

15-213

"The course that gives CMU its Zip!"

Dynamic Memory Allocation II Apr 3, 2002

Topics

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

class21.ppt

Admin

Conflicts for final.

Please email before 4/8 so we can setup an alternative date.

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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

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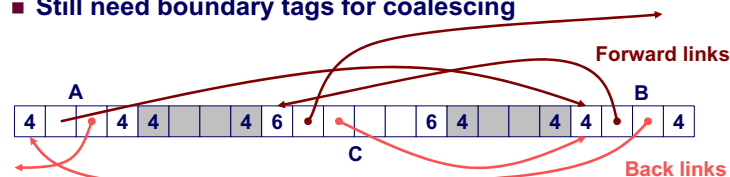
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Explicit Free Lists



Use data space for link pointers

- Typically doubly linked
- Still need boundary tags for coalescing

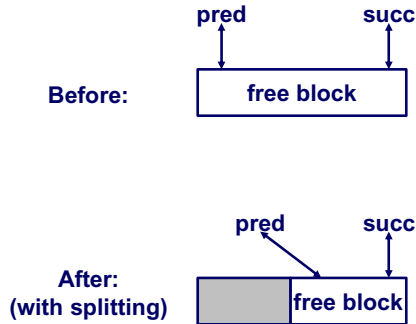


- It is important to realize that links are not necessarily in the same order as the blocks

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Allocating From Explicit Free Lists



Freeing With Explicit Free Lists

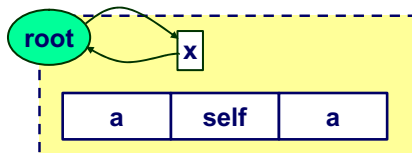
Insertion policy: Where in the free list do you put a newly freed block?

- 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

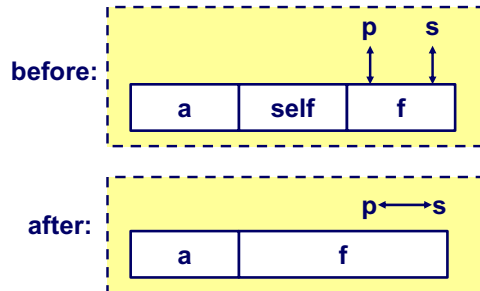
Case 1: a-a-a

- Insert self at beginning of free list



Case 2: a-a-f

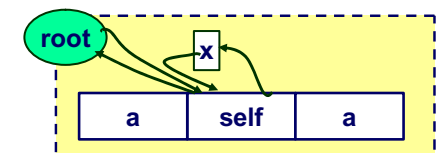
- Splice out next, coalesce self and next, and add to beginning of free list



Freeing With a LIFO Policy

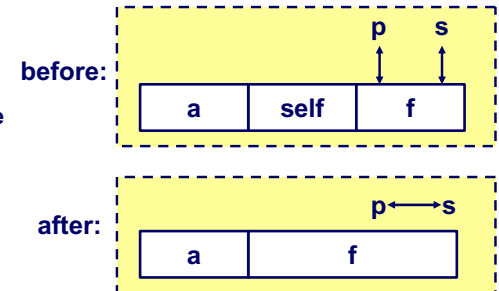
Case 1: a-a-a

- Insert self at beginning of free list



Case 2: a-a-f

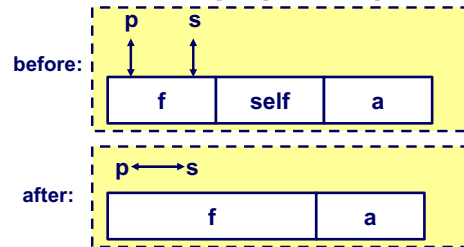
- Splice out next, coalesce self and next, and add to beginning of free list



Freeing With a LIFO Policy (cont)

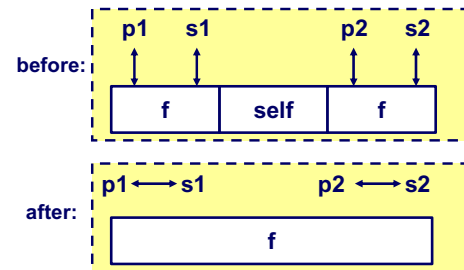
Case 3: f-a-a

- 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



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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) **Does this increase internal frag?**

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

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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*

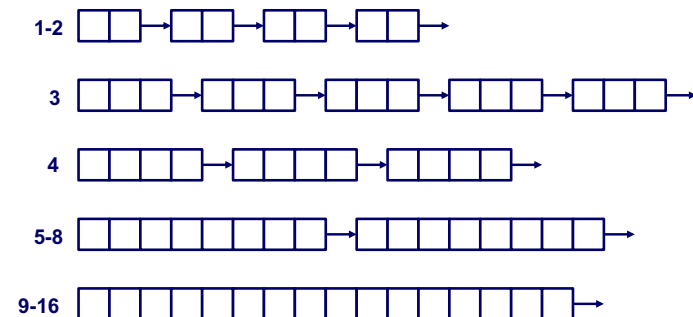
- Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

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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

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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

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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

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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)

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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++

- However, cannot necessarily collect all garbage

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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)

Generational Collectors (Lieberman and Hewitt, 1983)

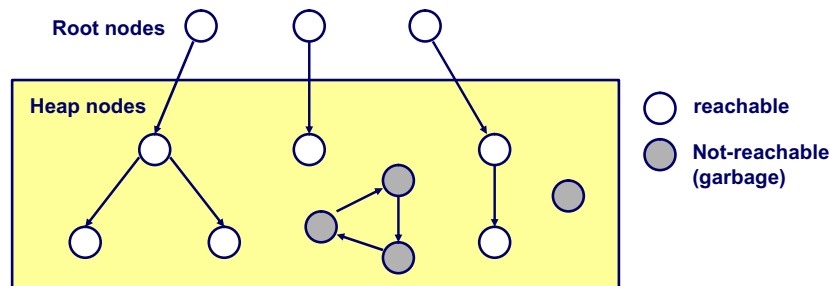
- Collects based on lifetimes

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

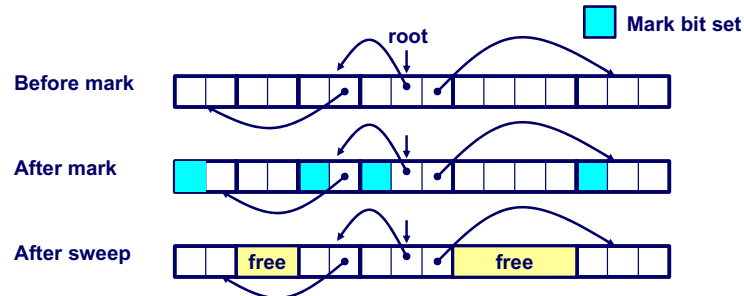
Mark and Sweep Collecting

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 sets **mark bit** on all reachable memory
- Sweep**: Scan all blocks and **free** blocks that are **not marked**



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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);
    }
}
```

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Conservative Mark and Sweep in C

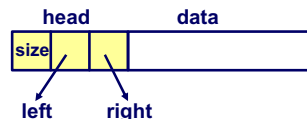
A conservative collector for C programs

- `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)



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Generational Collectors

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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

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Dereferencing Bad Pointers

The classic `scanf` bug

```
scanf("%d", val);
```

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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;
}
```

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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));
}
```

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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.