C for Science

Lecture 2 of 5

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Last Week...

- C is a language for creating fast, portable programs.
- We use an IDE to write source, compile, link and debug our C programs.
- The basic structure of a C program has been demonstrated and used.
- There are two categories of number in C: integers and floating point numbers.
- We have seen how logic and statements can control the flow of a program.
- `printf` and `scanf` will write and read from the console respectively.

Terse Code

There are shortcuts in the C language that allow for concise code.

1. Incrementing by 1: Pre-increment, and post-increment.
   `++i` Increment `i` by 1, then use it.
   `i++` Use `i`, then increment it by 1.
2. Increment by another variable.
   Normal code: `sum = sum + v[i];`
   Terse code: `sum += v[i];`

An example:

```
for (i=0; i < N; i++)
    sum += v[i];
```

More Shorthand

`--i;`	decrement `i` by 1.
`sum -= v[i];`	means `sum = sum - v[i];`
`sum *= v[i];`	means `sum = sum * v[i];`
`sum /= v[i];`	means `sum = sum / v[i];`
`sum %= 2;`	means `sum = sum % 2;`

Other operators can also be abbreviated this way.

Inline `if` - The Ternary Operator

The following code:

```
if (r1 > r2) { maxr = r1; }
else maxr = { r2; }
```

can be abbreviated:

```
maxr = (r1 > r2) ?  r1 :  r2;
```

Defining Functions

The C language only provides essential functionality, meaning a lot of functions need to be written yourself. Here are a few general rules for functions:

- Functions cannot define other functions within them.
- An optional single value can be returned.
- All arguments to functions are passed by value and remain unaffected by the function.
- Passing pointers to functions allows them to “return” multiple variables.

Declarations vs Definitions

Function Declarations

These tell the compiler about the *existence* of a function, which then allows us to call it. A declaration ends with a `;`.

```
int quad_roots (double A, double B, double C,
                double * r1, double * r2);
```

Function Definitions

The code making up the function is supplied to the compiler. A function can only be defined once. A definition contains braces { and }:

```
int quad_roots (double A, double B, double C,
                double * r1, double * r2)
{...}
```

An Example: Quadratic Equation Solver

As a worked example we write a function to solve the quadratic equation:

$$Ax^2 + Bx + C = 0 \qquad A, B, C \in \mathbb{R}$$

Our quadratic solver will:

- Take the three doubles `A`, `B` and `C` as arguments.
- Solve the quadratic and return an `int` signifying to the caller the type of answer available:

-1	`A` = 0, we have a linear equation.
0	There are two distinct real roots.
1	We have a pair of complex conjugate roots.
2	Both roots are real and identical.

The Code

One possible function prototype is:

```
int quad_roots (double A, double B, double C,
                double * r1, double * r2);
```

- The variables `A`, `B` and `C` are unchanged by `quad_roots`.
- We need to return two doubles (the roots of the equation), thus we take in pointers `double *r1` and `double *r2`.
- C90 does not allow for complex number types (C99 does support them), so we have to think a little bit about the complex number case.

Code Snippet for Calling `quad_roots`

```
...
int main()
{
    double A, B, C, root1, root2;
    int quad_case;
    ...
    quad_case = quad_roots(A, B, C, &root1,
                                   &root2);

    switch(quad_case)
    {
    case -1: linear equation
```

Code Snippet for `quad_roots`

```
int quad_roots(double A, double B, double C,
               double * r1, double *r2)
{
   double d;

   /* linear case */
   if (A == 0.0)
   {
      *r1 = -C/B;
      return -1;
   }

   /* compute the discriminant */
   d = B*B-4.0*A*C;
```

The Stack

Let's consider this example function.

```
int hasRealRoots(double A,
        double B, double C)
{
    double d = B*B-4.0*A*C;
    if (d < 0) return 0;
    return 1;
}
```

- We need space to hold a copy of `A`, `B` and `C`.
- We need space to store our computed `d`.
- When we've finished, we need to get back to the calling function.

This is achieved by using a *stack*.

