Modern C++ Programming

16. Utilities

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I/O Stream

I/O Stream

`<iostream>` input/output library refers to a family of classes and supporting functions in the C++ Standard Library that implement stream-based input/output capabilities

There are four predefined iostreams:

- `cin` standard input (`stdin`)
- `cout` standard output (`stdout`) [buffered]
- `cerr` standard error (`stderr`) [unbuffered]
- `clog` standard error (`stderr`) [unbuffered]

buffered: the content of the buffer is not write to disk until some events occur

Basic I/O Stream manipulator:

- `flush` flushes the output stream `cout << flush;`
- `endl` shortcut for `cout << "\n" << flush;`
  `cout << endl`
- `flush` and `endl` force the program to synchronize with the terminal → very slow operation!

I/O Stream (manipulator) 2/3

- **Set integral representation**: default: dec

  `cout << dec << 0xF;` prints 16

  `cout << hex << 16;` prints 0xF

  `cout << oct << 8;` prints 10

- Print the underlying **bit representation** of a value:

```
#include <bitset>
std::cout << std::bitset<32>(3.45f); // (32: num. of bits)
// print 01000000010111001100110011001101
```

- **Print true/false text**:

  `cout << boolalpha << 1;` prints `true`

  `cout << boolalpha << 0;` prints `false`

I/O Stream (manipulator) 3/3

<iomanip>

- **Set decimal precision**: default: 6

`cout << setprecision(2) << 3.538;` → 3.54

- **Set float representation**: default: `std::defaultfloat`

`cout << setprecision(2) << fixed << 32.5;` → 32.50

`cout << setprecision(2) << scientific << 32.5;` → 3.25e+01

- **Set alignment**: default: right

`cout << right << setw(7) << "abc" << "##";` → ␣␣␣␣abc##

`cout << left << setw(7) << "abc" << "##";` → abc␣␣␣␣##

(better than using tab `\t`)

I/O Stream - `std::cin`

`std::cin` is an example of *input* stream. Data coming from a source is read by the program. In this example `cin` is the standard input

```
#include <iostream>

int main() {
    int a;
    std::cout << "Please enter an integer value:" << endl;
    std::cin >> a;

    int b;
    float c;
    std::cout << "Please enter an integer value "
              << "followed by a float value:" << endl;
    std::cin >> b >> c; // read an integer and store into "b",
}                       // then read a float value, and store
                        // into "c"
```

`ifstream`, `ofstream` are output and input stream too

`<fstream>`

- **Open a file for reading**
  Open a file in input mode: `ifstream my_file("example.txt")`
- **Open a file for writing**
  Open a file in output mode: `ofstream my_file("example.txt")`
  Open a file in append mode: `ofstream my_file("example.txt", ios::out | ios::app)`
- **Read a line** `getline(my_file, string)`
- **Close a file** `my_file.close()`
- **Check the stream integrity** `my_file.good()`

- **Peek the next character**

```
char current_char = my_file.peek()
```

- **Get the next character (and advance)**

```
char current_char = my_file.get()
```

- **Get the position of the current character in the input stream**

```
int byte_offset = my_file.tellg()
```

- **Set the char position in the input sequence**

`my_file.seekg(byte_offset)` (absolute position)

`my_file.seekg(byte_offset, position)` (relative position)

where position can be: `ios::beg` (the begin), `ios::end` (the end), `ios::cur` (current position)

- **Ignore characters until the delimiter is found**

  `my_file.ignore(max_stream_size, <delim>)`

  e.g. skip until end of line `\n`

- **Get a pointer to the stream buffer object currently associated with the stream**

  `my_file.rdbuf()`

  can be used to redirect file stream

I/O Stream - Example 1

Open a file and print line by line:

```cpp
#include <iostream>
#include <fstream>

int main() {
  std::ifstream fin("example.txt");
  std::string str;
  while (std::getline(fin, str))
     std::cout << str << "\n";
  fin.close();
}
```

An alternative version with redirection:

```cpp
#include <iostream>
#include <fstream>

int main() {
  std::ifstream fin("example.txt");
  std::cout << fin.rdbuf();
  fin.close();
}
```

Reading files line by line in C++ using ifstream

I/O Stream - Example 2

example.txt:

```
23␣70␣␣␣44\n
\t57\t89
```

The input stream is independent from the type of space (multiple space, tab, newline `\n`, `\r\n`, `etc.`)

Another example:

```cpp
#include <iostream>
#include <fstream>

int main() {
    std::ifstream fin("example.txt");
    char c = fin.peek(); // c = '2'
    while (fin.good()) {
        int var;
        fin >> var;
        std::cout << var;
    }        // print 2370445789
    fin.seekg(4);
    c = fin.peek();  // c = '0'
    fin.close();
}
```

I/O Stream -Check the End of a File

- Check the current character

```
while (fin.peek() != std::char_traits<char>::eof()) // C: EOF
    fin >> var;
```

