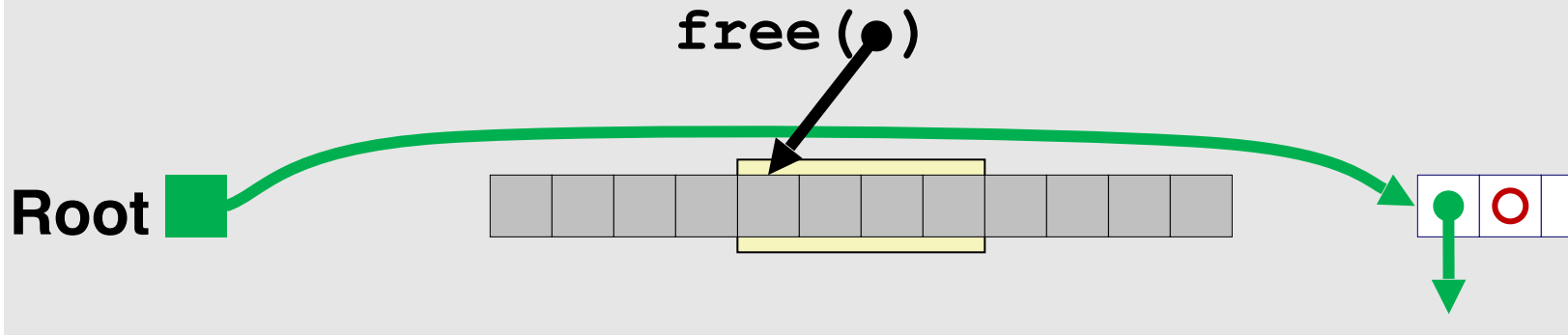


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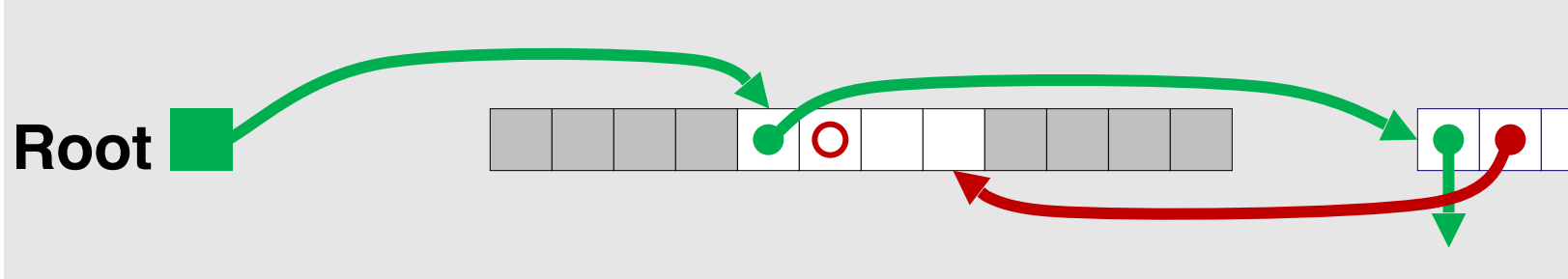
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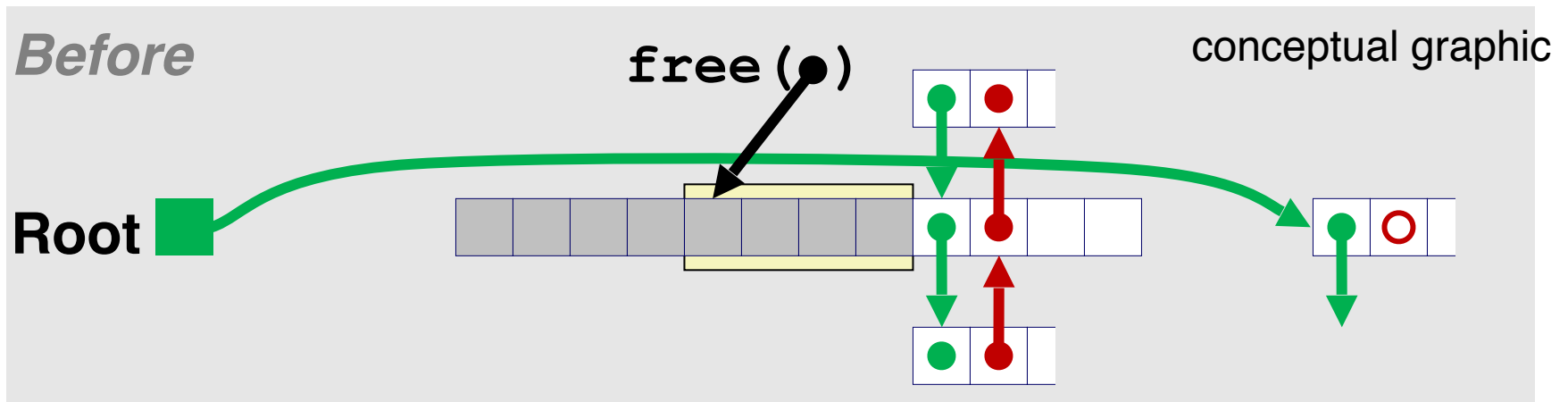


