CS319: Scientific Computing

Data types in C++; Input and output [DRAFT!]

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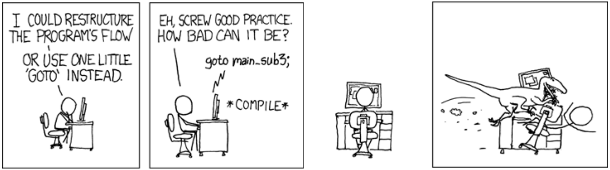

Source: xkcd (292)

	Mon	Tue	Wed	Thu	Fri
9 – 10				Lab	
10 – 11					???
11 – 12					Lecture
12 – 1					Lab
1 – 2					
2 – 3					
3 – 4					
4 – 5			Lecture		

... still working on the lab times...

Outline

Reminder: Programming Platform

To get started, we'll use an online C++ compiler. Try one of the following

- `http://cpp.sh`
- `https://www.programiz.com/cpp-programming/online-compiler/`
- `https://www.onlinegdb.com` (seems not to be working at the moment...)

If using a PC in the lab, try `Code::blocks`.

You should also install a compiler and IDE on your own device (see notes from Week 1).

Recall: variables

Last week, we learned that **variables** are used to temporarily store values (numerical, text, etc, ...) and refer to them by name, rather than value.

- Unlike Python, variables must be defined before they can be used. That means, we need to tell the compiler the variable's **name** and **type**
- Their **scope** is from the point they are declared to the end of the function.
- Formally, the variable's **name** is an example of an **identifier**. It must start with a letter or an underscore, and may contain only letters, digits and underscores.
- The **data types** we can define include `int`, `float`, `double`, `char`, and `bool`

Types

Integers (positive or negative whole numbers), e.g.,

```
int i; i=-1;
int j=122;
int k = j+i;
```

← most common.

Floats These are not whole numbers. They usually have a decimal places. E.g,

```
float pi=3.1415;
```

Note that one can initialize (i.e., assign a value to the variable for the first time) at the time of definition. We'll return to the exact definition of a `float` and `double` later.

Modifiers:

* unsigned int i = 12; // can't be negative.

* const int i =12 ; // can't be changed later

Types

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Types

Characters Single alphabetic or numeric symbols, are defined using the `char` keyword:

`char c;` or `char s='7';`

Note that again we can choose to initialize the character at time of definition. Also, the character should be enclosed by single quotes.

Arrays We can declare **arrays** or **vectors** as follows:

`int Fib[10];`

This declares a integer array called `Fib`. To access the first element, we refer to `Fib[0]`, to access the second: `Fib[1]`, and to refer to the last entry: `Fib[9]`.

As in Python, all vectors in C++ are indexed from `0`.

Types

Here is a list of common data types. Size is measured in bytes. = 8 bits

Type	**Description**	(*min*) **Size**
`char`	character	1
`int`	integer	4
`float`	floating point number	4
`double`	16 digit (approx) float	8
`bool`	`true` or `false`	1

See also: `00variables.cpp`

. . . .

In C++ there is a distinction between **declaration** and **assignment**, but they can be combined.

As noted above, a `char` is a fundamental data type used to store as single character. To store a word, or line of text, we can use either an *array of chars*, or a `string`.

If we've included the *string* header file, then we can declare one as in: `string message="Well, hello again";` This declares a variable called *message* which can contain a string of characters.

01stringhello.cpp

```
#include <iostream>
#include <string>
int main()
{
  std::string message="Well,␣hello␣again";
  std::cout << message << std::endl;
  return(0);
}
```

In previous examples, our programmes included the line

`#include <iostream>`

Further more, the objects it defined were global in scope, and not exclusively belonging to the *std* namespace...

This is a bit like, in Python:
import MOD; % now access members as MOD.whatever

A **namespace** is a declarative region that localises the names of identifiers, etc., to avoid name collision. One can include the line

`using namespace std;` *A bit like: from MOD import **

to avoid having to use `std::`

(The C++ world is a little divided on whether `using namespace std` is good or bad practice. Personally, I don't use it, because it can impact the portability of my code. Only exception is that sometimes it helps fit my code examples onto a slide!)

A closer look at `int`

It is important for a course in Scientific Computing that we understand how numbers are stored and represented on a computer.

Your computer stores numbers in binary, that is, in base 2. The easiest examples to consider are `int`egers.

Examples:

decimal	binary	
0	0	
1	1	
2	10	
3	11	
4	100	
5	101	
6	110	Etc.

A closer look at `int`

If just one byte were used to store an integer, then we could represent:

assuming the int is non-negative we can store

$$1\ 1\ 1\ 1\ 1\ 1\ 1\ 1 = 255 = 2^8 - 1$$

$64 + 32 + 16 + 8 + 4 + 2 + 1$

$+128$

A closer look at int

In fact, 4 bytes are used to store each `integer`. One of these is used for the sign. Therefore the largest `integer` we can store is $\boxed{2^{31}-1}$...