- Check if the read operation fails

```
while (fin >> var)
    ...
```

- Check if the stream past the end of the file

```
while (true) {
    fin >> var
    if (fin.eof())
        break;
}
```

I/O Stream (checkRegularType)

Check if a file is a **regular file** and can be read/written

```
#include <sys/types.h>
#include <sys/stat.h>
bool checkRegularFile(const char* file_path) {
    struct stat info;
    if (::stat( file_path, &info ) != 0)
        return false;          // unable to access
    if (info.st_mode & S_IFDIR)
        return false;                 // is a directory
    std::ifstream fin(file_path); // additional checking
    if (!fin.is_open() || !fin.good())
        return false;
    try {                       // try to read
        char c; fin >> c;
    } catch (std::ios_base::failure&) {
        return false;
    }
    return true;
}
```

I/O Stream - File size

Get the **file size** in bytes in a **portable** way:

```
long long int fileSize(const char* file_path) {
    std::ifstream fin(file_path);     // open the file
    fin.seekg(0, ios::beg);           // move to the first byte
    std::istream::pos_type start_pos = fin.tellg();
                                      // get the start offset
    fin.seekg(0, ios::end);           // move to the last byte
    std::istream::pos_type end_pos = fin.tellg();
                                      // get the end offset
    return end_pos - start_pos;       // position difference
}
```

see C++17 file system utilities

Strings and std::print

`std::string` is a wrapper of character sequences

More flexible and safer than raw char array but can be slower

```cpp
#include <string>

int main() {
    std::string a;          // empty string
    std::string b("first");

    using namespace std::string_literals;  // C++14
    std::string c = "second"s;             // C++14
}
```

`std::string` supports `constexpr` in C++20

`std::string` - Capacity and Search

- `empty()` returns `true` if the string is empty, `false` otherwise
- `size()` returns the number of characters in the string
- `find(string)` returns the position of the first substring equal to the given character sequence or **npos** if no substring is found
- `rfind(string)` returns the position of the last substring equal to the given character sequence or **npos** if no substring is found
- `find_first_of(char_seq)` returns the position of the first character equal to one of the characters in the given character sequence or `npos` if no characters is found
- `find_last_of(char_seq)` returns the position of the last character equal to one of the characters in the given character sequence or `npos` if no characters is found

`npos` special value returned by string methods

`std::string` - Operations

- `new_string substr(start_pos)`
  returns a substring [start_pos, end]
  `new_string substr(start_pos, count)`
  returns a substring [start_pos, start_pos + count)

- `clear()` removes all characters from the string

- `erase(pos)` removes the character at position
  `erase(start_pos, count)`
  removes the characters at positions [start_pos, start_pos + count)

- `replace(start_pos, count, new_string)`
  replaces the part of the string indicated by [start_pos, start_pos + count) with `new_string`

- `c_str()`
  returns a pointer to the raw char sequence

`std::string` - Overloaded Operators

- **access specified character** `string1[i]`
- **string copy** `string1 = string2`
- **string compare** `string1 == string2`
  works also with `!=`, $<$, $\leq$, $>$, $\geq$
- **concatenate two strings** `string_concat = string1 + string2`
- **append characters to the end** `string1 += string2`

Conversion from/to Numeric Values

Converts a string to a numeric value C++11:

- `stoi(string)` string to signed integer
- `stol(string)` string to long signed integer
- `stoul(string)` string to long unsigned integer
- `stoull(string)` string to long long unsigned integer
- `stof(string)` string to floating point value (float)
- `stod(string)` string to floating point value (double)
- `stold(string)` string to floating point value (long double)
- C++17 `std::from_chars(start, end, result, base)` fast string conversion (no allocation, no exception)

Converts a numeric value to a string:

- C++11 `to_string(numeric_value)` numeric value to string

Examples

```
std::string str("si vis pacem para bellum");
cout << str.size();       // print 24
cout << str.find("vis"); // print 3
cout << str.find_last_of("bla"); // print 21, 'l' found

cout << str.substr(7, 5);// print "pacem", pos=7 and count=5
cout << str[1];           // print 'i'
cout << (str == "vis");   // print false
cout << (str < "z");      // print true
const char* raw_str = str.c_str();

cout << string("a") + "b";      // print "ab"
cout << string("ab").erase(0); // print 'b'

char*       str2 = "34";
int         a    = std::stoi(str2);    // a = 34;
std::string str3 = std::to_string(a); // str3 = "34"
```

Tips

- Conversion from integer to char letter (e.g. 3 $\rightarrow$ 'C'):
  `static_cast<char>('A'+ value)`
  `value` $\in$ [0, 26] (English alphabet)

- Conversion from char to integer (e.g. 'C' $\rightarrow$ 3): `value - 'A'`
  `value` $\in$ [0, 26]

- Conversion from digit to char number (e.g. 3 $\rightarrow$ '3'):
  `static_cast<char>('0'+ value)`
  `value` $\in$ [0, 9]