After



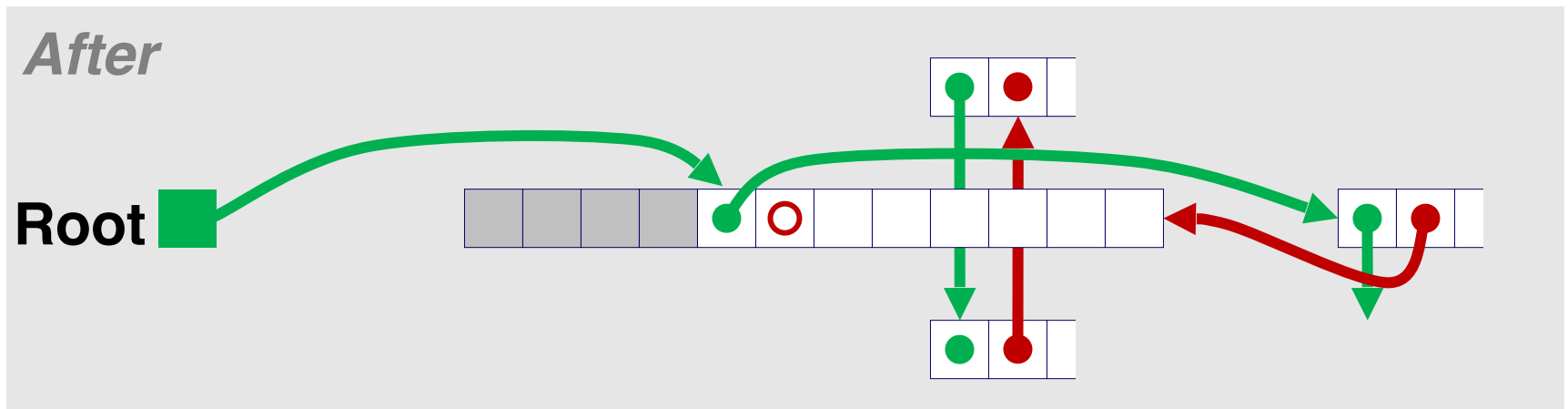
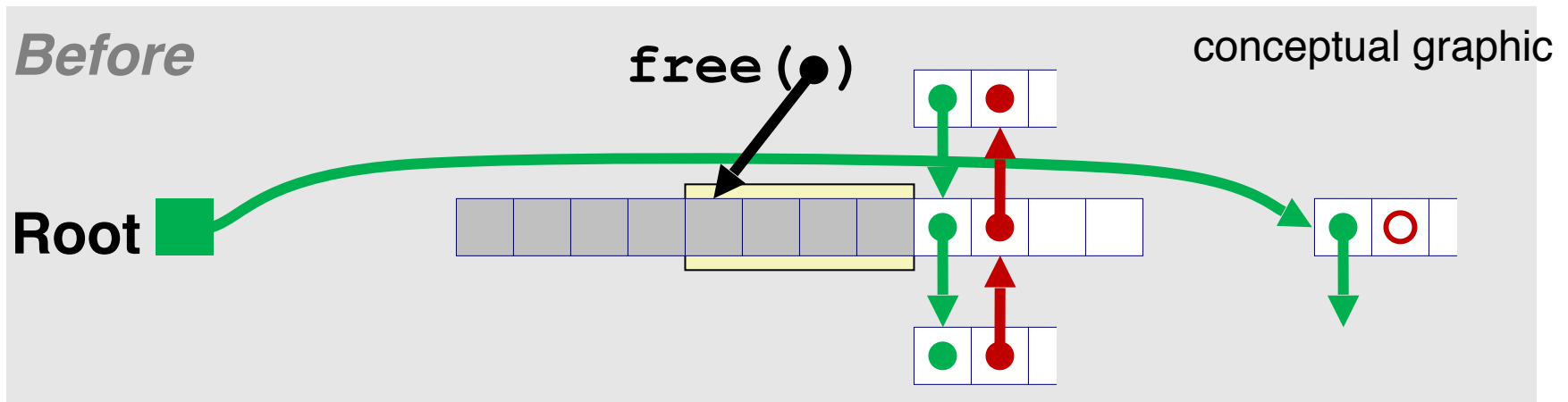
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- Splice out successor block, coalesce both memory blocks and insert the new block at the root of the list



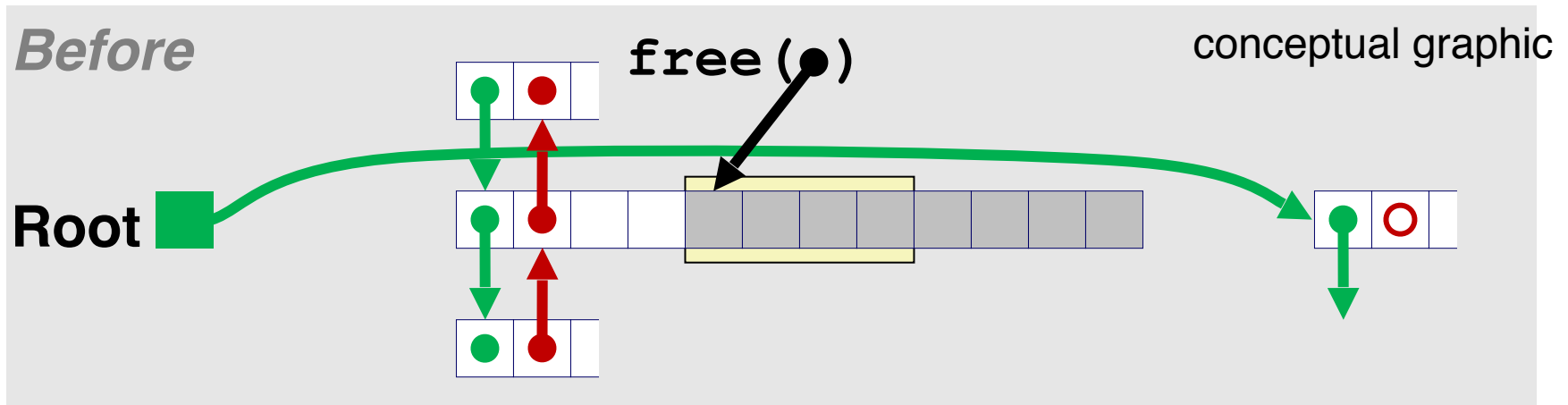
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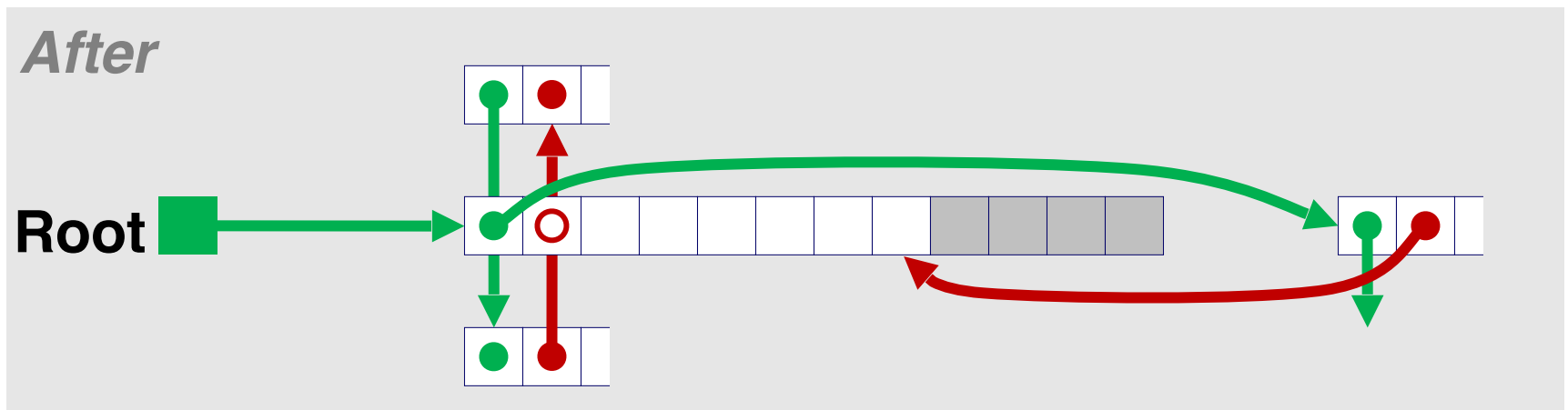
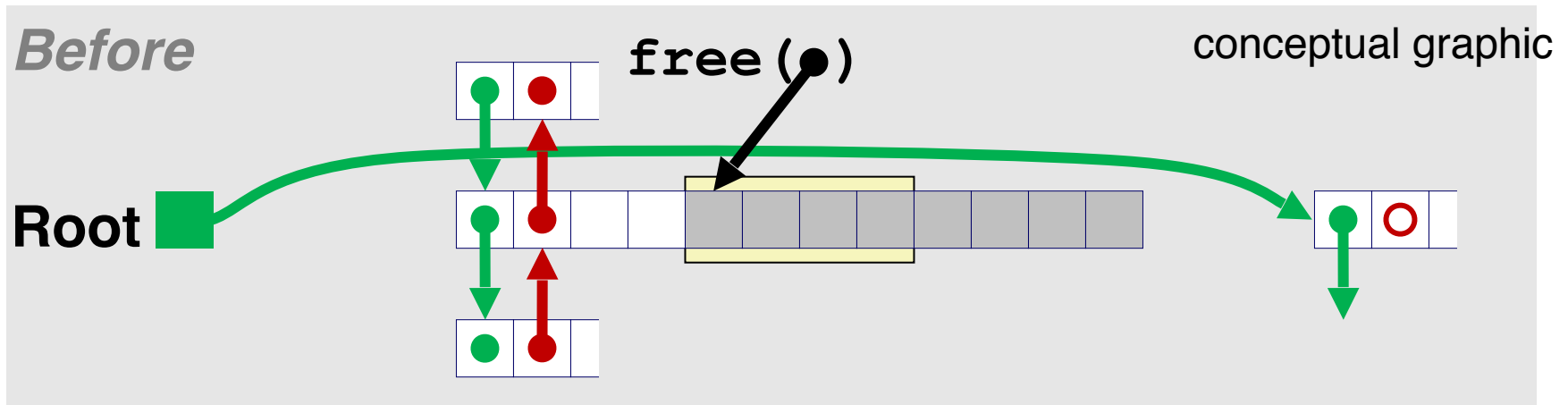
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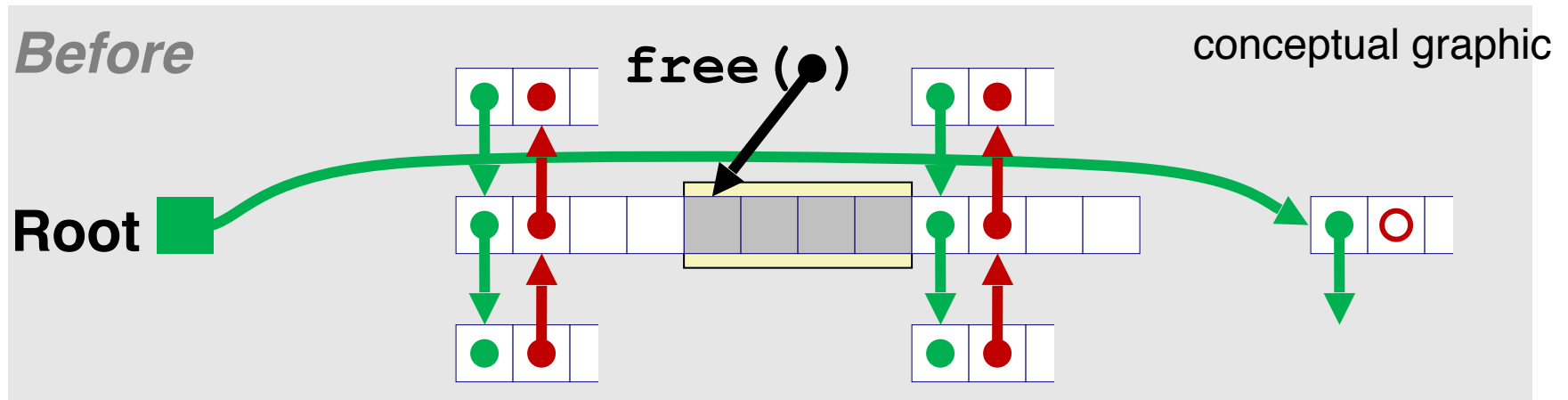
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Freeing With a LIFO Policy (Case 4)

