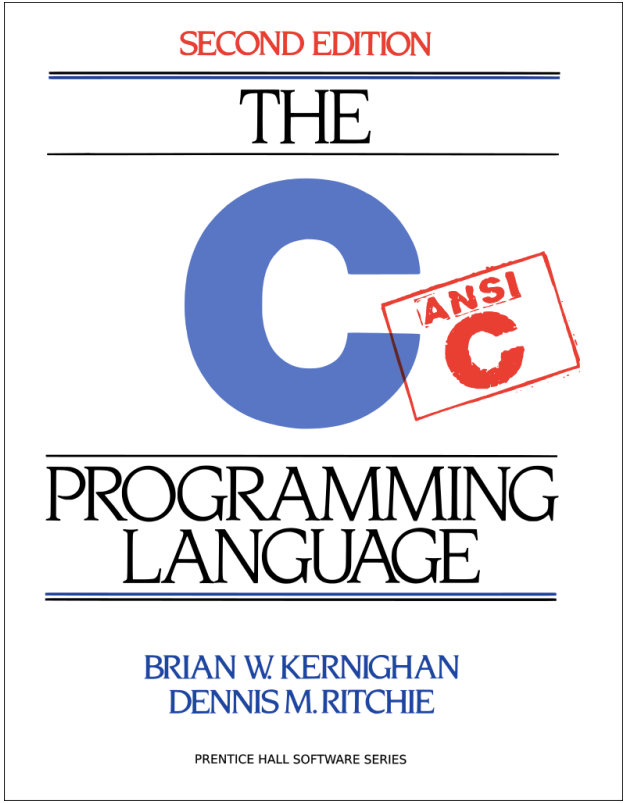
C Boot Camp

September 30, 2018



Agenda

- C Basics
- Debugging Tools / Demo
- Appendix
    - C Standard Library
        - getopt
        - stdio.h
        - stdlib.h
        - string.h

C Basics Handout

```
ssh <andrewid>@shark.ics.cs.cmu.edu
cd ~/private
wget http://cs.cmu.edu/~213/activities/cbootcamp.tar.gz
tar xvpf cbootcamp.tar.gz
cd cbootcamp
make
```

- Contains useful, self-contained C examples
- Slides relating to these examples will have the file names in the **top-right corner**!

C Basics

- The *minimum* you must know to do well in this class
  - You have seen these concepts before
  - Make sure you remember them.

- Summary:
  - Pointers/Arrays/Structs/Casting
  - Memory Management
  - Function pointers/Generic Types
  - Strings
  - GrabBag (Macros, typedefs, header guards/files, etc)

Pointers

- Stores address of a value in memory
  - e.g. `int*, char*, int**`, etc
  - Access the value by dereferencing (e.g. `*a`).
    Can be used to read or write a value to given address
  - Dereferencing `NULL` causes undefined behavior
    (usually a segfault)
- Pointer to type `A` references a block of `sizeof(A)` bytes
- Get the address of a value in memory with the '`&`' operator
- Pointers can be *aliased*, or pointed to same address

Call by Value vs Call by Reference

`./passing_args`

- Call-by-value: Changes made to arguments passed to a function *aren't* reflected in the calling function
- Call-by-reference: Changes made to arguments passed to a function *are* reflected in the calling function
- C is a ***call-by-value*** language
- To cause changes to values outside the function, use pointers
  - Do *not* assign the pointer to a different value (that won't be reflected!)
  - Instead, *dereference the pointer* and assign a value to that address

```
void swap(int* a, int* b) {
    int temp = *a;
    *a = *b;
    *b = temp;
}
```

```
int x = 42;
int y = 54;
swap(&x, &y);
printf("%d¥n", x); // 54
printf("%d¥n", y); // 42
```

