Dynamic Memory Allocation: Advanced Concepts

15-213/14-513/15-513: Introduction to Computer Systems
14th Lecture, October 13, 2022

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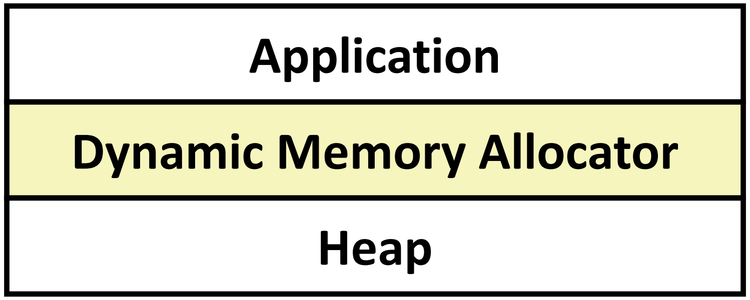
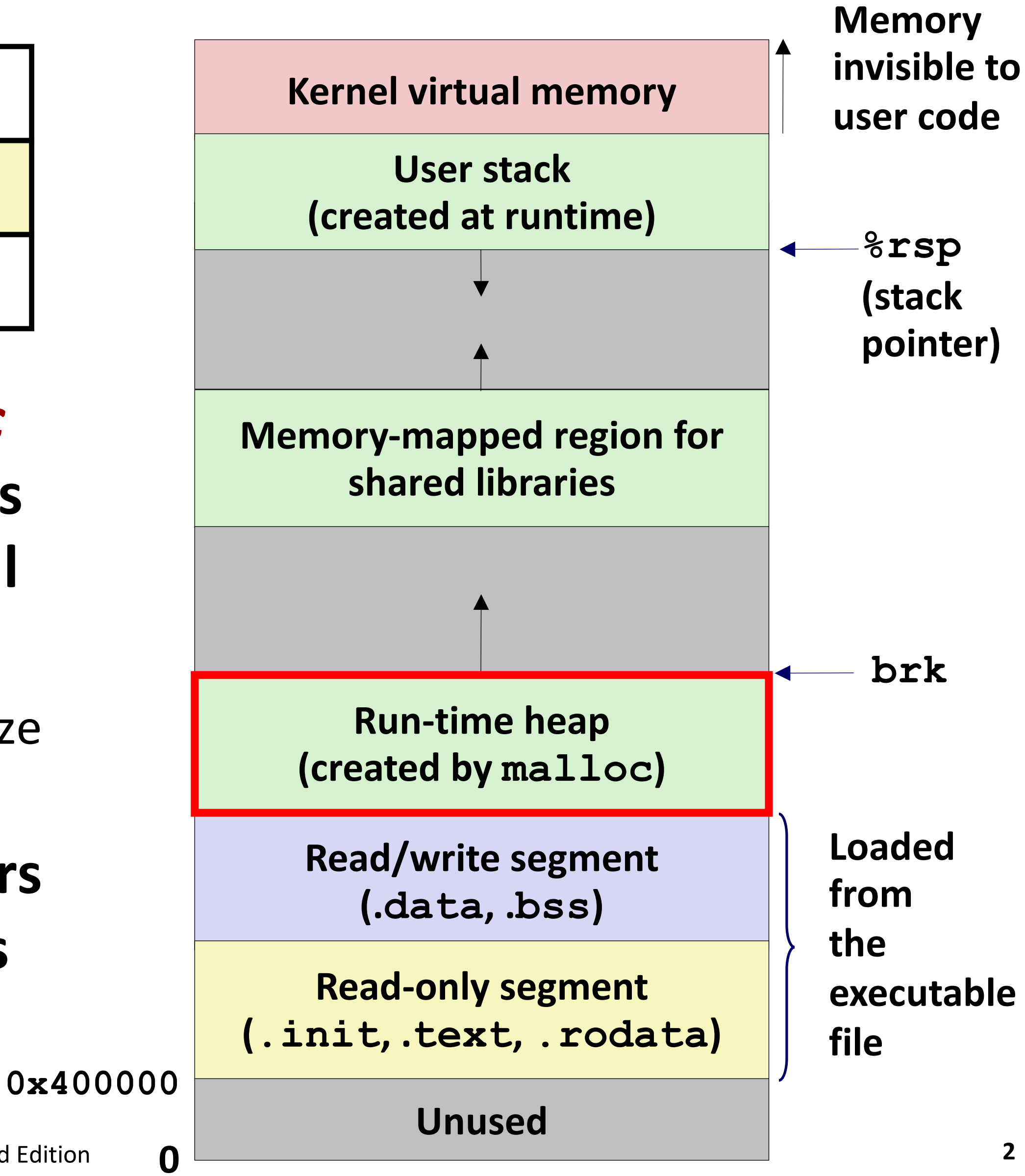
Review: Dynamic Memory Allocation

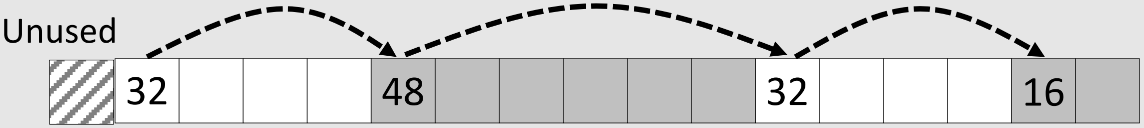


- Programmers use ***dynamic memory allocators*** (such as `malloc`) to acquire virtual memory (VM) at runtime
  - For data structures whose size is only known at runtime
- Dynamic memory allocators manage an area of process VM known as the ***heap***



