# Memory Allocation III

CSE 351 Spring 2022

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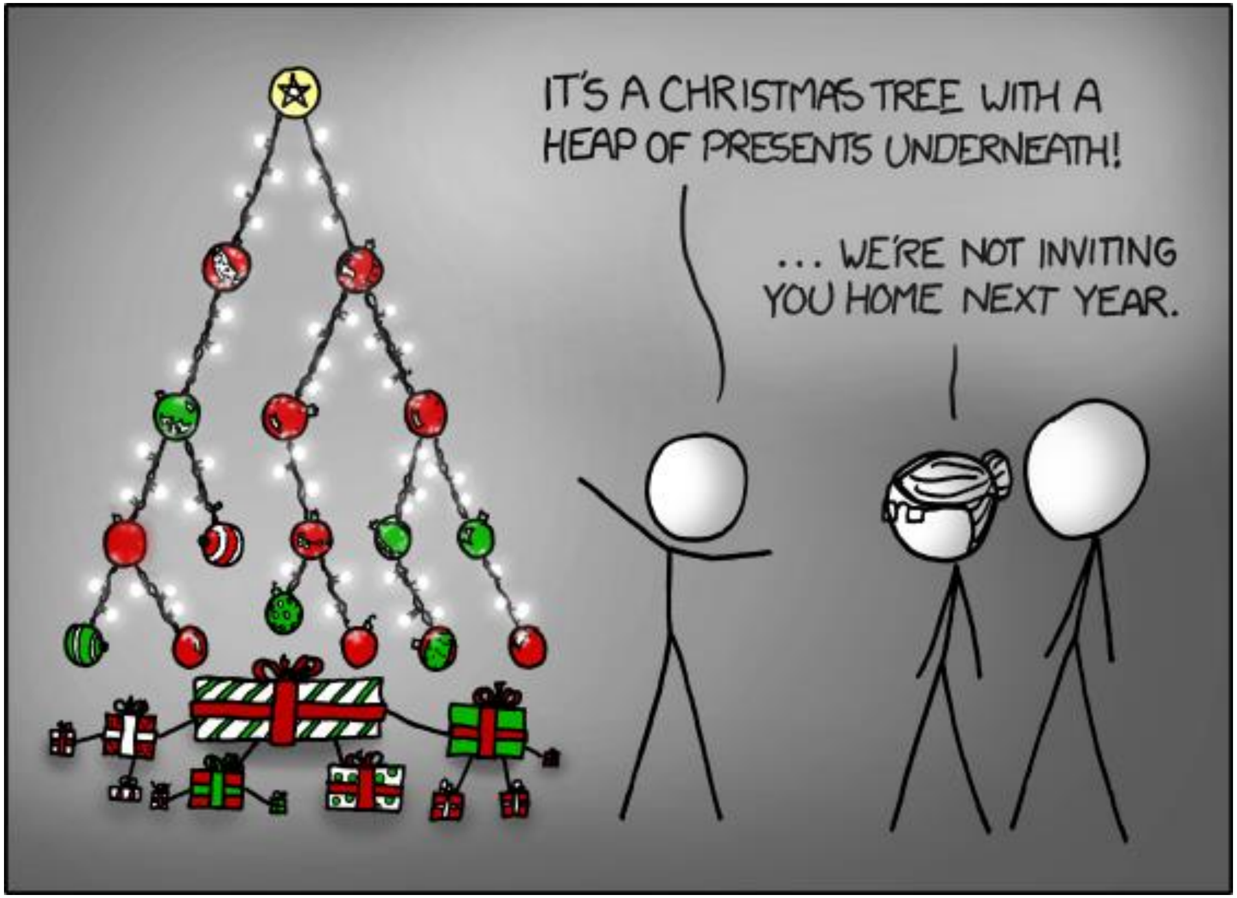



https://xkcd.com/835/

# Relevant Course Information

- hw24 due Wednesday (5/25)
- Lab 5 (on Mem Alloc) due Friday 6/03
  - Can be submitted at most ONE day late. (Sun 6/05)
  - The most significant amount of C programming you will do in this class – combines lots of topics from this class: pointers, bit manipulation, structs, examining memory
  - Understanding the concepts *first* and efficient *debugging* will save you lots of time
  - Light style grading
  - hw25 due Monday (5/30)– Do EARLY, will help with Lab 5

