Modern C++ Programming

2. Basic Concepts I

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What compiler should I use?

Popular (free) compilers:

- Microsoft Visual C++ (**MSVC**) is the compiler offered by Microsoft
- The GNU Compiler Collection (**GCC**) contains the most popular C++ Linux compiler
- **Clang** is a C++ compiler based on LLVM Infrastructure available for Linux/Windows/Apple (default) platforms

Suggested compiler: **Clang**

- Comparable performance with GCC/MSVC and low memory usage [`compilers comparison link`]
- Expressive diagnostics (examples and propose corrections)
- Strict C++ compliance. GCC/MSVC compatibility (inverse direction is not ensured)
- Includes very useful tools: memory sanitizer, static code analyzer, automatic formatting, linter, etc.
- Easy to install: `releases.llvm.org`

C++ compiler features support: `en.cppreference.com/w/cpp/compiler_support`

Install the compiler

Install the last gcc/g++ (v8)

```
$ sudo add-apt-repository ppa:ubuntu-toolchain-r/test
$ sudo apt update
$ sudo apt install gcc-8 g++-8
$ gcc-8 --version
```

Install the last clang/clang++ (v7)

```
$ wget -O - https://apt.llvm.org/llvm-snapshot.gpg.key \
    | sudo apt-key add -
$ sudo apt-add-repository \
    "deb http://apt.llvm.org/xenial/ llvm-toolchain-xenial-6.0 main"
$ sudo apt update
$ sudo apt install -y clang-7.0
$ clang-7.0 --version
```

What editor/IDE compiler should I use?

Popular C++ IDE (Integrated Development Environment) and editors:

- **Microsoft Visual Studio**. (free, Windows)
- **QT-Creator** (link). Fast (written in C++), simple
- **Clion** (link). (free for student). Powerful IDE with a lot of options
- **Atom** (link). Standalone editor oriented for programming (GitHub). Many useful plugins and modular
- **Sublime Text editor** (link). Stand-alone editor oriented to programming
- **XCode**, **Eclipse** (**Cevelop**, `www.cevelop.com`), **Vim**, etc.

Not suggested:

- `Notepad, Gedit, and other similar editors`
  Lack of support for programming

How to compile?

Compile C++11, C++14, C++17 programs:

```
g++ -std=c++11 <program.cpp> -o program
g++ -std=c++14 <program.cpp> -o program
g++ -std=c++17 <program.cpp> -o program
```

Compiler version and C++ Standard:

Compiler	C++11		C++14		C++17	
	Core	Library	Core	Library	Core	Library
g++	4.8.1	5.1	5.1	5.1	7.1	ongoing
clang++	3.3	3.3	3.4	3.5	5.0	ongoing
MSVC	19.0	19.0	19.10	19.0	19.14	19.14+

Reference:
https://en.cppreference.com/w/cpp/compiler_support

Hello World

C code with `printf`:

```
#include <stdio.h>

int main() {
    printf("Hello World!\n");
}
```

`printf` prints on standard output

C++ code with streams:

```
#include <iostream>

int main() {
    std::cout << "Hello World!\n";
}
```

`cout` : represent the standard output stream

Hello World 2/2

The previous example can be written with the global `std` namespace:

```cpp
#include <iostream>
using namespace std;

int main() {
    cout << "Hello World!\n";
}
```

I/O Stream (std::cout)

`std::cout` is an example of *output* stream. Data is redirected to a destination, in this case the destination is the standard output

C:

```c
#include <stdio.h>

int main() {
    int    a = 4;
    double b = 3.0;
    char*  c = "hello";
    printf("%d %f %s\n", a, b, c);
}
```

C++:

```cpp
#include <iostream>

int main() {
    int    a = 4;
    double b = 3.0;
    char*  c = "hello";
    std::cout << a << " " << b << " " << c << "\n";
}
```

I/O Stream (Why should we prefer I/O stream?) 2/3

- **Type-safe**: The type of object pass to I/O stream is known statically by the compiler. In contrast, `printf` uses "%" fields to figure out the types dynamically
- **Less error prone**: With IO Stream, there are no redundant "%" tokens that have to be consistent with the actual objects pass to I/O stream. Removing redundancy removes a class of errors
- **Extensible**: The C++ IO Stream mechanism allows new user-defined types to be pass to I/O stream without breaking existing code
- **Comparable performance**: If used correctly may be faster than C I/O (`printf`, `scanf`, `etc`)

I/O Stream (Common C errors)

Forget the number of parameters:

```
printf("long phrase %d long phrase %d", 3);
```

Use the wrong format:

```
int a = 3;
...many lines of code...
printf(" %f", a);
```

The "%c" conversion specifier does not automatically skip any leading whitespace:

```
scanf("%d", &var1);
scanf(" %c", &var2);
```

