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STD::SIMD — MERGE DATA-PARALLEL TYPES FROM THE PARALLELISM TS 2

ABSTRACT

After the Parallelism TS 2 was published in 2018, data-parallel types (`basic_simd<T>`) have been implemented and used. Now there is sufficient feedback to improve and merge Section 9 of the Parallelism TS 2 into the IS working draft.

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1 CHANGELOG

1.1 CHANGES FROM REVISION 0

Previous revision: P1928R0

- Target C++26, addressing SG1 and LEWG.
- Call for a merge of the (improved & adjusted) TS specification to the IS.
- Discuss changes to the ABI tags as consequence of TS experience; calls for polls to change the status quo.
- Add template parameter `T` to `simd_abi::fixed_size`.
- Remove `simd_abi::compatible`.
- Add (but ask for removal) `simd_abi::abi_stable`.
- Mention TS implementation in GCC releases.
- Add more references to related papers.
- Adjust the clause number for [numbers] to latest draft.
- Add open question: what is the correct clause for [simd]?
- Add open question: integration with ranges.
- Add `simd_mask` generator constructor.
- Consistently add simd and simd_mask to headings.
- Remove experimental and parallelism_v2 namespaces.
- Present the wording twice: with and without diff against N4808 (Parallelism TS 2).
- Default load/store flags to `element_aligned`.
- Generalize casts: conditionally `explicit` converting constructors.
- Remove named cast functions.

1.2 CHANGES FROM REVISION 1

Previous revision: P1928R1

- Add floating-point conversion rank to condition of `explicit` for converting constructors.
- Call out different or equal semantics of the new ABI tags.
- Update introductory paragraph of Section 4; R1 incorrectly kept the text from R0.
- Define simd::size as a `constexpr` static data-member of type `integral_constant<size_t, N>`. This simplifies passing the size via function arguments and still be useable as a constant expression in the function body.
- Document addition of `constexpr` to the API.
- Add `constexpr` to the wording.
- Removed ABI tag for passing `simd` over ABI boundaries.
- Apply cast interface changes to the wording.
- Explain the plan: what this paper wants to merge vs. subsequent papers for additional features. With an aim of minimal removal/changes of wording after this paper.
- Document rationale and design intent for `where` replacement.

1.3 CHANGES FROM REVISION 2

Previous revision: P1928R2

- Propose alternative to `hmin` and `hmax`.
- Discuss `simd_mask` reductions wrt. consistency with `<bit>`. Propose better names to avoid ambiguity.
- Remove `some_of`.
- Add unary `~` to `simd_mask`.
- Discuss and ask for confirmation of masked “overloads” names and argument order.
- Resolve inconsistencies wrt. `int` and `size_t`: Change `fixed_size` and `resize_simd` NTTPs from `int` to `size_t` (for consistency).
- Discuss conversions on loads and stores.

- Point to [P2509R0] as related paper.
- Generalize load and store from pointer to `contiguous_iterator`. (Section 4.6)
- Moved “`element_reference` is overspecified” to “Open questions”.

1.4 CHANGES FROM REVISION 3

Previous revision: P1928R3

- Remove wording diff.
- Add std::simd to the paper title.
- Update ranges integration discussion and mention formatting support via ranges (Section 5.6).
- Fix: pass iterators by value not const-ref.
- Add lvalue-ref qualifier to subscript operators (Section 4.11).
- Constrain `simd` operators: require operator to be well-formed on objects of `value_type` (28.9.6.7, 28.9.7.1).
- Rename mask reductions as decided in Issaquah.
- Remove R3 ABI discussion and add follow-up question.
- Add open question on first template parameter of `simd_mask` (Section 4.2).
- Overload loads and stores with mask argument (28.9.6.4, 28.9.6.5, 28.9.8.2, 28.9.8.3).
- Respecify `basic_simd` reductions to use a `basic_simd_mask` argument instead of `const_where_expression` (28.9.7.5).
- Add `basic_simd_mask` operators returning a `basic_simd` (28.9.8.5, 28.9.8.6)
- Add conditional operator overloads as hidden friends to `basic_simd` and `basic_simd_mask` (28.9.7.4, 28.9.9.4).
- Discuss `std::hash` for `basic_simd` (Section 4.20).
- Constrain some functions (e.g., min, max, clamp) to be `totally_ordered` (28.9.7.5, 28.9.7.7).
- Asking for reconsideration of conversion rules.
- Rename load/store flags (Section 4.15).

