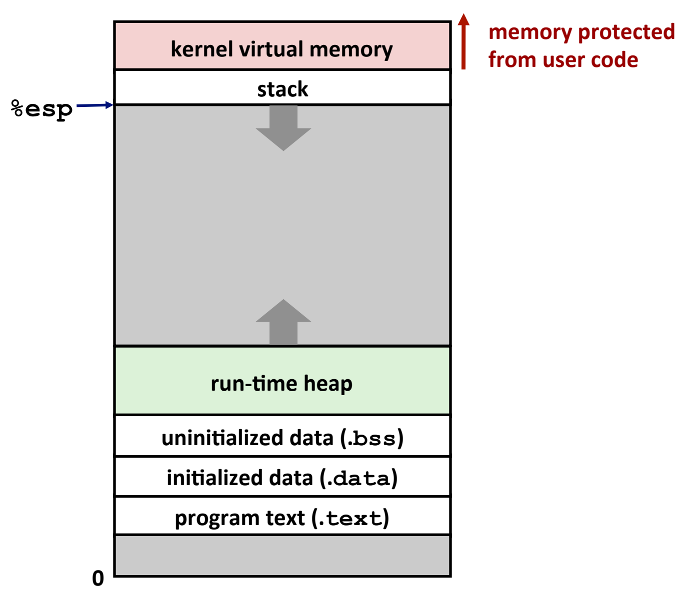
Today

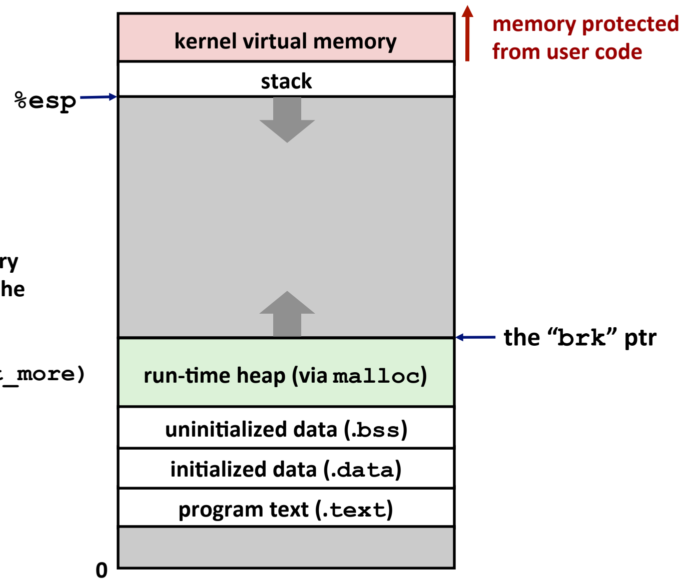
- **Dynamic memory allocation**
  - Size of data structures may only be known at run time
  - Need to allocate space on the heap
  - Need to de-allocate (free) unused memory so it can be re-allocated
- **Implementation**
  - Implicit free lists
  - Explicit free lists – subject of next programming assignment
  - Segregated free lists
- **Garbage collection**
- **Common memory-related bugs in C programs**

Process Memory Image



What is the heap for?
How do we use it?

Process Memory Image

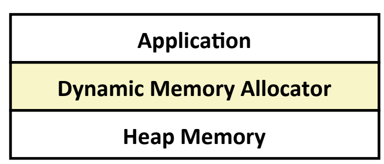


Allocators request additional heap memory from the kernel using the `sbrk()` function:

```
error = sbrk(amt_more)
```


Dynamic Memory Allocation

- **Memory allocator?**
  - VM hardware and kernel allocate pages
  - Application objects are typically smaller
  - Allocator manages objects within pages



- *How should the application code allocate memory?*

Dynamic Memory Allocation

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Application
Dynamic Memory Allocator
Heap Memory

- **Explicit vs. Implicit Memory Allocator**
  - ***Explicit:*** application allocates and frees space
    - In C: **`malloc()`** and **`free()`**
  - ***Implicit:*** application allocates, but does not free space
    - In Java, ML, Lisp: garbage collection
- **Allocation**
  - A memory allocator doles out memory blocks to application
  - A "block" is a contiguous range of bytes of the appropriate size
    - What is an appropriate size?

Malloc Package

- **`#include <stdlib.h>`**
- **`void *malloc(size_t size)`**
  - Successful:
    - Returns a pointer to a memory block of at least **`size`** bytes (typically) aligned to 8-byte boundary
    - If **`size == 0`**, returns NULL
  - Unsuccessful: returns NULL (0) and sets errno (a global variable)
- *Is this enough? That's it? ☺*

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- `void free(void *p)`
  - Returns the block pointed at by **`p`** to the pool of available memory
  - **`p`** must come from a previous call to **`malloc`** or **`realloc`**
- *anything_else()?* ☺

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  - Returns the block pointed at by **`p`** to the pool of available memory
  - **`p`** must come from a previous call to **`malloc`** or **`realloc`**
- `void *realloc(void *p, size_t size)`
  - Changes size of block **`p`** and returns pointer to new block
  - Contents of new block unchanged up to min of old and new size
  - Old block has been **`free`**'d (logically, if new != old)

