

15-213

“The course that gives CMU its Zip!”

Dynamic Memory Allocation II

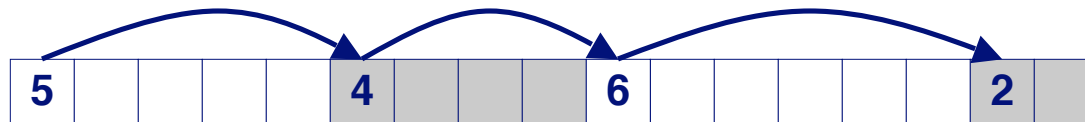
Nov 7, 2002

Topics

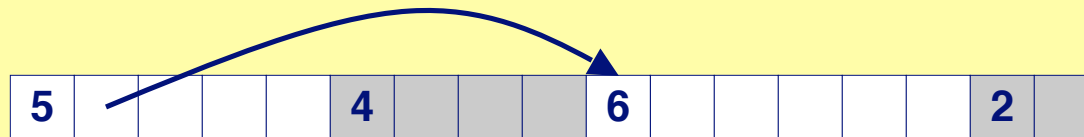
- Explicit doubly-linked free lists
- Segregated free lists
- Garbage collection
- Memory-related perils and pitfalls

Keeping Track of Free Blocks

- **Method 1**: Implicit list using lengths -- links all blocks



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



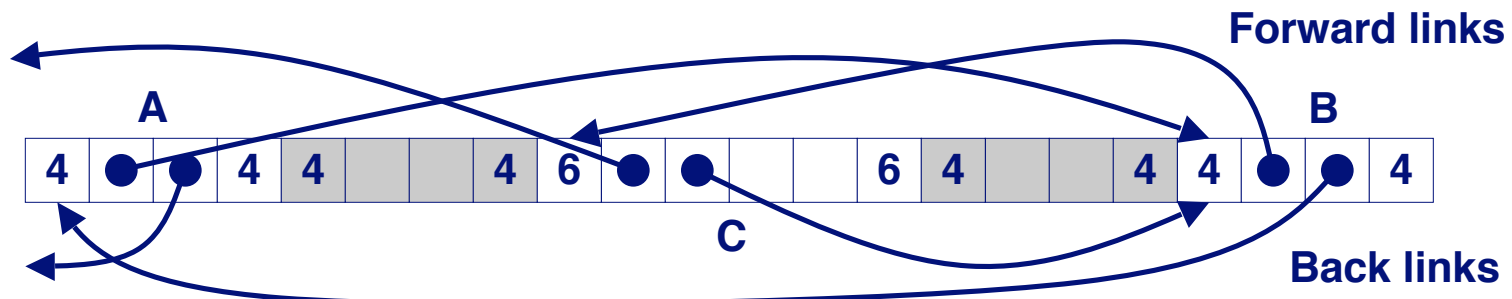
- **Method 3**: Segregated free lists
 - Different free lists for different size classes
- **Method 4**: Blocks sorted by size (not discussed)
 - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Explicit Free Lists



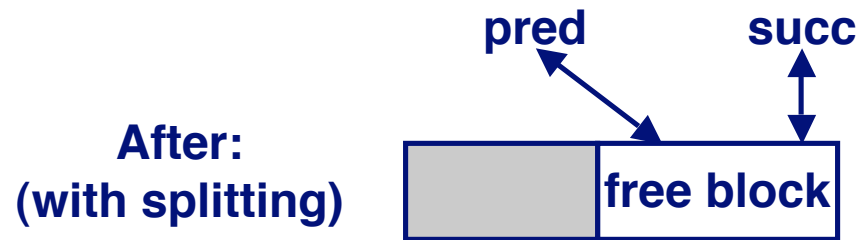
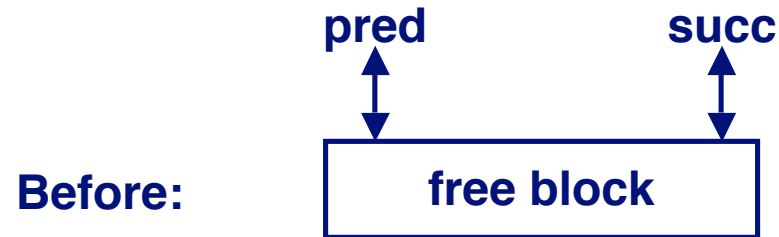
Use data space for link pointers

