Paper Number:	P1068R6
Title:	Vector API for random number generation
Authors:	Ilya Burylov <burylov@gmail.com> Pavel Dyakov <pavel.dyakov@intel.com> Ruslan Arutyunyan <ruslan.arutyunyan@intel.com> Andrey Nikolaev <af.nikolaev@gmail.com> Alina Elizarova <alina.elizarova@intel.com>
Audience:	LEWG
Date:	2022-10-13

I. Introduction

C++11 introduced a comprehensive mechanism to manage generation of random numbers in the <random> header file.

We propose to introduce an additional API based on iterators in alignment with algorithms definition. simd-type based interface presented in previous paper revisions will be submitted as a separate paper.

II. Revision history

Key changes for R6 compared with R5 after LEWG telecon review (2022-08-23):

- API was changed from member functions to CPO-based approach
- Iterators-based API was dropped based on weak consensus poll results
- New concepts introduced in previous revisions were removed (not needed for CPO)
- The section of design considerations was considerably extended with past and new aspects documented

Key changes for R5 compared with R4 after LEWG mail list review (Feb-March 2021):

- Renamed member function from operator() to generate()
- Replaced legacy iterators with C++20 iterator and ranges concepts.
- Added ranges-based API
- Discussed iterator constraints from performance perspective
- Added reference to __generate() API added in GNU* libstdc++
- Renamed uniform_vector_random_bit_generator to uniform_bulk_random_bit_generator and added uniform_range_random_bit_generator

Key changes for R4 compared with R3 after LEWGI review (Prague):

- Reverted changes in existing concept uniform_random_bit_generator and introduced uniform_vector_random_bit_generator. Updated corresponding wording.
- Ensured std::random_device benefits from vector API.

Key changes for R3 compared with R2 after SG1 and SG6 review (Belfast):

- Removed execution policies from API, based on Cologne meeting decision.
- Removed simd-based API, for separate consideration as a follow up paper, based on corresponding TS results.
- Added formal wording section for iterators-based API.

Key changes for R2 compared with R1 after SG1 review (Cologne):

- Proposed API for switching between Sequentially consistent and Sequentially inconsistent vectorized results.

- Added performance data measured on the prototype to show price for sequentially consistent results.
- Extended description of the role of generate_canonical in distributions implementations.
- Reworked *Possible approaches to address the problem* chapter to focus on two main approaches under consideration.

Key changes for R1 compared with R0 after SG1 review (Rapperswil):

- Extended the list of possible approaches with simd type direct usage.
- Added performance data measured on the prototype.
- Changed the recommendation to a combined approach.

III. Motivation and Scope

The C++11 random-number API is essentially a scalar one. Stateful nature and the scalar definition of underlying algorithms prevent auto-vectorization by the compiler.

However, most existing algorithms for generation of pseudo- [and quasi-]random sequences allow algorithmic rework to generate numbers in batches, which allows the implementation to utilize simd-based HW instruction sets.

Internal measurements show significant scaling over simd-size for key baseline Engines yielding a substantial performance difference on the table on modern HW architectures.

Extension and/or modification of the list of supported Engines and/or Distributions is out of the scope of this proposal.

IV. Libraries and other languages

Vector APIs are common for the area of generation random numbers. Examples:

* Intel® oneAPI Math Kernel Library (oneMKL)

  - Statistical Functions component includes Random Number Generators C vector based API

* Java* java.util.Random

  - Has doubles(), ints(), longs() methods to provide a stream of random numbers

* Python* NumPy* library

  - NumPy array has a method to be filled with random numbers

* NVIDIA* cuRAND

  - host API is vector based

* GNU* libstc++ extension

GNU* libstc++ library implementation has an extension, which introduces __generate() member function to all distributions (but not engines). It was added back in 2012 jointly with simd_fast_mersenne_twister_engine implementation in order to be able to benefit from simd instructions.

Intel oneMKL can be an example of the existing vectorized implementation for a variety of engines and distributions. Existing API is C [1] (and FORTRAN), but the key property which allows enabling vectorization is a vector-based interface.

Another example of implementation can be intrinsics for the Short Vector Random Number Generator Library [2], which provides an API on simd level and can be considered an example of internal implementation for proposed modifications.

V. Problem description

Main flow of random number generation is defined as a 3-level flow.