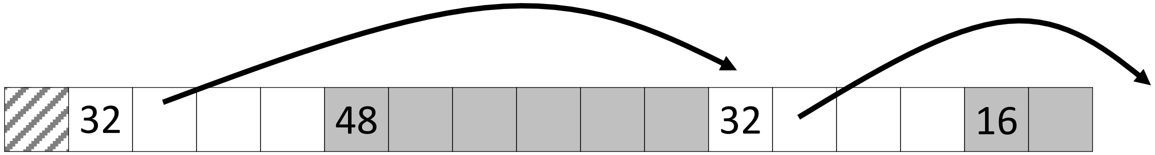
Review: Keeping Track of Free Blocks

- **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

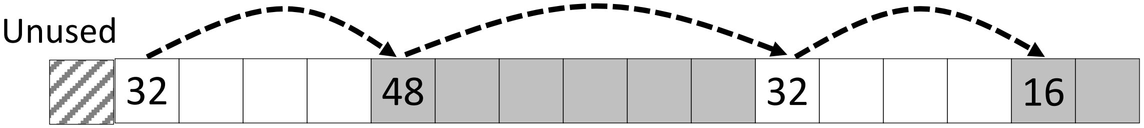
- **Implementation: very simple**
- **Allocate cost:**
  - linear time worst case
- **Free cost:**
  - constant time worst case
  - even with coalescing
- **Memory Overhead:**
  - Depends on placement policy
  - Strategies include first fit, next fit, and best fit
- **Not used in practice for `malloc/free`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

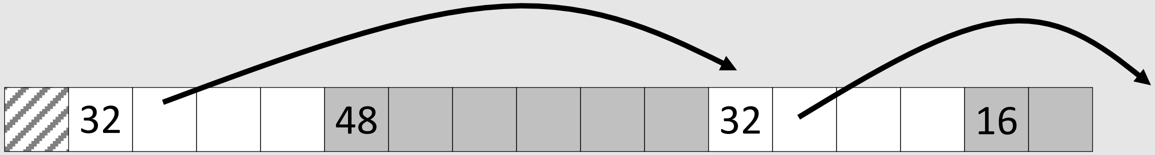
- **Explicit free lists**
- Segregated free lists
- Memory-related perils and pitfalls

Keeping Track of Free Blocks

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



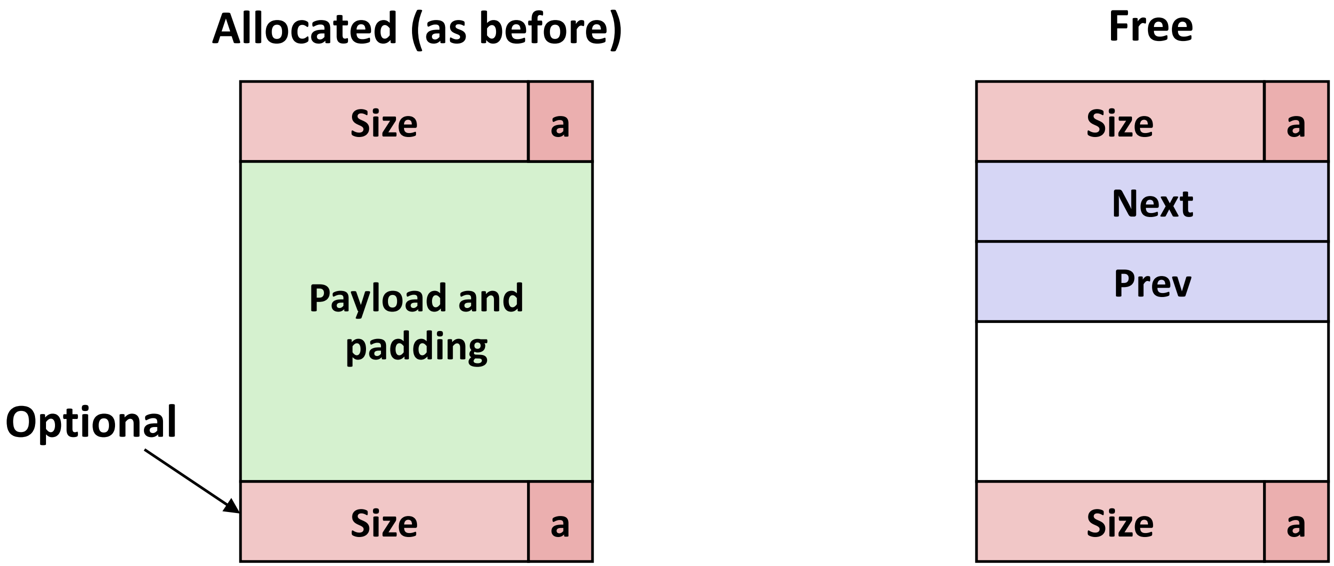
- **Method 2: *Explicit list* among the free blocks using pointers**



