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 written to disk until some events occur

I/O Stream (manipulator) 1/3

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:

```cpp
#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`

`<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()`

I/O Stream - `ofstream/ifstream`

- **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)

I/O Stream - `ofstream/ifstream`

- **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 (fin.good()) {
     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();
}
```

I/O Stream - Example 2

example.txt:

```
23␣70␣␣␣44\n
\t57\t89
```

The input stream is independent of the type of space (multiple space, tab, new-line `\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;
}
```

---

reading-files-in-c-using-ifstream

I/O Stream (checkRegularType)

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

```cpp
#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

```
#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

- `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 are 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 3/4

- `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 → 'C'):
  `static_cast<char>('A'+ value)`
  `value` ∈ [0, 26] (English alphabet)

- Conversion from char to integer (e.g. 'C' → 3): `value - 'A'`
  `value` ∈ [0, 26]

- Conversion from digit to char number (e.g. 3 → '3'):
  `static_cast<char>('0'+ value)`
  `value` ∈ [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'
```

`std::format` 1/2

`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
```

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

<cmath> Math Library

- `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 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
```

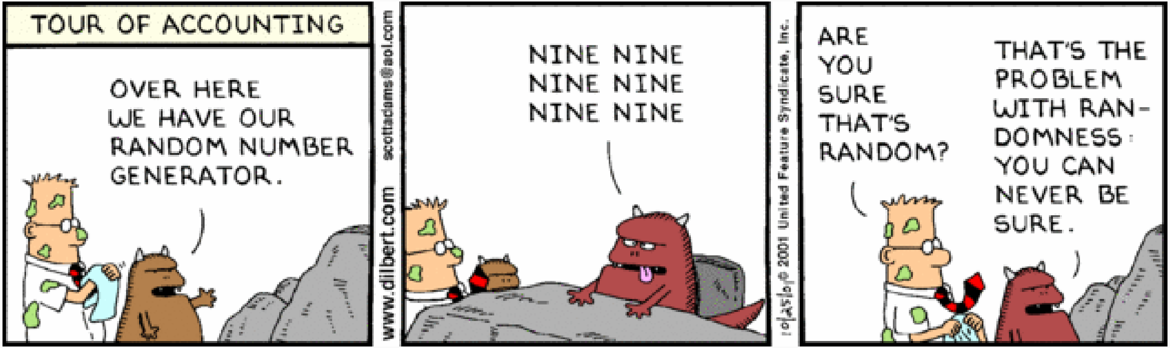
- **Rounded Division:** $\left\lfloor \frac{\texttt{value}}{\texttt{div}} + \frac{1}{2} \right\rfloor$

```
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)
```

C++ <random>

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:

```cpp
#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?	∼`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

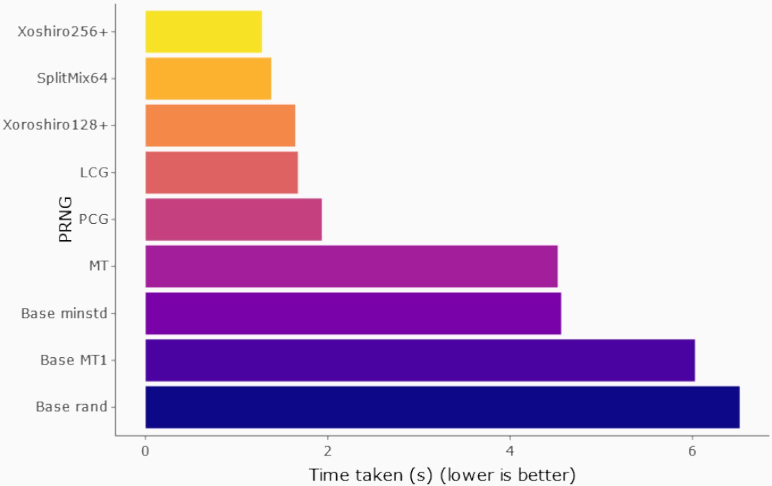
PRNG Quality:

- 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



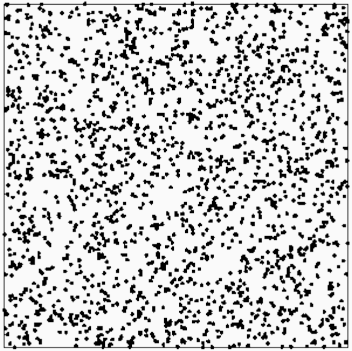
Random number generators for C++ performance tested

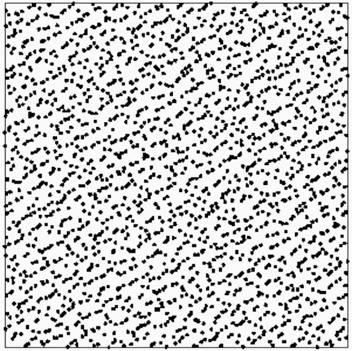
Quasi-random 1/2

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

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

Note: 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`

`::gettimeofday()` (Linux, not portable)

```
#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: not portable, the time is not monotonic increasing (timezone) `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 `std::clock`

```
#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
```

```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

`<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`

```cpp
#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**

```
#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'
```

std::any

`<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());
```