Malloc Example

```
void foo(int n, int m) {
  int i, *p;

  /* allocate a block of n ints */
  p = (int *)malloc(n * sizeof(int));
  if (p == NULL) {
    perror("malloc");
    exit(0);
  }
  for (i=0; i<n; i++) p[i] = i;

  /* add m bytes to end of p block */
  if ((p = (int *)realloc(p, (n+m) * sizeof(int))) == NULL) {
    perror("realloc");
    exit(0);
  }
  for (i=n; i < n+m; i++) p[i] = i;

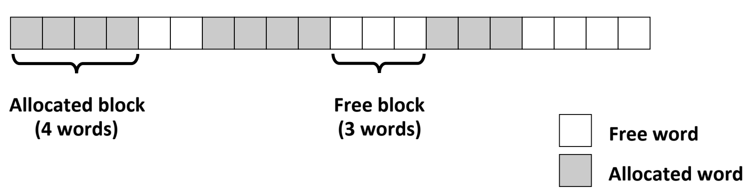
  /* print new array */
  for (i=0; i<n+m; i++)
    printf("%d\n", p[i]);

  free(p); /* return p to available memory pool */
}
```

Why?

Assumptions Made in This Lecture

- **Memory is word addressed (each word can hold a pointer)**
  - block size is a multiple of words



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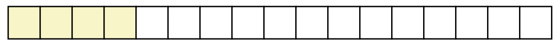

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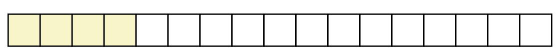

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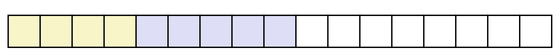

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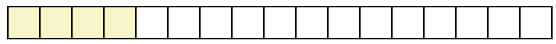

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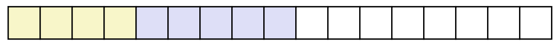

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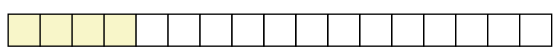

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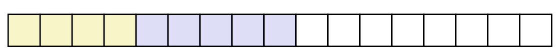

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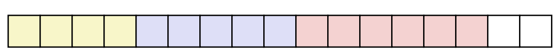

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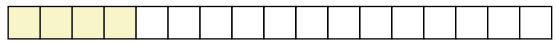

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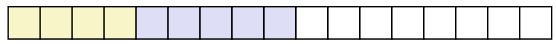

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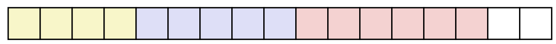

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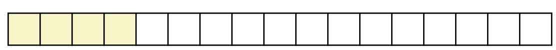

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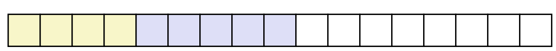

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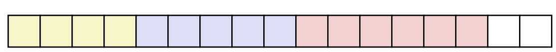

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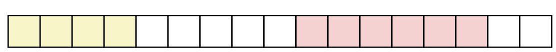

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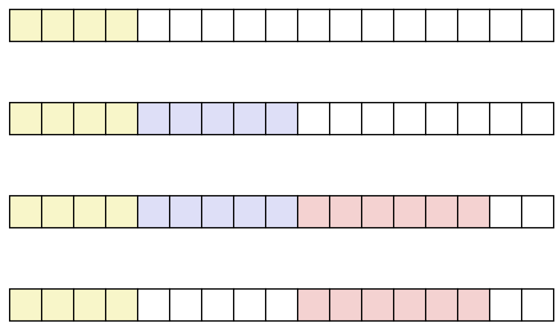

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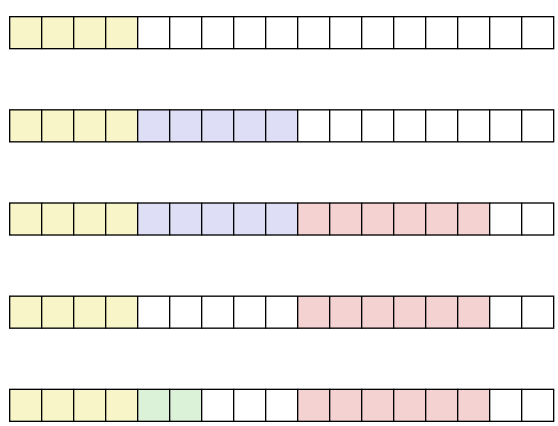

How are going to implement that?!?