- Extend load/store flags with a new flag for conversions on load/store. (Section 4.15).
- Update `hmin`/`hmax` discussion with more extensive naming discussion (Section 4.13).
- Discuss freestanding `basic_simd` (Section 4.21).
- Discuss `split` and `concat` (Section 4.16).
- Apply the new library specification style from P0788R3.

1.5 CHANGES FROM REVISION 4

Previous revision: P1928R4

- Added `simd_select` discussion.

1.6 CHANGES FROM REVISION 5

Previous revision: P1928R5

- Updated the wording for changes discussed in and requested by LEWG in Varna.
- Rename to `simd_cat` and `simd_split`.
- Drop `simd_cat(array)` overload.
- Replace `simd_split` by `simd_split` as proposed in P1928R4.
- Use `indirectly_writable` instead of `output_iterator`.
- Replace most `size_t` and `int` uses by *`simd-size-type`* signed integer type.
- Remove everything in `simd_abi` and the namespace itself.
- Reword section on ABI tags using exposition-only ABI tag aliases.
- Guarantee generator ctor calls callable exactly once per index.
- Remove `int`/`unsigned int` exception from conversion rules of broadcast ctor.
- Rename `loadstore_flags` to `simd_flags`.
- Make `simd_flags::operator| consteval`.
- Remove `simd_flags::operator&` and `simd_flags::operator^`.
- Increase minimum SIMD width to 64.

- Rename `hmin`/`hmax` to `reduce_min` and `reduce_max`.
- Refactor `simd_mask<T, Abi>` to `basic_simd_mask<Bytes, Abi>` and replace all occurrences accordingly.
- Rename `simd<T, Abi>` to `basic_simd<Bytes, Abi>` and replace all occurrences accordingly.
- Remove `long double` from the set of vectorizable types.
- Remove `is_abi_tag`, `is_simd`, and `is_simd_mask` traits.
- Make `simd_size` exposition-only.

1.7 CHANGES FROM REVISION 6

Previous revision: P1928R6

- Remove mask reduction precondition but ask LEWG for reversal of that decision (Section 6.3).
- Fix return type of `basic_simd_mask` unary operators.
- Fix `bool` overload of *`simd-select-impl`*(Section 6.1).
- Remove unnecessary implementation freedom in `simd_split` (Section 6.2).
- Use `class` instead of `typename` in template heads.
- Implement LEWG decision to SFINAE on *values* of constexpr-wrapper-like arguments to the broadcast ctor (28.9.6.4).
- Add relational operators to `basic_simd_mask` as directed by LEWG (28.9.9.3).
- Update section on `size_t` vs. `int` usage (Section 4.10).
- Remove all open design questions, leaving LWG / wording questions.
- Add LWG question on implementation note (Section 5.3).
- Add constraint for `BinaryOperation` to `reduce` overloads (28.9.7.5).

2 STRAW POLLS

2.1 SG1 AT KONA 2022

Poll: After significant experience with the TS, we recommend that the next version (the TS version with improvements) of `std::simd` target the IS (C++26)

SF	F	N	A	SA
10	8	0	0	0

Poll: We like all of the recommended changes to `std::simd` proposed in p1928r1 (Includes making all of `std::simd` `constexpr`, and dropping an ABI stable type)
→ unanimous consent

Poll: Future papers and future revisions of existing papers that target `std::simd` should go directly to LEWG. (We do not believe there are SG1 issues with `std::simd` today.)

SF	F	N	A	SA
9	8	0	0	0

2.2 LEWG AT ISSAQUAH 2023

Poll: Change the default SIMD ABI tag to simd_abi::native instead of simd_abi::compatible.

