LECTURE NOTES IN CIS300

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SECTION 2: C/C++ PROGRAMMING

REFERENCES

- "Unix Programming Tools", [link]
- Computer Systems: A Programmer's Perspective, Randal E. Bryant and David R. O'Hallaron, Chapter 1, [online pdf]

HELLOWORLD C

```c
#include <stdio.h> //preprocessor
int y = 3; //global var. (def. & init.)
//extern int y; //global var. (dec.)
int main() //function (def.)
{
    int x = 0; //local var. (def. & init.), literal,
    printf("helloworld: y = %d\n",y); //function (invocation)
    return 0;
}
```

- printf: format string
- header files

LIFE OF A C CONSTRUCT

	variable	function
declare	`extern int x;`	`void foo();`
define	`int x;`	`void foo(){}`
initialize	`int x=6;`	
reference	`y=x;x=1;`	`foo();` (invocation)
destroy		

COMPILATION & EXECUTION: BASICS

- GCC: GNU Compilation Collection
- In your terminal, run the following commands

```
gcc hello.c
./a.out
```

EXERCISES

- Write a C program that prints out your name. Compile and execute it in Ubuntu. Submit the C program to BB.
- Write a C program that computes the sum of 1,2,3,...,956. Compile and execute the program in Ubuntu. Submit the C program to BB.

GCC

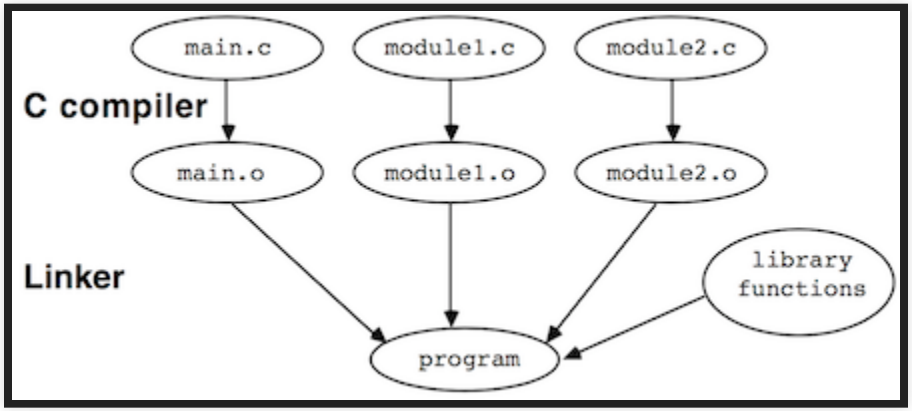
COMPILATION (1)

- Two steps of compilation:
  - *compiling*: text `.c` file to relocatable `.o` (object) file
  - *linking*: multiple relocatable `.o` files to one executable `.o` file
    - *symbol*: reference to link construct (declaration) in one `.o` file to construct (definition) in another `.o` file

COMPILATION (2)

```
gcc hello.c -o a.out
gcc -S hello.c -o hello.s #compiler
gcc -c hello.s -o hello.o #assembler
gcc hello.o -o a.out #linker
```

- compilation system
  - tools: *gcc/gdb* for compiling and debugging
  1. **preprocessor**: from source file to source
  2. **compiler**: from source to assembly file
     - *assembly file*
  3. **assembler**: from assembly file to relocatable object file
  4. **linker**: from multiple objects to an executable object


main.c
module1.c
module2.c
C compiler
main.o
module1.o
module2.o
Linker
library
functions
program

Linker

COMPILING MULTIPLE C PROGRAMS

In `file1.c`:

```c
#include <stdio.h>
extern void foo();
int main(){
    printf("main();\n");
    foo();
}
```

In `file2.c`:

```c
#include <stdio.h>
void foo(){
    printf("foo();\n");
}
```

COMPILING MULTIPLE C PROGRAMS (2)

```
gcc file1.c file2.c
# try this?
gcc file1.c
gcc file2.c
```

