Getopt and Debugging
(and some C technicalities)
What does “*p.q” mean in C?

- A) Dereference pointer p, then access field q
- B) Dereference field q of variable p
- C) Neither of the above
C technicalities

- **Precedence** is the order in which operators are applied
  - Example: `2+3*4` means `2+(3*4)` not `(2+3)*4`
  - Multiplication (*) is has **higher precedence** than addition (+)
- In C, some precedence relationships are non-intuitive
  - Member operator (.) is higher than dereference (*)
    - `*ptr.foo` means `*(ptr.foo)` not `(*ptr).foo`
    - This is partially why “->” is such a useful operator
  - Some unary operators (e.g., ++) are higher than dereference (*)
    - `*ptr++` means `*(ptr++)` not `(*ptr)++`
    - Use the latter to apply the operator through a dereference

**Full precedence list:**
C technicalities

• Assuming integers require 4 bytes each and pointers require 8 bytes each, how many bytes will be allocated by the following C code?

```c
int c[4];
int *d = c;
```
Array names are **aliases**, not pointers

```c
int c[4];  // c is not (strictly speaking) a pointer
int *d = c;  // d is a pointer
```

- Practically, they behave like constant pointers
- Except that `&c == &c[0]` (which is not true of `d`)
  - And `sizeof(c)` is the size (in bytes) of the whole array

```
   d  c
    0   |
```

Zero-length arrays are (generally) not allowed

```c
int a[0];  // compiler warning
int b[];  // same as "int b[1];"
```
Which of the following are safe in C?

- A) int a[] = {1, 2, 3, 4};
- B) int b[4] = {1, 2, 3, 4};
- C) int *c = {1, 2, 3, 4};
- D) char d[] = "hello";
- E) char e[6] = "hello";
- F) char *f = "hello";
C technicalities

- Initializing arrays w/ pointer declaration
  - Generally results in a buffer overrun (compiler warning)
    
    ```c
    int *a = {1, 2, 3, 4}  // buffer overrun!
    ```
  - Special case for C strings:
    
    ```c
    char *s = "hello";    // ok, but read-only
    ```
  - String "hello" is stored in a **read-only** section of static data
    - Regardless of whether `s` is local or global
  - Pointer `s` is initialized to point to "hello"
  - Read-only strings may be re-used by other portions of code
What does “void*” mean in C?

- A) Dereference variable void
- B) Increment variable void
- C) Address of variable void
- D) Generic value type
- E) Generic pointer type
The type "void *" denotes a generic pointer
- No information about what it is pointing to
- Must cast it to a specific pointer type before using it
  - E.g., (int*)ptr
- This can be very dangerous if we're wrong
- Use it sparingly
  - E.g., return value of malloc() when we know the type

```
double *temp_data = (double*)malloc(sizeof(double) * ndays);
```
C technicalities

- T/F: `malloc()` always returns a pointer to heap memory
C technicalities

- **malloc() can fail**
  - Potential cause: memory leak fills up all available memory
  - If malloc fails, it will return NULL
  - This will cause a segfault when you try to use the pointer
  - You must check for this every time you call malloc
  - Find a graceful and informative way to fail
    - Printing a message and aborting the program is fine in this course

```c
double *temp_data = (double*)malloc(sizeof(double) * ndays);
if (temp_data == NULL) {
    fprintf(stderr, "ERROR: Cannot allocate storage for temperature data\n");
    exit(EXIT_FAILURE);
}
<code that uses temp_data>
```
C technicalities

- T/F: If `malloc()` succeeds, it will clear (i.e., set to zero) the allocated memory before returning a pointer.
C technicalities