- *Ideas?*

Constraints

- **Applications**
  - Can issue arbitrary sequence of malloc() and free() requests
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  - Must align blocks so they satisfy all alignment requirements
    - 8 byte alignment for GNU malloc (`libc` malloc) on Linux boxes
  - Can't move the allocated blocks once they are malloc()'d
    - *i.e.*, compaction is not allowed. *Why not?*

Performance Goal: Throughput

- **Given some sequence of `malloc` and `free` requests:**
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$

- **Goals: maximize throughput and peak memory utilization**
  - These goals are often conflicting
  - *What's throughput?*

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- **Throughput:**
  - Number of completed requests per unit time
  - Example:
    - 5,000 **`malloc()`** calls and 5,000 **`free()`** calls in 10 seconds
    - Throughput is 1,000 operations/second
  - ***How to do `malloc()` and `free()` in O(1)? What's the problem?***

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Performance Goal: Peak Memory Utilization

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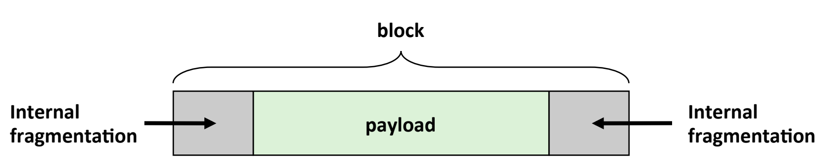
    - Allocator can increase size of heap using **`sbrk()`**
- ***Def: Peak memory utilization after k requests***
  - $U_k = (\max_{i<k} P_i) \; / \; H_k$
  - Goal: maximize utilization for a sequence of requests.
  - *Is this hard? Why? And what happens to throughput?*

Fragmentation

- **Poor memory utilization caused by *fragmentation***
  - ***internal*** fragmentation
  - ***external*** fragmentation

Internal Fragmentation

- **For a given block, *internal fragmentation* occurs if payload is smaller than block size**



- **Caused by**
  - overhead of maintaining heap data structures (inside block, outside payload)
  - padding for alignment purposes
  - explicit policy decisions (e.g., to return a big block to satisfy a small request)
    why would anyone do that?
- **Depends only on the pattern of *previous* requests**
  - thus, easy to measure

External Fragmentation

- Occurs when there is enough aggregate heap memory, but no single free block is large enough

```
p1 = malloc(4)

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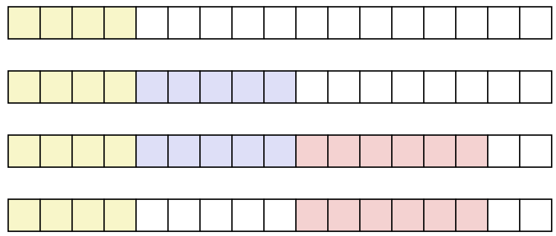

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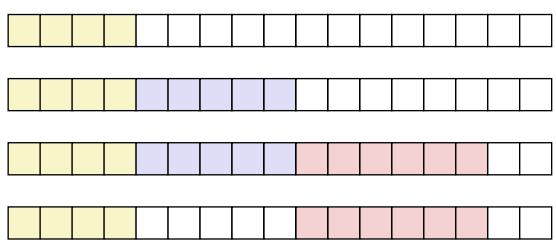

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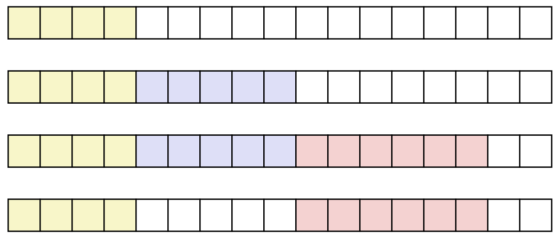

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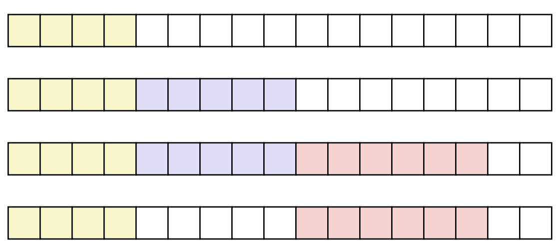


`p4 = malloc(6)` *Oops! (what would happen now?)*

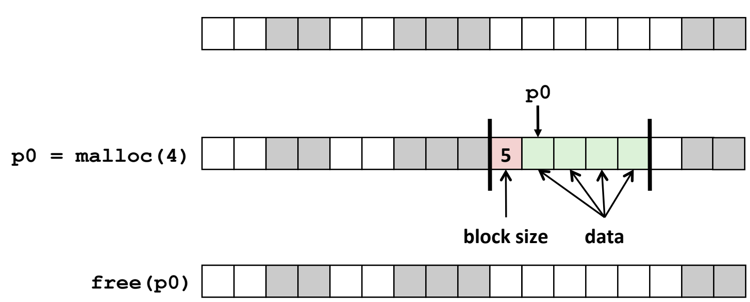
- Depends on the pattern of future requests
  - Thus, difficult to measure

Implementation Issues

- How to know how much memory is being `free()`'d when it is given only a pointer (and no length)?
- How to keep track of the free blocks?
- What to do with extra space when allocating a block that is smaller than the free block it is placed in?
- How to pick a block to use for allocation—many might fit?
- How to reinsert a freed block into the heap?

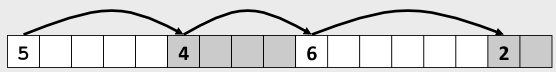
Knowing How Much to Free

- **Standard method**
  - Keep the length of a block in the word preceding the block.
    - This word is often called the ***header field*** or ***header***
  - Requires an extra word for every allocated block

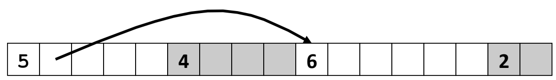


Keeping Track of Free Blocks

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



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



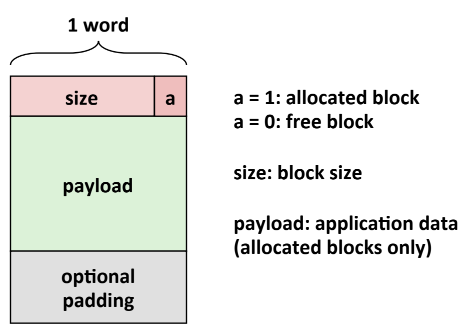
- Method 3: ***Segregated free list***
  - Different free lists for different size classes

- Method 4: ***Blocks sorted by size***
  - Can use a balanced binary tree (e.g. red-black tree) with pointers within each free block, and the length used as a key

Implicit List

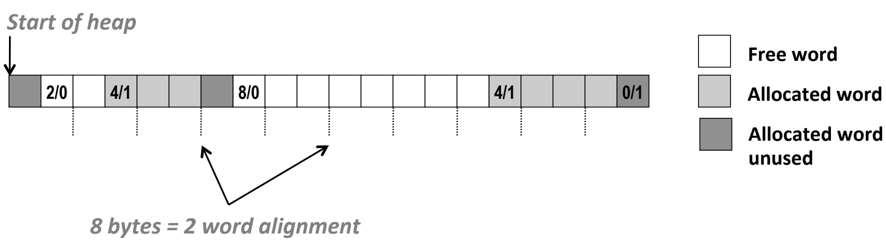
- **For each block we need: length, is-allocated?**
  - Could store this information in two words: wasteful!
- **Standard trick**
  - If blocks are aligned, some low-order address bits are always 0
  - Instead of storing an always-0 bit, use it as a allocated/free flag
  - When reading size, must remember to mask out this bit

Format of allocated and free blocks



Example

Sequence of blocks in heap: 2/0, 4/1, 8/0, 4/1



- **8-byte alignment**
  - May require initial unused word
  - Causes some internal fragmentation
- **One word (0/1) to mark end of list**
- **Here: block size in words for simplicity**

Implicit List: Finding a Free Block

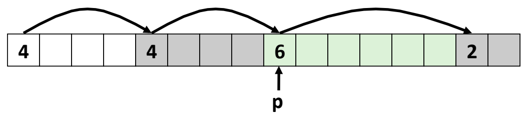
- ***First fit:***
  - Search list from beginning, choose ***first*** free block that fits: ***(Cost?)***

