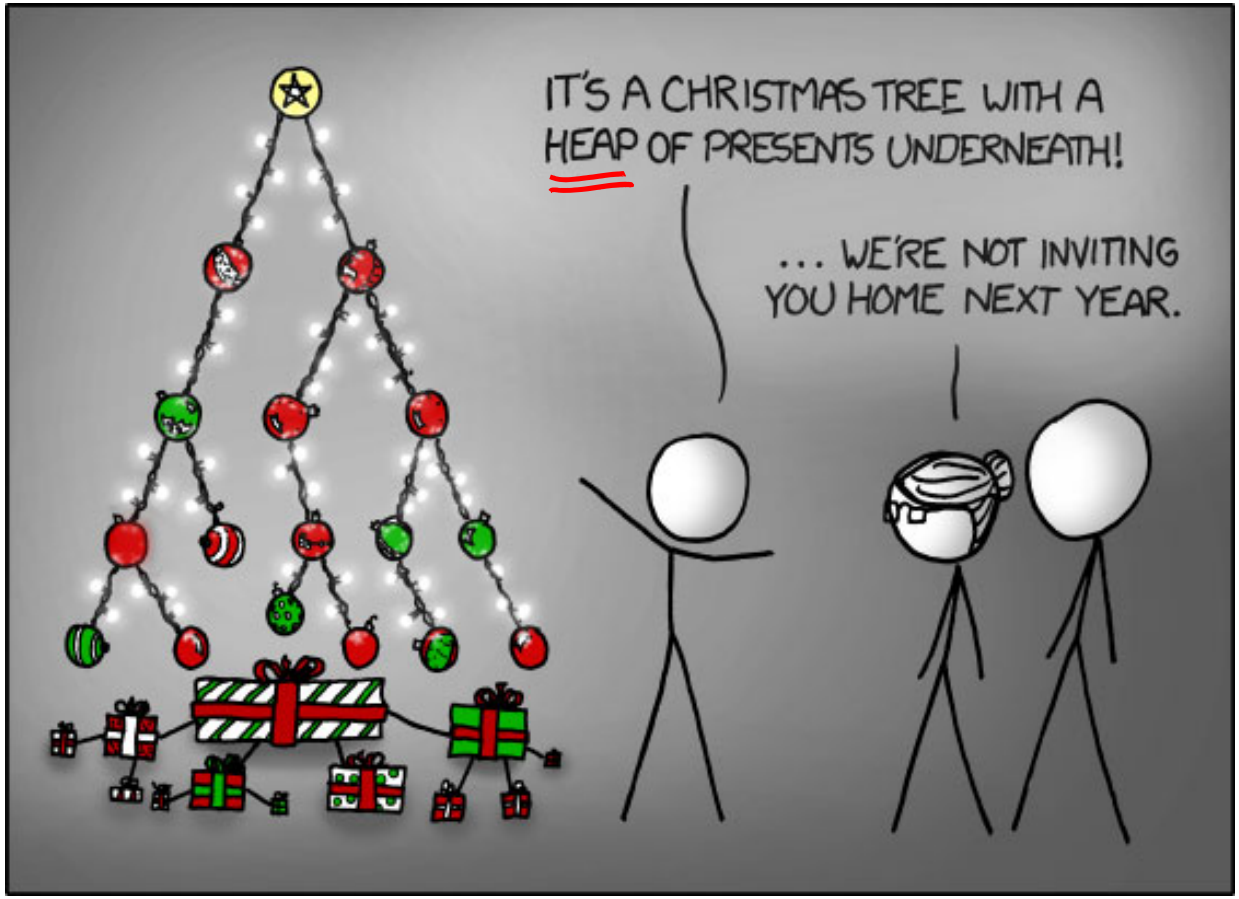
Memory Allocation III

CSE 351 Spring 2022

Instructor:
Ruth Anderson

Teaching Assistants:
Melissa Birchfield
Jacob Christy
Alena Dickmann
Kyrie Dowling
Ellis Haker
Maggie Jiang
Diya Joy
Anirudh Kumar
Jim Limprasert
Armin Magness
Hamsa Shankar
Dara Stotland
Jeffery Tian
Assaf Vayner
Tom Wu
Angela Xu
Effie Zheng



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
- DO NOT MISS SECTION TOMORROW!

