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Audience: LEWG
Target: C++23 (pending `simd` merge)

Integrating simd with parallel algorithms

ABSTRACT

This paper discusses a new execution policy for integrating `simd` with *parallel algorithms*.

CONTENTS

1 CHANGELOG

1.1 CHANGES FROM REVISION 0

Previous revision: P0350R0

- Update to apply against C++17 wording.
- Removed executors discussion because the executors design has not left SG1 yet.
- Updated example code to reflect changes in P0214.

1.2 CHANGES FROM REVISION 1

Previous revision: P0350R1

- Updated code to match [N4744].
- Fixed a bug in the `for_each` example implementation.
- Improved `iota` and `for_each` example implementations with constexpr-if.
- Discuss impact on all algorithms.

1.3 CHANGES FROM REVISION 2

Previous revision: P0350R2

- Discuss ABI tag of `std::generate` callables.
- Add a Tony Table.
- Note that `remove` and `remove_copy` are implicitly vectorizable.

1.4 CHANGES FROM REVISION 3

Previous revision: P0350R3

- Add heap algorithms to list of algorithms that may benefit from new execution policy.
- Discuss the 3 options for `generate`.
- Settle on `simd_mask` predicates.

2 STRAW POLLS

2.1 SG1 AT OULU

Poll: Ship it to LEWG?

SF	F	N	A	SA
6	6	2	0	0

2.2 LEWG AT ALBUQUERQUE

Poll: Forward the paper to LWG?

SF	F	N	A	SA
1	1	2	1	1

→ Paper needs a revision: LEWG wants a list of affected algorithms and an update to concept requirements.

2.3 LEWG AT COLOGNE 2019

Poll: Prefer expressing simd execution via policy tag (not newly named algorithms, `std::simd_transform`, etc).

SF	F	N	A	SA
4	9	3	0	0

Poll: What do we do with predicates? (Roughly option 2 from the paper, be mindful of the amount of wording that is thrown out of conformance.)
→ unanimous consent

Poll: Require that this goes first into `std::ranges` algorithms (which haven't been parallelized yet).

SF	F	N	A	SA
0	2	7	5	2

Revise and come back.

3 INTRODUCTION

Parallel Algorithms enable implementations of the existing STL algorithms to use non-sequential semantics when executing the user-supplied code (explicit callable or implicit operator call). The first argument to the algorithm function determines this change in execution semantics via an *execution policy*. This paper introduces a new execution policy, called `execution::simd`[1]. `execution::simd` requires user-provided function objects to be callable with `simd<T, Abi>` arguments instead of the `T` arguments the `execution::seq` variant would use. The algorithm therefore processes chunks of `simd<T, Abi>::size()` objects concurrently. The execution order of the chunks retains the sequential semantics of the non-parallel algorithms.

As a consequence, the applicability of the execution policy is limited to iterators where `Iterator::value_type` is a vectorizable type [N4744, [parallel.simd.general]]. A future extension of `simd` may lift this restriction by allowing certain (or all) user-defined types as first template argument to `simd`. A different conceivable extensions is a recursive destructuring applied inside the algorithm, subsequent creation of a corresponding number of `simd` objects, and a call to the function object with a corresponding number of arguments. (E.g. application of an algorithm on `std::vector<std::pair<float, float>>` calls the function object with `simd<float>, simd<float>` instead of `simd<std::pair<float, float>>`.)

before	with P0350R4

<pre>using V = stdx::native_simd<float>;
constexpr int N = 60;
 	
template <class T> T something(T);
 	
auto f(const std::array<float, N>& data)
{
  std::array<float, N> output;
 	
  size_t i = 0;
  for (; i + V::size() <= N; i += V::size()) {
    V x(&data[i], stdx::element_aligned);
    x = something(x + 1);
    x.copy_to(&output[i], stdx::element_aligned);
  }
  for (; i < N; ++i) {
    output[i] = something(data[i] + 1);
  }
 	
  return output;
}</pre>
	<pre>using V = stdx::native_simd<float>;
	constexpr int N = 60;
	
	template <class T> T something(T);
	
	auto f(const std::array<float, N>& data)
	{
	  std::array<float, N> output;
	
	  stdx::transform(std::execution::simd,
	    data.begin(), data.end(), output.begin(),
	    [](auto x) {
	      return something(x + 1);
	    });
	
	  return output;
	}</pre>

Tony Table 1: Transformation of an array. c.f. `https://godbolt.org/z/mEL3CK`

1 An alternative suggestion for the name is `execution::simd_type`.

```
std::vector<float> data;
data.resize(99);
iota(execution::simd, data.begin(), data.end(), 0.f);
for_each(execution::simd, data.begin(), data.end(), [](auto &x) {
  x *= x;
});
```

