# 15-213

*"The course that gives CMU its Zip!"*

# Dynamic Memory Allocation II
# Nov 7, 2000

### Topics

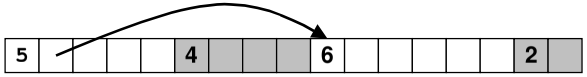
- doubly-linked free lists
- segregated free lists
- garbage collection
- memory-related perils and pitfalls



# 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



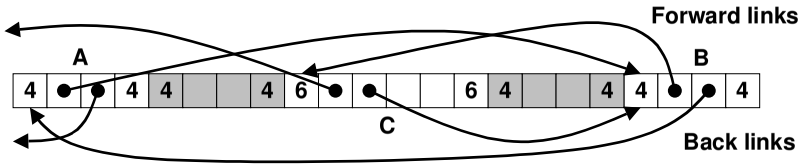

- ***Method 3***: segregated free lists
  - Different free lists for different size classes
- ***Method 4***: blocks sorted by size (not discussed)
  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key



# Explicit free lists

### Use data space for link pointers

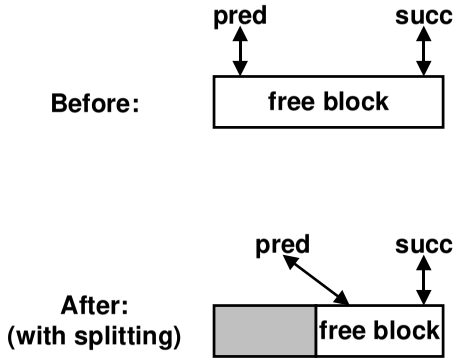
- Typically doubly linked
- Still need boundary tags for coalescing




- 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 to put the newly freed block in the free list**

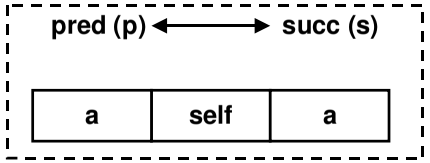
- **LIFO (last-in-first-out) policy**
  - insert freed block at the beginning of the free list
  - pro: simple and constant time
  - con: studies suggest fragmentation is worse than address ordered.
- **Address-ordered policy**
  - insert freed blocks so that free list blocks are always in address order
    - » i.e. addr(pred) < addr(curr) < addr(succ)
  - con: requires search
  - pro: studies suggest fragmentation is better than LIFO



# Freeing with a LIFO policy

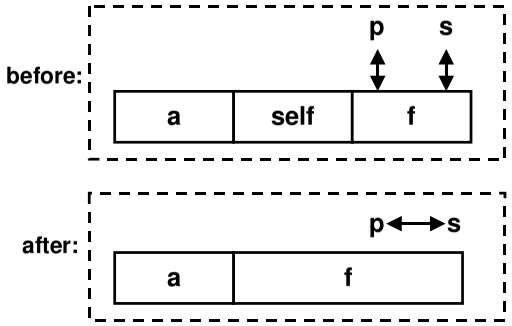
## Case 1: a-a-a

- **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**

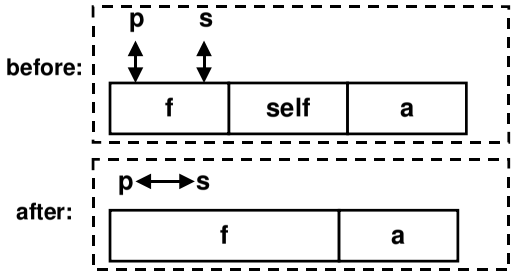





# Freeing with a LIFO policy (cont)

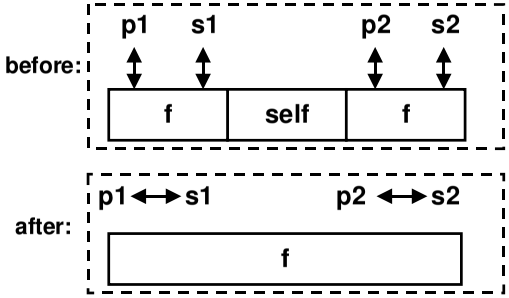
## Case 3: f-a-a

- **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:

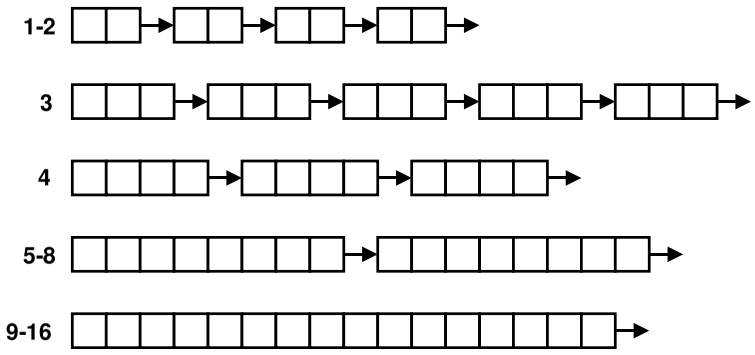
- **Allocate is linear time in number of free blocks instead of total blocks -- much faster allocates when most of the memory is full**
- **Slightly more complicated allocate and free since needs to splice blocks in and out of the list**
- **Some extra space for the links (2 extra words needed for each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

# Segregated Storage

**Each size "class" has its own collection of blocks**




- **Often have separate collection for every small size (2,3,4,...)**
- **For larger sizes typically have a collection 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 information of dynamic storage 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 the course web page (see Documents page)**

# Implicit Memory Management Garbage collector

*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)