# Allocation Policy Tradeoffs

- Data structure of blocks on lists
  - Implicit (free/allocated), explicit (free), segregated (many free lists) – others possible!
- Placement policy: first-fit, next-fit, best-fit
  - Throughput vs. amount of fragmentation
- When do we split free blocks?
  - How much internal fragmentation are we willing to tolerate?

# 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)

# Memory Allocation

- Dynamic memory allocation
  - Introduction and goals
  - Allocation and deallocation (free)
  - Fragmentation
- Explicit allocation implementation
  - Implicit free lists
  - Explicit free lists (Lab 5)
  - Segregated free lists
- **Implicit deallocation: garbage collection**
- **Common memory-related bugs in C**

# Reading Review

- Terminology:
  - Garbage collection: mark-and-sweep
  - Memory-related issues in C

# Wouldn't it be nice…

- If we never had to free memory?
- Do you free objects in Java?
  - Reminder: *implicit* allocator

# Garbage Collection (GC)
## (Automatic Memory Management)

- *Garbage collection:* automatic reclamation of heap-allocated storage – application never explicitly frees memory

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

- Common in implementations of functional languages, scripting languages, and modern object oriented languages:
  - Lisp, Racket, Erlang, ML, Haskell, Scala, Java, C#, Perl, Ruby, Python, Lua, JavaScript, Dart, Mathematica, MATLAB, many more…
- Variants ("conservative" garbage collectors) exist for C and C++
  - However, cannot necessarily collect all garbage

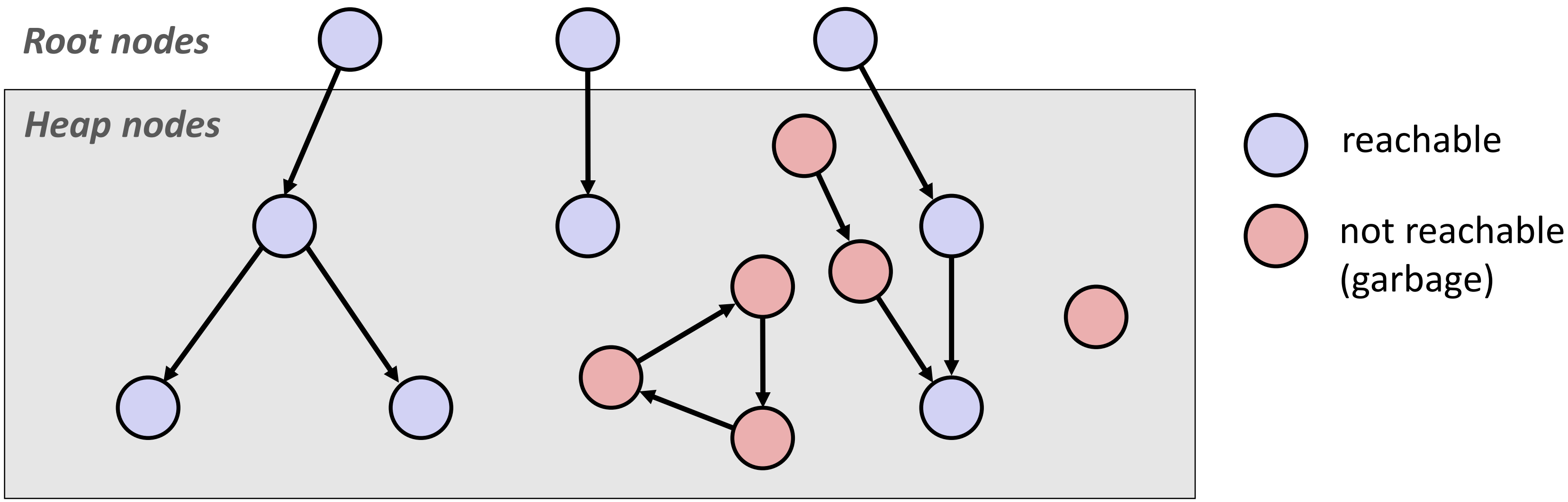
# Garbage Collection

- How does the memory allocator 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 they are *unreachable* (via pointers in registers/stack/globals)

