Dynamic Memory Allocation (2)

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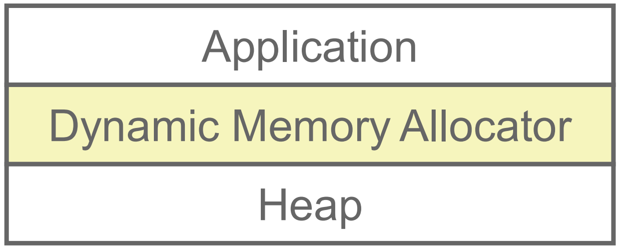
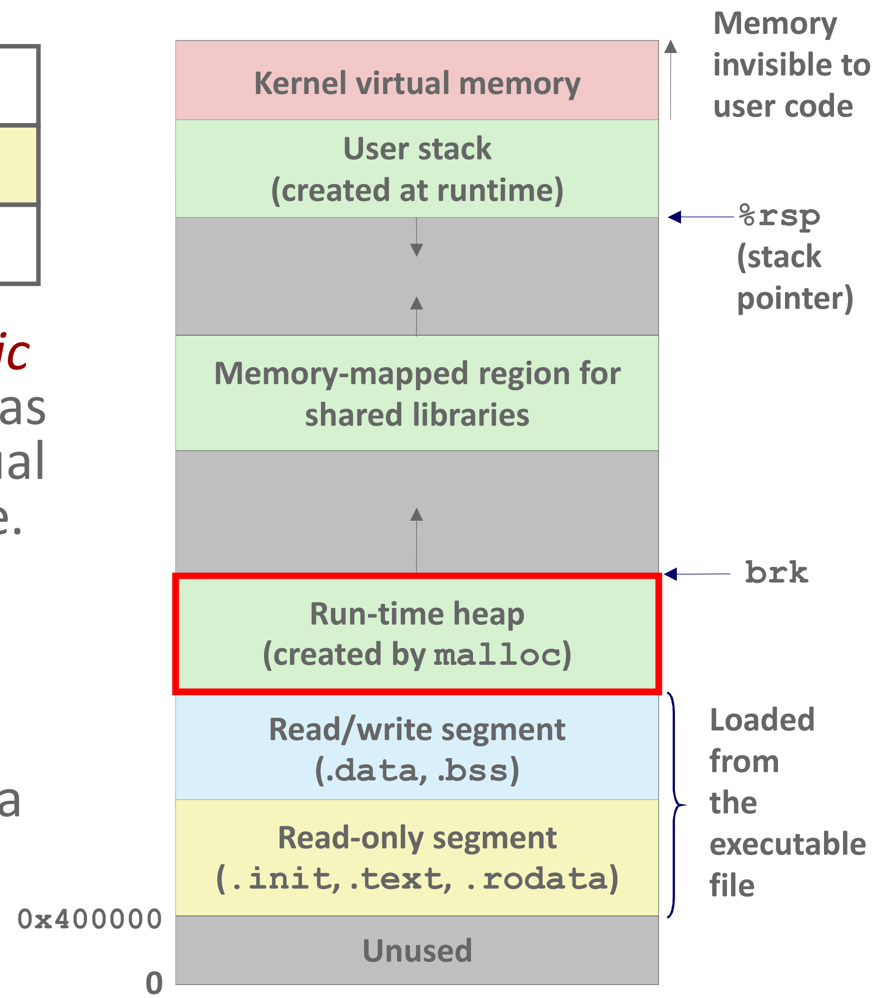
Slides adapted from CMU 15-213: CSAPP course

Review: Dynamic Memory Allocation

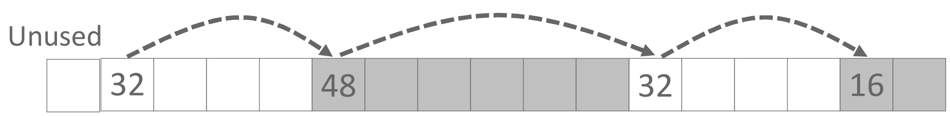


- Programmers use *dynamic memory allocators* (such as `malloc`) to acquire virtual memory (VM) at run time.
  - for data structures whose size is only known at runtime
- Dynamic memory allocators manage an area of process VM known as the *heap*.