C++ Primitive Types

Builtin Types

Type	Size (bytes)	Range	Fixed width types
`bool`	1	true, false	
`char` †	1	-127 to 127	
`signed char`	1	-128 to 127	int8_t
`unsigned char`	1	0 to 255	uint8_t
`short`	2	-2^{15} to $2^{15}-1$	int16_t
`unsigned short`	2	0 to $2^{16}-1$	uint16_t
`int`	4	-2^{31} to $2^{31}-1$	int32_t
`unsigned int`	4	0 to $2^{32}-1$	uint32_t
`long int`	4/8*		int32_t/int64_t
`long unsigned int`	4/8*		uint32_t/uint64_t
`long long int`	8	-2^{63} to $2^{63}-1$	int64_t
`long long unsigned int`	8	0 to $2^{64}-1$	uint64_t
`float` (IEEE 754)	4	$\pm 1.18 \times 10^{-38}$ to $\pm 3.4 \times 10^{+38}$	
`double` (IEEE 754)	8	$\pm 2.23 \times 10^{-308}$ to $\pm 1.8 \times 10^{+308}$	

* 4 bytes on Windows64 systems, † one-complement

Builtin Types

- C++ provides also `long double` (no IEEE-754) of size 8/12/16 bytes depending on the implementation

- **Any other entity in C++ is**
  - an *alias* to the correct type depending to the context and the architectures
  - a *composition* of builtin types: `struct`, `class`, `union`, etc.

- Interesting: C++ does not explicitly define the size of a byte

Other Data Types

- C++17 defines also `std::byte` type to represent a collection of bit (`<cstddef>`). It supports only bitwise operations (no conversions or arithmetic operations)

- C++ does not provide support for **half float** (16-bit) data type (IEEE 754-2008)
  - Some compilers already provide support for half float (GCC for ARM: `__fp16`, LLVM compiler: `half`)
  - Some modern CPUs (+ Nvidia GPUs) provide half-float instructions
  - There is a proposal (next standard) since 2016
  - Software support (OpenGL, Photoshop, Lightroom, `http://half.sourceforge.net/`)

Builtin Types (short name)

Signed Type	short name
`signed char`	`/`
`signed short int`	`short`
`signed int`	`int`
`signed long int`	`long`
`signed long long int`	`long long`

Unsigned Type	short name
`unsigned char`	`/`
`unsigned short int`	`unsigned short`
`unsigned int`	`unsigned`
`unsigned long int`	`unsigned long`
`unsigned long long int`	`unsigned long long`

http://en.cppreference.com/w/cpp/language/types

http://en.cppreference.com/w/cpp/types/integer

Builtin Types (suffix and prefix)

Builtin types suffix:

Type	Suffix	example
`int`	NO PREFIX	2
`unsigned int`	u	3u
`long int`	l	8l
`long unsigned`	ul	2ul
`long long int`	ll	4ll
`long long unsigned int`	ull	7ull
`float`	f	3.0f
`double`		3.0

Builtin types representation prefix:

Representation	Prefix	example
Binary C++14	0b	0b010101
Octal	0	0308
Hexadecimal	0x or 0X	0xFFA010

C++ provides fixed width integer types. They have the same size on any architecture (`#include <cstdint>`)

int8_t, uint8_t,

int16_t, uint16_t,

int32_t, uint32_t,

int64_t, uint64_t

Warning: I/O Stream interprets `uint8_t` and `int8_t` as `char` and not as integer values

```
int8_t var;
std::cin >> var;  // read '2'
std::cout << var; // print '2'
int a = var * 2;
std::cout << a;   // print 100 !!
```

Fixed Width Integers

`int*_t` types are <u>not</u> “real” types, they are merely *typedefs* to appropriate fundamental types

C++ standard does not ensure an one-to-one mapping:

- There are **five** distinct *fundamental types* (`char` , `short` , `int` , `long` , `long long`)
- There are **four** `int*_t` *overloads* (`int8_t` , `int16_t` , `int32_t` , and `int64_t`)

```
#include <cstddef>
void f(int8_t x)  {}
void f(int16_t x) {}
void f(int32_t x) {}
void f(int64_t x) {}
int main() {
    int x = 0;
    f(x); // compile error!! under 32-bit ARM GCC
} // "int" is not mapped to int*_t type in this (very) particular case
```

Full Story: `ithare.com/c-on-using-int_t-as-overload-and-template-parameters`

Pointer type and `size_t`

The **type of a pointer** (e.g. `void*`)is an unsigned integer of 32-bit/64-bit depending on the underlying architectures. It only supports the operators `+, -, ++, --` and comparisons `==, !=, <, <=, >, >=`

`size_t`

`size_t` is a data type capable of storing the biggest representable value on the current architecture (defined in `<cstddef>`)

- `size_t` is an unsigned integer type (of at least 16-bit)
- In common C++ implementations:
  - `size_t` is 4 bytes on 32-bit architectures
  - `size_t` is 8 bytes on 64-bit architectures
- `size_t` is commonly used to represent size measures

Conversion Rules

Implicit type conversion rules (applied in order) :

$\otimes$: any operations (*, +, /, -, %, etc.)