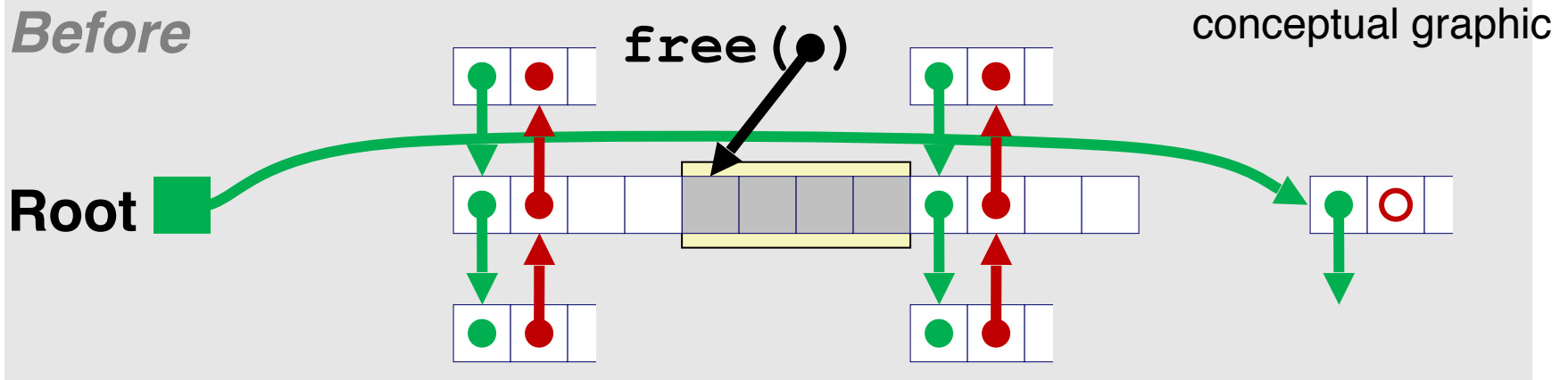
- Splice out predecessor and successor blocks, coalesce all 3 memory blocks and insert the new block at the root of the list



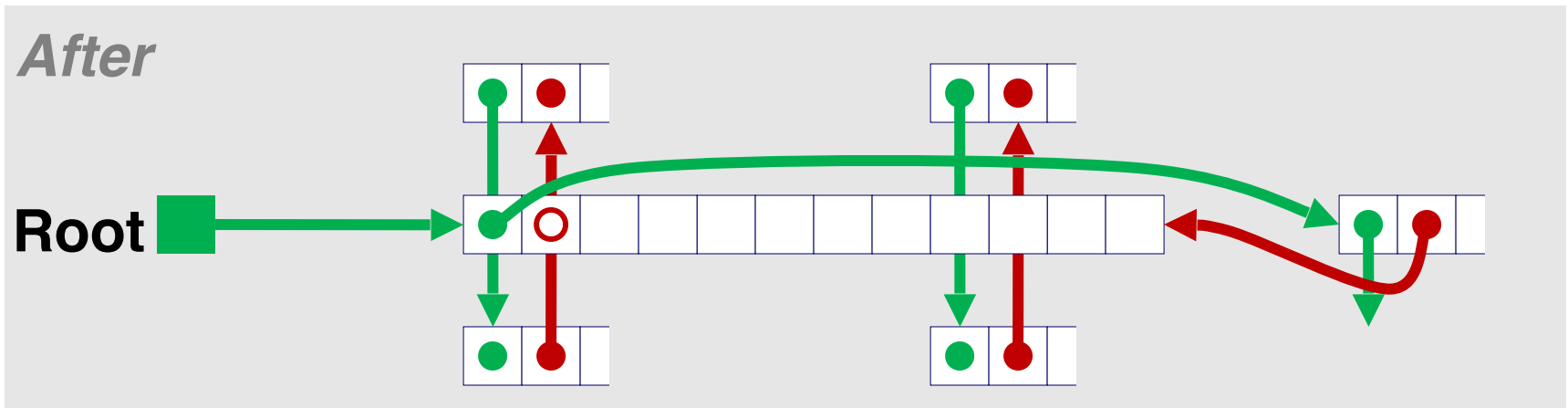
Freeing With a LIFO Policy (Case 4)