Pointer Arithmetic `./pointer_arith`

- Can add/subtract from an address to get a new address
  - Only perform when absolutely necessary (i.e., `malloclab`)
  - Result depends on the pointer type
- `A+i`, where `A` is a pointer = `0x100`, `i` is an `int`
  - `int*  A: A+i = 0x100 + sizeof(int)  * i = 0x100 + 4 * i`
  - `char* A: A+i = 0x100 + sizeof(char) * i = 0x100 + 1 * i`
  - `int** A: A+i = 0x100 + sizeof(int*) * i = 0x100 + 8 * i`
- Rule of thumb: ***explicitly*** cast pointer to avoid confusion
  - Prefer (`(char*)(A) + i`) to (`A + i`), even if `A` has type `char*`

Structs

./structs

- Collection of values placed under one name in a single block of memory
  - Can put structs, arrays in other structs
- Given a struct *instance*, access the fields using the '.' operator
- Given a struct *pointer*, access the fields using the '->' operator

```
struct inner_s {
   int i;
   char c;
};
```

```
struct outer_s {
   char ar[10];
   struct inner_s in;
};
```

```
outer_s out_inst;
out_inst.ar[0] = 'a';
out_inst.in.i = 42;
outer_s* out_ptr = &out_inst;
out_ptr->in.c = 'b';
```

Unions

- When to use
  - Saving memory
    - Malloclab!
- Tagged Unions

```
typedef union {
   char a;
   int b;
} myUnion;

myUnion *u = malloc(sizeof(myUnion))
printf(”size: %zu¥n”, sizeof(myUnion));

u->a = ‘A’;
printf(“u->b: %d”, u->b); // UNDEFINED
```

Arrays/Strings

- Arrays: fixed-size collection of elements of the same type
  - Can allocate on the stack or on the heap
  - `int A[10]; // A is array of 10 int's on the stack`
  - `int* A = calloc(10, sizeof(int)); // A is array of 10 int's on the heap`
- Strings: Null-character ('¥0') terminated character arrays
  - Null-character tells us where the string ends
  - All standard C library functions on strings assume null-termination.

Casting

- Can convert a variable to a different type
- Integer Casting:
  - Signed <-> Unsigned: Keep Bits - Re-Interpret
  - Small -> Large: Sign-Extend MSB
- Cautions:
  - Cast Explicitly: int x = (int) y instead of int x = y
  - Casting Down: Truncates data
  - Cast Up: Upcasting and dereferencing a pointer causes undefined memory access

- Rules for Casting Between Integer Types

Malloc, Free, Calloc

- Handle dynamic memory allocation on HEAP
- `void* malloc (size_t size);`
  - allocate block of memory of `size` bytes
  - does not initialize memory
- `void* calloc (size_t num, size_t size);`
  - allocate block of memory for array of `num` elements, each `size` bytes long
  - initializes memory to zero
- `void free(void* ptr);`
  - frees memory block, previously allocated by malloc, calloc, realloc, pointed by `ptr`
  - use exactly once for each pointer you allocate
- `size` argument*:*
  - *should* be computed using the `sizeof` operator
  - sizeof: takes a type and gives you its size
  - e.g., `sizeof(int), sizeof(int*)`

Memory Management Rules

`mem_mgmt.c`
`./mem_valgrind.sh`

- `malloc` what you `free`, `free` what you `malloc`
  - client should free memory allocated by client code
  - library should free memory allocated by library code
- Number mallocs = Number frees
  - Number mallocs > Number Frees: definitely a memory leak
  - Number mallocs < Number Frees: definitely a double free
- Free a malloc'ed block exactly once
  - Should not dereference a freed memory block
- Only malloc when necessary
  - Persistent, variable sized data structures
  - Concurrent accesses (we'll get there later in the semester)

Stack vs Heap vs Data

- Local variables and function arguments are placed on the *stack*
  - deallocated after the variable leaves scope
  - *do not* return a pointer to a stack-allocated variable!
  - *do not* reference the address of a variable outside its scope!
- Memory blocks allocated by calls to malloc/calloc are placed on the *heap*
- Globals, constants are placed in *data* section
- Example:
  - // a is a pointer on the *stack* to a memory block on the *heap*
  - int* a = malloc(sizeof(int));