(a) Floating point promotion

floating_type $\otimes$ integer_type = floating_type

(b) Size promotion

small_type $\otimes$ large_type = large_type

(c) Sign promotion

signed_type $\otimes$ unsigned_type = unsigned_type

Common Errors

- Integers are not floating points!

```
int   b = 7;
float a = b / 2;   // a = 3 not 3.5!!
int   a = b / 2.0; // again a = 3 not 3.5!!
```

- Integer type are more accurate than floating types for large numbers!!

```
cout << 16777217;            // print 16777217
cout << (int) 16777217.0f; // print 16777216!!
cout << (int) 16777217.0;  // print 16777217, double ok
```

- `float` numbers are different from `double` numbers!

```
cout << (1.1 != 1.1f); // print true !!!
```

Implicit Conversions

- Unary `+, -, ~` promotion:

```
char a = 48;       // '0'
cout << a;         // print '0'
cout << +a;        // print '48'
cout << (a + 0); // print '48'
```

- Binary `+, -, &, etc.` promotion:

```
unsigned char a = 255;
unsigned char b = 255;
cout << (a + b);  // print '510' (no overflow)

unsigned short a = 65535;
unsigned short b = 65535;
cout << (a + b);  // print '131070' (no overflow)
```

Signed and **unsigned** integers use the same hardware for their operations, but they have very different semantic:

signed integers

- represent positive, negative, and zero values ($\mathbb{Z}$)
- overflow/underflow is undefined
- discontinuity in -2^{31}, $2^{31}-1$
- bit-wise operations are implementation-defined

unsigned integers

- represent only *non-negative* values ($\mathbb{N}$)
- overflow/underflow is well-defined (modulo 2^{32})
- discontinuity in 0, $2^{32}-1$
- bit-wise operations are well-defined

Common errors:

```
unsigned a = 10;
int      b = -1;
array[10 + a * b] = 0;
```

☠ Segmentation fault!

```
int f(int a, unsigned b, int* array) {
    if (a > b)
        return array[a - b];
    return 0;
}
```

☠ Segmentation fault!

```
// v.size() return unsigned
for (size_t i = 0; i < v.size() - 1; i++)
    array[i] = 3;
```

☠ Segmentation fault for v.size() = 0!

When Use Signed/Unsigned Integer? 3/3

Google Style Guide

> Because of historical accident, the C++ standard also uses unsigned integers to represent the size of containers - many members of the standards body believe this to be a mistake, but it is effectively impossible to fix at this point

Solution: use `int64_t`

max value: $2^{63} - 1 =$ 9,223,372,036,854,775,807 or
9 quintillion (9 billion of billion),
about 292 years (nanoseconds),
9 million terabytes

Overflow/Underflow

Detect overflow/underflow for floating point types is **easy** ($\pm$`inf`)

Detect overflow/underflow for unsigned integral types is **not trivial**

```
bool isAddOverflow(unsigned a, unsigned b) {
    return (a + b) < a || (a + b) < b;
}

bool isMulOverflow(unsigned a, unsigned b) {
    unsigned x = a * b;
    return a != 0 && (x / a) != b;
}
```

Overflow/underflow for signed integral types is **not defined** !!
Undefined behavior must be checked before perform the operation

`void` Type

`void` is an incomplete type (not defined) without a values

- `void` indicates also a function has no return type
  e.g. `void f()`
- `void` indicates also a function has no parameters
  e.g. `f(void)`
- In C `sizeof(void) == 1` (GCC), while in C++ `sizeof(void)` does not compile!!

```
int main() {
//  sizeof(void); // compile error!!
}
```

nullptr Keyword

C++11 introduces the new keyword `nullptr` to represent `null` pointers (instead of `NULL` macro)

```
int* p1 = NULL;    // ok, equal to int* p1 = 0
int* p2 = nullptr; // ok

int n1 = NULL;     // ok, we are assigning 0 to n1
// int n2 = nullptr;  // error! we are assigning a null pointer
//                       to an integer variable

// int* p2 = true ? 0 : nullptr; // incompatible types
```

Remember: `nullptr` is not a pointer, but an object of type `nullptr_t` → safer

auto Keyword

The `auto` keyword (C++11) specifies that the type of the variable will be automatically deduced by the compiler (from its initializer)

```
auto a = 1 + 2;   // 1 is int, 2 is int, 1 + 2 is int!
//    -> 'a' must be int
auto b = 1 + 2.0; // 1 is int, 2.0 is double. 1 + 2.0 is double
//    -> 'b' must be double
```

`auto` keyword may be very useful for maintainability.

```
for (auto i = k; i < size; i++)
    ...
```

On the other hand, it may make the code less readable if excessively used because of type hiding

Note: `auto x = 0;` in general makes no sense (`x` is int)

Builtin type limits

Query properties of arithmetic types C++11:

```cpp
#include <limits>

std::numeric_limits<int>::max();        // 2^31 - 1
std::numeric_limits<float>::max();      // 3.4 * 10^38

std::numeric_limits<int>::min();        // -2^31
std::numeric_limits<float>::min();      // 1.17 * 10^-38   !!!

std::numeric_limits<int>::lowest();     // -2^31
std::numeric_limits<float>::lowest();   // -3.4 * 10^38

std::numeric_limits<float>::infinity(); // inf
```

Floating-point Arithmetic

Floating Point

In general, C/C++ adopt IEEE754 floating-point standard

- Single precision (32-bit) (`float`)

