18-600 Foundations of Computer Systems

Lecture 19:
"Dynamic Memory Allocation"

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November 7, 2016

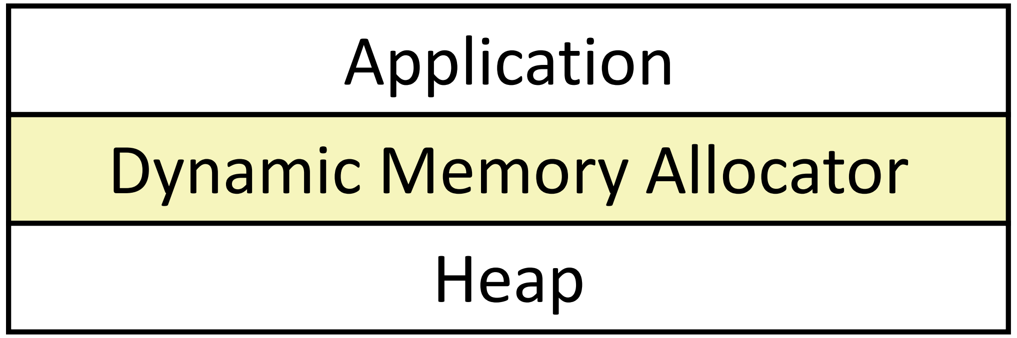
➢ Required Reading Assignment:
- **Chapter 9 of CS:APP (3rd edition) by Randy Bryant & Dave O'Hallaron**

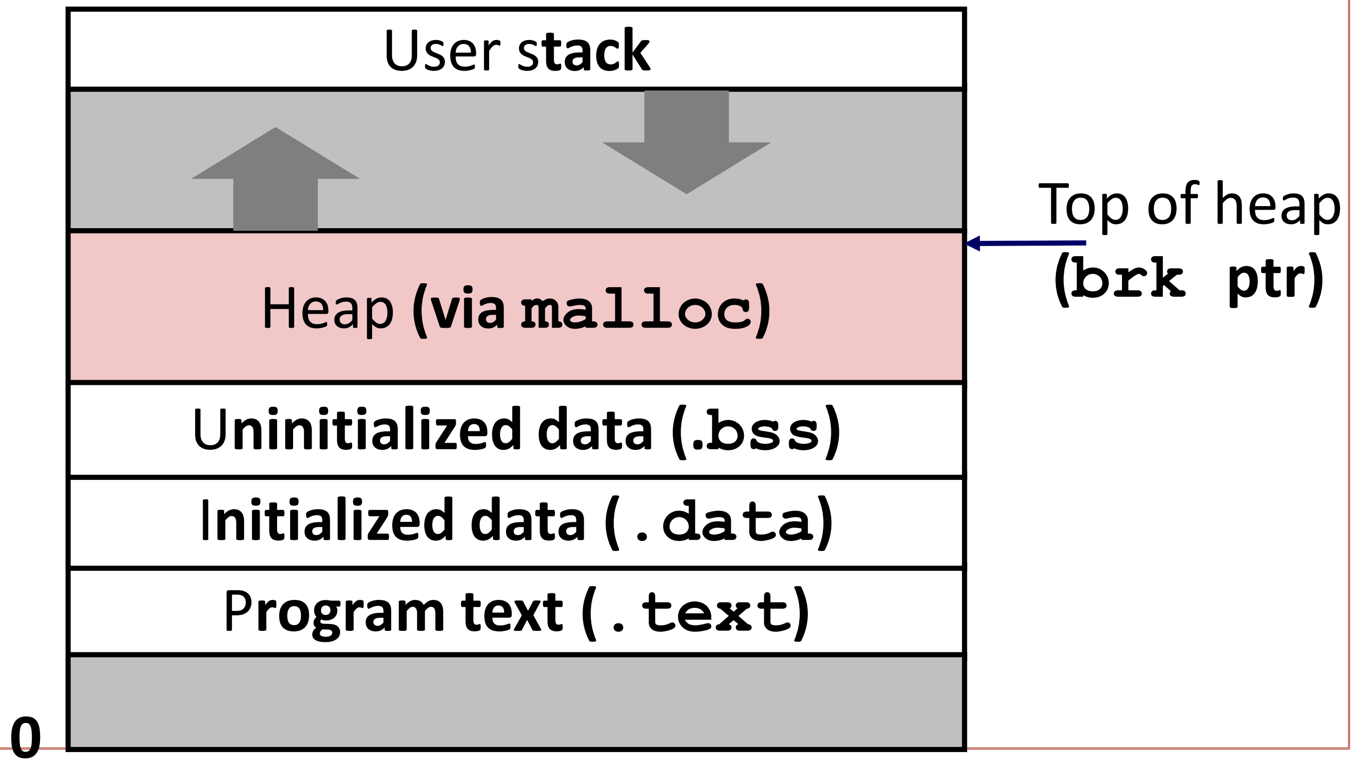
Today

- Basic concepts
- Implicit free lists
- Explicit free lists
- Segregated free lists
- Garbage collection
- Memory-related perils and pitfalls

Dynamic Memory Allocation

- Programmers use *dynamic memory allocators* (such as `malloc`) to acquire VM at run time.
  - For data structures whose size is only known at runtime.
- Dynamic memory allocators manage an area of process virtual memory known as the *heap*.
- Allocator maintains heap as collection of variable sized *blocks*, which are either *allocated* or *free*
- Types of allocators
  - ***Explicit allocator***: application allocates and frees space
    - E.g., `malloc` and `free` in C
  - ***Implicit allocator:*** application allocates, but does not free space
    - E.g. garbage collection in Java, ML, and Lisp





The `malloc` Package

```
#include <stdlib.h>
```

```
void *malloc(size_t size)
```

- Successful:
  - Returns a pointer to a memory block of at least **`size`** bytes aligned to an 8-byte (x86) or 16-byte (x86-64) boundary
  - If **`size == 0`**, returns NULL
- Unsuccessful: returns NULL (0) and sets **`errno`**

```
void free(void *p)
```

- Returns the block pointed at by **`p`** to pool of available memory
- **`p`** must come from a previous call to **`malloc`** or **`realloc`**

Other functions

- **`calloc`**: Version of **`malloc`** that initializes allocated block to zero.
- **`realloc`**: Changes the size of a previously allocated block.
- **`sbrk`**: Used internally by allocators to grow or shrink the heap

malloc Example

```
#include <stdio.h>
#include <stdlib.h>

void foo(int n) {
   int i, *p;

   /* Allocate a block of n ints */
   p = (int *) malloc(n * sizeof(int));
   if (p == NULL) {
      perror("malloc");
      exit(0);
   }

   /* Initialize allocated block */
   for (i=0; i<n; i++)
            p[i] = i;

   /* Return allocated block to the heap */
   free(p);
}
```

Allocation Example

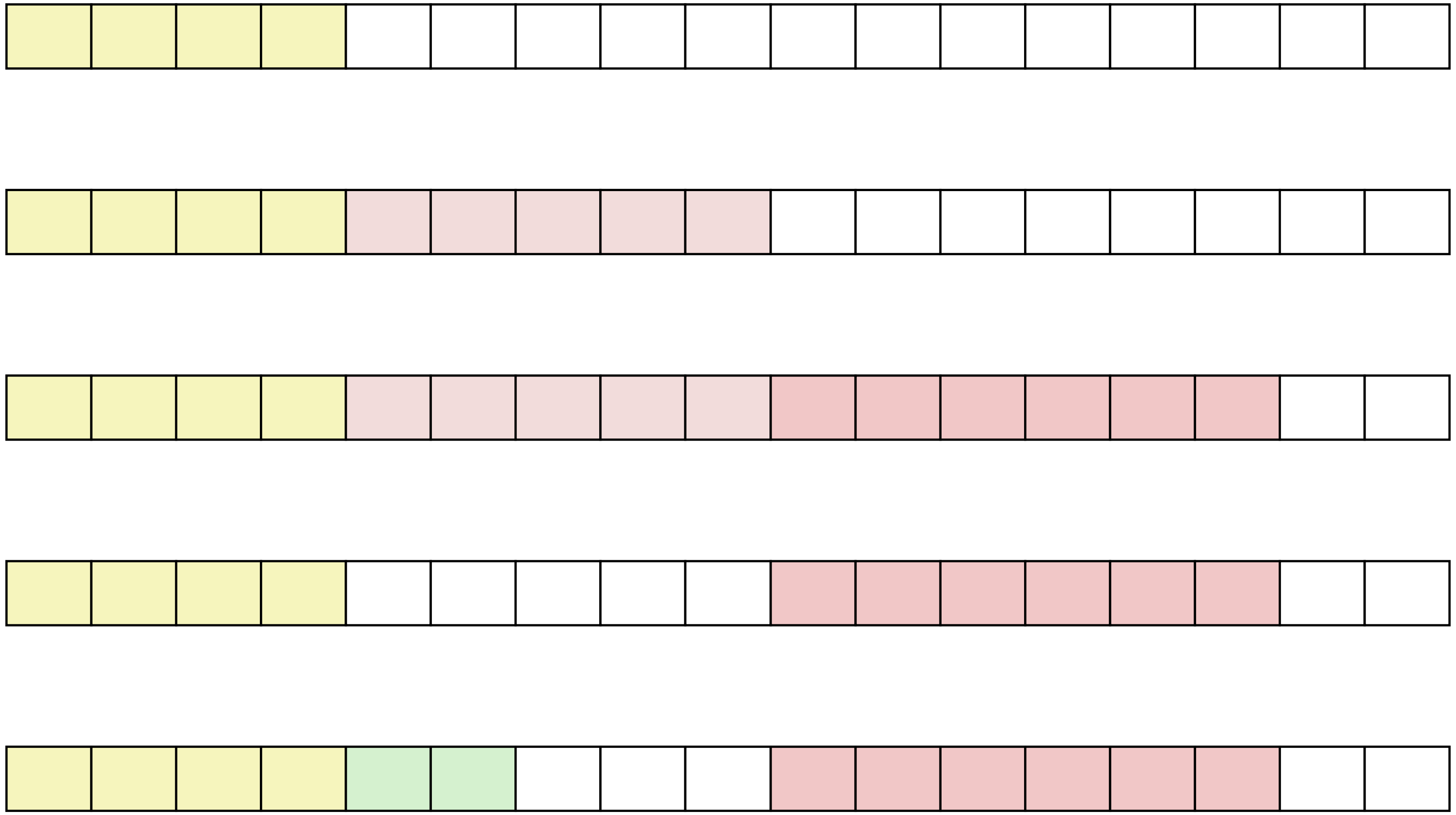
```
p1 = malloc(4)

p2 = malloc(5)

p3 = malloc(6)

free(p2)

p4 = malloc(2)
```



- Assumption
  - Memory is word addressed.
  - Words are int-sized.