- Typically doubly linked
- Still need boundary tags for coalescing



- It is important to realize that links are not necessarily in the same order as the blocks

Allocating From Explicit Free Lists



Freeing With Explicit Free Lists

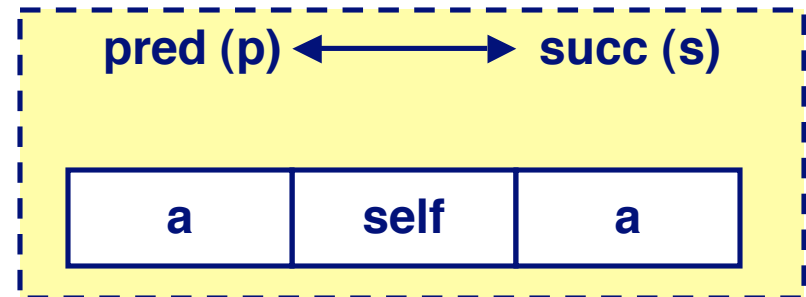
Insertion policy: Where in the free list do you put a newly freed block?

- **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
 - » i.e. $\text{addr}(\text{pred}) < \text{addr}(\text{curr}) < \text{addr}(\text{succ})$
 - Con: requires search
 - Pro: studies suggest fragmentation is better than LIFO