- **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

Explicit Free Lists

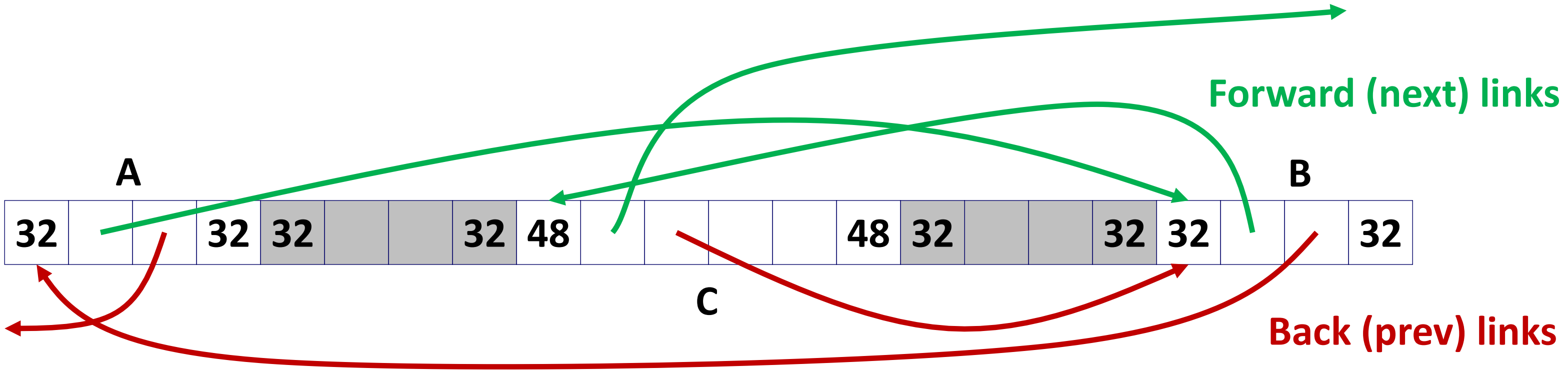


- **Maintain list(s) of *free* blocks, not *all* blocks**
  - Luckily we track only free blocks, so we can use payload area
  - The "next" free block could be anywhere
    - So we need to store forward/back pointers, not just sizes
  - Still need boundary tags for coalescing
    - To find adjacent blocks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

Explicit Free Lists

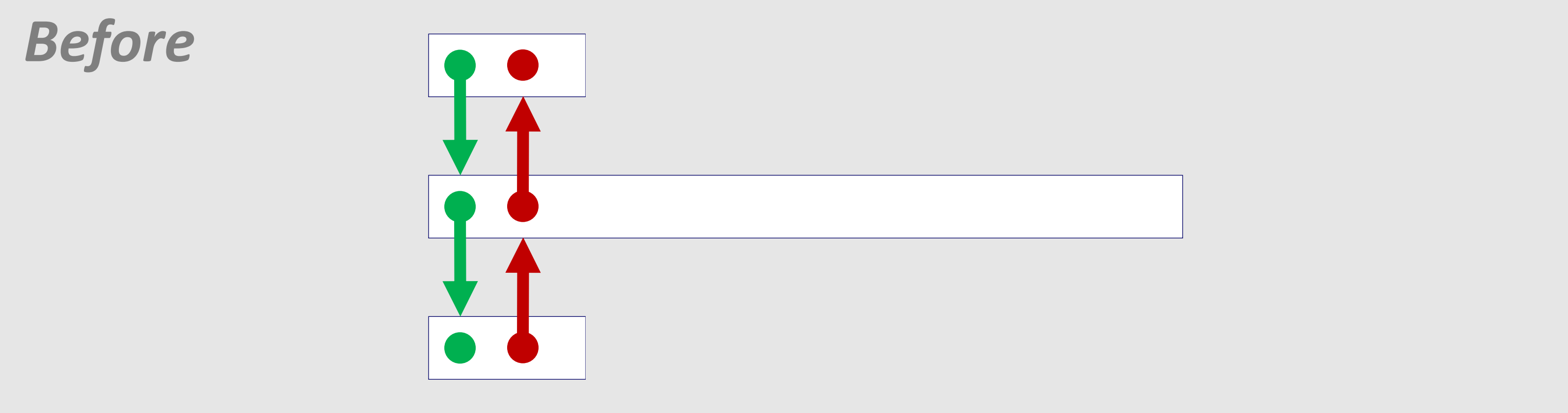
- **Logically:**

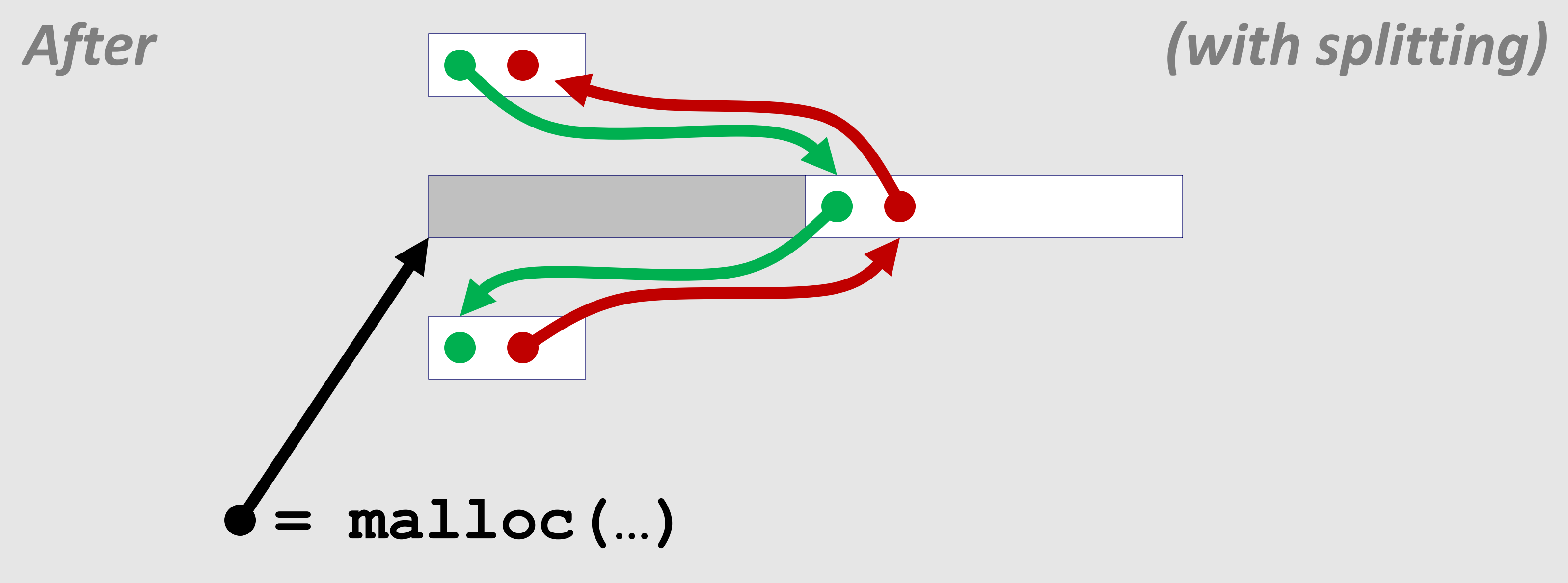
- **Physically: blocks can be in any order**



