CS 3650 Computer Systems – Summer 2025

Introduction to C

Unit 4

* Acknowledgements: created based on Ji-Yong Shin's slides for the same course

Introduction

- Goal: learn C programming language
- Many languages look like C
  - C++, C#, Objective-C, Java, JavaScript, Go, Rust, Swift, etc.
- Many constructs look the same and have similar semantics
- C is a front-end for assembly
- Keeping that in mind, the lecture is not a full-fledged introduction
- Use tutorials on the web or books to teach yourself C
- We want to make sure that we discuss the important bits of C
- Do ask questions, if any

C Background

- Programming language developed by Dennis Ritchie in 1972
- A successor language of Bell lab's programming language "B"
- C was intended to make programming Unix easier
- Early Unix versions in Assembly
- High-level, compared to assembly
- But still low-level conceptual model
- Types - kind of "strong" but not really
- You manage memory
- You can even inline assembly

C hello world

- Compilation: gcc hello.c -o hello
- `#include <stdio.h>`
  - imports the library for printf
- Getting command line arguments
  - `int argc`: number of arguments (> 1)
  - `char * argv[]`: array of strings
  - `./hello argument test 1`
    - `argc= 4,`
    - `argv[0] = "./hello"` (always the path to binary file name)
    - `argv[1] = "argument"`
    - `argv[2] = "test"`
    - `argv[3] = "1"`
- printf
  - "Print"s according to the format string
  - "\n" adds new line at the end of the string

```
#include <stdio.h>

int main(int argc, char *argv[])
{
     printf("hello world!\n");
     return 1;
}

// prints
// hello world
```

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Other familiar features

- Blocks of scope are delimited by { and }
  - Variables are declared at the top of the block before calling other statements
  - Variable declared in the block is only visible in that block and any sub-blocks
  - Once the block ends, variable is not visible anymore
  - Blocks can be nested

- ; is used at the end of a statements

- Functions are declared pretty much like Java methods:
  - `return_type function_name(type1 arg1, type2 arg2, ...)`
    - E.g.,: `int max(int first, int second)`
  - Functions that don't return anything have a return type void
    - E.g.,: `void print_many_ints(int first, int second, int third)`

Data types

- Basic types
  - short: 16 bit integer
  - int: 32 bit integer
  - long int: 64 bit integer

  - char: 8 bit character (‘a’, ‘b’, ‘c’, ‘.’, ‘#’)

  - float: 32 bit floating point numbers
  - double: 64 bit floating point numbers (3.14, -123.456)

  - No Boolean types: integer with 0 or 1 is used instead

- When in doubt about the size you can print `sizeof(type)`

Control flows: if

```
if (condition) {
    // do stuff
}
```

```
if (condition) {
   // do stuff
} else {
   // do other stuff
}
```

Control flows: while

```
while (condition) {

    // do this while condition holds

}

do {

    // do this at least once and then
    // keep doing it again while condition holds

} while (condition); // don't forget the semicolon
```

Control flows: for

1. run the initializer expression
2. if condition holds go to 3, else go to 6
3. do stuff in body
4. run the updater expression
5. Go to 2
6. End

```
for (initializer; condition; updater) {

}
```

Operators

- Comparison operators: <, >, <=, >=, ==, !=
  - `while (a <= b)`
  - `while (a != b)`
  - `for (i = 0; i < 10; i++)`

- Logical operators: !, &&, ||
  - `if(x > 0 && x <10)`
  - `while(x > 0 || y > 0)`

Continue and break

- You can skip the rest of the current iteration of the innermost loop with continue
- You can break out of the innermost loop with break

```
1  while (x > 0) {
2      if (x > 100) {
3          break;
4      }
5      if (x > 10) {
6          // do something 1
7          continue;
8      }
9      // do something 2
10 }
11 // do something 3
```

What line gets executed after line 8? Line 3?

