

Dynamic Memory Allocation: Advanced Concepts

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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



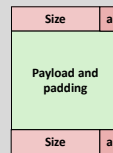
- Method 2: **Explicit free list** among the free blocks using pointers



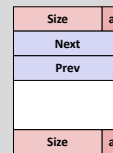
- Method 3: **Segregated free list**
 - Different free lists for different size classes
- Method 4: **Blocks sorted by size**
 - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Explicit Free Lists

Allocated (as before)



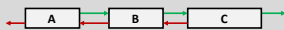
Free



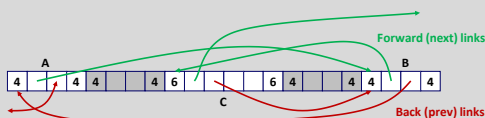
- Maintain list(s) of **free** blocks, not **all** blocks
 - The "next" free block could be anywhere
 - So we need to store forward/back pointers, not just sizes
 - Still need boundary tags for coalescing
 - Luckily we track only free blocks, so we can use payload area

Explicit Free Lists

- Logically:



- Physically: blocks can be in any order



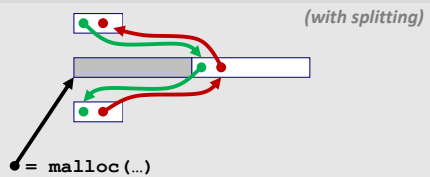
Allocating From Explicit Free Lists

Before



conceptual graphic

After



(with splitting)

Freeing With Explicit Free Lists

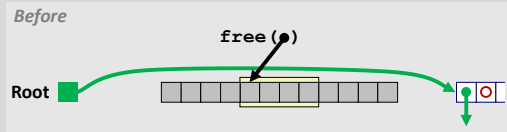
- **Insertion policy:** Where in the free list do you put a newly freed block?
 - **LIFO (last-in-first-out) policy**
 - Insert freed block at the beginning of the free list
 - **Pro:** simple and constant time
 - **Con:** studies suggest fragmentation is worse than address-ordered
 - **Address-ordered 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

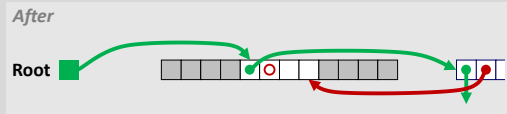
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Freeing With a LIFO Policy (Case 1)

conceptual graphic



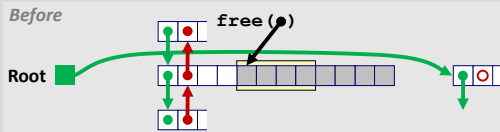
- Insert the freed block at the root of the list



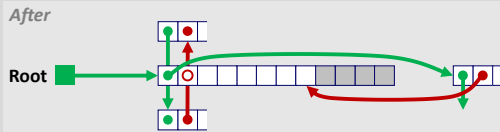
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Freeing With a LIFO Policy (Case 2)

conceptual graphic



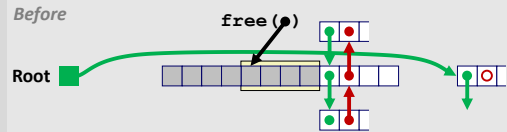
- Splice out predecessor block, coalesce both memory blocks, and insert the new block at the root of the list



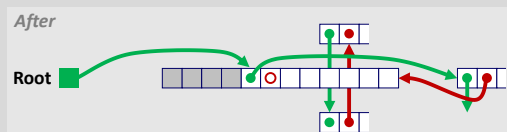
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Freeing With a LIFO Policy (Case 3)

conceptual graphic



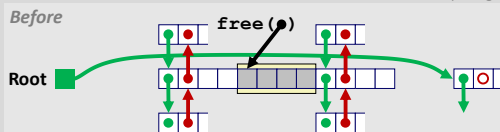
- Splice out successor block, coalesce both memory blocks and insert the new block at the root of the list



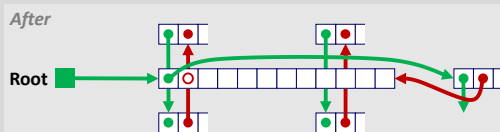
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Freeing With a LIFO Policy (Case 4)

conceptual graphic



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



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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 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

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Keeping Track of Free Blocks

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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

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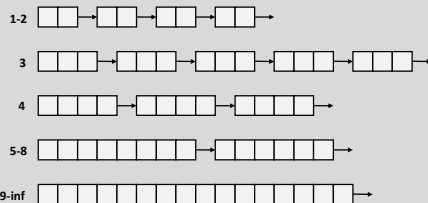
Today

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- Segregated free lists
- Garbage collection
- Memory-related perils and pitfalls

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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 power-of-two size

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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 (maybe)
 - 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.

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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.