4 bytes = 4x8 = 32 bit.

One is needed for the sign (+ or -)

and 31 for the value

We'll return to related types (`unsigned int`, `short int`, and `long int`) later.

$2^{31}-1 = 2{,}147{,}483{,}647$

A closer look at `float`

C++ (and just about every language you can think of) uses IEEE Standard Floating Point Arithmetic to approximate the real numbers. This short outline, based on Chapter 1 of O'Leary "*Scientific Computing with Case Studies*".

A floating point number ("**float**") is one represented as, say, 1.2345×10^2. The "fixed" point version of this is 123.45.

Other examples:

$$50.0 = 5.00 \times 10^{1}$$

$$0.123 = 1.23 \times 10^{-1} = \boxed{1 \times 10^{-1} + 2 \times 10^{-2} + 3 \times 10^{-3}}$$

$$0.0045 = 4.5 \times 10^{-3}$$

$$9.15 = 9.15 \times 10^{0}$$

A closer look at `float`

As with integers, all floats are really represented as binary numbers.

Just like in decimal where 0.03142 is:

$$3.142 \times 10^{-2} = (3 \times 10^{0} + 1 \times 10^{-1} + 4 \times 10^{-2} + 2 \times 10^{-3}) \times 10^{-2}$$
$$= 3 \times 10^{-2} + 1 \times 10^{-3} + 4 \times 10^{-4} + 2 \times 10^{-5}$$

For the floating point binary number (for example)

$$1.1001 \times 2^{-2} = (1 \times 2^{0} + 1 \times 2^{-1} + 0 \times 2^{-2} + 0 \times 2^{-3} + 1 \times 2^{-4}) \times 2^{-2}$$
$$= 1 \times 2^{-2} + 1 \times 2^{-3} + 0 \times 2^{-4} + 0 \times 2^{-4} + 1 \times 2^{-6}$$
$$= \frac{1}{4} + \frac{1}{8} + \frac{1}{64} = \frac{25}{16} = 0.390625.$$

But notice that we can choose the exponent so that the representation always starts with 1. That means we don't need to store the 1: it is **implied**.

A closer look at `float`

The format of a float is

$$x = (-1)^{Sign} \times (Significant) \times 2^{(offset+Exponent)},$$

where

- *Sign* is a single bit that determines of the float is positive or negative;
- the *Significant* (also called the "**mantissa**") is the "fractional" part, and determines the precision;
- the *Exponent* determines how large or small the number is, and has a fixed offset (see below).

A `float` is a so-called "single-precision" number, and it is stored using 4 bytes ($= 32$ bits). These 32 bits are allocated as:

- 1 bit for the *Sign*;
- 23 bits for the *Significant* (as well as an leading implied bit); and
- 8 bits for the *Exponent*, which has an offset of $e = -127$.

So this means that we write x as

$$x = \underbrace{(-1)^{Sign}}_{\text{1 bit}} \times 1.\underbrace{abcdefghijklmnopqrstuvw}_{\text{23 bits}} \times \underbrace{2^{-127+Exponent}}_{\text{8 bits}}$$

Since the *Significant* starts with the implied bit, which is always 1, it can never be zero. We need a way to represent zero, so that is done by setting all 32 bits to zero.

Finish here.

A closer look at `float`

The smallest the *Significant* can be is

$$1.\underbrace{0000000000000000000000}_{\text{22 zeros}}1 \approx 1.$$

The largest it can be is

$$1.\underbrace{11111111111111111111111}_{\text{23 ones}} = 2 - 2^{23} \approx 2.$$

A closer look at `float`

The *Exponent* has 8 bits, but since they can't all be zero (as mentioned above), the smallest it can be is $-127 + 1 = -126$. That means the smallest positive float one can represent is $x = (-1)^0 \times 1.000\cdots 1 \times 2^{-126} \approx 2^{-126} \approx 1.1755 \times 10^{-38}$.

We also need a way to represent ∞ or "Not a number" (`NaN`). That is done by setting all 32 bits to 1. So the largest *Exponent* can be is $-127 + 254 = 127$. That means the largest positive float one can represent is
$x = (-1)^0 \times 1.111\cdots 1 \times 2^{127} \approx 2 \times 2^{127} \approx 2^{128} \approx 3.4028 \times 10^{38}$.

As well as working out how small or large a `float` can be, one should also consider how **precise** it can be. That often referred to as the **machine epsilon**, can be thought of as *eps*, where $1 - eps$ is the largest number that is less than 1 (i.e., $1 - eps/2$ would get rounded to 1).

The value of *eps* is determined by the *Significant*.

For a `float`, this is $x = 2^{-23} \approx 1.192 \times 10^{-7}$.

As a rule, if `a` and `b` are floats, and we want to check if they have the same value, we don't use `a==b`.

This is because the computations leading to `a` or `b` could easily lead to some round-off error.