Control flows: switch

- Condition checks based on matching an expression (usually just a variable)

```
switch(expression) {
    case constant-expression:
        // do something
        break;    // optional: if you don't break the next
                  // block will be executed unconditionally
    case constant-expression:
        // do something
        break;
    …
    default:
        // do something
}
```

Pointers

- DataType * pointer
  - int *int_pointer;
  - double *element = NULL; // good practice to make initialize to NULL
- A pointer stores a memory address of a data instance

```
int main() {
      int a = 10;
      int * int_pointer; // currently points to an
arbitrary location
      int_pointer = &a; //  & returns the address of the
variable

      printf("%p\n", int_pointer);

      // *pointer accesses the value stored in the
memory address
      printf("%d\n", *int_pointer);

      *int_pointer = 20;

      printf("%p\n", int_pointer);
      printf("%d\n", *int_pointer);
      printf("%d\n", a);

      return 1;
}
```

Addr 0x0016	a	~~10~~ 20
Addr 0x1234	int_pointer	0x0016

Sample Output:
0x0016
10
0x0016
20
20

Pointer of pointer

```
int i = 42;
int *pi = &i;
int **ppi = &pi;
printf("%d %d %d\n", i, *pi, **ppi);
```

Addr 0x0016	i	42
Addr 0x0020	pi	0x0016
Addr 0x0030	ppi	0x0020

What should be printed?

42 42 42

ppi = pointer to (address of) pi

*ppi = pointer to (address of) i

**ppi = value of i

Reason why pointers are considered difficult

- Some program languages do not expose memory addresses
- Accessing an arbitrary address through pointers causes runtime errors
  - When you pass around pointer variables you will often see this
- Memory address is not a value that you directly use in a program
  - But it is often more convenient to have access to
- Little control over memory addresses (program assigns for you)
  - You will only directly assign NULL or copy existing addresses
  - But sometimes you will access RELATIVE addresses

Arrays

- Arrays are just pointers with some fancy syntax
- There are static (size known at compile-time) and dynamic array

- We will first discuss static arrays

```
float nums[4]; // create an array of 4 floats
```

- These will be stored contiguously in memory
- **nums points to the first element**

Arrays

- We can access them individually using indices, starting from 0

```
float nums[4]; // create an array of 4
floats nums[0] = 0.1;
nums[1] = 3.14;
nums[2] = 1.5;
nums[3] = 3214;
printf("2nd element: %f\n", nums[1]);
```

- Arrays can also be initialized:

```
float nums[4] = { 0.1, 3.14, 1.5, 3214 };
printf("2nd element: %f\n", nums[1]);
```

Arrays

- Pointer-based access

```
float nums[4] = { 0.1, 3.14, 1.5, 3214 };
printf("2nd element: %f\n", nums[1]);
```

```
printf("1st element: %f\n", *nums);
printf("2nd element: %f\n", *(nums+1));
printf("3rd element: %f\n", *(nums+2));
printf("4th element: %f\n", *(nums+3));
```

String

- In C (like in Assembly for us), strings are just arrays of characters, terminated by a 0 byte (also written '\0')

- Relevant functions are in <string.h>

- A string literal "Hello, world!" is just the corresponding array of characters with an extra char for \0

```
// msg1 and msg2 define exactly the same object in memory
char msg1[6] = "Hello";
char msg2[6] = { 'H', 'e', 'l', 'l', 'o', '\0' };
```

Structs

- Structs are the most useful user-defined data types in C
- Think of them as Java classes, but everything is public
- Structs do not have methods
- A struct stores multiple values of different types together
- It is defined using the struct keyword:

```
struct address {
   unsigned int house_no;
   char street[32];
   char city[24];
   char state[3];
   unsigned int zip;
} ; // don't forget the semicolon.

struct address home, work; // this will allocate two
                           // structs on the stack
```

Structs

- To access a field, we use "."

```
work.house_no = 360;
strcpy(work.street, "Huntington Ave"); // see man 3
strcpy
strcpy(work.city, "Boston");
strcpy(work.state, "MA");
work.zip = 02115;
```

- Structs can, of course, be nested:

```
struct person {
    char first[32];
    char last[32];
    struct address home;
};
```

- They can be passed to and returned from a function:

```
struct address get_address(struct person p) { ... }
```

Structs

- Is this allowed?

```
struct person {
   char first[32];
   char last[32];
   struct person p;
};
```

Structs

- Is this allowed?

```
struct person {
   char first[32];
   char last[32];
   struct person p;
};
```

No. Infinite recursion.

