Memory Allocation III

CSE 351 Autumn 2016

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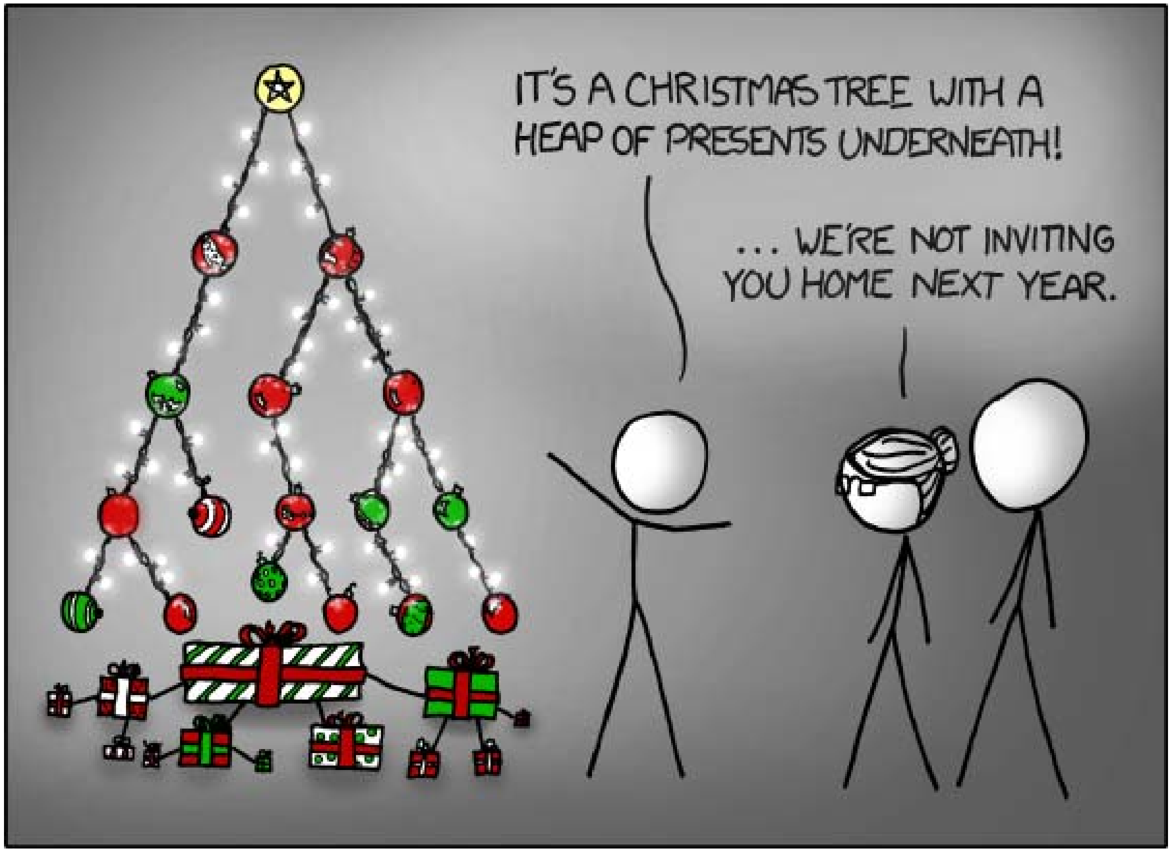


