C Boot Camp

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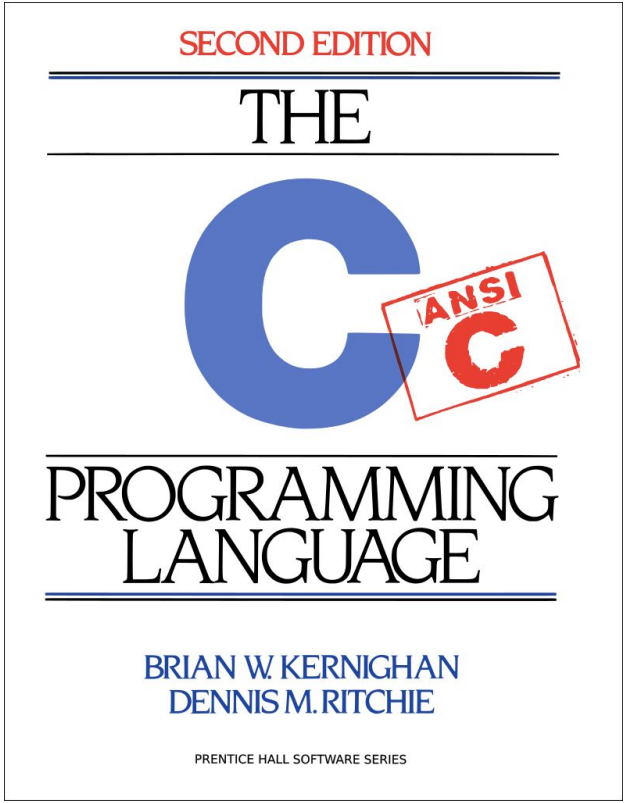
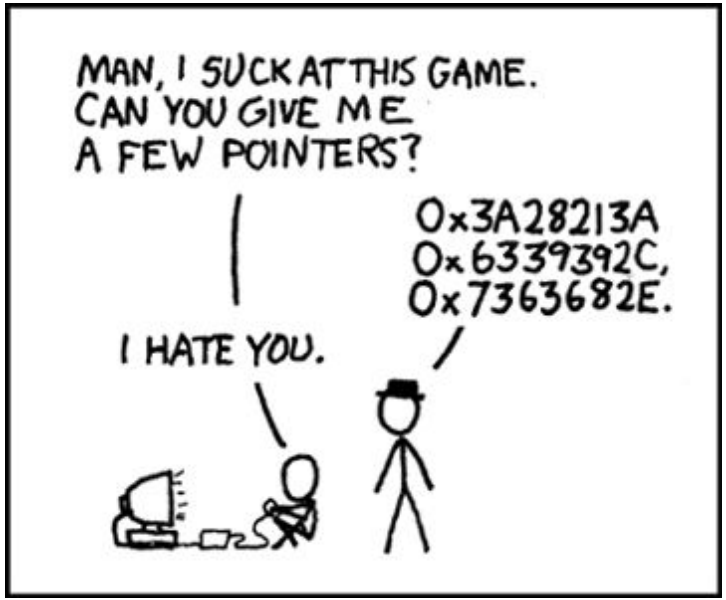


Agenda

- 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**!

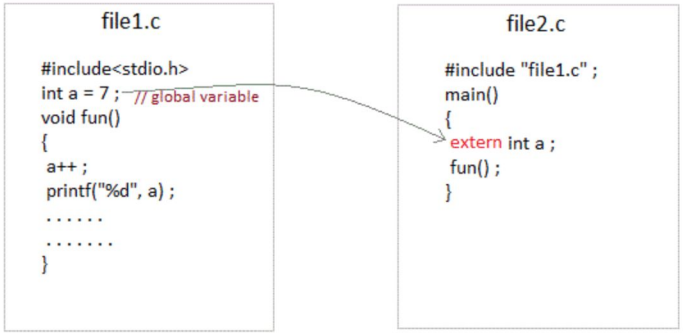
C Basics

- 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

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
  - 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 (not visible outside of object file)



global variable from one file can be used in other using **extern** keyword.

```c
#include<stdio.h>
int fun()
{
  static int count = 0;
  count++;
  return count;
}

int main()
{
  printf("%d ", fun());
  printf("%d ", fun());
  return 0;
}
```