Freeing With a LIFO Policy

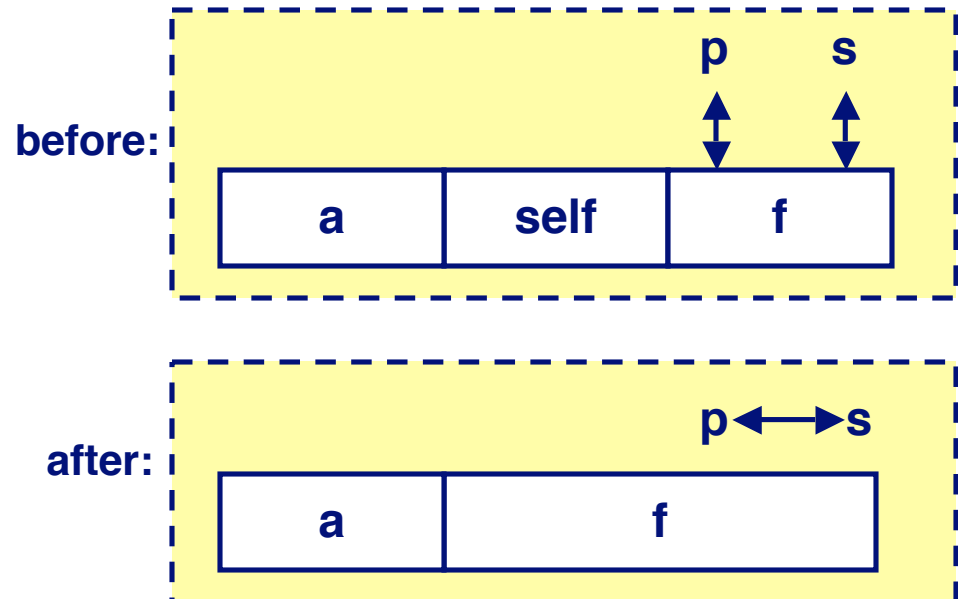
Case 1: a-a-a

- Insert self at beginning of free list



Case 2: a-a-f

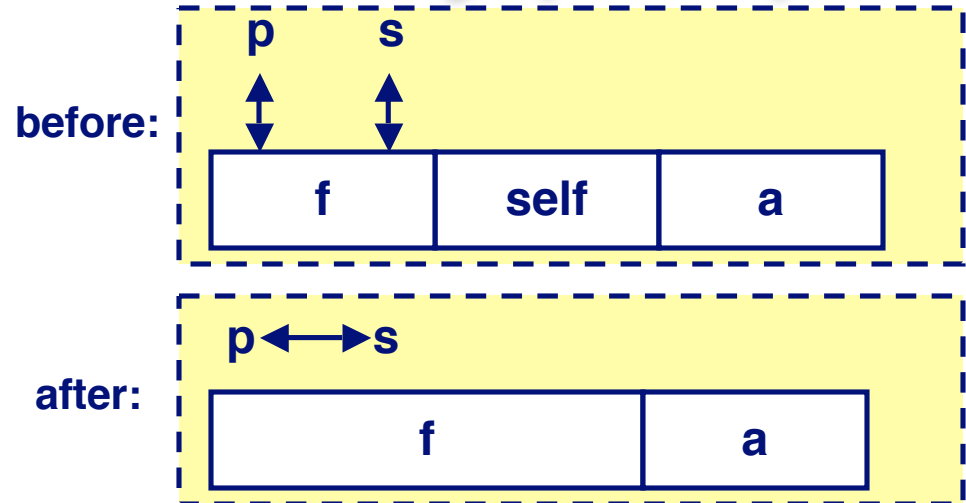
- Splice out next, coalesce self and next, and add to beginning of free list



Freeing With a LIFO Policy (cont)

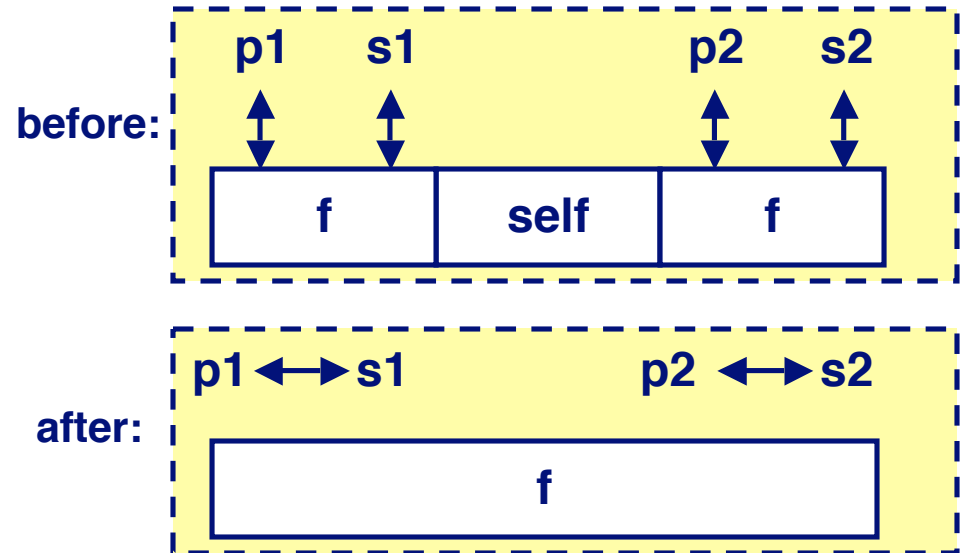
Case 3: f-a-a

- Splice out prev, coalesce with self, and add to beginning of free list



Case 4: f-a-f

- Splice out prev and next, coalesce with self, and add to beginning of list



Explicit List Summary

Comparison to implicit list:

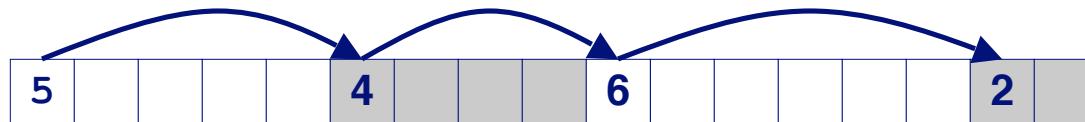
- Allocate is linear time in number of free blocks instead of total blocks -- much faster allocates when most of the memory is full
- Slightly more complicated allocate and free since needs to splice blocks in and out of the list
- Some extra space for the links (2 extra words needed for each block)

Main use of linked lists is in conjunction with segregated free lists

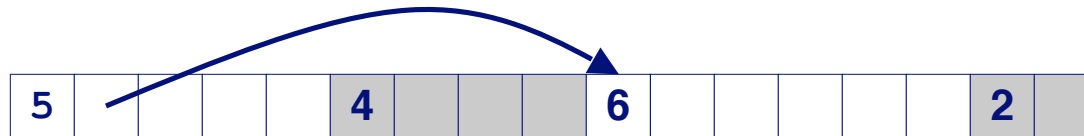
- Keep multiple linked lists of different size classes, or possibly for different types of objects