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Before



After

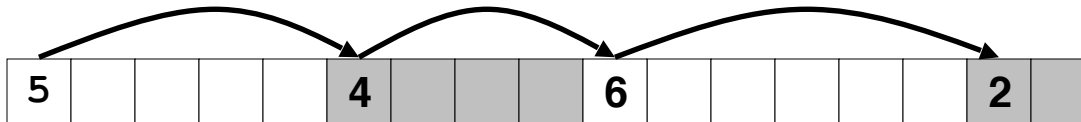


Explicit List Summary

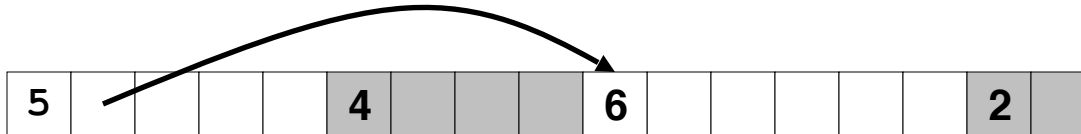
- Comparison to implicit list:
 - Allocate is linear time in number of **free** blocks instead of **all** blocks. Much faster when most of the memory is full.
 - Slightly more complicated allocate and free since needs to splice blocks in and out of the list
 - Some extra space for the links (2 extra words needed for each block). Increase internal fragmentation.

Keeping Track of Free Blocks

- Method 1: *Implicit list* using length—links all blocks



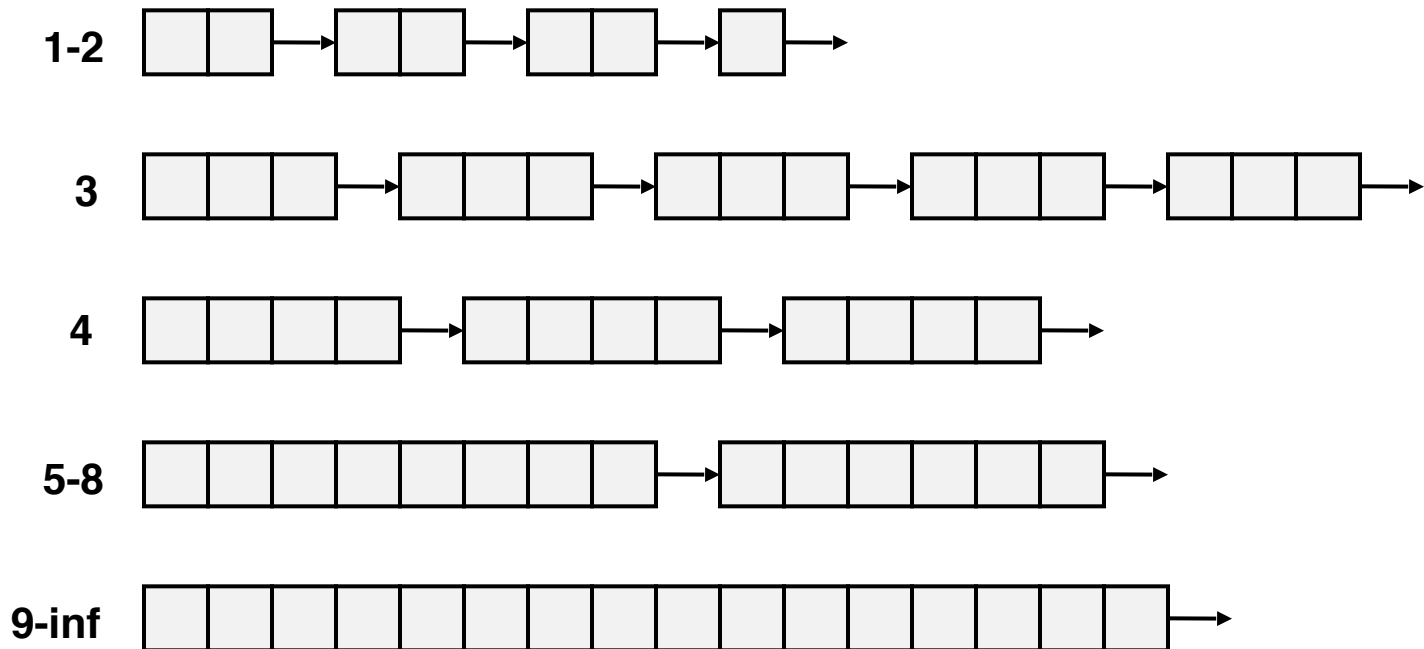
- Method 2: *Explicit list* among the free blocks using pointers



- Method 3: *Segregated free list*
 - Different free lists for different size classes

Segregated List (Seglist) Allocators

- Each *size class* of blocks has its own free list



- Often have separate classes for each small size
- For larger sizes: One class for each two-power size

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- To allocate a block of size n :
 - Search appropriate free list for block of size $m > n$
 - If an appropriate block is found:
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 - If no block is found, try next larger class
 - Repeat until block is found

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- If no block is found:
 - Request additional heap memory from OS (using `sbrk()`)
 - Remember heap is in VM, so request heap memory in pages
 - Allocate block of n bytes from this new memory
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- To free a block:
 - Coalesce and place on appropriate list

Advantages of Seglist allocators

- Higher throughput
 - log time for power-of-two size classes
- Better memory utilization
 - First-fit search of segregated free list approximates a best-fit search of entire heap.
 - Extreme case: Giving each block its own size class is equivalent to best-fit.