Typedefs

./typedefs

- Creates an *alias* type name for a different type
- Useful to simplify names of complex data types
- Be careful when typedef-ing away pointers!

```
struct list_node {
   int x;
};

typedef int pixel;
typedef struct list_node* node;
typedef int (*cmp)(int e1, int e2); // you won't use this in 213

pixel x; // int type
node foo; // struct list_node* type
cmp int_cmp; // int (*cmp)(int e1, int e2) type
```

Macros

./macros

- A way to replace a name with its macro definition
  - No function call overhead, type neutral
  - Think “find and replace” like in a text editor
- Uses:
  - defining constants (INT_MAX, ARRAY_SIZE)
  - defining simple operations (MAX(a, b))
  - 122-style contracts (REQUIRES, ENSURES)
- Warnings:
  - Use parentheses around arguments/expressions, to avoid problems after substitution
  - Do not pass expressions with side effects as arguments to macros

```
#define INT_MAX 0x7FFFFFFF
#define MAX(A, B) ((A) > (B) ? (A) : (B))
#define REQUIRES(COND) assert(COND)
#define WORD_SIZE 4
#define NEXT_WORD(a) ((char*)(a) + WORD_SIZE)
```

Generic Types

- void* type is C's provision for generic types
  - Raw pointer to some memory location (unknown type)
  - Can't dereference a `void*` (what is type `void`?)
  - Must cast void* to another type in order to dereference it
- Can cast back and forth between `void*` and other pointer types

```
// stack implementation:

typedef void* elem;

stack stack_new();
void push(stack S, elem e);
elem pop(stack S);
```

```
// stack usage:

int x = 42; int y = 54;
stack S = stack_new():
push(S, &x);
push(S, &y);
int a = *(int*)pop(S);
int b = *(int*)pop(S);
```

Header Files

- Includes C declarations and macro definitions to be shared across multiple files
  - Only include function prototypes/macros; implementation code goes in .c file!
- Usage: #include <header.h>
  - `#include <lib>` for standard libraries (eg `#include <string.h>`)
  - `#include "file"` for your source files (eg `#include "header.h"`)
  - Never include .c files (bad practice)

```
// list.h
struct list_node {
   int data;
   struct list_node* next;
};
typedef struct list_node* node;

node new_list();
void add_node(int e, node l);
```

```
// list.c
#include "list.h"

node new_list() {
   // implementation
}

void add_node(int e, node l) {
   // implementation
}
```

```
// stacks.h
#include "list.h"
struct stack_head {
   node top;
   node bottom;
};
typedef struct stack_head* stack

stack new_stack();
void push(int e, stack S);
```

Header Guards

- Double-inclusion problem: include same header file twice

```
//grandfather.h
```

```
//father.h
#include “grandfather.h”
```

```
//child.h
#include “father.h”
#include “grandfather.h”
```

Error: child.h includes grandfather.h twice

- Solution: header guard ensures single inclusion

```
//grandfather.h
#ifndef GRANDFATHER_H
#define GRANDFATHER_H


#endif
```

```
//father.h
#ifndef FATHER_H
#define FATHER_H


#endif
```

```
//child.h
#include “father.h”
#include “grandfather.h”
```