- Memory allocator needs to know what is a pointer and what is not – how can it do this?
  - Sometimes with help from the compiler

# Memory as a Graph

- We view memory as a directed graph
  - Each allocated heap 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, stack locations, 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)

# Garbage Collection

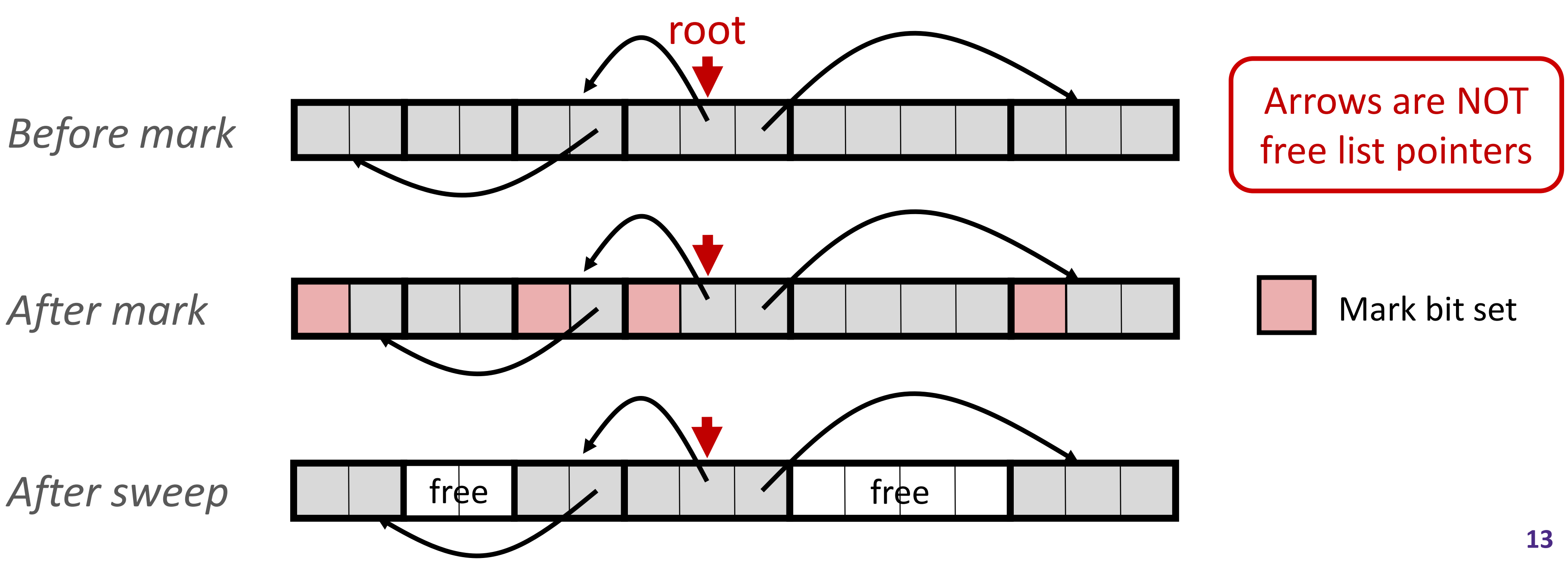
- Dynamic memory allocator can free blocks if there are no pointers to them
- How can it know what is a pointer and what is not?
- We'll make some *assumptions* about pointers:
  - Memory allocator can distinguish pointers from non-pointers
  - All pointers point to the start of a block in the heap
  - Application cannot hide pointers (*e.g.* by coercing them to a `long`, 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)
  - Most allocations become garbage very soon, so focus reclamation work on zones of memory recently allocated.
- For more information:
  - Jones, Hosking, and Moss, *The Garbage Collection Handbook: The Art of Automatic Memory Management*, CRC Press, 2012.
  - Jones and Lin, *Garbage Collection: Algorithms for Automatic Dynamic Memory*, John Wiley & Sons, 1996.

