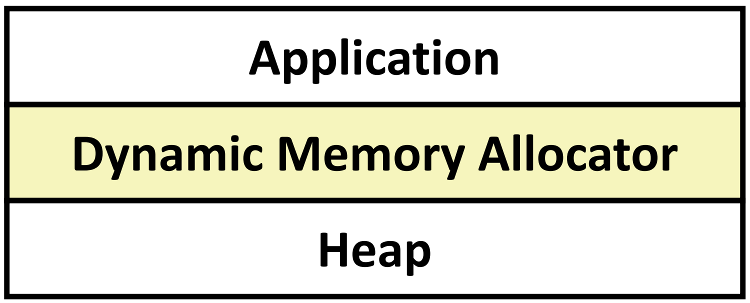
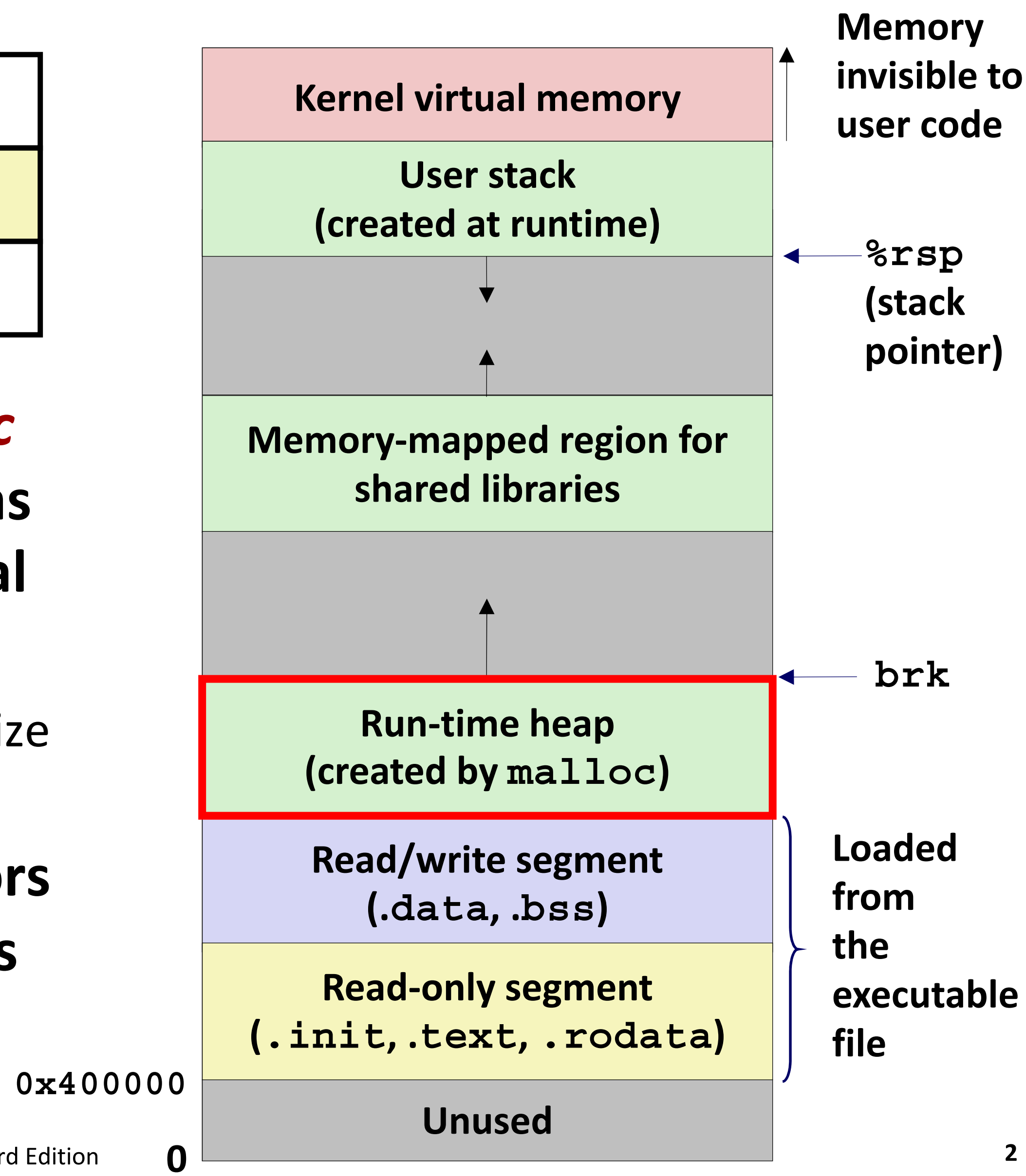
Dynamic Memory Allocation: Advanced Concepts

15-213/18-213/15-513/18-613: Introduction to Computer Systems
16th Lecture, March 5, 2020

Review: Dynamic Memory Allocation

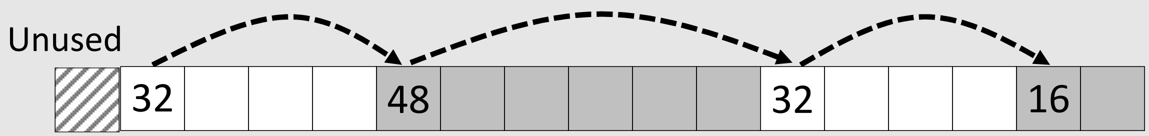


- Programmers use ***dynamic memory allocators*** (such as `malloc`) to acquire virtual memory (VM) at runtime
  - For data structures whose size is only known at runtime
- Dynamic memory allocators manage an area of process VM known as the ***heap***



