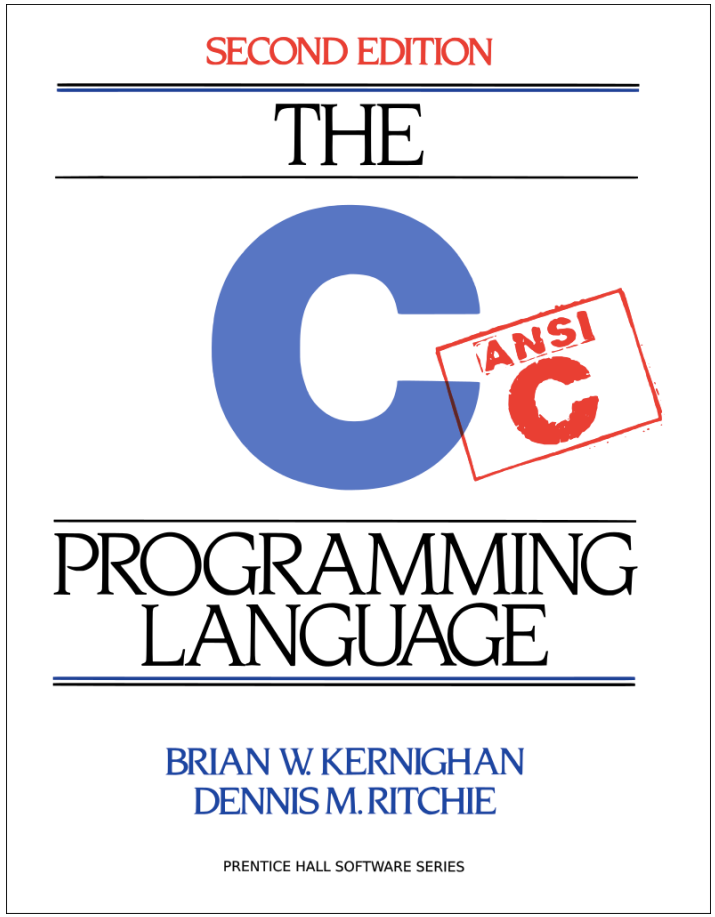
C Programming Language

13 Sep. 2024
Ocean Moon



Linux

- Linux Machine
  - Windows : VMWare Workstation Player
  - MacOS (Intel) : VMWare Fusion Player
  - MacOS (M1) : UTM
  - Or Linux Server on my office (ssh -p 2222 `your_id`@122.38.251.9)
- Installed program
  - terminator
  - vim
  - socat
  - pwndbg
  - python3, pip
  - pwntools
  - ROPgadget
  - checksec