- char to string `std::string(1, char_value)`

C++17 `std::string_view` describes a minimum common interface to interact with string data:

- `const std::string&`
- `const char*`

The purpose of `std::string_view` is to avoid copying data which is already owned by the original object

```
#include <string>
#include <string_view>

std::string str  = "abc";  // new memory allocation + copy
std::string_view = "abc";  // only the reference
```

`std::string_view` provides similar functionalities of `std::string`

```
#include <iostream>
#include <string>
#include <string_view>

void string_op1(const std::string& str) {}
void string_op2(std::string_view   str) {}


string_op1("abcdef"); // allocation + copy
string_op2("abcdef"); // reference

const char* str1 = "abcdef";
std::string str2("abcdef");      // allocation + copy
std::cout << str2.substr(0, 3); // print "abc"

std::string_view str3(str1);     // reference
std::cout << str3.substr(0, 3); // print "abc"
```

`std::string_view` supports `constexpr` constructor and methods

```
constexpr std::string_view str1("abc");
constexpr std::string_view str2 = "abc";

constexpr char c = str1[0];         // 'a'
constexpr bool b = (str1 == str2); // 'true'

constexpr int size = str1.size();                  // '3'
constexpr std::string_view str3 = str1.substr(0, 2); // "ab"

constexpr int pos = str1.find("bc");               // '1'
```

`printf` *functions*: no automatic type deduction, error prone, not extensible

`stream` *objects*: very verbose, hard to optimize

C++20 `std::format` provides python style formatting:

- Type-safe
- Support positional arguments
- Extensible (support user-defined types)
- Return a `std::string`

Integer formatting

```
std::format("{}", 3);   // "3"
std::format("{:b}", 3); // "101"
```

Floating point formatting

```
std::format("{:.1f}", 3.273); // "3.1"
```

Alignment

```
std::format("{:>6}", 3.27); // "  3.27"
std::format("{:<6}", 3.27); // "3.27  "
```

Argument reordering

```
std::format("{1} - {0}", 1, 3); // "3 - 1"
```

`std::print`

C++23 introduces `std::print()` `std::println()`

```
std::print("Hello, {}!\n", name);

std::println("Hello, {}!", name);  // prints a newline
```

View

C++20 introduces `std::span` which is a non-owning view of an underlying sequence or array

A `std::span` can either have a *static* extent, in which case the number of elements in the sequence is known at compile-time, or a *dynamic* extent

```
template<
    class       T,
    std::size_t Extent = std::dynamic_extent
> class span;
```

```cpp
#include <span>
#include <array>
#include <vector>

int array1[] = {1, 2, 3};
std::span s1{array1};     // static extent

std::array<int, 3> array2 = {1, 2, 3};
std::span s2{array2};     // static extent

auto array3 = new int[3];
std::span s3{array3, 3}; // dynamic extent

std::vector<int> v{1, 2, 3};
std::span s4{v.data(), v.size()}; // dynamic extent

std::span s5{v};          // dynamic extent
```

```cpp
void f(std::span<int> span) {
    for (auto x : span) // range-based loop (safe)
        cout << x;
    std::fill(span.begin(), span.end(), 3); // std algorithms
}

int array1[] = {1, 2, 3};
f(array1);

auto array2 = new int[3];
f({array2, 3});
```

Math Libraries

`<cmath>`

- `fabs(x)` computes absolute value, $|x|$, C++11
- `exp(x)` returns e raised to the given power, e^x
- `exp2(x)` returns 2 raised to the given power, 2^x, C++11
- `log(x)` computes natural (base e) logarithm, $\log_e(x)$
- `log10(x)` computes base 10 logarithm, $\log_{10}(x)$
- `log2(x)` computes base 2 logarithm, $\log_2(x)$, C++11
- `pow(x, y)` raises a number to the given power, x^y
- `sqrt(x)` computes square root, $\sqrt{x}$
- `cqrt(x)` computes cubic root, $\sqrt[3]{x}$, C++11

- `sin(x)` computes sine, $\sin(x)$
- `cos(x)` computes cosine, $\cos(x)$
- `tan(x)` computes tangent, $\tan(x)$
- `ceil(x)` nearest integer not less than the given value, $\lceil x \rceil$
- `floor(x)` nearest integer not greater than the given value, $\lfloor x \rfloor$
- `round|lround|llround(x)` nearest integer, $\lfloor x + \frac{1}{2} \rfloor$
  (return type: floating point, `long`, `long long` respectively)

Math functions in C++11 can be applied directly to integral types without implicit/explicit casting (return type: floating point).

en.cppreference.com/w/cpp/numeric/math

<limits> Numerical Limits

Get numeric limits of a given type:

`<limits>` C++11

```
T numeric_limits<T>:: max()  // returns the maximum finite value
                             // value representable

T numeric_limits<T>:: min()  // returns the minimum finite value
                             // value representable

T numeric_limits<T>:: lowest()  // returns the lowest finite
                                // value representable
```