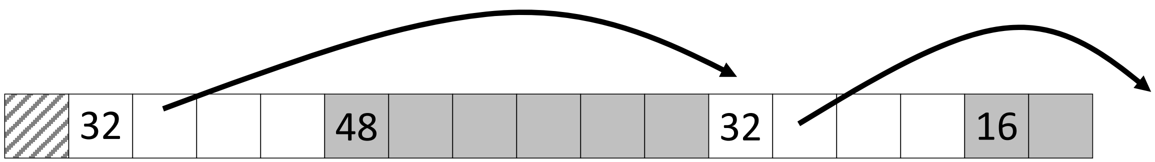
Review: Keeping Track of Free Blocks

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



Need to tag each block as allocated/free

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



Need space for 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

Review: Implicit Lists Summary

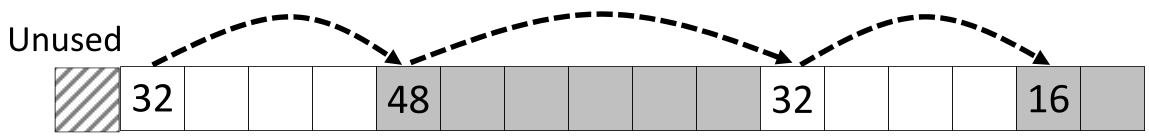
- **Implementation: very simple**
- **Allocate cost:**
  - linear time worst case
- **Free cost:**
  - constant time worst case
  - even with coalescing
- **Memory Overhead:**
  - Depends on placement policy
  - Strategies include first fit, next fit, and best fit
- **Not used in practice for `malloc/free` 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**

Today

- **Explicit free lists**
- Segregated free lists
- Garbage collection
- Memory-related perils and pitfalls

Keeping Track of Free Blocks

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



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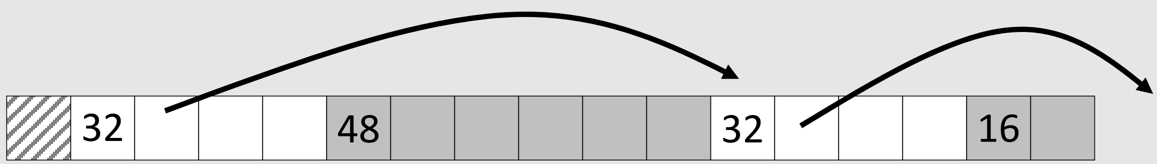
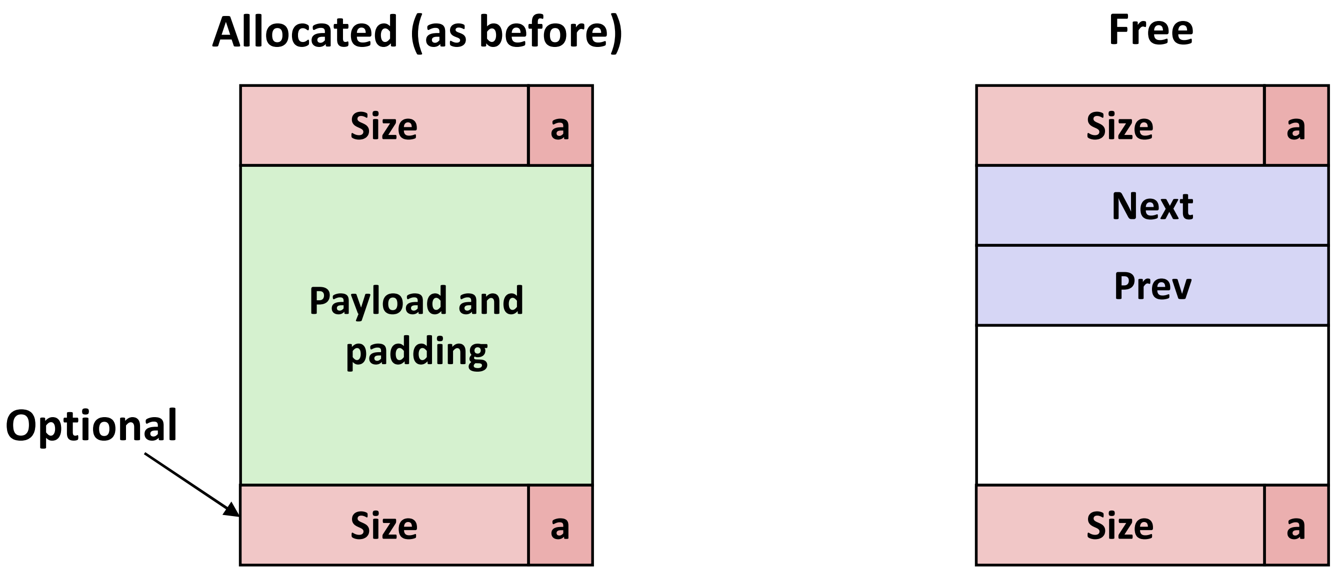


- **Method 3: *Segregated free list***
  - Different free lists for different size classes

- **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

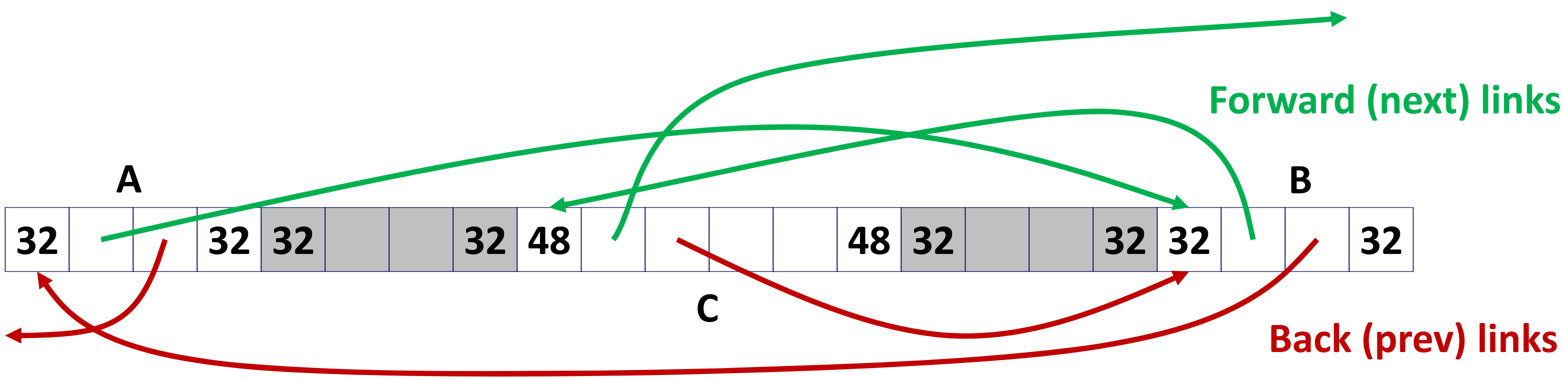


- **Maintain list(s) of *free* blocks, not *all* blocks**
  - Luckily we track only free blocks, so we can use payload area
  - The "next" free block could be anywhere
    - So we need to store forward/back pointers, not just sizes
  - Still need boundary tags for coalescing
    - To find adjacent blocks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