```
p = start;
while ((p < end) &&      \\ not passed end
       ((*p & 1) ||      \\ already allocated
       (*p <= len)))     \\ too small
  p = p + (*p & -2);     \\ goto next block (word addressed)
```

  - Can take linear time in total number of blocks (allocated and free)
  - In practice it can cause "splinters" at beginning of list
- ***Next fit:***
  - Like first-fit, but search list starting where previous search finished
  - Should often be faster than first-fit: avoids re-scanning unhelpful blocks
  - Some research suggests that fragmentation is worse
- ***Best fit:***
  - Search the list, choose the ***best*** free block: fits, with fewest bytes left over
  - Keeps fragments small—usually helps fragmentation
  - Will typically run slower than first-fit

Implicit List: Allocating in Free Block

- **Allocating in a free block: *splitting***
  - Since allocated space might be smaller than free space, we might want to split the block



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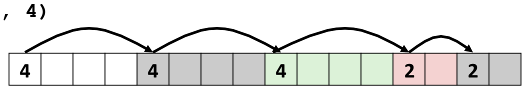


```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;
  int oldsize = *p & -2;
  *p = newsize | 1;
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;
}
```


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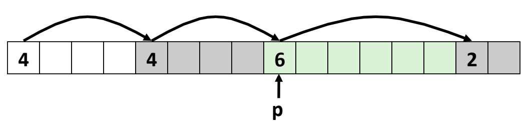

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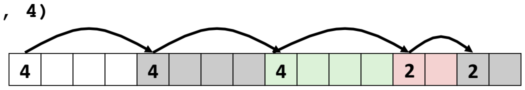


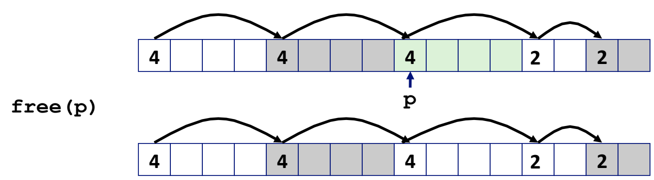

```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // round up to even
  int oldsize = *p & -2;                // mask out low bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining
}                                       //   part of block
```

Implicit List: Freeing a Block

- **Simplest implementation:**
  - Need only clear the "allocated" flag