SF	F	N	A	SA
16	12	0	0	1

Poll: Change simd_abi::fixed_size to not recommend implementations make it ABI compatible.

SF	F	N	A	SA
16	7	1	0	1

Poll: Make simd::size an integral_constant instead of a static member function.

SF	F	N	A	SA
9	8	7	1	0

Poll: simd masked operations should look like (vote for as many options as you'd like):

Option	Votes
where(u > 0, v).copy_from(ptr)	12
v.copy_from_if(u > 0, ptr)	1
v.copy_from_if(ptr, u > 0)	2
v.copy_from(ptr, u > 0)	14
v.copy_from(u > 0, ptr)	3
v.copy_from_where(u > 0, ptr)	4
v.copy_from_where(ptr, u > 0)	11

Poll: simd masked operations should look like (vote once for your favorite):

Option	Votes
where(u > 0, v).copy_from(ptr)	5
v.copy_from(ptr, u > 0)	12
v.copy_from_where(ptr, u > 0)	6

Poll: Make copy_to, copy_from, and the load constructor only do value-preserving conversions by default and require passing a flag to do non-value-preserving conversions.

SF	F	N	A	SA
14	9	1	0	0

Poll: SIMD types and operations should be value preserving, even if that means they're inconsistent with the builtin numeric types.

SF	F	N	A	SA
3	10	6	3	0

Poll: 2 * simd<float> should produce simd<double> (status quo: simd<float>).

SF	F	N	A	SA
1	5	9	6	1

Poll: Put SIMD types and operations into std:: and add the simd_ prefix to SIMD specific things (such as split and vector_aligned).

SF	F	N	A	SA
4	5	4	9	2

Poll: Put SIMD types and operations into a nested namespace in std::.

SF	F	N	A	SA
4	7	0	5	9

Poll: simd should be a range.

SF	F	N	A	SA
4	9	5	4	4

Poll: There should be an explicit way to get a view to a simd.

SF	F	N	A	SA
8	12	3	3	0

Poll: simd should have explicitly named functions for horizontal minimum and horizontal maximum.

SF	F	N	A	SA
4	5	7	4	2

Poll: Rename all_of/ any_of/none_of to reduce_all_of/reduce_any_of/reduce_none_of.

SF	F	N	A	SA
2	1	1	8	5

Poll: Rename all_of/any_of/none_of to reduce_and/reduce_or/reduce_nand.

SF	F	N	A	SA
2	6	2	4	3

Poll: Rename popcount to reduce_count.

SF	F	N	A	SA
4	9	2	1	2

Poll: Rename find_first_set/find_last_set to reduce_min_index/reduce_max_index.

SF	F	N	A	SA
2	7	3	2	3

2.3 LEWG AT VARNA 2023

The conditional operator CPO should be called: (vote for as many options as you like)

Option	Votes
conditional_operator	10
ternary	12
inline_if	0
iif	1
blend	2
select	14
choose	4

The conditional operator CPO should be called: (vote once for your favorite)

Option	Votes
conditional_operator	2
ternary	8
select	10

Poll: The conditional operator CPO should be called `ternary`

SF	F	N	A	SA
1	7	0	10	2

Poll: The conditional operator CPO should be called `select`

SF	F	N	A	SA
2	9	2	5	2

Poll: The conditional operator CPO should be called `conditional_operator`

SF	F	N	A	SA
0	11	4	3	2

Poll: The conditional operator facility should not be user customizable, should work both scalar and SIMD types and should be marketed as part of the SIMD library.

SF	F	N	A	SA
3	8	9	2	0

The conditional operator facility should be called (vote once for your favorite):

Option	Votes
simd_ternary	4
simd_bland	6
simd_select	12
simd_choose	0

Tuesday afternoon polls missing in minutes and/or GitHub issue.

