C Boot Camp

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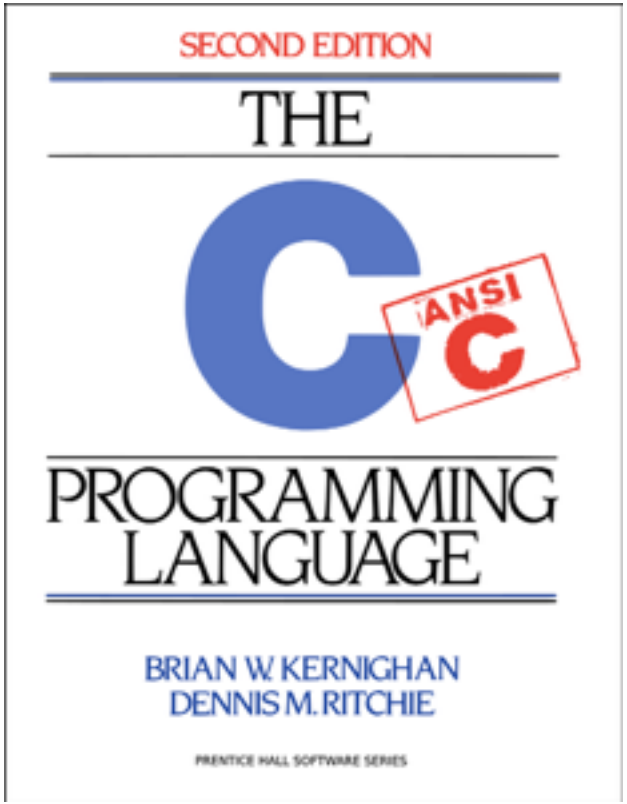


Agenda

- C Basics
- C Libraries
- Debugging Tools
- Version Control
- Compilation
- Demo

C Basics

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
  - eg `int*, char*, int**`, etc
  - Access the value by dereferencing (`*a`); can be used to read value or write value to given address
  - Can't dereference `NULL`
- Pointer to type `a` references a block of `sizeof(a)` bytes
- Get the address of a value in memory with the '`&`' operator
- Can alias pointers to same address

Demo Time!

Call by Value vs Call by Reference

- 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 reflect changes to arguments 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

- Can add/subtract from an address to get a new address
  - Only perform when absolutely necessary (ie `malloc`)
  - Result depends on the pointer type

- `A+i`, where `A` is a pointer = `0x100`, `i` is an `int` (*x86-64*)
  - `int* A: A+i = 0x100 + sizeof(int) * i = 0x100 + 4 * i`
  - `char* A: A+i = 0x100 + sizeof(char) * i = 0x100 + i`
  - `int** A: A + i = 0x100 + sizeof(int*) * i = 0x100 + 8 * i`
- Rule of thumb: cast pointer explicitly to avoid confusion
  - Prefer `(char*)(A) + i` vs `A + i`, even if `char* A`
  - Absolutely do this in macros (ie `malloc`)

Demo Time!

Structs

- Group of variables placed under one name in a block of memory
  - Can embed 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 foo_s {
   int a;
   char b;
};
```

```
struct bar_s {
   char ar[10];
   foo_s baz;
};
```

```
bar_s biz; // bar_s instance
biz.ar[0] = 'a';
biz.baz.a = 42;
bar_s* boz = &biz; // bar_s ptr
boz->baz.b = 'b';
```

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.

Puzzle Time!

Casting

- Can cast a variable to a different type
- Changes the interpretation of the element
- Integer Type Casting:
  - signed <-> unsigned: change interpretation of most significant bit
  - smaller signed -> larger signed: sign-extend (duplicate the sign bit)
  - smaller unsigned -> larger unsigned: zero-extend (duplicate 0)
- Cautions:
  - cast explicitly, out of practice
  - never cast to a smaller type; will truncate (lose) data
  - never cast a pointer to a larger type and dereference it

Puzzle Time!

Malloc, Free, Calloc

- Handle dynamic memory
- `void* malloc (size_t size);`
  - allocate block of memory of `size` bytes
  - does not initialize memory to zero values
- `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 values
- `void free(void* ptr);`
  - frees memory block, previously allocated by malloc, calloc, realloc, pointed by `ptr`
- `size` argument:
  - *should* be computed using the `sizeof` operator
  - sizeof: can be applied to a type or an actual variable (please don't do the later)
  - eg `sizeof(int), sizeof(int*)`

Memory Management Rules

- 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'd block only once
  - Should not dereference a free'd memory block

Puzzle Time!

Stack Vs Heap Allocation

- Temporary variables (scope bound) 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 elsewhere
- Example:
  - // a is a pointer on the *stack* to a memory block on the *heap*
  - int* a = malloc(sizeof(int));

Typedefs

- Creates an *alias* type name for a different type
- Useful to simplify names of complex data types