Allocating From Explicit Free Lists

conceptual graphic



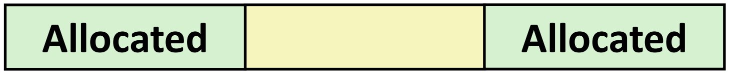


Freeing With Explicit Free Lists

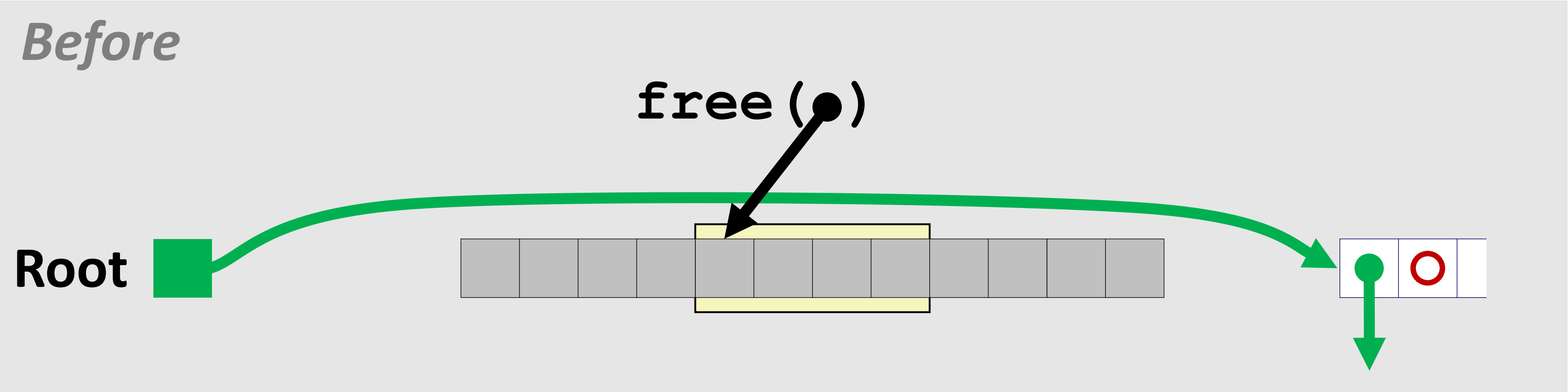
- ***Insertion policy*: Where in the free list do you put a newly freed block?**
- **Unordered**
  - LIFO (last-in-first-out) policy
    - Insert freed block at the beginning of the free list
  - FIFO (first-in-first-out) policy
    - Insert freed block at the end of the free list
  - ***Pro:*** simple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

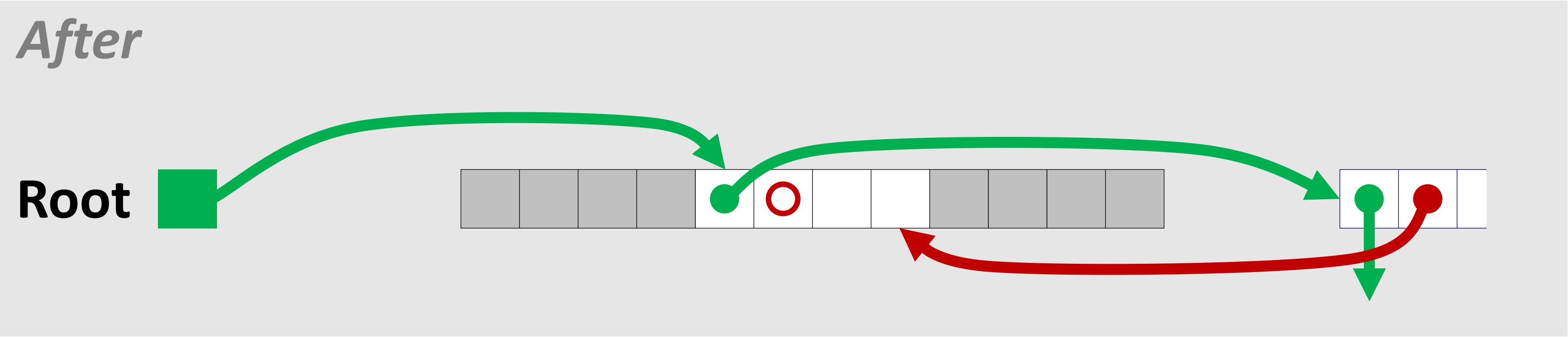
Freeing With a LIFO Policy (Case 1)