Explicit Free Lists

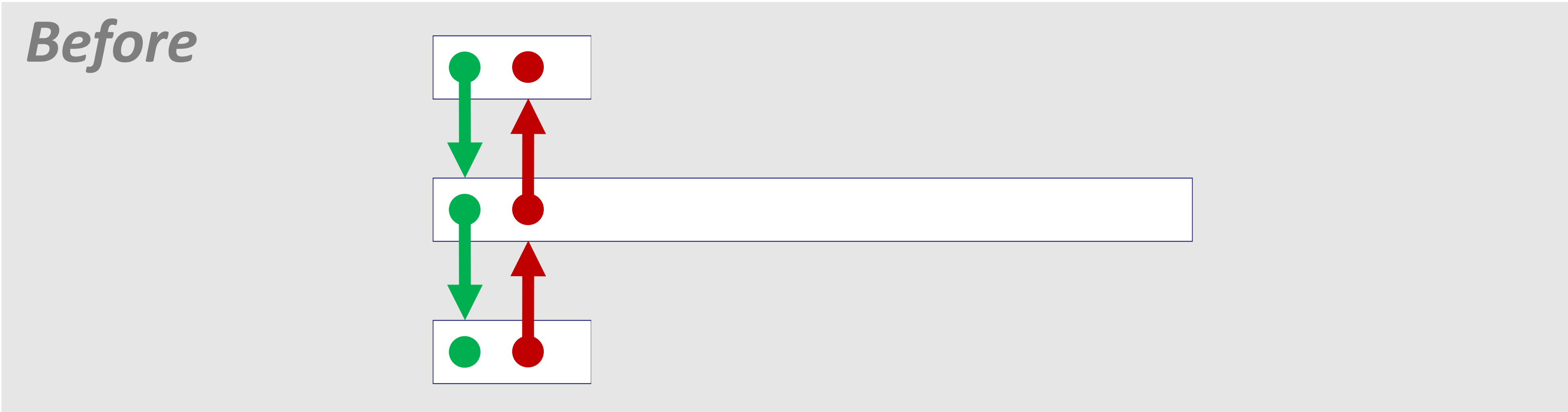
- **Logically:**

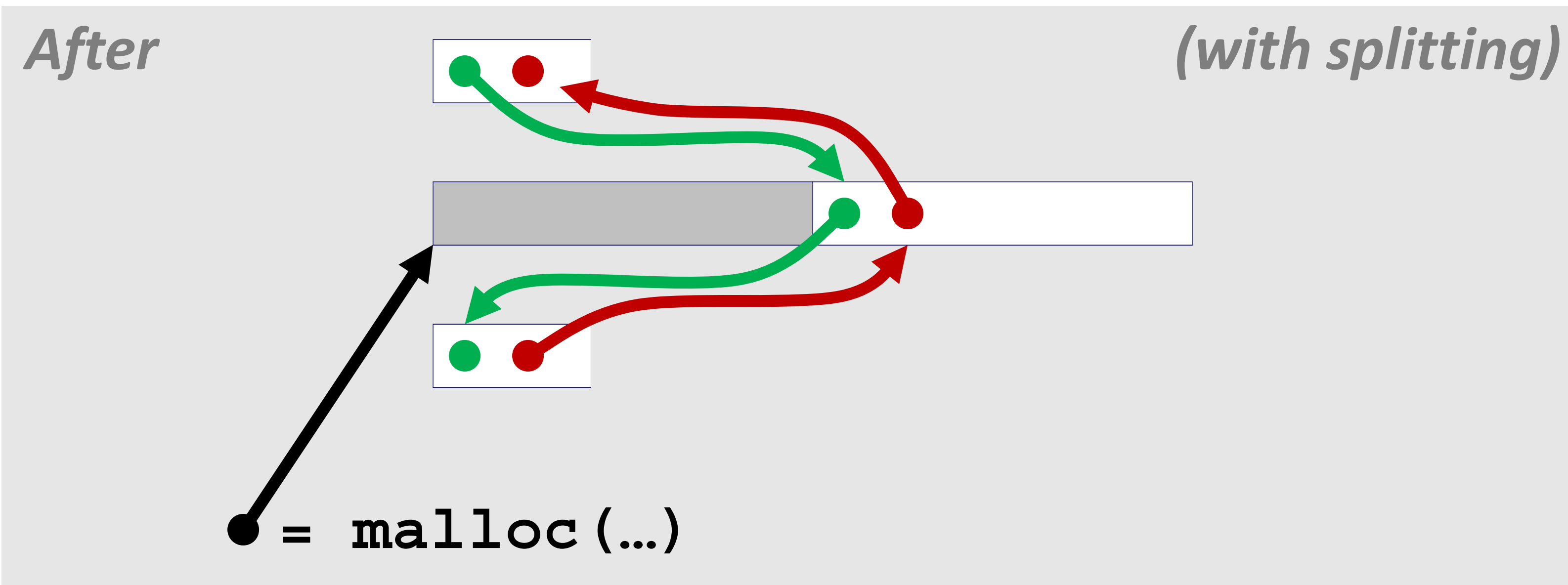
- **Physically: blocks can be in any order**