Listing 1: Example using `execution::simd` with `iota` and `for_each`.

4 PARALLEL ALGORITHMS

4.1 EXAMPLE

Consider the example in Listing 1. The `iota` and `for_each` functions each could create an internal `simd` iterator adaptor, depending on the iterator category. Being able to determine whether the storage, the iterator points to, is contiguous, is most important in this context as it enables vector loads and stores. Since the `std::vector` iterators are *contiguous iterators*, the example implementations shown in Listing 2 and Listing 3 could be used for the example.

Both implementations might be improved with a prologue that enables aligned loads and stores. Also note that `for_each` allows the `Function` parameter to mutate the argument if the iterator is a mutable iterator. The implementation uses a compile-time trait to determine whether the function `f` uses a reference parameter, in which case it stores the temporary `simd` object back. Otherwise, the store is optimized away.

Figure 1 shows a visualization how the `iota` implementation works. The `init simd` object is stored via vector stores to 4 (assuming native `simd::size() == 4`) elements in the `std::vector`. In each iteration the `init` object is incremented by `simd::size()` and stored to the following elements in the `std::vector`. Since the `std::vector` has 99 elements, the last three elements cannot be initialized with a vector store of four elements. Instead the `epilogue` recursion generates a new `init simd` object for size 2 and subsequently for size 1.

Figure 2 visualizes the end of the `for_each` implementation. The main `for` loop processes four elements of the `std::vector` in parallel. It executes a vector load, calls the user-provided function with the temporary `simd` object, and executes a vector store back to the same memory location. The remaining three elements are again handled by an `epilogue` recursion which divides the number of processed elements by 2 with every step.

For both algorithms it would be perfectly valid to implement the epilogue as a sequential loop using `simd` objects with size 1.

```
template <size_t N, class ContiguousIterator>
inline void epilogue(ContiguousIterator first, ContiguousIterator last,
                     typename ContiguousIterator::value_type first_value) {
  if constexpr (N > 0) {
    if (distance(first, last) >= N) {
      using T = ContiguousIterator::value_type;
      using V = simd<T, simd_abi::deduce_t<T, N>>;
      const V init = V([&](auto i) { return T(i); }) + first_value;
      store(init, std::addressof(*first), element_aligned);
      first += V::size();
    }
    epilogue<V::size() / 2>(first, last, init[V::size() - 1] + 1);
  }
}

template <class ContiguousIterator>
void iota(execution::simd_policy, ContiguousIterator first, ContiguousIterator last,
          typename ContiguousIterator::value_type first_value) {
  using T = ContiguousIterator::value_type;
  using V = native_simd<T>;
  V init = V([&](auto i) { return T(i); }) + first_value;
  const V stride = T(V::size());
  for (; distance(first, last) >= V::size(); first += V::size(), init += stride) {
    store(init, std::addressof(*first), element_aligned);
  }
  epilogue<V::size() / 2>(first, last, init[V::size() - 1] + 1);
}
```