User creates Engine and Distribution and calls operator() of Distribution object, providing Engine as a parameter:

```
std::array<float, arrayLength> stdArray;

std::mt19937 gen(777);
std::uniform_real_distribution dis(1.f, 2.f);

for(auto& el : stdArray) {
    el = dis(gen);
}
```

operator() of a Distribution implements scalar algorithm and typically (but not necessarily so) calls generate_canonical(), passing Engine object further down:

```
uniform_real_distribution::operator()(_URNG& __gen) {
    return (b() - a()) * generate_canonical<_RealType>(__gen) + a();

}
```

It is necessary to note that C++ standard does not require calling generate_canonical() function inside any distribution implementation and it does not specify the number of Engine numbers per distribution number. Having said that, 3 main standard library implementations share the same schema, described here.

generate_canonical() has a main intention to generate enough entropy for the type used by Distribution, and it calls operator() of an Engine one or more times (number of times is a compile-time constant):

```
_RealType generate_canonical(_URNG& __gen) {
    …

    _RealType _Sp = __gen() - _URNG::min();

    for (size_t __i = 1; __i < __k; ++__i, __base *= _Rp)
        _Sp += (__gen() - _URNG::min()) * __base;

    return _Sp / _Rp;

}
```

operator() of an Engine is (almost) always stateful with non-trivial dependencies between iterations, which prevents any auto-vectorization:

```
mersenne_twister_engine<…>::operator()() {

    const size_t __j = (__i_ + 1) % __n;

    …

    const result_type _Yp = (__x_[__i_] & ~__mask) | (__x_[__j] & __mask);
    const size_t __k = (__i_ + __m) % __n;
    __x_[__i_] = __x_[__k] ^ __rshift<1>(_Yp) ^ (__a * (_Yp & 1));
    result_type __z = __x_[__i_] ^ (__rshift<__u>(__x_[__i_]) & __d);
    __i_ = __j;

    …

    return __z ^ __rshift<__l>(__z);
```

```
}
```

operator() of the most distributions can be implemented in a way, which the compiler can inline and auto-vectorize. generate_canonical() adds an additional challenge for the compiler due to the loop, but it is resolvable. operator() on the engine level is the key showstopper for the auto-vectorization.

VI. New API

The following API extension is targeting to cover generation of bigger chunks of random numbers, which allows internal optimizations hidden inside implementation.

A new CPO is added in std::ranges namespace to cover generation in chunks.

Ranges-based overload to cover engines, engine adaptors and random_device:

```
std::array<std::uint_fast32_t, arrayLength> intArray;
std::mt19937 eng(777);

std::ranges::generate_random(eng, intArray);
```

It is equivalent to:

```
for(auto& el : intArray)
    el = eng();
```

Ranges-based overload to cover distributions:

```
std::array<float, arrayLength> fltArray;
std::mt19937 eng(777);
std::uniform_real_distribution dist(1.f, 2.f);

std::ranges::generate_random(eng, dist, fltArray);
```

It is equivalent to:

```
for(auto& el : fltArray)
    el = dist(eng);
```

New CPO allows writing customizations primarily for generation of random numbers in chunks, which can rely on vectorization internally in implementation details.

VII. Wording proposal

26.6.1 Header <random> synopsis [rand.synopsis]

```
namespace std {
...

// 26.6.8.2, function template generate_canonical
template<class RealType, size_t bits, class URBG>
RealType generate_canonical(URBG& g);

namespace ranges {
  // 26.6.x.x, customization point objects
  inline namespace unspecified { // 26.6.x.x, ranges::generate_random
    inline constexpr unspecified generate_random = unspecified;
  }
}

// 26.6.9.2.1, class template uniform_int_distribution
```

```
template<class IntType = int>
class uniform_int_distribution;
...
}
```

Add a new section after 26.6.9 Random number distribution class templates [rand.dist].

26.6.10 Customization point objects [rand.cust]

26.6.10.1 ranges::generate_random [rand.cust.generate]

The name ranges::generate_random denotes a customization point object (16.3.3.3.6).

Given subexpressions E and R, the expression ranges::generate_random(E, R) is expression-equivalent (3.21) to the following:

- generate_random(E, R), if it is a well-formed expression with overload resolution performed in a context that does not include a declaration of std::ranges::generate_random. generate_random customization effects shall be equivalent to std::ranges::generate(R, std::ref(E)).
- Otherwise, std::ranges::generate(R, std::ref(E)), if E is *uniform_random_bit_generator* and R is *output_range* for E::result_type.
- Otherwise, ranges::generate_random(E, R) is ill-formed.