```
void free_block(ptr p) { *p = *p & -2 }
```

  - But can lead to "false fragmentation"

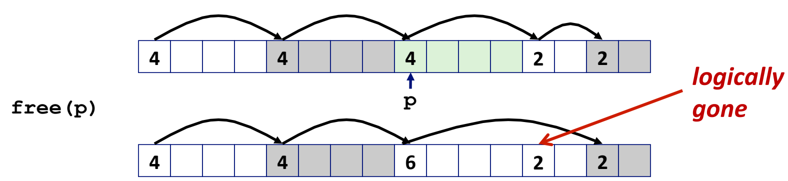


`malloc(5)` ***Oops!***

There is enough free space, but the allocator won't be able to find it

Implicit List: Coalescing

- **Join *(coalesce)* with next/previous blocks, if they are free**
  - Coalescing with next block

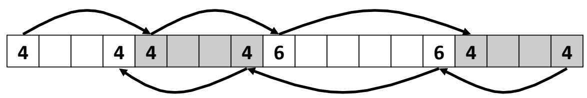



```
void free_block(ptr p) {
    *p = *p & -2;          // clear allocated flag
    next = p + *p;         // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;     // add to this block if
}                          //    not allocated
```

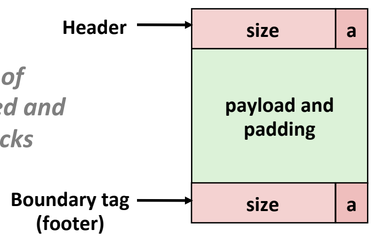
  - But how do we coalesce with *previous* block?

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

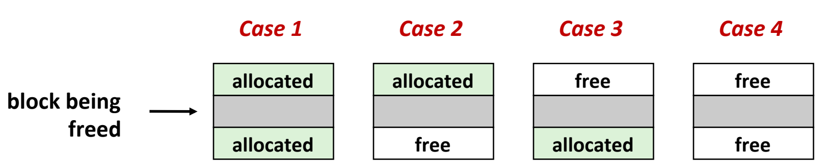


a = 1: allocated block
a = 0: free block

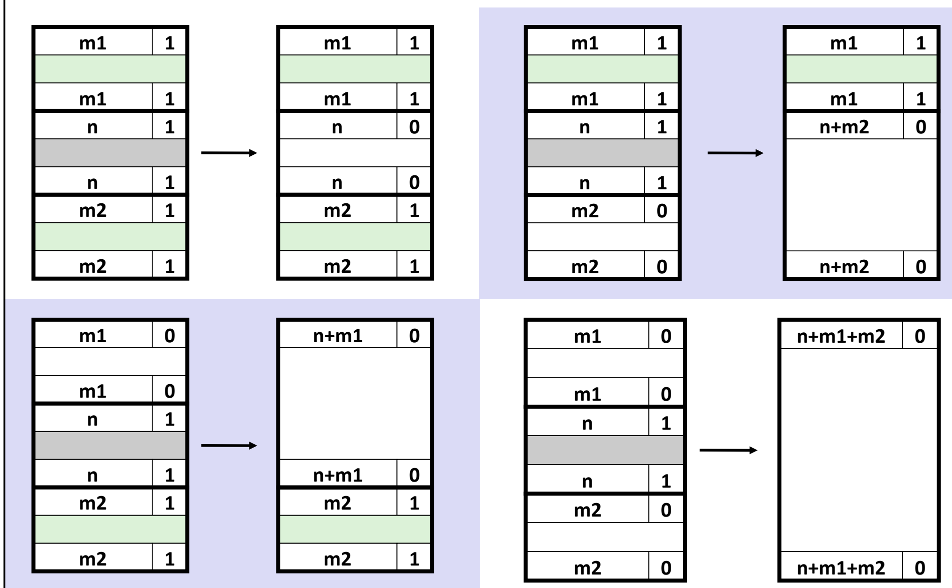
size: total block size

payload: application data (allocated blocks only)

Constant Time Coalescing



Constant Time Coalescing



Implicit Lists: Summary

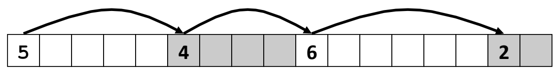
- **Implementation: very simple**
- **Allocate cost:**
  - linear time worst case
- **Free cost:**
  - constant time worst case
  - even with coalescing
- **Memory usage:**
  - will depend on placement policy
  - First-fit, next-fit or best-fit

- **Not used in practice for `malloc()`/`free()` because of linear-time allocation**
  - used in many special purpose applications

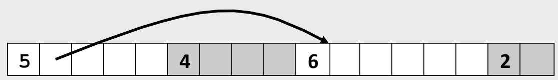
- **The concepts of splitting and boundary tag coalescing are general to *all* allocators**

Keeping Track of Free Blocks

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



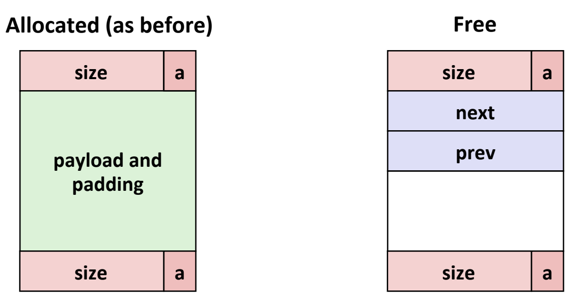
- **Method 2: *Explicit free list* among the free blocks using pointers**



- **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

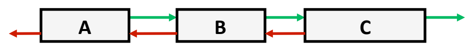
Explicit Free Lists



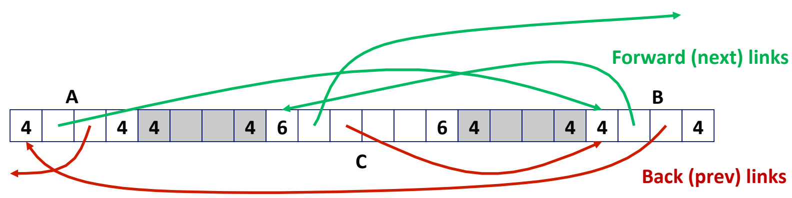
- **Maintain list(s) of *free* blocks, not *all* blocks**
  - The "next" free block could be anywhere
    - So we need to store forward/back pointers, not just sizes
  - Still need boundary tags for coalescing