Listing 2: Implementation idea for the `iota` function used in Listing 1.

```
template <size_t N, class ContiguousIterator, class UnaryFunction>
inline void epilogue(ContiguousIterator first, ContiguousIterator last,
                     UnaryFunction f) {
  if constexpr (N > 0) {
    using T = ContiguousIterator::value_type;
    using V = simd<T, simd_abi::deduce_t<T, N>>;
    if (distance(first, last) >= V::size()) {
      V tmp(std::addressof(*first), element_aligned);
      f(tmp);
      if constexpr (is_functor_argument_mutable_v<UnaryFunction, V>) {
        store(tmp, std::addressof(*first), element_aligned);
      }
    }
    epilogue<V::size() / 2>(first, last, f);
  }
}

template <class ContiguousIterator, class UnaryFunction>
void for_each(execution::simd_policy, ContiguousIterator first,
              ContiguousIterator last, UnaryFunction f) {
  using V = native_simd<ContiguousIterator::value_type>;
  for (; distance(first, last) >= V::size(); first += V::size()) {
    V tmp(std::addressof(*first), element_aligned);
    f(tmp);
    if constexpr (is_functor_argument_mutable_v<UnaryFunction, V>) {
      store(tmp, std::addressof(*first), element_aligned);
    }
  }
  epilogue<V::size() / 2>(first, last, f);
}
```

Listing 3: Implementation idea for the `for_each` function used in Listing 1.

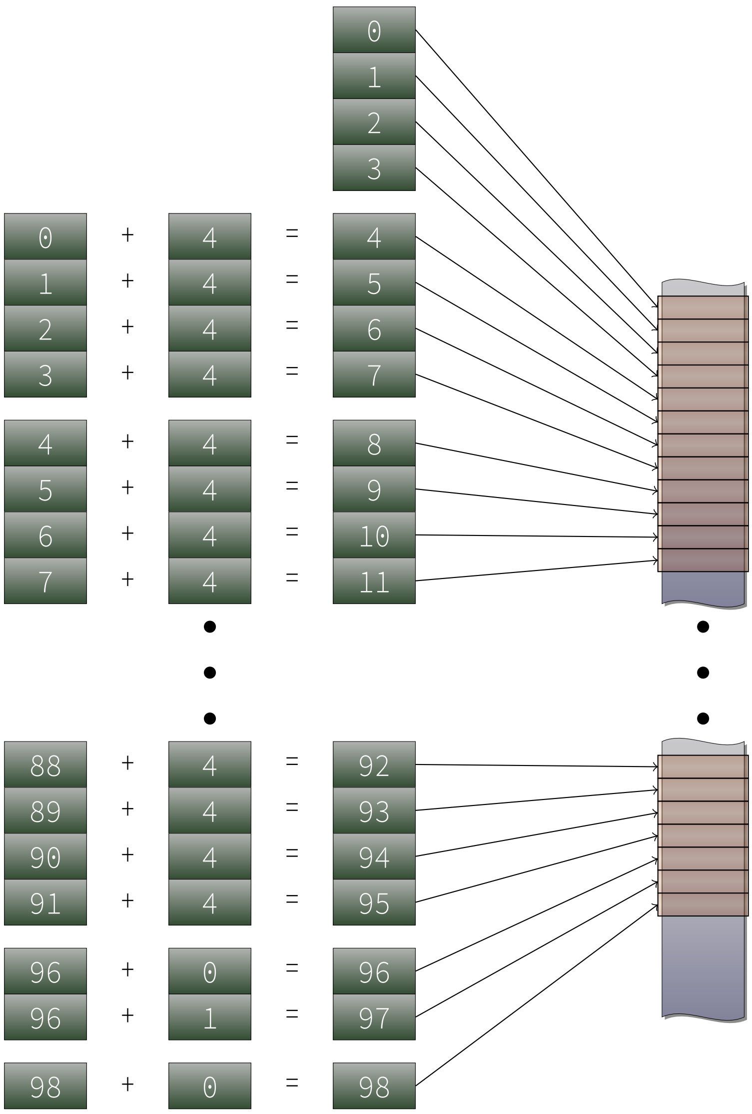

Figure 1: Visualization of chunking the `iota` call with $\mathcal{W}_{\mathsf{T}} = 4$ in Listing 1.