Linux

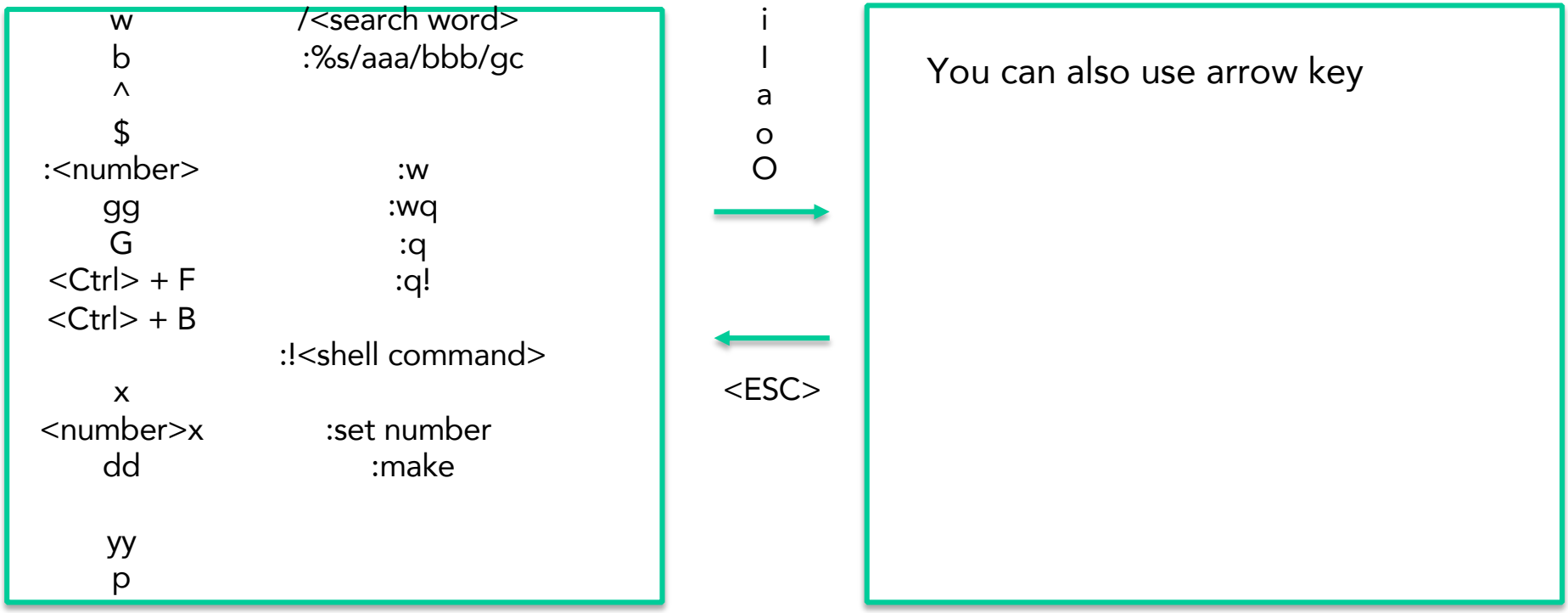
- File sharing
  - VMware shared folder
  - scp
  - Filezilla
- Editor
  - Vim
  - Your favorite editor + File sharing

Linux

- Hexdump
  - How to handle file
  - Edit with Vim
  - make
  - debugging with gdb
  - Disassemble/Decompile with Ghidra

Linux

- Vi


w
b
^
$
:<number>
gg
G
<Ctrl> + F
<Ctrl> + B
x
<number>x
dd
yy
p
/<search word>
:%s/aaa/bbb/gc
:w
:wq
:q
:q!
:!<shell command>
:set number
:make
i
I
a
o
O
<ESC>
You can also use arrow key
Command mode
Insert (Edit) mode

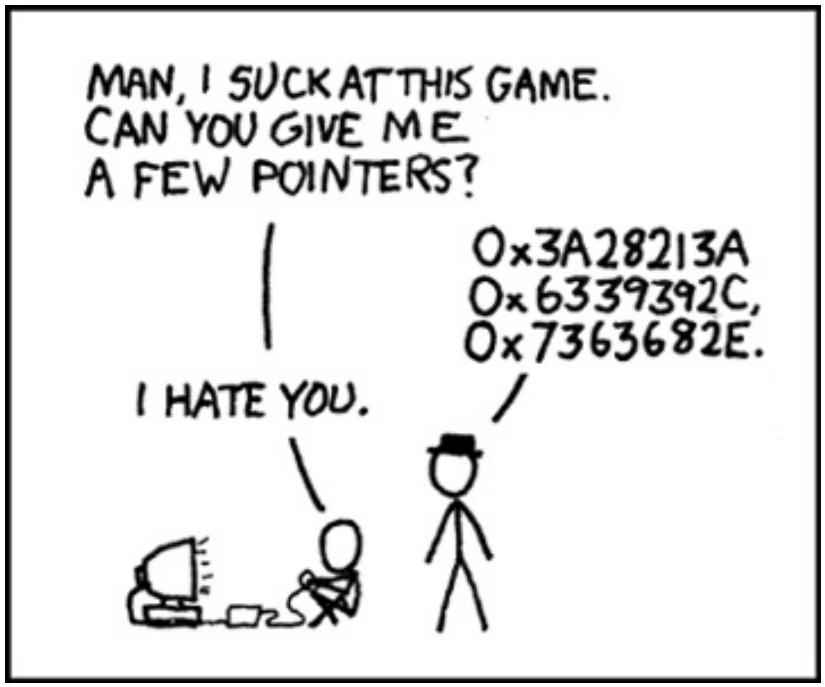
Linux

- Vi

vi *
:n
:files
:file
:sp .
:vs .
:make -f Makefile.hexdump
<shift>+k
:copen
:cclose
:cn
:cp
<ctrl>+w+w
:q