Okay: child.h only includes grandfather.h once

Debugging

GDB, Valgrind

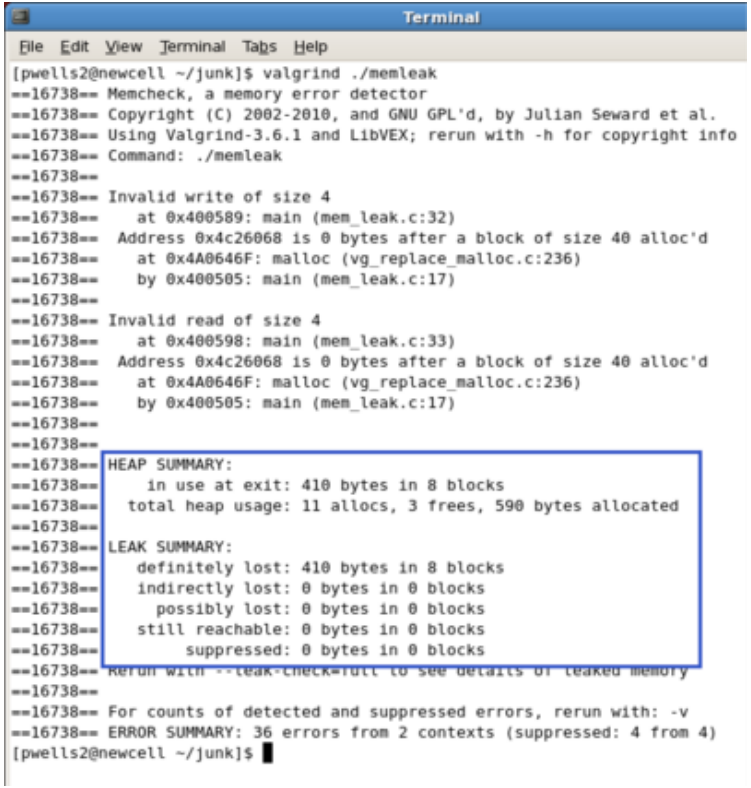
GDB

- No longer stepping through assembly! Some GDB commands are different:
  - si / si → step / next
  - break file.c:line_num
  - disas → list
  - print <any_var_name> (in current frame)

- Use TUI mode (layout src)
  - Nice display for viewing source/executing commands
  - Buggy, so only use TUI mode to step through lines (no continue / finish)

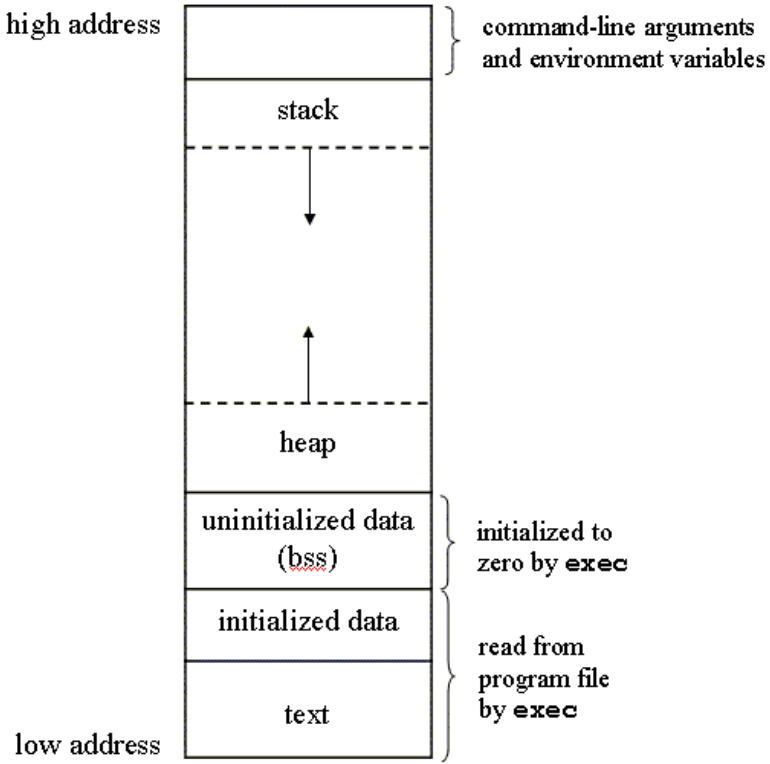
Valgrind

- Find memory errors, detect memory leaks
- Common errors:
  - Illegal read/write errors
  - Use of uninitialized values
  - Illegal frees
  - Overlapping source/destination addresses
- Typical solutions
  - Did you allocate enough memory?
  - Did you accidentally free stack variables/something twice?
  - Did you initialize all your variables?
  - Did use something that you just free'd?
- --leak-check=full
  - Memcheck gives details for each definitely/possibly lost memory block (where it was allocated