Poll: Don't publicly expose `simd_abi` (`deduce_t`, `fixed_size`, `scalar`, `native`). Preserve ABI tagging semantics. Rename `simd` to `basic_simd`. Add a `simd` alias: `simd<T, size_t N = basic_simd<T>::size()> = basic_simd<T, __deduce_t<T, N>>`

SF	F	N	A	SA
5	6	2	0	0

Poll: Spell the flags template `std::simd_flags` and spell the individual flags `std::simd_flag_x`.

SF	F	N	A	SA
2	8	3	0	0

Poll: Make `simd_mask<T, N>` an alias for `basic_simd_mask<sizeof(TT), __deduce_t<T, N>>`.

SF	F	N	A	SA
3	11	0	1	0

Poll: Remove `simd_mask<T, N>::simd_type` and make `simd_mask<T, N>` unary plus and unary minus return `simd<I, N>` where `I` is the largest standard signed integer type where `sizeof(I) <= sizeof(T)`.

SF	F	N	A	SA
2	6	2	0	0

Poll: Remove `concat(array<simd>)` overload.

SF	F	N	A	SA
4	9	1	0	0

Poll: Replace all `split`/`split_by` functions by the proposed `split` function in P1928R4.

SF	F	N	A	SA
2	8	3	0	0

Poll: Rename `split` to `simd_split` and `concat` to `simd_cat`.

SF	F	N	A	SA
5	11	1	0	0

Poll: SIMD types and operations should be value preserving, even if that means they're inconsistent with the builtin numeric types (status quo, option 3 in P1928R4).

SF	F	N	A	SA
9	9	2	0	0

Poll: Remove broadcast constructor exceptions for `int` and `unsigned int`, and instead ensure `constexpr_v` arguments work correctly (ext: `2 * simd<float>` will no longer compile).

SF	F	N	A	SA
4	6	4	1	0

Poll: The broadcast constructor should take `T` directly and rely on language implicit conversion rules and optionally enabled compiler warnings to catch errors (ex: `2 * simd<float>` will return `simd<float>`, `3.14 * simd<float>` will return `simd<float>` and may warn)

SF	F	N	A	SA
2	7	3	1	3

Poll: Remove `is_simd`, `is_simd_v`, `is_simd_mask`, and `is_simd_mask_v`.

SF	F	N	A	SA
1	9	3	2	0

Poll: Make `simd_size` exposition only and cause `simd` to have the size static data member if and only if `T` is a vectorizable type and `Abi` is an ABI tag.

SF	F	N	A	SA
1	7	4	1	0

Poll: Replacement name for `memory_alignment` and `memory_alignment_v` should feature a `simd_-` prefix

SF	F	N	A	SA
12	3	1	0	0

Poll: There should be a marker in the name of `memory_alignment` and `memory_alignment_v` indicating that it applies only to loads and stores.

SF	F	N	A	SA
1	3	9	2	0

The name of `memory_alignment` should be (with `memory_alignment_v` having the same name followed by `_v`)

Option	Votes
simd_memory_alignment	2
simd_alignment	13
simd_loadstore_alignment	2

Poll: We're interested in exploring `rebind_simd` and `resize_simd` as members of `simd` and `simd_-mask`

SF	F	N	A	SA
1	0	8	5	1

Poll: Introduce an exposition only simd-size-t signed integer type and use this type consistently throughout P1928 (rather than `size_t` and `int` being used inconsistently).

SF	F	N	A	SA
8	7	1	0	0

Several Thursday morning polls missing in minutes and/or GitHub issue.

Poll: Simd `reduce` should not have a binary operator

SF	F	N	A	SA
0	0	4	4	3

Poll: Modify P1928D6 (“simd”) as described above, and then send the revised paper to library for C++26, to be confirmed with a library evolution electronic poll.

SF	F	N	A	SA
16	3	1	0	0

3 INTRODUCTION

[P0214R9] introduced `std::experimental::simd<T>` and related types and functions into the Parallelism TS 2 Section 9. The TS was published in 2018. An incomplete and non-conforming (because P0214 evolved) implementation existed for the whole time P0214 progressed through the committee. Shortly after the GCC 9 release, a complete implementation of Section 9 of the TS was made available. Since GCC 11 a complete `simd` implementation of the TS is part of its standard library.