Structs

- Is this allowed?

```
struct person {
   char first[32];
   char last[32];
   struct person *p;
};
```

Structs

- Is this allowed?

```
struct person {
   char first[32];
   char last[32];
   struct person *p;
};
```

Yes! This is how a linked list works.

Typedef

- Writing out struct every time can be tiring

```
struct address my_home;
struct person myself;
struct address get_home_addr(struct person arg);
```

- C allows us to introduce type synonyms using typedef:

```
typedef struct person person_t; // now we can use person_t
                                // to mean struct person
```

- typedef can be used with any type to make code more readable:

```
typedef unsigned char age_t;
```

Dynamic memory allocations

- Memory can be allocated using the library function malloc
  - It is defined in stdlib.h
  - Takes the number of bytes we want
  - Returns a pointer to the block of memory (if successful)
  - Allocated memory needs to be freed using free

```
int *one_int = malloc(4);
*one_int = 42;
free(one_int);
```

Dynamic memory allocations

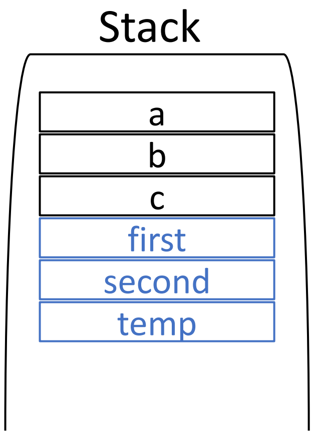
- We will mostly use malloc to allocate arrays and structs (below)

```
int *fifty_ints = malloc(50 * sizeof(int));

for (int i = 0; i < 50; ++i) {
   fifty_ints[i] = i * i;
}

free(fifty_ints);
```

Pointers and memory management

- Stack vs heap
  - Stack memory is automatically managed (maintains variables in the scope)

```
int addsquare(int first, int second) {
     int temp = first + second;
     return (temp * temp);
}

int main() {
     int a = 1;
     int b = 2;
     int c = addsquare(a, b);
     printf("%d\n", c);
     return 1;
}
```

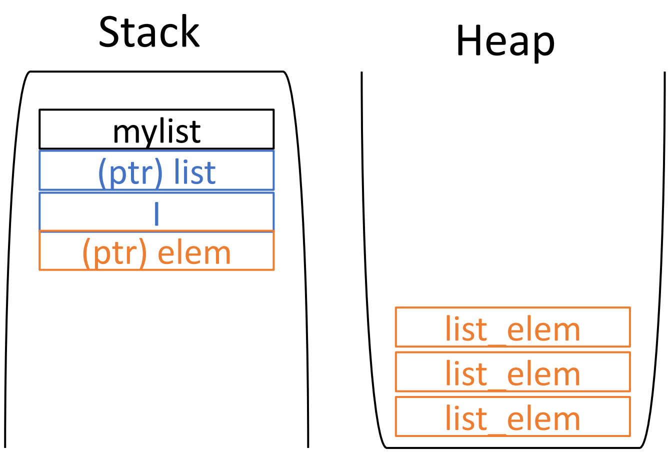


Pointers and memory management

- Stack vs heap
  - Heap memory is dynamically allocated and you should manage it
  - “malloc” allocates memory
  - “free” deallocates memory

```
void add_elements(struct list *list) {
  int I;
  for (I = 0; I < 3; I ++) {
    struct list_elem *elem = malloc(sizeof(struct list_elem));
    list_push_back(list, elem);
  }
}

int main() {
   struct list my_list;
   list_init(&my_list);
  add_elements(&my_list);
  while (list_size(&my_list) > 0) {
    struct_list_elem *elem = list_pop_front(&my_list);
    free(elem);
  }
  return 1;
}
```

If you forget to delete, memory space will be wasted and in the long run, you can run out of memory space (memory leak)



Pointers to structs

- Of course, we can have pointers to structs:

```
struct person *p; // OR person_t *p;
```

- We can use the address-of operator & to get the address of a struct:

```
struct address *current = &work;
```

- We can also allocate memory for structs dynamically, using malloc and sizeof:

```
struct person *alice = malloc(sizeof(struct person));
person_t *alice = malloc(sizeof(person_t));
```