Constraints

- Applications
  - Can issue arbitrary sequence of **`malloc`** and **`free`** requests
  - **`free`** request must be to a **`malloc`**'d block
- Allocators
  - Can't control number or size of allocated blocks
  - Must respond immediately to **`malloc`** requests
    - *i.e.*, can't reorder or buffer requests
  - Must allocate blocks from free memory
    - *i.e.*, can only place allocated blocks in free memory
  - Must align blocks so they satisfy all alignment requirements
    - 8-byte (x86) or 16-byte (x86-64) alignment on Linux boxes
  - Can manipulate and modify only free memory
  - Can't move the allocated blocks once they are **`malloc`**'d
    - *i.e.*, compaction is not allowed

Performance Goal: Throughput

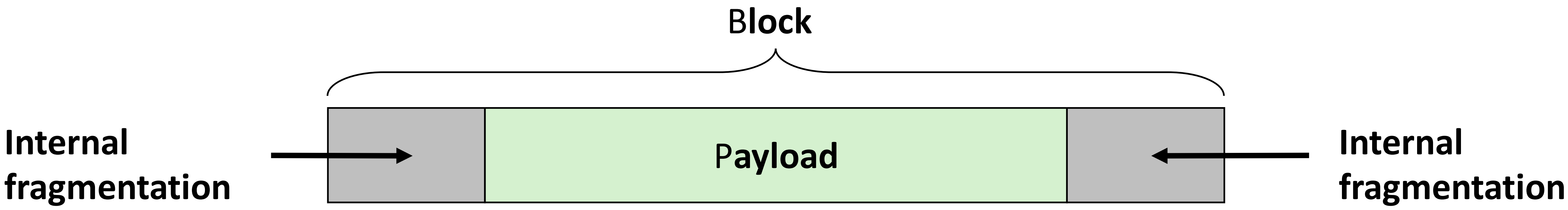
- Given some sequence of `malloc` and `free` requests:
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$
- Goals: maximize throughput and peak memory utilization
  - These goals are often conflicting
- Throughput:
  - Number of completed requests per unit time
  - Example:
    - 5,000 **`malloc`** calls and 5,000 **`free`** calls in 10 seconds
    - Throughput is 1,000 operations/second

Performance Goal: Peak Memory Utilization

- Given some sequence of `malloc` and `free` requests:
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$
- *Def: Aggregate payload P_k*
  - **`malloc(p)`** results in a block with a ***payload*** of **`p`** bytes
  - After request R_k completed, the ***aggregate payload*** P_k is the sum of currently allocated payloads
- *Def: Current heap size H_k*
  - Assume H_k is monotonically nondecreasing
    - i.e., heap only grows when allocator uses **`sbrk`**
- *Def: Peak memory utilization after k+1 requests*
  - $U_k = (\max_{i<=k} P_i) \ / \ H_k$
- Poor memory utilization caused by *fragmentation*: ***internal*** fragmentation and ***external*** fragmentation

Internal Fragmentation

- For a given block, *internal fragmentation* occurs if payload is smaller than block size



- Caused by
  - Overhead of maintaining heap data structures
  - Padding for alignment purposes
  - Explicit policy decisions
    (e.g., to return a big block to satisfy a small request)

- Depends only on the pattern of *previous* requests
  - Thus, easy to measure

External Fragmentation

- Occurs when there is enough aggregate heap memory, but no single free block is large enough

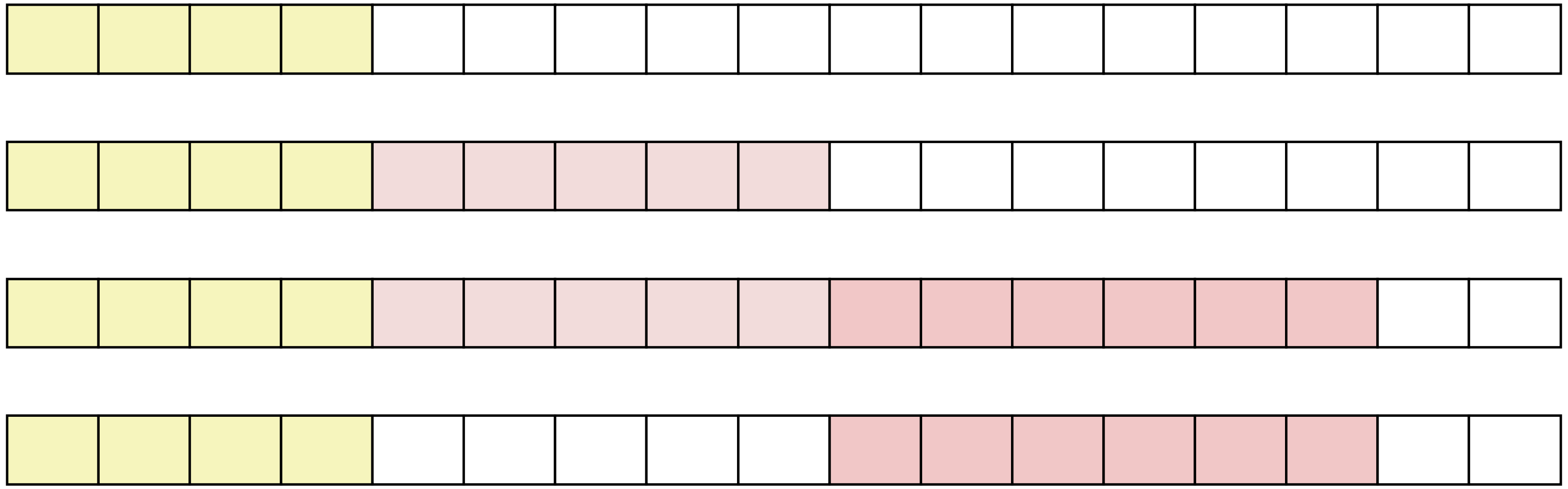
```
p1 = malloc(4)

p2 = malloc(5)

p3 = malloc(6)

free(p2)

p4 = malloc(6)
```



Oops! (what would happen now?)

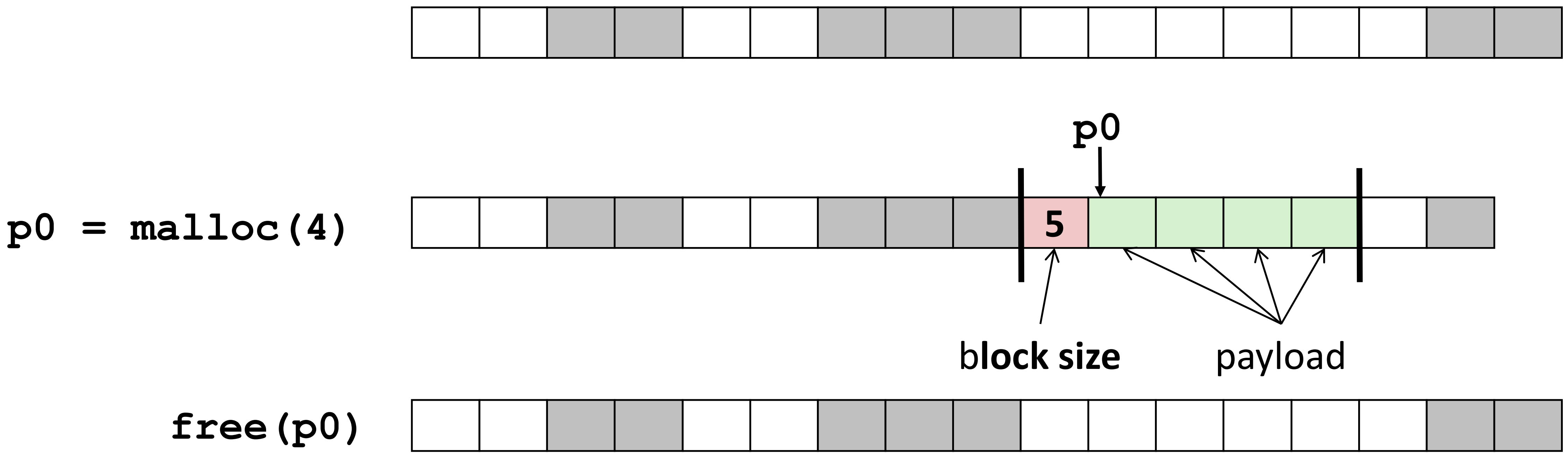
- Depends on the pattern of future requests
  - Thus, difficult to measure

Implementation Issues

- How do we know how much memory to free given just a pointer?
- How do we keep track of the free blocks?
- 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 pick a block to use for allocation -- many might fit?
- How do we reinsert freed block?

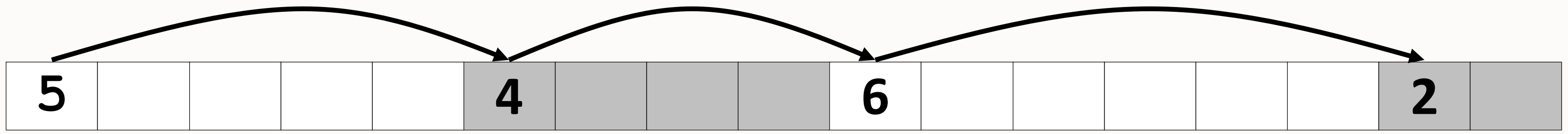
Knowing How Much to Free

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

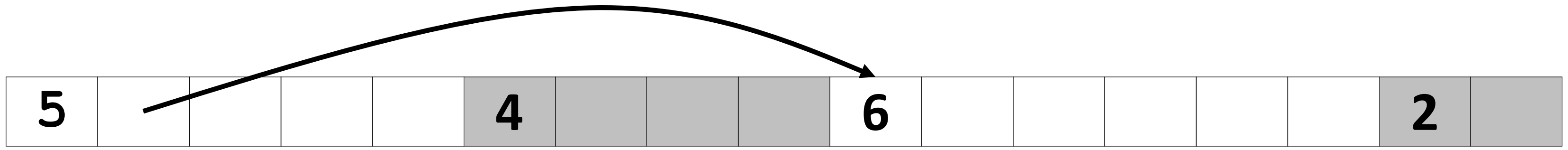


Keeping Track of Free Blocks

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

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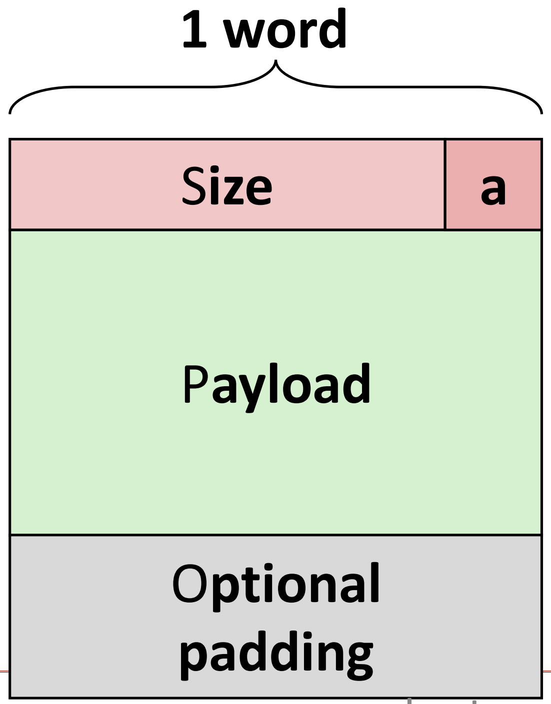
Method 1: Implicit List

- For each block we need both size and allocation status
  - Could store this information in two words: wasteful!
- 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
  - When reading size word, must mask out this bit