Allocating From Explicit Free Lists

conceptual graphic



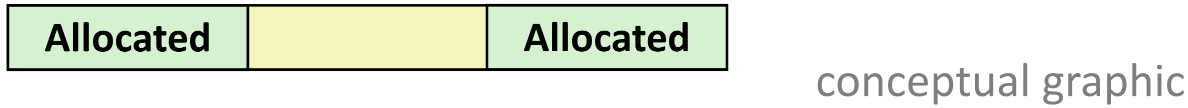


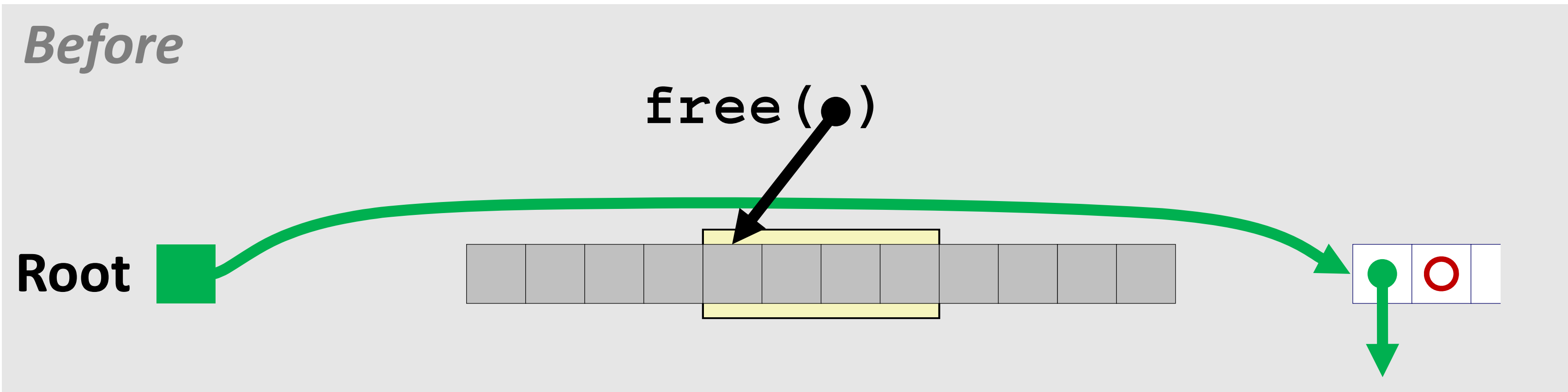
Freeing With Explicit Free Lists

- ***Insertion policy***: **Where in the free list do you put a newly freed block?**
- **Unordered**
  - LIFO (last-in-first-out) policy
    - Insert freed block at the beginning of the free list
  - FIFO (first-in-first-out) policy
    - Insert freed block at the end 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:

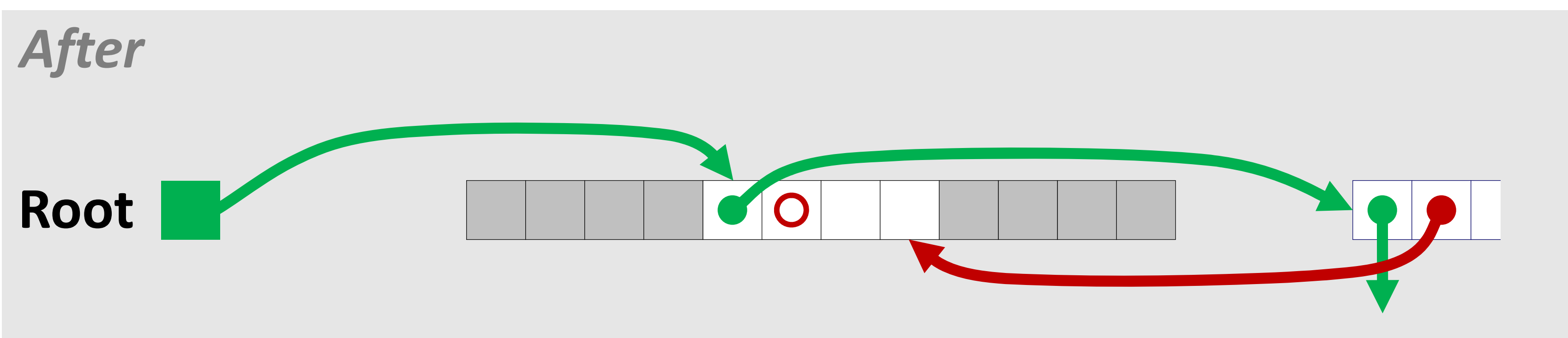
    addr(prev) < addr(curr) < addr(next)
  - ***Con:*** requires search
  - ***Pro:*** studies suggest fragmentation is lower than LIFO/FIFO

Freeing With a LIFO Policy (Case 1)