Sign	Exponent (or base)	Mantissa (or significant)
1-bit	8-bit	23-bit

- Double precision (64-bit) (`double`)

Sign	Exponent (or base)	Mantissa (or significant)
1-bit	11-bit	52-bit

Floating Point (Exponent Bias)

Exponent Bias

In IEEE 754 floating point numbers, the exponent value is offset from the actual value by the **exponent bias**

- The exponent is stored as an unsigned value suitable for comparison
- Floating point values are lexicographic ordered
- For a single-precision number, the exponent is stored in the range $[1, 254]$ (0 and 255 have special meanings), and is biased by subtracting 127 to get an exponent value in the range $[-126, +127]$

- Example

0	10000111	11000000000000000000000
+	$2^{(135-127)} = 2^8$	$\frac{1}{2^1} + \frac{1}{2^2} = 0.5 + 0.25 = 0.75 \overset{normal}{\rightarrow} 1.75$

$$+1.75 * 2^8 = 448.0$$

Normal number

A **normal** number is a floating point number that can be represented without *leading zeros* in its mantissa (one in the first left position)

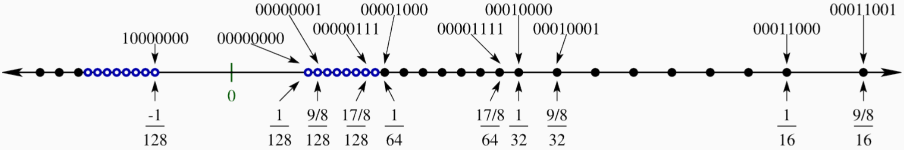
Denormal number

Denormal (or subnormal) numbers fill the underflow gap around zero in floating-point arithmetic. Any non-zero number with magnitude smaller than the smallest normal number is denormal

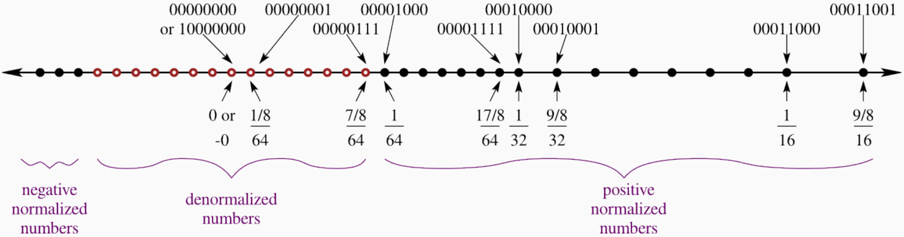
If the exponent is all 0s, but the mantissa is non-zero (else it would be interpreted as zero), then the value is a denormal number

Floating point online tool:
`www.h-schmidt.net/FloatConverter/IEEE754.html`

Why denormal numbers make sense: (↓ normal numbers)



The problem: distance values from zero (↓ denormal numbers)



reference: `www.toves.org/books/float/`

Floating Point (Special Values)

- ± infinity

*	11111111	00000000000000000000000

- `NaN` (mantissa $\neq 0$)

*	11111111	***********************

- ± 0

*	00000000	00000000000000000000000

- Denormal number ($< 2^{-126}$)(minimum: $1.4 * 10^{-45}$)

*	00000000	***********************

- Minimum (normal) ($\pm 1.17549 * 10^{-38}$)

*	00000001	00000000000000000000000

- Lowest/Largest ($\pm 3.40282 * 10^{+38}$)

*	11111110	11111111111111111111111

NaN Properties

NaN

In the IEEE754 standard, NaN (not a number) is a numeric data type value representing an undefined or unrepresentable value

Operations generating NaN:

- Operations with a NaN as at least one operand
- $\pm\infty \mp \infty$
- $0 \cdot \infty$
- $0/0, \infty/\infty$
- $\sqrt{x} \mid x < 0$
- $\log(x) \mid x < 0$
- $\sin^{-1}(x), \cos^{-1}(x) \mid x < -1 \text{ or } x > 1$

Comparison: `(NaN == x)` $\rightarrow$ false, for every `x`

`(NaN == NaN)` $\rightarrow$ false!!

Floating Point Issues

The floating point precision is finite!

```
cout << setprecision(20);
cout << 3.33333333f; // print 3.333333254!!
cout << 3.33333333;  // print 3.333333333
cout << (0.1 + 0.1 + 0.1 + 0.1 + 0.1 + 0.1);
// print 0.59999999999999998
```

Floating point arithmetic is commutative, but <u>not</u> associative and <u>not</u> reflexive (see `NaN`) !!

```
cout << 0.1 + (0.2 + 0.3) == (0.1 + 0.2) + 0.3; // print false
```

Floating-point computation guarantee to produce **deterministic** output, namely the exact bitwise value for each run, <u>if and only if</u> the **order of the operations is always the same**