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```
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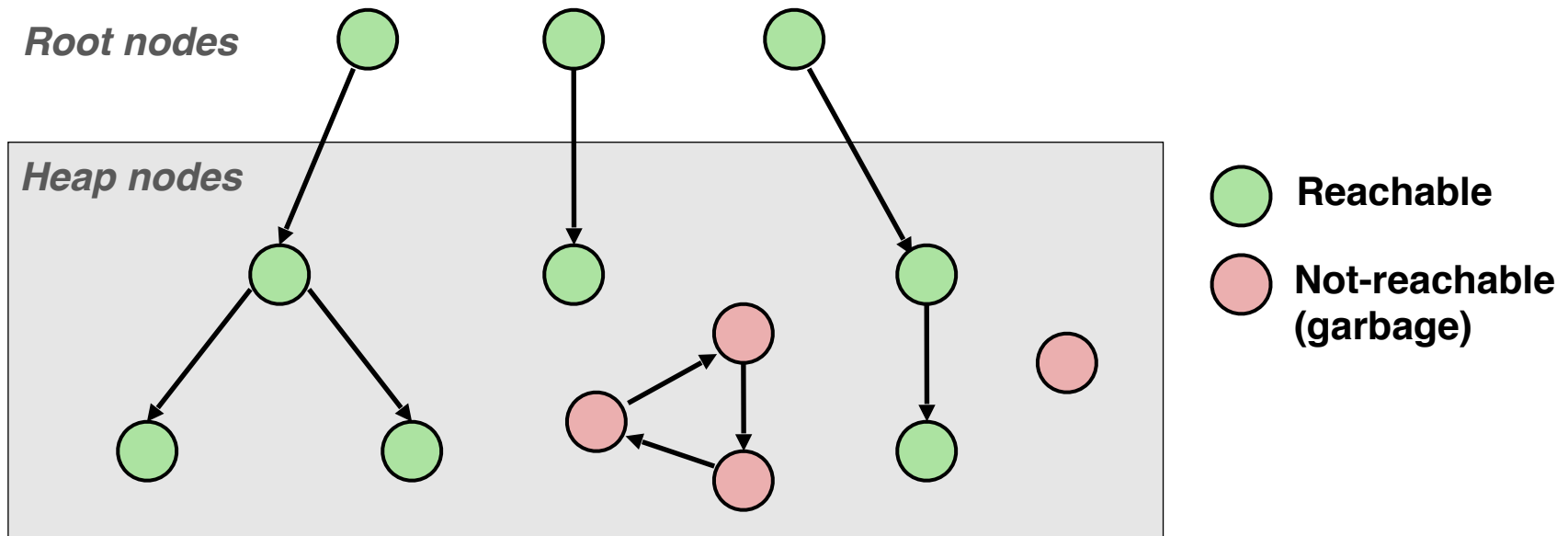
- Alternative: implicit memory management; the programmers never explicitly request/free memory
- Common in many dynamic languages:
 - Python, Ruby, Java, JavaScript, Perl, ML, Lisp, Mathematica
- The key: **Garbage collection**
 - Automatic reclamation of heap-allocated storage — application never has to free

Garbage Collection

- How does the memory manager know when certain memory blocks can be freed?
 - In general we cannot know what is going to be used in the future since it depends on program's future behaviors
 - But we can tell that certain blocks cannot possibly be used if *there are no pointers to them*
 - Garbage collection is essentially to obtain all **reachable** blocks and discard unreachable blocks.

Memory as a Graph

- We view memory as a directed graph
 - Each block is a node in the graph
 - Each pointer is an edge in the graph
 - Locations not in the heap that contain pointers into the heap are called **root** nodes (e.g. registers, locations on the stack, global variables)



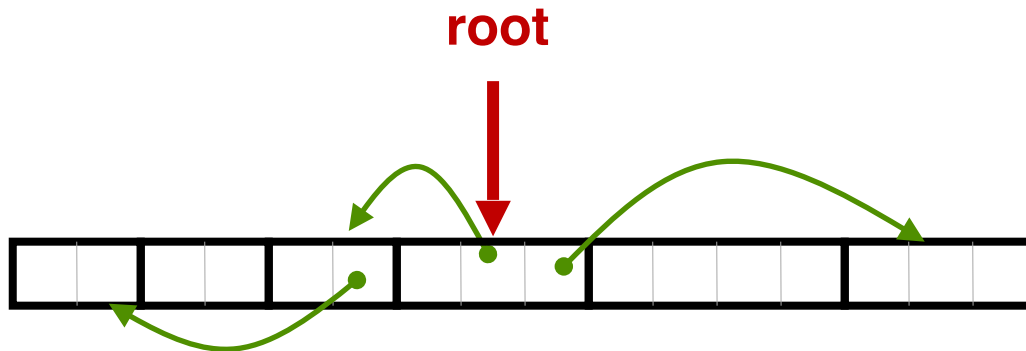
A node (block) is **reachable** if there is a path from any root to that node.

Non-reachable nodes are **garbage** (cannot be needed by the application)

Mark and Sweep Collecting

- Idea:

- Use extra **mark bit** in the head to indicate if a block is reachable
- **Mark**: Start at roots and set mark bit on each reachable block
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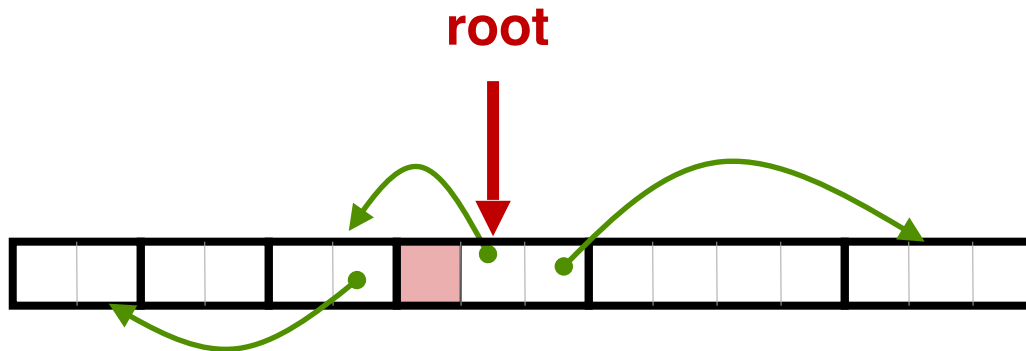
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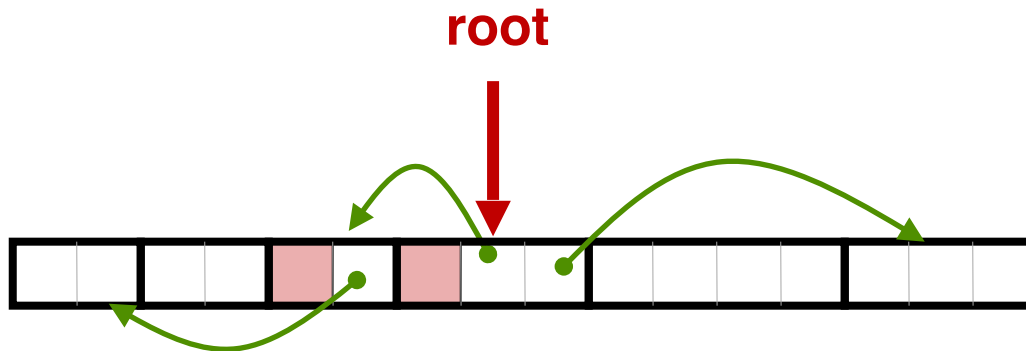
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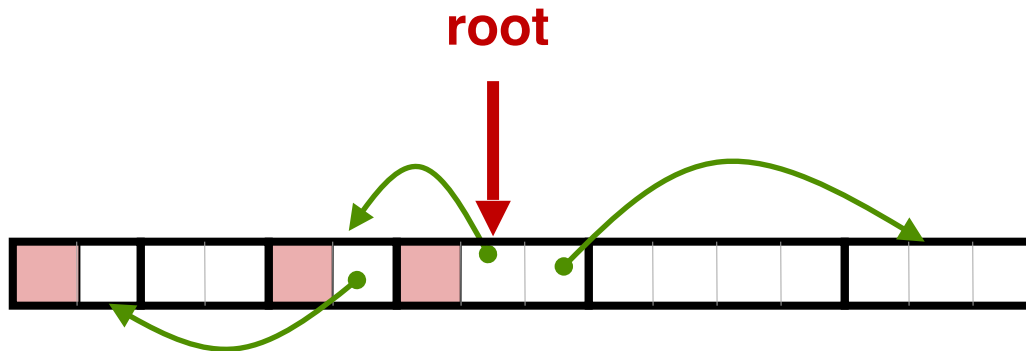
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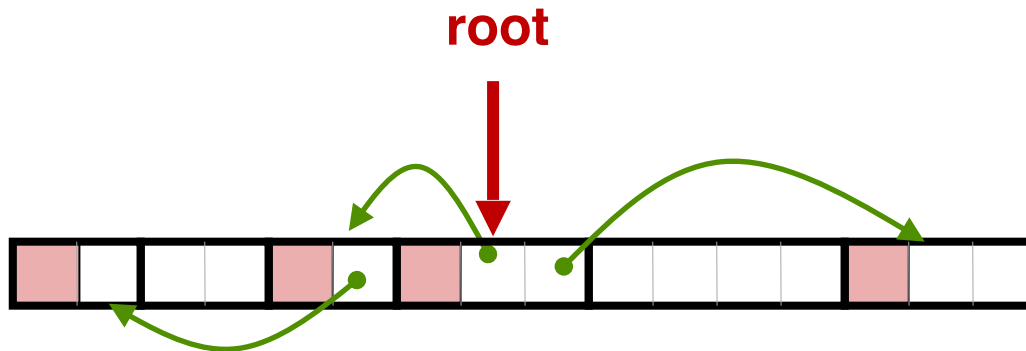
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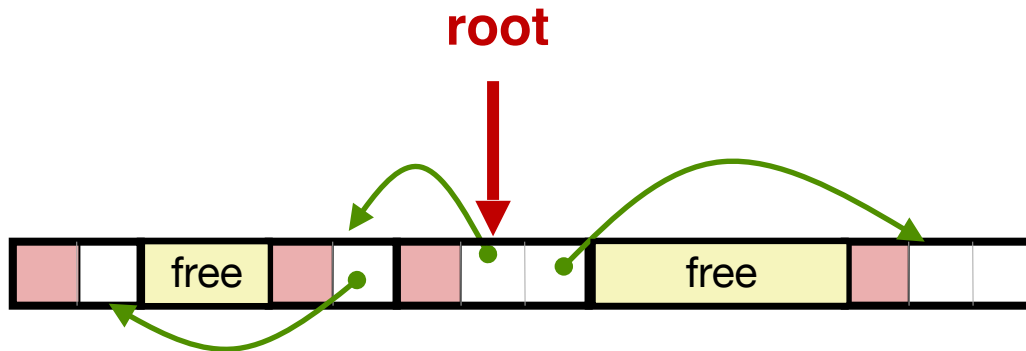
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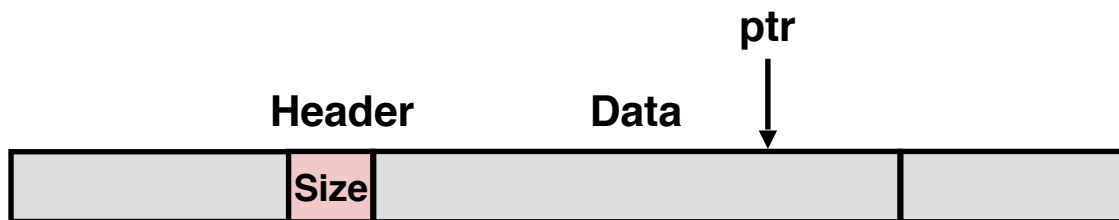