Agenda

- C Basics
- C Libraries
- Debugging Tools
- Version Control
- Compilation
- Reversing
- 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
  - dereferencing `NULL` causes a runtime error
- 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 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
```

Demo Time!

Pointer Arithmetic

- Can add/subtract from an address to get a new address
  - Only perform when absolutely necessary (i.e., `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 (i.e., `malloc`)

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 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.

Casting

- Can cast a variable to a different type
- 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. C will cast operations involving different types implicitly, often leading to errors
  - never cast to a smaller type; will truncate (lose) data
  - never cast a pointer to a larger type and dereference it, this accesses memory with undefined contents

Malloc, Free, Calloc

- Handle dynamic memory
- `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 values
- `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

- 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 malloced block exactly once
  - Should not dereference a freed memory block

Stack Vs Heap Allocation

- 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 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))
  - 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; 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
- Variable/function modifiers:
  - global variables: defined outside functions, seen by all files
  - static variables/functions: seen only in file it's declared in
  - Refer to K&R for other modifiers and their meanings

C Libraries

string.h: Common String/Array Methods

- One the most useful libraries available to you
- 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)

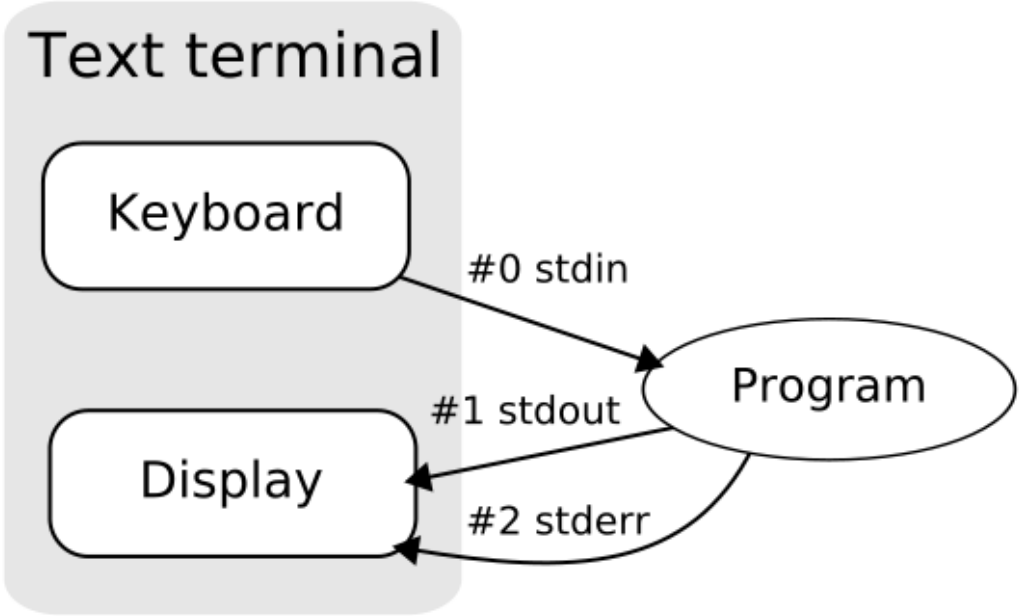
- Searching:
  - `char* strstr (char * str1, char * str2)`: return pointer to *first* occurrence of str2 in str1, else NULL
  - `char* strtok (char * str, char * delimiters)`: tokenize `str` according to delimiter characters provided in `delimiters`, return the next token per successive stroke call, 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 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