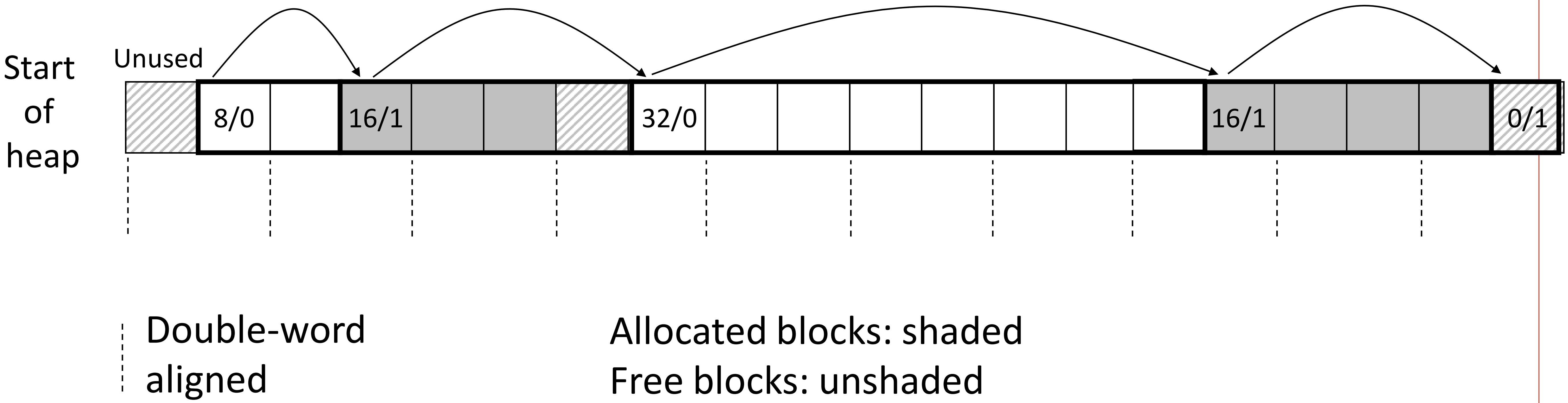
Format of allocated and free blocks

a = 1: Allocated block
a = 0: Free block

Size: block size

Payload: application data (allocated blocks only)

Detailed Implicit Free List Example



Allocated blocks: shaded
Free blocks: unshaded
Headers: labeled with size in bytes/allocated bit

Implicit List: Finding a Free Block

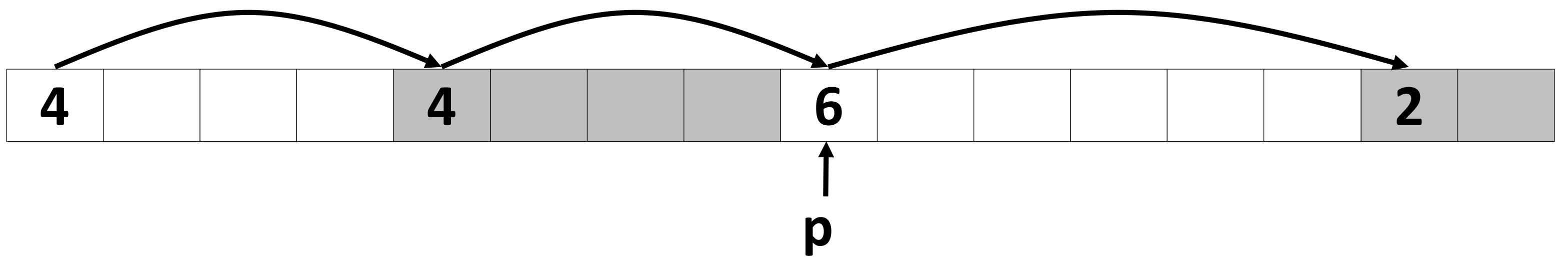
- *First fit:*
  - Search list from beginning, choose ***first*** free block that fits:

```
p = start;
while ((p < end) &&       \\ not passed end
       ((*p & 1) ||       \\ already allocated
       (*p  <= len)))     \\ too small
  p = p + (*p & -2);      \\ goto next block (word addressed)
```

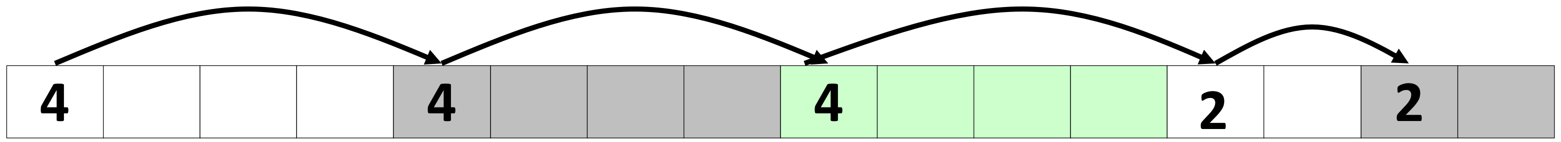
  - Can take linear time in total number of blocks (allocated and free)
  - In practice it can cause "splinters" at beginning of list
- *Next fit:*
  - Like first fit, but search list starting where previous search finished
  - Should often be faster than first fit: avoids re-scanning unhelpful blocks
  - Some research suggests that fragmentation is worse
- *Best fit:*
  - Search the list, choose the ***best*** free block: fits, with fewest bytes left over
  - Keeps fragments small—usually improves memory utilization
  - Will typically run slower than first fit

Implicit List: Allocating in Free Block

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



addblock(p, 4)



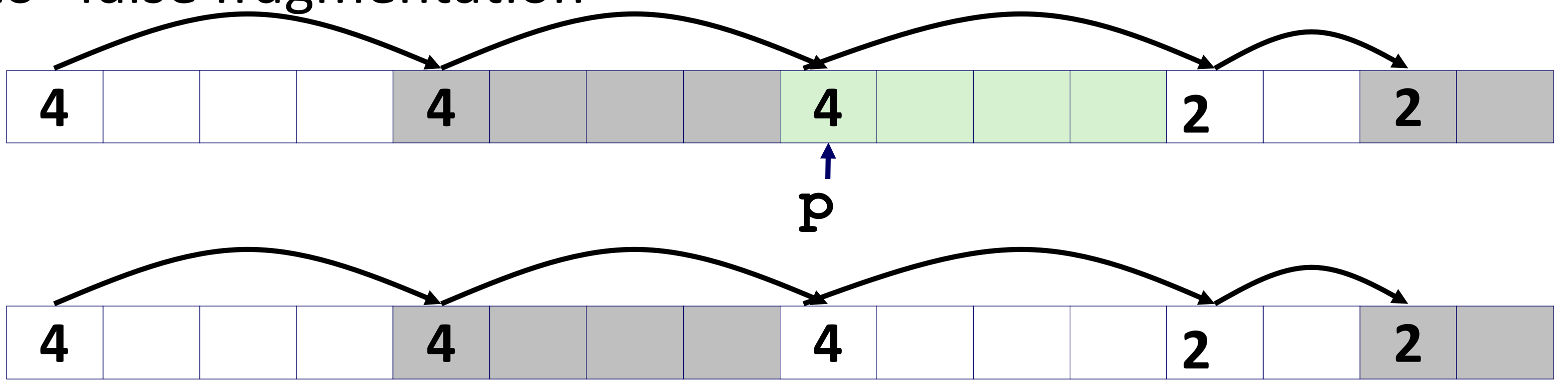

```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;   // round up to even
  int oldsize = *p & -2;                 // mask out low bit
  *p = newsize | 1;                      // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;    // set length in remaining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

Implicit List: Freeing a Block

- Simplest implementation:
  - Need only clear the "allocated" flag

```
void free_block(ptr p) { *p = *p & -2 }
```

  - But can lead to "false fragmentation"



`free(p)`

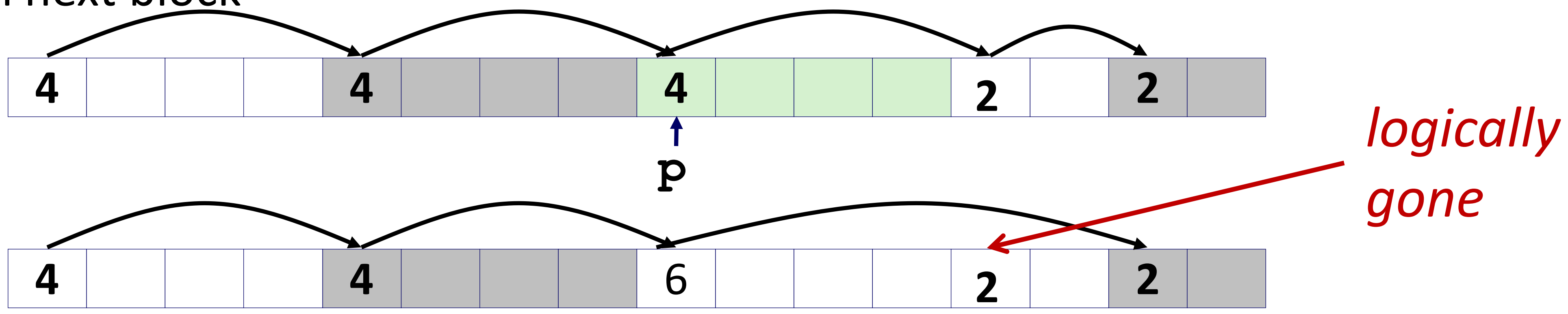
`malloc(5)` ***Oops!***

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

Implicit List: Coalescing

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

free(p)

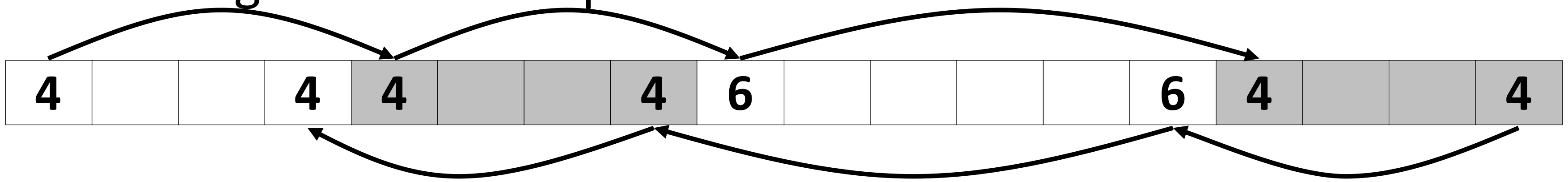