- Memory is uninitialized by default
  - You should manually initialize values to useful defaults if you need to rely on them
  - One easy way to do this: `memset()`
    - Set all bytes in a region of memory to a given character
    - Often used to "zero out" (set to 0) a structure
  - You could also copy from another region with `memcpy()`
    - Inappropriate for strings because it does not append a null terminator
  - If on the heap, you can initialize and allocate with `calloc()`
    - Alternative to `malloc` that will zero out all allocated bytes
    - Slower than `malloc`!
What does the following code do?

```c
printf("%s", NULL);
```

- A) Segfault
- B) Print “(null)"
- C) Print “0”
- D) Erase the entire hard drive
- E) There is not enough information to tell
C technicalities

• The C standard does not specify **everything** about how C should be compiled
  - E.g., integer type sizes
  - This allows compiler writers to optimize more highly for a particular architecture (e.g., struct field alignment)

• Printing a null string pointer is **undefined behavior**:

  7.1.4 Use of library functions

  Each of the following statements applies unless explicitly stated otherwise in the detailed descriptions that follow: **If an argument to a function has an invalid value (such as a value outside the domain of the function, or a pointer outside the address space of the program, or a null pointer, or a pointer to non-modifiable storage when the corresponding parameter is not const-qualified) or a type (after promotion) not expected by a function with variable number of arguments, the behavior is undefined.** If a function argument is

  [URL](http://www.open-std.org/jtc1/sc22/WG14/www/docs/n1256.pdf)
Thought exercise

- Write a program that takes command-line parameters according to the following usage text:

Usage: ./args [options] <filename>

Valid options:
- a        Print an 'A'
- b        Print a 'B'

Valid commands:
- ./args file.txt
- ./args -a file.txt
- ./args -a -b file.txt
- ./args -ab file.txt

Invalid commands:
- ./args
- ./args -a
- ./args -c file.txt

What could go wrong?

```c
int main (int argc, char **argv)
{
    // parse options
    for (int i = 0; i < argc; i++) {
        switch (argv[i][1]) {
            case 'a':    a_flag = true;    break;
            case 'b':    b_flag = true;    break;
            default:     report_err();     break;
        }
    }

    // get filename
    char *fn = argv[argc-1];
}
```
Thought exercise

- Write a program that takes command-line parameters according to the following usage text:

Usage: ./args [options] <filename>

Valid options:
- a     Print an 'A'
- b     Print a 'B'

Valid commands:
./args file.txt
./args -a file.txt
./args -a -b file.txt
./args -ab file.txt

Invalid commands:
./args
./args -a
./args -c file.txt

What if there's no filename at the end?
What if there are two filenames?
How to handle parameters (e.g., “-n 5”)?
How to handle combined flags (e.g., “-ab”)?
What if there is no argv[i][1]?

```c
int main (int argc, char **argv)
{
    // parse options
    for (int i = 0; i < argc; i++) {
        switch (argv[i][1]) {
            case 'a':    a_flag = true;    break;
            case 'b':    b_flag = true;    break;
            default:     report_err();     break;
        }
    }

    // get filename
    char *fn = argv[argc-1];
}
```
There’s a better way: `getopt()` and `getopt_long()`

- The latter enables longer options (e.g., “--help”)
  - Useful (and mostly standard now), but we won’t require it in this course
- Basic idea: call `getopt()` repeatedly
  - It will return each of the flags individually even if they are grouped or out of order
  - Returns -1 when done
- Need to pass an **optstring** (list of valid flags as a string)
  - E.g., "abc" indicates that "-a", "-b", and "-c" are valid (any any any combinations)
  - Use a colon to indicate a flag that takes a parameter (e.g., "n:" to allow “-n 4”)

**Global variables**

- `optarg`: pointer to string parameter for flags that take them
- `optind`: index of next flag (use to check for extra arguments at the end!)
```
#include <getopt.h>

int main (int argc, char **argv)
{
    // parse options
    int opt;
    while ((opt = getopt(argc, argv, "ab")) != -1) {
        switch (opt) {
            case 'a':   a_flag = true;     break;
            case 'b':   b_flag = true;     break;
            default:    report_err();      break;
        }
    }

    // check for and get filename
    if (optind != argc-1) {
        report_err();
        return 1;
    }

    char *fn = argv[optind];
}
```

Much more robust!
An Unfortunately-Common Scenario

• “It’s 11pm and I just wrote 200 lines of code!”
  – “All the functions are there.”
  – “I’m done now, right?”