Given subexpressions E, D and R, the expression ranges::generate_random(E, D, R) is expression-equivalent (3.21) to the following:

- generate_random(E, D, R), if it is a well-formed expression with overload resolution performed in a context that does not include a declaration of std::ranges::generate_random. generate_random customization effects shall be equivalent to std::ranges::generate(R, [&E,&D]() {return D(E);}).
- Otherwise, std::ranges::generate(R, [&E,&D]() {return D(E);}), if E is *uniform_random_bit_generator,* D is *invokable* with D(E) and R is *output_range* for D::result_type.
- Otherwise, ranges::generate_random(E, D, R) is ill-formed.

[Note: Implementations are encouraged to provide customizations of generate_random for engines, distributions, random_device and engine adaptors for performance optimizations. -end note]

VIII. Past poll results

LEWG telecon review (2022-08-23):

POLL: .generate should be an algorithm e.g. generate_random/random_fill instead of a member function

SF	F	N	A	SA
-	-	-	-	-
8	4	7	0	0

Outcome: Strongly in favor

POLL: This proposal should drop the iterator overloads and provide only the ranges one, assuming it's an algorithm.

SF	F	N	A	SA
-	-	-	-	-
2	6	8	2	0

Outcome: *Weak consensus in favor.*

IX. Design considerations

a) Performance without API modification

Why is a new API needed and why can't we achieve the same performance gains within the existing API?

There are two major ways to try achieving similar performance gains within existing scalar API:

Library only solution (buffer under the hood)

Engines and/or distributions can implement buffers under the hood, generating a pack of numbers at a time, then returning them back these numbers in a scalar way.

Problem with engines: buffers will increase the state of an engine. This size can be extremely important. Heavy monte carlo simulation may require huge numbers of engines existing at the same time and increasing their size will increase pressure on cache/memory, which will overcome all benefits from vectorization.

This is why the state of engines is predefined in the standard. E.g. see [rand.eng.lcong]: "The state x_i of a linear_congruential_engine object x is of size 1 and consists of a single integer."

If we can't do it on the engines side, we can try to do it on the distributions side.

Problem with distributions: buffer is impossible on the distribution side, because:

1. API allows using different engines for each scalar call and thus implementation can not speculatively assume that the same engine is used further on;
2. API allows using the same engine for the different purpose in between the scalar distribution calls and thus implementation can not speculatively assume that the state of the engine will not change between the calls.

Library only solution (overloads for std::ranges::generate)

Library may provide a number of dedicated overloads for std::ranges::generate, which would apply optimization when available.

Problem with engines: there are not so many. There can be a shadow implementation for existing engines, which would be executed when used via std::ranges::generate with a suitable chunk size. This API is not guiding users that it is a path for performance and it is easy to overlook, but it is partially solvable via more documentation.

Problem with distributions: the key problem is that distribution is not invokable without arguments, it always needs an engine at least, which brings in limitations. Distribution should be wrapped with std::bind and optimization is applied to expressions of the following form only:

```
std::ranges::generate(range, std::bind(distribution, engine));
```

1. Engine is copied inside std::bind result without access to this copy for the user, thus engine cannot be used to continue generation after this call.

2. Implementation should heavily rely on std::bind unspecified implementation details, like function type for overloading, a way to access std::bind engine to get its state for vectorization, etc.
3. An average user will unlikely to rely on std::bind in this case, and compiler would likely to see the following code, which is completely unusable for optimizations via overloads:

```
std::ranges::generate(range, [&](){ distribution(engine); });
```

Compiler+library solution

As it was discussed earlier, a compiler can not vectorize the scalar engine implementation on its own. But if a library implementation can provide internal tips for a compiler that there is a dedicated unrolled implementation for the engine and it can be used for this vectorization, then it can be implemented. E.g. with OpenMP* **declare simd** directive (see section 7.7 of OpenMP* 5.2 specification [6]).

Similar approach is implemented in Intel® C++ Compiler in the Short Vector Random Number Generator Library (see section Usage Model [2]).

While this model is attractive in its simplicity, its performance outcome should be carefully controlled on the user side, because the loop, which will be vectorized, is in the user code and any small modification or change in compiler heuristics may affect the outcome of the vectorization.

b) Why not represent a proposed API as a C++20 range?

Algorithms with ranges are scalar by nature. For example the following pseudo-code shows that std::ranges::copy expects a single output value per iteration.

std::ranges::copy(*engine_view(e)*, output_it);

This leads to the very similar problems described in the previous section.