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**

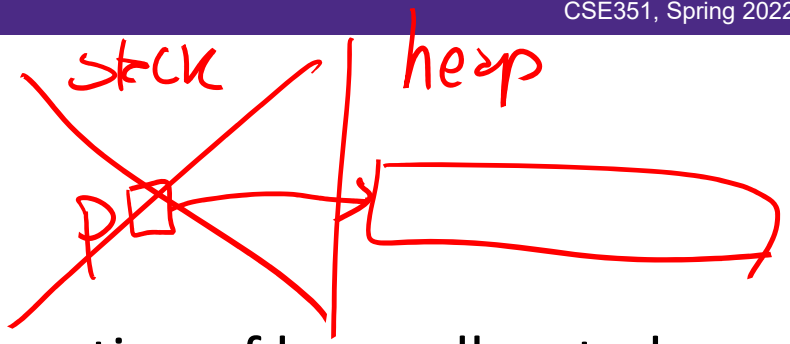
Reading Review

- 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

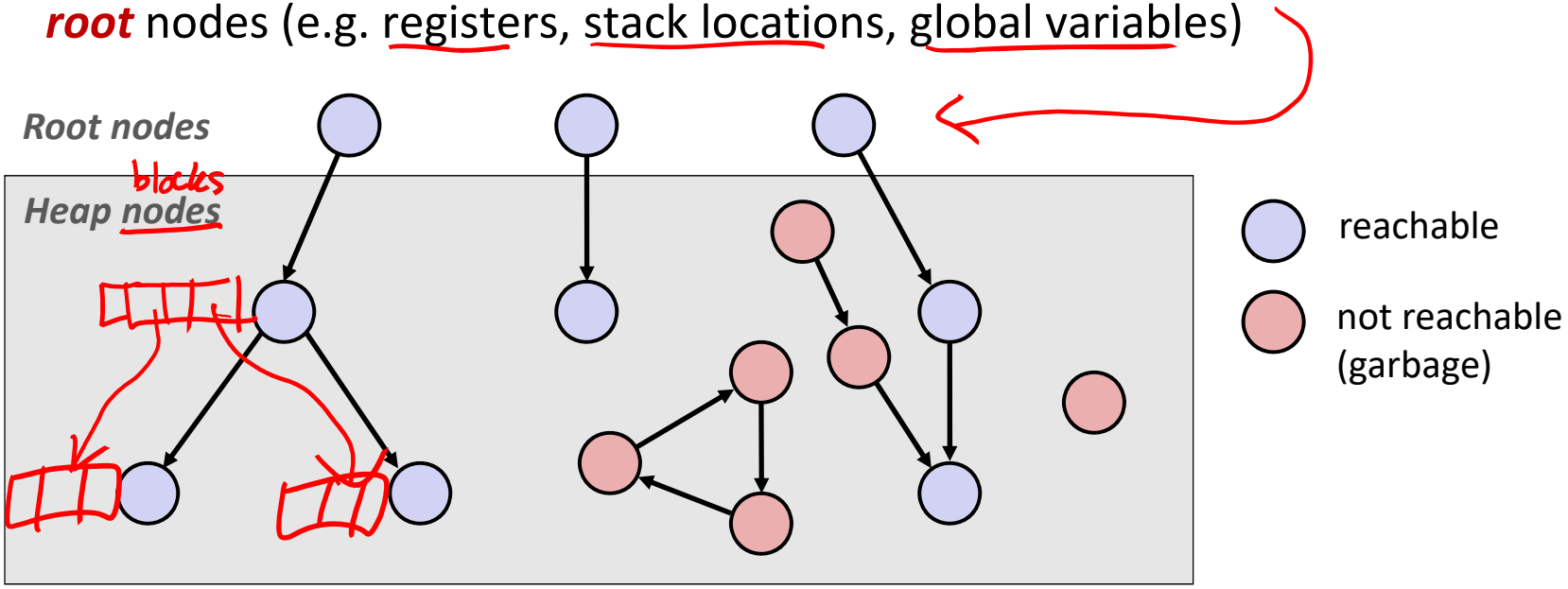
Garbage Collection

- 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 (heap) 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?