```
void free_block(ptr p) {
    *p = *p & -2;           // clear allocated flag
    next = p + *p;          // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;      // add to this block if
}                           //    not allocated
```

  - But how do we coalesce with *previous* block?

Implicit List: Bidirectional Coalescing

- *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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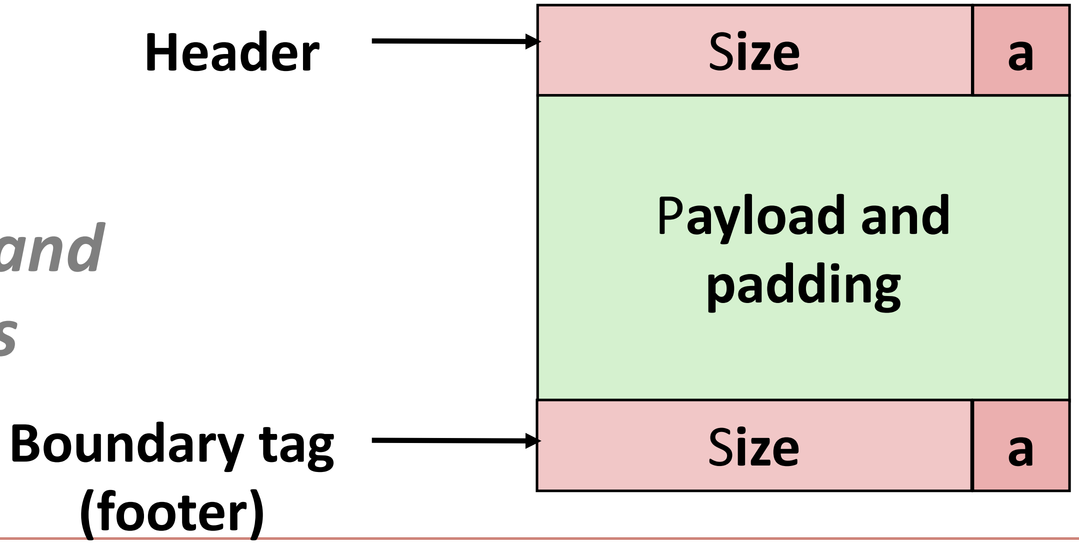

a = 1: Allocated block
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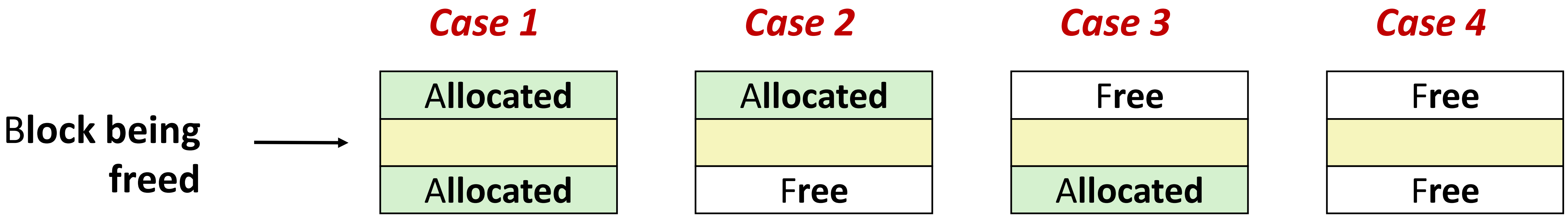
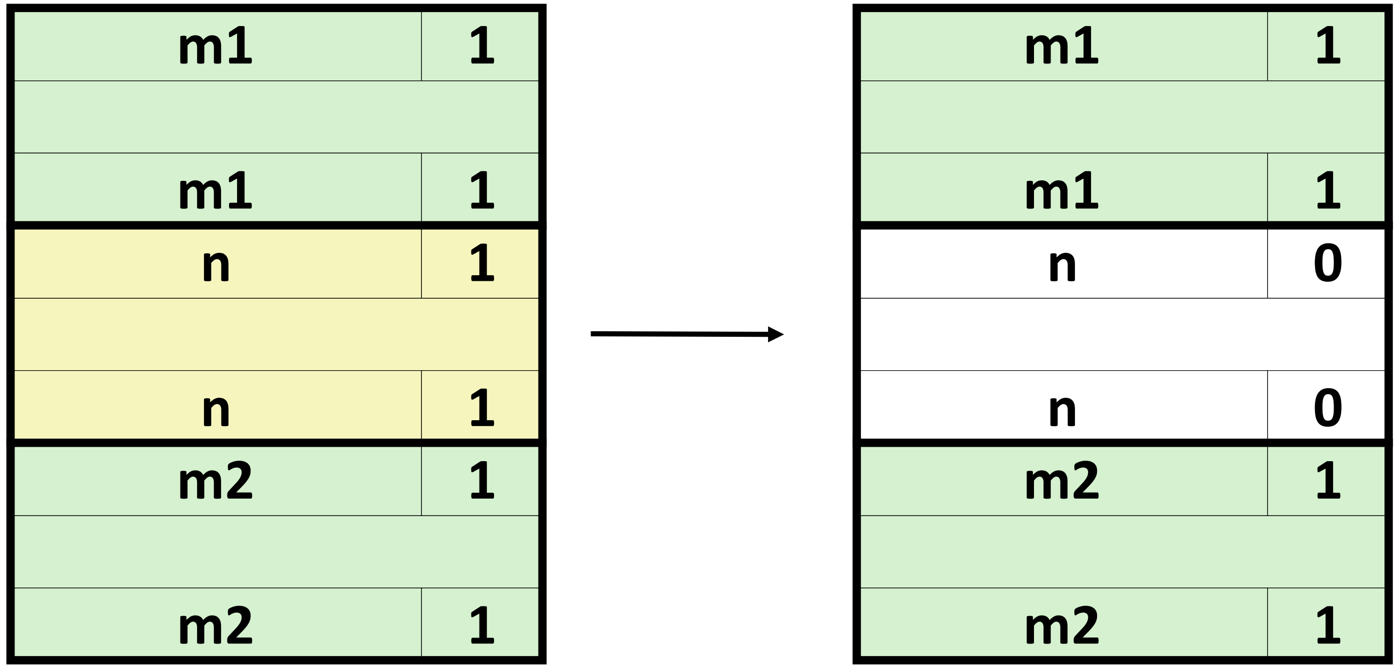
Size: Total block size

Payload: Application data (allocated blocks only)

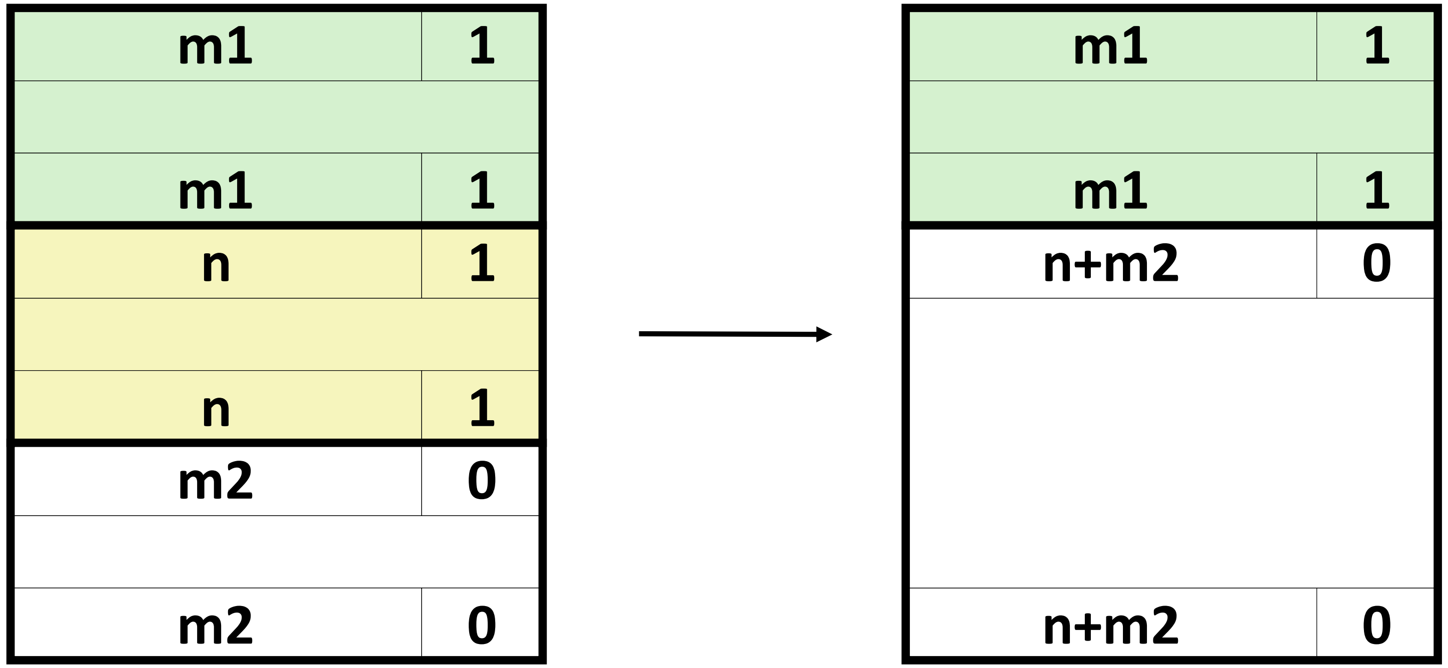
Constant Time Coalescing



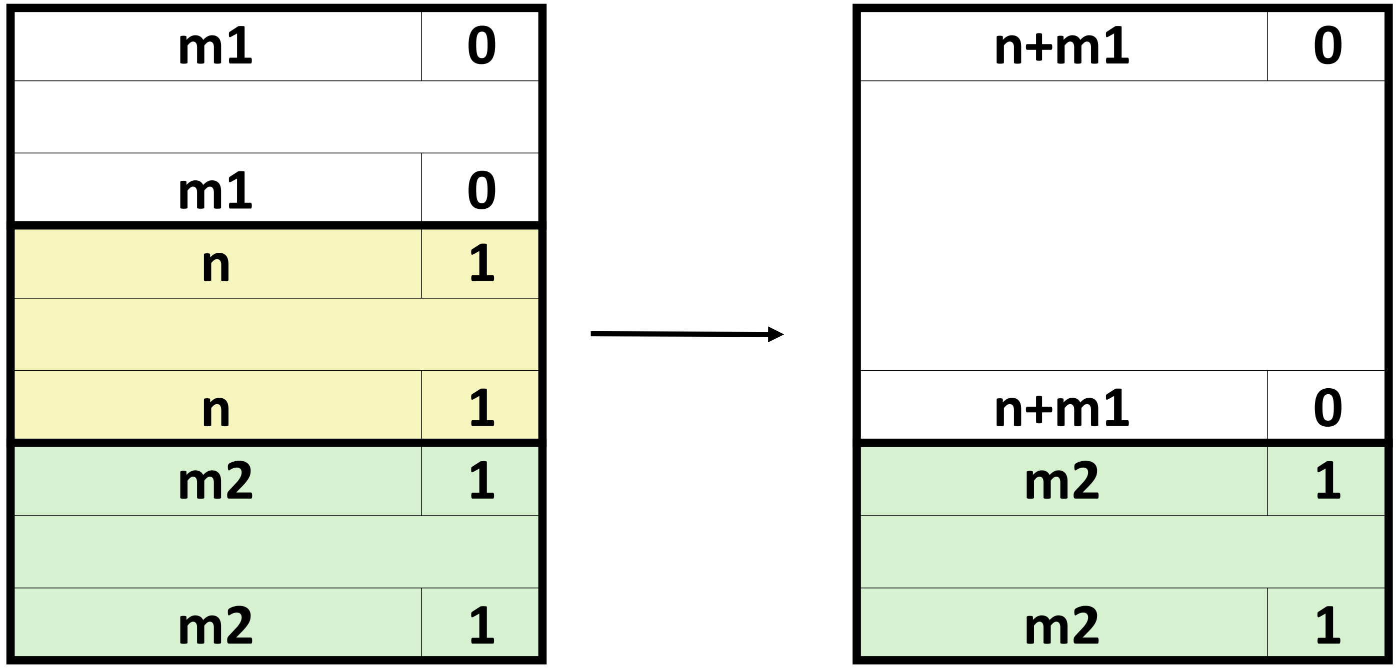
Constant Time Coalescing (Case 1)



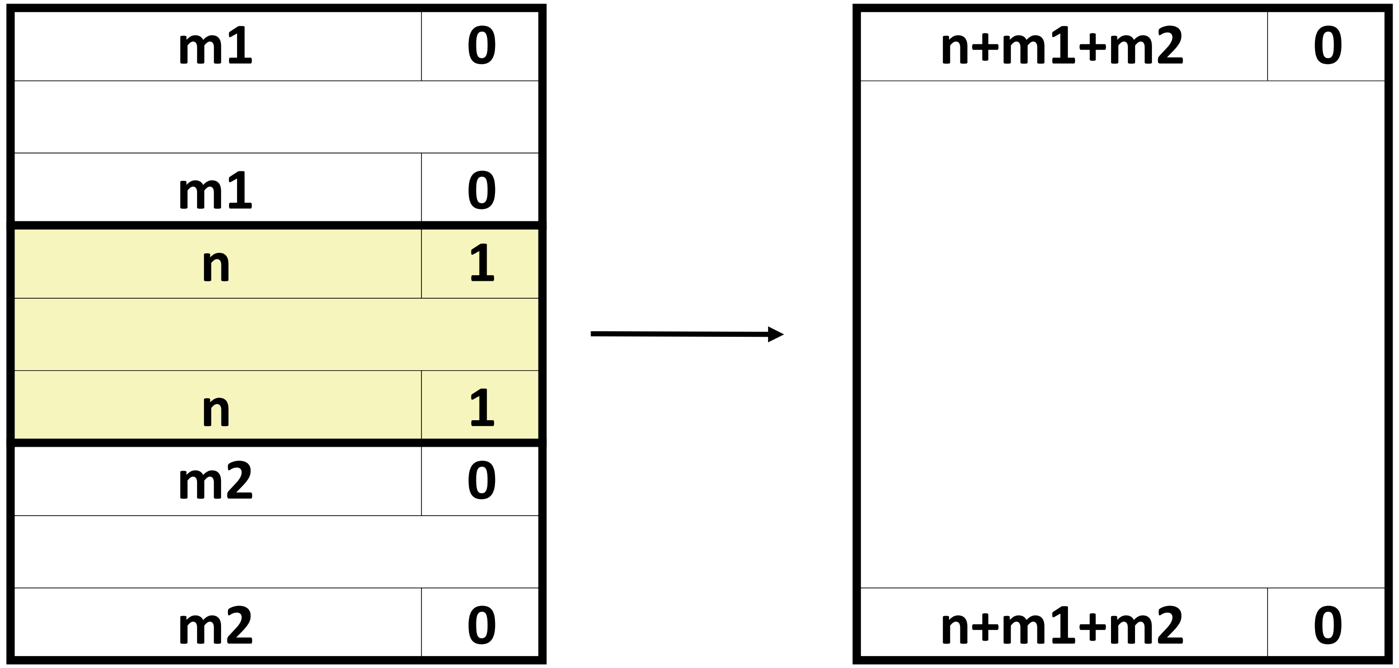
Constant Time Coalescing (Case 2)



Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)



Disadvantages of Boundary Tags

- Internal fragmentation

- Can it be optimized?
  - Which blocks need the footer tag? Only free blocks
  - What does that mean? Use another free bits to indicate free/allocated blocks

Summary of Key Allocator Policies

- Placement policy:
  - First-fit, next-fit, best-fit, etc.
  - Trades off lower throughput for less fragmentation
  - ***Interesting observation***: segregated free lists (next lecture) approximate a best fit placement policy without having to search entire free list
- Splitting policy:
  - When do we go ahead and 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

Implicit Lists: Summary

- Implementation: very simple
- Allocate cost:
  - linear time worst case
- Free cost:
  - constant time worst case
  - even with coalescing
- Memory usage:
  - will depend on placement policy
  - First-fit, next-fit or best-fit

- Not used in practice for `malloc/free` 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

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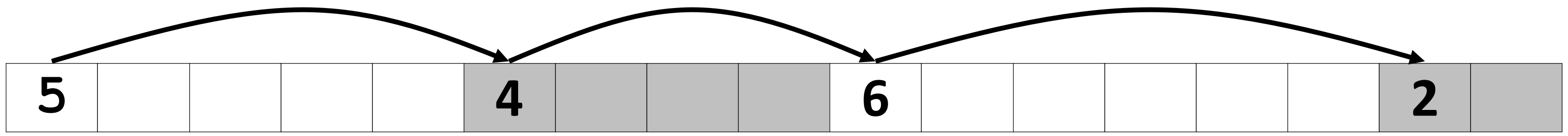
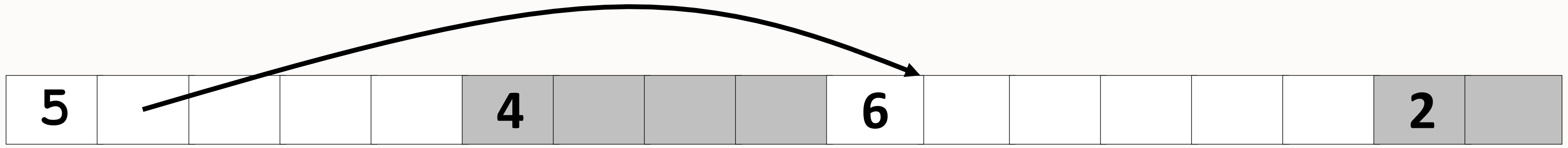
Keeping Track of Free Blocks

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

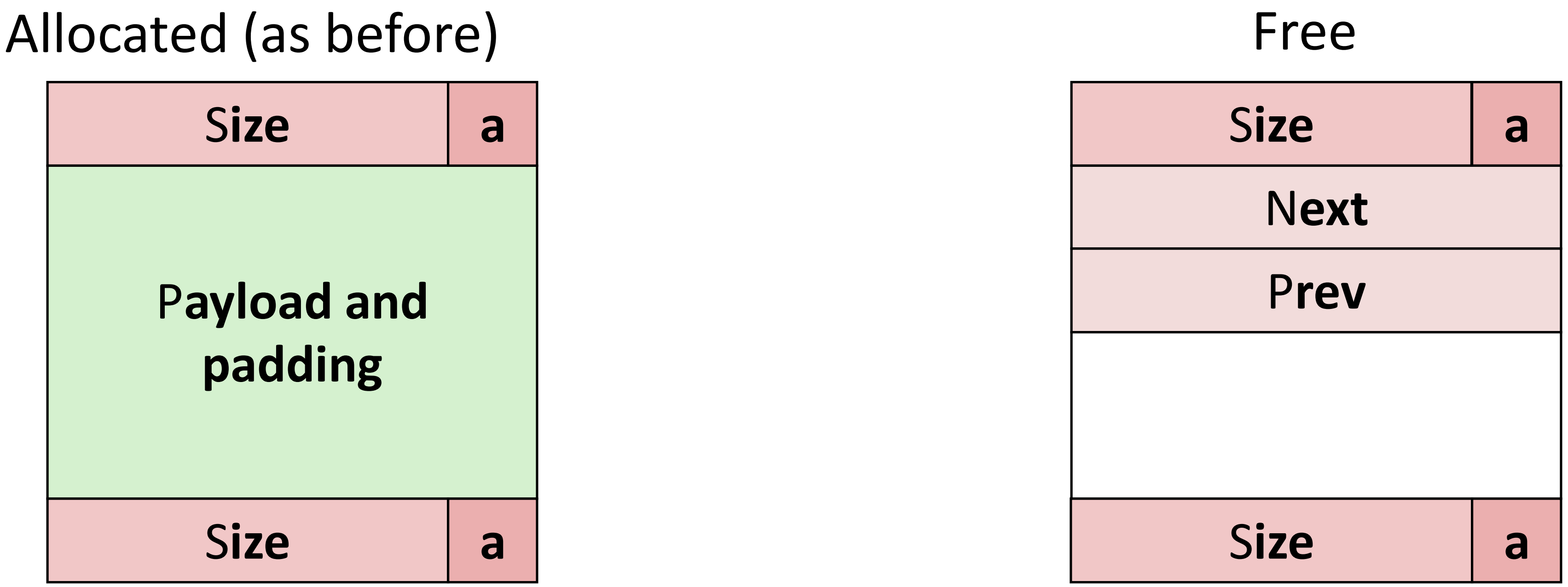


- Method 2: *Explicit free list* among the free blocks using pointers



- Method 3: *Segregated free list*
  - Different free lists for different size classes
- Method 4: *Blocks sorted by size*
  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Explicit Free Lists

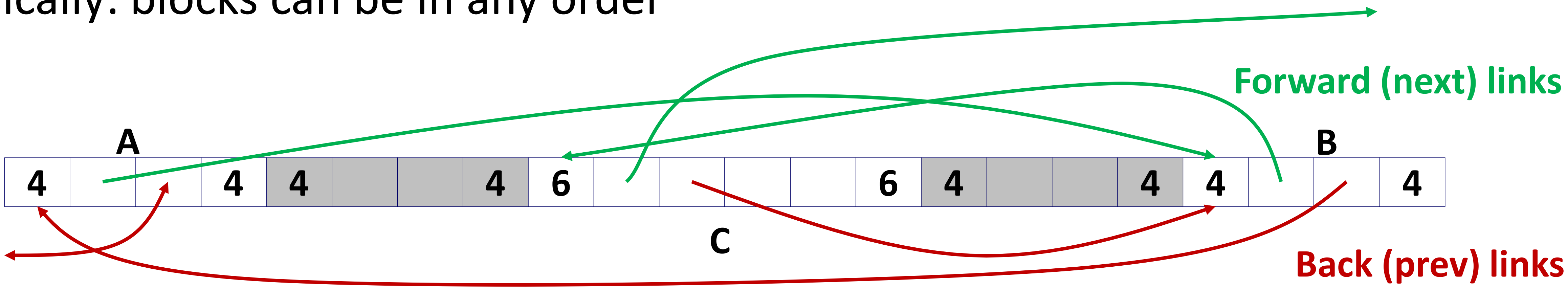


- Maintain list(s) of *free* blocks, not *all* blocks
  - The "next" free block could be anywhere
    - So we need to store forward/back pointers, not just sizes
  - Still need boundary tags for coalescing
  - Luckily we track only free blocks, so we can use payload area