Problem with engines: We would need to keep a buffer within *engine_view* that stores a generated pack of numbers returning them one by one per algorithm iteration. That increases the size of *engine_view,* which is basically the same as increasing the size of the engine itself. See the “monte carlo simulation” use-case considerations in the previous section.

Problem with distributions: For the imagining pipable API like *engine_view(e) | distribution_view(d);* the buffer is impossible to keep in *distribution_view* because of the same problems for distributions described in the previous section. For alternative API like *engine_view(e,d)* we have the same problems as described for engines and, furthermore, it’s unclear how to reuse the same engine object in other RNG APIs since *engine_view* could keep the tail of an already generated pack of random numbers.

c) Standalone function vs. member function

Original revisions of the paper proposed operator(begin, end) as the interface for vector generation.

We changed it to member function generate(begin, end) starting revision R5 based on discussion in LEWG mailing list it was renamed to member function .generate() in R5.

It was refactored to become an algorithm-like interface based on POLL on LEWG telecon (2022-08-28).

The main arguments for the refactoring are:

- It is consistent with current approach to introduce customizable API via CPO
- It is aligned with other algorithm-like functionality
- Additional concepts are not required, which simplify the feature

Drawbacks:

- It is different from existing experimental feature in GNU C++ standard library where it is member function called .__generate()
- Using .generate() member function could allow a use case of applying random_device or simpler engines to initialize a big initial state for more sophisticated engines. See, for example, *subtract_with_carry_engine* description, which is initialized by *linear_congruential_engine* by default. But it may be considered a controversial feature.

d) Arguments order

Arguments order of the new API:

```
std::ranges::generate_random(engine, range);
```

It is different from what would be seen for generic algorithm with similar semantics:

```
std::ranges::generate(range, engine);
```

The order of the arguments was discussed on LEWG telecon 2022-08-23 without poll. Proposed reason for the changed order is the assumption that it might be more natural to keep parameters of the generation first and the range, to which it is applied, the last. It might be more prominent, when we have more than one argument:

```
std::ranges::generate_random(engine, distribution, range);
```

It should be noted though, that with the proposed API introduced, there still be a possibility to write both following lines with similar effects and user may consider the changed order inconsistent:

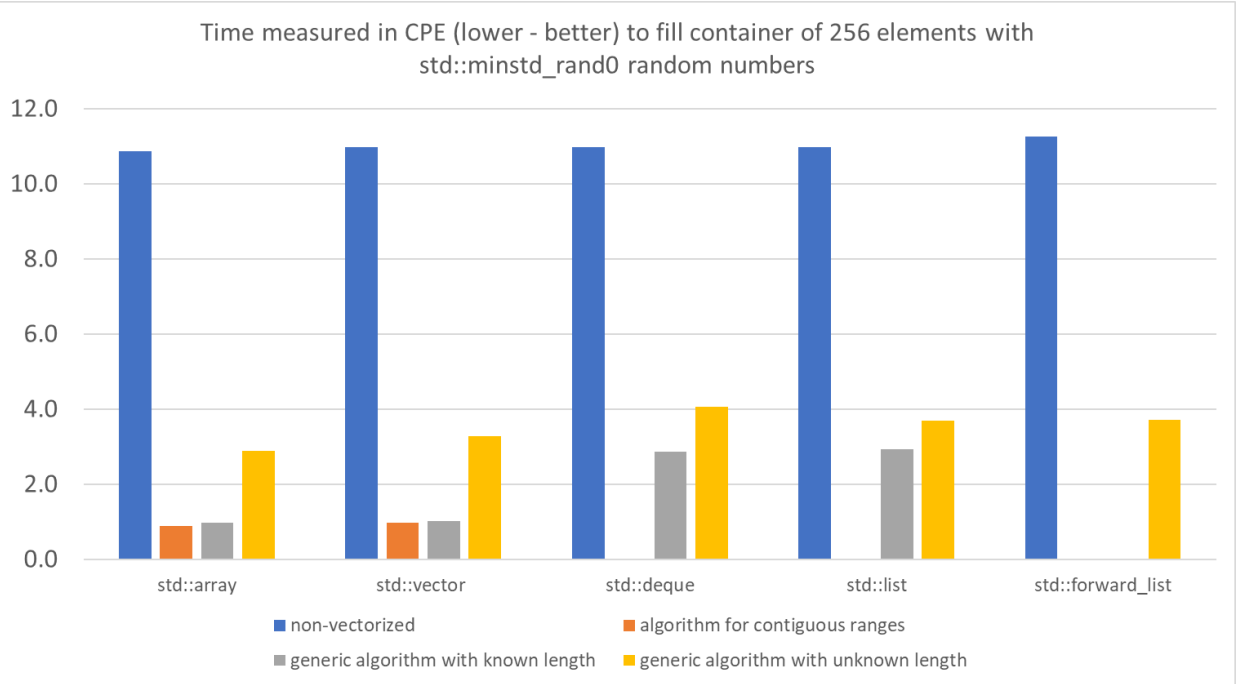
```
std::ranges::generate(range, engine);

std::ranges::generate_random(engine, range);
```