Floating Point Issues

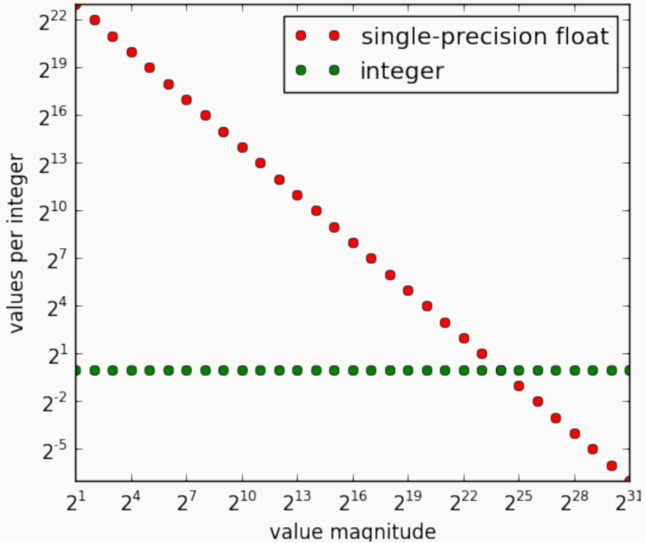
Floating point type has special values (C++11):

```
#include <limits>
std::numeric_limits<float>::infinity;  // float infinity
std::numeric_limits<float>::quiet_NaN; // float NaN
```

```
#include <cmath>
INFINITY // float infinity
NAN      // float NaN
```

```
cout << 0 / 0;          // undefined behavior
cout << 0.0 / 0.0;      // print "nan"

cout << (-0.0 == 0.0); // true
cout << 5.0 / 0.0;      // print "inf"
cout << -5.0 / 0.0;     // print "-inf"
cout << ((5.0 / 0.0) == ((5.0 / 0.0) + 9999999.0);  // true
cout << ((5.0f / INFINITY) == ((-5.0f / INFINITY)); // true
```



Intersection $= 16,777,216 = 2^{24}$

Floating-point increment

```
float x = 0.0f;
for (int i = 0; i < 20000000; i++)
    x += 1.0f;
```

What is the value of `x` at the end of the loop?

Ceiling division $\left\lceil \frac{a}{b} \right\rceil$

```
//          std::ceil((float) 101 / 2.0f) -> 50.5f -> 51
float x = std::ceil((float) 20000001 / 2.0f);
```

Floating Point - Useful Functions

where T is a numeric type C++11

```
#include <cmath>

bool isnan(T value) // returns true if value is nan, false otherwise
bool isinf(T value) // returns true if value is ±inf, false otherwise
bool isfinite(T value) // returns true if value is not nan or infinite,
                       // false otherwise
bool isnormal(T value); // true if normal, false otherwise

T ldexp(T x, p)     // multiplies a number by 2 raised to a power.
                    // returns x * 2^p
int ilogb(T value) // extracts exponent of the number

#include <limits>
// Check if the actual C++ implementation adopts the IEEE754 standard:
std::numeric_limits<float>::is_iec559;  // should return true
std::numeric_limits<double>::is_iec559; // should return true
```

The problem

```
cout << (0.11f + 0.11f < 0.22f); // print true!!
cout << (0.1f + 0.1f > 0.2f);    // print true!!
```

Do not use absolute error margins!!

```
bool areFloatNearlyEqual(float a, float b) {
    if (std::abs(a - b) < epsilon); // epsilon is fixed by the user
        return true
    return false;
}
```

Problems:

- Fixed `epsilon` "looks small" but, it could be too large when the numbers being compared are very small
- If the compared numbers are very large, the epsilon could end up being smaller than the smallest rounding error, so that the comparison always returns `false`

Solution: Use relative error $\frac{|a-b|}{b} < \varepsilon$

```
bool areFloatNearlyEqual(float a, float b) {
    if (std::abs(a - b) / b < epsilon); // epsilon is fixed
        return true
    return false;
}
```

Problems:

- `a=0, b=0` The division is evaluated as `0.0/0.0` and the whole `if` statement is `(nan < espilon)` which always returns `false`
- `b=0` The division is evaluated as `abs(a)/0.0` and the whole `if` statement is `(+inf < espilon)` which always returns `false`
- **`a and b very small.`** The result should be `true` but the division by `b` may produces wrong results
- **`It is not commutative.`** We always divide by `b`

Floating Point Comparison

Possible solution: $\frac{|a-b|}{\max(|a|,|b|)} < \varepsilon$

```
bool areFloatNearlyEqual(float a, float b) {
    const float epsilon = <user_defined>

    if (a == b) // a=0,b=0 and a = ±∞, b = ±∞
        return true;
    if (std::isnan(a) || std::isnan(b)) // optional
        return false;

    float abs_a = std::abs(a);
    float abs_b = std::abs(b);
    float diff  = std::abs(a - b);
    return (diff / std::max(abs_a, abs_b)) < epsilon; // relative error
}
```

References:

[1] floating-point-gui.de/errors/comparison

[2] www.cygnus-software.com/papers/comparingfloats

Relative errors is susceptible to the scale of the computation

Suppose you have two non-trivial computations. At the end you get `0.0` and `0.5`

- if the scale of the computation is small e.g. $[0.0, 1.0]$ the relative error is high
- if the scale of the computation is large e.g. $[-100.0, 100.0]$ the relative error is small

Many times it is not possible to compare the result with the **true** value obtained by using other methods (symbolic computation, external sources, etc.)