```
struct list_node {
   int x;
};

typedef int pixel;
typedef struct list_node* node;
typedef int (*cmp)(int e1, int e2);

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

Macros

- Fragment of code given a name; replace occurrence of name with contents of macro
  - No function call overhead, type neutral
- Uses:
  - defining constants (INT_MAX, ARRAY_SIZE)
  - defining simple operations (MAX(a, b))
  - 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)
```

Function Pointers

- Stores the address of a function.
- Invoke the function by dereferencing the pointer, passing arguments to the function obtained
- Syntax: <return_type> (*<fn_name>)(args)
  - `int (*cmp)(int e1, int e2) = &compare_ints;`
  - `int val = (*cmp)(42, 54);`
- Uses:
  - memory management (client defines type used in implementation, must declare a method to free it!)
  - generic data structures and algorithms (eg comparators for different element types)

Puzzle Time!

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; no implementation code!
- 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

Odds and Ends

- Prefix vs Postfix increment/decrement
  - `a++`: use `a` in the expression, then increment `a`
  - `++a`: increment `a`, then use `a` in the expression
- Switch Statements:
  - remember break statements after every case, unless you want fall through (may be desirable in some cases)
  - should probably use a default case
- Inline functions:
- Variable/function modifiers:
  - global variables: defined outside functions, seen by all files
  - static variables/functions: seen only in file it's declared in
  - extern: storage for variable is defined elsewhere

C Libraries

string.h: Common String/Array Methods

- Possibly the most useful library 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, return dest
- Concatenation:
  - `char * strcat (char * dest, char* src)`: append copy of src to end of dest, return dest
- Comparison:
  - `int strcmp (char * str1, char * str2)`: compare str1, str2 by character (based on ASCII value of each character, then string length), return comparison result
    str1 < str2: -1,
    str1 == str2: 0,
    str1 > str2: 1

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

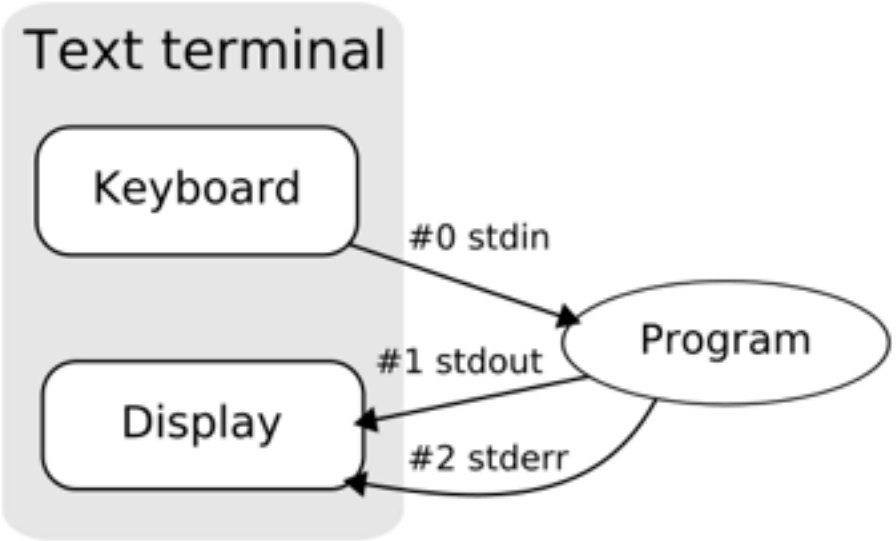
- Searching:
  - `char* strstr (char * str1, char * str2)`: return pointer to *first* occurrence of str2 in str1, else NULL
  - `char* strtok (char * str, char * delimiters)`: tokenize `str` according to delimiter characters provided in `delimiters`, return the next token per successive stroke call, using `str = NULL`
- Other:
  - `size_t strlen ( const char * str )`: returns 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 this for *setting bytes only;* don't use to set `int` arrays or anything else!)

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)

stdio.h

- Another really useful library.
- Used heavily in cache/ shell/proxy labs
- Used for:
  - argument parsing
  - file handling
  - input/output



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 the `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 `getopt.h` and `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
- May be useful for Cache lab!