  - Luckily we track only free blocks, so we can use payload area

Explicit Free Lists

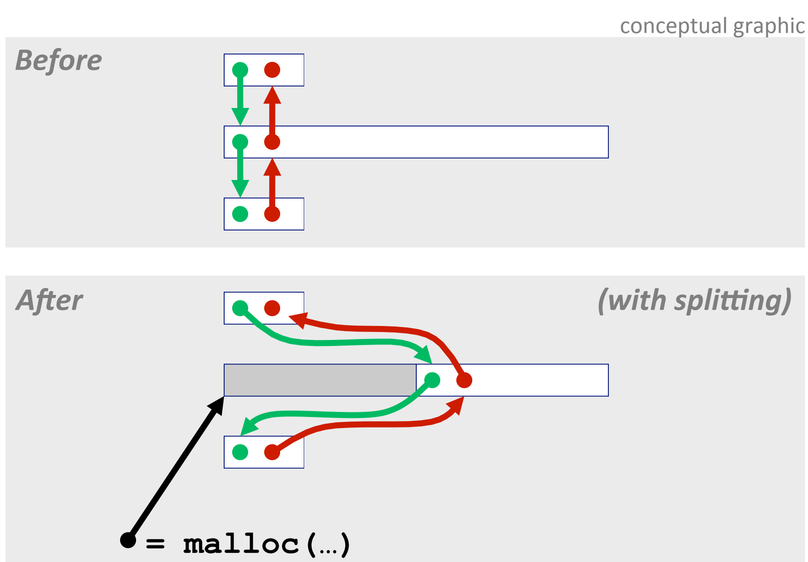
- **Logically (doubly-linked lists):**



- **Physically: blocks can be in any order**



Allocating From Explicit Free Lists



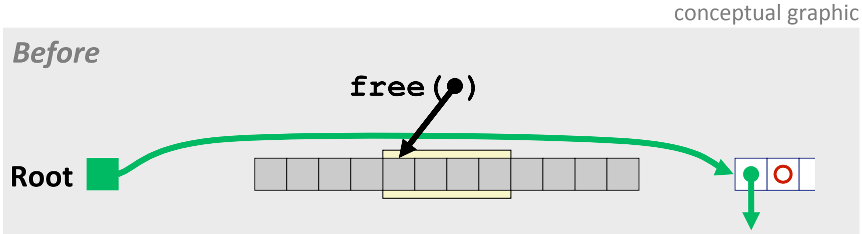
Freeing With Explicit Free Lists

- ***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:

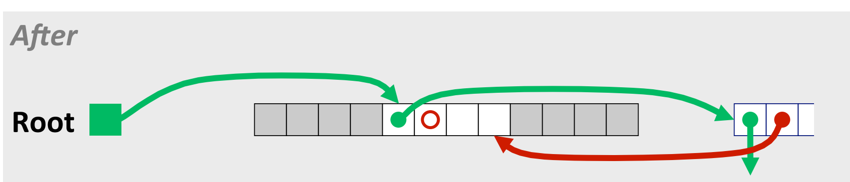
      addr(prev) < addr(curr) < addr(next)
    - ***Con:*** requires search
    - ***Pro:*** studies suggest fragmentation is lower than LIFO

Freeing With a LIFO Policy (Case 1)

conceptual graphic

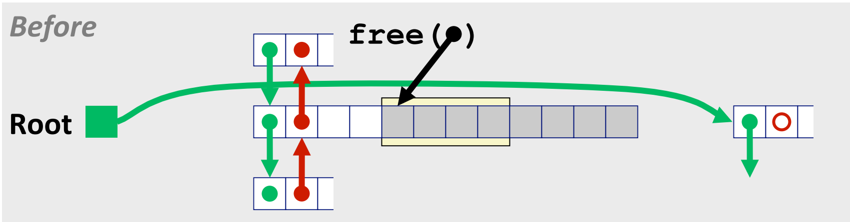


- **Insert the freed block at the root of the list**

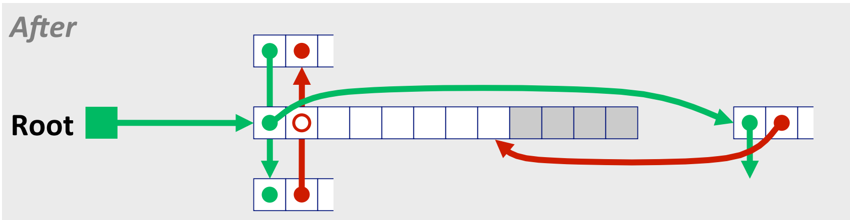


Freeing With a LIFO Policy (Case 2)

conceptual graphic

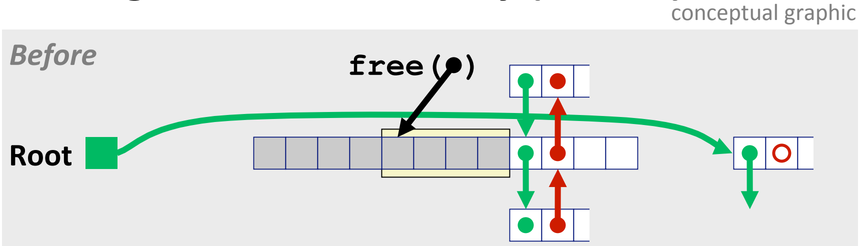


- Splice out predecessor block, coalesce both memory blocks, and insert the new block at the root of the list

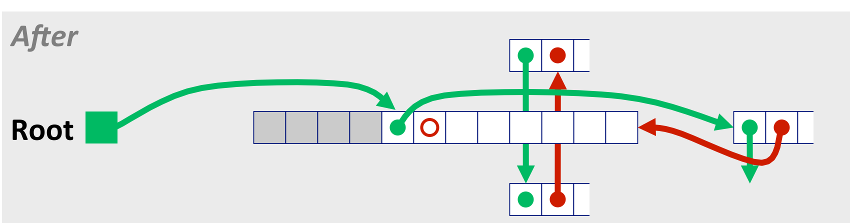


Freeing With a LIFO Policy (Case 3)

conceptual graphic

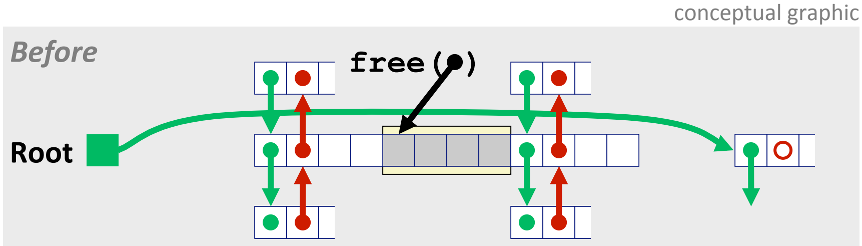


- Splice out successor block, coalesce both memory blocks and insert the new block at the root of the list

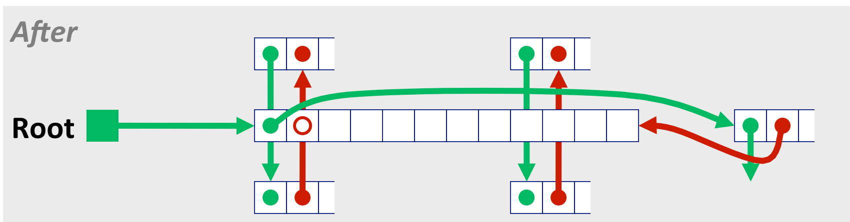


Freeing With a LIFO Policy (Case 4)

conceptual graphic



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



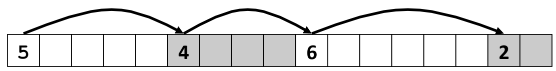
Explicit List Summary

- **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?

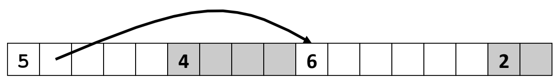
- **Most common use of linked lists is in conjunction with segregated free lists**
  - Keep multiple linked lists of different size classes, or possibly for different types of objects

Keeping Track of Free Blocks

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



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

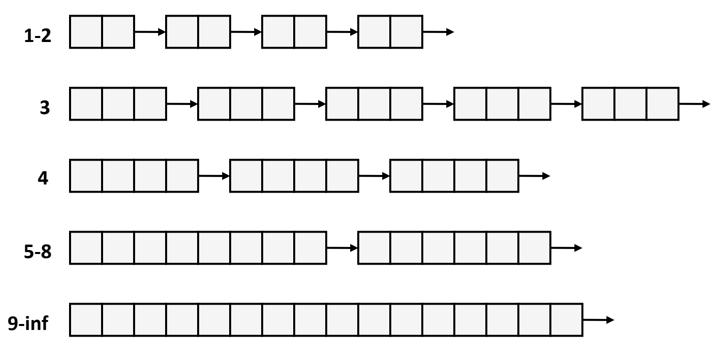


- **Method 3: *Segregated free list***
  - Different free lists for different size classes

- **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

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 `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.