Output:

```
1 2
```

Casting

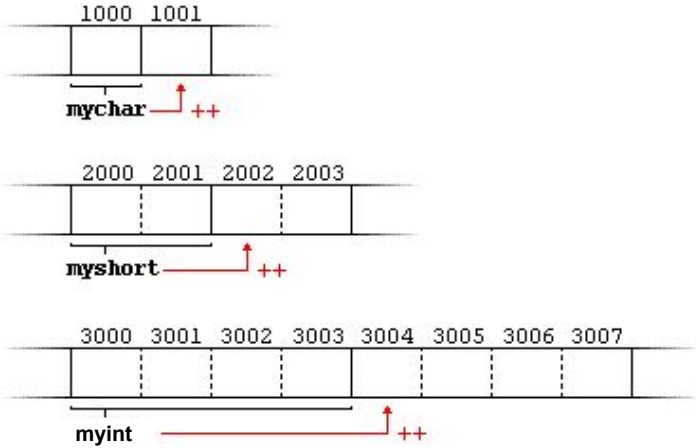
- Can convert a variable to a different type
- Rules for Casting Between Integer Types
- Integer Casting:
  - Signed <-> Unsigned: Keep Bits - Re-Interpret
  - Small -> Large: Sign-Extend MSB, preserve value
- Cautions:
  - Cast Explicitly: int x = (int) y instead of int x = y
  - Casting Down: Truncates data
  - Casting across pointer types: Dereferencing a pointer may cause undefined memory access

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)

Pointers

- 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



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*`

Pointer Arithmetic `./pointer_arith`

- The ‘pointer_arith’ program demonstrates how values of different sizes can be written to and read back from the memory.
- The examples are to show you how the ~type~ of the pointer affects arithmetic done on the pointer.
- When adding x to a pointer A (i.e. A + x), the result is really (A + x * sizeof(TYPE_OF_PTR_A)).
- Run the ‘pointer_arith’ program
  $ `./pointer_arith`

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
```

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.

Structs

`./structs`

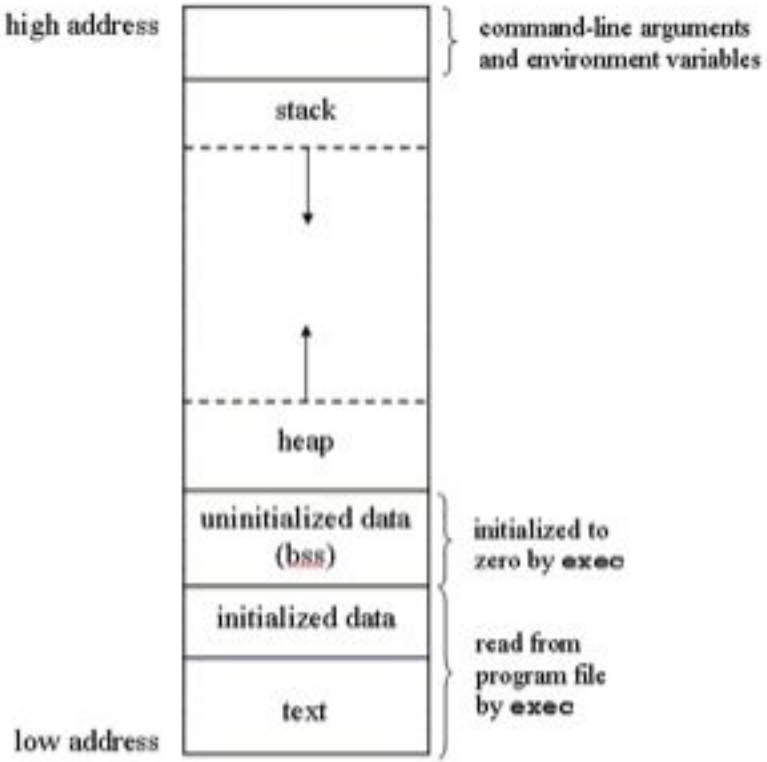
- Collection of values placed under one name in a single block of memory
  - Can put structs, arrays in other structs
- Given a struct *instance*, access the fields using the '.' operator
- Given a struct *pointer*, access the fields using the '->' operator

```
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';
```

C Program Memory Layout



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*
- Example:
  - int* a = malloc(sizeof(int));
  - //a is a pointer stored on the *stack* to a memory block within the *heap*

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:
  - number of bytes you want, can use 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)

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 or free something twice?
  - Did you initialize all your variables?
  - Did use something that you just freed?
- --leak-check=full
  - Memcheck gives details for each definitely/possibly lost memory block (where it was allocated

Debugging

GDB

GDB

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

- 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)

Additional Topics

- Headers files and header guards
- Macros
- Appendix (C libraries)

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
#include "grandfather.h"

#endif
```

```
//child.h
#include "father.h"
#include "grandfather.h"
```