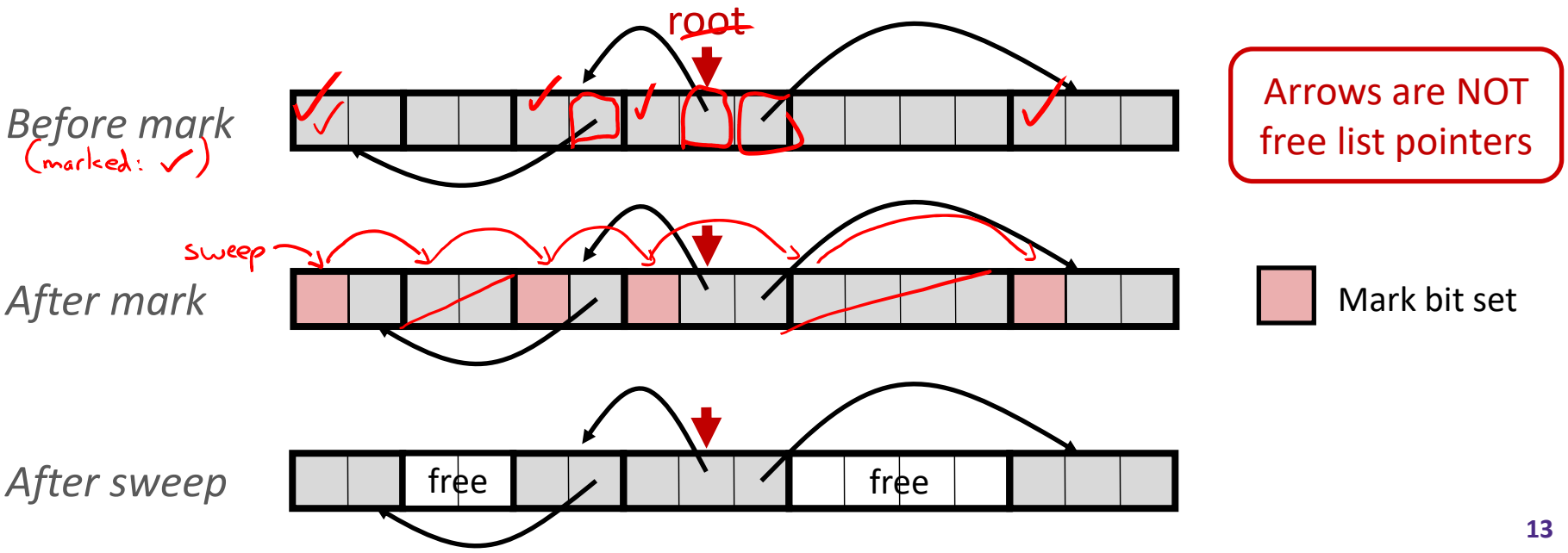
- We'll make some *assumptions* about pointers:
  - Memory allocator can distinguish pointers from non-pointers
  - All pointers point to the start of a block in the heap
  - Application cannot hide pointers
    (*e.g.* by coercing them to a `long`, and then back again)

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]`)

the magic that handles our assumptions!