e) Constraining iterators and ranges

Additional performance results were collected to support discussion regarding additional constraints for iterators and ranges. One would likely need 3 different internal implementations to get optimal performance on existing sequence container:

- Algorithm optimal for contiguous ranges
- Generic algorithm for ranges on known length
- Generic algorithm for ranges on unknown length



CPE – cycles per element of the container filled with numbers. Measured on Intel® Xeon® Gold 6152 Processor.

- Contiguous-aware implementation is simpler than generic implementation, but performance benefit can be marginal.
- Knowledge of length allows one to make decisions on vectorization of small chunks of numbers and we get a measurable overhead if length is unavailable.

Our experience shows that a contiguous memory use case is the most important for this API. Random access use case is possible in an unfortunate case of AOS data layout. Other use cases are exotic for random numbers generation and are not expected to be the target for vectorization.

CPO-based API proposed in revision 6 of this paper is no longer limited by range constraints: default implementation allows any *output_range* and choosing a constraint for specific engines and/or distributions becomes a quality of implementation question.

f) Bit-to-bit Reproducibility

This paper allows customizations for engines, engine adaptors, distributions and random_device.

*"*generate_random customization effects shall be equivalent to std::ranges::generate(R, std::ref(E))*"* wording for *engines* and *engine adaptors* is intended to guarantee bit-to-bit equivalence of the following use case:

```
std::ranges::generate_random(eng, range);
```

and

```
for(auto& el : range) {
    el = gen();
}
```

This guarantee is needed to keep statistical properties of random numbers sequence, which was justified for each specific engine by its authors in corresponding papers.

random_device sequences are not guaranteed to be anyhow reproducible by fundamental design of this feature.

Bit-to-bit reproducibility of *distributions* sequences is not guaranteed by current wording of the standard even for scalar API. One of the main reasons for that is to allow different distribution algorithms to be implemented by different standard libraries. The main guarantee provided by the standard in this case is a statistical property of the sequence of the numbers.

"generate_random customization effects shall be equivalent to std::ranges::generate(R, [&E,&D]() {return D(E);})" wording for distributions is intended to provide the same guarantees – those two code snippets will result in values, which have the same statistical properties, but are not required to be bit-to-bit exact values:

```
std::ranges::generate_random(gen, dist, range);
```

and

```
for(auto& el : range) {
    el = dist(gen);
}
```

X. Impact on the standard

This is a library-only extension. It adds a new CPO. This change is ABI compatible with existing random numbers generation functionality.

XI. References

1. Intel oneMKL documentation: https://software.intel.com/content/www/us/en/develop/documentation/onemkl-developer-reference-c/top/statistical-functions/random-number-generators/basic-generators.html
2. Intrinsics for the Short Vector Random Number Generator Library https://software.intel.com/content/www/us/en/develop/documentation/cpp-compiler-developer-guide-and-reference/top/compiler-reference/intrinsics/intrinsics-for-the-short-vector-random-number-generator-library.html
3. Box-Muller method https://en.wikipedia.org/wiki/Box%E2%80%93Muller_transform
4. Inverse transform sampling https://en.wikipedia.org/wiki/Inverse_transform_sampling
5. Allow Seeding Random Number Engines with std::random_device http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2016/p0205r0.html
6. OpenMP API 5.2 Specification https://www.openmp.org/wp-content/uploads/OpenMP-API-Specification-5-2.pdf

Notices & Disclaimers

Performance varies by use, configuration and other factors. Learn more on the Performance Index site.

Performance results are based on testing as of dates shown in configurations and may not reflect all publicly available updates. See backup for configuration details. No product or component can be absolutely secure.

Your costs and results may vary.

Intel technologies may require enabled hardware, software or service activation.