Computer Architecture (Practical Class)
Introduction to the C Programming Language
aka C for Java Programmers

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The C programming language

- Developed in the early 1970s at Bell Labs, C is a general-purpose, imperative programming language.
- Created to enable porting the UNIX operating system across different hardware, C's history is intrinsically tied to UNIX.
- Designed for simplicity and minimalism: the seminal book *The C Programming Language* (2nd ed., Kernighan & Ritchie) covers the entire language, its standard library, and includes examples/exercises in just 261 pages.
- Today, C remains a cornerstone of systems programming (OS kernels, device drivers, compilers) and embedded development.
- Notable projects written in C include the Linux kernel and MySQL.

Why C?

- **Extremely popular**: consistently top-ranked in the TIOBE Index (1st in 2020–2021, 2nd in 2019, ...)
- **Highly influential**: inspired many major languages — C++, Java, Objective-C, Swift, C#, PHP, Go, ...
- **Close to the metal**: gives direct access to memory, manual management, and low-level operations
- **Efficient**: produces fast, compact code — ideal for systems programming and performance-critical tasks

Philosophical reason

C helps you understand what really happens — from the UI to the electrons. :)

Operators, conditionals, loops, ...

- Operators, conditionals, loops and other languages constructs are similar to Java
- Operators:
  - Arithmetic: +,-,*,/,%, ++, −−
  - Assigment: =,+=, -=, *=, ...
  - Relational: <,>,<=,>=,==,!=
  - Logical: &&, ||, !
  - Bitwise: &,|,^,~,«,»
- Language constructs:
  - if( ){ } else { }
  - while( ){ }
  - do { } while( )
  - for(i=0; i<100; i++){ }
  - switch( ) { case 0: ... }
  - break, continue, return
- **No exception handling** statements

C vs Java

what	C	Java
type of language	function oriented	object oriented
basic programming unit	function	class = ADT
portability of source code	possible with discipline	yes
portability of compiled code	no, recompile for each architecture	yes, bytecode is 'write once, run anywhere'
compilation	creates machine language code	creates Java virtual machine language bytecode
execution	loads and executes program	interprets byte code
variable auto-initialization	not guaranteed	all variables must be initialized; compile-time error to access uninitialized variables

Note

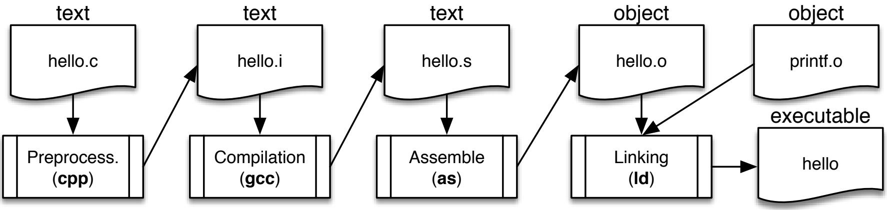
You can find a more detailed comparison in
`http://introcs.cs.princeton.edu/java/faq/c2java.html`

Listing 1: hello.c

```
/*
 This program uses printf(), defined in the C standard library "stdio"
 Lines starting with '#' are called preprocessor directives, and do not
 have a ';' at the end.
 (this is a multiline comment)
*/
#include <stdio.h>

/*
 Function main() returns an integer and, in this case, receives
 no arguments (void).
 main() is the first function to be called when the program is executed
*/
int main(void){
   /* printf() prints formatted output;
      \n is a newline */
   printf("Hello, World ! \n");

   // the main function returns the value 0 (single line comment)
   return 0;
}
```

Compiling C programs

- C programs must be transformed into machine-code so they can be executed, in a process called **compilation**
- The compilation process involves several other steps:
  - preprocessing; compilation; assembling; linking



Cross-compilation and emulation for RISC-V

- Our development environment is a Linux x86-64 virtual machine
- Compile the code with `riscv32-linux-gcc`
- Execute the resulting binary using `qemu-riscv`

Why a cross-compiler?

- Without a cross compiler, we cannot create a RISC-V binary from our x86_64 environment
  - Our VM runs Linux on x86_64, but we want to **build code for a 32-bit RISC-V target**.
  - A standard gcc on x86_64 produces binaries that only run on x86-compatible hardware
  - The *riscv32-linux-gcc* generates executables with the correct RISC-V RV32I instruction encoding and ELF headers

How to use

```
riscv32-linux-gcc -march=rv32imd -mabi=ilp32d -Wall -Wextra -fanalyzer -g
main.c -o program.elf
```

- Do not ignore warnings!
- Warnings often provide indication about errors that will manifest themselves at runtime

Why QEMU emulation?