https://xkcd.com/835/

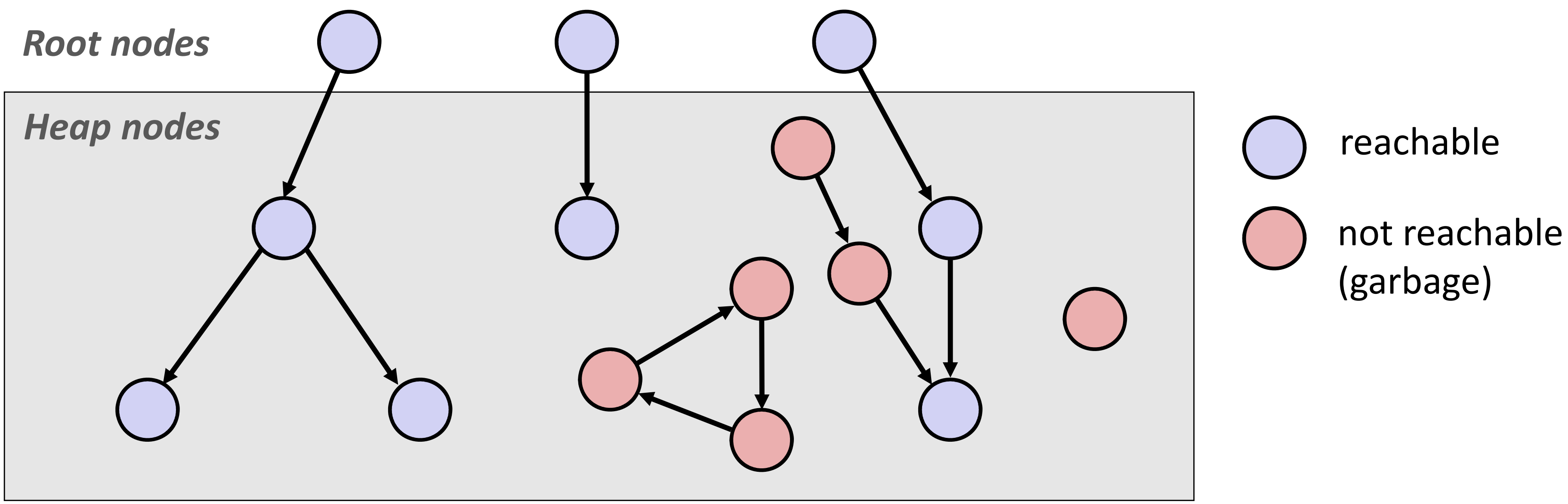
Administrivia

- Homework 4 due today @ 11:45pm
- Lab 5 due Dec. 9 @ 11:45pm
  - New Lab 5 videos on website!

- **Final Exam:** Tue, Dec. 13 @ 12:30pm in Kane 120
  - Review Session: Sun, Dec. 11 @ 1:30pm in EEB 105
  - Cumulative (midterm clobber policy applies)
  - You get TWO double-sided handwritten 8.5×11" cheat sheets
    - Recommended that you reuse or remake your midterm cheat sheet
  - Reference sheet on website & passed out today

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?

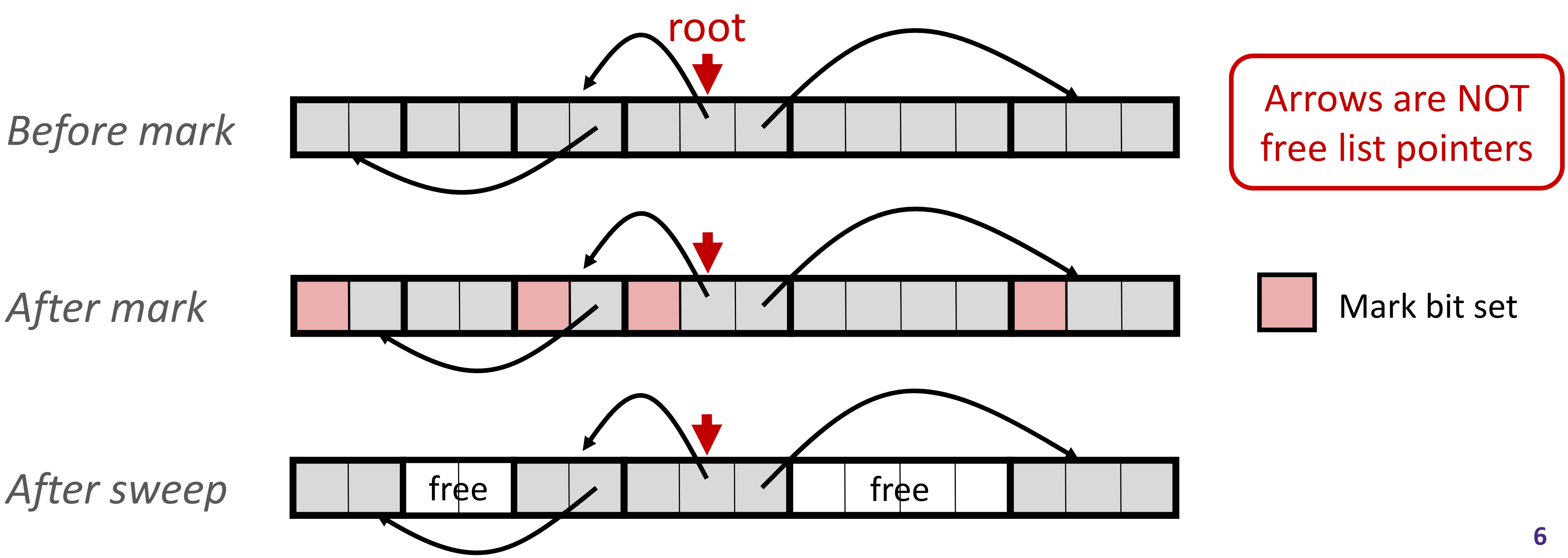
- We'll make some *assumptions* about pointers:
  - Memory allocator can distinguish pointers from non-pointers
  - All pointers point to the start of a block in the heap
  - Application cannot hide pointers (e.g. by coercing them to an `int`, and then back again)