# 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 header 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

Non-testable Material

- Application can use functions to allocate memory:
  - `b=new(n)` returns pointer, `b`, to new block with all locations cleared
  - `b[i]` read location `i` of block `b` into register
  - `b[i]=v` write `v` into location `i` of block `b`

- Each block will have a header word (accessed at `b[-1]`)

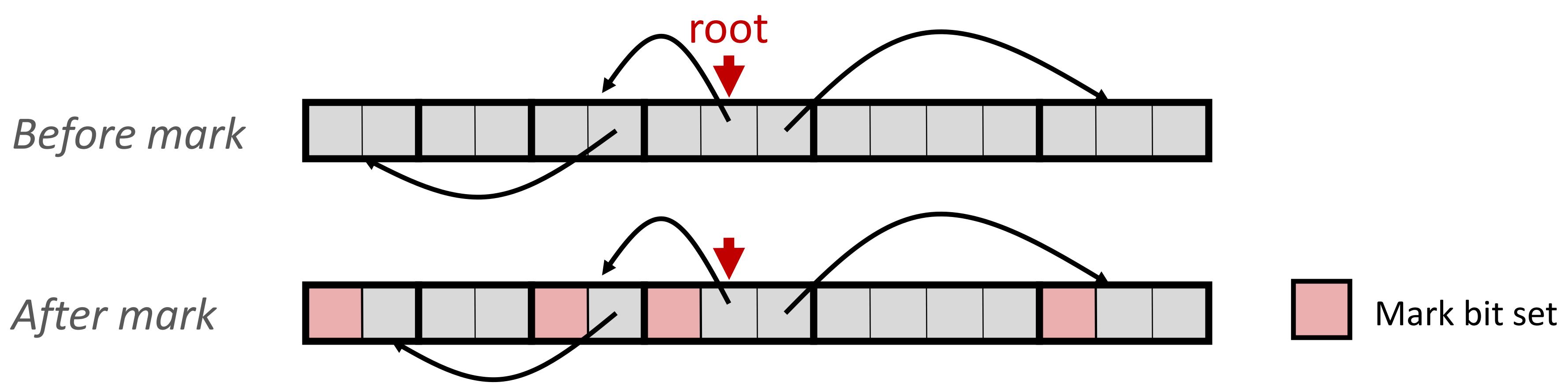
- Functions used by the garbage collector:
  - `is_ptr(p)` determines whether `p` is a pointer to a block
  - `length(p)` returns length of block pointed to by `p`, not including header
  - `get_roots()` returns all the roots

# Mark

Non-testable Material

- Mark using depth-first traversal of the memory graph

```
ptr mark(ptr p) {                          // p: some word in a heap block
   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;
}
```