COMPILING MULTIPLE C PROGRAMS (3)

```
gcc -c file1.c # compiler & assembler
gcc -c file2.c # compiler & assembler
gcc file1.o file2.o # linker
```

Or

```
gcc -S file1.c # compiler
gcc -c file1.s # assembler
gcc -S file2.c # compiler
gcc -c file2.s # assembler
gcc file1.o file2.o # linker
```

LINK LIBRARY FILES

```
gcc -S file1.c # compiler
gcc -c file1.s # assembler
gcc file1.o file2.o # linker
```

```
mv file2.o ../libfile2.a
gcc file1.o ../libfile2.a # linker
gcc file1.o -L.. file2.o # linker
gcc file1.c -L.. file2.o # linker
```

- Gcc flag: `-Ldir -lmylib` for library to link

INCLUD HEADER FILE

In `header1.h`:

```
extern foo();
```

In `file11.c`:

```
#include <stdio.h>
#include "header1.h"
int main(){
    printf("main();\n");
    foo();
}
```

```
gcc file11.c file2.c
```

INCLUDE HEADER FILE (2)

Header file in another directory

```
mv header1.h ..
#will this work?
gcc file11.c file2.c
gcc -I .. file11.c file2.c
```

- Gcc flag: `-I dir`

GCC FLAGS (SUMMARY)

- `-c` for compile, `-o` for output
- `-Ldir -lmylib` for linking a library
  - search library for unsolved symbols (functions, global variables) when linking
- `-I` for `#include`
  - header file (storing declarations)
- `-Wall`, w for warning
- `-g` for debug (later): `gcc -g file1.c file2.c`
- ref [link]

EXERCISE

- Write two C files:
  - `filea.c` defines functions `main()` and `bar()`
  - `fileb.c` defines function `foo()`
  - function `main()` calls `foo()`
  - function `foo()` calls `bar()`
  - Compile your program.
  - Submit the program and commands to BB.

MAKE AND MAKEFILE

DOWNLOAD COURSE REPO.

To download course repository, type the following commands

```
sudo apt-get update
sudo apt-get upgrade
sudo apt-get install git
git clone https://github.com/SUCourses/cis300-18spring.git
```

MAKEFILE: DEPENDENCY RULES

- `make` is a tool for project management in shell
- `Makefile` is the configuration file that tells the `make` tool what to do
- A `Makefile` is a series of dependency rules
- Each dep. rule is a IFTTT clause (if-this-then-that)

```
target: files/objects
(tab)commands
```

There is a **tab** before the commands

HELLOWORLD `MAKEFILE`

In `Makefile` (All files are under `demos/mar7` dir.)

```
all:
    gcc file1.c file2.c
```

To run it, in shell terminal

```
make
```

(Try change `file.c`, and `make` it again).

MAKEFILE OF MULTIPLE RULES

```
c:
    gcc file1.c file2.c

exec: c
    ./a.out

clean:
    rm *.o *.out
```

Note there are empty lines btwn. rules.

USE `MAKEFILE` TO LINK (1)

Recall how to run compiler, assembler and linker

```
gcc -c file1.c # compiler & assembler
gcc -c file2.c # compiler & assembler
gcc file1.o file2.o # linker
```

USE `MAKEFILE` TO LINK (2)

A `Makefile` that does them separately

```
link: file1.o file2.o
    gcc file1.o file2.o

file1.o: file1.c
    gcc -c file1.c

file2.o: file2.c
    gcc -c file2.c
```

```
make
make
```

USE `MAKEFILE` TO LINK (3)

Use default rule to compile individual C file

```
link: file1.o file2.o
    @gcc file1.o file2.o
```

```
make
make
```

- `@` used to hide the command in printout.