`<numeric>` Mathematical Constants

`<numeric>` C++20

The header provides numeric constants

- `e` Euler number e
- `pi` π
- `phi` Golden ratio $\frac{1+\sqrt{5}}{2}$
- `sqrt2` $\sqrt{2}$

Integer Division

Integer ceiling division and rounded division:

- **Ceiling Division:** $\left\lceil \frac{\texttt{value}}{\texttt{div}} \right\rceil$

```
unsigned ceil_div(unsigned value, unsigned div) {
    return (value + div - 1) / div;
} // note: may overflow
```

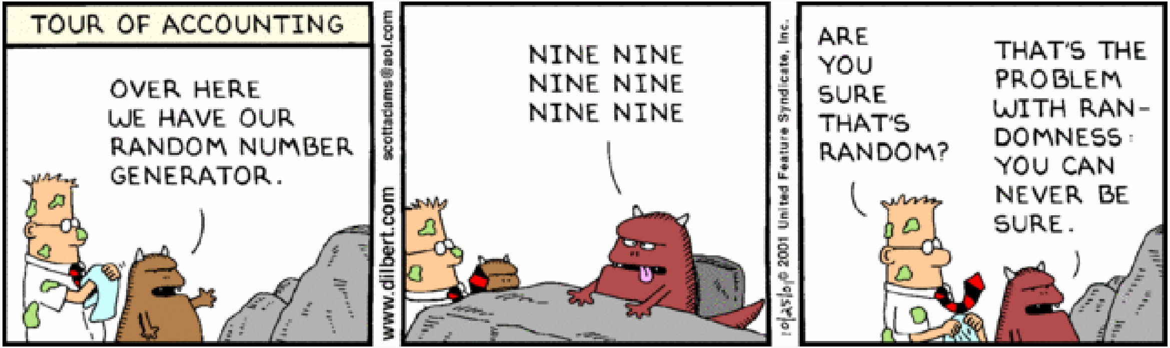
- **Rounded Division:** $\left\lfloor \frac{\texttt{value}}{\texttt{div}} + \frac{1}{2} \right\rfloor$

```
unsigned round_div(unsigned value, unsigned div) {
    return (value + div / 2) / div;
} // note: may overflow
```

Note: do not use floating-point conversion (see `Basic Concept I`)

Random Number

Random Number



"Random numbers should not be generated with a method chosen at random"
— Donald E. Knuth

Applications: cryptography, simulations (e.g. Monte Carlo), etc.

Random Number

see Lavarand

Basic Concepts

- A **pseudorandom (PRNG)** *sequence of numbers* satisfies most of the statistical properties of a truly random sequence but is generated by a *deterministic* algorithm (deterministic finite-state machine)
- A **quasirandom** *sequence of n-dimensional points* is generated by a *deterministic* algorithm designed to fill an *n*-dimensional space evenly
- The **state** of a PRNG describes the status of the generator (the values of its variables), namely where the system is after a certain amount of transitions
- The **seed** is a value that initializes the *starting state* of a PRNG. The same seed always produces the same sequence of results
- The **offset** of a sequence is used to skip ahead in the sequence
- PRNGs produce **uniformly distributed** values. PRNGs can also generate values according to a probability function (binomial, normal, etc.)

The problem:

C `rand()` *function produces poor quality random numbers*

- C++14 discourage the use of `rand()` and `srand()`

C++11 introduces pseudo random number generation (PRNG) facilities to produce random numbers by using combinations of generators and distributions

A random generator requires four steps:

(1) **Select the seed**

(2) **Define the random engine**

```
<type_of_random_engine> generator(seed)
```

(3) **Define the distribution**

```
<type_of_distribution> distribution(range_start, range_end)
```

(4) **Produce the random number**

```
distribution(generator)
```

Simplest example:

```
#include <iostream>
#include <random>

int main() {
    unsigned seed = ...;
    std::default_random_engine generator(seed);
    std::uniform_int_distribution<int> distribution(0, 9);

    std::cout << distribution(generator);  // first random number
    std::cout << distribution(generator);  // second random number
}
```

It generates two random integer numbers in the range [0, 9] by using the default random engine

Given a **seed**, the generator produces always the **same sequence**

The seed could be selected randomly by using the current time:

```
#include <random>
#include <chrono>

unsigned seed = std::chrono::system_clock::now()
                .time_since_epoch().count();
std::default_random_engine generator(seed);
```

`chrono::system_clock::now()` returns an object representing the current point in time

`.time_since_epoch().count()` returns the count of ticks that have elapsed since January 1, 1970 (midnight UTC/GMT)

Problem: Consecutive calls return *very similar* seeds

A **random device** `std::random_device` is a uniformly distributed integer generator that produces non-deterministic random numbers (e.g. from a hardware device)
Note: Not all systems provide a random device

```
#include <random>

std::random_device         rnd_device;
std::default_random_engine generator(rnd_device());
```