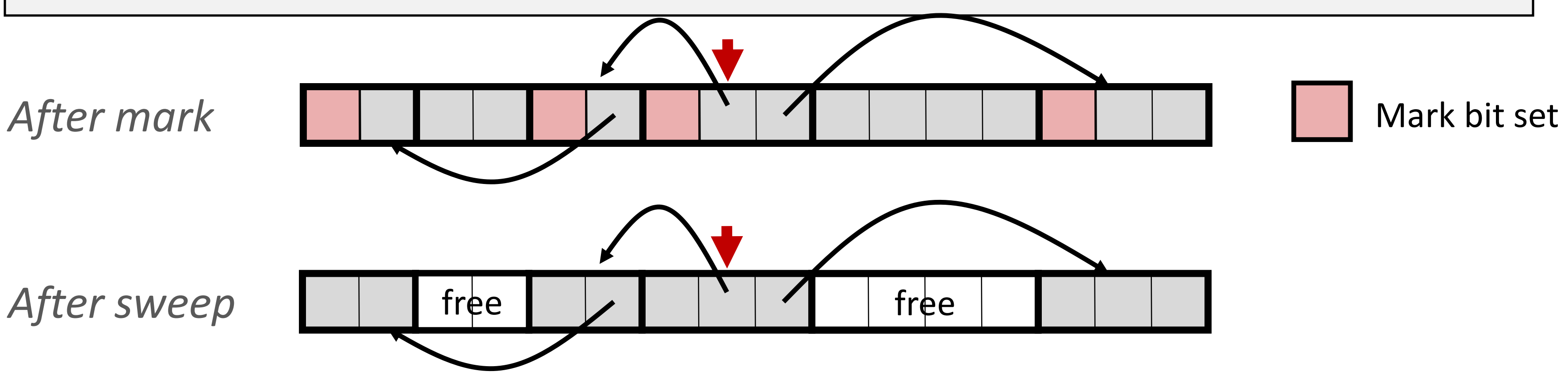


# Sweep

Non-testable Material

- Sweep using sizes in headers

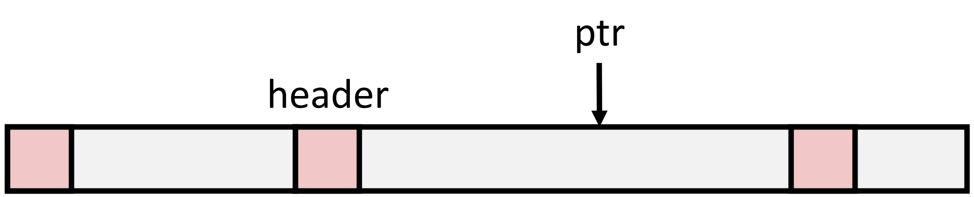
```
ptr sweep(ptr p, ptr end) {          // ptrs to start & end of heap
    while (p < end) {                // while not at end of heap
        if (markBitSet(p))           // check if block is marked
            clearMarkBit(p);         // if so, reset mark bit
        else if (allocateBitSet(p)) 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



Non-testable Material

# Conservative Mark & Sweep in C

- Would mark & sweep work in C?
  - `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 into the middle of allocated blocks (not so in Java)
    - Makes it tricky to find all allocated blocks in mark phase




  - There are ways to solve/avoid this problem in C, but the resulting garbage collector is conservative:
    - Every reachable node correctly identified as reachable, but some unreachable nodes might be incorrectly marked as reachable
  - In Java, all pointers (*i.e.* references) point to the starting address of an object structure – the start of an allocated block

# Memory-Related Perils and Pitfalls in C

| | | Slide | Program stop possible? | Fixes: |
|---|---|---|---|---|
| A) | Dereferencing a non-pointer | | | |
| B) | Freed block – access again | | | |
| C) | Freed block – free again | | | |
| D) | Memory leak – failing to free memory | | | |
| E) | No bounds checking | | | |
| F) | Reading uninitialized memory | | | |
| G) | Referencing nonexistent variable | | | |
| H) | Wrong allocation size | | | |

# Q1: Find That Bug! (Slide 19)

```
char s[8];
int i;

gets(s);  /* reads "123456789" from stdin */
```

**Error Type:**

**Prog stop Possible?**

**Fix:**

# Q2: Find That Bug! (Slide 20)

```
int* foo() {
   int val = 0;

   return &val;
}

void bar() {
  int* addr = foo();
  *addr = 351;
}
```

Error Type: 

Prog stop Possible? 

Fix:

# Q3: Find That Bug! (Slide 21)

```
int** p;

p = (int**)malloc( N * sizeof(int) );

for (int i = 0; i < N; i++) {
   p[i] = (int*)malloc( M * sizeof(int) );
}
```

- `N` and `M` defined elsewhere (`#define`)

**Error Type:** ☐  **Prog stop Possible?** ☐  **Fix:**

# Q4: Find That Bug! (Slide 22)