• “I should probably run some tests”
  – “Just to be sure…”

• “@#$%, it’s not working!”
  – “But it looks like it should work…”
Software testing

- **Test-Driven Development**: write the tests first!
  - Popular software engineering technique
  - Describe the behavior of correct code
    - Write a series of test cases to test individual features
    - Make sure you consider edge/corner cases!
    - Save these tests in a test suite that is easy to run
  - THEN write the code
    - Now you have some indication of when you're "done"
    - Work incrementally and deliberately with regular testing
    - Write more tests as you go if new cases arise

 Project tip: don't rely on the provided test suite—devise your own tests!
Debugging

- A **software defect** is an error in code that produces incorrect or undesired behavior
  - Colloquially called “bugs”
  - Many types: syntax, logic, integration, concurrency
  - Many causes: typos, incorrect code, design flaws, ambiguous spec
- Fundamental issue: mismatches between user’s expectations and machine’s behavior
  - Proximate cause (symptom) vs. root cause (defect)
  - **Debugging** is the process of starting from the former and working towards discovering the latter
  - Basically: the process of continually asking “why is this happening?”
  - One of the most important practical skills in programming
1) Understand the system
2) Make it fail
3) Quit guessing and look
4) Divide and conquer
5) Change one thing at a time
6) Keep an audit trail
7) Check the obvious
8) Get a fresh view
9) If you didn’t fix it, it isn’t fixed
Debugging

- The nature of C makes it possible to explore the kinds of things we want to explore in CS 261
  - However, the power comes at a cost: it is easier to make a mistake!
- Debugging in C will be harder than it was in Java
  - The failure point (e.g., segfault location) is usually not where the bug is!
- Main question: **Where is the earliest point at which the program diverges from your expectations?**
  - Use debug output or a debugger tool to help
- Other useful questions:
  - What *data type(s)* are you dealing with?
  - Which *memory regions* are involved?
  - What is the *size* and *lifetime* of the variables?
A debugger (e.g., gdb) is a program that allows you to examine another program while it is running
- Execute the program step-by-step
- Examine the contents of memory at any point
- Add breakpoints and watchpoints
- Reverse execution to find the root cause

Debuggers are more useful with extra information from the compiler
- In gcc, compile with the “-g” option to enable this
- It’s also useful to disable optimization (“-00”)
GDB quick reference

gdb ./program - launch GDB on program (include “--tui” for “graphical” interface)
run <args> - begin/restart execution
start <args> - begin/restart execution and pause at main
break <func> - set a breakpoint ("pause here") at the beginning of a function
break <file>:<line> - set a breakpoint at a specific line of code
watch <loc> - pause when a specific variable or memory location changes
continue - resume execution (until a breakpoint, watchpoint, or segfault)
next - run one line of code then pause (skips over function calls)
step - run one line then pause (descends into functions)
print <expr> - print current value of a variable or expression
print /x <expr> - print current value of a variable or expression in hex
ptype <expr> - print the type of a variable or expression
backtrace - print stack trace (list of active functions on the stack)
   (up and down to cycle through function call sites)
quit - exit GDB

most of these can be abbreviated to the first letter (e.g., ‘p’ for ‘print’)
(see also CS:APP 3.10.2 and Fig. 3.39)
Valgrind

- **Valgrind** is a tool framework for memory analysis
  - Most useful tool (and the default) is **memcheck**, which searches for memory leaks, uninitialized variables, and other memory problems
  - We use memcheck to check for memory leaks on projects
  - You can also use it to help find memory bugs
  - To run: `valgrind <exe-name> <exe-options>`