`std::seed_seq` consumes a sequence of integer-valued data and produces a number of unsigned integer values in the range $[0, 2^{32} - 1]$. The produced values are distributed over the entire 32-bit range even if the consumed values are close

```cpp
#include <random>
#include <chrono>

unsigned seed1 = std::chrono::system_clock::now()
                .time_since_epoch().count();
unsigned seed2 = seed1 + 1000;

std::seed_seq seq1{ seed1, seed2 };
std::default_random_engine generator1(seq);

std::random_device rnd;
std::default_random_engine generator1(rnd());
```

PRNG Period and Quality

PRNG Period

The **period** (or **cycle length**) of a PRNG is the length of the sequence of numbers that the PRNG generates before repeating

PRNG Quality

(*informal*) If it is hard to distinguish a generator output from *truly* random sequences, we call it a **high quality** generator. Otherwise, we call it **low quality** generator

Generator	Quality	Period	Randomness
Linear Congruential	Poor	$2^{31} \approx 10^9$	Statistical tests
Mersenne Twister 32/64-bit	High	10^{6000}	Statistical tests
Subtract-with-carry 24/48-bit	Highest	10^{171}	Mathematically proven

Random Engines

- **Linear congruential (LF)**
  The simplest generator engine. Modulo-based algorithm:
  $x_{i+1} = (\alpha x_i + c) mod\ m$ where α, c, m are implementation defined
  C++ Generators: `std::minstd_rand`, `std::minstd_rand0`, `std::knuth_b`

- **Mersenne Twister** *(M. Matsumoto and T. Nishimura, 1997)*
  Fast generation of high-quality pseudorandom number. It relies on Mersenne prime number. (used as default random generator in linux)
  C++ Generators: `std::mt19937`, `std::mt19937_64`

- **Subtract-with-carry (LF)** *(G. Marsaglia and A. Zaman, 1991)*
  Pseudo-random generation based on Lagged Fibonacci algorithm (used for example by physicists at CERN)
  C++ Generators: `std::ranlux24_base`, `std::ranlux48_base`, `std::ranlux24`, `std::ra`

Statistical Tests

The table shows after how many iterations the generator fails the statistical tests

Generator	256M	512M	1G	2G	4G	8G	16G	32G	64G	128G	256G	512G	1T
`ranlux24_base`	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
`ranlux48_base`	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
`minstd_rand`	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
`minstd_rand0`	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
`knuth_b`	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
`mt19937`	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
`mt19937_64`	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗
`ranlux24`	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
`ranlux48`	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Space and Performance

Generator	Predictability	State	Performance
Linear Congruential	Trivial	`4-8 B`	**Fast**
Knuth	Trivial	`1 KB`	**Fast**
Mersenne Twister	Trivial	`2 KB`	**Good**
randlux_base	Trivial	`8-16 B`	**Slow**
randlux	Unknown?	$\sim$`120 B`	**Super slow**

Distribution

- **Uniform distribution** `uniform_int_distribution<T>(range_start, range_end)` where T is integral type

  `uniform_real_distribution<T>(range_start, range_end)` where T is floating point type

- **Normal distribution** $P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$

  `normal_distribution<T>(mean, std_dev)`

  where T is floating point type

- **Exponential distribution** $P(x, \lambda) = \lambda e^{-\lambda x}$

  `exponential_distribution<T>(lambda)`

  where T is floating point type

Examples

```
unsigned seed = ...

// Original linear congruential
minstd_rand0  lc1_generator(seed);
// Linear congruential (better tuning)
minstd_rand   lc2_generator(seed);
// Standard mersenne twister (64-bit)
mt19937_64    mt64_generator(seed);
// Subtract-with-carry (48-bit)
ranlux48_base swc48_generator(seed);

uniform_int_distribution<int>     int_distribution(0, 10);
uniform_real_distribution<float> real_distribution(-3.0f, 4.0f);
exponential_distribution<float>  exp_distribution(3.5f);
normal_distribution<double>       norm_distribution(5.0, 2.0);
```

References

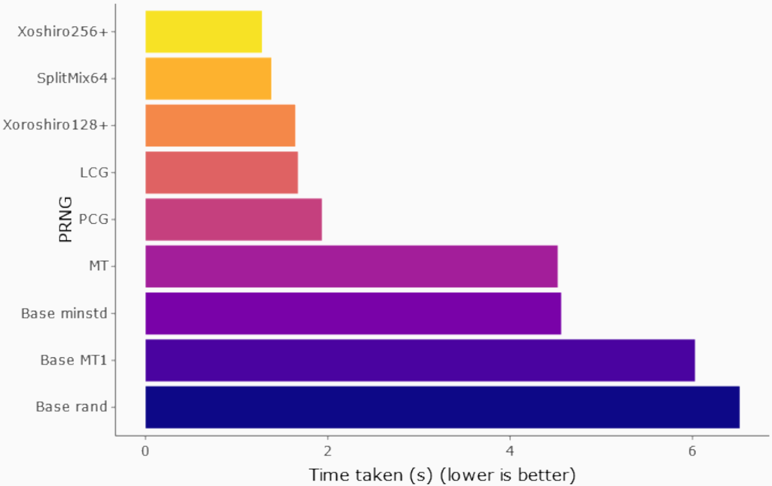
PRNG Quality:

- On C++ Random Number Generator Quality
- It is high time we let go of the Mersenne Twister
- The Xorshift128+ random number generator fails BigCrush

Recent algorithms:

- PCG, A Family of Better Random Number Generators
- Xoshiro / Xoroshiro generators and the PRNG shootout

Performance Comparison

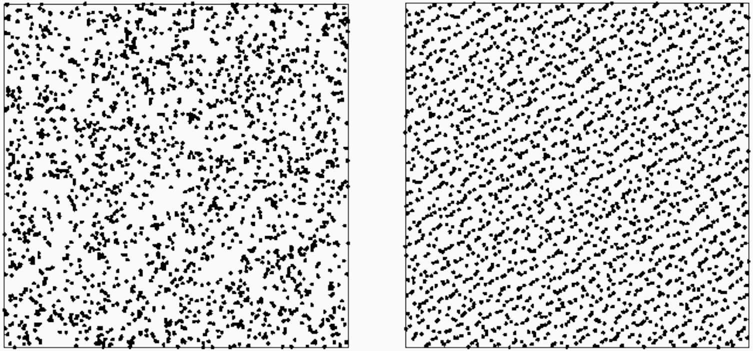


Random number generators for C++ performance tested

The **quasi-random** numbers have the low-discrepancy property that is a measure of *uniformity for the distribution* of the point for the multi-dimensional case

- Quasi-random sequence, in comparison to pseudo-random sequence, distributes evenly, namely this leads to spread the number over the entire region
- The concept of low-discrepancy is associated with the property that the successive numbers are added in a position as away as possible from the other numbers that is, avoiding *clustering* (grouping of numbers close to each other)

Pseudo-random vs. Quasi random



Time Measuring

Wall-Clock/Real time

It is the human perception of the passage of time from the start to the completion of a task

User/CPU time

The amount of time spent by the CPU to compute in user code

System time

The amount of time spent by the CPU to compute system calls (including I/O calls) executed into kernel code

The *Wall-clock time* measured on a concurrent process platform may include the time elapsed for other tasks

The *User/CPU time* of a multi-thread program is the sum of the execution time of all threads

If the system workload (except the current program) is very low and the program uses only one thread then
`Wall-clock time = User time + System time`

Time Measuring - Wall-Clock Time 1/3

`::gettimeofday()` : time resolution $1\mu s$

```
#include <time.h>      //struct timeval
#include <sys/time.h> //gettimeofday()

struct timeval start, end; // timeval {second, microseconds}
::gettimeofday(&start, NULL);
...   // code
::gettimeofday(&end, NULL);

long start_time = start.tv_sec * 1000000 + start.tv_usec;
long end_time   = end.tv_sec * 1000000 + end.tv_usec;
cout << "Elapsed: " << end_time - start_time;  // in microsec
```

Problems: Linux only (not portable), the time is not monotonic increasing (timezone), time resolution is big `std::chrono` C++11

```
#include <chrono>
auto start_time = std::chrono::system_clock::now();
... // code
auto end_time   = std::chrono::system_clock::now();

std::chrono::duration<double> diff = end_time - start_time;
cout << "Elapsed: " << diff.count(); // in seconds
cout << std::chrono::duration_cast<milli>(diff).count(); // in ms
```

Problems: The time is not monotonic increasing (timezone)

An alternative of `system_clock` is **`steady_clock`** which ensures monotonic increasing time.

`steady_clock` is implemented over `clock_gettime` on POSIX system and has $1ns$ time resolution

```
#include <chrono>
auto start_time = std::chrono::steady_clock::now();
... // code
auto end_time   = std::chrono::steady_clock::now();
```

However, the overhead of C++ API is not always negligible, e.g.
`Linux libstdc++` → 20ns, `Mac libc++` → 41ns

`Measuring clock precision`

Time Measuring - User Time

`std::clock`, implemented over `clock_gettime` on POSIX system and has $1ns$ time resolution

```cpp
#include <chrono>

clock_t start_time = std::clock();
... // code
clock_t end_time   = std::clock();

float diff = static_cast<float>(end_time - start_time) / CLOCKS_PER_SEC;
cout << "Elapsed: " << diff; // in seconds
```