- 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

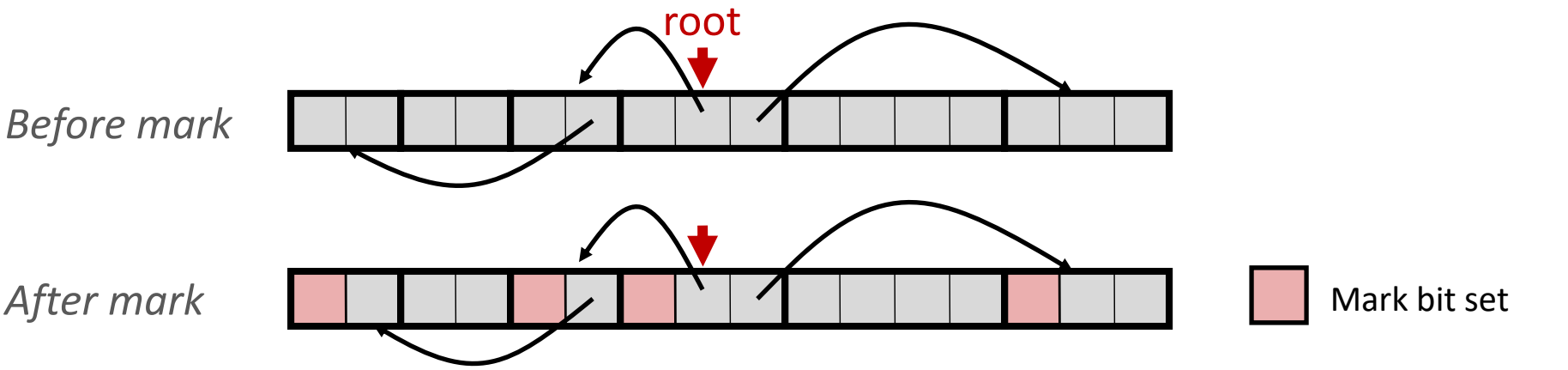
x = get_roots()
for p in x:
    mark(p)

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;
}
```

avoids graph cycles and presumably already traversed



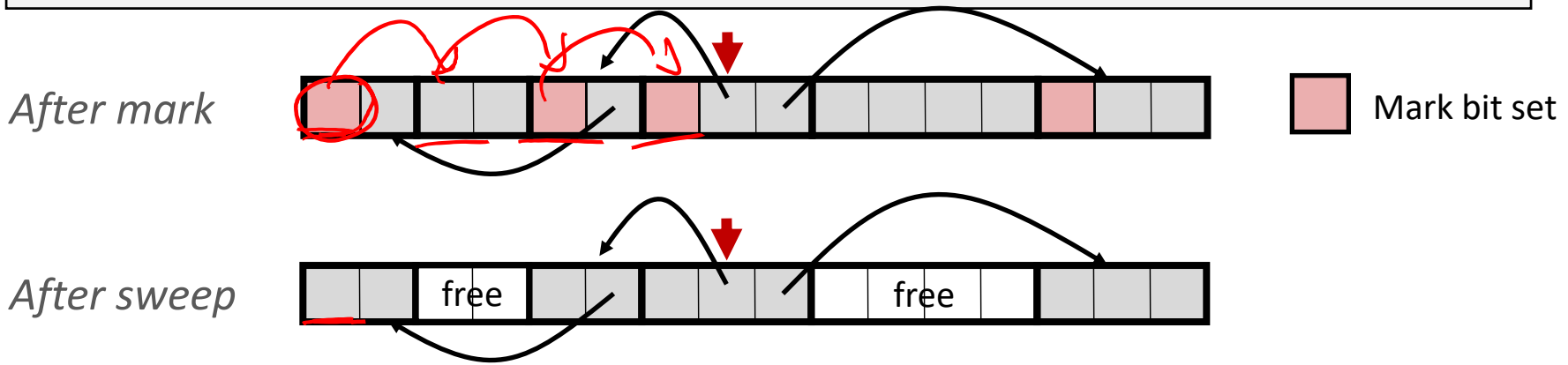
Sweep

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
   }
}
```

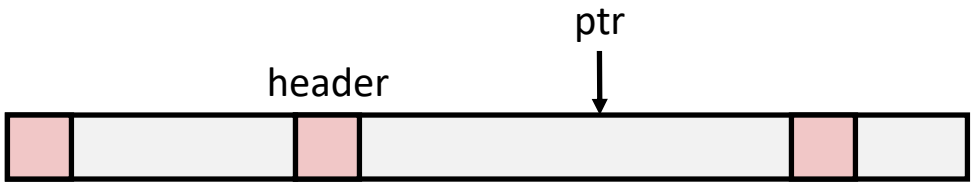
next block →



Conservative Mark & Sweep in C

Non-testable Material

- 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];   //small buffer
int i;

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

no bounds checking

buffer overflow!