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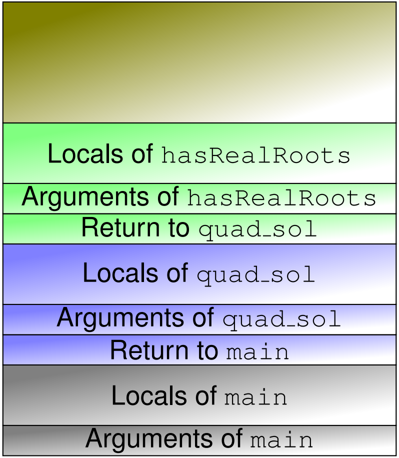
The Stack - Rough Sketch (Stack Frames)



- Consider the case where we have `main`, which calls `quad_sol`, which in turn calls `hasRealRoots`.
- We add and remove items from the stack as the program executes.
- Adding/removing items from the stack takes very little time.
- The stack is fixed in size, if we go over the top (“smash the stack”) , our program crashes.

Recursive Functions

As C uses a stack by default when calling functions, we are able to write functions that call themselves. These are called *recursive functions*.

An Example: Computing the Factorial

$$n! = \prod_{i=1}^{n} i, \quad 0! = 1, \qquad n \in \mathbb{N}.$$

Lends itself to be coded up as a recursive function.

A Tougher Example: Fibonacci Numbers

$$F_n = F_{n-1} + F_{n-2}, \qquad F_0 = F_1 = 1.$$

A naïve implementation of this will kill the stack, and take a very long time to execute.

Computing the Factorial

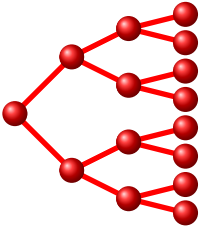
```c
#include <stdio.h>

int NFact(int N)
{
    if (N>1) return N*NFact(N-1);
    return 1;
}

int main()
{
    int n;
    printf("Enter n:");
    scanf("%d", &n);
    printf("%d! = %d\n", n, NFact(n));
    return 0;
}
```

Computing Fibonacci Numbers

```
int BadFib(int N)
{
    if (N < 2) return 1;
    return (BadFib(N-1) +
            BadFib(N-2));
}
```



```
int utilf(int a, int b, int n)
{
    if(n < 1) return b;
    return utilf(b, a+b, n-1);
}
int GoodFib(int n)
{
    return utilf(0, 1, n);
}
```

Imperative versus Functional Programming

Two programming techniques are popular in C:

Imperative

- Very long functions.
- Lots of global variables.
- Very few function calls.

Functional

- Lots of small functions.
- Each function has a clearly defined rôle.
- Global variables avoided as much as possible.

I would encourage leaning towards the latter, a good program will contain traits from both styles.

Functions with Variable Number of Arguments

Sometimes we don't know in advance how many arguments (or what type) a function needs, so C allows functions to have an unknown number of arguments. Two examples we've seen so far are `printf` and `scanf`.

- The first parameter must be of a normal type (i.e. `int`).
- Three dots (`...`) are used for the last parameter.

```
int printf(char * formatString, ...)
```

Handling variable arguments

Variable arguments are manipulated using `va_start()`, `va_arg()`, and `va_end()`. These are found in `<stdarg.h>`.

Having just introduced these, I'm going to ask you **not** to use them! Arrays are almost always more appropriate to use.

Handling the command-line in C

- So far, we have used the prototype: `int main(void)`.
- UNIX and Windows support command-line arguments to programs, and these need to be passed to main somehow.
- There is another prototype of `main` we are allowed to use:

```
int main(int argc, char ** argv)
```

The example below prints out the command-line arguments to a program:

```
#include <stdio.h>

int main(int argc, char ** argv)
{
   int loop;
   for (loop = 0; loop < argc; loop++)
      printf("argv[%d] = %s\n", loop, argv[loop]);
   return 0;
}
```

Functions - Summary

- Functions need to be declared before they are used. This is often done in *header files*.
- Up to one value can be returned from a function using the `return` statement.
- A variable `var` can be changed by a function if we pass the pointer `&var`.
- Pointers are declared using `type * variable;`