```
int main(int argc, char** argv){
  int opt, x;
  /* looping over arguments */
  while(-1 != (opt = getopt(argc, argv, "x:"))){
    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
  - 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)

Version Control

Version Control

- You should use it. Now.
- Avoid suffering during large labs (malloc, proxy)
- Basic ideas:
  - complete record of everything that happened in your code repository
  - ability to create branches to test new components of code
  - ease in sharing code with other.
- A skill that will pay you dividends in the future

Version Control Basics (Git)

- git init:
  - Create a new repository
  - Indicated by .git file
- git status:
  - Show working tree-status
  - Untracked files, modified files, deleted files, staged files
- git add <file_name>
  - Stage a file to be committed (does *not* perform the commit)
  - git add . stages all files in current directory
- git commit
  - Make a commit from all the stage files
  - git commit -m “Commit message”

Distributing your Source

- Should probably also use a website for hosting a remote repository (github, bitbucket)
  - MUST ensure that your repository is PRIVATE
- git push:
  - Pushes the local repository to a remote repository
- git pull:
  - Pushes the local repository to a remote repository
- git clone:
  - Clone a repository into a new directory
  - git clone <online-repo-name>

Other Git stuff

- Git is complicated; be careful
- Run into a problem, look it up
  - StackOverflow
  - Github
  - http://git-scm.com/docs/
  - man pages
- Some online tutorials:
  - http://pcottle.github.io/learnGitBranching/
  - https://try.github.io/

Debugging

GDB, Valgrind

GDB

- No longer stepping through assembly!
  - Use the step/next commands
  - break on line numbers, functions
  - Use list to display code at line-numbers and functions
  - Use print with variables

- Use gdbtui
  - Nice display for viewing source/ executing commands

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

Compilation

GCC, Make Files

GCC

- Used to compile C/C++ projects
  - List the files that will be compiled to form an executable
  - Specify options via flags
- Important Flags:
  - -g: produce debug information (**important**; used by GDB/valgrind)
  - -Werror: treat all warnings as errors (this is our **default**)
  - -Wall/-Wextra: enable all construction warnings
  - -pedantic: indicate all mandatory diagnostics listed in C-standard
  - -O1/-O2: optimization levels
  - -o <filename>: name output binary file ‘filename’
- Example:
  - gcc -g -Werror -Wall -Wextra -pedantic foo.c bar.c -o baz

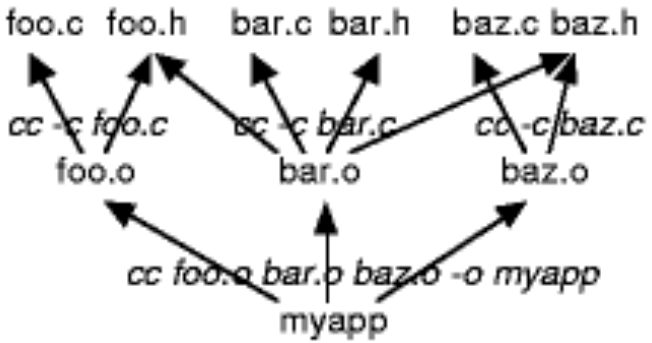
Make Files

- Command-line compilation becomes inefficient when compiling many files together
- Solution: use make-files
  - Single operation to compile files together
  - Only recompiles updated files

```
# Makefile for the malloc lab driver
#
CC = gcc
CFLAGS = -Wall -Wextra -Werror -O2 -g -DDRIVER -std=gnu99

OBJS = mdriver.o mm.o memlib.o fsecs.o fcyc.o clock.o ftimer.o

all: mdriver

mdriver: $(OBJS)
     $(CC) $(CFLAGS) -o mdriver $(OBJS)

mdriver.o: mdriver.c fsecs.h fcyc.h clock.h memlib.h config.h mm.h
memlib.o: memlib.c memlib.h
mm.o: mm.c mm.h memlib.h
fsecs.o: fsecs.c fsecs.h config.h
fcyc.o: fcyc.c fcyc.h
ftimer.o: ftimer.c ftimer.h config.h
clock.o: clock.c clock.h

clean:
     rm -f *~ *.o mdriver
```

Make File Rules

- Comments start with a '#', Commands start with a TAB.
- Common Make File Format:
  - target: source(s)
    TAB: command
    TAB: command
- Macros: similar to C-macros, find and replace:
  - CC = gcc
    CCOPT = -g -DDEBUG -DPRINT
    foo.o: foo.c foo.h
    $(CC) $(CCOPT) -c foo.c
- See http://www.andrew.cmu.edu/course/15-123-kesden/index/lecture_index.html for more details



Demo Time!

Putting it all together

Questions?


OKAY, HUMAN.
HUH?
BEFORE YOU HIT 'COMPILE', LISTEN UP.
YOU KNOW WHEN YOU'RE FALLING ASLEEP, AND YOU IMAGINE YOURSELF WALKING OR SOMETHING.
AND SUDDENLY YOU MISSTEP, STUMBLE, AND JOLT AWAKE?
YEAH!
WELL, THAT'S WHAT A SEGFAULT FEELS LIKE.
DOUBLE-CHECK YOUR DAMN POINTERS, OKAY?