conceptual graphic



- **Insert the freed block at the root of the list**

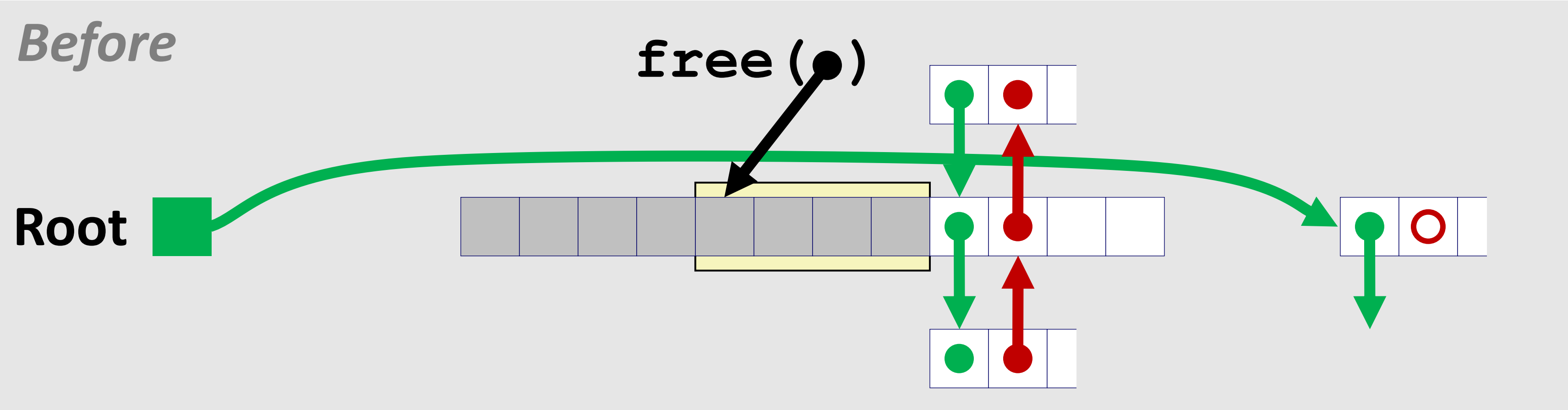


Freeing With a LIFO Policy (Case 2)