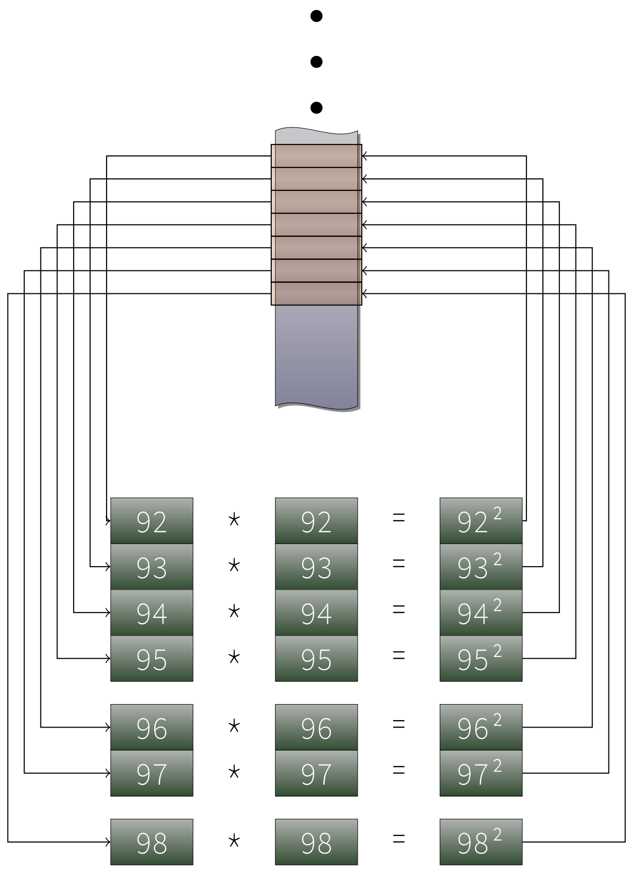

Figure 2: Visualization of chunking the `for_each` call with $\mathcal{W}_T = 4$ in Listing 1.

Copies In general, the `execution::simd` policy requires algorithms to make a copy from the input sequence. For now, since `simd` only supports arithmetic types and `simd` does not return lvalue references to its values, it is not observable whether a copy was made. With two exceptions:

- Modification of the input sequence via different means than the function parameter(s), which is UB anyway, will not modify the value of the function parameter(s).
- Using mutable iterators, assignment to the `simd` (lvalue reference) parameter of the user-supplied function object will not modify the output sequence until after the function has returned (cf. Listing 3).

Note that most non-modifying sequence operations allow modification of the sequence by using a non-const lvalue reference parameter for the user-supplied function object.

Predicates Algorithms that take a predicate returning a `bool` have two possible vectorization strategies:

1. The predicate still returns `bool`. In this case, every predicate must execute a `simd_mask` reduction. This makes it simple to short-circuit in the algorithm implementation but may unnecessarily restrict the achievable parallelization.
2. The predicate returns `simd_mask`. In this case $\mathcal{W}_{\texttt{ForwardIterator::value\_type}}$ reductions can happen in parallel. Short-circuiting is still possible, but requires a `simd_mask` reduction on each step (QoI question).

It would also be possible to allow both and let the algorithm switch the strategy depending on the return type of the predicate.

In Cologne 2019, LEWG unanimously recommended to exclusively go with predicates returning `simd_mask`: The use of `bool` would effectively change the algorithms.

Complexity requirements For many algorithms, the complexity requirement states “Applies `f` *exactly* `last - first` times”. In the `execution::simd` case, the number of applications of `f` is reduced by an unspecified factor.

Sorting The `Compare` function object type is required to return a value that is contextually convertible to `bool`. For sorting, it is important that overloads using the `execution::simd` policy work with `simd_mask` instead of `bool`. It is not useful for the sort algorithm to know whether all/any/some/none of the compared values are "less than". It requires a mask object to know the "less than" relation for each individual value.

4.3 DESIGN ALTERNATIVE

In Cologne 2019, LEWG recommended to not pursue this design alternative. It is still provided in this paper for completeness.

There are subtle differences in how the `execution::simd` specializations need to be used (e.g. `std::generate` currently requires the generator function to return objects that can be assigned to a dereferenced `ForwardIt`; the `execution::simd` specialization requires the generator function to return objects of type `simd<ForwardIt::value_type>`). An attempt to fit `execution::simd_policy` into the existing wording results in some special-casing in the algorithm specifications. This observation leads to the question whether a new execution policy is really the best approach. The alternative would be a duplication of algorithms to variants with a `simd_` prefix in their name. Example:

```
simd_for_each(data.begin(), data.end(), [](auto &x) {
  x *= x;
});
```

This alternative would not reduce the amount of wording/complexity though, since now a lot of the algorithm wording would need to be duplicated. However, this would allow a very simple reduction of the number of algorithms that support `simd` execution.

