C as compared with C++ and Java

- Unlike Java and C++, C does not have:
  - Classes
  - Packages/namespaces
  - Templates/generics
  - Exceptions
  - Operator or function overloading
  - Anonymous functions/closures/lambdas
  - A rich standard data-structure library

- Unlike Java, C allows potentially-unsafe operations:
  - Uninitialized variables and memory
  - Out-of-bounds array accesses
  - Creating pointers from integers
  - Deallocating memory that is still in use

C programs are made up of functions

- The primary unit of structure is a function
  - AKA "procedure", "subroutine"

```
type name (type arg1, type arg2)
{
  statements
}
```

```
int add(int arg1, int arg2)
{
  return arg1 + arg2;
}
```

Hello world in detail

standard library function declarations

```
#include<stdio.h>

int main(int argc, char **argv)
{
  printf("Hello, world!\n");
  return 0;
}
```

standard library function to print a message

command-line arguments

Return values and prototypes

- Functions can return a value with a `return` statement
- No return value, or no arguments, are signified by the keyword `void`
- To tell the compiler about a function without defining it, write a function prototype:

```
int add(int arg1, int arg2);
```

- In a single file program, prototypes mostly not needed if functions are defined lower-level first
  - But, give stylistic freedom to change function order
Numeric types

- Integer types:
  - Type name | Common minimum size
  - char 8 bits
  - short 16 bits
  - int 32 bits
  - long 32 bits — for us, 64 bits
  - long long 64 bits

- “unsigned” variants cannot be negative

- Common floating point types:
  - float: usually 32 bits
  - double: usually 64 bits

Characters

- char’s name comes from representing characters
- Actually three types:
  - signed char: -128 to 127
  - unsigned char: 0 to 255
  - char: might be either signed or unsigned
- On almost all systems, values 0-127 represent ASCII
  - US-standardized code for roman alphabet, numbers, symbols, etc.
- Wider variety of standards for meanings of 128-255
  - Windows-1252, Latin-1: add accented letters and a few symbols
  - UTF-8: multiple bytes represent >100,000 Unicode characters
- Escape sequences starting with \ for hard-to-type ones:
  - E.g., ‘\n’ for newline, ‘\0’ for character zero

Declaration, initialization, assignment

- A new variable is introduced with a declaration:

  ```c
  int weight, height;
  ```

- Optionally, give it a value by including an initialization:

  ```c
  int score = 100;
  ```

- An assignment statement changes the value of an already-declared variable:

  ```c
  score = score - 5;
  ```

Type conversion and casts

- Values are automatically converted between numeric types, sometimes with strange effects:

  ```c
  long x = 1000000;
  char c = x;
  /* c is now 64 */
  ```

- The act of converting can be written explicitly as a cast operation:

  ```c
  long x = 1000000;
  char c = (char)x;
  /* c is now 64 */
  ```

Local, global, and static

- A variable defined inside a function (local) is usually:
  - Created once per call to the function
  - Visible only inside the function
- Variable can be declared outside any function, global:
  - Exists during the whole program
  - Visible in any (later) function
- If a local variable is declared with keyword static:
  - One version for the whole execution
  - Still visible only inside the function
  - E.g., useful for counter function

Arithmetic operators

- C has the standard math operators:
  - +, - (both unary and binary)
  - *, multiplication
  - /, integer or floating-point division
  - %, integer division remainder
- Precedence rules define the default grouping
  - E.g., 1 + 2 * 3 is 1 + (2 * 3) i.e. 7, not 9
- When in doubt, use parentheses
  - Rules are mostly, but not always, what you’d expect
Assignment abbreviations
- Unary ++ and -- add or subtract 1, respectively
  - E.g., c++ is short for c = c + 1
  - Also called increment and decrement
- Putting a = after an operator makes an update operator
  - E.g., c += 10 is short for c = c + 10
- You can string together multiple assignment left-hand sides
  - assignment_grade = course_grade = 0;

Comparisons and logic
- Numbers can be compared with the usual operators:
  - <, >
  - <=, >= mean ≤, ≥
  - ==, != mean =, ≠; note double equals
- Integers used for logic (no separate Boolean type):
  - 0 represents false
  - any non-zero interpreted as true, produced as 1
  - (C99 defines <stdbool.h>, hasn’t caught on)
- Logic operators:
  - && for and, || for or, ! for not
  - (d != 0) && (n / d < 10) is safe (“short-circuiting”)

Arrays in C
- Arrays are the key building block for large data structures
- C arrays have limited features, allowing for simple compilation strategies
  - Local and global arrays can only have fixed size
  - At runtime, no way to ask how long an array is
  - No bounds checking
  - First index is always 0
- Implementation is just a sequence of adjacent values
- C arrays are closely related with C’s pointers