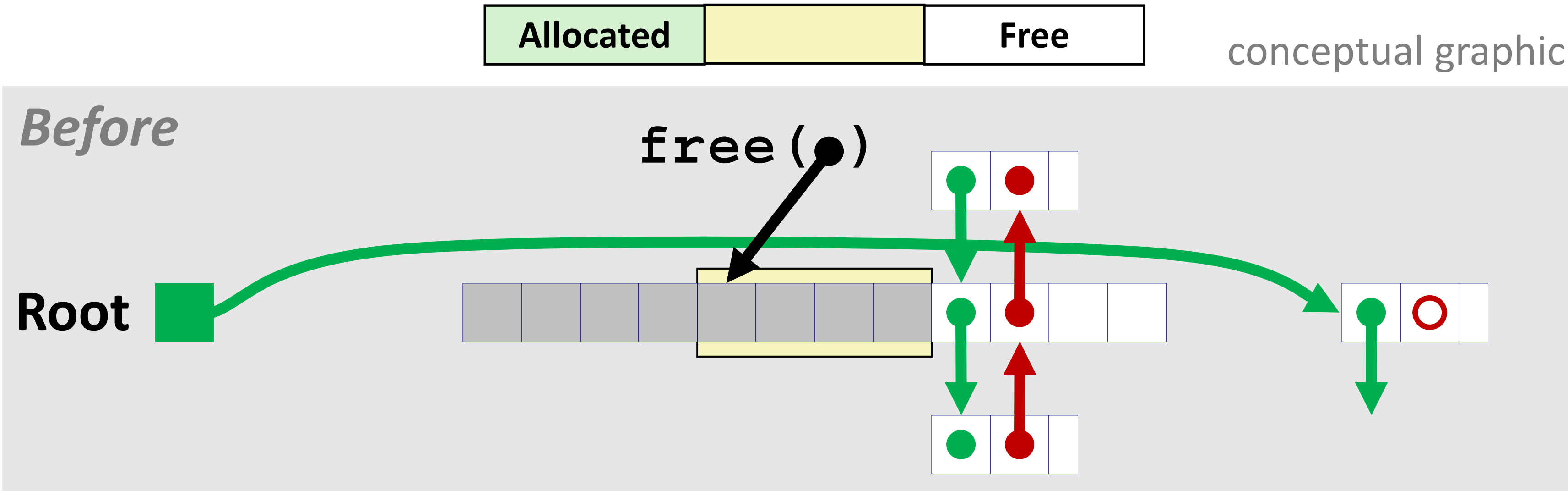




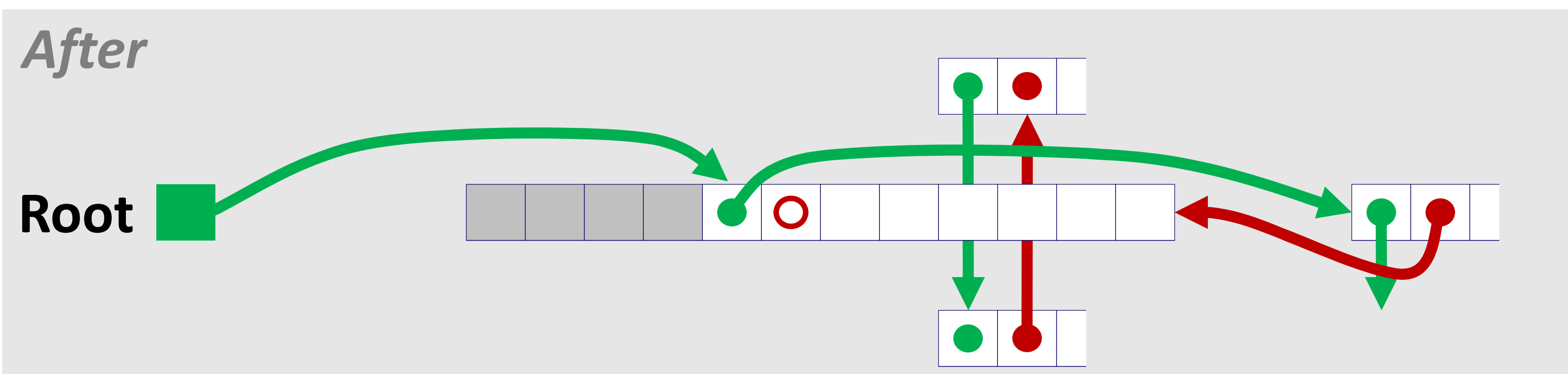
- Insert the freed block at the root of the list



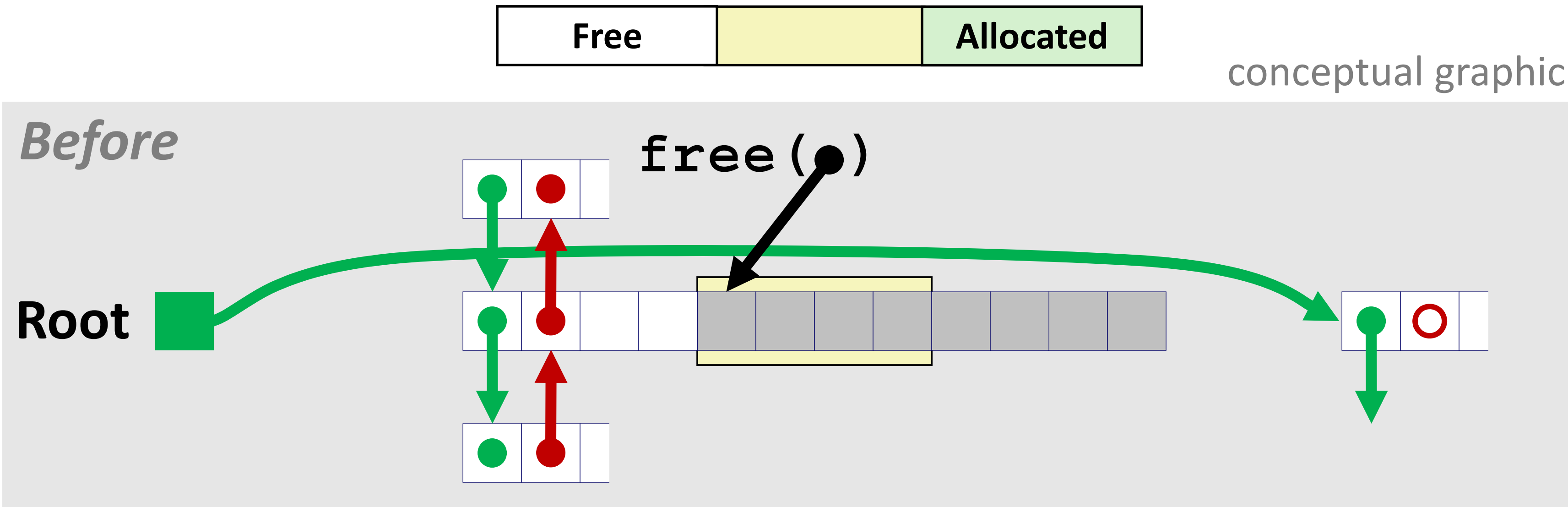
Freeing With a LIFO Policy (Case 2)



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



Freeing With a LIFO Policy (Case 3)