Explicit Free Lists

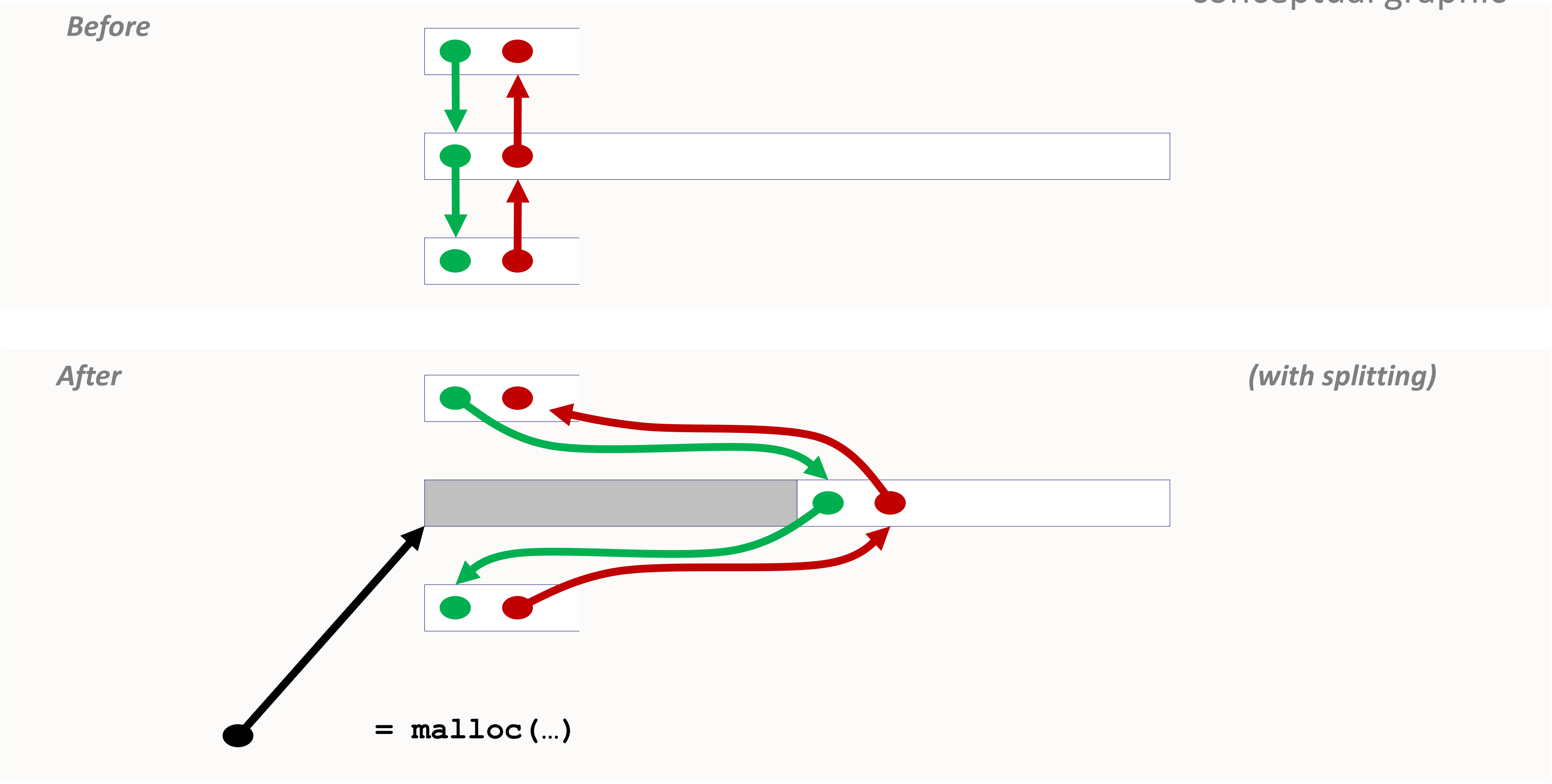
- Logically:

- Physically: blocks can be in any order



Allocating From Explicit Free Lists

conceptual graphic



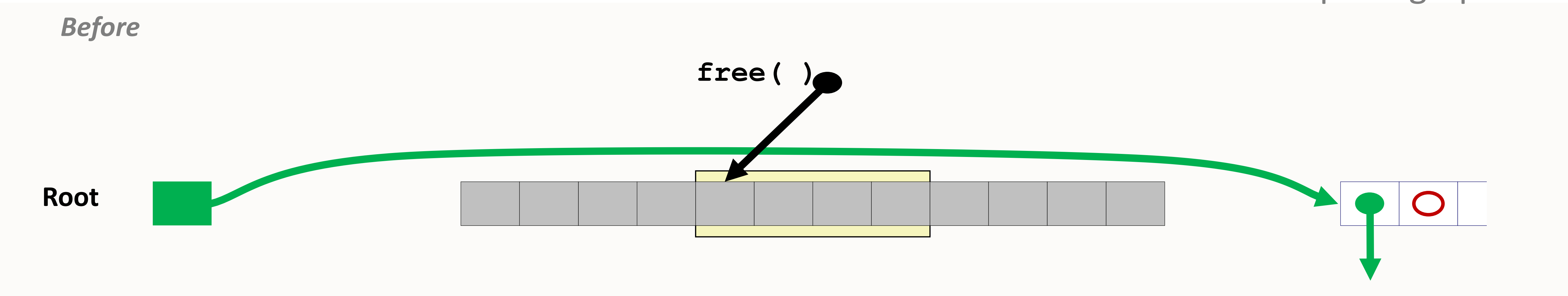
Freeing With Explicit Free Lists

- *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:

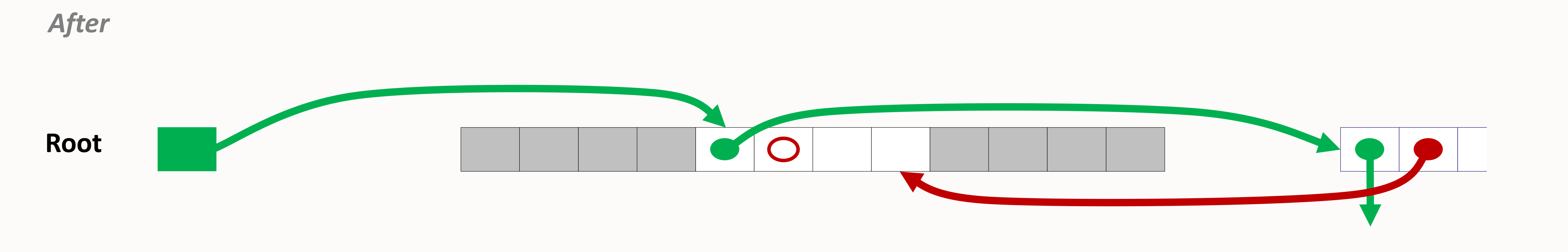
    addr(prev) < addr(curr) < addr(next)
  - ***Con:*** requires search
  - ***Pro:*** studies suggest fragmentation is lower than LIFO

Freeing With a LIFO Policy (Case 1)

conceptual graphic

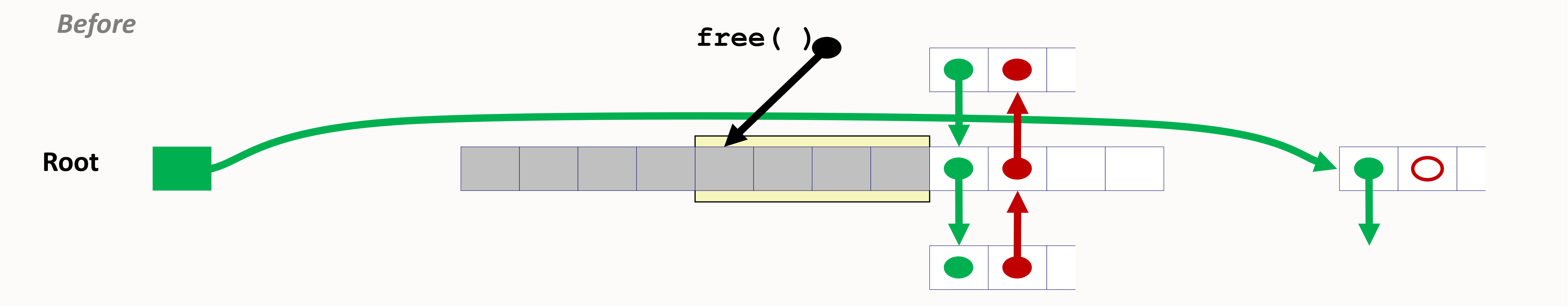


- Insert the freed block at the root of the list

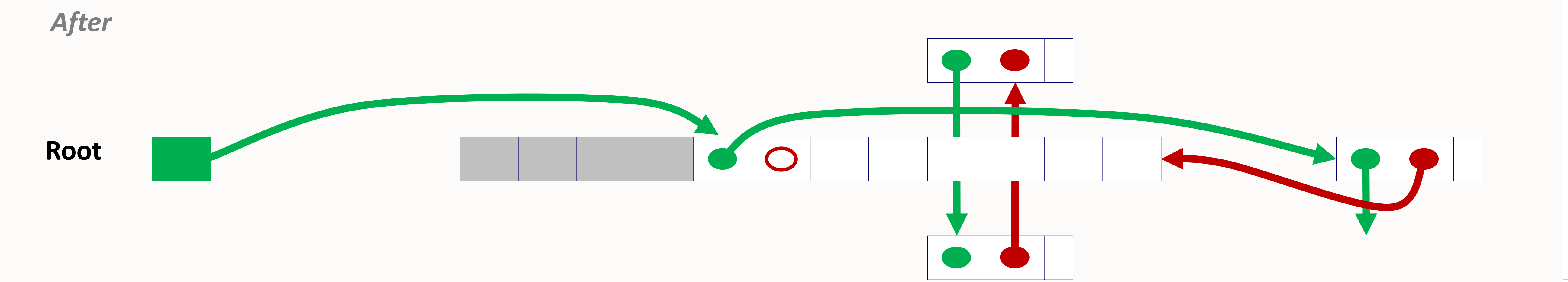


Freeing With a LIFO Policy (Case 2)

conceptual graphic

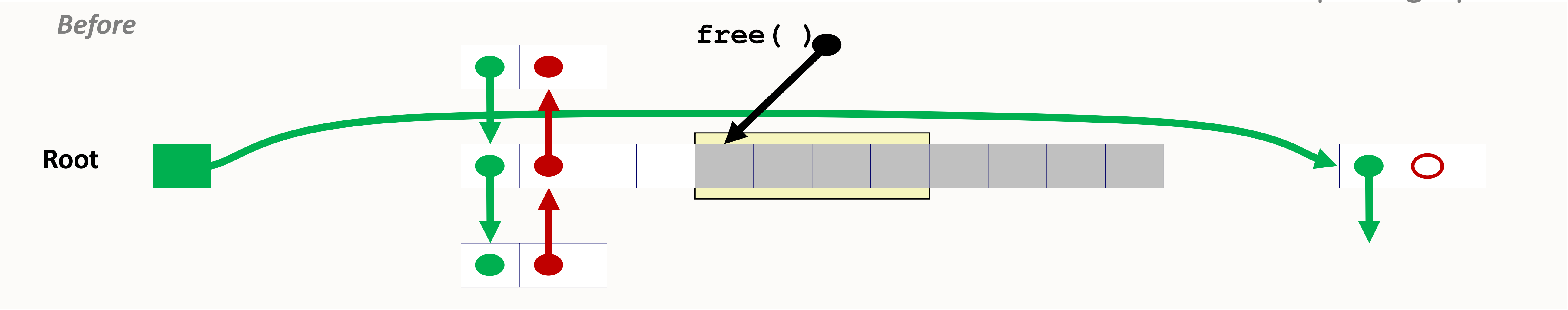


- Splice out successor block, coalesce both memory blocks and insert the new block at the root of the list

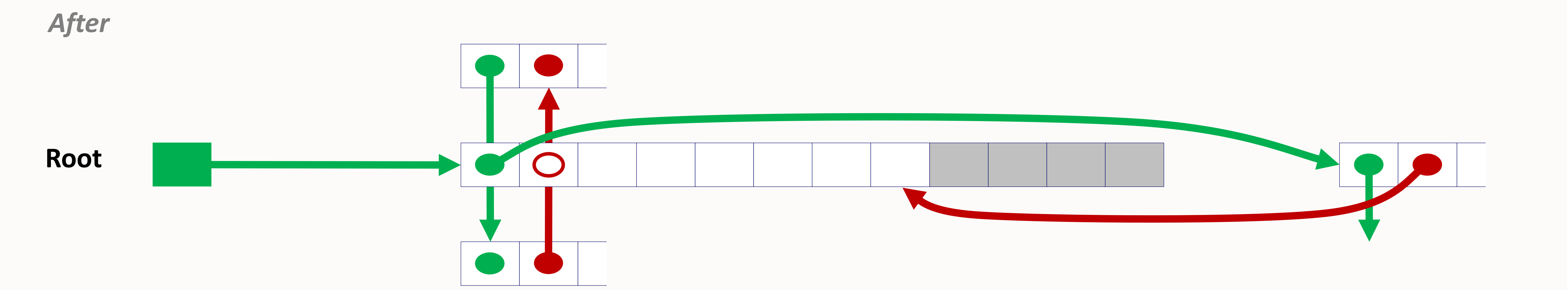


Freeing With a LIFO Policy (Case 3)

conceptual graphic

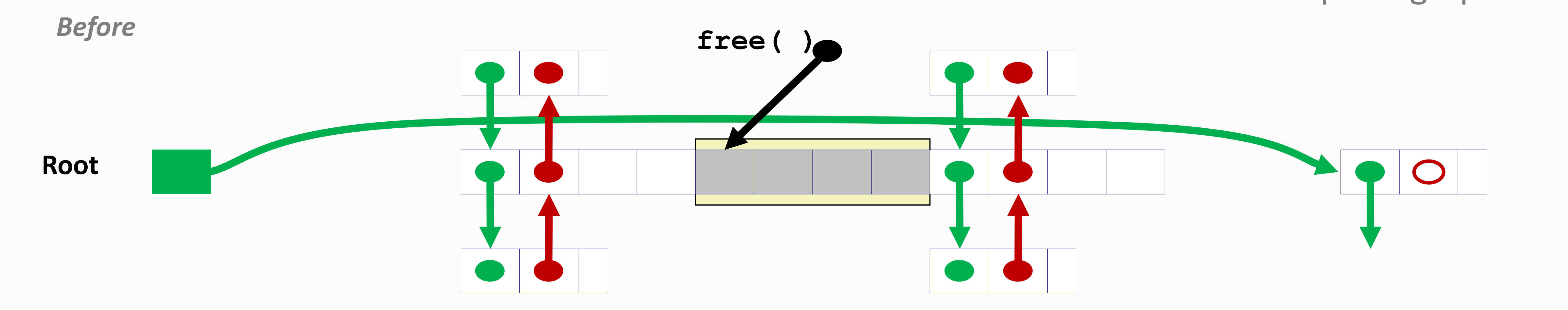


- Splice out predecessor block, coalesce both memory blocks, and insert the new block at the root of the list

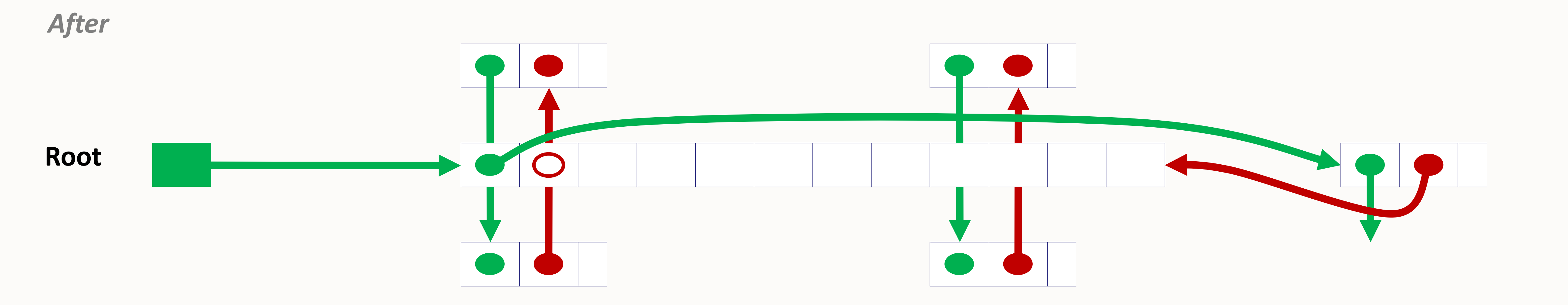


Freeing With a LIFO Policy (Case 4)

conceptual graphic



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



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)
    - Does this increase internal fragmentation?

- Most common use of linked lists is in conjunction with segregated free lists
  - Keep multiple linked lists of different size classes, or possibly for different types of objects

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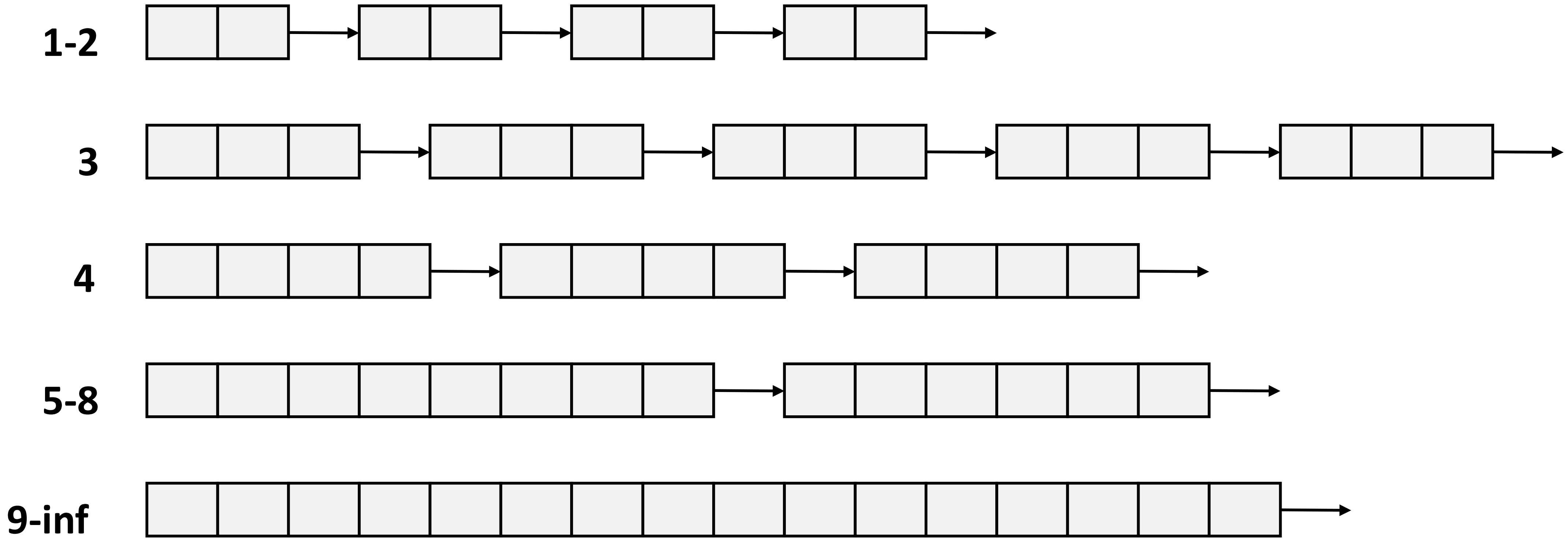
Segregated List (Seglist) Allocators

- 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

Seglist Allocator

- Given an array of free lists, each one for some size class

- To allocate a block of size *n*:
  - Search appropriate free list for block of size *m* > *n*
  - If an appropriate block is found:
    - Split block and place fragment on appropriate list (optional)
  - If no block is found, try next larger class
  - Repeat until block is found

- If no block is found:
  - Request additional heap memory from OS (using **`sbrk()`**)
  - Allocate block of *n* bytes from this new memory
  - Place remainder as a single free block in largest size class.

Seglist Allocator (cont.)

- 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.

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)

Today

- Basic concepts
- Implicit free lists
- Explicit free lists
- Segregated free lists
- Garbage collection
- Memory-related perils and pitfalls

Implicit Memory Management: Garbage Collection

- *Garbage collection:* automatic reclamation of heap-allocated storage—application never has to free