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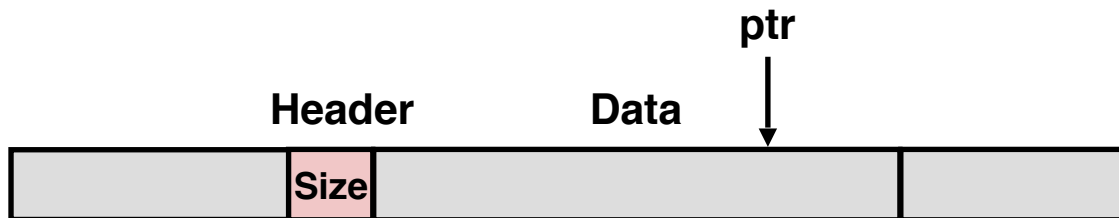
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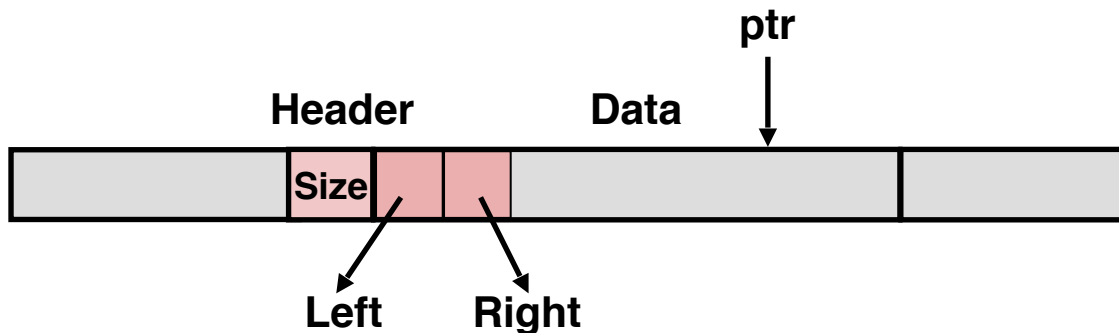
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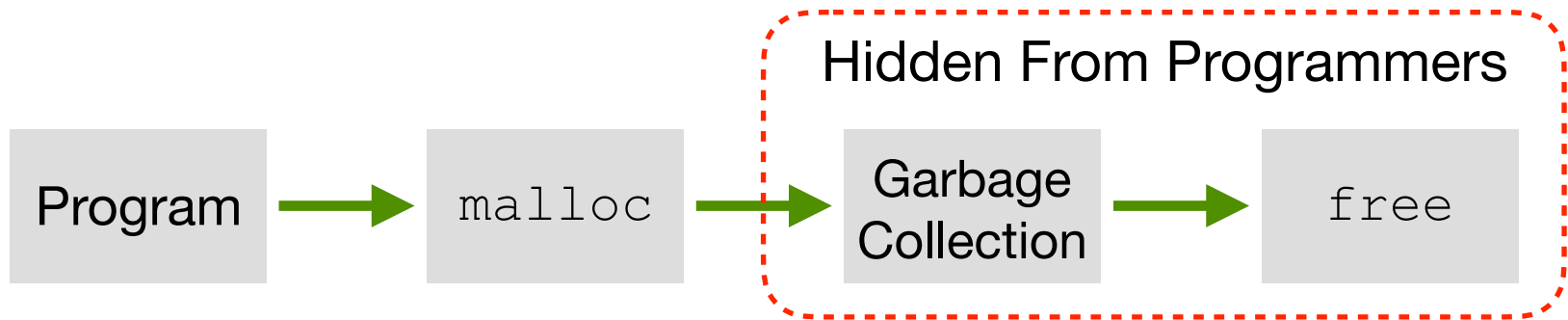
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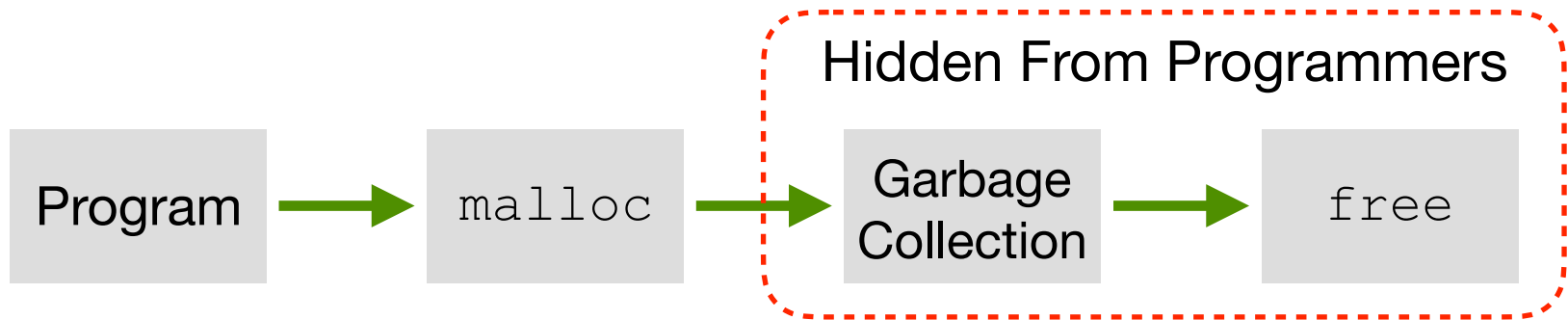
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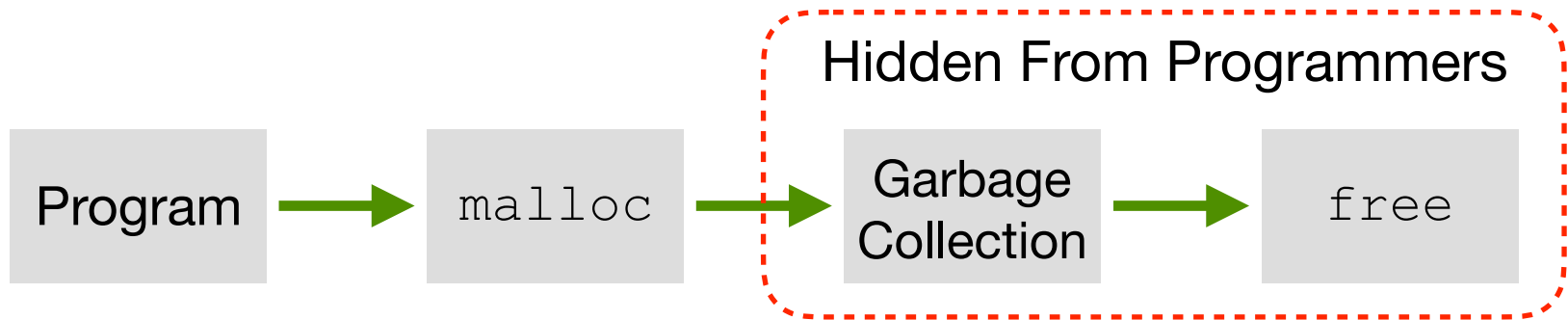
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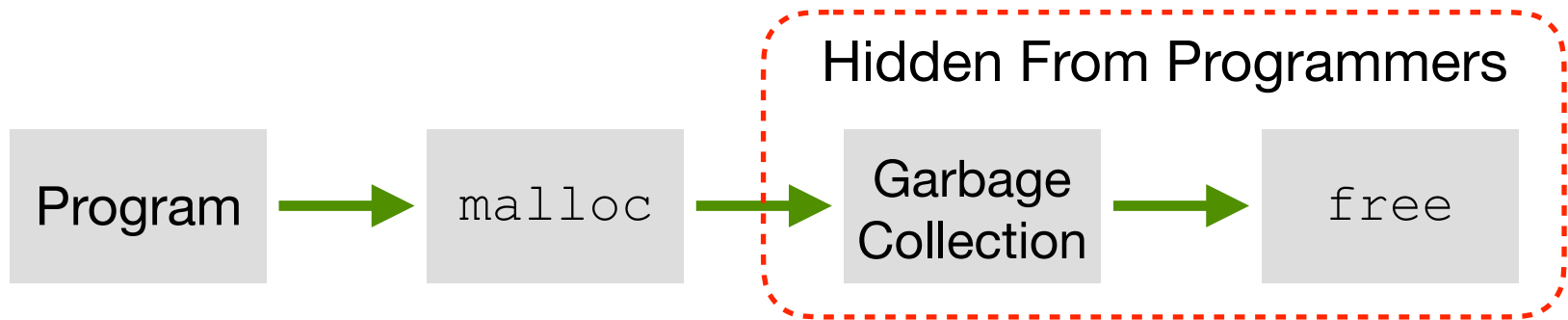
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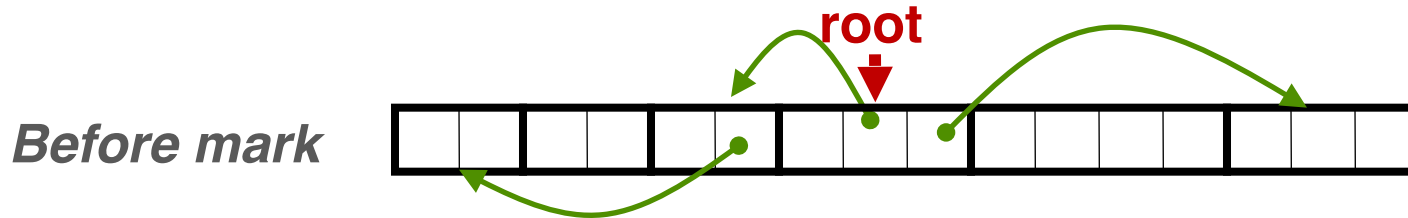