Appendix

C Program Memory Layout



Variable Declarations & Qualifiers

- Global Variables:
  - Defined outside functions, seen by all files
  - Use “extern” keyword to use a global variable defined in another file
- Const Variables:
  - For variables that won’t change
  - Data stored in read-only data section
- Static Variables:
  - For locals, keeps value between invocations
  - USE SPARINGLY
  - Note: static has a different meaning when referring to functions
- Volatile Variables:
  - Compiler will not make assumptions about current value, useful for asynchronous reads/writes, i.e. interrupts
  - “volatile” == “subject to change at any time”

C Libraries

string.h: Common String/Array Methods

- One the most useful libraries available to you
- Used heavily in shell/proxy labs
- Important usage details regarding arguments:
  - prefixes: `str` -> strings, `mem` -> arbitrary memory blocks.
  - ensure that all strings are '`¥0`' terminated!
  - ensure that `dest` is large enough to store `src`!
  - ensure that `src` actually contains `n` bytes!
  - ensure that `src`/`dest` don't overlap!

string.h: Common String/Array Methods

- Copying:
  - `void *memcpy (void *dest, void *src, size_t n)`
    Copy n bytes of src into dest, return dest
  - `char *strcpy(char *dest, char *src)`
    Copy src string into dest, **including the NUL terminator**, return dest.
    Make sure dest is large enough to contain src.
  - `char *strncpy(char *dest, char *src, size_t count)`
    Copy src string into dest, **including the NUL terminator**, return dest.
    Copies at most count bytes.
    Make sure dest is large enough to contain src.

string.h: Common String/Array Methods (Continued)

- Concatenation:
  - `char *strncat (char *dest, char *src, size_t n)`
    Append copy of src to end of dest reading at most n bytes, return dest
  - `char *strcat (char *dest, char *src)`
    Works for arbitrary length strings, but has the safety issues you've seen in attacklab

string.h: Common String/Array Methods (Continued)

- Comparison:
  - `int strncmp (char *str1, char *str2, size_t n)`
    Compare at most n bytes of str1, str2 by character
    (based on ASCII value of each character, then string length),
    return comparison result
    -1 if str1 < str2
    0 if str1 == str2
    1 if str1 > str2

  - `int strcmp(char *str1, char *str2)`
    Compare str1 to str2.
    Make sure each string is long enough to be safely compared.

string.h: Common String/Array Methods (Continued)

- Searching:
  - `char *strstr (char *str1, char *str2)`
    Return pointer to *first* occurrence of str2 in str1, else NULL
  - `char *strtok (char *str, char *delimiters)`
    Tokenize `str` according to delimiter characters provided in `delimiters`.
    Return the one token for each `strtok` call, using `str = NULL`

string.h: Common String/Array Methods (Continued)

- Other:
  - `size_t strlen (const char *str)`
    Return length of the string (up to, but not including the '¥0' character)