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

- Common in many dynamic languages:
    - Python, Ruby, Java, Perl, ML, Lisp, Mathematica
- Variants ("conservative" garbage collectors) exist for C and C++
    - However, cannot necessarily collect all garbage

Garbage Collection

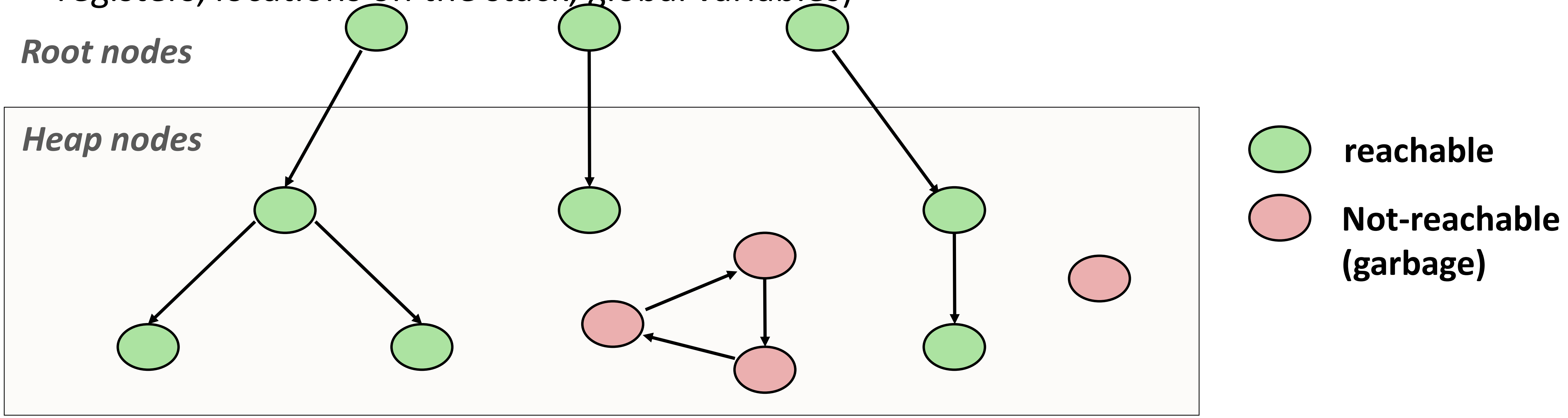
- How does the memory manager know when memory can be freed?
  - In general we cannot know what is going to be used in the future since it depends on conditionals
  - But we can tell that certain blocks cannot be used if there are no pointers to them
- Must make certain assumptions about pointers
  - Memory manager can distinguish pointers from non-pointers
  - All pointers point to the start of a block
  - Cannot hide pointers (e.g., by coercing them to an `int`, and then back again)

Classical GC Algorithms

- Mark-and-sweep collection (McCarthy, 1960)
  - Does not move blocks (unless you also "compact")
- Reference counting (Collins, 1960)
  - Does not move blocks (not discussed)
- Copying collection (Minsky, 1963)
  - Moves blocks (not discussed)
- Generational Collectors (Lieberman and Hewitt, 1983)
  - Collection based on lifetimes
    - Most allocations become garbage very soon
    - So focus reclamation work on zones of memory recently allocated
- For more information:
  Jones and Lin, "*Garbage Collection: Algorithms for Automatic Dynamic Memory*", John Wiley & Sons, 1996.

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)

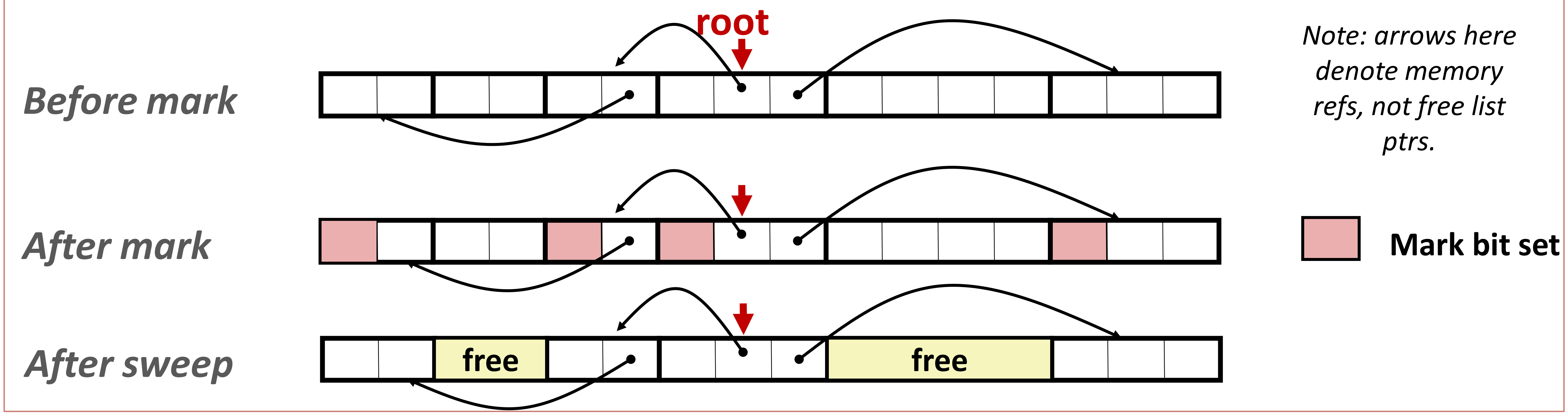


A node (block) is *reachable* if there is a path from any root to that node.

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

Mark and Sweep Collecting

- Can build on top of malloc/free package
  - Allocate using `malloc` until you "run out of space"
- When out of space:
  - Use extra ***mark bit*** in the head of each block
  - ***Mark:*** Start at roots and set mark bit on each reachable block
  - ***Sweep:*** Scan all blocks and free blocks that are not marked



Note: arrows here denote memory refs, not free list ptrs.

Assumptions For a Simple Implementation

- Application
  - **`new(n)`**: returns pointer to new block with all locations cleared
  - **`read(b,i)`**: read location **`i`** of block **`b`** into register
  - **`write(b,i,v)`**: write **`v`** into location **`i`** of block **`b`**
- Each block will have a header word
  - addressed as **`b[-1]`**, for a block **`b`**
  - Used for different purposes in different collectors
- Instructions used by the Garbage Collector
  - **`is_ptr(p)`**: determines whether **`p`** is a pointer
  - **`length(b)`**: returns the length of block **`b`**, not including the header
  - **`get_roots()`**: returns all the roots

Mark and Sweep (cont.)

Mark using depth-first traversal of the memory graph