Summary of Key Allocator Policies

- **Placement policy:**
  - First-fit, next-fit, best-fit, etc.
  - Trades off lower throughput for less fragmentation
  - ***Interesting observation*****:** segregated free lists approximate a best fit placement policy without having to search entire free list
- **Splitting policy:**
  - When do we go ahead and split free blocks?
  - How much internal fragmentation are we willing to tolerate?
- **Coalescing policy:**
  - ***Immediate coalescing:*** coalesce each time **`free()`** is called
  - ***Deferred coalescing:*** try to improve performance of **`free()`** by deferring coalescing until needed. Examples:
    - Coalesce as you scan the free list for **`malloc()`**
    - Coalesce when the amount of external fragmentation reaches some threshold

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

- **Must make certain assumptions about pointers**
  - Memory manager can distinguish pointers from non-pointers
  - All pointers point to the start of a block in the heap

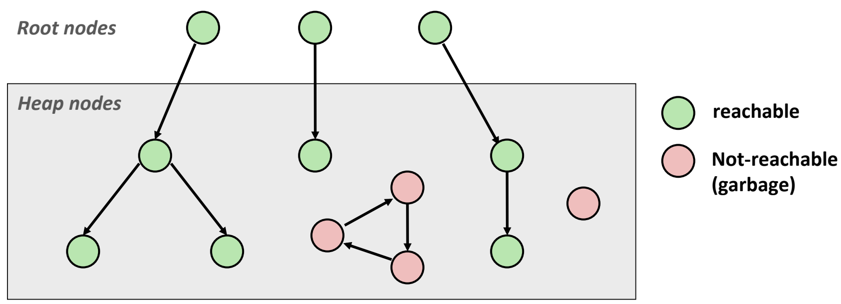
Classical GC Algorithms

- **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.

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)

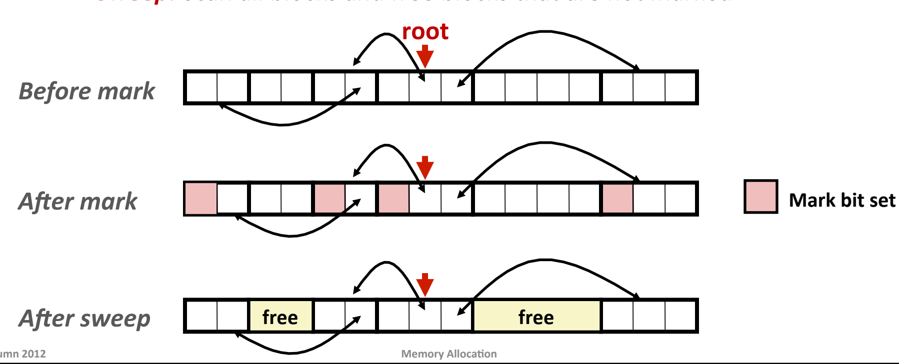


A node (block) is *reachable* if there is a path from any root to that node

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



Assumptions For a Simple Implementation

- **Application can use functions such as:**
  - `new(n)`: returns pointer to new block with all locations cleared
  - `read(b,i)`: read location `i` of block `b` into register
    - `b[i]`
  - `write(b,i,v)`: write `v` into location `i` of block `b`
    - `b[i] = v`
- **Each block will have a header word**
    - `b[-1]`

- **Instructions used by the garbage collector**
  - `is_ptr(p)`: determines whether `p` is a pointer to a block, ***how?***
  - `length(p)`: returns length of block pointed to by `p`, not including header
  - `get_roots()`: returns all the roots

Mark and Sweep (cont.)

Mark using depth-first traversal of the memory graph

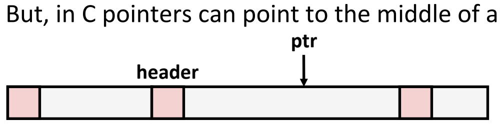
```
ptr mark(ptr p) {
   if (!is_ptr(p)) return;        // do nothing if not pointer