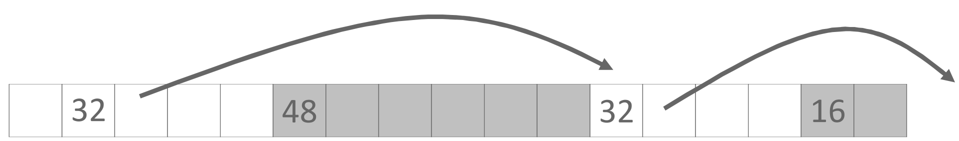
Review: Keeping Track of Free Blocks

- 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

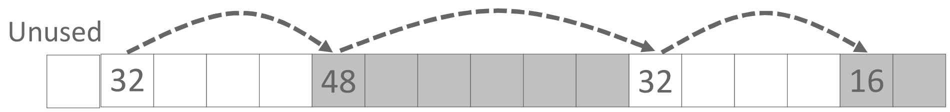
- Implementation: very simple
- Allocate cost:
  - linear time worst case
- Free cost:
  - constant time worst case
  - even with coalescing
- Memory Overhead:
  - Depends on placement policy
  - Strategies include first fit, next fit, and best fit
- Not used in practice for `malloc/free` because of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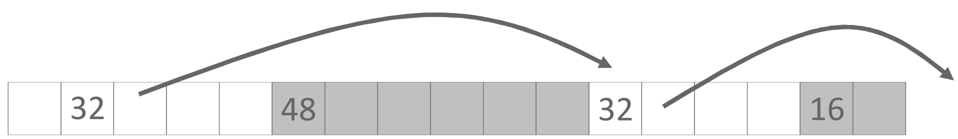

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  - Different free lists for different size classes
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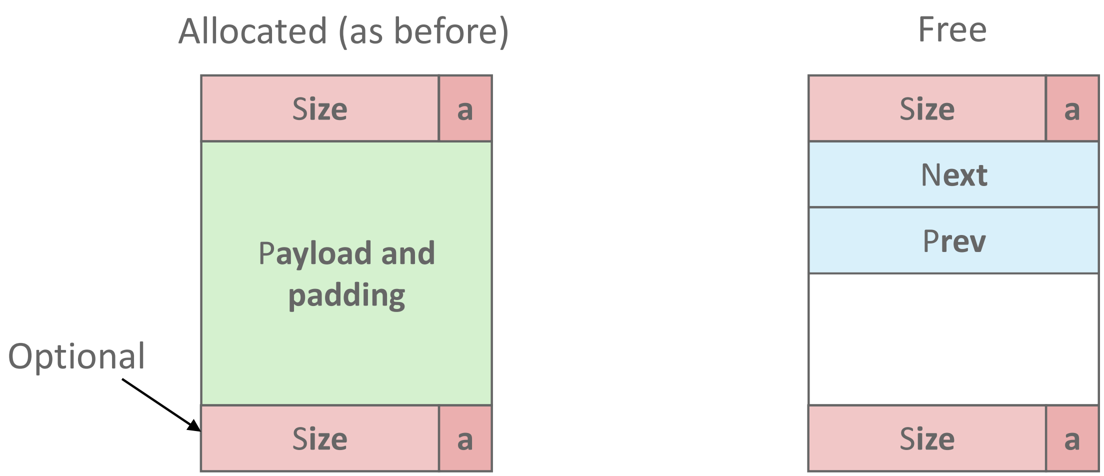
Explicit Free Lists