- We can also create arrays of structs:

```
person_t class[80];
person_t *friends = malloc(5 * sizeof(person_t));
// ...
for (int i = 0; i < 5; ++i) {
    if (strcmp(friends[i].home.street, "Huntington Ave") == 0) {
        printf("%s lives close!\n", friends[i].first);
    }

}
```

Pointers to structs

- Often, pointers are used to pass a struct to a function
  - This avoids copying the contents into the function's stack frame

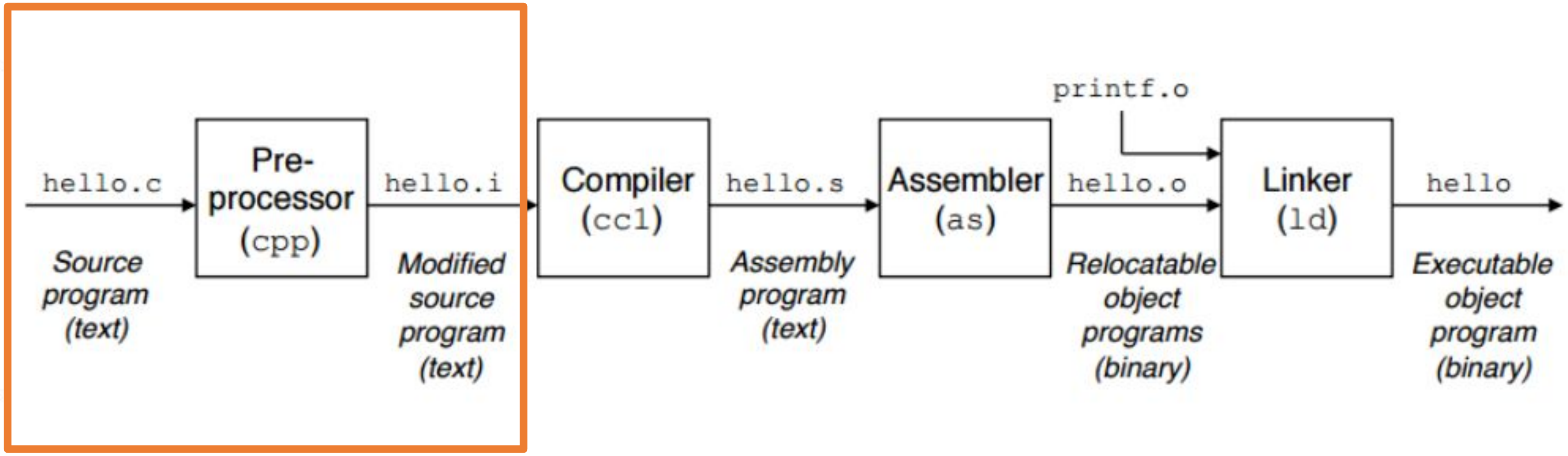
- When accessing fields via a pointer, we use **->**

```
int lives_in_boston(person_t *p) {
   return strcmp(p->home.city, "Boston") != 0;
   // equivalent to
   // return strcmp((*p).home.city, "Boston") != 0;
}
```

C Demo

Preprocessor

- The C preprocessor (CPP) is a separate phase run at the very beginning of the compilation process



Preprocessor

- Just text processing engine
- Modifies the source text based on preprocessor directives

- The main job of CPP is to:
  - Include the requested header files
  - Define “global constants” – IMPORTANT: these are just textual macros, that is, pieces of C code that will get spliced wherever the constant name is mentioned
  - Choose which parts of code to include for compilation based on various conditions

Preprocessor: #define

- This directive is used to define a textual macro
- The macro can be a constant macro or a parametrized macro
  - E.g.,

```
#define COUNT 100
#define COURSE "Computer Systems"
```

  - This will define the macros COUNT and COURSE;
  - Everywhere else where COUNT is mentioned, it will be replaced with 100, and COURSE will be replaced with "Computer Systems"

Preprocessor: #define

- Note, that the expression is simply substituted for the macro
- It does not get evaluated at the definition site
- Hence there is a subtlety that one has to keep in mind: Consider,

```
#define X 10 + 2

int a = X;           // expands to 10 + 2
int b = 3 * X;       // expands to 2 * 10 + 2
                     //this might not be what we expect
```