MAKEFILE: USING VARIABLES

```
SRCS = file1.c file2.c
OBJS = $(SRCS:.c=.o)
CFLAGS = -g -Iheaders
#LDFLAGS = -L. -lxxx

link: $(OBJS)
    $(CC) $(LDFLAGS) $(OBJS)
```

`MAKEFILE`: USING VARIABLES (2)

- A Makefile variable is a text string
- There're standard variables
  - `CC` is the compiler
  - `OBJS = $(SRCS:.c=.o)`:
    - This incantation says that the object files have the same name as the .c files, but with .o extension
  - `LDFLAGS` library search path (`-L`)
  - `CFLAGS` default compile flags

EXERCISE

1. Write a `Makefile` such that `make` always clean .o files, recompiles all .c files and executes the new .o file.
2. Write a `Makefile` such that `make link` will compile a `file.c` file against a library file `libxxx.a`

GDB

REFERENCES

- "Reviewing gcc, make, gdb, and Linux Editors", [pdf]
- "Unix Programming Tools", [link]

A BUGGY C PROGRAM

```c
#include<stdio.h> //printf
int array_stack[] = {0,1,2};
int main(){
  int sum; // local variable
  for(int i=0; i<=3; i++){
    sum += array_stack[i];
  }
  printf("sum = %d\n", sum);
  return 0;
}
```

USE GDB TO FIND BUG

- Installing gdb
  - on MacOS: [youtu.be/Vj33vsrDkE80]
  - on Ubuntu: `sudo apt-get install gdb`
- Compile: `gcc -g`
- Run gdb: `gdb a.out`

GDB COMMAND: CONTROL EXECUTION

- CPU executes a C program statement by statement
- Breakpoint: tell where the CPU should stop/pause execution
  - `break/b file:n|fn|file:fn`: breakpoint can be file:line number, function name or file:function name.
  - `disable/enable/delete i`: i is the index of breakpoint
- Stepping: tell CPU to resume the execution
  - `run/r`: run
  - `next/n`: next statement (step over a function call)
  - `continue/c`: continue till breakpoint

GDB COMMAND: EXAMINE RUNTIME

- Examine runtime data
  - `print v`/`p v`: print variable `v`
- Examine code (with `gcc -g`)
  - `list`/`l`
- Examine execution environment: e.g. stack (later)

GDB COMMANDS

functionality	commands
breakpoints	`b`,`disable/enable/delete breakpoi`
stepping	`r`,`s`,`n`,`c`,`finish`,`return`
examine_data	`p/i v`,`display/undisplay`,`watch`,`set`
examine_code	`list`
examine_stack	`bt`,`where`,`info`,`up/down`,`frame`
misc.	`editmode vi`,`b fn if expression`,`h` disassembler, `shell cmd`

DEMO

- Debug the following program using gdb

```c
#include<stdio.h> //printf
int array_stack[] = {0,1,2};
int main(){
  int sum; // local variable
  for(int i=0; i<=3; i++){
    sum += array_stack[i];
  }
  printf("sum = %d\n", sum);
  return 0;
}
```

EXERCISE

- Exercise: Debug the following program using gdb, upload the correct program to BB.

```c
#include<stdio.h>
int main() {
    int x = 5;
    int y = 3;
    int z = x - y;
    int a = x * y;
    int b = a - 7*z;
    b--;
    int c = z + y;
    int d = c / b;
    int e = a + 12;
    int f = e - b;
    printf("%d\n",f);
}
```

POINTER IN C

REFERENCES

- Pointer Basics: [http://cslibrary.stanford.edu/106/]
- Point fun with Binky: [http://cslibrary.stanford.edu/104/]

C POINTER

- A C pointer is a C variable that stores the reference to something.
  - "something", called pointee, is usually another variable.
- In the figure below, a pointer variable named `x` stores a reference to a "pointee" variable of value `42`.

pointer pointee

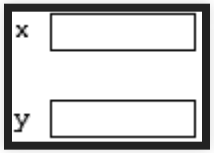
POINTER OPERATIONS

- Definition/initialization: `int *p1 = p2;`
- Assignment: `p1 = p2;`
- Dereference: `*p`
- Get reference of: `& a`
  - get the *address* (memory location) of variable `a`

```c
#include<stdio.h>
int main(){
    int a = 10;
    int * p = & a;
    int b = *p;
    printf("a=%d,b=%d,*p=%d,p=%p\n",a,b,*p,p);
}
```