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)
  - 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]`)

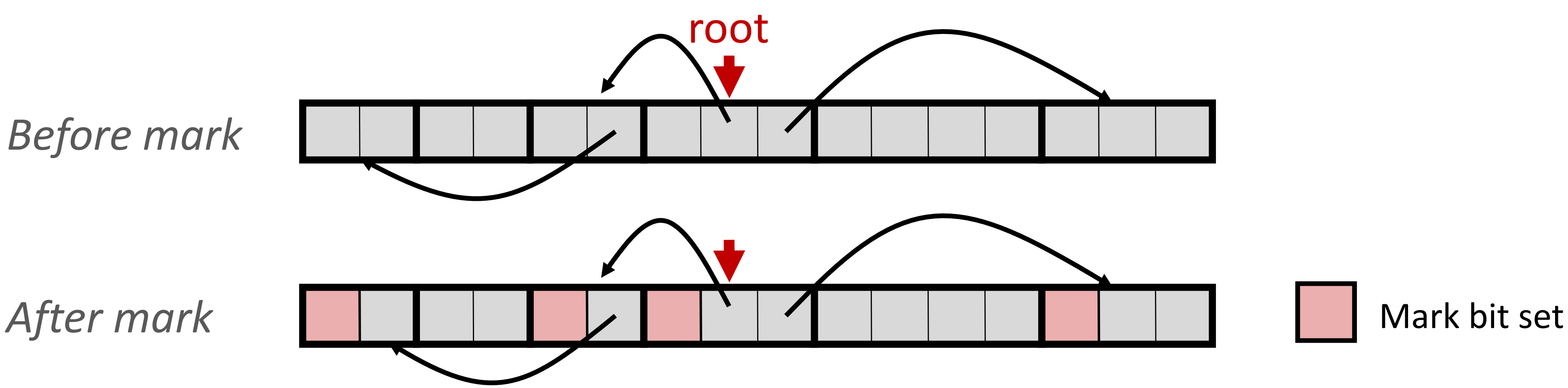
- Functions used by the garbage collector:
  - `is_ptr(p)` determines whether p is a pointer to a block
  - `length(p)` returns length of block pointed to by p, not including header
  - `get_roots()` returns all the roots