Array syntax
- Syntax is based on square brackets [ ] as a suffix
- On a type, inside brackets is the size
- On a value, inside brackets is the index
  - Can appear on left or right side of assignment
  - Note, 0-based means index always less than size
  - double point[3] = {1.0, 1.0, 0.0};
  - point[0] = -2.0;
  - double dist =
    - sqrt(point[0]*point[0] +
      - point[1]*point[1] +
      - point[2]*point[2]);

Multidimensional arrays
- Repeat sets of brackets for tables with more numeric indexes
- E.g., chess board:
  - char board[8][8];
  - board[0][0] = ‘r’;
- Note, not commas
- Again, only usable when the dimensions are fixed

Pointer basics
- A pointer is a value that stores the location of another value
  - As we’ll later see in detail, it’s implemented as a memory address
- The type of a pointer variable keeps track of the type of what it can point to
  - E.g., pointer-to-char, pointer-to-int
- Type declaration syntax puts a * before the variable name:
  - int num, *num_ptr;
Basic pointer operations

- & creates a pointer
  - If x is an int variable, &x is an int pointer, pointing at x
- * gets what the pointer points to
  - If ip is an int pointer, *ip is the int it points at
  - Also called "following" or "dereferencing"
- Multiple levels are possible

```c
int i = 5;
int *ip = &i;
int **ipp = &ip;
(**ipp)++;
/* i and **ipp are now 6 */
```

Strings are arrays of characters

- String length is unknown at compile time
  - Thus, type is char *
- Length of string indicated by \0 character after contents
  - "Null termination"
  - Many C programs don’t cope well with \0 characters in their input

```c
void caesar_string(char *s, int amt) {
    int i;
    for (i = 0; s[i] != '\0'; i++) {
        s[i] = rotate(s[i], amt);
    }
}
```

Basics of printf

- Standard library function for formatted output
- First argument, format string, may contain format specifiers starting with %
  - Generally, each corresponds to a later argument
- Most basic format specifiers:
  - %d: signed int, printed in decimal
  - %g: double, in scientific notation if needed
  - %s: char *, interpreted as string

```c
printf("One %s one is %d\n", "plus", 1 + 1);
/* One plus one is 2 */
```

String constants

- Put text inside double quote marks: "string"
  - Can also include escape sequences
  - Usually put \ at end of lines to be printed
- Normally string constants are read-only
  - Type is const char *
- Can be used to initialize a modifiable character array

```c
char a[] = "hi!";
/* size 4, including \0 */
char a[3] = "hi!";
/* size 3, no \0 */
```

if and if-else statements

- Basic way to make decisions. if does either something, or nothing:
  ```c
  if (x % 2 == 0)
      printf("x is even\n");
  ```
- if-else does one thing if true, other if false
  ```c
  if (x % 2 == 0)
      printf("x is even\n");
  else
      printf("x is odd\n");
  ```

Pointer arithmetic

- Adding an integer to a pointer advances it by that number of objects
- If p is an int *, p + 1 is a pointer to the int next to it
  - Type indicates how much to move
  - Programmer’s responsibility to know there is an int there
- p[i] is equivalent to *(p + i)
- Thus, a pointer is roughly equivalent to an array of unknown size
- Array converted into pointer in most places it appears
  - E.g. in function argument type, int x[] and int *x are equivalent
Blocks and indentation

- Use curly braces to group multiple statements, e.g. inside an if statement
  - Without braces, only one statement inside if
- Can declare variables inside a block, not visible outside
- Safer to use braces than not: they make grouping clear, like parentheses
  - Example “dangling else” ambiguity: else after nested ifs
- It is conventional to use indentation to show nesting level
  - But compiler completely ignores whitespace
  - Many opinions and arguments about where to put braces relative to indentation

while and for loops

- A while loop repeats a statement/block as many times as a condition is true (can be 0 times)

```markdown
while (x > 0) {
  x--;
} /* x is now 0 or negative */
```

- A for loop groups a while with two other statements, commonly assignment and update of the same variable

```markdown
for (A; B; C) D;
/* is equivalent to: */
A;
while (B) { D; C }
```

Leaving in the middle of a loop

- A break statement jumps to the end of the innermost enclosing loop
- A continue statement jumps to the next iteration of a loop
  - For a for loop, the increment part is executed
- A return statement ends the entire function
- There is also a goto statement, but don’t use it
  - One arguable application: jumping out of an outer loop

Debugging and debuggers

- You have probably already had the experience of making a mistake in a program
- Speaking roughly, “debugging” is the process:
  - After you know that your code is wrong
  - But before you know how it is wrong
- Some kinds of debugging that don’t need much tool support:
  - Code review
  - Rubber duck debugging
  - Printf debugging

Debugging in the development cycle

What is a debugger for?