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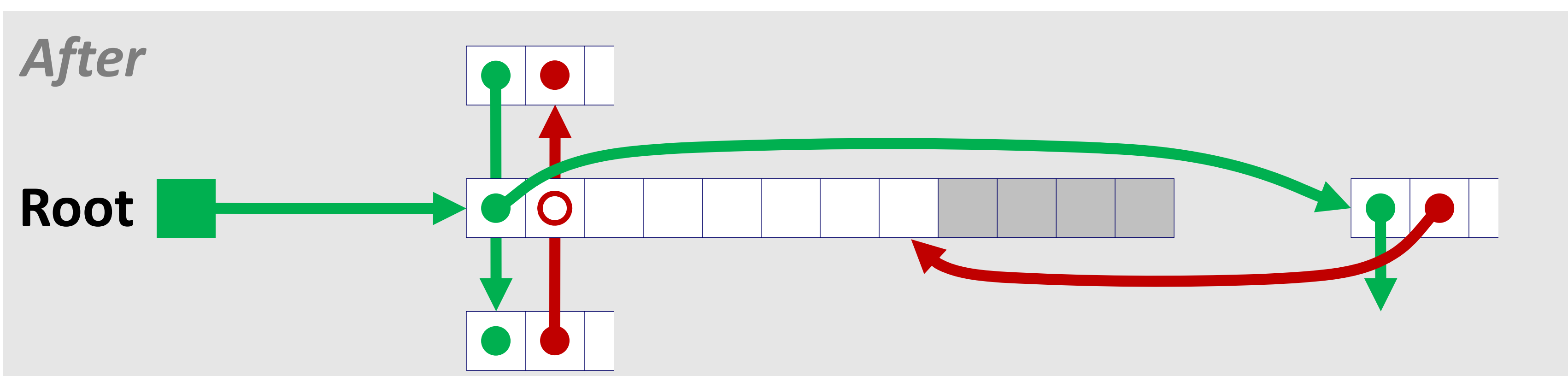
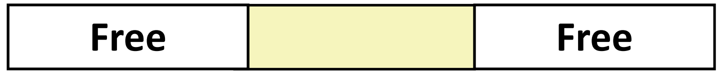
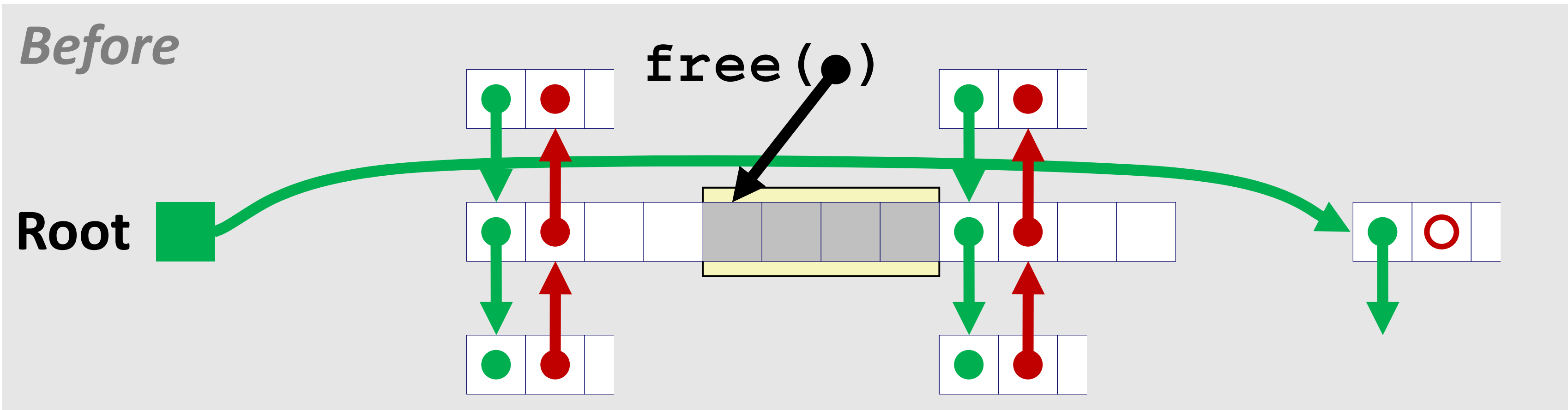


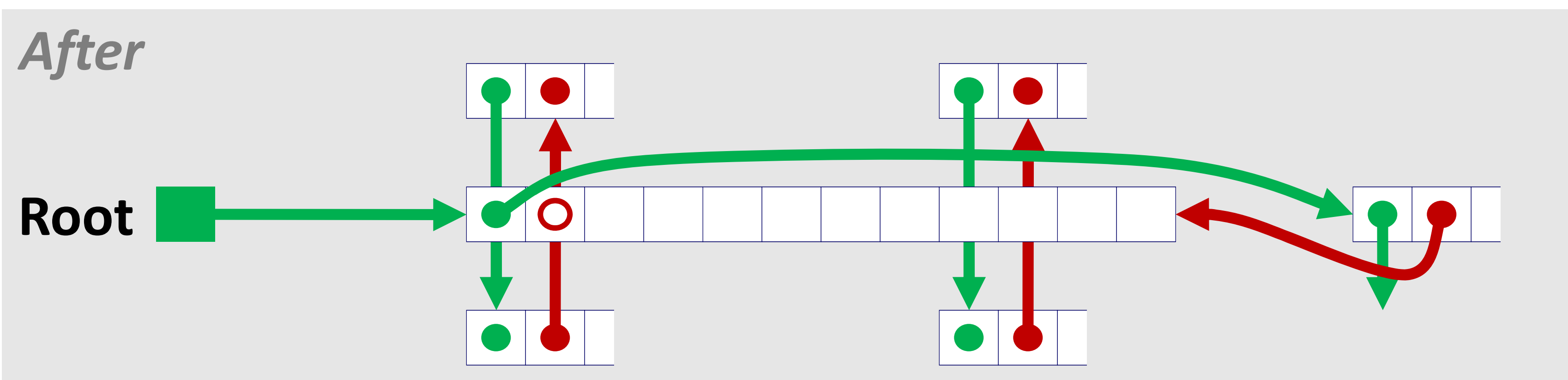
Freeing With a LIFO Policy (Case 4)



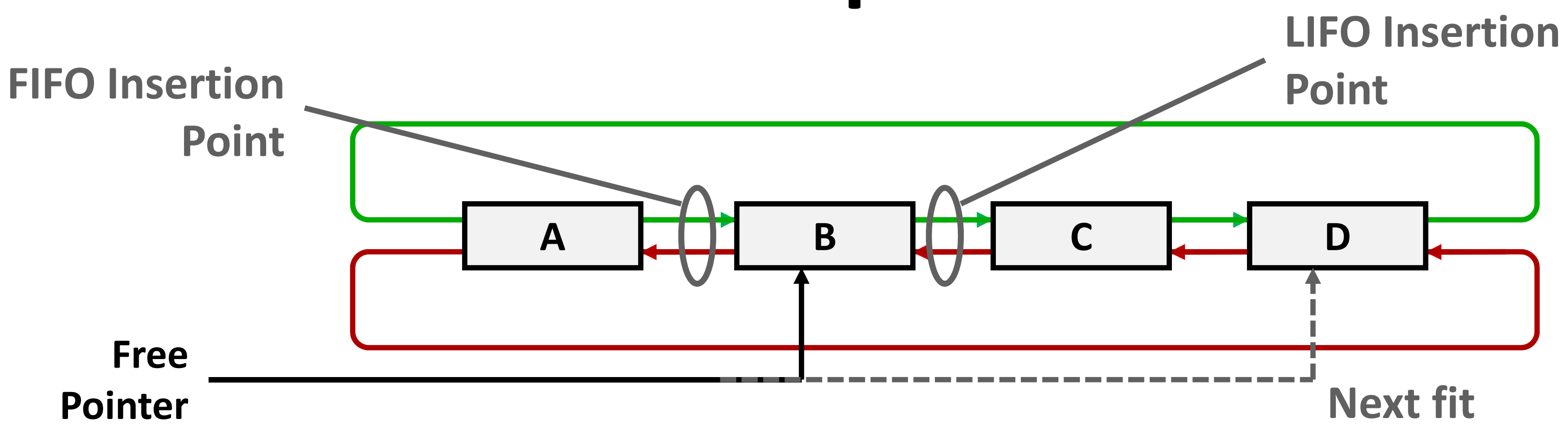
conceptual graphic



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



Some Advice: An Implementation Trick



- **Use circular, doubly-linked list**
- **Support multiple approaches with single data structure**
- **First-fit vs. next-fit**
  - Either keep free pointer fixed or move as search list
- **LIFO vs. FIFO**
  - Insert as next block (LIFO), or previous block (FIFO)