In the meantime the TS feedback progressed to a point where a merge should happen ASAP. This paper proposes to merge only the feature-set that is present in the Parallelism TS 2. (Note: The first revision of this paper did not propose a merge.) If, due to feedback, any of these features require a change, then this paper (P1928) is the intended vehicle. If a new feature is basically an addition to the wording proposed here, then it will progress in its own paper.

3.1 RELATED PAPERS

P0350 Before publication of the TS, SG1 approved [P0350R0] which did not progress in time in LEWG to make it into the TS. P0350 is moving forward independently.

P0918 After publication of the TS, SG1 approved [P0918R2] which adds `shuffle`, `interleave`, `sum_to`, `multiply_sum_to`, and `saturated_simd_cast`. P0918 will move forward independently.

P1068 R3 of the paper removed discussion/proposal of a `simd` based API because it was targeting C++23 with the understanding of `simd` not being ready for C++23. This is unfortunate as the presence of `simd` in the IS might lead to a considerably different assessment of the iterator/range-based API proposed in P1068.

P0917 The ability to write code that is generic wrt. arithmetic types and `simd` types is considered to be of high value (TS feedback). Conditional expressions via the `where` function were not all too well received. Conditional expressions via the conditional operator would provide a solution deemed perfect by those giving feedback (myself included).

DRAFT ON NON-MEMBER OPERATOR[] TODO

P2600 The fix for ADL is important to ensure the above two papers do not break existing code.

P0543 The paper proposing functions for saturation arithmetic expects `simd` overloads as soon as `simd` is merged to the IS.

P0553 The bit operations that are part of C++20 expects `simd` overloads as soon as `simd` is merged to the IS.

P2638 Intel's response to P1915R0 for `std::simd`

P2663 `std::simd<std::complex<T>>`.

P2664 Permutations for `simd`.

P2509 D'Angelo [P2509R0] proposes a "type trait to detect conversions between arithmetic-like types that always preserve the numeric value of the source object". This matches the *value-preserving* conversions the `simd` specification uses.

The papers P0350, P0918, P2663, P2664, and the `simd`-based P1068 fork currently have no shipping vehicle and are basically blocked on this paper.

4 CHANGES AFTER TS FEEDBACK

[P1915R0] (Expected Feedback from `simd` in the Parallelism TS 2) was published in 2019, asking for feedback to the TS. I received feedback on the TS via the GitHub issue tracker, e-mails, and personal conversations. There is also a lot of valuable feedback published in P2638 "Intel's response to P1915R0 for `std::simd`".

4.1 IMPROVE ABI TAGS

Summary:

- Change the default SIMD ABI tag to `simd_abi::native<T>` instead of `simd_abi::compatible<T>`.
- Change `simd_abi::fixed_size` to not recommend implementations make it ABI compatible.

- At the Varna LEWG meeting it was decided to remove the `simd_abi` namespace and all standard ABI tags altogether. Rationale: The initial goal was to let `fixed_size` be equivalent to `std::experimental::simd_abi::deduce_t`. This implies that `std::experimental::fixed_size_simd<T, N>` becomes the generic interface for deducing an efficient ABI tag. The next logical step is to give `fixed_size_simd` a shorter name and hide ABI tags. Consequently, `std::simd<T, N =` *`native-size`*`>` is an alias for `std::basic_simd<T, Abi>` now.

For a discussion, see P1928R3 Section 4.1 and P1928R4 Section 5.2.

4.2 BASIC_SIMD_MASK<SIZEOF, ABI>

Following the polls by LEWG in Issaquah 2023, P1928R4 made mask types interconvertible. The next simplification was to make interconvertible types the same type instead. This is achieved by renaming the `std::experimental::simd_mask` class template to `std::basic_simd_mask` and changing the first template parameter from element type `T` to `sizeof(T)`. An alias `simd_mask<T, N> = basic_simd_mask<sizeof(T),` *`native-size`*`>` provides the simpler to use API.