- Not to fix your bugs for you, alas
  - Computers aren’t that smart yet
- Instead, helps you examine your program’s execution in more detail
  - See what is happening if something is obviously wrong
  - Walk through normal execution, to compare with your expectations
- Standard practice is source-level debugging
  - I.e., the debugger shows your program in terms of its source code
  - For binaries, made possible by debugging information (enabled with compiler option -g)
The GNU debugger GDB

- Standard command-line, source and binary-level debugger on Linux
- Start up with `gdb ./my_program`
- Supply program arguments to the GDB `run` command
  - Abbreviated just `r`
- Or, use `gdb --args ./my_program arg1 arg2`
  - This mode doesn’t work for redirection (shell `<`, `>``
- Today: using GDB as a source-level debugger

break, step, next, continue

- Normally, GDB will execute your program normally
- To get it to stop to let you look around, turn on a breakpoint with the command `break b`
  - Argument can be function name, file and line number, others
- When the breakpoint is reached, your program will stop and you can give GDB commands
- Run the program for one line with `step s`
  - Variant `next n` does not go into other functions
- To go back to full-speed execution, use `continue c`

print

- The most important command for examining program state is `print p`
  - The argument is a source-level (i.e., C) expression
- Some features to know about
  - Can do arithmetic
  - Can refer to any variable in scope
  - Can call functions
  - Can do assignments
  - `p/x` prints in hexadecimal (other formats also available)

Crashes, interrupts, and backtrace

- GDB will automatically stop if the program runs into a crash like a segfault (technically: a Unix signal)
- To stop in the middle of execution, type `Ctrl-C`
  - Good for debugging infinite loops
- The command `backtrace bt` summarizes all the currently executing functions
  - Similar to what Java and Python print for an unhandled exception

Watchpoints

- A watchpoint is sort of like a breakpoint, but based on data
- The command `watch` takes an argument like `print`
- A watchpoint stops execution when that value changes
- Useful for tracking down problems caused to pointers
- If you use a source-level expression, you’ll usually get a software watchpoint, which is slow
  - Later, we’ll see hardware watchpoints

Pass by value

- The parameters to a C function are always just copies of values from the caller
  - Called “pass by value”
- I.e., they are local variables; changing them has no effect outside the function

```c
int global;
void f(int a, int b) {
    a++; /* does not change global */
    b--; /* does not change 2 + 2 */
}
void g(void) { f(global, 2 + 2); }
```
Recursion
- A function can call itself, directly or indirectly
- Each instance has its own copy of local variables
  - Used to implement algorithms like quicksort, parsing
- Can also be used as an alternative form of loop
  - Not as common in C as in functional languages
- Each instance usually uses some memory
  - Deep recursion is not too common in C

Simulating pass by reference
- What if you want a function to modify caller’s variables?
  - Called “pass by reference”
- Simulated in C by passing explicit pointers

```c
void increment_by(int *ip, int amt) {
    *ip += amt;
}
void f(void) {
    int x;
    increment_by(&x, 5);
}
```
- Commonly used instead of multiple return values
  - Pointer parameters classified as "in", "out", "in/out"

Structures
- Data type that groups multiple named values

```c
struct student {
    char *name;
    int grade;
};
```
- Fields accessed with the . operator

```c
struct student jane;
jane.name = "Jane";
jane.grade = 100;
```
- Compared to OO languages, like objects but without methods, inheritance, or visibility restrictions

Points to structures
- In more complex situations, you often want to refer to structs with pointers
- sp->f is short for (*sp).f

```c
void mark_off(struct student *sp) {
    sp->grade += 10;
}
```
- Note for Java users: Java object (references) are like structure pointers
  - Even though pointer aspect is not explicit in syntax
  - E.g., two variables can refer to the same object
  - Despite the symbol, Java’s . is like C’s ->

Demo break: string array in GDB
```c
char *str_array[2] = { "Dear", "John" };
```

Allocating structures
- If structs are like objects, what’s the equivalent of new?

```c
struct student *sp = malloc(sizeof(struct student));
```
- Malloc is a basic routine for dynamically allocating memory
  - Argument is size in bytes
  - Return value has type void *, automatically converted
  - Contents can be anything, you must initialize
- For now, learn as an idiom; we’ll see more details later
  - Use with arrays
  - Changing size with realloc
  - Returning memory with free (don’t need to do this in Proj 1)
Null pointers
- Pointers have a special value that means not pointing at anything
  - Often used to represent endpoints or empty data structures
- Integer 0 converted to pointer, also NULL macro
  - On most systems, internal representation is 0
- A null pointer counts as false, any other pointer is true
- Dereferencing a null pointer usually causes a segfault
  - So you need to check first