Floating Point (In)Accuracy

Machine epsilon

Machine epsilon ε (or *machine accuracy*) is defined to be the smallest number that can be added to 1.0 to give a number other than one.

IEEE 754 Single precision : $\varepsilon = 1.17549435 * 10^{-38}$

```
#include <limits>
T std::numeric_limits<T>:: epsilon() // returns the machine epsilon
```

Truncation error

A number x that is **Truncated** (or *Chopped*) at the m^{th} digit means that all $n - m$ digits after the n^{th} digit are removed.

- Machine floating-point representation of x is denoted **fl**(x)

The relative error as a result of truncation is

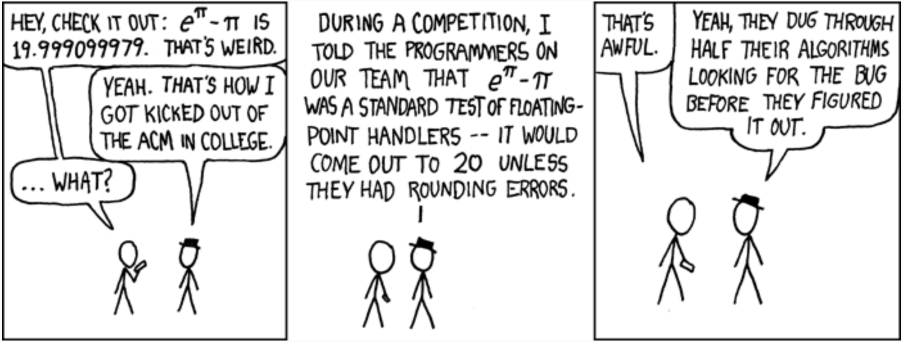
$$\left|\frac{fl\,(x) - x}{x}\right| \leq \frac{1}{2}\varepsilon \qquad fl\,(x) = x\,(1+\delta) \qquad |\delta| \leq \frac{1}{2}\varepsilon$$

Minimize Error Propagation

- Prefer **multiplication/division** rather than addition/subtraction
- Scale by a **power of two** is safe
- Try to reorganize the computation to **keep near** numbers with the same scale (maybe sorting numbers)
- Consider to **put a zero** very small number (under a threshold). Common application: iterative algorithms
- **Switch to log scale**. Multiplication becomes Add, and Division becomes Subtraction

Suggest reading:
D. Golberg, *"What Every Computer Scientist Should Know About Floating-Point Arithmetic*, 1991, link

Minimize Error Propagation



Enumerators

Enumerated Types

Enumerator

An **enumerator** (`enum`) is a data type that groups a set of named integral constants

```
enum color_t { BLACK, BLUE, GREEN = 2 };

color_t color = BLUE;
cout << (color == BLACK); // print false
```

The problem:

```
enum color_t { BLACK, BLUE, GREEN };
enum fruit_t { APPLE, CHERRY };

color_t color = BLACK;    // int: 0
fruit_t fruit = APPLE;    // int: 0
cout << (color == fruit); // print 'true'!!
// and, most importantly, does the match between a color and
// a fruit makes any sense?
```

Enumerated Types (Strongly Typed)

enum class

C++11 introduces a *type safe* enumerator `enum class` (scoped enum) data type that are not implicitly convertible to `int`

Syntax: `<enum_class>::<enum_value>`

```
enum class color_t { BLACK, BLUE, GREEN = 2 };
enum class fruit_t { APPLE, CHERRY };

color_t color = color_t::BLUE;
fruit_t fruit = fruit_t::APPLE;

// cout << (color == fruit); // compile error!!
//      we are trying to match colors with fruits
//      BUT, they are different things entirely

// int a = color_t::GREEN;  // compile error!!
```

- Strongly typed enumerators can be compared

```
enum class Colors { RED = 1, GREEN = 2, BLUE = 3 };

cout << (Colors::RED < Colors::GREEN); // print true
```

- Strongly typed enumerators do not support other operations

```
enum       WColors { RED = 1, GREEN = 2, BLUE = 3 };
enum class SColors { RED = 1, GREEN = 2, BLUE = 3 };

int v = RED + GREEN; // ok
// int v = SColors::RED + SColors::GREEN; // compile error!
```

- The size of `enum class` can be set

```
#include <cstdint>
enum class Colors : int8_t { RED = 1, GREEN = 2, BLUE = 3 };
```

Enumerated Types Features 2/3

- Strongly typed enumerators can be converted

```
int a = (int) color_t::GREEN; // ok
```

- Enum class objects should be always initialized

```
enum class SColors { RED = 1, GREEN = 2, BLUE = 3 };

int main() {
    SColors my_color;  // "my_color" maybe 0!!
}
```

- Enum (class) objects are automatically enumerated

```
enum class SColors { RED, GREEN = -1, BLUE, BLACK };
//                    (0)   (-1)        (0)   (1)
int main() {
    SColors::RED == SColors::BLUE; // true
}
```

- Cast from *out-of-range values* to enum object leads to undefined behavior (C++17)

```
enum Colors { RED = 0, GREEN = 1, BLUE = 2 };

int main() {
    Colors value = (int) 3; // undefined behavior
}
```