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;
}
```

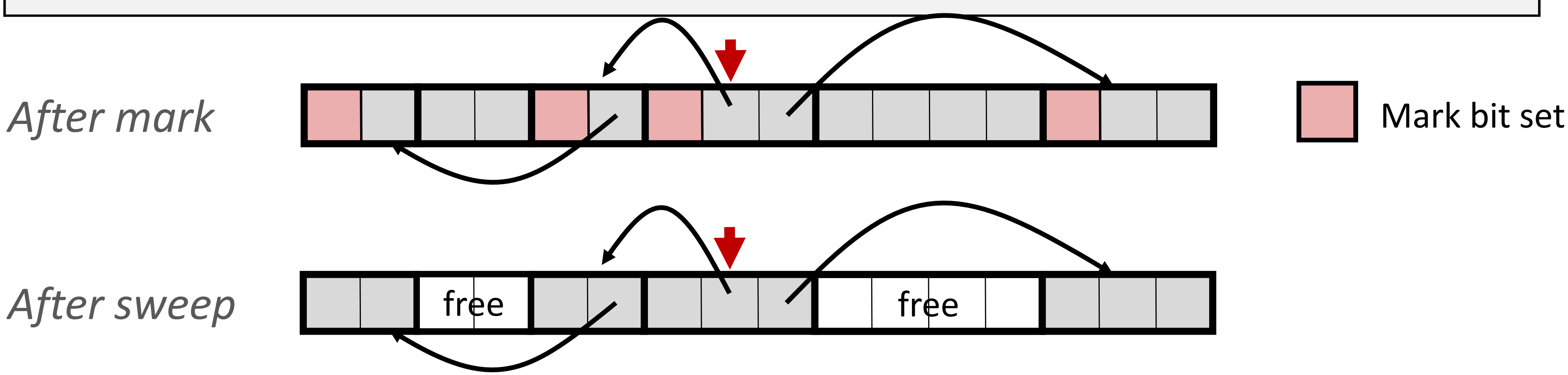


Sweep

Non-testable Material

- Sweep using sizes in headers

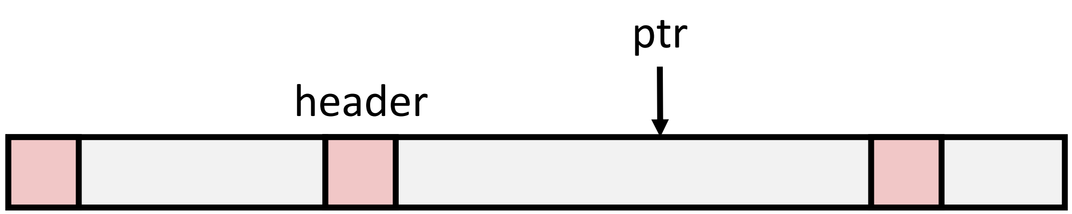
```
ptr sweep(ptr p, ptr end) {          // ptrs to start & end of heap
   while (p < end) {                  // while not at end of heap
      if (markBitSet(p))              // check if block is marked
         clearMarkBit(p);             // if so, reset mark bit
      else if (allocateBitSet(p))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



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	Prog stop Possible?	Security Flaw?
A)	Bad order of operations			
B)	Bad pointer arithmetic			
C)	Dereferencing a non-pointer			
D)	Freed block – access again			
E)	Freed block – free again			
F)	Memory leak – failing to free memory			
G)	No bounds checking			
H)	Off-by-one error			
I)	Reading uninitialized memory			
J)	Referencing nonexistent variable			
K)	Wrong allocation size			

Find That Bug! (Slide 12)

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

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

Error Type:

Prog stop Possible?

Security flaw Possible?

Fix:

Find That Bug! (Slide 13)

```
/* 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?** ☐ **Security flaw Possible?** ☐ **Fix:**

Find That Bug! (Slide 14)

```
int **p;

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

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

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

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

Find That Bug! (Slide 15)

```
int **p;

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

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

Error Type: [ ] Prog stop Possible? [ ] Security flaw Possible? [ ] Fix:

Find That Bug! (Slide 16)

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

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

Error Type: ☐ Prog stop Possible? ☐ Security flaw Possible? ☐ Fix:

Find That Bug! (Slide 17)

```
int *search(int *p, int val) {

   while (p && *p != val)
      p += sizeof(int);

   return p;
}
```

Error Type: | Prog stop Possible? | Security flaw Possible? | Fix:

Find That Bug! (Slide 18)

```
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;
}
```

- ‘- -’ and ‘*’ operators have same precedence and associate from right-to-left, so - - happens first

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

Find That Bug! (Slide 19)

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

   return &val;
}
```

Error Type: [ ]

Prog stop Possible? [ ]

Security flaw Possible? [ ]

Fix:

Find That Bug! (Slide 20)

```
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?		Security flaw Possible?		Fix:

Find That Bug! (Slide 21)

```
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?		Security flaw Possible?		Fix:

Find That Bug! (Slide 22)

```
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?** ☐ **Security flaw Possible?** ☐ **Fix:**

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_ 2`**
  - 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

What about Java or ML or Python or …?

- 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