The resulting mask types are explicitly convertible if the SIMD width is equal, otherwise they are not convertible at all. Note that for some target hardware the (explicitly) convertible masks are convertible without any cost. However, that's not the case for all targets, which is why the conversion is still marked `explicit`.

4.3 SIMPLIFY/GENERALIZE CASTS

For a discussion, see P1928R3 Section 4.2.

Summary of changes wrt. TS:

1. `simd<T0, A0>` is convertible to `simd<T1, A1>` if `simd_size_v<T0, A0> == simd_size_v<T1, A1>`.
2. `simd<T0, A0>` is implicitly convertible to `simd<T1, A1>` if, additionally,
   - the conversion `T0` to `T1` is value-preserving, and
   - if both `T0` and `T1` are integral types, the integer conversion rank of `T1` is greater than or equal to the integer conversion rank of `T0`, and
   - if both `T0` and `T1` are floating-point types, the floating-point conversion rank of `T1` is greater than or equal to the floating-point conversion rank of `T0`.
3. `simd_mask<T0, A0>` is convertible to `simd_mask<T1, A1>` if `simd_size_v<T0, A0> == simd_size_v<T1, A1>`.
4. `simd_mask<T0, A0>` is implicitly convertible to `simd_mask<T1, A1>` if, additionally, `sizeof(T0) == sizeof(T1)`. (This point is irrelevant if Section 4.2 is accepted.)

5. `simd<T0, A0>` can be `bit_casted` to `simd<T1, A1>` if `sizeof(simd<T0, A0>) == sizeof(simd<T1, A1>)`.
6. `simd_mask<T0, A0>` can be `bit_casted` to `simd_mask<T1, A1>` if `sizeof(simd_mask<T0, A0>) == sizeof(simd_mask<T1, A1>)`.

4.4 ADD SIMD_MASK GENERATOR CONSTRUCTOR

This constructor was added:

```
template<class G> simd_mask(G&& gen) noexcept;
```

For a discussion, see P1928R3 Section 4.3.

4.5 DEFAULT LOAD/STORE FLAGS TO ELEMENT_ALIGNED

Different to the TS, load/store flags default to `element_aligned`. For a discussion, see P1928R3 Section 4.4.

4.6 CONTIGUOUS ITERATORS FOR LOADS AND STORES

Different to the TS, loads and stores use `contiguous_iterator` instead of pointers. For a discussion, see P1928R3 Section 4.5.

4.7 CONSTEXPR EVERYTHING

The merge adds `constexpr` to all functions. For a discussion, see P1928R3 Section 4.6.

4.8 SPECIFY SIMD::SIZE AS INTEGRAL_CONSTANT

Different to the TS, this paper uses a static data member `size` of type `std::integral_constant<std::size_t, N>` in `basic_simd` and `basic_simd_mask`. For a discussion, see P1928R3 Section 4.7.

4.9 REPLACE WHERE FACILITIES

The following load/store overloads have been added as a replacement for `std::experimental::where_expression::copy_from` and `std::experimental::const_where_expression::copy_to`:

- `simd::simd(contiguous_iterator, const mask_type&, Flags = {})` (selected elements are copied from given range, otherwise use value-initialization)
- `simd::copy_from(contiguous_iterator, const mask_type&, Flags = {})` (selected elements are copied from given range)

- `simd::copy_to(contiguous_iterator, const mask_type&, Flags = {})` (selected elements are copied to given range)
- `simd_mask::simd_mask(contiguous_iterator, const mask_type&, Flags = {})` (selected elements are copied from given range, otherwise use value-initialization)
- `simd_mask::copy_from(contiguous_iterator, const mask_type&, Flags = {})` (selected elements are copied from given range)
- `simd_mask::copy_to(contiguous_iterator, const mask_type&, Flags = {})` (selected elements are copied to given range)

The `reduce`, `hmin`, and `hmax` overloads with `const_where_expression` argument have been replaced by overloads with `basic_simd` and `basic_simd_mask` arguments.