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More Info on Allocators

- D. Knuth, *"The Art of Computer Programming"*, 2nd 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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Today

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- **Garbage collection**
- Memory-related perils and pitfalls

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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, Python, Mathematica, etc.
- 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
- 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)

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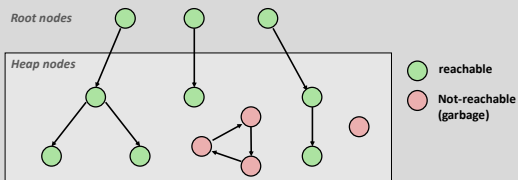
Classical GC Algorithms

- 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: Jones and Lin, “*Garbage Collection: Algorithms for Automatic Dynamic Memory*”, John Wiley & Sons, 1996.

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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)

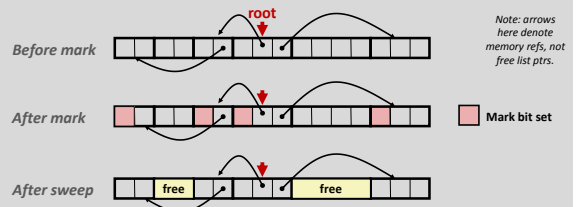


A node (block) is **reachable** if there is a path from any root to that node.
Non-reachable nodes are **garbage** (cannot be needed by the application)

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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 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



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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

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

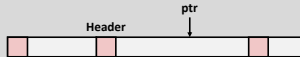
Sweep using lengths to find next block

```
ptr sweep(ptr p, ptr end) {
    while (p < end) {
        if (markBitSet(p))
            clearMarkBit(p);
        else if (allocateBitSet(p))
            free(p);
        p += length(p) + 1;
    }
}
```

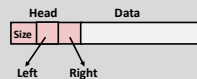
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Conservative Mark & Sweep in C

- 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)



Left: smaller addresses
Right: larger addresses

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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

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C Operators

Operators	Associativity
<code>() [] -></code>	left to right
<code>! ~ ++ -- + - * & (type) sizeof</code>	right to left
<code>* / %</code>	left to right
<code>+ -</code>	left to right
<code><< >></code>	left to right
<code>< <= > >=</code>	left to right
<code>== !=</code>	left to right
<code>&</code>	left to right
<code>^</code>	left to right
<code> </code>	left to right
<code>&&</code>	left to right
<code> </code>	left to right
<code>?:</code>	right to left
<code>= += -= *= /= %= &= ^= != << >>=</code>	right to left
<code>,</code>	left to right

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

Source: K&R page 53 30

C Pointer Declarations: Test Yourself!

<code>int *p</code>	<code>p</code> is a pointer to <code>int</code>
<code>int *p[13]</code>	<code>p</code> is an array[13] of pointer to <code>int</code>
<code>int *(p[13])</code>	<code>p</code> is an array[13] of pointer to <code>int</code>
<code>int **p</code>	<code>p</code> is a pointer to a pointer to an <code>int</code>
<code>int (*p) [13]</code>	<code>p</code> is a pointer to an array[13] of <code>int</code>
<code>int *f()</code>	<code>f</code> is a function returning a pointer to <code>int</code>
<code>int (*f) ()</code>	<code>f</code> is a pointer to a function returning <code>int</code>
<code>int (*(*f()) [13]) ()</code>	<code>f</code> is a function returning ptr to an array[13] of pointers to functions returning <code>int</code>
<code>int (*(*x[3]) ()) [5]</code>	<code>x</code> is an array[3] of pointers to functions returning pointers to array[5] of <code>ints</code>

Source: K&R Sec 5.12 31

Dereferencing Bad Pointers

- The classic `scanf` bug

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

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Reading Uninitialized Memory

- Incorrectly 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));
}
```

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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

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Overwriting Memory

- Misunderstanding pointer arithmetic

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

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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);  
}
```

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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);  
}
```

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Referencing Nonexistent Variables

- Forgetting that local variables disappear when a function returns

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

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Freeing Blocks Multiple Times

- Nasty!

```
x = malloc(N*sizeof(int));  
    <manipulate x>  
free(x);  
  
y = malloc(M*sizeof(int));  
    <manipulate y>  
free(x);
```

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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]++;
```

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Failing to Free Blocks (Memory Leaks)

- Slow, long-term killer!

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

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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;
}
```

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Dealing With Memory Bugs

- Conventional debugger (gdb)
 - Good for finding bad pointer dereferences
 - Hard to detect many other memory bugs
 - Sometimes helpful: watchpoints
- Debugging malloc (some features now in glibc 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

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Dealing With Memory Bugs (cont.)

- Some malloc implementations contain checking code
 - Linux glibc malloc: `setenv MALLOC_CHECK_ 2`
 - FreeBSD: `setenv MALLOC_OPTIONS AJR`
- Binary translator: valgrind (Linux), Purify (commercial)
 - 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.

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