Okay: child.h only includes grandfather.h once

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)
```

C Libraries

<string.h>: Common String/Array Methods

- Used heavily in shell/proxy labs
- Reminders:
  - 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>: Dealing with memory

- `void *memset (void *ptr, int val, size_t n);`
  - Starting at `ptr`, write `val` to each of `n` bytes of memory
  - Commonly used to initialize a value to all 0 bytes
  - Be careful if using on non-`char` arrays
- `void *memcpy (void *dest, void *src, size_t n);`
  - Copy `n` bytes of `src` into `dest`, returns `dest`
  - `dest` and `src` should not overlap! see `memmove()`

Whenever using these functions, a `sizeof` expression is in order, since they only deal with lengths expressed in **bytes**. For example:

```
int array[32];
memset(array, 0, sizeof(array));
memset(array, 0, 32 * sizeof(array[0]));
memset(array, 0, 32 * sizeof(int));
```

<string.h>: Copying and concatenating strings

Many of the string functions in `<string.h>` have "n" versions which read at most n bytes from `src`. They can help you avoid buffer overflows, but their behavior may not be intuitive.

- `char *strcpy (char *dest, char *src);`
  `char *strncpy (char *dest, char *src, size_t n);`
  - Copy the string `src` into `dest`, stopping once a `'\0'` character is encountered in `src`. Returns `dest`.
  - **Warning:** `strncpy` will write at most `n` bytes to `dest`, including the `'\0'`. If `src` is more than `n-1` bytes long, `n` bytes will be written, but no `'\0'` will be appended!

<string.h>: Concatenating strings

On the other hand, `strncat` has somewhat nicer semantics than `strncpy`, since it always appends a terminating `'\0'`. This is because it assumes that `dest` is a null-terminated string.

- ```
  char *strcat (char *dest, char *src);
  char *strncat (char *dest, char *src, size_t n);
  ```
  - Appends the string `src` to end of the string `dest`, stopping once a `'\0'` character is encountered in src. Returns `dest`.
  - *Make sure `dest` is large enough to contain both `dest` and `src`.*
  - `strncat` will read at most `n` bytes from `src`, and will append those bytes to `dest`, followed by a terminating `'\0'`.
  ```

<string.h>: Comparing strings

- `int strcmp(char *str1, char *str2);`
  `int strncmp (char *str1, char *str2, size_t n);`
  - Compare `str1` and `str2` using a lexicographical ordering. Strings are compared based on the ASCII value of each character, and then based on their lengths.
  - `strcmp(str1, str2) < 0` means `str1` is less than `str2`, etc.
  - `strncmp` will only consider the first `n` bytes of each string, which can be useful even if you don't care about buffer overflows.

<string.h>: Miscellaneous

- `char *strstr (char *haystack, char *needle);`
  - Returns a pointer to first occurrence of `needle` in `haystack`, or `NULL` if no occurrences were found.
- `char *strtok (char *str, char *delimiters);`
  - Destructively tokenize `str` using any of the delimiter characters provided in `delimiters`.
  - Each call returns the next token. After the first call, continue calling with `str = NULL`. Returns `NULL` if there are no more tokens.
  - Not reentrant.
- `size_t strlen (const char *str);`
  - Returns the length of the string `str`.
  - Does not include the terminating '`\0`' character.

What's wrong?

```
char *copy_string(char *in_str) {
    size_t len = strlen(in_str);
    char *out_str = malloc(len * sizeof(char));
    strcpy(out_str, in_str);
    return out_str;
}
```

What's wrong?

```
char *copy_string(char *in_str) {
    size_t len = strlen(in_str);
    char *out_str = malloc((len + 1) * sizeof(char));
    strcpy(out_str, in_str);
    return out_str;
}
```

- `malloc` should be paired with `free` if possible
- **One-byte buffer overflow**

<stdlib.h>: General Purpose Functions

- `int atoi(char *str);`
  - Parse string into integral value
  - Returns 0 on failure…
- `int abs(int n);`
  - Returns absolute value of `n`
  - See also: `long labs(long n);`
- `void exit(int status);`
  - Terminate calling process
  - Return `status` to parent process
- `void abort(void);`
  - Aborts process abnormally

<stdlib.h>: What's a `size_t`, anyway?