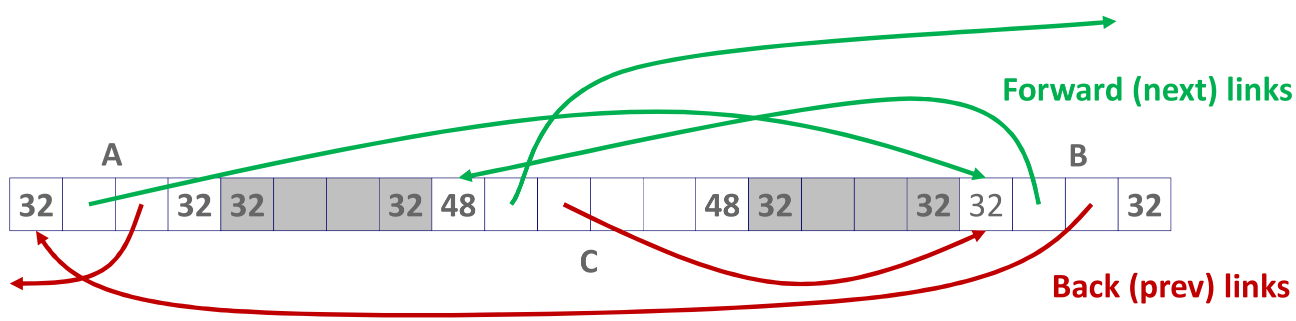


- Maintain list(s) of *free* blocks, not *all* blocks
  - Luckily we track only free blocks, so we can use payload area
  - The "next" free block could be anywhere
    - So we need to store forward/back pointers, not just sizes
  - Still need boundary tags for coalescing
    - To find adjacent blocks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

Explicit Free Lists

- Logically:

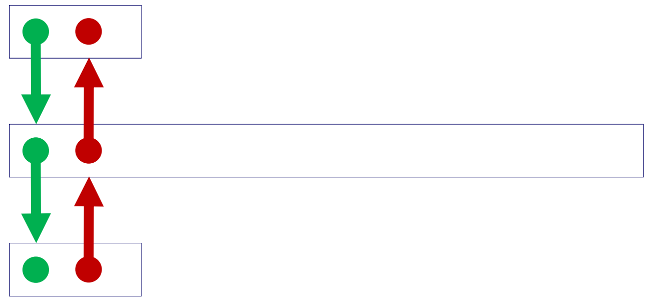
- Physically: blocks can be in any order



Allocating From Explicit Free Lists

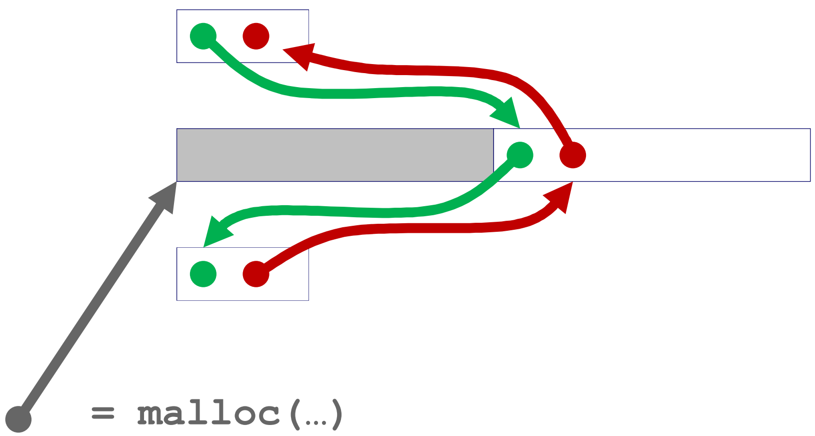
conceptual graphic

Before



After

(with splitting)