4.4 AFFECTED ALGORITHMS

The following algorithms have an `ExecutionPolicy` overload and can work with a `execution::simd_policy` specialization:

- `all_of`, `any_of`, `none_of`
- `for_each`, `for_each_n`
- `find`, `find_if`, `find_if_not`
- `find_end`
- `find_first_of`
- `adjacent_find`
- `count`, `count_if`
- `mismatch`

- equal
- search, search_n
- copy, copy_n (no real need; can be implicitly vectorized)
- copy_if
- swap (no real need; can be implicitly vectorized)
- transform
- replace, replace_if, replace_copy, replace_copy_if
- fill, fill_n (no real need; can be implicitly vectorized)
- generate, generate_n (see Section 4.5)
- remove, remove_copy (no real need; can be implicitly vectorized)
- remove_if, remove_copy_if
- unique, unique_copy
- reverse, reverse_copy (no real need; can be implicitly vectorized)
- rotate, rotate_copy (no real need; can be implicitly vectorized)
- is_partitioned, partition, stable_partition, partition_copy, partition_point
- sort,stable_sort, partial_sort, partial_sort_copy, is_sorted, is_sorted_until
- nth_element
- merge, inplace_merge
- includes, set_union, set_intersection, set_difference, set_symmetric_difference
- min_element, max_element, minmax_element
- lexicographical_compare
- is_heap, is_heap_until, make_heap, push_heap, pop_heap, and sort_heap (The comparison function object can use simd and simd_mask.)

```
std::vector<float> v;

// 0. Existing (scalar) interface
std::generate(v.begin(), v.end(), [&]() { return 0.f; })

// 1. Choose ABI via template parameter
// template <class Gen>
// void generate(/*...*/, Gen g) { g.template operator()<native_simd<float>>(); }
std::generate(v.begin(), v.end(), []<typename T>() { return T(); });

// 2. Choose ABI via return type
// template <class Gen>
// void generate(/*...*/, Gen g) {
//   auto x = g(); // discard if x has more values than needed
// }
std::generate(v.begin(), v.end(), []() { return native_simd<float>(); });

// 3. Choose ABI via unused parameter
// template <class Gen>
// void generate(/*...*/, Gen g) {
//   constexpr native_simd<float>* tag = nullptr;
//   g(tag);
// }
std::generate(v.begin(), v.end(), []<typename T>(T*) { return T(); });
```

Listing 4: Use `std::generate` to fill a container with random numbers.

The remaining algorithms have no obvious use for the specialization:

- `move` makes no sense until we can create `simd<T>` types for pointers (likely) and class types (less likely).

`lower_bound`, `upper_bound`, `equal_range`, and `binary_search` may benefit from `simd` usage, but currently do not provide `ExecutionPolicy` overloads.

4.5 The generate algorithm

The generator function passed to `generate`/`generate_n` does not expect any arguments and thus has no interface for the algorithm to request a certain ABI tag from the function (template). Consequently, there are three ideas how to make it work for `simd`:

1. Require the generator function object to take a template argument (no function arguments).
2. Let the algorithm implementation cope with the return type defined by the generator function object. It may have to discard values if the number of values in the range is not a multiple of the number of values in the return type.

3. Pass a parameter that is not used other than for deducing the expected return type of the generator function object.

See Listing 4 for examples.

Ideas 1 and 3 require the user to supply a type with a template call operator. Idea 2 may lead the user to unintentionally drop generated values. For the user, idea 3 requires to write boilerplate with no apparent use: it's an implementation detail shining through. Idea 1 was preferred in the discussion in LEWG in Cologne 2019. However, it is still unclear whether the need for explicit instantiation of the call operator in the standard library implementation is acceptable. There is no apparent technical reason not to use this variant.