Time Measuring - User/System Time

```cpp
#include <sys/times.h>

struct ::tms start_time, end_time;
::times(&start_time);
... // code
::times(&end_time);

auto  user_diff = end_time.tmus_utime - start_time.tms_utime;
auto  sys_diff  = end_time.tms_stime - start_time.tms_stime;
float user      = static_cast<float>(user_diff) / ::sysconf(_SC_CLK_TCK);
float sys       = static_cast<float>(sys_diff)  / ::sysconf(_SC_CLK_TCK);
cout << "user time: "   << user;  // in seconds
cout << "system time: " << sys;   // in seconds
```

Std Classes

`std::pair`

`<utility>`

`std::pair` class couples together a pair of values, which may be of different types

Construct a `std::pair`

- `std::pair<T1, T2> pair(value1, value2)`
- `std::pair<T1, T2> pair = {value1, value2}`
- `auto pair = std::make_pair(value1, value2)`

Data members:

- `first` access first field
- `second` access second field

Methods:

- comparison `==, <, >, ≥, ≤`
- swap `std::swap`

```
#include <utility>

std::pair<int, std::string> pair1(3, "abc");
std::pair<int, std::string> pair2 = { 4, "zzz" };
auto pair3 = std::make_pair(3, "hgt");

cout << pair1.first;  // print 3
cout << pair1.second; // print "abc"

swap(pair1, pair2);
cout << pair2.first;  // print "zzz"
cout << pair2.second; // print 4

cout << (pair1 > pair2); // print 1
```

`<tuple>`

`std::tuple` is a fixed-size collection of heterogeneous values. It is a generalization of `std::pair`. It allows <u>any</u> number of values

Construct a `std::tuple` (of size 3)

- `std::tuple<T1, T2, T3> tuple(value1, value2, value3)`
- `std::tuple<T1, T2, T3> tuple = {value1, value2, value3}`
- `auto tuple = std::make_tuple(value1, value2, value3)`

Data members:

`std:get<I>(tuple)` returns the *i*-th value of the tuple

Methods:

- comparison `==, <, >, ≥, ≤`
- swap `std::swap`

- `auto t3 = std::tuple_cat(t1, t2)`
  concatenate two tuples

- `const int size = std::tuple_size<TupleT>::value`
  returns the number of elements in a tuple at compile-time

- `using T = typename std::tuple_element<TupleT>::type` obtains the type of the specified element

- `std::tie(value1, value2, value3) = tuple`
  creates a tuple of references to its arguments

- `std::ignore`
  an object of unspecified type such that any value can be assigned to it with no effect

```cpp
#include <tuple>
std::tuple<int, float, char> f() { return {7, 0.1f, 'a'}; }

std::tuple<int, char, float> tuple1(3, 'c', 2.2f);
auto tuple2 = std::make_tuple(2, 'd', 1.5f);

cout << std::get<0>(tuple1); // print 3
cout << std::get<1>(tuple1); // print 'c'
cout << std::get<2>(tuple1); // print 2.2f
cout << (tuple1 > tuple2);   // print true

auto concat = std::tuple_cat(tuple1, tuple2);
cout << std::tuple_size<decltype(concat)>::value; // print 6

using T = std::tuple_element<4, decltype(concat)>::type; // T is int
int value1; float value2;
std::tie(value1, value2, std::ignore) = f();
```

`<variant>` C++17

`std::variant` represents a **type-safe union** as the corresponding objects know which type is currently being held

It can be indexed by:

- `std::get<index>(variant)` an integer
- `std::get<type>(variant)` a type

```
#include <variant>

std::variant<int, float, bool> v(3.3f);
int  x = std::get<0>(v);    // return integer value
bool y = std::get<bool>(v); // return bool value
//  std::get<0>(v) = 2.0f;  // run-time exception!!
```

Another useful method is `index()` which returns the position of the type currently held by the variant

```
#include <variant>

std::variant<int, float, bool> v(3.3f);

cout << v.index(); // return 1

std::get<bool>(v) = true
cout << v.index(); // return 2
```

It is also possible to query the index at run-time depending on the type currently being held by providing a **visitor**

```cpp
#include <variant>

struct Visitor {
    void operator()(int& value)   { value *= 2; }

    void operator()(float& value) { value += 3.0f; } // <--

    void operator()(bool& value)  { value = true; }
};

std::variant<int, float, bool> v(3.3f);

std::visit(v, Visitor{});

cout << std::get<float>(v); // 6.3f
```

`<optional>` C++17

`std::optional` provides facilities to represent potential “no value” states

As an example, it can be used for representing the state when an element is not found in a set

```
#include <optional>

std::optional<std::string> find(const char* set, char value) {
    for (int i = 0; i < 10; i++) {
        if (set[i] == value)
            return i;
    }
    return {}; // std::nullopt;
}
```

```
#include <optional>

char set[] = "sdfslgfsdg";
auto x     = find(set, 'a'); // 'a' is not present
if (!x)
    cout << "not found";
if (!x.has_value())
    cout << "not found";

auto y = find(set, 'l');
cout << *y << " " << y.value(); // print '4' '4'

x.value_or(-1); // returns '-1'
y.value_or(-1); // returns '4'
```