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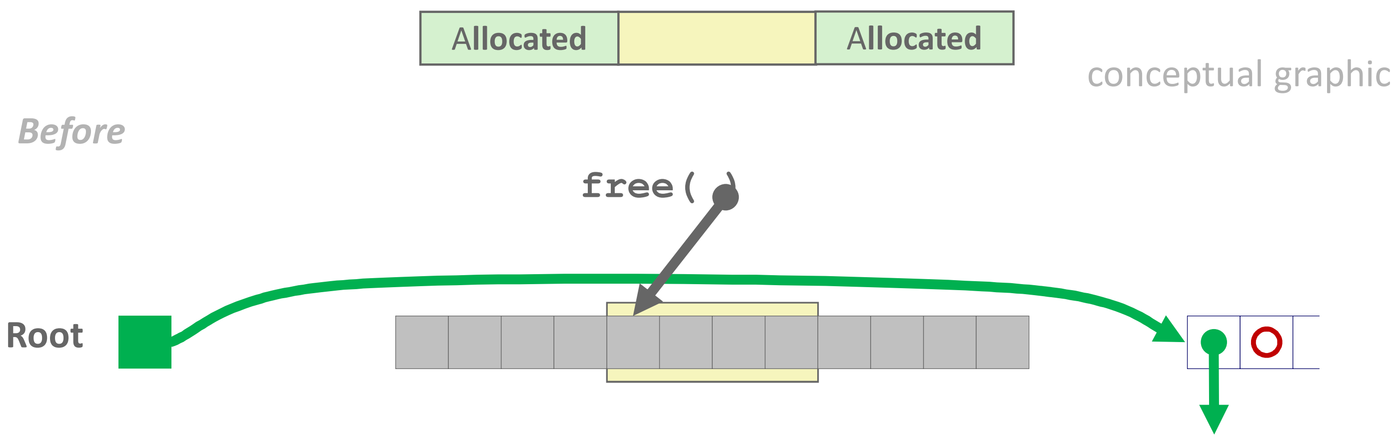
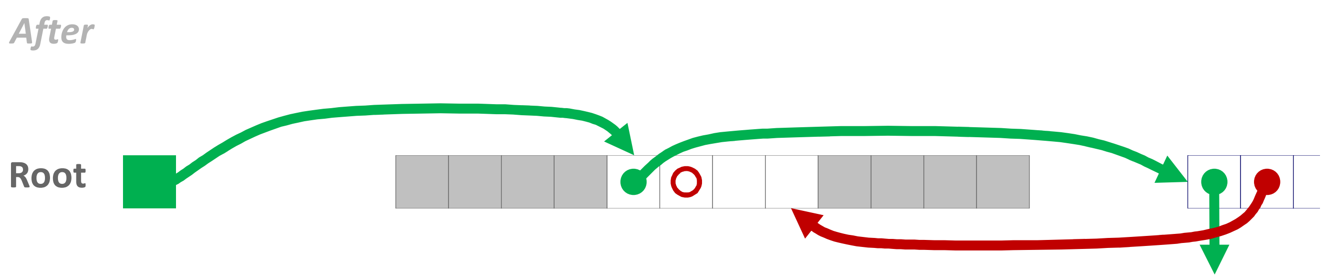
Freeing With Explicit Free Lists

- *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

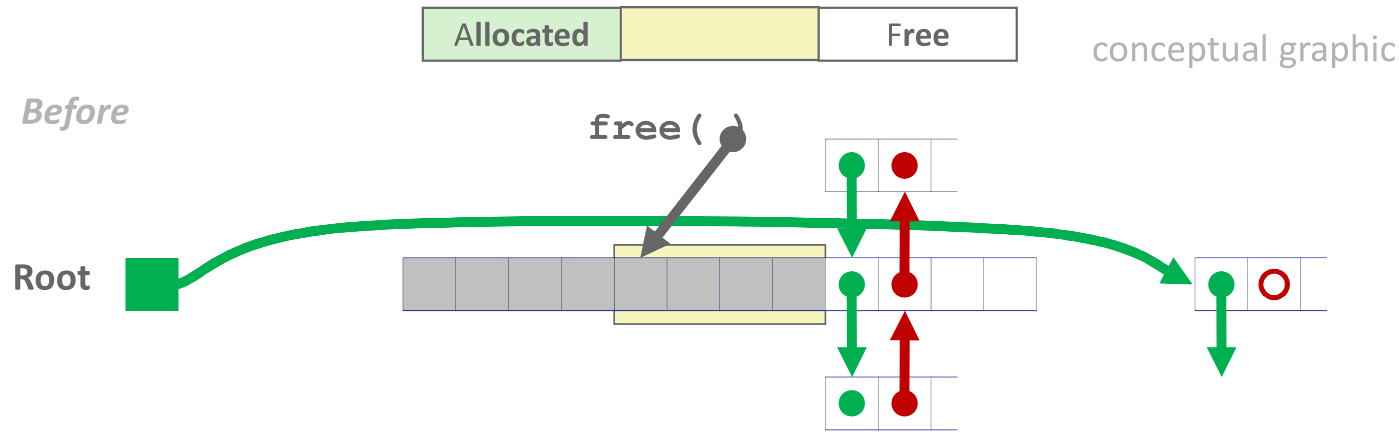
Freeing With a LIFO Policy (Case 1)



