CSE 374
Programming Concepts & Tools

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(Thanks to Hal Perkins)

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Lecture 10 – C: the heap and manual memory management

Pointer syntax

- A review (for completeness)
- **Declare** a variable to have a pointer type:

  t * x; or t* x; or t *x; or t*x; (matter of style)

  (where t is a type and x is a variable)
- An expression to **dereference** a pointer:

  *x (or more generally *e)

  where e is an expression
- C's designers used the same character (*) on purpose, but declarations (create space) and expressions (compute a value) are **totally different things**

Heap allocation

- So far, all of our ints, pointers, and arrays, have been stack-allocated, which in C has two huge limitations:
  - The space is reclaimed when the allocating function returns
  - The space required must be a constant (only an issue for arrays)
- Heap-allocation has neither limitation
- Comparison: new T(...) in Java does all this:
  - Allocate space for a T (exception if out-of-memory)
  - Initialize the fields to null or 0
  - Call the user-written constructor function
  - Return a reference (hey, a pointer!) to the new object
    - And the reference has a specific type: T
- In C, these steps are almost all separated

malloc, part 1

- malloc is “just” a library function: it takes a number, heap-allocates that many bytes and returns a pointer to the newly-allocated memory
  - Returns NULL on failure
  - Does not initialize the memory
  - You must cast the result to the pointer type you want
  - You do *not* know how much space different values need!
    - Do ***not*** do things like malloc(17) ! (use sizeof)

malloc, part 2

- malloc is “always” used in a specific way:

  (t*)malloc(e * sizeof(t))
- Returns a pointer to memory large enough to hold an array of length e with elements of type t
- It is still not initialized (use a loop)!
  - Underused friend: calloc (takes e and sizeof(t) as separate arguments, initializes everything to 0)
- malloc returns an untyped pointer (void*); the **cast** (t*) tells C to treat it as a pointer to a block of type t

Half the battle

- We can now allocate memory of any size and have it “live” forever
- For example, we can allocate an array and use it indefinitely
- Unfortunately, computers do not have infinite memory so “living forever” could be a problem
- Java solution: Conceptually objects live forever, but the system has a **garbage collector** that finds unreachable objects and reclaims their space
- C solution: You **explicitly** free an object’s space by passing a pointer to it to the library function free
- Freeing heap memory correctly is ***very*** *hard* in complex software and is the *disadvantage* of C-style heap-allocation

Everybody wants to be free(d once)

```
int * p = (int*)malloc(sizeof(int));
p = NULL; /* LEAK! (forgot to free the above memory)*/
int * q = (int*)malloc(sizeof(int));
free(q);
free(q); /* already freed, might crash */
int * r = (int*)malloc(sizeof(int));
free(r);
int * s = (int*)malloc(sizeof(int));
*s = 19;
*r = 17; /* might crash, but maybe *s==17 ?! */
```

- Problems much worse with functions:
  - f returns a pointer; (when) should f's caller free the pointed-to object?
  - g takes two pointers and frees one pointed-to object. Can the other pointer be dereferenced?

The Rules

- For every run-time call to malloc there should be one run-time call to free
- If you “lose all pointers” to an object, you can’t ever call free (a leak)!
- If you “use an object after it’s freed” (or free it twice), you used a dangling pointer!

- Note: It’s possible but rare to use up too much memory without creating “leaks via no more pointers to an object”
- Interesting side-note: The standard-library must “remember” how big the object is (but it won’t tell you)
  - We will explore this further…

later ….

Valgrind

- Ideally there are no memory leaks, dangling pointers, or other bugs, but how do we check?
- valgrind *program program-arguments*
  - Runs *program* with *program-arguments*
  - Catches pointer errors during execution
  - At end, prints summary of heap usage, including details of any memory leaks at termination
- But it *really* slows down execution
  - But still a fantastic diagnostic, debugging tool
- Valgrind has other options/tools but memory check is the default and most commonly used

Processes and the heap

- Recall: a process (running program) has a single address space (code, static/global, heap, stack)
- When a program terminates the address space is released by the OS
  - So any allocated memory is “reclaimed” since it no longer exists
- Good practices
  - OK to rely on this if appropriate, but…
  - Any data structure package that allocates storage should normally provide routines to free it so client code can release the space if the client wants to