Arrays

- These are blocks of data, all of the same type. Each element is indexed using the array index operator:
  e.g. `myArray[index]` or `primes[3]`.
- Arrays are declared with types and sizes:
  e.g. `double xVector[3];`
- Arrays can be initialised:
  e.g. `int primes[6] = {2, 3, 5, 7, 11, 13};`
- All the elements of an array can be initialised to the *same* value:
  e.g. `double lotsOfDoubles[100] = {0.0};`
- **Arrays in C are indexed from 0!**

Accessing Array Elements

Arrays in C are indexed from 0!

```
#include <stdio.h>

int main()
{
    int primes[6] = {2, 3, 5, 7, 11, 13};

    printf("first prime = %d\n", primes[0]);
    printf("next prime = %d\n", primes[1]);

    return 0;
}
```

A little more on pointers

Reminder

- Declared using: `type * ptrVar;`
- Variable to pointer (pointer *referencing*): `ptrA = &A;`
- Pointer to variable (pointer *de-referencing*): `*ptrA = newVar;`

In addition

Pointers are memory addresses, and as such allow arithmetic!

Pointer Arithmetic

- Different data types in C are different sizes.
- Pointers are usually declared with a type (i.e. `int *`, `float *`, `double *`).

Relation to Arrays

Given the array `myArray` and an integer `index`, the following is true:

```
myArray[index] = *(myArray + index)
```

- And this is the reason array indices start at 0...

Debugging

- Once you've designed, typed up and successfully compiled your program, the difficult part begins: debugging!
- Problems in the code are usually either easy to locate or stubbornly elusive.

Easier Problems

- Program crash/fault at the same point every run.

Nastier Problems

- Numerical output differs to what is expected.
- Program crashes seemingly randomly.

Debugging Techniques

In increasing order of difficulty:

Create Verbose Output

- A few strategically placed `printf` statements can prove to be helpful, but they have to be read (by a human):
  - too few and you miss the problem,
  - too many and they rapidly become useless.
- Straightforward to implement (and to comment out).

Code Defensively

- Consider specialised test cases.
- Write code to test intermediate results.
- Use the `assert` macro.

Use a Debugger

For those non-trivial problems.

Assertion Checking

In the header `<assert.h>`, the macro `assert` is defined. It has the following syntax:

```
assert(logical_expression);
```

If *logical_expression* evaluates to false (zero) then:

- Program execution stops immediately.
- An error message is sent to *stderr* (the console) stating the line number where the assertion failed.

```
assert( a != 0); /* a should never be zero */
```

Switching it off

Placing `#define NDEBUG` before all the `#include <assert.h>` statements de-activates assertion checking.

Assertion Checking - An Example

```c
#include <stdio.h>
#include <assert.h>
/* the sqrt function is much better than this... */
double squareRoot(double N)
{
   double x = 1.0;
   int loop;
   /* negative numbers are not allowed! */
   assert(N >= 0.0);
   if (N == 0.0) return 0.0;
   for (loop = 0; loop < 10; loop++)
      x = (x*x+N)/(2.0*x);
   return x;
}

int main()
{
   double square;
   printf("Enter a non-negative number:");
   scanf("%lg", &square);
   /* SHOULD HAVE: if (x < 0.0) ...         */
   printf("Square root = %g\n", squareRoot(square));
   return 0;
}
```

The C Preprocessor - Conditional Compilation

We have already seen the `#include` and `#define` statements. Conditional statements are also possible:

```
#include <stdio.h>

int main(int argc, char ** argv)
{
#ifdef NDEBUG
    printf("Assertions DISABLED\n");
    printf("%d arguments\n", argc);
#else
    printf("Assertions ENABLED\n");
#endif
    return 0;
}
```

This logic is performed at *compile time*.

Using a Debugger

- Microsoft's Visual Studio contains a brilliant interactive debugger.
- GNU debugger (`gdb`) is also very good, and is essential for certain scenarios.
- Programs need to be compiled with debug information.
- Running a program straight through a debugger will show you the line of code that crashed it (if it crashes).

Interactive Analysis of Running Code

- Program execution can be paused at *breakpoints*.
- Functions can be *stepped into*, *stepped over*, or *stepped out from*.
- Variables/arrays can be *watched*.

