15-213
“The course that gives CMU its Zip!”
Dynamic Memory Allocation
October 30, 2003

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

Keeping Track of Free Blocks (recap.)
- **Method 1:** Implicit list using lengths -- links all blocks
  ![Diagram of implicit list]
- **Method 2:** Explicit list among the free blocks using pointers within the free blocks
  ![Diagram of explicit list]
- **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
- ![Diagram of explicit free list]
  - 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
- **Before:**
  ![Before diagram]
  - (with splitting)
- **After:**
  ![After diagram]
  - `malloc(...)`
**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. addr(pred) < addr(curr) < addr(succ)
  - Con: requires search
  - Pro: studies suggest fragmentation is better than LIFO

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**Freeing With a LIFO Policy (Case 1)**

**Before:**

Root

**After:**

Root

Insert the freed block at the root of the list

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**Freeing With a LIFO Policy (Case 2)**

**Before:**

Root

**After:**

Root

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

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**Freeing With a LIFO Policy (Case 3)**

**Before:**

Root

**After:**

Root

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

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Freeing With a LIFO Policy (Case 4)

Before:

Root

After:

Root

Splice out predecessor and successor blocks, coalesce all 3 memory blocks and insert the new block at the root of the 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)

Does this increase internal fragmentation?

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, 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

- The classic reference on dynamic storage allocation

- 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
Invented 1958 by John McCarthy for Lisp

```c
void free() {
    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
Useful malloc Related Information

Debugging Tools for Dynamic Storage Allocation and Memory Management
http://www.cs.colorado.edu/om/ompublic.html/MallocDebug.html

Electric Fence from Bruce Perens
http://perens.com/Fw/Software/

IBM P-Series (AIX) systems

Memory Allocator for Multithreaded programs (FYI)
http://www.cs.utexas.edu/users/semlyen/heap/

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


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

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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 header 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
    markBitSet(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

Idea: exploit the fact that many memory objects are short-lived and “older” memory objects are likely to live longer.

How?
- Partition Heap logically into multiple generations (for example 2-8)
- GC youngest generation more frequently
- Promote objects in generation x to generation x+1 once they survived a certain number of GC cycles

Implementation issues:
- To copy or not-to-copy (compaction)
- How to tell which generation an object belongs to?
  - Partition the Heap address space vs. record it in header
  - Pointer from older to younger generations
  - Write-barrier: at start of generation begin recording write to objects in older generation
- Use a card-table to locate modified old memory objects

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

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

Reading Uninitialized Memory

Assuming that heap data is initialized to zero

```c
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

```c
int **p;
p = malloc(N*sizeof(int));
for (i=0; i<N; i++) {
    p[i] = malloc(N*sizeof(int));
}
```

Overwriting Memory
Off-by-one error

```c
int **p;
p = malloc(N*sizeof(int *));
for (i=0; i<N; i++) {
    p[i] = malloc(N*sizeof(int));
}
```

Overwriting Memory
Not checking the max string size

```c
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

```c
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

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

Referencing Nonexistent Variables
Forgetting that local variables disappear when a function returns

```c
int *foo () {
    int val;
    return &val;
}
```

Freeing Blocks Multiple Times
Nasty!

```c
x = malloc(N*sizeof(int));
*manipulate x*
free(x);
y = malloc(N*sizeof(int));
*manipulate y*
free(x);
```

Referencing Freed Blocks
Evil!

```c
x = malloc(N*sizeof(int));
*manipulate x*
free(x);
...
y = malloc(N*sizeof(int));
for (i=0; i<N; i++)
y[i] = x[i++];
```
Failing to Free Blocks (Memory Leaks)

Slow, long-term killer!

```c
foo() {
    int *x = malloc(N*sizeof(int));
    ...
    return;
}
```

Failing to Free Blocks (Memory Leaks)

Freeing only part of a data structure

```c
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.