```
/* return y = Ax */
int* matvec(int** A, int* x) {
   int* y = (int*)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;
}
```

- A is NxN matrix, x is N-sized vector (so product is vector of size N)
- N defined elsewhere (#define)

**Error Type:** ☐ **Prog stop Possible?** ☐ **Fix:**

# Q5: Find That Bug! (Slide 23)

- The classic `scanf` bug
  - `int scanf(const char *format, ...)`

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

See: http://www.cplusplus.com/reference/cstdio/scanf/?kw=scanf

**Error Type:** ☐ **Prog stop Possible?** ☐ **Fix:**

# Q6: Find That Bug! (Slide 24)

```
x = (int*)malloc( N * sizeof(int) );
   // manipulate x
free(x);

   ...

y = (int*)malloc( M * sizeof(int) );
   // manipulate y
free(x);
```

Error Type: 

Prog stop Possible? 

Fix:

# Q7: Find That Bug! (Slide 25)

```
x = (int*)malloc( N * sizeof(int) );
   // manipulate x
free(x);

   ...

y = (int*)malloc( M * sizeof(int) );
for (i=0; i<M; i++)
   y[i] = x[i]++;
```

**Error Type:** ☐ **Prog stop Possible?** ☐ **Fix:**

# (Not in Ed) Find That Bug! (Slide 26)

```
typedef struct L {
   int val;
   struct L *next;
} list;

void foo() {
   list *head = (list *) malloc( sizeof(list) );
   head->val = 0;
   head->next = NULL;
      // create and manipulate the rest of the list
      ...
   free(head);
   return;
}
```

**Error Type:**

**Prog stop Possible?**

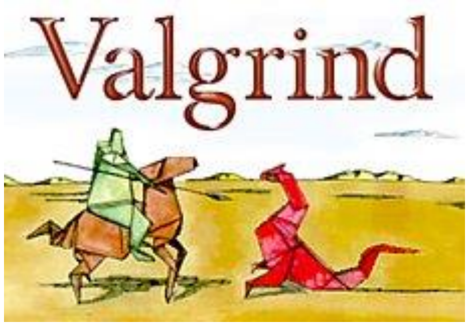
**Fix:**

# Quick Debugging Note

- Staring at code until you think you spot a bug is generally *not* an effective way to debug!
  - Of course it looks logically correct to you – you wrote it!
  - Language like C doesn't abstract away memory – it's part of your program state that you need to keep track of
    - Your code will only get longer and more complicated in the future: there's too much to try to keep track of mentally
- Instead, start with bad/unexpected behavior to guide your search
  - Memory bugs/"errors" can be especially tricky because they often don't result in explicit errors or program stoppages

# Dealing With Memory Bugs

- Make use of all of the tools available to you:
  - Pay attention to compiler warnings and errors
  - Use debuggers like GDB to track down runtime errors
    - Good for bad pointer dereferences, bad with other memory bugs
  - `valgrind` is a powerful debugging and analysis utility for Linux, especially good for memory bugs
    - Checks each individual memory reference at *runtime* (*i.e.*, only detects issues with parts of code used in a specific execution)
    - Can catch many memory bugs, including bad pointers, reading uninitialized data, double-frees, and memory leaks



# What about Java or ML or Python or …?

Non-testable Material

- In *memory-safe languages*, most of these bugs are impossible
  - Cannot perform arbitrary pointer manipulation
  - Cannot get around the type system
  - Array bounds checking, null pointer checking
  - Automatic memory management
- But one of the bugs we saw earlier is possible. Which one?

# Memory Leaks with GC

- Not because of forgotten `free` — we have GC!
- Unneeded "leftover" roots keep objects reachable
- *Sometimes* nullifying a variable is not needed for correctness but is for performance
- Example: Don't leave big data structures you're done with in a static field