`<any>` C++17

`std::any` holds arbitrary values and provides **type-safety**

```
#include <any>

std::any var = 1;           // int
cout << var.type().name(); // print 'i'

cout << std::any_cast<int>(var);
// cout << std::any_cast<float>(var); // exception!!

var = 3.14; // double
cout << std::any_cast<double>(var);

var.reset();
cout << var.has_value(); // print 'false'
```

C++23 introduces `std::stacktrace` library to get the current function call stack, namely the sequence of calls from the `main()` entry point

```
#include <print>
#include <stacktrace> // the program must be linked with the library
                      // -lstdc++_libbacktrace
                      // (-lstdc++exp with gcc-14 trunk)
void g() {
    auto call_stack = std::stacktrace::current();
    for (const auto& entry : call_stack)
        std::print("{}\n", entry);
}

void f() { g(); }

int main() { f(); }
```

the previous code prints

```
 g() at /app/example.cpp:6
 f() at /app/example.cpp:11
main at /app/example.cpp:13
     at :0
__libc_start_main at :0
_start at :0
```

The library also provides additional functions for `entry` to allow fine-grained control of the output `description()`, `source_file()`, `source_line()`

```
for (const auto& entry : call_stack) { // same output
    std::print("{} at {}:{}\n", entry.description(), entry.source_file(),
                                entry.source_line());
}
```

Filesystem Library

Filesystem Library

C++17 introduces abstractions and facilities for performing operations on file systems and their components, such as **paths**, **files**, and **directories**

- Follow the Boost filesystem library
- Based on POSIX
- Fully-supported from `clang 7`, `gcc 8`, etc.
- Work on Windows, Linux, Android, etc.

Basic concepts

- **file**: a file system object that holds data
  - **directory** a container of directory entries
  - **hard link** associates a name with an existing file
  - **symbolic link** associates a name with a path
  - **regular file** a file that is not one of the other file types
- **file name**: a string of characters that names a file. Names `.` (dot) and `..` (dot-dot) have special meaning at library level
- **path**: sequence of elements that identifies a file
  - **absolute path**: a path that unambiguously identifies the location of a file
  - **canonical path**: an absolute path that includes no symlinks, `.` or `..` elements
  - **relative path**: a path that identifies a file relative to some location on the file system

path Object

A `path` object stores the pathname in native form

```
#include <filesystem> // required
namespace fs = std::filesystem;

fs::path p1 = "/usr/lib/sendmail.cf"; // portable format
fs::path p2 = "C:\\users\\abcdef\\";  // native format

cout << "p1: " << p1;            // /usr/lib/sendmail.cf
cout << "p2: " << p2;            // C:\users\abcdef\

out << "p3: " << p2 + "xyz\\";  // C:\users\abcdef\xyz\
```

`path` Methods

Decomposition (member) methods:

- **Return root-name of the path**
  `root_name()`
- **Return path relative to the root path**
  `relative_path()`
- **Return the path of the parent path**
  `parent_path()`
- **Return the filename path component**
  `filename()`
- **Return the file extension path component**
  `extension()`

Filesystem Methods - Query

- **Check if a file or path exists**
  `exists(path)`
- **Return the file size**
  `file_size(path)`
- **Check if a file is a directory**
  `is_directory(path)`
- **Check if a file (or directory) is empty**
  `is_empty(path)`
- **Check if a file is a regular file**
  `is_regular_file(path)`
- **Returns the current path**
  `current_path()`

Directory Iterators

Iterate over files of a directory (recursively/non-recursively)

```
#include <filesystem>

namespace fs = std::filesystem;

for(auto& path : fs::directory_iterator("/usr/tmp/"))
    cout << path << '\n';

for(auto& path : fs::recursive_directory_iterator("/usr/tmp/"))
    cout << path << '\n';
```

Filesystem Methods - Modify

- Copy files or directories
  `copy(path1, path2)`
- Copy files
  `copy_file(src_path, src_path, [fs::copy_options::recursive])`
- Create new directory
  `create_directory(path)`
- Remove a file or empty directory
  `remove(path)`
- Remove a file or directory and all its contents, recursively
  `remove_all(path)`
- Rename a file or directory
  `rename(old_path, new_path)`

Examples

```
#include <filesystem> // required

namespace fs = std::filesystem;
fs::path p1 = "/usr/tmp/my_file.txt";

cout << p1.exists();          // true
cout << p1.parent_path();     // "/usr/tmp/"
cout << p1.filename();        // "my_file"
cout << p1.extension();       // "txt"
cout << p1.is_directory();    // false
cout << p1.is_regular_file(); // true

fs::create_directory("/my_dir/");
fs::copy(p1.parent_path(), "/my_dir/", fs::copy_options::recursive);
fs::copy_file(p1, "/my_dir/my_file2.txt");
fs::remove(p1);
fs::remove_all(p1.parent_path());
```