Keeping Track of Free Blocks

Method 1: Implicit list using lengths -- links all blocks



Method 2: Explicit list among the free blocks using pointers within the free blocks



Method 3: Segregated free list

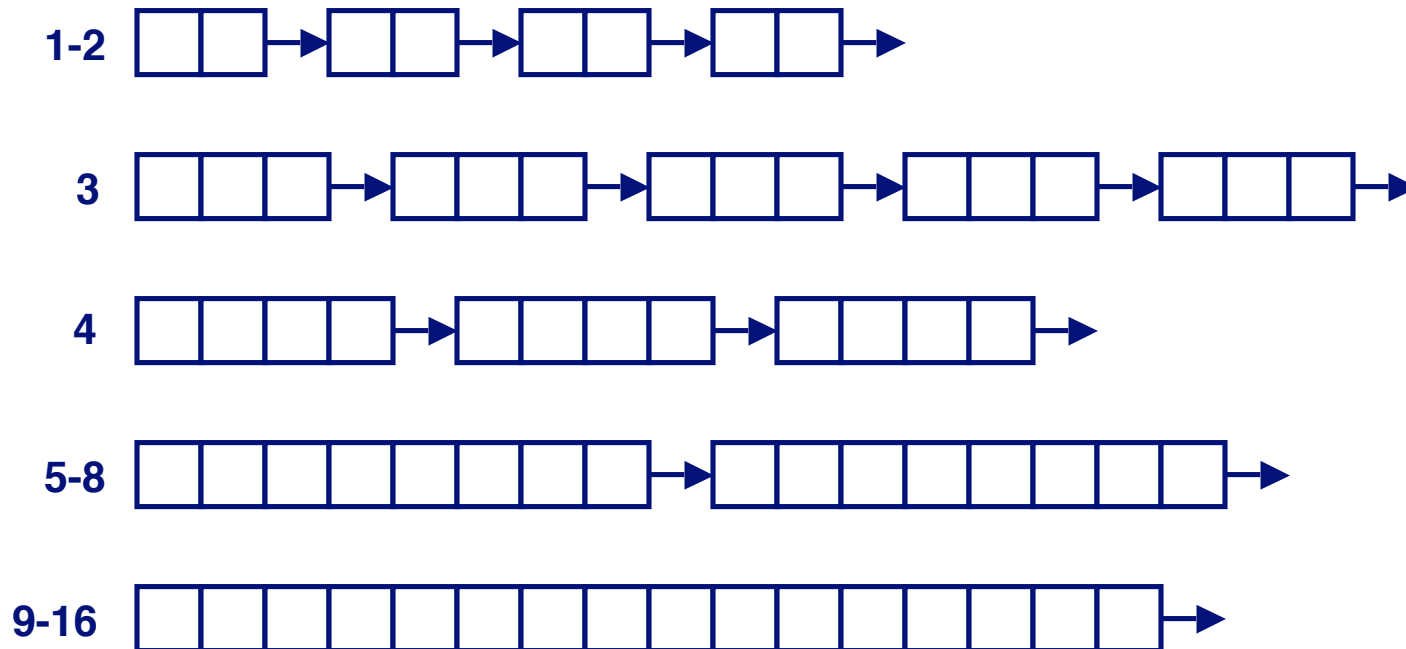
- Different free lists for different size classes

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

Segregated Storage

Each *size class* has its own collection of blocks



- Often have separate size class for every small size (2,3,4,...)
- For larger sizes typically have a size class for each power of 2

Simple Segregated Storage

Separate heap and free list for each size class

No splitting

To allocate a block of size n:

- **If free list for size n is not empty,**
 - **allocate first block on list (note, list can be implicit or explicit)**
- **If free list is empty,**
 - **get a new page**
 - **create new free list from all blocks in page**
 - **allocate first block on list**
- **Constant time**

To free a block:

- **Add to free list**
- **If page is empty, return the page for use by another size (optional)**

Tradeoffs:

- **Fast, but can fragment badly**

Segregated Fits

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

To free a block:

- Coalesce and place on appropriate list (optional)

Tradeoffs

- Faster search than sequential fits (i.e., log time for power of two size classes)
- Controls fragmentation of simple segregated storage
- Coalescing can increase search times
 - Deferred coalescing can help