The following operators were added to `basic_simd_mask`:

- `basic_simd_mask::operator basic_simd<U, A>() const noexcept`
- *`simd-type`* `basic_simd_mask::operator+() const noexcept`
- *`simd-type`* `basic_simd_mask::operator-() const noexcept`
- *`simd-type`* `basic_simd_mask::operator~() const noexcept`

The following hidden friends were added to `basic_simd_mask`:

- `basic_simd_mask` *`simd-select-impl`*`(const basic_simd_mask&, const basic_simd_mask&, const basic_simd_mask&) noexcept`
- `basic_simd_mask` *`simd-select-impl`*`(const basic_simd_mask&, bool, bool) noexcept`
- `simd<`*`non-promoting-common-type`*`<T0, T1>` *`simd-select-impl`*`(const basic_simd_mask&, const T0&, const T1&) noexcept`

The following hidden friend was added to `basic_simd`:

- `basic_simd` *`simd-select-impl`*`(const mask_type& mask, const basic_simd& a, const basic_simd& b) noexcept`

Instead of *`simd-select-impl`* we would have preferred to overload `operator?:` but that requires a language change first. As long as we don't have the language feature for overloading `?:`, generic code must use an inferior function instead. Knowing that other libraries would benefit from an overloadable `operator?:` P1928R4 proposed a `std::conditional_operator` CPO that 3rd-party libraries could have extended. However, the use of a function (or CPO) instead of overloading `operator?:` cannot keep the semantics of `?:`, which doesn't evaluate an expression unless its result is actually needed. For a function, we cannot pass expressions but only their results. Relevant papers: [P0927R2], [D0917].

Therefore LEWG decided in Varna to define a `std::simd_select` function instead of a general CPO, with the following goals:

- Analogue semantics to `?:`, but without lazy evaluation.
- User's should not be able to extend the facility.
- Make it "value based", i.e. don't bother about references for non-simd arguments.

4.10 MAKE USE OF INT AND SIZE_T CONSISTENT

Different to the TS, this paper uses *`simd-size-type`* instead of `size_t` for

- the SIMD width (number of elements),
- the generator constructor call argument,
- the subscript operator arguments, and
- the `basic_simd_mask` reductions that return an integral value.

Alignments and values identifying a `sizeof` still use `size_t`.

The type *`simd-size-type`* is an exposition-only alias for a signed integer type. I.e. the implementation is free to choose any signed integer type.

The rationale given in the LEWG discussion was a desire to avoid type conversions when using the result of a `basic_simd_mask` reduction as subscript argument. Since `<bit>` functions like `std::popcount`, `std::bit_width`, `std::countl_zero`, …return `int`, the natural choice is to stick with that type and make subscript arguments use the same type. Since the SIMD width is also sometimes used in expressions in the subscript argument, the SIMD width should also have the same type.

4.11 ADD LVALUE-QUALIFIER TO NON-CONST SUBSCRIPT

The `operator[]` overloads of `basic_simd` and `basic_simd_mask` returned a proxy reference object for non-`const` objects and the `value_type` for `const` objects. This made expressions such as `(x * 2)[0] = 1` well-formed. However, assignment to temporaries can only be an error in the code (or code obfuscation). Therefore, both `operator[]` overloads are now lvalue-ref qualified to make `(x * 2)[0]` pick the const overload, which returns a prvalue that is not assignable.

4.12 RENAME `SIMD_MASK` REDUCTIONS

Summary:

- The function `std::experimental::some_of` was removed.
- The function `std::experimental::popcount` was renamed to `std::reduce_count`.
- The function `std::experimental::find_first_set` was renamed to `std::reduce_min_index`.
- The function `std::experimental::find_last_set` was renamed to `std::reduce_max_index`.

For a discussion of this topic see P1928R3 Section 5.2.

4.13 RENAME `HMIN` AND `HMAX`

The functions `hmin(simd)` and `hmax(simd)` were renamed to `reduce_min` and `reduce_max` according to guidance from LEWG in Varna 2023.