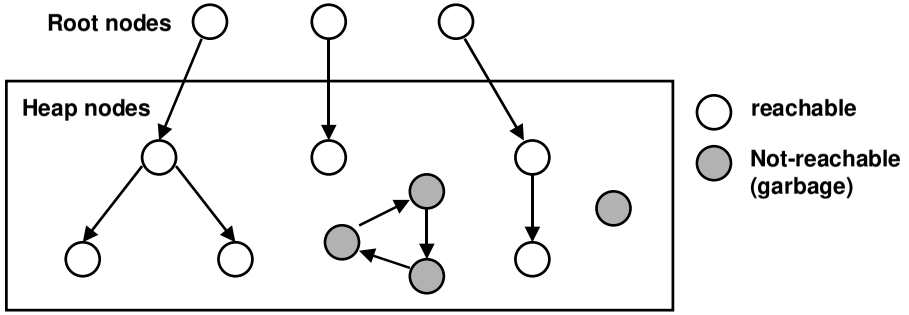
For more information see *Jones and Lin, "Garbage Collection: Algorithms for Automatic Dynamic Memory", John Wiley & Sons, 1996.*



# 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



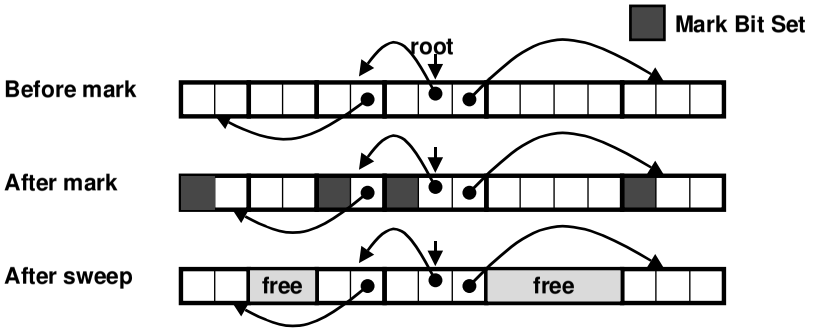
# Mark and sweep collecting

## 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**

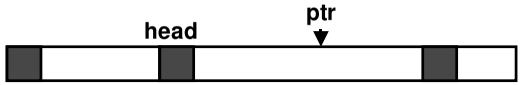
```
ptr sweep(ptr p, ptr end) {
   while (p < end) {
      if markBitSet(p)
         clearMarkBit();
      else if (allocateBitSet(p))
         free(p);
      p += length(p);
}
```



# Mark and sweep in C

## A C Conservative Collector

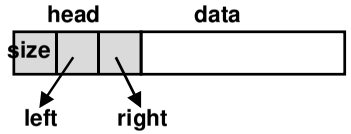
- `Is_ptr()` determines if a word is a pointer by checking if it points to an allocated block of memory.
- But, in C pointers can point to the middle of a block.




**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 head (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*

```
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*

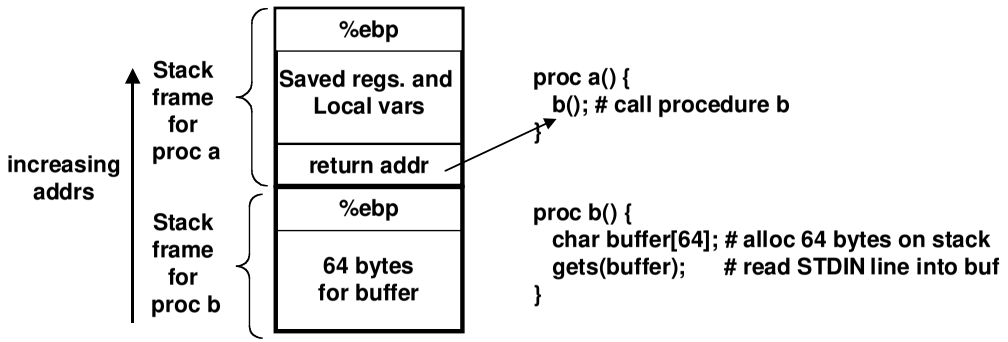
- 1988 Internet worm
- modern attacks on Web servers
- AOL/Microsoft IM war



# Buffer overflow attacks

## Description of hole:

- Servers that use C library routines such as gets() that don't check input sizes when they write into buffers on the stack.
- The following description is based on the IA32 stack conventions. The details will depend on how the stack is organized, which varies between compilers and machines

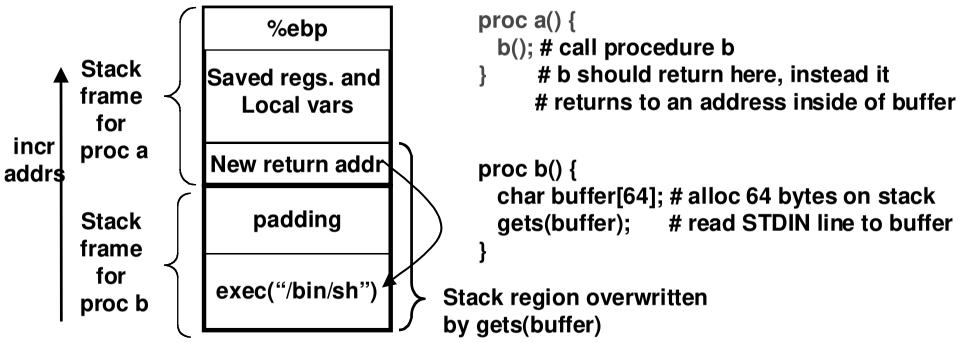





# Buffer overflow attacks

## Vulnerability stems from possibility of the gets() routine overwriting the return address for b.

- overwrite stack frame with
  - machine code instruction(s) that execs a shell
  - a bogus return address to the instruction



# 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.**