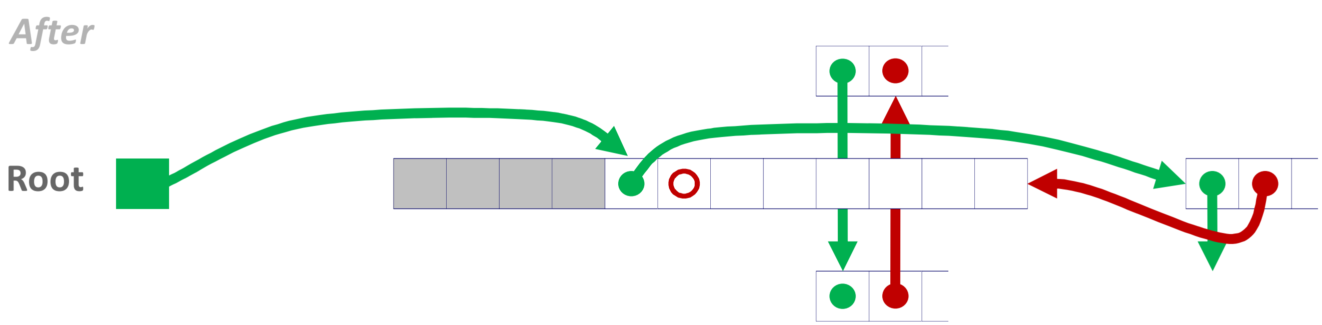
- Insert the freed block at the root of the list



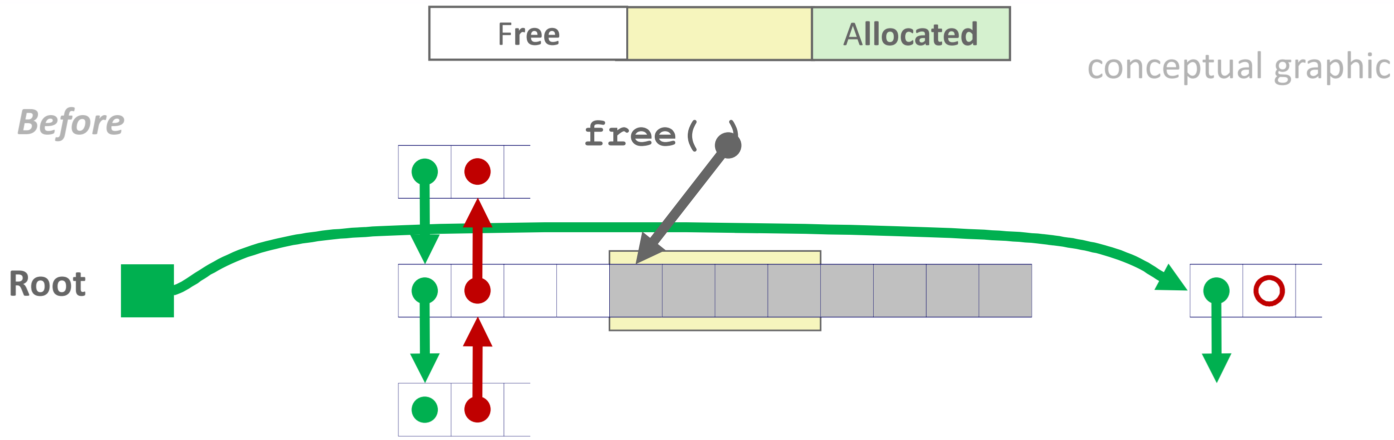
Freeing With a LIFO Policy (Case 2)



