CS 261
Fall 2022

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C Miscellaneous Topics

(C technicalities, getopt, and debugging)

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:

`http://en.cppreference.com/w/c/language/operator_precedence`

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?

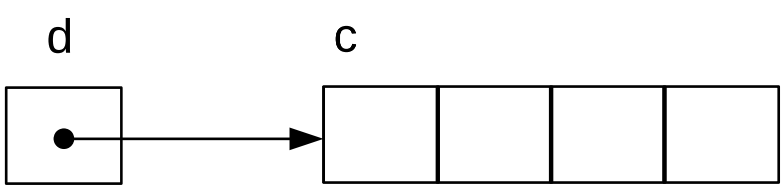
```
int c[4];
int *d = c;
```

C technicalities

- Array names are **aliases**, not pointers

```
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



- Zero-length arrays are (generally) not allowed

```
int a[0];   // compiler warning
int b[];    // same as "int b[1];"
```

C technicalities

- 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)

```
int *a = {1, 2, 3, 4}  // buffer overrun!
```

  - Special case for C strings:

```
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

C technicalities

- 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

C technicalities

- 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

```
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`!

C technicalities

- What does the following code do?

```
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

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
```

```
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];
}
```

What could go wrong?

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
```

```
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];
}
```

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]`?

Getopt

- 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 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!)

Getopt example

```
#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();
    }
    char *fn = argv[optind];
}
```

Much more robust!

Getopt example

```
#include <getopt.h>

int main (int argc, char **argv)
{
    bool a_flag = false, b_flag = false;

    // 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;    // invalid option
        }
    }

    // check for presence of filename (i.e., next index should be last index)
    if (optind != argc-1) {
        report_err();
    }

    // save filename
    char *fn = argv[optind];

    // TODO: open fn

    if (a_flag) {
        // do something
    }
    if (b_flag) {
        // do something else
    }
}
```

(closer to P1-P4 code)

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

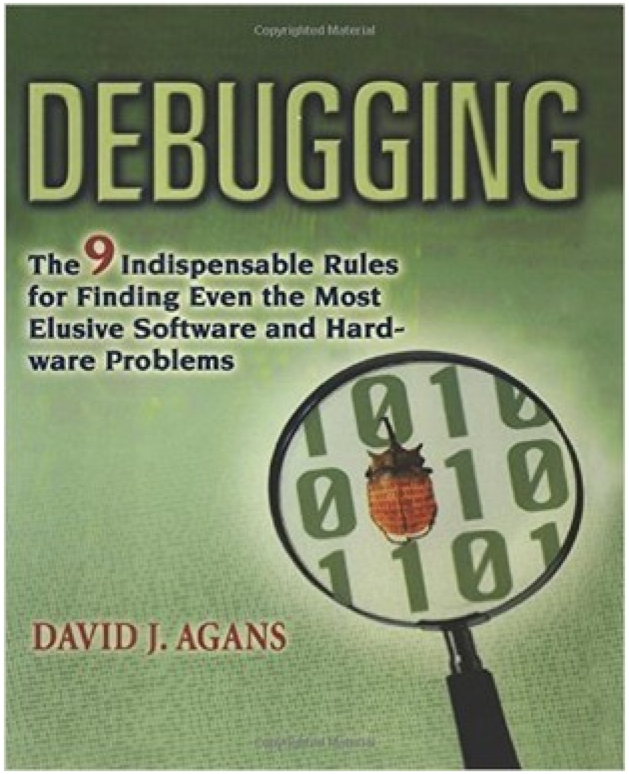
- Test-Driven Development: write the tests first!
  - Popular software engineering technique
  - Describe the behavior of correct code
    - Write a series of test cases to test individual features
    - Make sure you consider edge/corner cases!
    - Save these tests in a test suite that is easy to 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

"9 Rules of Debugging"



Recommended book
ISBN-13: 978-0814474570

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**

Author: David Agans

`www.debuggingrules.com`

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?

Debuggers

- 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 ("`-O0`")

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>`