BINKY'S CODE (1)

```
void main() {
    int*    x;  // Allocate the pointers x and y
    int*    y;  // (but not the pointees)
}
```



Allocate pointer

BINKY'S CODE (2)

```
void main() {
    int*    x;  // Allocate the pointers x and y
    int*    y;  // (but not the pointees)
    x = malloc(sizeof(int));    // Allocate an int pointee,
                                // and set x to point to it
}
```

Allocate pointee

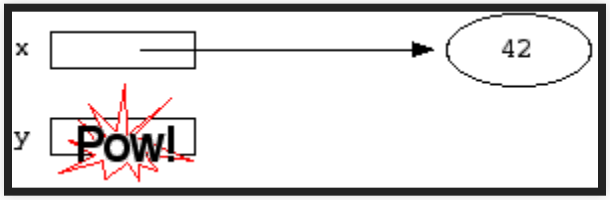
BINKY'S CODE (3)

```
void main() {
    int*    x;  // Allocate the pointers x and y
    int*    y;  // (but not the pointees)
    x = malloc(sizeof(int));    // Allocate an int pointee,
                                // and set x to point to it
    *x = 42;    // Dereference x to store 42 in its pointee
}
```

Dereference pointer

BINKY'S CODE (4)

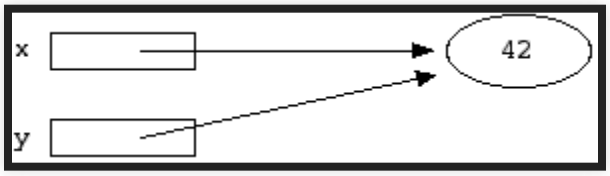
```
void main() {
    int*    x;  // Allocate the pointers x and y
    int*    y;  // (but not the pointees)
    x = malloc(sizeof(int));    // Allocate an int pointee,
                                // and set x to point to it
    *x = 42;    // Dereference x to store 42 in its pointee
    *y = 13;    // CRASH -- y does not have a pointee yet
}
```



Dereference failure

BINKY'S CODE (5)

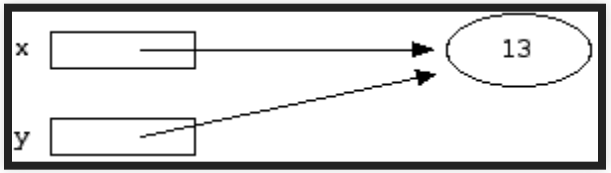
```
void main() {
    int*    x;  // Allocate the pointers x and y
    int*    y;  // (but not the pointees)
    x = malloc(sizeof(int));    // Allocate an int pointee,
                                // and set x to point to it
    *x = 42;    // Dereference x to store 42 in its pointee
    *y = 13;    // CRASH -- y does not have a pointee yet
    y = x;      // Pointer assignment sets y to point to x's pointee
}
```



Pointer assignment

BINKY'S CODE (6)

```
void main() {
    int*    x;  // Allocate the pointers x and y
    int*    y;  // (but not the pointees)
    x = malloc(sizeof(int));    // Allocate an int pointee,
                                // and set x to point to it
    *x = 42;    // Dereference x to store 42 in its pointee
    *y = 13;    // CRASH -- y does not have a pointee yet
    y = x;      // Pointer assignment sets y to point to x's pointee
    *y = 13;    // Dereference y to store 13 in its (shared) pointee
}
```



Deference pointer

LIFE CYCLE OF A C POINTER

	pointer	variable	fur
declare	`extern int * p`	`extern int x`	vo
define	`int *p;`	`int x`	vo
initialize	`int *p=&a;`	`int x=6`	
	`int*q=malloc(7)`		
(de)reference	`*p=x;x=*p`	`y=x`	fo
destroy	`delete p`		