- Without QEMU (or another emulator), we'd need physical RISC-V hardware at every stage of development
  - We do not have physical RISC-V board hardware available for development or testing in our labs
  - `qemu-riscv` can emulate an RV32I machine entirely in software
- Emulation allows us to:
  - Load and run the RISC-V binary directly on our x86_64 VM
  - Step through instructions and debug with `gdb`, if needed
  - Validate functionality before deploying to real hardware

How to use

```
qemu-riscv32 -L $HOME/bin/bootlin/riscv32-buildroot-linux-gnu/sysroot
./program.elf
```

- **Note**: we will construct a Makefile to simplify this process of compiling and executing our applications

Important gcc switches

option	**Description**
-Wall	all warnings – **use always!**
-o*filename*	output filename for object or executable
-c	compile only, do not link; used to create an object file (.o) for a single (non-main) .c file (module)
-g	insert debugging information
-E	stop after the preprocessing stage; output goes to standard output
-v	show information about gcc and/or compilation process
-S	performs preprocessing and compilation only; that is, convert C source into assembly
-save-temps	keep temporary files created (.i, .s, .o, ...)
-l*library-name*	link with library called *library-name*
-I*dir*	add *dir* to the list of dirs to be searched for header files
-L*dir*	add *dir* to the list of dirs to be searched for the libraries specified with -l;

More details at: `http://aeno-refs.com/qr-linux/programming.html#gcc`

Notes about gcc output

Important note

Always read the output of gcc carefully!

- Gives pretty good indications about the origin of the error
- Several sources of errors:
  - preprocessor: missing include files
  - parser: syntax errors
  - assembler: syntax errors in assembly code (only if you are coding assembly)
  - linker: missing libraries
- Often, one error causes lots of subsequent errors
  - fix first error, and then retry – ignore the rest
- Often, errors are caused by previous mistakes
  - for example a missing ';' often will cause an error in the subsequent line(s)

The C preprocessor

- The C preprocessor (cpp) allows defining macros, which are brief abbreviations for longer constructs
- Preprocessor directives start with a ‘#’ at the beginning of the line and are used for:
    - Inserting content of another file into file to be compiled: #include
    - Conditional compilation: #if; #ifdef
    - Definition of macros and constants: #define
- Before compilation, the preprocessor reads the source code and transforms it

- Example 1:

```
#include <stdio.h> // searches for stdio.h in system defined directories
#include ‘‘mydefs.h’’ // searches for mydefs.h in the current directory
```

- Example 2:

```
#define MAX 100
#define check(x) ((x) < MAX)
if check(i) { ... }
```

  - Becomes:

```
if ((i) < 100) { ... }
```

Use the C preprocessor with caution

- It is easy to introduce subtle errors
- Not visible in debugging
- Code hard to read

Integer types

Type	Storage size	Value range
char	1 byte	-128 to 127
unsigned char	1 byte	0 to 255
short	2 bytes	-32 768 to 32 767
unsigned short	2 bytes	0 to 65 535
int/long	4 bytes	-2 147 483 648 to 2 147 483 647
unsigned int/long	4 bytes	0 to 4 294 967 295
long long	8 bytes	-9 223 372 036 854 775 808 to 9 223 372 036 854 775 807
unsigned long long	8 bytes	0 to 18 446 744 073 709 551 615

Floating-point types

Type	Storage size	Value range	Precision
float	4 bytes	1.2E-38 to 3.4E+38	6 significant digits
double	8 bytes	2.3E-308 to 1.7E+308	15 significant digits

C data types - Example declarations

```c
char c = 'A';

char b = 100;

int i = -2343234;

unsigned int ui = 100000000;

float pi = 3.14;

double longer_pi = 3.14159265359;
```

- The storage size of some types **varies** among architectures
  - E.g. A *long* is 8 bytes in x86-64 machines and 4 bytes in RV32I machines

- *char* is misleading. It is a numeric type that happens to be sometimes used to store ASCII character codes

- The *void* type comprises an empty set of values; it is an incomplete type that cannot be completed
  - You cannot define variables of type *void*, however *void* can be used to:
    - Indicate that a function has no parameters. E.g. `int func(void);`
    - Indicate that a function has no return. E.g. `void func(int n);`
    - Define a pointer that does not specify the type it points to (more on this in the following lectures). E.g. `void* ptr;`