Explicit List Summary

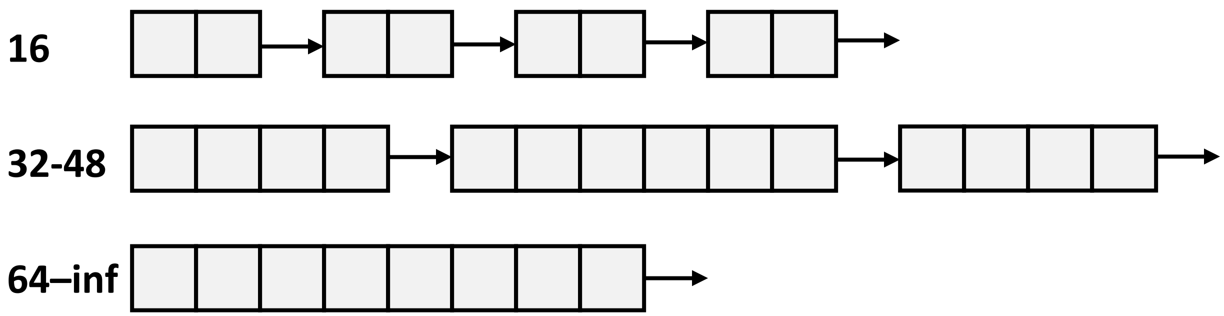
- **Comparison to implicit list:**
  - Allocate is linear time in number of ***free*** blocks instead of ***all*** blocks
    - ***Much faster*** when most of the memory is full
  - Slightly more complicated allocate and free because need to splice blocks in and out of the list
  - Some extra space for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

Today

- Explicit free lists
- **Segregated free lists**
- Garbage collection
- Memory-related perils and pitfalls

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 size $[2^i + 1, 2^{i+1}]$

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 $m > n$ (i.e., first fit)
  - If an appropriate block is found:
    - Split block and place fragment on appropriate list
    - 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 appropriate size class.

Seglist Allocator (cont.)

- **To free a block:**
  - Coalesce and place on appropriate list

- **Advantages of seglist allocators vs. non-seglist allocators (both with first-fit)**
  - Higher throughput
    - log time for power-of-two size classes vs. linear time
  - 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,* vol 1, 3rd edition, Addison Wesley, 1997**
  - 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)

Quiz Time!

Check out:

https://canvas.cmu.edu/courses/13182/quizzes/31659

Today

- 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 explicitly free memory**

```
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

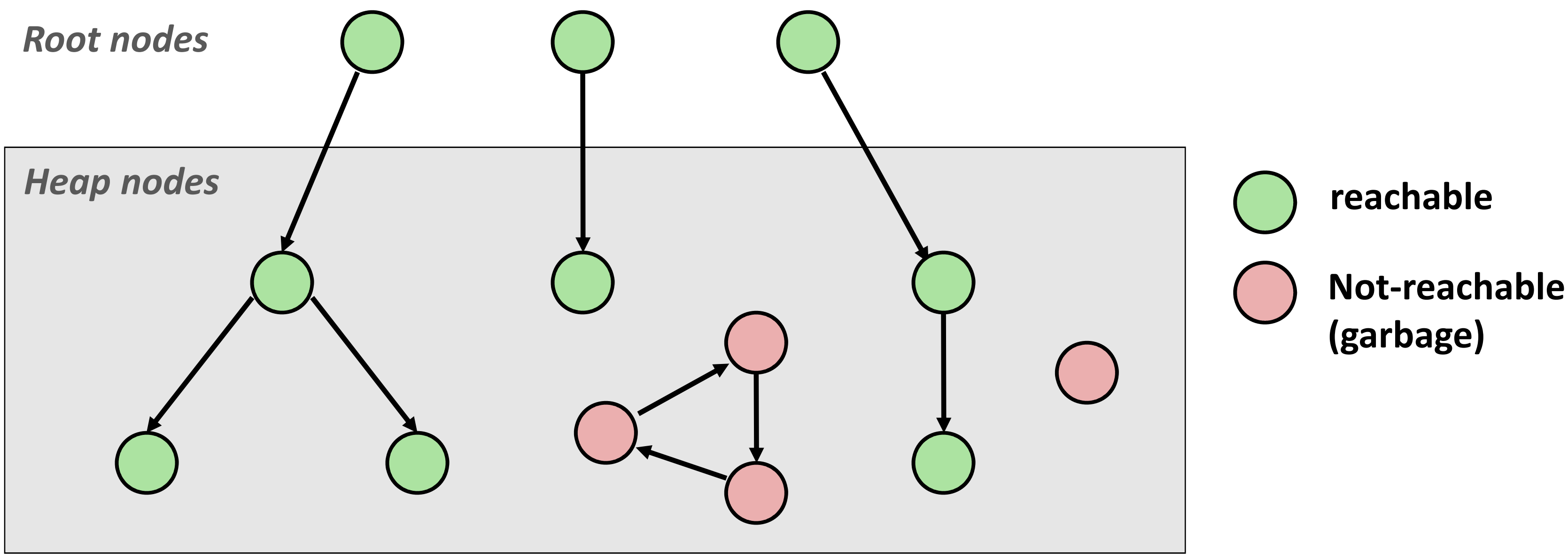
- **Must make certain assumptions about pointers**
  - Memory manager can distinguish pointers from non-pointers
  - All pointers point to the start of a block
  - Cannot hide pointers
    (e.g., by coercing them to an `int`, and then back again)

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)

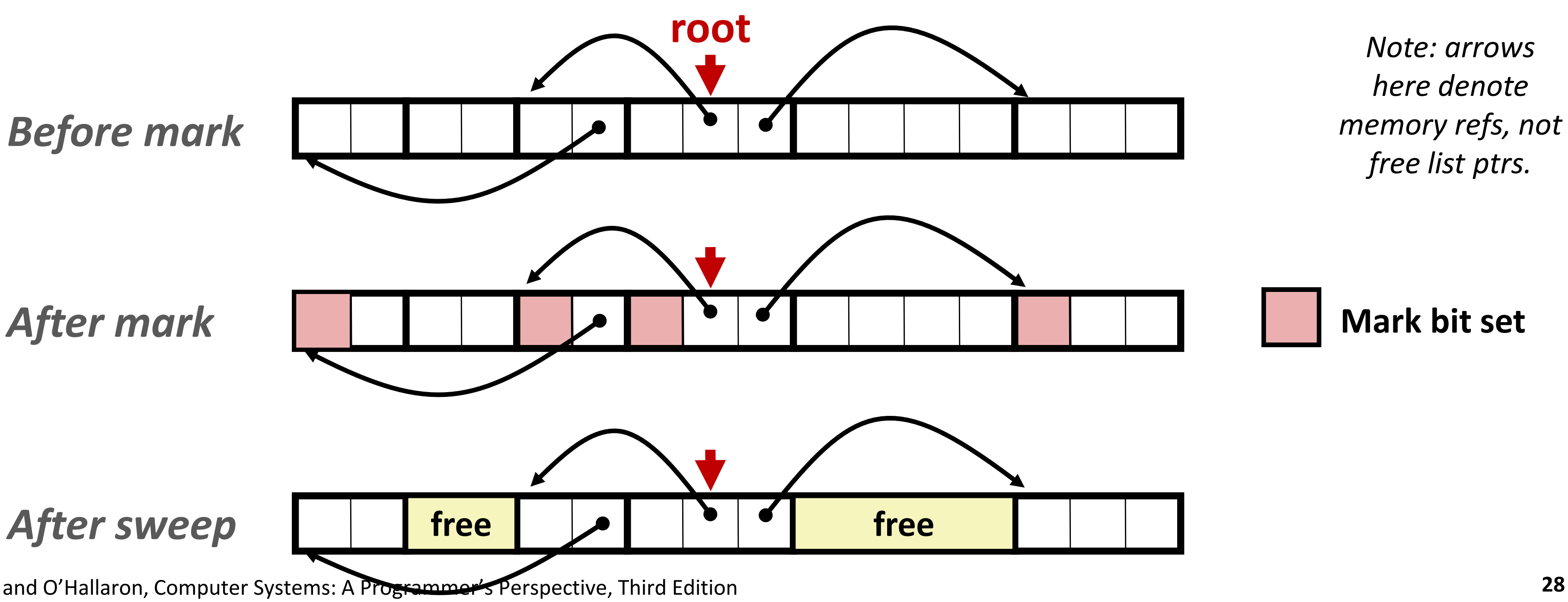


A node (block) is *reachable* if there is a path from any root to that node.

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



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 Pseudocode

Mark using depth-first traversal of the memory graph

