15-213

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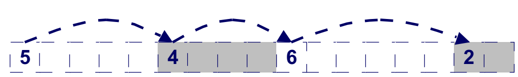
Dynamic Memory Allocation II
November 4, 2004

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

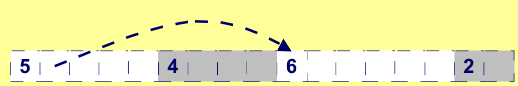
`class20.ppt`

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

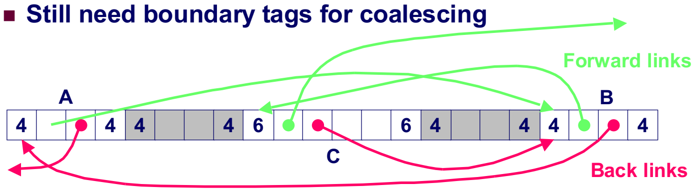


- ***Method 3***: Segregated free lists
  - Different free lists for different size classes
- ***Method 4***: Blocks sorted by size (not discussed)
  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Explicit Free Lists

Use data space for link pointers

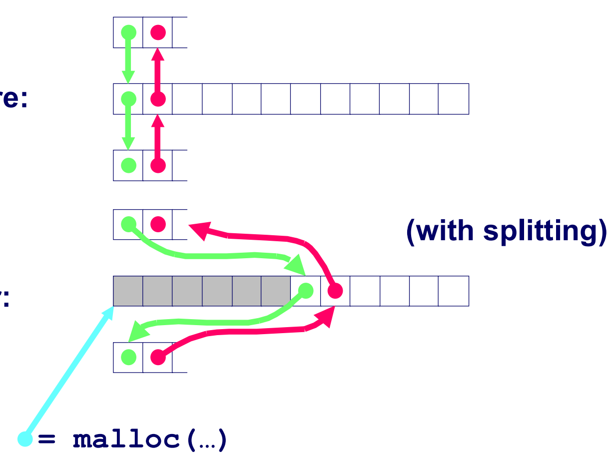
- Typically doubly linked
- Still need boundary tags for coalescing



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

Allocating From Explicit Free Lists

Before:



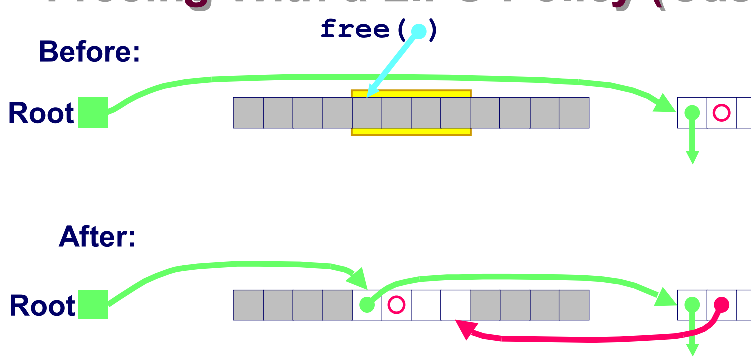
After:

Freeing With Explicit Free Lists

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

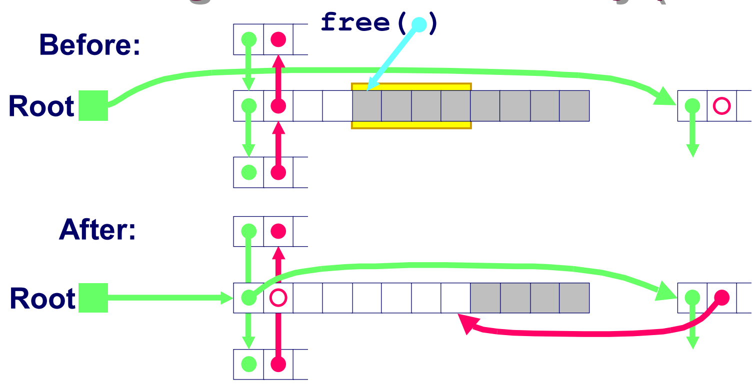
- **LIFO (last-in-first-out) policy**
  - **Insert freed block at the beginning of the free list**
  - **Pro: simple and constant time**
  - **Con: studies suggest fragmentation is worse than address ordered.**
- **Address-ordered policy**
  - **Insert freed blocks so that free list blocks are always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

Freeing With a LIFO Policy (Case 1)



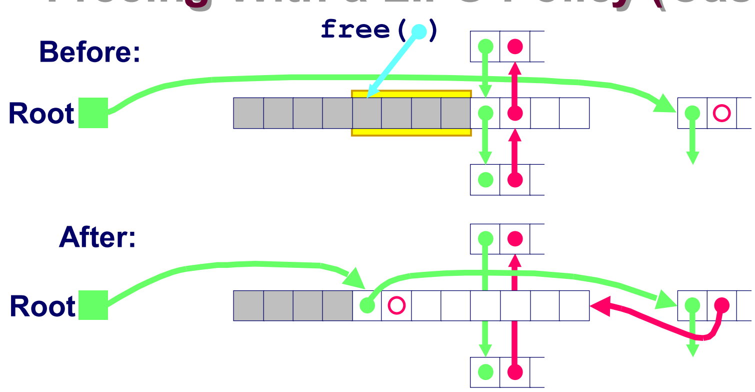
Insert the freed block at the root of the list