- Two kinds of type conversions
  - Implicit: automatic type conversion by the compiler.
    E.g.: `int a=1000; char b=a; // b=-24 (lower 8 bits of a=...11101000)`
  - Explicit: explicitly defined by the programmer.
    E.g.: `float f=1.2; int d=(int)f; // d=1`

Example: Compute the average of two integers

Listing 2: avg.c

```
#include <stdio.h> /* for declaration of printf */

/* globals (really necessary?) */
int n1=6, n2=4, avg=0;

/* this function computes the (integer) average of two integers */
int calc_avg(int a, int b) {
  int c=0;    /* local variable */
  c=(a+b)/2;
  return c;
}

/* the program starts by executing this function */
int main(void) {

  avg = calc_avg(n1, n2); /* call function and save return */
  printf("Avg = %d\n", avg);

  return 0;      /* returns 0 */
}
```

Using `sizeof`

- C has a unary compile-time operator `sizeof`, that can be used to get the storage size of variables and data types, *measured in the number of char type storage size*.
- Examples:
  - `sizeof(int)`: returns the size of *int*
  - `sizeof(a)`: returns the size of the variable *a*
  - `sizeof(char)`: returns the size of type char; **guaranteed to always be 1**

Important

- While, for most modern systems, the char type has 8 bits, *there is no guarantee that this is always true*.
- The number of bits of type char is defined in the CHAR_BIT constant in `<limits.h>` .

- Check the file `<limits.h>` for the sizes and limits of the integer types
  - e.g. CHAR_MAX, CHAR_MIN, INT_MAX, INT_MIN
- Check the file `<float.h>` for the sizes and limits of the floating-point types
  - e.g. FLT_MIN, FLT_MAX

Using sizeof: Example (1/3)

- The next slide will present an example using `sizeof` and several constants from `<limits.h>` and `<float.h>`

`printf()` format specifiers quick reference

- %d or %i: Signed decimal integer
- %u: Unsigned decimal integer
- %lu: Unsigned long integer
- %f: Decimal floating point, lowercase
- %E: Scientific notation (mantissa/exponent), uppercase
- %c: Character
- %s: String of characters
- see: `http://www.cplusplus.com/reference/cstdio/printf/`

Using sizeof: Example (2/3)

Listing 3: sizeof.c

```
#include <stdio.h> // needed for printf
#include <limits.h> // needed for CHAR_BIT, INT_MAX, INT_MIN
#include <float.h> // needed for FLT_MAX, FLT_MIN, FLT_DIG

int main() {
   char n='A';

   printf("\nStorage size for variable n: %lu\n", sizeof(n));

   printf("\nStorage size for char: %lu\n", sizeof(char));
   printf("Number of bits in a char: %d\n", CHAR_BIT);

   printf("\nStorage size for int: %lu\n", sizeof(int));
   printf("Minimum int value: %d\n", INT_MIN );
   printf("Maximum int value: %d\n", INT_MAX );

   printf("\nStorage size for float : %lu \n", sizeof(float));
   printf("Minimum float positive value: %E\n", FLT_MIN );
   printf("Maximum float positive value: %E\n", FLT_MAX );
   printf("Precision value for float: %d\n", FLT_DIG );

   printf("\nStorage size for double=%lu\n", sizeof(double));

   return 0;
}
```

Using sizeof: Example (3/3)

Output of the example (Listing 2; sizeof.c)

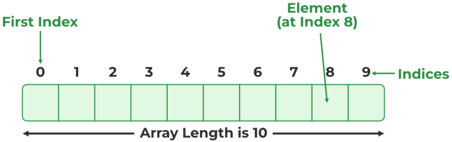
```
Storage size for variable n: 1

Storage size for char: 1
Number of bits in a char: 8

Storage size for int: 4
Minimum int value: -2147483648
Maximum int value: 2147483647

Storage size for float : 4
Minimum float positive value: 1.175494E-38
Maximum float positive value: 3.402823E+38
Precision value for float: 6

Storage size for double=8
```

- C allows to define arrays of elements of **the same type**
  - Historically, C only supports arrays where the size can be determined at compile time
  - Programmers requiring variable-size arrays have to allocate storage for these arrays using functions such as `malloc`

Listing 4: Examples of arrays, with statically defined sizes (size is fixed)

```
int a[10];                          // array of 10 integers
int a1[] = {1, 2, 3, 4, 5}; // array of 5 integers,
                                    // initialized to 1, 2, 3, 4 and 5
int a2[1000] = {0};                // array of 1000 integers,
                                    // all initialized to 0
short s[100];                       // array of 100 shorts
float m[10][10];                    // 10x10 matrix of floats
```