- Unsigned type used by library functions to represent **memory sizes**
- `ssize_t` is its signed counterpart (often used for -1)
- Machine word size: 64 bits on Shark machines
- `int` may not be able to represent size of large arrays

```
warning: comparison between signed and unsigned integer
expressions [-Wsign-compare]
   for (int i = 0; i < strlen(str); i++) {
                       ^
```

More standard library friends

`<stdbool.h>`

- `bool`

`<stdint.h>`

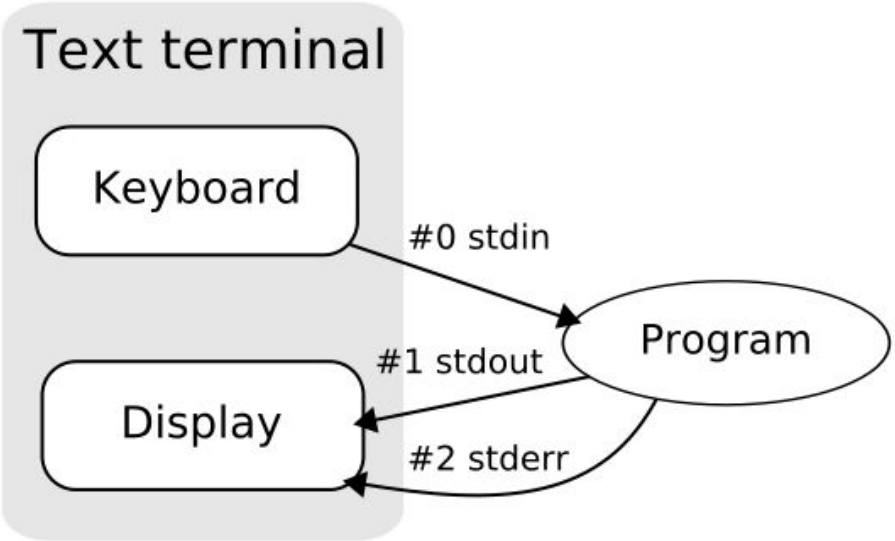
- `SIZE_MAX`, `INT_MIN`, etc

`<assert.h>`

- `void assert(scalar expression);`
  - Aborts program if `expression` evaluates as false
  - 122 wasn't completely useless!

<stdio.h>: C standard library I/O

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



<stdio.h>: File I/O

- `FILE *fopen (char *filename, char *mode);`
  - Open the file with specified filename
  - Open with specified `mode` (read, write, append)
  - Returns file object, or `NULL` on error
- `int fclose (FILE *stream);`
  - Close the file associated with `stream`
  - Returns `EOF` on error
- `char *fgets (char *str, int num, FILE *stream);`
  - Read at most `num-1` characters from `stream` into `str`
  - Stops at newline or `EOF`; appends terminating `'\0'`
  - Returns `str`, or `NULL` on error

<stdio.h>: `scanf` and friends

```
int scanf (char *format, ...);
int fscanf (FILE *stream, char *format, ...);
int sscanf (char *str, char *format, ...);
```

- Read data from `stdin`, another file, or a string
- Additional arguments are **memory locations** to read data into
- `format` describes types of values to read
- Return number of items matched, or `EOF` on failure

<stdio.h>: `printf` and friends

```
int printf (char *format, ...);
int fprintf (FILE *stream, char *format, ...);
int sprintf (char *str, char *format, ...);
int snprintf (char *str, size_t n, char *format, ...);
```

- Write data to `stdout`, a file, or a string buffer
- `format` describes types of argument values
- Returns number of characters that would be written by the string (unless truncated in the case of `snprintf`)

<stdio.h>: Format strings crash course

Placeholders

- **`%d`**: signed integer
- **`%u`**: unsigned integer
- **`%x`**: hexadecimal
- **`%f`**: floating-point
- **`%s`**: string (char *)
- **`%c`**: character
- **`%p`**: pointer address

Size specifiers

Used to change the size of an existing placeholder.

- **`h`**: `short`
- **`l`**: `long`
- **`ll`**: `long long`
- **`z`**: `size_t`

For example, consider these modified placeholders:

- **`%ld`** for `long`
- **`%lf`** for `double`
- **`%zu`** for `size_t`

What's wrong?

```
int parse_int(char *str) {
    int n;
    sscanf(str, "%d", n);
    return n;
}
```

```
void echo(void) {
    char buf[16];
    scanf("%s", buf);
    printf(buf);
}
```

What's wrong?

```
int parse_int(char *str) {
    int n;
    sscanf(str, "%d", &n);
    return n;
}
```

- Don't forget to pass pointers to `scanf`, not uninitialized values!
- At least checking return value of `scanf` tells you if parsing failed – which you can't do with `atoi`

```
void echo(void) {
    char buf[16];
    scanf("%15s", buf);
    printf("%s", buf);
}
```

- Avoid using `scanf` to read strings: buffer overflows.
- Need room for null terminator
- Never pass a non-constant string as the format string for `printf`!

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)
    ```

Style

- Documentation
  - file header, function header, comments
- Variable Names & Magic Numbers
  - `new_cache_size` is good, not `new_cacheSize` or `size`
  - Use `#define CACHESIZE 128`
- Modularity
  - helper functions
- Error Checking
  - malloc, library functions...
- Memory & File Handling
  - free memory, close files
- Check style guide for detailed information