- C++17 Enum class objects support *direct-list-initialization*

```
enum class Colors { RED = 0, GREEN = 1, BLUE = 2 };

int main() {
    Colors a{2};            // ok, equal to Colors:BLUE
//  Colors b{4};            // compile error!!
//  Colors c = {2};         // compile error!!
    Colors d = Colors{2}; // ok, equal to Colors:BLUE
}
```

Union and Bitfield

Union 1/2

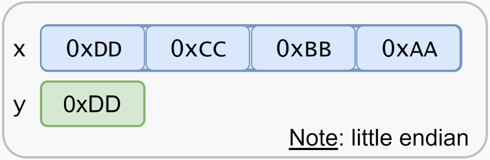
Union

A **union** is a special data type that allows to store different data types in the same memory location

- The `union` is only as big as necessary to hold its *largest* data member
- The `union` is a kind of *"overlapping"* storage

```
union A {
  int  x;
  char y;
};
```

```
A a;
A.x = 0xAABBCCDD
```



```cpp
union A {
    int  x;
    char y;
};  // sizeof(A): 4

A a;
a.x = 1023;       // bits: 00..000001111111111
a.y = 0;          // bits: 00..000001100000000
std::cout << a.x; // print 512 + 256 = 768
```

C++17 introduces `std::variant` to represent a type-safe union

Bitfield

A **bitfield** is variable of a structure with a predefined bit width.

A bitfield can hold bits instead byte

```
struct S1 {
    int b1 : 10;  // range [0, 1023]
    int b2 : 10;  // range [0, 1023]
    int b3 : 8;   // range [0, 255]
}; // sizeof(S1): 4 bytes

struct S2 {
    int b1 : 10;
    int    : 0;   // reset: force the next field
    int b2 : 10;  //        to start at bit 32
}; // sizeof(S1): 8 bytes
```

using and decltype

`using` and `decltype`

- In C++11, the `using` keyword has the same semantics of `typedef` specifier (alias-declaration), but with better syntax

```
typedef int distance_t;  // equal to:
using distance_t = int;
```

- In C++11, `decltype` captures the type of an object or an expression

```
int a = 3;
decltype(a) b = 5;             // 'b' is int
decltype(2.0f) c = 3.0f;       // 'c' is float
decltype(a + 2.0f) d = 3.0f;   // 'd' is float
decltype(f(a)) e = ...;        // 'e' depends on f(a)

using T = decltype(a);         // T is int
T value = 3;
```

Math Operators

Math Operators (Precedence) 1/3

Precedence	Operator	Description	Associativity
1	`a++` `a--`	Suffix/postfix increment and decrement	Left-to-right
2	`++a` `--a`	Prefix increment and decrement	Right-to-left
3	`a*b` `a/b` `a%b`	Multiplication, division, and remainder	Left-to-right
4	`a+b` `a-b`	Addition and subtraction	Left-to-right
5	$\ll$ $\gg$	Bitwise left shift and right shift	Left-to-right
6	`<` `<=` `>` `>=`	Relational operators	Left-to-right
7	`==` `!=`	Equality operators	Left-to-right
8	&	Bitwise AND	Left-to-right
9	ˆ	Bitwise XOR	Left-to-right
10	$\vert$	Bitwise OR	Left-to-right
11	&&	Logical AND	Left-to-right
12	$\vert\vert$	Logical OR	Left-to-right

In general:

- **Unary** operators have higher precedence than **binary operators**
- **Standard math operators** (`+, *, etc.`) have higher precedence than **comparison**, **bitwise**, and **logic** operators
- **Comparison** operators have higher precedence than **bitwise** and **logic operators**
- **Bitwise** operators have higher precedence than **logic** operators

Full table

`en.cppreference.com/w/cpp/language/operator_precedence`

Examples:

```
a + b * 4;          // a + (b * 4)

a * b / c % d;      // ((a * b) / c) % d

a + b < 3 >> 4;     // (a + b) < (3 >> 4)

a && b && c || d; // (a && b && c) || d

a | b & c || e && d;  // ((a | (b & c)) || (e && d)
```

Important: sometimes parenthesis can make expression worldly... but they can help!

Undefined Behavior

Expressions with undefined (implementation-defined) behavior:

```
int i = 0;
i = ++i + 2;       // undefined behavior until C++11,
// otherwise i = 3
i = 0;
i = i++ + 2;       // undefined behavior until C++17,
// modern compilers (clang, gcc): i = 3

f(i = 2, i = 1);   // undefined behavior until C++17
// modern compilers (clang, gcc): i = 2
i = 0;
a[i] = i++;        // undefined behavior until C++17
// modern compilers (clang, gcc): a[1] = 1

f(++i, ++i);       // undefined behavior
i = ++i + i++;     // undefined behavior

n = ++i + i;       // undefined behavior
```

Statements and Control Flow

Assignment and Ternary Operator

- Assignment special cases:

```
int a;
int b = a = 3;  // (a = 3) return value 3
if (b = 4)      // it is not an error, but BAD programming
```