For More Info on Allocators

D. Knuth, “The Art of Computer Programming, Second 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)**

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 functional languages, scripting languages, and modern object oriented languages:

- Lisp, ML, Java, Perl, Mathematica,

Variants (conservative garbage collectors) exist for C and C++

- Cannot 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

Need to 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)

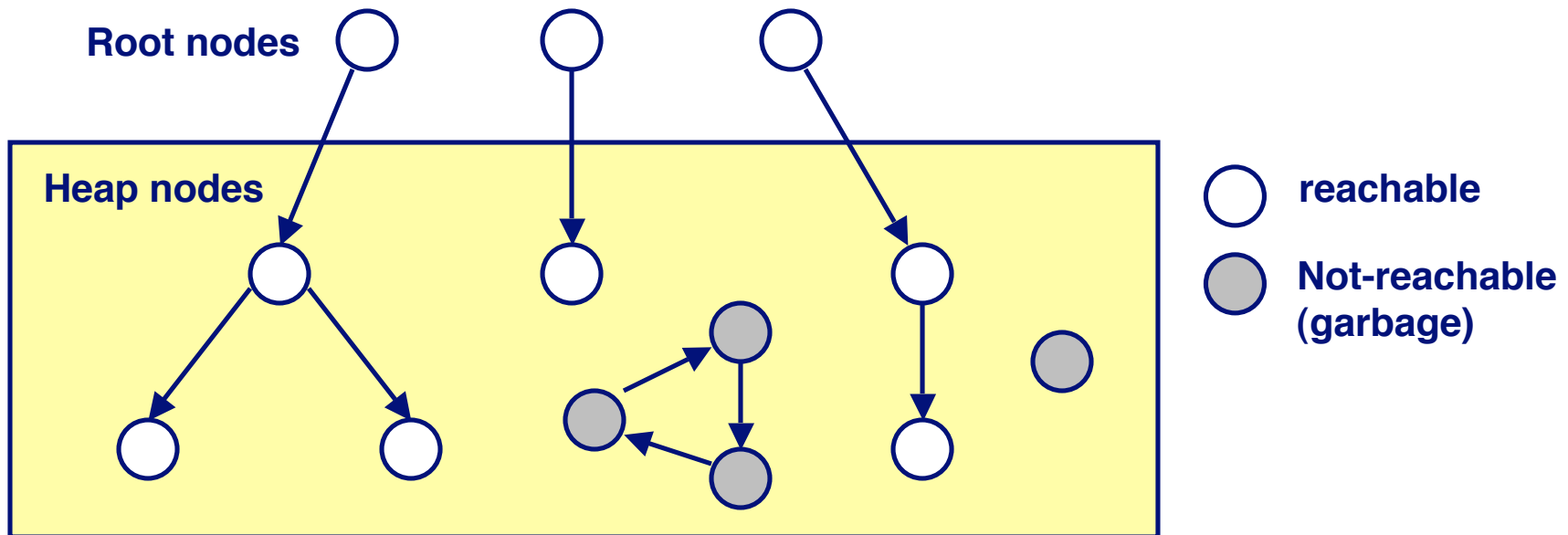
- Moves blocks (not discussed)

For more information, see *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* (never needed by the application)