- 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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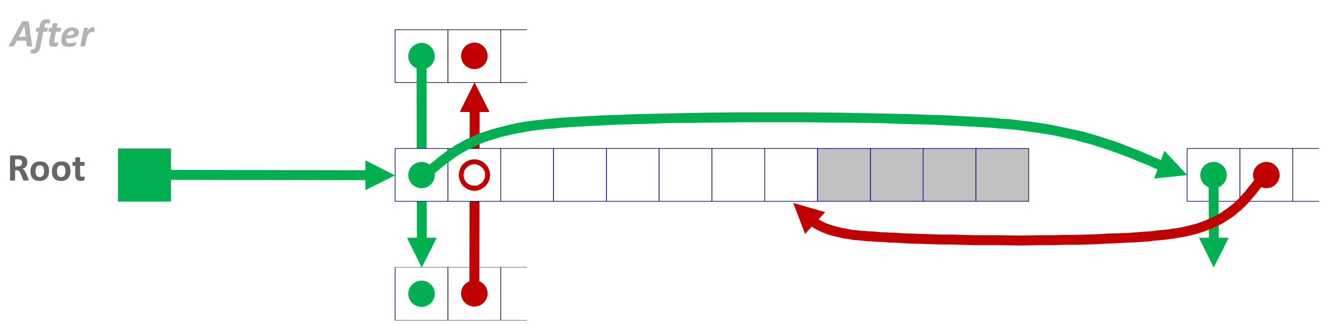
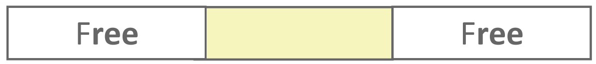
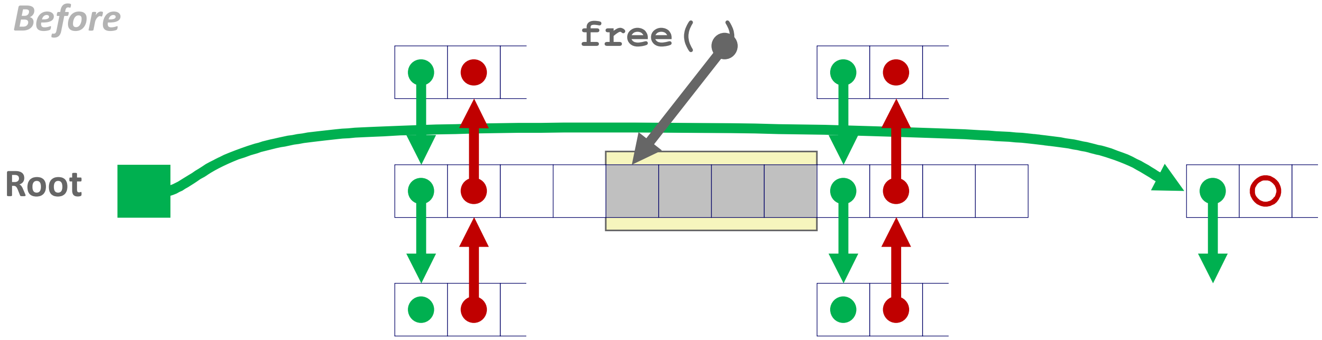


Freeing With a LIFO Policy (Case 4)