```
ptr mark(ptr p) {
   if (!is_ptr(p)) return;
   if (markBitSet(p)) return;
   setMarkBit(p);
   for (i=0; i < length(p); i++)
     mark(p[i]);
   return;
}
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}
```

Sweep using lengths to find next block

```
ptr sweep(ptr p, ptr end) {
   while (p < end) {                // for entire heap
      if markBitSet(p)
         clearMarkBit();
      else if (allocateBitSet(p))
         free(p);
      p += length(p+1);
}
```

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}
```

Today

- Explicit free lists
- Segregated free lists
- Garbage collection
- **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

Dereferencing Bad Pointers

- **The classic `scanf` bug**

```
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;
}
```

- Can avoid by using `calloc`

Overwriting Memory

- Allocating the (possibly) wrong sized object

```
int **p;

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

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

- Can you spot the bug?

Overwriting Memory

- **Off-by-one errors**

```
char **p;

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

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

```
char *p;

p = malloc(strlen(s));
strcpy(p,s);
```

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);
}
```

- What gets decremented?
  - (See next slide)

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

Postfix

Prefix

Unary

Unary

Binary

Binary

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

Source: K&R page 53, updated

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);
}
```

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

- **Same effect as**
  - `size--;`
- **Rewrite as**
  - `(*size)--;`

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;
}
```

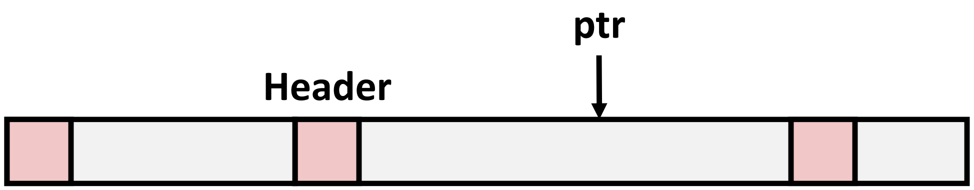
Dealing With Memory Bugs

- **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`

Supplemental slides

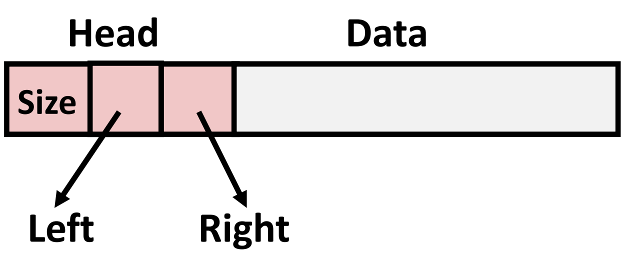
Conservative Mark & Sweep in C

- **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



Assumes ptr in middle can be used to reach anywhere in the block, but no other block

- **To mark header, need 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

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 (*(*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

C Pointer Declarations: Test Yourself!

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

Source: K&R Sec 5.12

Parsing: `int (*(*f())[13])()`

`int (*(*f())[13])()`	`f`
`int (*(*f())[13])()`	`f is a function`
`int (*(*f())[13])()`	`f is a function that returns a ptr`
`int (*(*f())[13])()`	`f is a function that returns a ptr to an array of 13`
`int (*(*f())[13])()`	`f is a function that returns a ptr to an array of 13 ptrs`
`int (*(*f())[13])()`	`f is a function that returns a ptr to an array of 13 ptrs to functions returning an int`