Interactive debugging is very tricky at first, but soon becomes invaluable for isolating subtle problems.

Common Problems

1. Misuse of Power!
   x^2 should always be written `x*x`, *NOT* `pow(x, 2.0)`.
   $\sqrt{x}$ should be written `sqrt(x)`, *NOT* `pow(x, 0.5)`.
2. Integer Division
   Remember a fraction such as `1/3` is equal to zero. To get a floating point fraction, this should be rewritten `1.0/3.0`.

Floating Point Numbers (IEEE 754 Standard)

(from the previous lecture)

On my machine, a `float` (single precision) looks like:

b	e	e	e	e	e	e	e	e	f	f	f	f	f	f	f	f	f	f	f	f	f	f	f	f	f	f	f	f	f	f	f

It consists of three parts, the *sign bit*(b), the *biased exponent*(e) and the *fraction*(f). We break down a number x:

$$x^{\text{float}} = (-1)^b \times 2^{e-127} \times \left(1 + f \times 2^{-23}\right), \quad \begin{array}{c} 0 < e < 255 \\ 0 \leq f \leq 2^{23} - 1 \end{array},$$

We have three special numbers, `-Inf` $(-\infty)$, `Inf` (∞) and `NaN` (Not a Number).

For `double` (double precision) we have:

$$x^{\text{double}} = (-1)^b \times 2^{e-1023} \times \left(1 + f \times 2^{-52}\right), \quad \begin{array}{c} 0 < e < 2047 \\ 0 \leq f \leq 2^{52} - 1 \end{array}.$$

Floating Point Number Analysis

In <float.h>, there are some useful quantities:

Quantity	Float	Double
Maximum Value	`FLT_MAX`	`DBL_MAX`
Minimum Value	`FLT_MIN`	`DBL_MIN`
Max Decimal Exponent	`FLT_MAX_10_EXP`	`DBL_MAX_10_EXP`
Min Decimal Exponent	`FLT_MIN_10_EXP`	`DBL_MIN_10_EXP`
ϵ	`FLT_EPSILON`	`DBL_EPSILON`

Floating point ϵ

ϵ is the smallest (in magnitude) number such that:

$$1.0+\epsilon \;\; != \;\; 1.0$$

Floating Point Accuracy

- Some numbers can be represented in floating point exactly: e.g. 2^i, any integers that fit in the significand (mantissa).
- Most numbers need to be approximated, e.g. $\sqrt{2}$, π.
- One overlooked example is `0.1`!
- It is possible (though rare) to get exact answers from floating point arithmetic
- Relative errors of $\approx 10^{-15}$ for `double` and $\approx 10^{-6}$ for `float` are considered to be very good.
- Multiplication and division generally preserve relative error (but can take us outside the floating point range).

The Largest Source of Floating Point Errors

Addition and subtraction are the largest contributors to floating point error.

The Golden Rule

Do not subtract two very similar floating point numbers!

(This leads to “*catastrophic cancellation*”.)

Casting

Casting can either be *implicit* or *explicit*.

Implicit Casting

Conversion where there is no ambiguity (i.e. to a “bigger” data type) can be done automatically:

```
double x = 5; /* conversion from int to double */
double fEps = FLT_EPSILON; /* float to double */
```

Explicit Casting

If we wish to force a type conversion we place the destination type in brackets before the source variable:

```
oldtype oldData = ...
newtype newData = (newtype) oldData;
```

Explicit casting should be avoided if possible.

Operator Precedence and Associativity

From K&R2:

Operators	Associativity
() [] -> .	left to right
! ~ ++ -- + - * & (*type*) sizeof	right to left
* / %	left to right
+ -	left to right
<< >>	left to right
< <= > >=	left to right
== !=	left to right
&	left to right
^	left to right
|	left to right
&&	left to right
||	left to right
?:	right to left
= += -= *= /= %= &= ^= |= <<= >>=	right to left
,	left to right

Operator Precedence and Associativity - Examples

```
a - b * c / d
```

1. `*` and `/` are carried out before `-` due to precedence.
2. `*` is carried out before `/` due to (left to right) associativity.

```
if (x & MASK == 0)
```

- `==` has a higher precedence than `&` so is executed first!
- To get what we originally intended, parentheses are needed:

```
if ((x& MASK) == 0)
```

If in doubt

Put brackets around things...