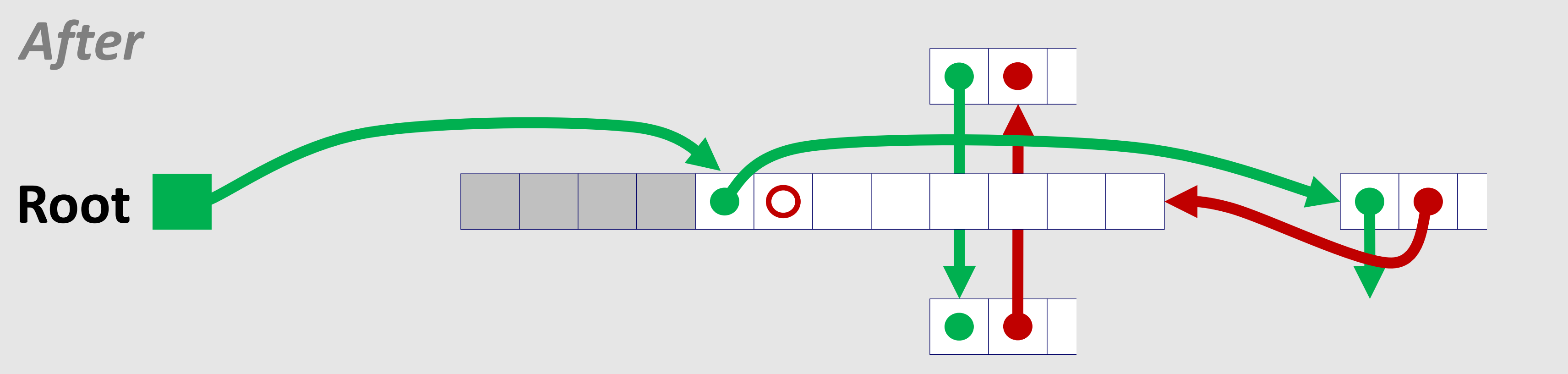
Allocated

Free

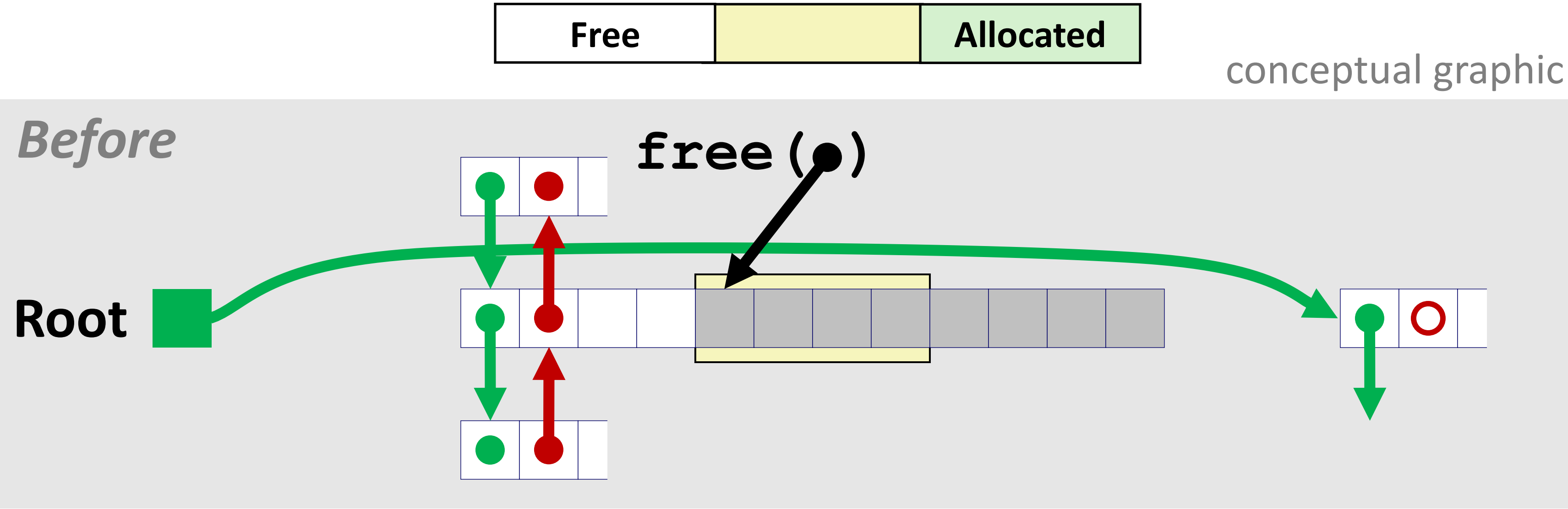
conceptual graphic



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

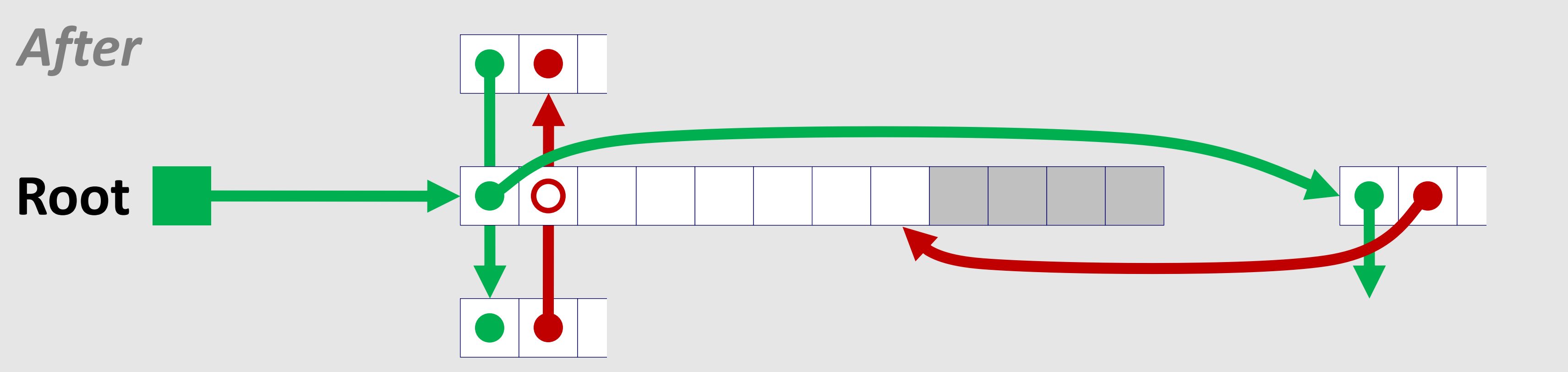


Freeing With a LIFO Policy (Case 3)

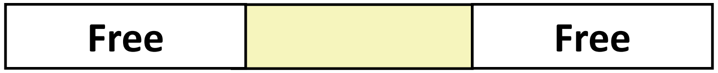


conceptual graphic

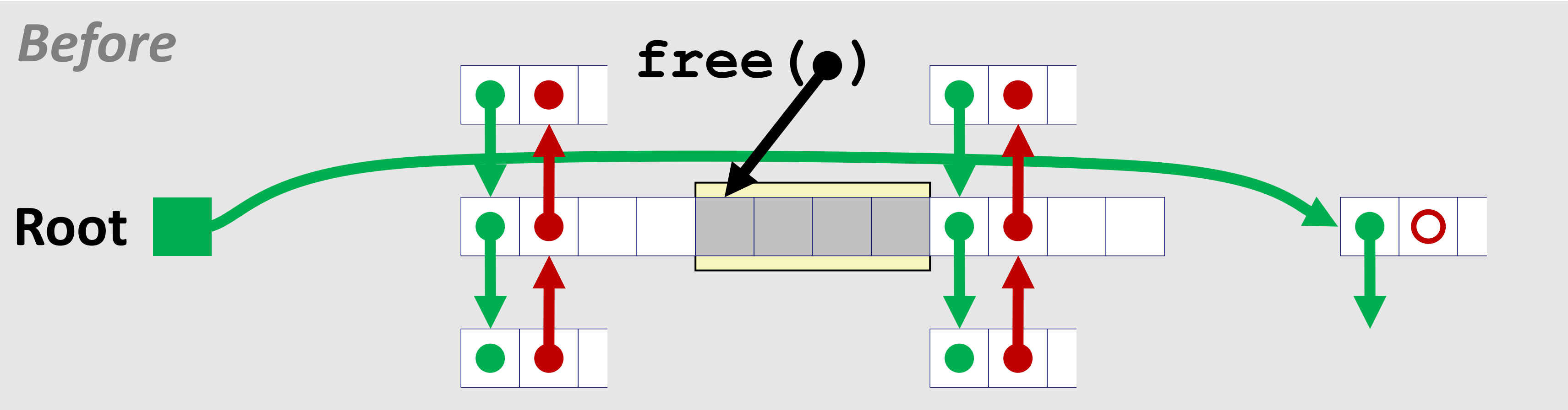
- Splice out adjacent predecessor block, coalesce both memory blocks, and insert the new block at the root of the list