   if (markBitSet(p)) return;     // check if already marked
   setMarkBit(p);                 // set the mark bit
   for (i=0; i < length(p); i++)  // recursively call mark on
     mark(p[i]);                  //   all words in the block
   return;
}
```

Sweep using lengths to find next block

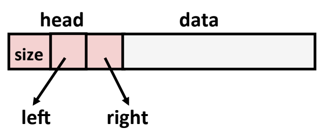
```
ptr sweep(ptr p, ptr end) {
   while (p < end) {              // while not at end of heap
      if markBitSet(p)            // check if block is marked
         clearMarkBit();          // if so, reset mark bit
      else if (allocateBitSet(p)) // if not marked, but allocated
         free(p);                 // free the block
      p += length(p)+1;           // adjust pointer to next block
}
```

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 (but use two additional words)



Left: smaller addresses
Right: larger addresses

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**

Dereferencing Bad Pointers

- The classic `scanf` bug

```
int val;

...

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) );
}
```


University of Washington

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**
  - Your lab assignment #3

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);
```

- What does the free list look like?

```
x = malloc( N * sizeof(int) );
        <manipulate x>
free(x);
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, silent, long-term killer!

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

Too much is reachable

- **Mark procedure is recursive**
  - Will we have enough stack space?
- **We are garbage collecting because we are running out of memory, right?**

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;
}
```

Overwriting Memory

- **Referencing a pointer instead of the object it points to**

```
int *getPacket(int **packets, int *size) {
   int *packet;
   packet = packets[0];
   packets[0] = packets[*size - 1];
   *size--;    // what is happening here?
   reorderPackets(packets, *size);
   return(packet);
}
```


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

How can we make memory bugs go away?

- Does garbage collection solve everything?

- If not, what else do we need?