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
Implicit List: Bidirectional Coalescing

- **Boundary tags** [Knuth73]
  - Replicate size/allocated word at “bottom” (end) of free blocks
  - Allows us to traverse the “list” backwards, but requires extra space
  - Important and general technique!

Format of allocated and free blocks

<table>
<thead>
<tr>
<th>Header</th>
<th>Size</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload and padding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>a</td>
<td></td>
</tr>
</tbody>
</table>

a = 1: Allocated block
a = 0: Free block

Size: Total block size
Payload: Application data (allocated blocks only)
Coalescing Cases

Block being freed

Case 1
- Allocated
- Allocated

Case 2
- Allocated
- Free

Case 3
- Free
- Allocated

Case 4
- Free
- Free

<table>
<thead>
<tr>
<th></th>
<th>m1</th>
<th>n</th>
<th>m2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Case 2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case 3</td>
<td>n+m1</td>
<td>0</td>
<td>m2</td>
</tr>
<tr>
<td>Case 4</td>
<td>n+m1+m2</td>
<td>0</td>
<td>m2</td>
</tr>
</tbody>
</table>
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**
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- **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:

```
  A <--- B <--- C
```

- Physically: blocks can be in any order

```
4 4 4 4 6 6 4 4 4 4
```

Forward (next) links

Back (prev) links
Allocating From Explicit Free Lists

Before

After (with splitting)

= malloc(…)

classical 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)

**Before**

- **Root**

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

**After**

- **Root**
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

conceptual graphic
Freeing With a LIFO Policy (Case 4)

Before

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

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

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Segregated List (Seglist) Allocators

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

- 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 \texttt{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)
Today

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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

![Diagram showing Mark and Sweep](image.png)

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)

```plaintext
left: smaller addresses
right: larger addresses
```
Today

- Explicit free lists
- Segregated free lists
- 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

### Operators

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

- `->, ( ), [ ]` 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!

<table>
<thead>
<tr>
<th>Declaration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>int *p</code></td>
<td><code>p</code> is a pointer to <code>int</code></td>
</tr>
<tr>
<td><code>int *(p[13])</code></td>
<td><code>p</code> is an array[13] of pointer to <code>int</code></td>
</tr>
<tr>
<td><code>int **p</code></td>
<td><code>p</code> is a pointer to a pointer to an <code>int</code></td>
</tr>
<tr>
<td><code>int (*p)[13]</code></td>
<td><code>p</code> is a pointer to an array[13] of <code>int</code></td>
</tr>
<tr>
<td><code>int *f()</code></td>
<td><code>f</code> is a function returning a pointer to <code>int</code></td>
</tr>
<tr>
<td><code>int (*f)()</code></td>
<td><code>f</code> is a pointer to a function returning <code>int</code></td>
</tr>
<tr>
<td><code>int (**f)()</code></td>
<td><code>f</code> is a function returning <code>ptr</code> to an array[13] of pointers to functions returning <code>int</code></td>
</tr>
<tr>
<td><code>int (*(*f())[13])()</code></td>
<td><code>f</code> is a function returning <code>ptr</code> to an array[13] of pointers to functions returning <code>int</code></td>
</tr>
<tr>
<td><code>int (*(*x[3]))()[5]</code></td>
<td><code>x</code> is an array[3] of pointers to functions returning pointers to array[5] of <code>int</code>s</td>
</tr>
</tbody>
</table>

*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;
}
```
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 (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 (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.