Dynamic Memory Allocation: Advanced Concepts

15-213 / 18-213: Introduction to Computer Systems
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Today

- Explicit free lists
- Segregated free lists
- Garbage collection
- Memory-related perils and pitfalls
Keeping Track of Free Blocks

- **Method 1:** *Implicit free list* using length—links all blocks

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

- **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
Explicit Free Lists

- Maintain list(s) of *free* blocks, not *all* blocks
  - The “next” free block could be anywhere
    - So we need to store forward/back pointers, not just sizes
  - Still need boundary tags for coalescing
  - Luckily we track only free blocks, so we can use payload area
Explicit Free Lists

- Logically:

- Physically: blocks can be in any order
Allocating From Explicit Free Lists

Before

After (with splitting)

= malloc(…)

case conceptual graphic
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:
    
    $$\text{addr}(\text{prev}) < \text{addr}(\text{curr}) < \text{addr}(\text{next})$$
  - **Con:** requires search
  - **Pro:** studies suggest fragmentation is lower than LIFO
Freeing With a LIFO Policy (Case 1)

Before

- Insert the freed block at the root of the list

After
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)

Before

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

After
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.

**Before**

**After**
Explicit List Summary

- **Comparison to implicit list:**
  - Allocate is linear time in number of *free* blocks instead of *all* blocks
    - *Much faster* 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?

- **Most common 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 length—links all blocks

  ![Implicit list diagram]

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

  ![Explicit list diagram]

- **Method 3:** *Segregated free list*
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  - 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 List (Seglist) Allocators

- Each *size class* of blocks has its own free list

  1-2
  3
  4
  5-8
  9-inf

- Often have separate classes for each small size
- For larger sizes: One class for each two-power size
Seglist Allocator

- Given an 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

- If no block is found:
  - Request additional heap memory from OS (using `sbrk()`)
  - Allocate block of $n$ bytes from this new memory
  - Place remainder as a single free block in largest size class.
Seglist Allocator (cont.)

- To free a block:
  - Coalesce and place on appropriate list (optional)

- Advantages of seglist allocators
  - Higher throughput
    - log time for power-of-two size classes
  - Better memory utilization
    - First-fit search of segregated free list approximates a best-fit search of entire heap.
    - Extreme case: Giving each block its own size class is equivalent to best-fit.
More Info on Allocators

  - The classic reference on dynamic storage allocation

  - 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

```c
void foo() {
    int *p = malloc(128);
    return; /* p block is now garbage */
}
```

- **Common in many dynamic languages:**
  - Python, Ruby, Java, Perl, ML, Lisp, 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

Must 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)
  - Collection based on lifetimes
    - Most allocations become garbage very soon
    - So focus reclamation work on zones of memory recently allocated

For more information:
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* (cannot be needed by the application)
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 each reachable block
  - **Sweep**: Scan all blocks and free blocks that are not marked

Before mark

After mark

After sweep

Note: arrows here denote memory refs, not free list ptrs.
Assumptions For a Simple Implementation

- **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 (cont.)

Mark using depth-first traversal of the memory graph

```c
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++) // call mark on all words
        mark(p[i]); // in the block
    return;
}
```

Sweep using lengths to find next block

```c
ptr sweep(ptr p, ptr end) {
    while (p < end) {
        if markBitSet(p)
            clearMarkBit();
        else if (allocateBitSet(p))
            free(p);
        p += length(p);
    }
}
```
Conservative Mark & Sweep in C

- A “conservative garbage 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 to find the beginning of the block?
  - Can use a balanced binary tree to keep track of all allocated blocks (key is start-of-block)
  - Balanced-tree pointers can be stored in header (use two additional words)

```
Header ptr
```

```
Left: smaller addresses
Right: larger addresses
```
Today

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- Garbage collection
- Memory-related perils and pitfalls
Memory-Related Perils and Pitfalls

- Dereferencing bad pointers
- Reading uninitialized memory
- Overwriting memory
- Referencing nonexistent variables
- Freeing blocks multiple times
- Referencing freed blocks
- Failing to free blocks
# C operators

<table>
<thead>
<tr>
<th>Operators</th>
<th>Associativity</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ) [ ] -&gt; . ! ~ ++ -- + - * &amp; (type) sizeof</td>
<td>left to right right to left left to right left to right left to right left to right left to right left to right left to right left to right left to right left to right</td>
</tr>
<tr>
<td>, , , , , &amp; , ^</td>
<td>right to left right to left right to left right to left right to left right to left right to left</td>
</tr>
<tr>
<td>= += -= *= /= %= &amp;= ^= != &lt;&lt;= &gt;&gt;= ? :</td>
<td>right to left right to left left to right</td>
</tr>
</tbody>
</table>

- ->, ( ), and [ ] have high precedence, with * and & just below
- Unary +, -, and * have higher precedence than binary forms

Source: K&R page 53
C Pointer Declarations: Test Yourself!

```c
int *p

// p is a pointer to int

int *p[13]

// p is an array[13] of pointer to int

int *(p[13])

// p is an array[13] of pointer to int

int **p

// p is a pointer to a pointer to an int

int (*p)[13]

// p is a pointer to an array[13] of int

int *f()

// f is a function returning a pointer to int

int (*f)()

// f is a pointer to a function returning int

int (**f())[13])()

// f is a function returning ptr to an array[13]
of pointers to functions returning int

int (**x[3]))()[5]

// x is an array[3] of pointers to functions
returning pointers to array[5] of ints
```

Source: K&R Sec 5.12
Dereferencing Bad Pointers

- The classic `scanf` bug

```c
int val;
...
scanf("%d", val);
```
Reading Uninitialized Memory

- Assuming that heap data is initialized to zero

```c
/* 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

```c
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

```c
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

```c
char s[8];
int i;
gets(s); /* reads "123456789" from stdin */
```

- Basis for classic buffer overflow attacks
Overwriting Memory

- Misunderstanding pointer arithmetic

```c
int *search(int *p, int val) {
    while (*p && *p != val)
        p += sizeof(int);
    return p;
}
```
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);
}
```
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(M*sizeof(int));
    <manipulate y>
free(x);
```
Referencing Freed Blocks

Evil!

```c
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 (MemoryLeaks)

- 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 (UToronto CSRI 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.)

- Some malloc implementations contain checking code
  - Linux glibc malloc: `setenv MALLOC_CHECK_ 3`
  - FreeBSD: `setenv MALLOC_OPTIONS AJR`

- Binary translator: valgrind (Linux), 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.