Error Type: E

Prog stop Possible? Y

Fix: fgets(s, 8)

Q2: Find That Bug! (Slide 20)

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

    return &val;
}

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

can't be in a register

referencing nonexistent variables

valid address, on the stack

Error Type: G

Prog stop Possible? N

Fix: pass-by-reference to foo or use malloc instead

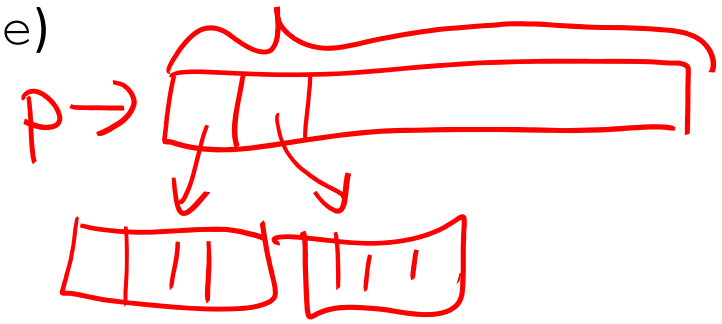
Q3: Find That Bug! (Slide 21)

```
int** p;

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

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

allocates N ints = 4*N bytes

writes to N int* = 8*N bytes

- N and M defined elsewhere (#define)



wrong allocation size

Error Type: H

runs off end of allocated block

Prog stop Possible? Y

Fix: N * sizeof(int*)

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;
}
```

y[i] = y[i] + A[i][j] * x[j];
↑ reads uninitialized values!

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

reading uninitialized memory

just using uninitialized values - runs fine but get weird results

Error Type: F

Prog stop Possible? N

Fix: calloc (N, sizeof(int))

Q5: Find That Bug! (Slide 23)

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

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

← reads input, parses int, stores into location val

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

dereferencing a non-pointer

segfault if val does not contain a valid address

Error Type: A

Prog stop Possible? Y

Fix: `scanf("%d", &val);`

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);
```

free again

undefined behavior (some systems will segfault)

Error Type: C

Prog stop Possible? Y

Fix: free(y) ← probably a typo

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]++;
```

access freed memory

undefined behavior

Error Type: B

Prog stop Possible? Y

Fix: free(x) later (at bottom)

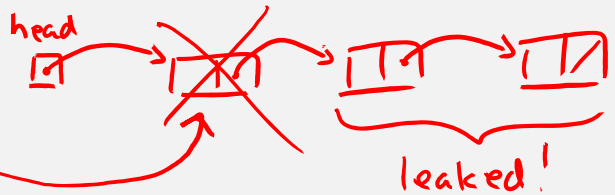
(Not in Ed) Find That Bug! (Slide 26)

```
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;
}
```

node: val next

mallocs here

only frees first node!



how do you detect?

memory leak

Error Type: D

Prog stop Possible? N

Fix: recursive/iterative free over list

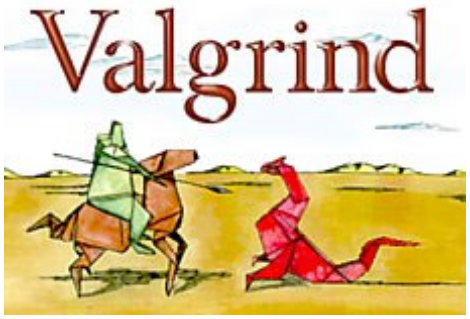
Quick Debugging Note

- 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