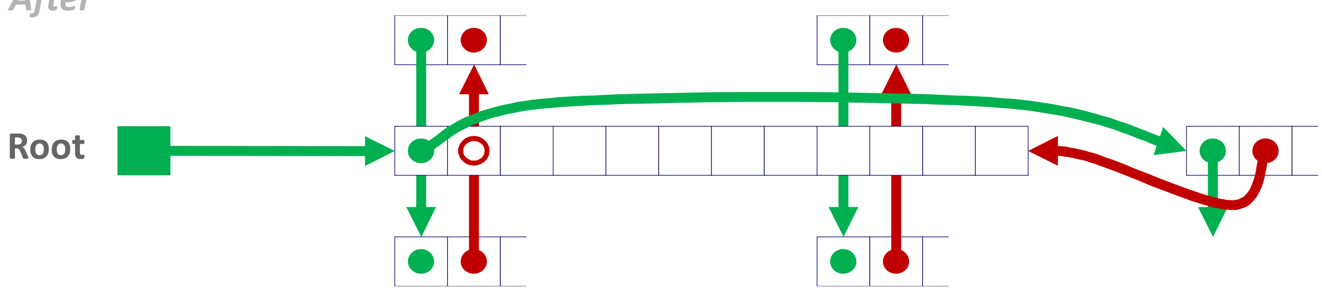
conceptual graphic

Before

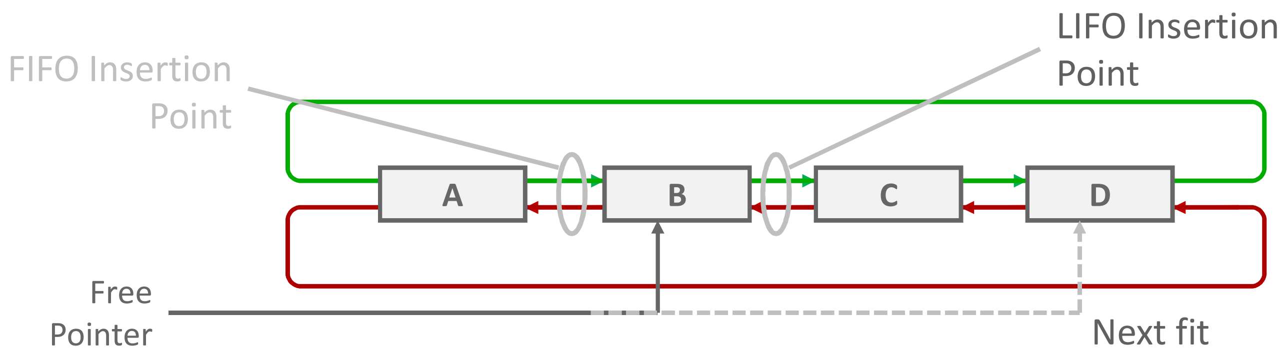


- Splice out adjacent predecessor and successor blocks, coalesce all 3 blocks, and insert the new block at the root of the list

After



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

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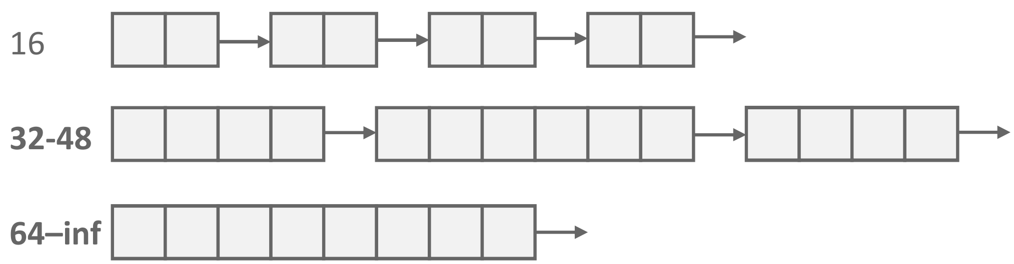
Segregated List (Seglist) Allocators

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

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.

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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

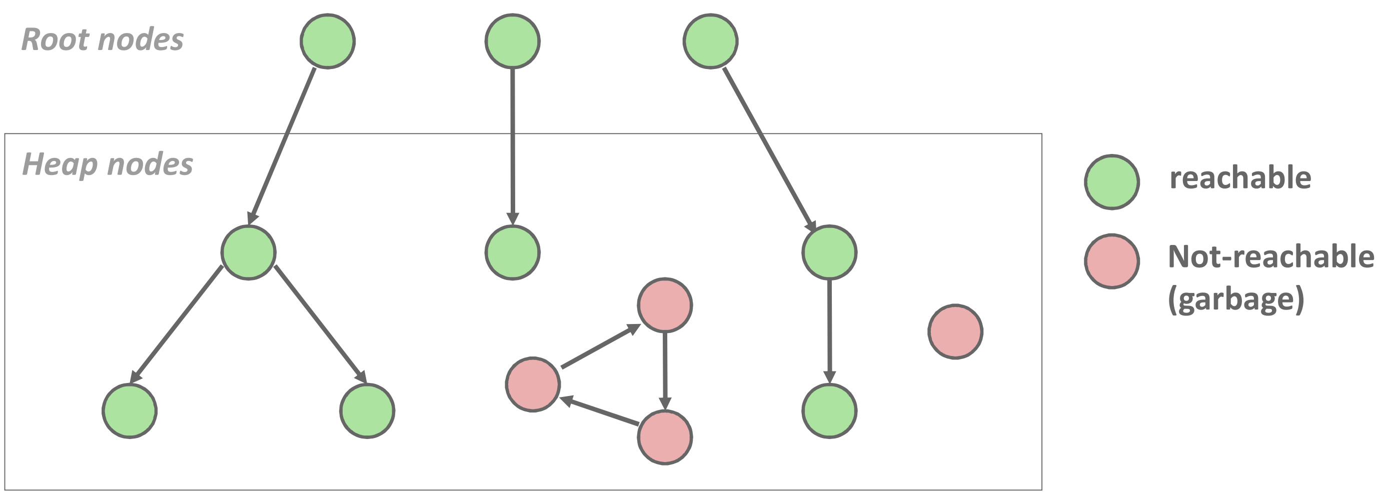
- How does the memory manager know when memory can be freed?
  - In general we cannot know what is going to be used in the future since it depends on conditionals
  - But we can tell that certain blocks cannot be used if there are no pointers to them
- Must make certain assumptions about pointers
  - 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)