Freeing With a LIFO Policy (Case 2)



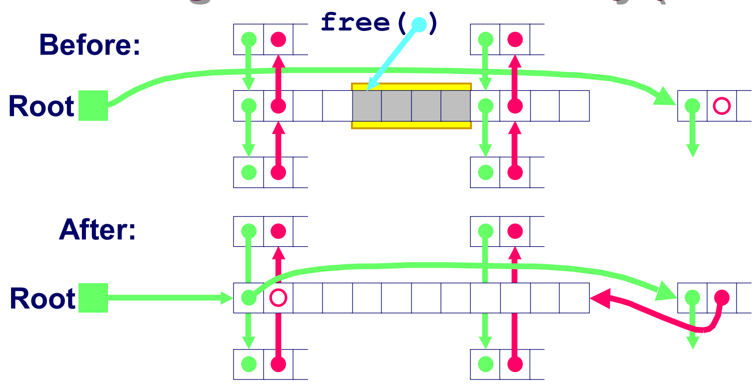
Splice out predecessor block, coalesce both memory blocks and insert the new block at the root of the list

Freeing With a LIFO Policy (Case 3)



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

Freeing With a LIFO Policy (Case 4)



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:

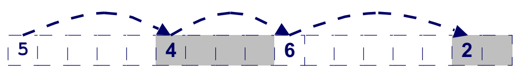
- Allocate is linear time in number of free blocks instead of total blocks -- much faster allocates when most of the memory is full
- Slightly more complicated allocate and free since needs to splice blocks in and out of the list
- Some extra space for the links (2 extra words needed for each block)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

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

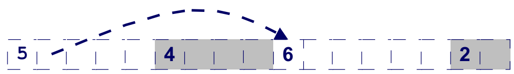
- Keep multiple linked lists of different size classes, or possibly for different types of objects

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*

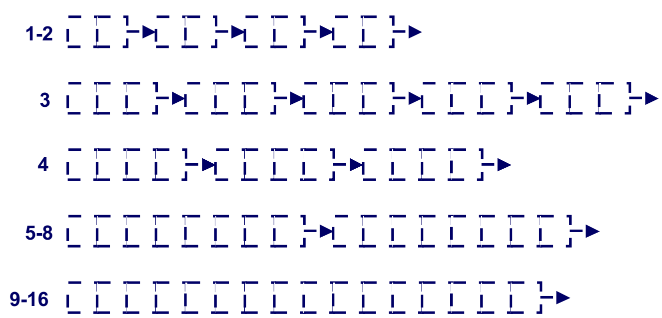
- Different free lists for different size classes

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)

Useful `malloc` Related Information

Debugging Tools for Dynamic Storage Allocation and Memory Management

http://www.cs.colorado.edu/homes/zorn/public_html/MallocDebug.html

Electric Fence from Bruce Perens

http://perens.com/FreeSoftware/

IBM P-Series (AIX) systems

http://publib16.boulder.ibm.com/pseries/en_US/aixprggd/genprogc/mastertoc.htm

Memory Allocator for Multithreaded programs (FYI)

http://www.cs.utexas.edu/users/emery/hoard/

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**

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)

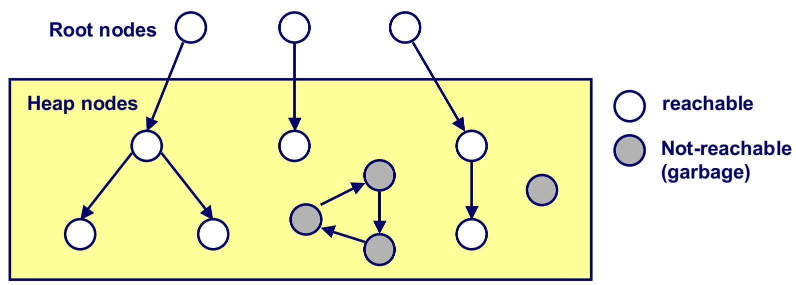
- Collects based on lifetimes

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 <u>cleared</u>
- `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

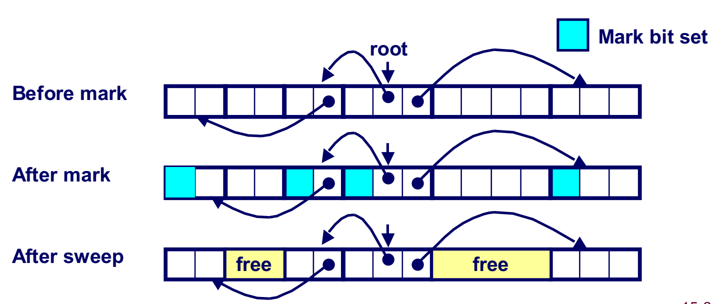
Mark and Sweep Collecting

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**



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;
}
```

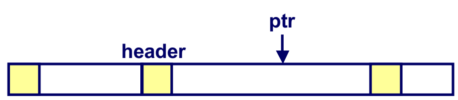
Sweep using lengths to find next block

```
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

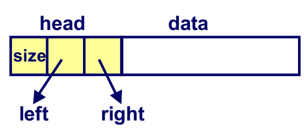
A conservative collector for C programs

- `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)



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

```
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, valgrind [Linux])

- 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.