```
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

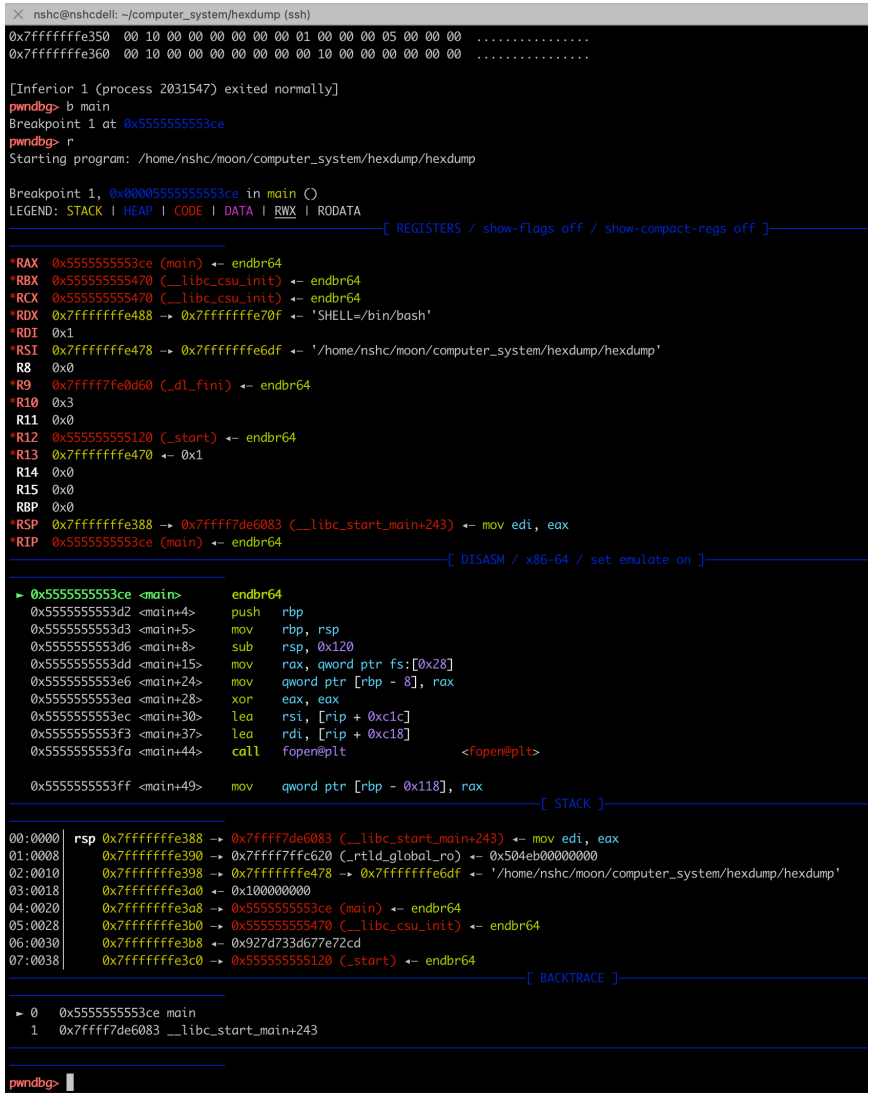
- These functions can return error codes
  - `malloc` could fail
  - a file couldn't be opened
  - a string may be incorrectly parsed
- Remember to check for the error cases and handle the errors accordingly
  - may have to terminate the program (eg `malloc` fails)
  - may be able to recover (user entered bad input)

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 pwndbg
  - 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
  - -O0/-O1/-O2: optimization levels
  - -o <filename>: name output binary file ‘filename’
- Example:
  - gcc -g -Werror -Wall -Wextra -pedantic foo.c bar.c -o baz