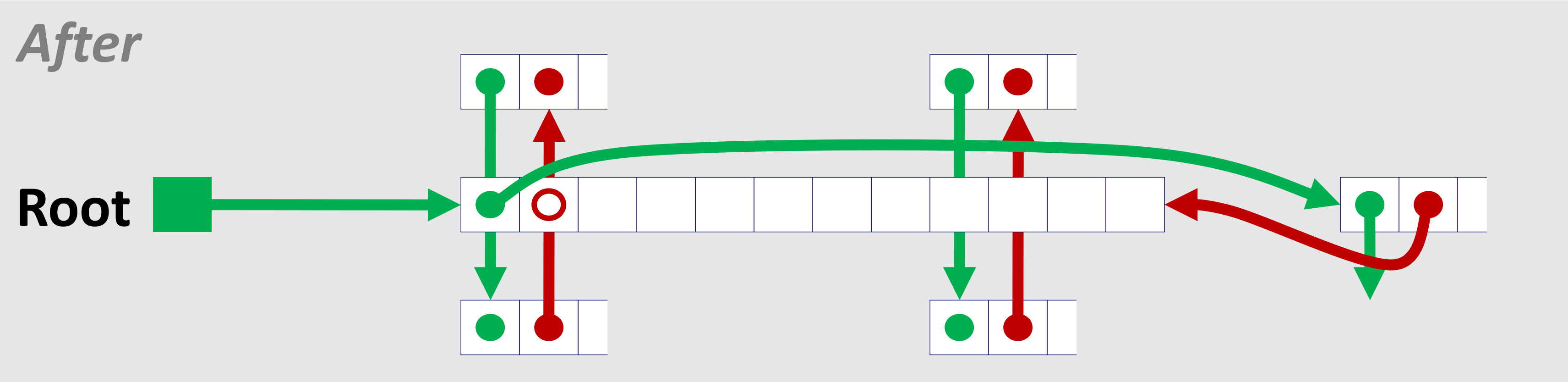
Freeing With a LIFO Policy (Case 4)



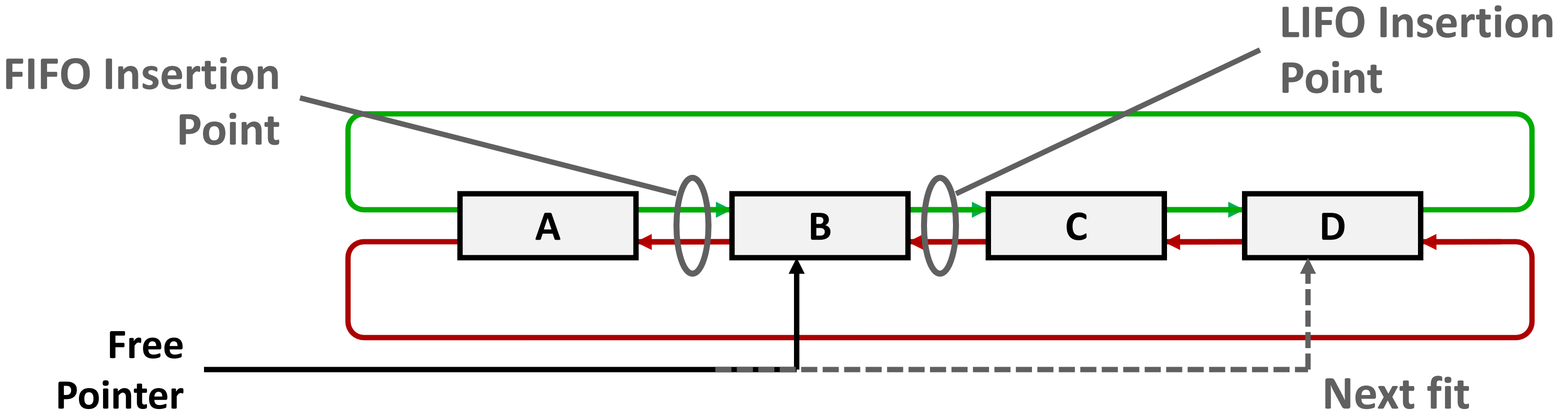
conceptual graphic



- Splice out 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

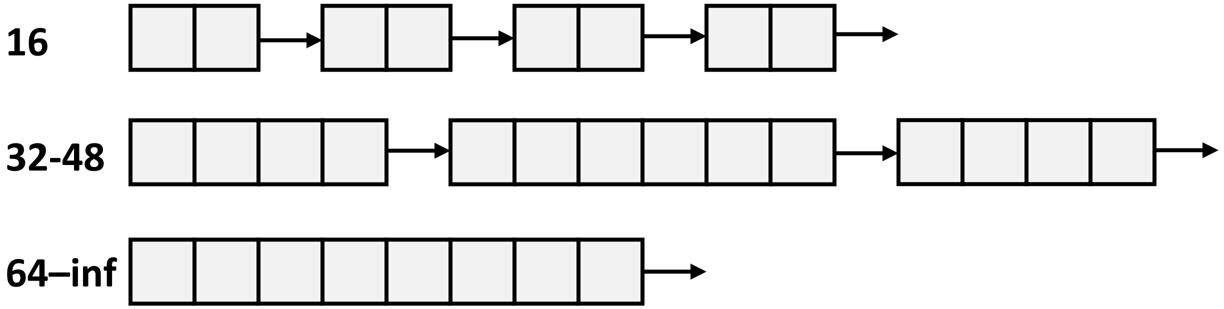
- **Comparison to implicit list:**
  - Allocate is linear time in number of ***free*** blocks instead of ***all*** blocks
    - ***Much faster*** when most of the memory is full
  - Slightly more complicated allocate and free because need to splice blocks in and out of the list
  - Some extra space for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

Today

- Explicit free lists
- **Segregated free lists**
- 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 $[2^i + 1, 2^{i+1}]$**
- **The list for the *largest* blocks must have no upper limit**
  - (well, 2^{64})

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 $m \geq n$ (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

https://canvas.cmu.edu/courses/30386/quizzes

Today

- Explicit free lists
- Segregated free lists
- **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);
```

```
case 'd': {
    int *valp = va_arg(ap, int *);
    *valp = (int)strtol(valbuf, &endp, 10);
}
```

**Crash here …
if you’re lucky**

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;
}
```