C Keywords

The following keywords are recognised by all C compilers as special commands. These words should not be used for variable names, function names etc.

`auto`	`break`	`case`	`char`
`const`	`continue`	`default`	`do`
`double`	`else`	`enum`	`extern`
`float`	`for`	`goto`	`if`
`int`	`long`	`register`	`return`
`short`	`signed`	`sizeof`	`static`
`struct`	`switch`	`typedef`	`union`
`unsigned`	`void`	`volatile`	`while`

Preprocessor Keywords

- We also have the following preprocessor keywords:

`#include`	`#define`	`#undef`
`#if`	`#ifdef`	`#ifndef`
`#elif`	`#else`	`#endif`
`#error`	`#line`	`#pragma`

Scope: The Accessibility of Variables

Every variable in C has, associated with it, a *scope*. This defines how the variable can be accessed by functions in C. Some of the scoping rules are:

- All variables declared in the normal way inside a function are *local* to that function.
- Local variables can only be changed within the function they are defined, *unless*:
  - A pointer to a local variable may be passed to a function, extending the scope of that variable.
  - The are declared to be `extern` (more on this later).

Scope: Example 1

```c
#include <stdio.h>

void F1()
{
    int i = 4;
    printf("In F1(): I = %d\n", i);
}

int main()
{
    int i = 2;
    printf("In main(): I = %d\n", i);
    F1();
    printf("In main() again: I = %d\n", i);
    return 0;
}
```

Scope: Example 2

```c
#include <stdio.h>

void F1(int i)
{
    printf("In F1(): I = %d\n", i);
    i = 3;  /* what does this do? */
}

int main()
{
    int i = 2;
    printf("In main(): I = %d\n", i);
    F1(i);
    printf("In main() again: I = %d\n", i);
    return 0;
}
```

Scope: Example 3

```c
#include <stdio.h>

void F1(int * i)
{
    printf("In F1(): I = %d\n", *i);
    *i = 3;  /* what does this do? */
}

int main()
{
    int i = 2;
    printf("In main(): I = %d\n", i);
    F1(&i);
    printf("In main() again: I = %d\n", i);
    return 0;
}
```

Projects and Makefiles

- It is possible (and encouraged) to build a program from multiple `.c` files.
- This maximises the portability of the code, and
- Speeds up compiling - if we only change one `.c` file we only need to recompile one file...
- Visual Studio manages programs in to so-called *projects*, and everything is done graphically.
- If using `gcc` at the command line there is a program called `make` which manages projects. Information for building programs is stored in a `Makefile`.

A sample Makefile

```
CFLAGS = -O2 -DNDEBUG -Wall -ansi
LFLAGS = -lm
CC = gcc
CLEANFILES = fst.o matrixfunctions.o fst fst.exe

fouriersinetrans: fst.c matrixfunctions.c
	$(CC) fst.c matrixfunctions.c $(LFLAGS) -o fst

clean:
	touch $(CLEANFILES)
	rm $(CLEANFILES)
```

- This compiles `fst.c` and `matrixfunctions.c`.
- It then links them to produce `fst.exe` (MinGW) or `fst` (*NIX).
- It has two rules `fouriersinetrans` (default) to build the program and `clean` to clean up all the compiled output.

The C Preprocessor - How to #define Externally

We are not restricted to `#define` statements in source code.

Visual Studio

In the Visual Studio “project properties” $\rightarrow$ “C/C++” $\rightarrow$ “Preprocessor” option we can specify preprocessor definitions.

gcc

In gcc we can specify define statements in the command line as follows:

```
gcc myfile.c -DNDEBUG -o myprogram
```

Summary

- Shorthand exists to allow us to create more concise code.
- Functions are used to structure, tidy and allow us to reuse code.
- Thought must be given to the stack when calling functions recursively.
- Arrays are data blocks of the same type.
- Debugging is the process of fixing code that is not giving the correct results.
- Variables can only be used within their 'scope' (shown with $\{\ldots\}$).
- Multiple `.c` files can be used to create one program.