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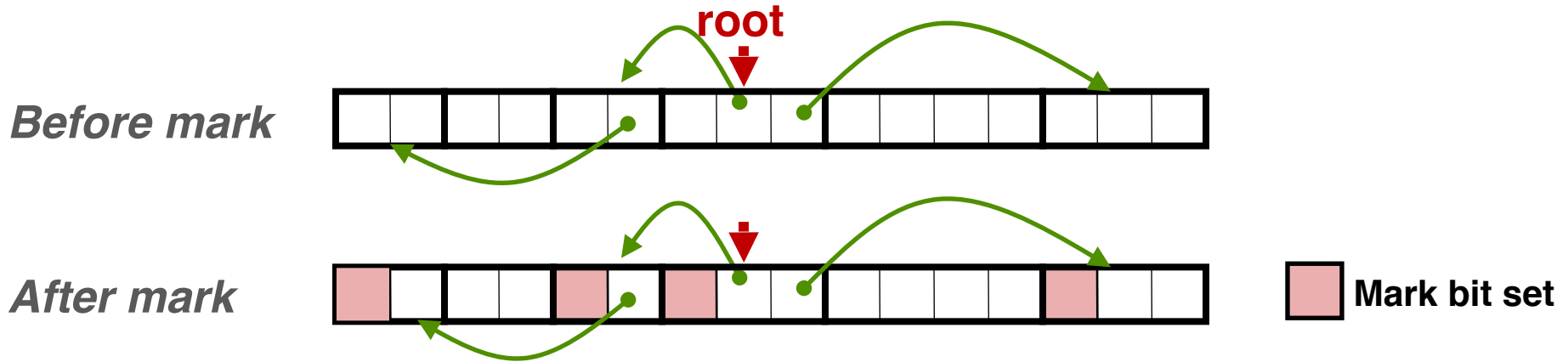
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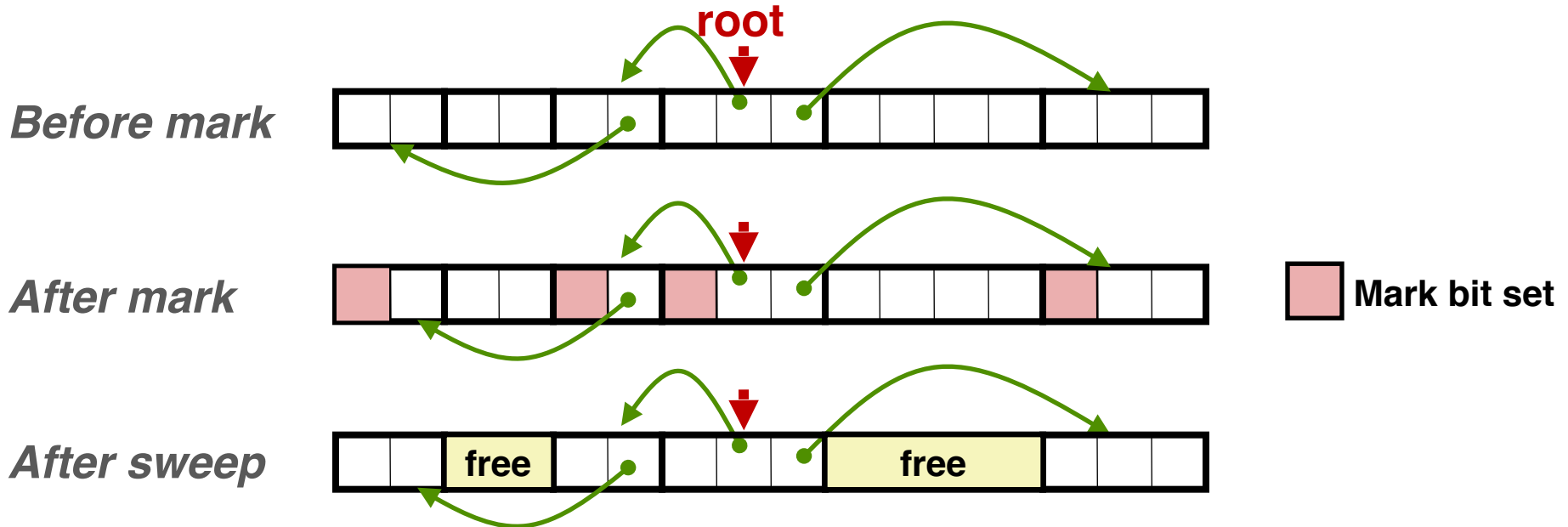
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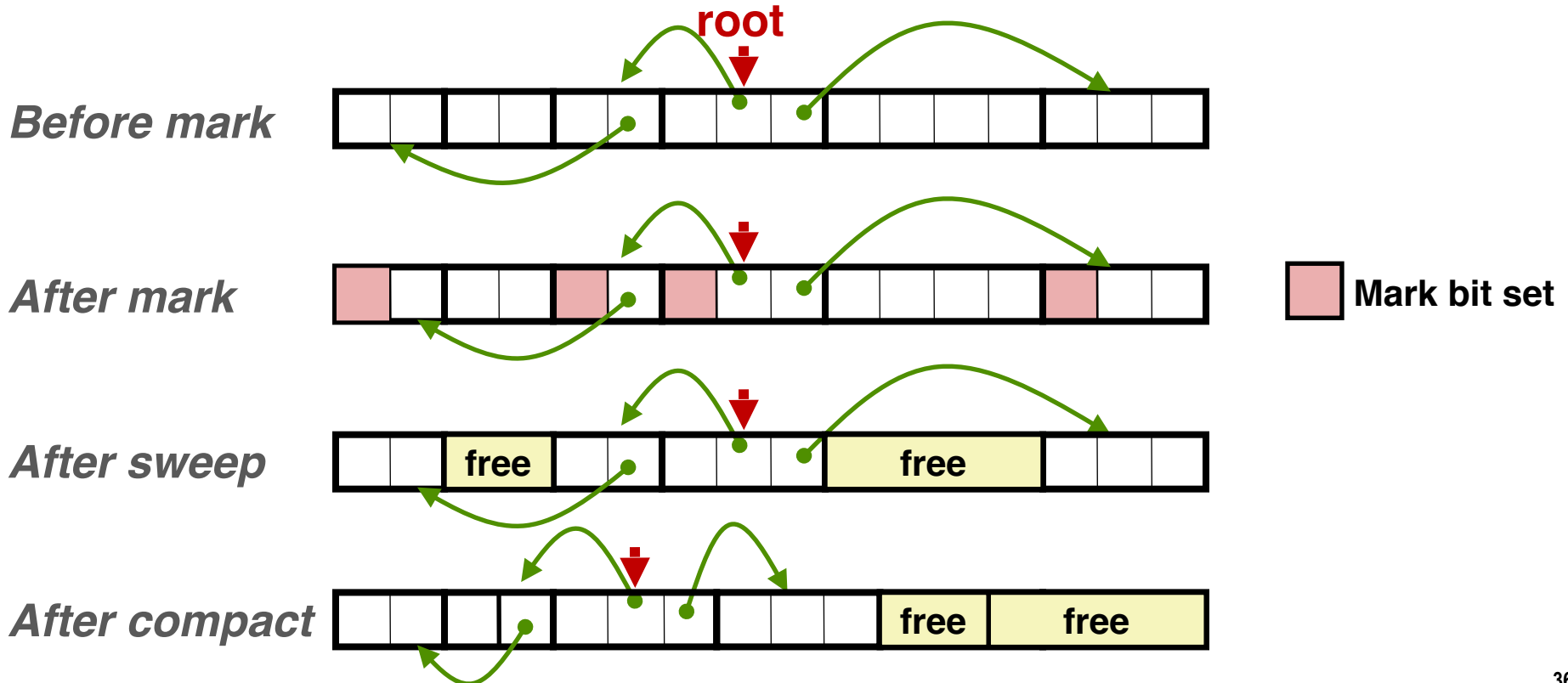
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- **Question: Can all these algorithms be used for GC in C?**

Jones and Lin, “Garbage Collection: Algorithms for Automatic Dynamic Memory”, 1996.

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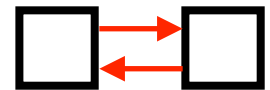
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