- *Structure Binding* declaration: C++17

```
struct A {
    int x = 1;
    int y = 2;
} a;

auto [x, y] = a;
cout << x << " " << y;
```

- Ternary operator:

```
<cond> ? <expression1> : <expression2>
```

<expression1> and <expression2> must return a value of the same type

```
int value = (a == b) ? a : (b == c ? b : 3); // nested
```

`if` Statement

- *Short-circuiting*:

```
if (<true expression> || array[-1] == 0)
... // no error!! even though index is -1
// left-to-right evaluation
```

- C++17 `if` statement with *initializer*:

```
void f(int x, int y) {
    if (int ret = x + y; ret < 10)
        cout << "a";
}
```

It aims at simplifying complex statement before the condition evaluation. Available also for `switch` statements

Loops

C++ provides three kinds of loop:

- **for loop**

```
for ([init]; [cond]; [increment]) {
    ...
}
```

  To use when number of iterations is known

- **while loop**

```
while (cond) {
    ...
}
```

  To use when number of iterations is not known

- **do while loop**

```
do {
...
} while (cond);
```

  To use when number of iterations is not known, but there is at least one iteration

for Loop

- C++ allows "in loop" definitions:

```
for (int i = 0, k = 0; i < 10; i++, k += 2)
    ...
```

- Infinite loop:

```
for (;;)
...
```

- Jump statements:

```
for (int i = 0; i < 10; i++) {
    if (<condition>)
        break;    // exit from the loop
    if (<condition>)
        continue; // continue with a new iteration and exec. i++
    return;       // exit from the function
}
```

C++11 introduces the **range loop** to simplifies the verbosity of traditional `for` loop constructs. They are equivalent to the `for` loop operating over a range of values

```
for (int v : { 3, 2, 1 }) // INITIALIZER LIST
    cout << v << " ";      // print: 3 2 1

for (auto c : "abcd")     // RAW STRING
    cout << c << " ";     // print: a b c d

int values[] = { 3, 2, 1 };
for (int v : values)      // ARRAY OF VALUES
    cout << v << " ";     // print: 3 2 1

char letters[] = "abcd";
for (auto c : letters)    // ARRAY OF CHARS
    cout << c << " ";     // print: a b c d
```

C++17 extends the concepts of **range loop** for *structure binding*

```
struct A {
    int x;
    int y;
};

A array[10] = { {1,2}, {5,6}, {7,1} };
for (auto [x, y] : array)
    cout << x << "," << y << "  ";  // print: 1,2  5,6  7,1
```

C++ `switch` can be defined over `int`, `char`, `enum class`, `enum`, `etc`.

```
int f(char x) {
    int y;
    swicth (x) {
        case 'a': y = 1; break;
        default:  return -1;
    }
    return y;
}
```

```
int f(MyEnum x) {
    int y = 0;
    swicth (x) {
        case MyEnum::A:        // fallthrough
        case MyEnum::B:        // fallthrough
        case MyEnum::C: return 0;
        default: return -1;
    }
}
```

C++17 `[[fallthrough]]` attribute

```
int f(char x) {
    swicth (x) {
        case 'a': x++;
                  [[fallthrough]]; // C++17: avoid warning
        case 'b': return 0;
        default:  return -1;
    }
}
```

Switch scope:

```
int x = 1;
swicth (1) {
    case 0: int x;      // nearest scope
    case 1: cout << x;  // undefined!!
    case 2: { int y; }  // ok
//  case 3: cout << y;  // compile error!!
//  case 4: int x;      // compile error!!
}
```

When it is useful:

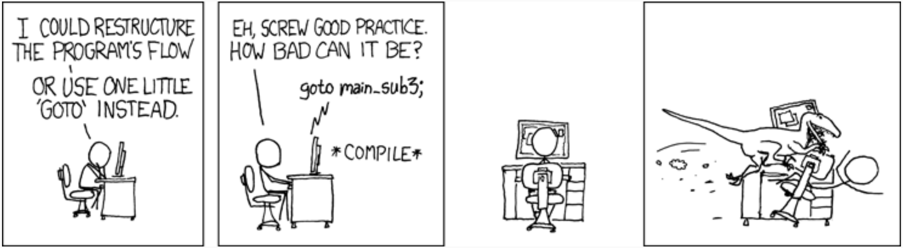
```
bool flag = true;
for (int i = 0; i < N && flag; i++) {
    for (int j = 0; j < M && flag; j++) {
        if (<condition>)
            flag = false;
    }
}
```

become:

```
for (int i = 0; i < N; i++) {
    for (int j = 0; j < M; j++) {
        if (<condition>)
            flag = false;
            goto LABEL;
    }
}
LABEL: ;
```

Best solution:

```
bool my_function(int M, int M) {
    for (int i = 0; i < N; i++) {
        for (int j = 0; j < M; j++) {
            if (<condition>)
                return false;
        }
    }
    return true;
}
```


I COULD RESTRUCTURE THE PROGRAM'S FLOW
OR USE ONE LITTLE 'GOTO' INSTEAD.
EH, SCREW GOOD PRACTICE. HOW BAD CAN IT BE?
goto main_sub3;
COMPILE