So, instead, should only check if they are very "similar" to each other: `abs(a-b) <= 1.0e-6`

A closer look at `float`

For a `double` in C++, 64 bits are used to store numbers:

- 1 bit for the *Sign*;
- 52 bits for the *Significant* (as well as an leading implied bit); and
- 11 bits for the *Exponent*, which has an offset of $e = -1023$.

The smallest positive double that can stored is $2^{-1022} \approx 2.2251e - 308$, and the largest is

$$1.111111 \cdots 111 \times 2^{2046-1023} = \left(1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \frac{1}{16} + \ldots\right) \times 2^{2046-1023}$$
$$\approx 2 \times 2^{1023} \approx 1.7977e + 308.$$

(One might think that, since 11 bits are devoted to the exponent, the largest would be $2^{2048-1023}$. However, that would require all bits to be set to 1, which is reserved for NaN).

For a `double`, machine epsilon is $2^{-53} \approx 1.1102 \times 10^{-16}$.

A closer look at float double

An important example:

02Rounding.cpp

```
   int i, n;
   float x=0.0, increment;

   std::cout << "Enter a (natural) number, n: ";
   std::cin >> n;
   increment = 1/( (float) n);

   for (i=0; i<n; i++)
      x+=increment;

   std::cout << "Difference between x and 1: " << x-1
             << std::endl;

   return(0);
```

What this does:

A closer look at `float` `double`

- If we input $n = 8$, we get:

- If we input $n = 10$, we get:

We now know...

- An `int` is a whole number, stored in 32 bytes. It is in the range $-2,147,483,648$ to $2,147,483,647$.
- A `float` is a number with a fractional part, and is also stored in 32 bits.
  A positive `float` is in the range 1.1755×10^{-38} to 3.4028×10^{38}.
  Its **machine epsilon** is $2^{-23} \approx 1.192 \times 10^{-7}$.
- A `double` is also number with a fractional part, but is stored in 64 bits.
  A positive `double` is in the range 2.2251×10^{-308} to 31.7977×10^{308}.
  Its **machine epsilon** is $2^{-53} \approx 1.1102 \times 10^{-16}$.

Basic Output

Last week we had this example: *To output a line of text in C++:*

```
#include <iostream>
int main() {
  std::cout << "Howya World.\n";
  return(0);
}
```

- the identifier `cout` is the name of the **Standard Output Stream** – usually the terminal window. In the programme above, it is prefixed by `std::` because it belongs to the *standard namespace*...
- The operator `<<` is the **put to** operator and sends the text to the *Standard Output Stream*.
- As we will see `<<` can be used on several times on one lines. E.g.

```
    std::cout << "Howya World." << "\n";
```

As well as passing variable names and string literals to the output stream, we can also pass **manipulators** to change how the output is displayed.

For example, we can use `std::endl` to print a new line at the end of some output.

In the following example, we'll display some Fibbonaci numbers. Note that this uses the `for` construct, which we have not yet seen before. It will be explained next week

03Manipulators.cpp

```cpp
#include <iostream>
#include <string>
#include <iomanip>
int main()
{
  int i, fib[16];
  fib[0]=1; fib[1]=1;

  std::cout << "Without setw  manipulator" << std::endl;
  for (i=0; i<=12; i++)
  {
    if( i >= 2)
      fib[i] = fib[i-1] + fib[i-2];
    std::cout << "The " << i << "th " <<
      "Fibonacci Number is " <<  fib[i] << std::endl;
  }
```

Output Manipulators

- `std::setw(n)` will the width of a field to *n*. Useful for tabulating data.

03Manipulators.cpp

```
std::cout << "With the setw  manipulator" << std::endl;
for (i=0; i<=12; i++)
{
  if( i >= 2)
    fib[i] = fib[i-1] + fib[i-2];
  std::cout
    << "The " << std::setw(2) << i << "th "
    << "Fibonacci Number is "
    << std::setw(3) <<  fib[i] << std::endl;
}
```

Output Manipulators

Other useful manipulators:

- `setfill`
- `setprecision`
- `fixed` and `scientific`
- `dec`, `hex`, `oct`

Input

In C++, the object *cin* is used to take input from the standard input stream (usually, this is the keyboard). It is a name for the *C***onsole** *IN***put**.

In conjunction with the operator >> (called the **get from** or **extraction** operator), it assigns data from input stream to the named variable.

(In fact, `cin` is an **object**, with more sophisticated uses/methods than will be shown here).

Input

04Input.cpp

```cpp
#include <iostream>
#include <iomanip> // needed for setprecision
int main()
{
  const double StirlingToEuro=1.16541; // Correct 17/01/2024
  double Stirling;
  std::cout << "Input amount in Stirling: ";
  std::cin >> Stirling;
  std::cout << "That is worth "
            << Stirling*StirlingToEuro << " Euros\n";
  std::cout << "That is worth " << std::fixed
            << std::setprecision(2) << "\u20AC"
            << Stirling*StirlingToEuro << std::endl;
  return(0);
}
```