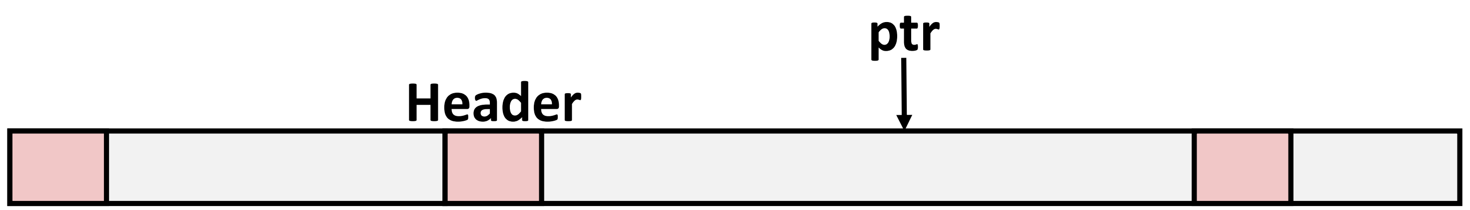
```
ptr mark(ptr p) {
   if (!is_ptr(p)) return;          // do nothing if not pointer
   if (markBitSet(p)) return;       // check if already marked
   setMarkBit(p);                   // set the mark bit
   for (i=0; i < length(p); i++)    // call mark on all words
     mark(p[i]);                    //    in the block
   return;
}
```

Sweep using lengths to find next block

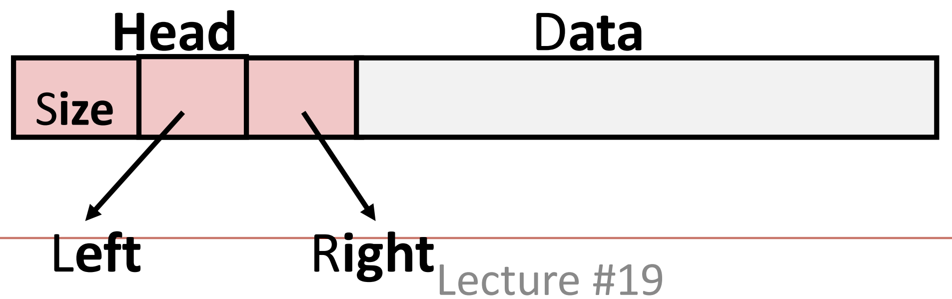
```
ptr sweep(ptr p, ptr end) {
   while (p < end) {
      if markBitSet(p)
         clearMarkBit();
      else if (allocateBitSet(p))
         free(p);
      p += length(p);
}
```

Conservative Mark & Sweep in C

- A "conservative garbage collector" for C programs
  - `is_ptr()` determines if a word is a pointer by checking if it points to an allocated block of memory
  - But, in C pointers can point to the middle of a block



- So how to find the beginning of the block?
  - Can use a balanced binary tree to keep track of all allocated blocks (key is start-of-block)
  - Balanced-tree pointers can be stored in header (use two additional words)



Left: smaller addresses
Right: larger addresses

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- Memory-related perils and pitfalls

Memory-Related Perils and Pitfalls

- Dereferencing bad pointers
- Reading uninitialized memory
- Overwriting memory
- Referencing nonexistent variables
- Freeing blocks multiple times
- Referencing freed blocks
- Failing to free blocks

C operators

Operators	*Associativity*
`()  []  ->  .`	left to right
`!  ~  ++  --  +  -  *  &  (type) sizeof`	right to left
`*  /  %`	left to right
`+  -`	left to right
`<<  >>`	left to right
`<  <=  >  >=`	left to right
`==  !=`	left to right
`&`	left to right
`^`	left to right
`|`	left to right
`&&`	left to right
`||`	left to right
`?:`	right to left
`= += -= *= /= %= &= ^= != <<= >>=`	right to left
`,`	left to right

- `->`, `()`, and `[]` have high precedence, with `*` and `&` just below
- Unary `+`, `-`, and `*` have higher precedence than binary forms

Source: K&R page 53

C Pointer Declarations: Test Yourself!

`int *p`	p is a pointer to int
`int *p[13]`	p is an array[13] of pointer to int
`int *(p[13])`	p is an array[13] of pointer to int
`int **p`	p is a pointer to a pointer to an int
`int (*p)[13]`	p is a pointer to an array[13] of int
`int *f()`	f is a function returning a pointer to int
`int (*f)()`	f is a pointer to a function returning int
`int (*(*f())[13])()`	f is a function returning ptr to an array[13] of pointers to functions returning int
`int (*(*x[3])())[5]`	x is an array[3] of pointers to functions returning pointers to array[5] of ints

Source: K&R Sec 5.12

Dereferencing Bad Pointers

- The classic `scanf` bug (val need to be an address)