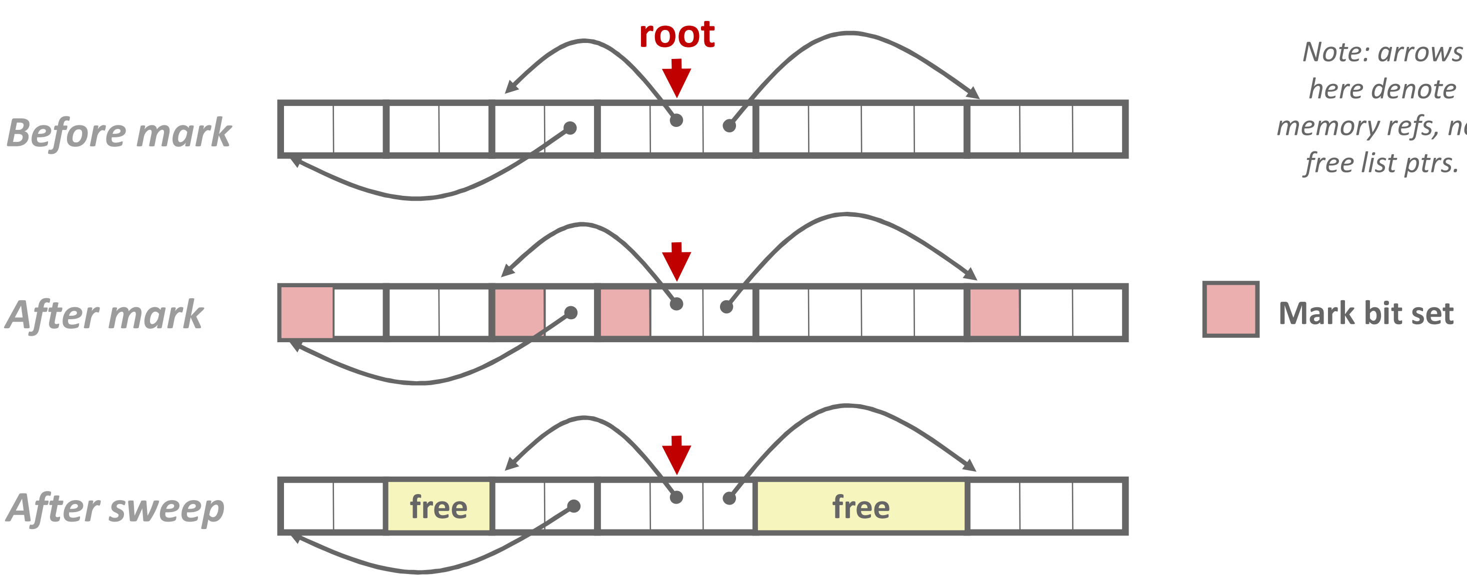


A node (block) is ***reachable*** if there is a path from any root to that node.

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



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 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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      p += length(p+1);             // goto next block
}
```

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)

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C operators

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

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

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`**