EXERCISE

- Do the following to complete the code snippet at the bottom. Then compile and execute your program. Submit the completed program to BB.
  1. define two pointers `p1` and `p2`, both pointing to variable `x`.
  2. Use `p1` to update `x`'s value to `5`.
  3. Then use `p2` to read the value of variable `x` and `printf` it on terminal.

```c
#include<stdio.h>
int main(){
    int x = 4;
    // To complete the program below:


}
```

C POINTER AND DATA TYPES

DATA TYPE

- C is a typed language
- Data type in C determines:
  - How much space to allocate for storing a variable in memory
  - How to interpret bit-string stored in the memory
  - How to carry out the arithmetics on primitive types

PRIMITIVE TYPES

- types: signed, unsigned, long long, float, char

type	signed	unsigned	short	long long	float	char
`sizeof()`	4	4	2	8	4	1

- unsigned: a 32-bit unsigned integer, value from 0 to $2^{32} - 1$.
- signed: a 32-bit signed integer, value from -2^{31} to $2^{31} - 1$.
  - first bit determines whether negative
- Typecasting: convert the type of a variable.
  - `int x = 1; double f = (double) x;`

DEMO 1: TYPE INTEPRETATION

```c
#include<stdio.h>
int main(){
  unsigned int u = 2147483649;
  int v = (int) u;
  printf("unsigned vs signed: %ud,%d\n",u,v);

  int i=1;
  float f = (float) i;
  printf("float vs int: %f,%d\n",f/3,i/3);
}
```

DEMO 2: DATA TYPE SIZE

```c
#include<stdio.h>
int main(){
    signed int a;
  unsigned int b;
  short c;
  long long d;
  float e;
  char f;
  printf("signed int: %lu\n", sizeof(a));
  printf("unsigned int: %lu\n", sizeof(b));
  printf("short: %lu\n", sizeof(c));
  printf("long long: %lu\n", sizeof(d));
  printf("float: %lu\n", sizeof(e));
  printf("char: %lu\n", sizeof(f));
  return 0;
}
```

POINTER AND ARRAY

- A array in C stores a list of elements in adjacent memory locations.
- Use pointer to access array element
  - Pointer type: `char *`, `int *`
  - Pointer arithmetic:
    - `int * p = array; p += 1;`
    - `int pp = array; pp += sizeof(int);`

```c
#include<stdio.h>
int main(){
    int a[] = {2,1,0};
    int *b = a; // b points to the first element in a
    unsigned long c = (unsigned long)a;//long
    for (int i=0; i<3; i++){
        printf("%d,%d,%d,%d,%d\n",a[i],*(b+i),*(a+i),b[i],*((int *)(c
    }
}
```

FUNCTION POINTER

- Two classes of pointer
- Data pointer: pointer to variable, array
- Code pointer: function pointer

```c
#include <stdio.h>  /* for printf */
// https://en.wikipedia.org/wiki/Function_pointer
double cm_to_inches(double cm) {
  return cm / 2.54;
}
int main(void) {
  double (*func1)(double) = cm_to_inches;
  printf("%f\n", func1(15.0));
  return 0;
}
```

EXERCISE

1. Write a C program that defines function `void foo(void)` and `int bar(long x)`. Call these two functions through function pointers. Upload your program to BB.
2. Complete the following program that scans the array using index `long_index`. Upload your program to BB.

```c
#include<stdio.h>
int main(){
    int a[] = {7,9,6};
    unsigned long long_index = (unsigned long)a;
    for(int i=0; i<3; i++){
        printf("%d,",*(int *)(long_index));
        long_index += XXX;// fill out XXX
    }
}
```

FILE I/O

REFERENCES

- "Advance Programming in the Unix Environment" (APUE), Chapter 3 [link]

INTRODUCTION

- Five functions: `open`, `read`, `write`, `lseek`, `close`
- They are unbuffered IO in the sense that each call (`read`) invokes a syscall. - Unbuffered IO functions are not ISO C, but part of POSIX.1.
- Atomic functions over shared resources.