```
int val;

...

scanf("%d", val);
```

Reading Uninitialized Memory

- Assuming that heap data is initialized to zero

```
/* return y = Ax */
int *matvec(int **A, int *x) {
   int *y = malloc(N*sizeof(int));
   int i, j;

   for (i=0; i<N; i++)
      for (j=0; j<N; j++)
         y[i] += A[i][j]*x[j];
   return y;
}
```

Overwriting Memory

- Allocating the (possibly) wrong sized object (should be *int)

```
int **p;

p = malloc(N*sizeof(int));

for (i=0; i<N; i++) {
   p[i] = malloc(M*sizeof(int));
}
```

Overwriting Memory

- Off-by-one error (should be N+1)

```
int **p;

p = malloc(N*sizeof(int *));

for (i=0; i<=N; i++) {
    p[i] = malloc(M*sizeof(int));
}
```

Overwriting Memory

- Not checking the max string size

```
char s[8];
int i;

gets(s);   /* reads "123456789" from stdin */
```

- Basis for classic buffer overflow attacks

Overwriting Memory

- Misunderstanding pointer arithmetic

```
int *search(int *p, int val) {

   while (*p && *p != val)
      p += sizeof(int);

   return p;
}
```

Overwriting Memory

- Referencing a pointer instead of the object it points to

```
int *BinheapDelete(int **binheap, int *size) {
    int *packet;
    packet = binheap[0];
    binheap[0] = binheap[*size - 1];
    *size--;
    Heapify(binheap, *size, 0);
    return(packet);
}
```

Referencing Nonexistent Variables

- Forgetting that local variables disappear when a function returns

```
int *foo () {
    int val;

    return &val;
}
```

Freeing Blocks Multiple Times

- Nasty!

```
x = malloc(N*sizeof(int));
        <manipulate x>
free(x);

y = malloc(M*sizeof(int));
        <manipulate y>
free(x);
```

Referencing Freed Blocks

- Evil!

```
x = malloc(N*sizeof(int));
  <manipulate x>
free(x);
   ...
y = malloc(M*sizeof(int));
for (i=0; i<M; i++)
   y[i] = x[i]++;
```

Failing to Free Blocks (Memory Leaks)

- Slow, long-term killer!

```
foo() {
   int *x = malloc(N*sizeof(int));
   ...
   return;
}
```

Failing to Free Blocks (Memory Leaks)

- Freeing only part of a data structure

```
struct list {
   int val;
   struct list *next;
};

foo() {
   struct list *head = malloc(sizeof(struct list));
   head->val = 0;
   head->next = NULL;
   <create and manipulate the rest of the list>
     ...
   free(head);
   return;
}
```

Dealing With Memory Bugs

- Debugger: `gdb`
  - Good for finding bad pointer dereferences
  - Hard to detect the other memory bugs
- Data structure consistency checker
  - Runs silently, prints message only on error
  - Use as a probe to zero in on error
- Binary translator: `valgrind`
  - Powerful debugging and analysis technique
  - Rewrites text section of executable object file
  - Checks each individual reference at runtime
    - Bad pointers, overwrites, refs outside of allocated block
- glibc malloc contains checking code
  - **`setenv MALLOC_CHECK_ 3`**

18-600 Foundations of Computer Systems

Lecture 20: "Overview of Parallel Architectures"

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Next Time …

Electrical & Computer ENGINEERING