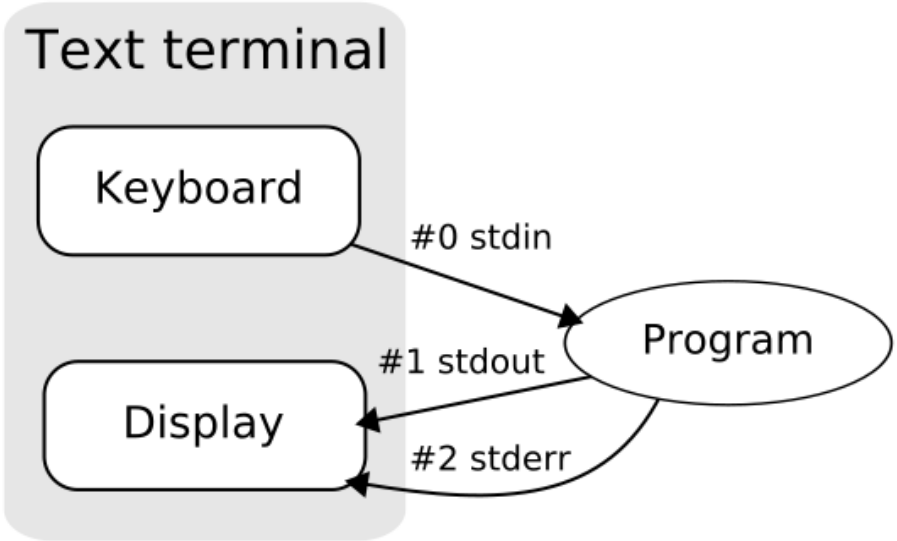
  - `void *memset (void *ptr, int val, size_t n)`
    Set first n bytes of memory block addressed by `ptr` to `val`.
    Use for *setting bytes only.* Don't use it to set or initialize `int` arrays, for example.

stdlib.h: General Purpose Functions

- Dynamic memory allocation:
  - `malloc, calloc, free`
- String conversion:
  - `int atoi(char *str)`: parse string into integral value (return 0 if not parsed)
- System Calls:
  - `void exit(int status)`: terminate calling process, return `status` to parent process
  - `void abort()`: aborts process abnormally
- Searching/Sorting:
  - provide array, array size, element size, comparator (function pointer)
  - `bsearch`: returns pointer to matching element in the array
  - `qsort`: sorts the array destructively
- Integer arithmetic:
  - `int abs(int n)`: returns absolute value of `n`
- Types:
  - `size_t`: unsigned integral type (store size of *any* object)
    - In a format string, print with `%zu`

stdio.h

- Another really useful library.
- Used heavily in cache/shell/proxy labs
- Used for:
  - argument parsing
  - file handling
  - input/output
- `printf`, a fan favorite, comes from this library!



stdio.h: Common I/O Methods

- `FILE *fopen (char *filename, char *mode)`: open the file with specified filename in specified `mode` (read, write, append, etc), associate it with stream identified by returned file pointer
- `int fscanf (FILE *stream, char *format, ...)`: read data from the `stream`, store it according to the parameter `format` at the memory locations pointed at by additional arguments.
- `int fclose (FILE *stream)`: close the file associated with `stream`
- `int fprintf (FILE *stream, char *format, ... )`: write the C string pointed at by `format` to the `stream`, using any additional arguments to fill in format specifiers.

Getopt

- Need to include `unistd.h` to use
- Used to parse command-line arguments.
- Typically called in a loop to retrieve arguments
- Switch statement used to handle options
  - colon indicates required argument
  - `optarg` is set to value of option argument
- Returns -1 when no more arguments present
- See recitation 6 slides for more examples

```
int main(int argc, char **argv)
{
  int opt, x;
  /* looping over arguments */
  while((opt=getopt(argc,argv,"x:"))>0){
    switch(opt) {
      case 'x':
        x = atoi(optarg);
        break;
      default:
        printf("wrong argument¥n");
        break;
    }
  }
}
```

Note about Library Functions

- These functions can return error codes
  - `malloc` could fail
  - ```
    int x;
    if ((x = malloc(sizeof(int))) == NULL)
      printf("Malloc failed!!!¥n");
    ```
  - a file couldn't be opened
  - a string may be incorrectly parsed
- Remember to check for the error cases and handle the errors accordingly
  - may have to terminate the program (eg `malloc` fails)
  - may be able to recover (user entered bad input)
    ```