FILE DESCRIPTORS

- All open files are referred to by file descriptors.
- A file descriptor is a non-negative integer.
- FD is returned by `open` or `creat`, and is used as argument to `read` or `write`.
- 0 is FD for stdin, 1 is the FD for stdout, 2 is FD of stderr.

OPEN

Open a file

```
#include <fcntl.h>
int open(const char * pathname, int oflag, ...);
//returns: file descriptor if OK, -1 on error
```

- `oflag` takes one of three mandatory values and OR with optional values.
  - mandatory: `O_RDONLY`, `O_WRONLY`, `O_RDWR`
  - optional:
    - `O_CREAT`: Create a file if it doesn't exist
    - `O_TRUNC`: Truncate a file to zero if it exists and if it is opened for write-only or read-write
- the file descriptor returned is the lowest-numbered unused descriptor.

CREAT

Create a file

```c
#include <fcntl.h>
int creat(const char * pathname, mode_t mode);
//returns: file descriptor opened for write-only if OK, -1 on error
//equiv. to
open(pathname, O_WRONLY | O_CREAT | O_TRUNC, mode);
```

CLOSE

Close a file

```c
#include <unistd.h>
int close(int fd);
//return: 0 if OK, -1 on error
```

LSEEK

- Every open file has a "current file offset"
- `Read` and `write` starts at the offset and cause it to increment by the number of bytes read/written.

```
#include <unistd.h>
off_t lseek(int fd, off_t offset, int whence);
//Returns: new file offset if OK, 1 on error
```

- whence:
  - `SEEK_SET`: set offset to be `offset` plus the beginning of the file.
  - `SEEK_CUR`: set offset to `offset` plus the current value.
  - `SEEK_END`: set offset to be file size plus `offset`

READ AND WRITE

```
#include <unistd.h>
ssize_t read(int fd, void *buf, size_t nbytes);
Returns: number of bytes read, 0 if end of file, 1 on error
```

- It requests to read `nbytes` bytes from `fd` and stores them in `buf`.
- If the read is successful, it returns the actual number of bytes read.
- If the end of a file is reached, it returns 0

```
#include <unistd.h>
ssize_t write(int fd, const void *buf, size_t nbytes);
Returns: number of bytes written if OK, 1 on error
```

- It requests to write `nbytes` bytes to `fd` from `buf`.

SEEKABLE FILES

```c
#include<unistd.h>
#include<stdio.h>
#include<stdlib.h>

int main(void){
    if (lseek(STDIN_FILENO, 0, SEEK_CUR) == -1)
        printf("cannot seek\n");
    else
        printf("seek OK\n");
    exit(0);
}
```

```
> ./a.out
> ./a.out < file #redirection is seekable
> cat file | ./a.out #pipe file is not seekable
```

CREAT FILE WITH A HOLE

- header.h

```
#include<stdio.h>
#include<unistd.h> //lseek, STDIN_FILENO
#include<stdlib.h>
#include <fcntl.h>
#define FILE_MODE (S_IRUSR | S_IWUSR | S_IRGRP | S_IROTH)
void err_sys(const char* x) {
    perror(x);
    exit(1);
}
```

```c
#include "header.h"
char buf1[] = "abcdefghij";
char buf2[] = "ABCDEFGHIJ";
int main(void){
 int fd;
 if ((fd = creat("file.hole", FILE_MODE)) < 0)
  err_sys("creat error");
 if (write(fd, buf1, 10) != 10)
  err_sys("buf1 write error");/* offset now = 10 */
 if (lseek(fd, 16384, SEEK_SET) == -1)
  err_sys("lseek error"); /* offset now = 16384 */
 if (write(fd, buf2, 10) != 10)
  err_sys("buf2 write error");/* offset now = 16394 */
 exit(0);
}
```

```
> ls -ls file.hole
> od -c file.hole
```

EXERCISE

- Write a C program that does the same thing to the following shell script. Upload your code to BB.

```
touch file1.txt
cat "Alice" >> file1.txt
cat file1.txt
```