- The solution is to always put an expression in parentheses:

```
#define X (10 + 2)
int b = 3 * X;       // expands to 2 * (10 + 2)
```

Preprocessor: #define

- Parametric ("function-like") Macros
  - We can also define macros with arguments using #define
  - These look like function calls, but they get expanded at compile-time
  - Example,

```
#define max(a, b)    (a > b ? a : b)
printf("%d\n", max(3, 4));
```

- The argument to a macro does not get evaluated before being used in the macro, so we have a similar problem as above:

```
#define dbl(x)   (2 * x)
printf("%d\n", dbl(10 + 1));   // expands to 2 * 10 + 1,
                               // so prints 21, not 22!
```

- So any argument use in a macro body should be enclosed in ():

```
#define max(a, b) ((a) > (b) ? (a) : (b))
#define dbl(x) (2 * (x))
```

Preprocessor: #define

- Another caveat: consider the following:

```
#define foomacro(x) ((x) + (x))
int foofun(int x) { return x + x; }
```

- Although both seem to be computing the same result, they will behave differently if the expression passed in has side-effects:

```
int x = 10;
printf("%d\n", foomacro(++x));  // will likely print 23
x = 10;
printf("%d\n", foofun(++x));    // prints 22
```

- Why?

- Note: a good modern C compiler will usually warn you about this

Preprocessor: #include

- The `#include` directive performs a textual inclusion of the given file

- Generally, only ever use this for headers - .h files
  - Example: `#include <stdio.h>`
  - DO NOT INCLUDE C FILES

- Headers contain
  - Declarations and definitions of functions
  - Macros
  - Sometimes also global variables

Preprocessor: #if/#ifdef/#ifndef/#elif/#else

- This set of directives allows conditional compilation
- Basically, these are compile-time conditionals that hide or expose parts of the source file from or to the compiler
- `#ifdef` checks if the given is true
- Example:

```
#ifdef UNIX
    PATH_SEPARATOR "/"
#elif
    defined WINDOWS PATH_SEPARATOR "\\"
#endif
```

- Other example:

```
for (int i = 0; i < length; i++) {
    sum += array[i];
#if DEBUG_LEVEL >= 1
    printf("array[%d] = %d, sum = %d\n", i, array[i], sum);

#endif

}
```

Header files

- Commonly include
  - Function declarations

```
int max(int a, int b);
int min(int a, int b);
```

  - Structs
  - Macros

mycode.h

```
#ifndef __MYCODE_H__
#define __MYCODE_H__

struct my_struct {
    int x;
    int y;
};

int my_func(struct my_struct *my_arg);

#endif
```

mycode.c

```
#include "mycode.h"

int my_function(struct my_struct *my_arg)
{
    int z;
    // do something
    return z;
}
```

Separate Compilation

- my_max.h

```
int my_max(int a, int b);
```

- my_max.c

```
int my_max(int a, int b) { return ((a > b) ? a : b); }
```

- my_min.h

```
int my_min(int a, int b);
```

- my_min.c

```
int my_min(int a, int b) { return ((a < b) ? a : b); }
```

- main.c

```
#include "my_max.h"
#include "my_min.h"

int main(void) {
        x = 1;
        y = 2;
        z = 3;
       nin(x, y);
       nax(y, z);
       urn 0;
}
```

Double quote to include custom header files

gcc –c my_max.c –o my_max.o
gcc –c my_min.c –o my_min.o
gcc –c main.c –o main.o
gcc my_max.o my_min.o main.o -o my_prog

gcc –c my_max.c my_min.c main.c
gcc my_max.o my_min.o main.o –o my_prog

gcc my_max.c my_min.c main.c –o my_prog

Global variables

- Global variables can be declared outside of functions
- They can be accessed by anywhere in the program
- Pros
  - Convenient because all functions can access
- Cons
  - Can accidentally change
  - Abusing global variables can easily introduce bugs

main.c

```
int global_var = 100;
void print_global_var() {
    printf("%d\n", global_var);
}
int main(void) {
    // do something
    return 0;
}
```

inc_dec.c

```
extern int global_var;

void inc_global_var() { global_var++; }
void dec_global_var() { global_var--; }
```