4.6 INITIAL WORDING FOR THE POLICY

Add a new execution policy to [N4842, §20.18.2]:

§20.18.2 [execution.syn]

```
// 20.18.7, unsequenced execution policy
class unsequenced_policy;

// 20.18.8, simd execution policy
class simd_policy;

// 20.18.~~8~~9, execution policy objects:
inline constexpr sequenced_policy seq{ unspecified };
inline constexpr parallel_policy par{ unspecified };
inline constexpr parallel_unsequenced_policy par_unseq{ unspecified };
inline constexpr unsequenced_policy unseq{ unspecified };
inline constexpr simd_policy simd{ unspecified };
```

Renumber §20.18.8 to §20.18.9 and add §20.18.8 [execpol.simd]:

```
class simd_policy { unspecified };
```

1 The class `simd_policy` is an execution policy type used as a unique type to disambiguate parallel algorithm overloading and indicate that a parallel algorithm's execution may be vectorized using `simd` for interfacing with user-provided functionality.

2 During the execution of a parallel algorithm with the `execution::simd_policy` policy, if the invocation of an element access function exits via an uncaught exception, `terminate()` shall be called.

Add to §20.18.9 [execpol.objects]:

```
inline constexpr execution::simd_policy execution::simd{ unspecified };
```

[N4842, §25.3.2] defines requirements on user-provided function objects. This might be the right place to add:

§25.3.2 [algorithms.parallel.user]

2 Function objects passed into parallel algorithms instantiated with the `execution::simd` execution policy shall:

- be callable with arguments of type `simd<Iterator::value_type, Abi>`, for any ABI tag `Abi`, for all arguments that otherwise would be of type `Iterator::value_type`;
- return objects of type `simd<Iterator::value_type, Abi>`, if the function object is otherwise expected to return objects assignable to a dereferenced `Iterator` object;
- return objects of type `simd_mask<Iterator::value_type, Abi>` or `bool`, if the function object is otherwise expected to return `bool`.

The following subsection in [N4842, §25.3.3] defines the semantics of the execution policies. A new paragraph for `execution::simd` is needed. The intent is to

1. constrain execution to the calling thread,
2. allow implementations to assume unordered access for all internal element access functions (most importantly loads and stores),
3. apply user-provided function objects in the order the `simd` chunks are created from sequential iteration over the iterator(s).

§25.3.3 [algorithms.parallel.exec]

8 The invocations of element access functions in parallel algorithms invoked with an execution policy object of type `execution::simd_policy` are permitted to execute in an unordered fashion in the calling thread, except for the application of user-provided function objects. User-provided function objects are called with an implementation-defined number of sequence elements combined into a `simd<T, Abi>` object. The type for `Abi` is chosen by the implementation. It may be different for subsequent applications of the user-provided function in the same parallel algorithm invocation. The type for `T` is the decayed type of the sequence elements. The order of elements in the `simd` object is equal to the order of the corresponding elements in the sequence argument. The invocation order of user-provided function objects is sequential.

It is my understanding that we do not want to add anything to [N4842, §25.3.4 [algorithms.parallel.exceptions]] at this point. The situation is simpler for the `execution::simd` policy. It is almost equivalent to the `seq` policy.

4.7 WORDING FOR INDIVIDUAL ALGORITHMS

§25.7 [alg.sorting]

2 `Compare` is a function object type. The return value of the function call operation applied to an object of type `Compare`, when contextually converted to `bool`, yields `true` if the first argument of the call is less than the second, and `false` otherwise. If the `ExecutionPolicy` is `execution::simd_policy`, the return type of the function call operation applied to an object of type `Compare` is a specialization of `simd_mask`. Its i-th element in the `simd_mask` yields `true` if the value of the i-th element of the first argument of the call is less than the corresponding element of the second, and `false` otherwise. `Compare comp` is used throughout for algorithms assuming an ordering relation. It is assumed that `comp` will not apply any non-constant function through the dereferenced iterator.

Further wording work is necessary where individual algorithms refer to boolean results from predicates. (E.g. `all_of` returns `false` if `any_of`(E) is `false` ...)

A BIBLIOGRAPHY

[N4744] Jared Hoberock, ed. *Technical Specification for C++ Extensions for Parallelism Version 2*. ISO/IEC JTC1/SC22/WG21, 2018. URL: https://wg21.link/n4744.

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