- Arrays are stored as a continuous linear arrangement of elements
  - For an array containing N elements, indexes are $0..N-1$, accessed using `a[0]`, `a[1]`, `...`, `a[N-1]`



- The compiler **does not check** when you access invalid indexes
  - `int x[10]; x[10] = 5;` is an overflow of the array, and will result in undefined behaviour (it may work for a while...usually results in a segmentation fault and program termination)
- An array **cannot be the target of an assignment**
  - Assume an array `int v[5]`, declared previously in your program. The following statement is **not valid**: `v = {1, 2, 3, 4, 5};`
  - We can only initialize arrays when they are declared, not attribute values in "bulk" after. After the declaration, a valid statement would be: `for (i=0; i<5; i++) v[i] = i+1;`
  - If you want to copy arrays, use `memcpy(dest, src, size);`

Arrays in C (3/4)

Important note

C **does not remember** how large arrays are (i.e., no length attribute)

- `sizeof` works **only** for statically defined arrays, within the scope they are declared
- Example:

```
{
  int a[10];
  printf("%lu", sizeof(a)); // prints 40 in RV32
}
```

- The {} define the scope of these statements
- Size of array can be computed with `sizeof(a) / sizeof(a[0])`

- When the array is passed as an argument to a function, the size information is not available
- Example:

```
void func(int a[10]) {
  printf("%lu", sizeof(a)); // prints 4 in RV32I
}
```

  - More on this in the folowing classes
- The solution is for the programmer to **maintain the length of the array**:
  - By passing the size as an argument of the function;
  - By using a globally defined constant;
  - By defining a data structure for storing the array and its size together;
  - By defining a value that indicates the end of the the array (e.g. an int array ends with a -1 value).

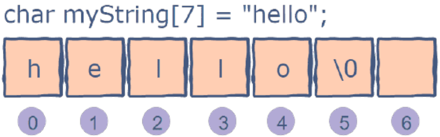
Strings in C (1/2)

C does not have a specific data type for strings

- Strings are just char arrays with a NUL (‘\0’) terminator (value zero)
- *printf*, with the %s option, will continue printing characters until it sees the NUL character

```
char a[10]="abc";
```

- Defines an array of 7 chars. The first 5 chars will have the ASCII codes of characters ‘h’, ‘e’, ’l’, ’l’, and ‘o’. The fourth will be the NUL terminator:



Strings in C (2/2)

Listing 5: xpto.c

```
int xpto(char s[]){
    int c=0;

    while (s[c]!=0) c=c+1;

    return c;
}
```

- What is the functionality of the function?
    - A. The function returns the ASCII code of the last character.
    - B. The function returns the number of elements of the string.
    - C. The function returns the number of words of the string.
    - D. None of the above.

Remember!

- Arrays (strings - arrays of char - included) cannot be target of assignments after the declaration

- The following statement is valid, and declares an array s[6], initialized with the characters ‘H’, ‘e’, ‘l’, ‘l’, ‘o’, ‘\0’: `char s[]="Hello";`
- However, after declaring `s[]`, you **cannot assign it a new value**: `s="World"; // this is not a valid statement!`
- Keep in mind that strings should be copied with `strncpy(dest_str, src_str, n_chars)`: `strncpy(s, ’’World’’, 6);`
- Also, note that it is the programmer’s responsibility to check that the destination string has enough storage.

Good C code

- Good code should be mostly self-documenting
  - Variables and function names should generally help making clear what you are doing
  - Comments should not describe what the code does, but why. What the code does should be self-evident (assume the reader knows C)
  - Do comment: each source file, function headers, large blocks of code, tricky bits of code (e.g. bit manipulations)
- Use C-style naming conventions:
  - E.g. prefer `get_radius()` to `GetRadius();`
  - *i* and *j* for loop variables.
- Bodies of functions, loops, if-else statements, etc. should be indented

Good C code

- Define constants and use them. Constants make your code more readable, and easier to change
- Avoid global variables. Pass variables as arguments to functions
- Initialize variables before using them!
- Use good error detection and handling. *Always* check return values from functions, and handle errors appropriately

Making the best use of C

- Read `https://www.gnu.org/prep/standards/html_node/Writing-C.html` for advice on how to use the C language

Practice

- Implement a C program that reads 10 integers into an array and computes their average.
- The average should be calculated in a separate function, but its value should be printed by the main().