Pointer and sharing pitfalls
- Passing a pointer to data is usually faster than copying it
  - Only one copy of data exists; it is shared by different users
- But, sharing can also lead to unexpected behavior
  - E.g., data changing when you do not expect it to
- Pointer to a local variable is valid only until its function finishes
  - Attempts to access later may cause a crash
- Sometimes you do want to make a copy of data
  - Allocate a new struct/array and copy contents over
  - strdup is a convenience function for duplicating a null-terminated string

Example: linked list length
- Can iterate over a singly-linked list with a for loop:

```c
struct list_node {
    struct list_node *next;
    int value;
};

int length(struct list_node *root) {
    struct list_node *p; int i = 0;
    for (p = root; p; p = p->next)
        i++;
    return i;
}
```

Logistics intermission: Piazza reminder
- As of earlier this afternoon, about half of you had already registered for the Piazza forum
- The rest of you should do so too, using the “Piazza” link from the main course web page
- Please use Piazza for questions and discussions about the lab exercises
  - Including an interesting bug in one of the lab questions

A few more fun operators
- The “ternary” operator ?: is like an if-then-else
  ```c
  printf("Found %d objects\n", n, 
         ((n == 1) ? "1" : "s"));
  ```
- The comma , evaluates two expressions and returns the right-hand one
  - Useful for putting multiple assignments in a for loop header
- ++ and -- can also be prefixes, and return a value
  - Prefix versions like ++x first update, then return new value, “pre-increment”
  - Postfix versions like x++ update, but return old value, “post-increment”
- Overusing these operators can make code hard to read

typedef
- Used to create a type name that is a synonym for another type
  - Syntax is like that of a variable declaration
    ```c
    typedef char zipcode[5];
    zipcode umn = "55455";
    ```
- Commonly used to save typing “struct”:
  ```c
  typedef struct list_node node;
  node table[100];
  ```
### switch statement

- Used for making a choice based on several integer values

```c
switch ('a' + (letter % 26)) {
    case 'a': case 'e': case 'i':
        printf("Vowel\n");
        break;
    case 'y':
        printf("Maybe y\n");
        break;
    default:
        printf("Consonant\n");
        break;
}
```

### The C standard library

- Every C implementation implements a large number of common routines
  - Load the declarations with an appropriate include
    - `stdio.h`: `printf`, `scanf`, `fopen`, `fclose`, `fread`, `fwrite`
    - `stdlib.h`: `malloc`, `exit`, `NULL`, `atoi`, `qsort`
    - `math.h`: `sqrt`, `sin`, `pow`
    - `string.h`: `strlen`, `strcpy`, `strncpy`, `memcpy`
    - `assert.h`: `assert`
    - `ctype.h`: `isalpha`, `isspace`

- Still limited compared to Java, C++, or Python
  - Some interfaces have old/poor designs (e.g., `gets`)
  - Lacking general-purpose data structures
  - Other stuff also in a typical OS-specific C library / C runtime

### The C preprocessor

- The first step of compiling C code is text-level processing
  - Also available as a separate tool, `cpp` on Unix
- Preprocessor directives are lines that start with `#`
  - `#include` reads in another file
    - Typically a header `.h` file that contains declarations
    - `<>` for system headers, `""` for program headers
  - `#define` creates a macro
    - Synonym for a value that is substituted in later
    - Simple uses similar to `typedef` or `const` variable
    - ```c
        #define TABLE_SIZE 1000
        int table[TABLE_SIZE];
    ```

### Conditional compilation

- Use macros and simple arithmetic to decide what code to use
  ```c
  #ifdef __i386__
  typedef long long int64;
  #elif defined(__amd64__)
  typedef long int64;
  #else
  #error "No known 64-bit type"
  #endif
  ```

- `#if 0 / #endif` can "comment-out" code containing comments

### Function-like macros

- Macros can also define simple computations
  - Implemented by textual substitution
    - ```c
        #define MAX(x, y) \n        (x > (y) ? (x) : (y))
    ```
- A number of pitfalls to be aware of:
  - Should have parentheses around outside, and each argument
  - Multiple lines need `\` continuation
  - Variables can cause name clashes
  - Multiple side-effects possible with `,`
  - Statement needs do `{ ... }` while `(0)`
- Often better to use a real function, compiler can inline