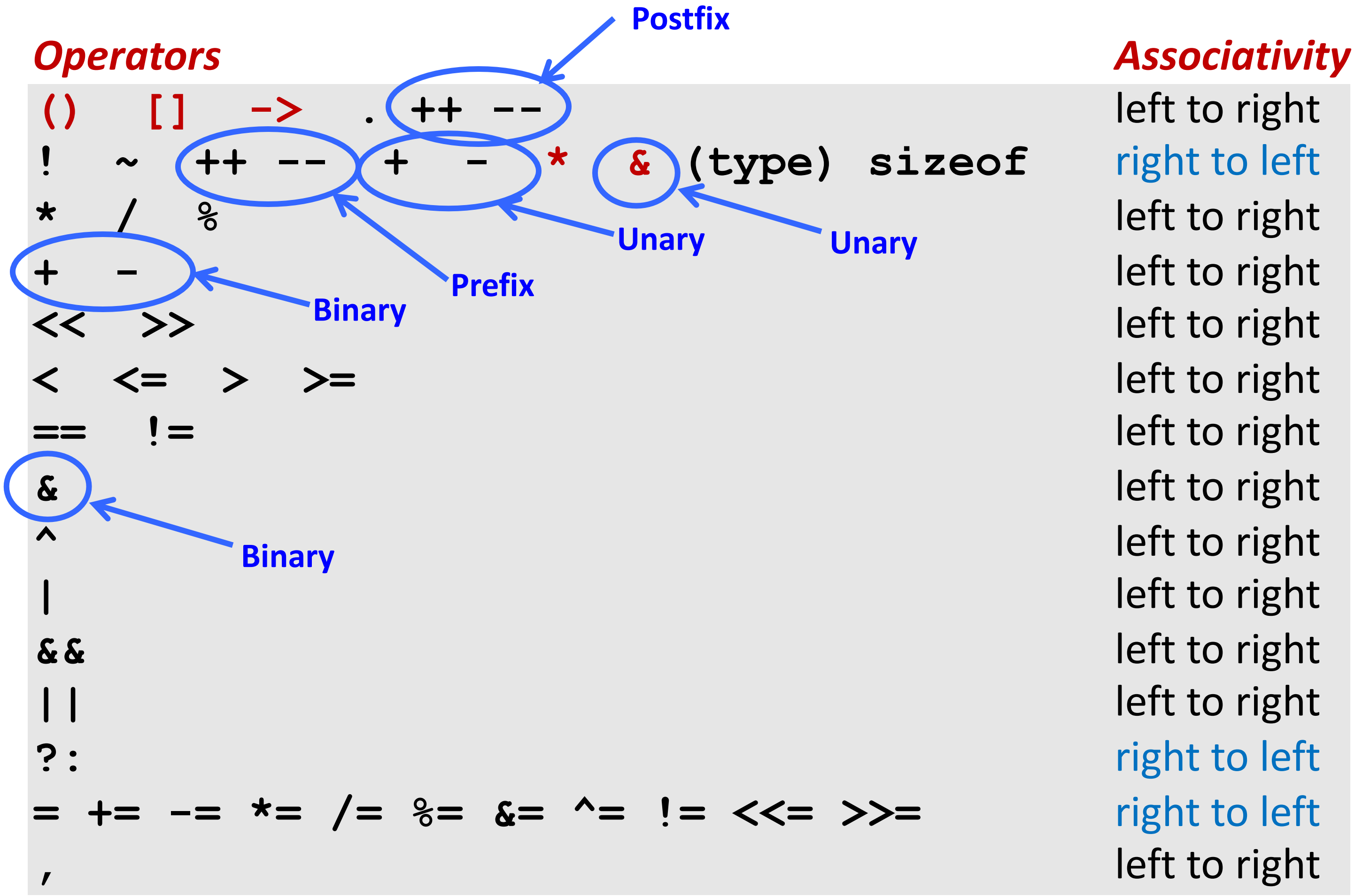
Overwriting Memory

- **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



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

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

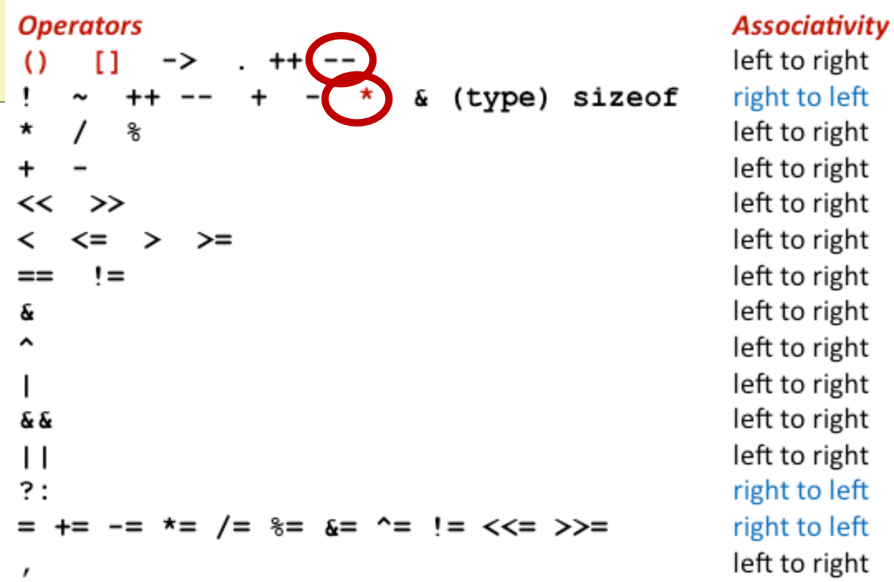
Source: K&R page 53, updated

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);
}
```

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



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

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`