Assumptions For This Lecture

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

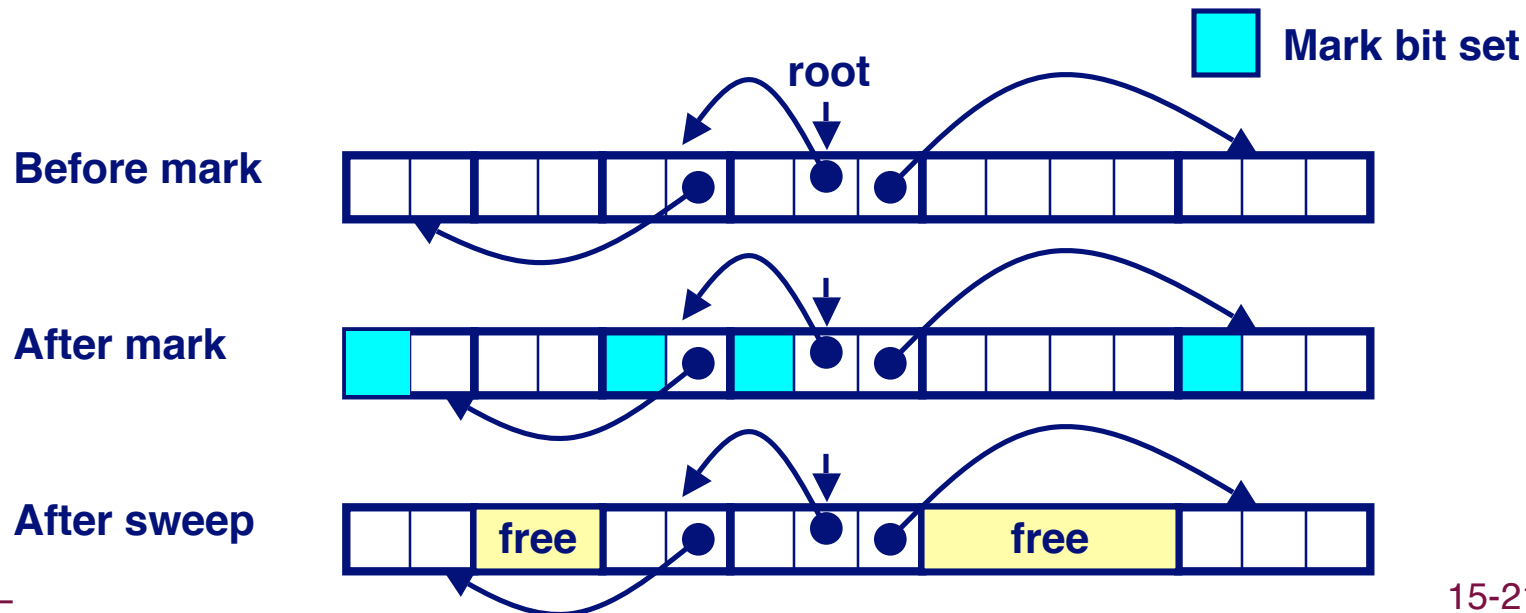
Mark and Sweep Collecting

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 all reachable memory
- **Sweep**: Scan all blocks and **free** blocks that are **not marked**



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++)   // mark all children
        mark(p[i]);
    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 and Sweep in C

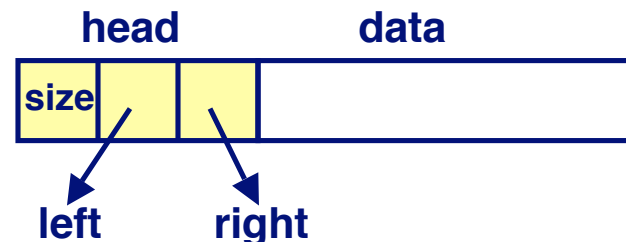
A conservative collector for C programs

- `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 do we find the beginning of the block?

- Can use balanced tree to keep track of all allocated blocks where the key is the location
- Balanced tree pointers can be stored in header (use two additional words)



Memory-Related Bugs

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

```
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

```
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

```
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

- 1988 Internet worm
- Modern attacks on Web servers
- AOL/Microsoft IM war

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);
}
```

Overwriting Memory

Misunderstanding pointer arithmetic

```
int *search(int *p, int val) {  
    while (*p && *p != val)  
        p += sizeof(int);  
  
    return p;  
}
```

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

Conventional debugger (gdb)

- Good for finding bad pointer dereferences
- Hard to detect the other memory bugs

Debugging malloc (CSRI UToronto malloc)

- Wrapper around conventional malloc
- Detects memory bugs at malloc and free boundaries
 - Memory overwrites that corrupt heap structures
 - Some instances of freeing blocks multiple times
 - Memory leaks
- Cannot detect all memory bugs
 - Overwrites into the middle of allocated blocks
 - Freeing block twice that has been reallocated in the interim
 - Referencing freed blocks

Dealing With Memory Bugs (cont.)

Binary translator (Atom, Purify)

- Powerful debugging and analysis technique
- Rewrites text section of executable object file
- Can detect all errors as debugging `malloc`
- Can also check each individual reference at runtime
 - Bad pointers
 - Overwriting
 - Referencing outside of allocated block

Garbage collection (Boehm-Weiser Conservative GC)

- Let the system free blocks instead of the programmer.