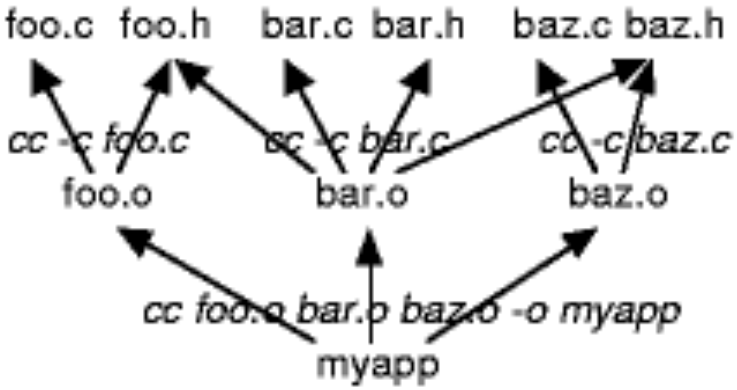
Make Files

- 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

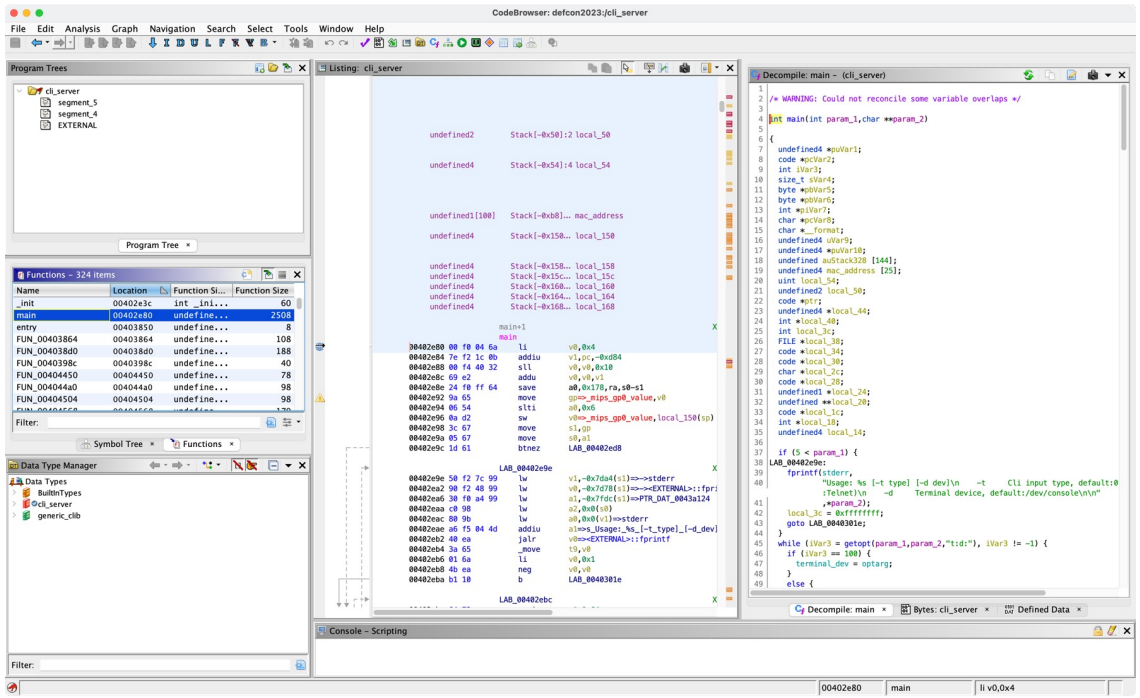


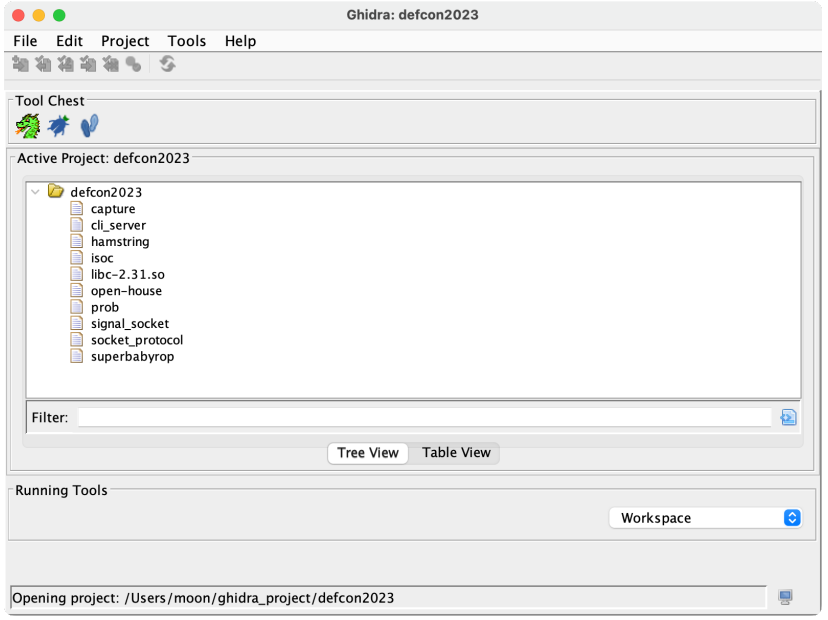
Reversing

Ghidra

Reversing

- Installation
  - https://github.com/NationalSecurityAgency/ghidra/releases
- Decompile executable file





Assignment explanation

- Make it short

Questions?