4.14 ADDED CONSTRAINTS ON OPERATORS AND FUNCTIONS TO MATCH THEIR UNDERLYING ELEMENT TYPES

Previously some operators (e.g., `operator<`) and functions which relied on some property of the element type (e.g., `min` relies on ordering) were unconstrained. Operations which were not permitted on individual elements were still available in the overload set for `basic_simd` objects of those types. Constraints have been added where necessary to remove such operators and functions from the overload set where they aren't supported.

4.15 RENAME ALIGNMENT FLAGS AND EXTEND LOAD/STORE FLAGS FOR OPT-IN TO CONVERSIONS

For some discussion, see P1928R3 Section 5.4.

In addition to the TS, the load/store flag mechanism is extended to enable combination of flags. A new flag enables conversions that are not *value-preserving* on loads and stores. (Without this new flag, only *value-preserving* conversions are allowed.) The new flags facility also keeps the design space open for adding new flags after C++26. The changes relative to the TS are shown in Table 1.

Note that the wording also allows additional implementation-defined load and store flags.

The trait `std::experimental::is_simd_flag_type` has been removed because the flag parameter is now constrained via the `simd_flags` class template.

TS	P1928R7
`std::experimental::element_aligned`	`std::simd_flag_default`
`std::experimental::vector_aligned`	`std::simd_flag_aligned`
`std::experimental::overaligned<N>`	`std::simd_flag_overaligned<N>`
implicit	`std::simd_flag_convert`

Table 1: Load/store flag changes

As a result, executing a not-value-preserving store on 16-Byte aligned memory now reads as:

TS

```
float *addr = ...;
void f(stdx::native_simd<double> x) {
  x.copy_to(addr, stdx::overaligned<16>);
}
```

P1928R7

```
float *addr = ...;
void f(std::simd<double> x) {
  x.copy_to(addr, std::simd_flag_convert |
                  std::simd_flag_overaligned<16>);
}
```

4.16 REDUCE OVERLOADS AND RENAME SPLIT AND CONCAT

The `std::experimental::concat(array)` overload was removed in favor of using `std::apply`. The remaining `std::experimental::concat` function was renamed to `std::simd_cat` following the `std::tuple_cat` naming precedent.

The two `std::experimental::split` and one `std::experimental::split_by` functions from the TS were consolidated into a single `std::simd_split` function. The design intent for the `simd_split` function is to support the use case of splitting an “oversized” `basic_simd` into register-sized parts. Example: `simd<float, 20>` could be made up of one AVX-512 and one SSE register on an x86 target. `simd_split` is a simple interface for splitting `simd<float, 20>` into `simd<float>` and `basic_simd<float, impl-defined-abi-tag>`[1].

`std::simd_split<T>(x)` does the following: `simd_split<simd<float>>(x)` returns a `tuple` of as many `simd<float>` as `x.size()` allows plus an “epilogue” of one `simd<float, impl-defined-abi-tag` object as necessary to return all elements of `x`. If no “epilogue” is necessary, the return type is an `array` instead of a `tuple`. Then `simd_split<simd<float>>(simd<float, 20>)` returns

- `tuple<simd<float>, simd<float, 4>>` with AVX-512,
- `tuple<simd<float>, simd<float>, simd<float, 4>>` with AVX, and
- `array<simd<float>, 5>` with SSE.

The `simd_split` function is overloaded for `basic_simd` and `basic_simd_mask`.

---

[1] same as `simd<float, 4>`.

4.17 REMOVE INT EXCEPTION FROM BROADCAST CONVERSION RULES

LEWG discussed conversions in Issaquah 2023 and Varna 2023. P1928R4 Section 5.4 presented alternatives and their implications. LEWG decided in Varna to stick with value-preserving conversions as used in the TS. However, the exception for `int` and `unsigned int` conversions to `simd` were removed. Instead, `integral_constant`-like arguments, which will hopefully be available as literals in C++26, will be supported and their values (instead of types) determine whether the conversion is allowed.

4.18 REMOVE LONG DOUBLE FROM VECTORIZABLE TYPES

Rationale: TS experience. It's a headache. It's not worth the specification and implementation effort.

4.19 INCREASE MINIMUM SUPPORTED WIDTH TO 64

The TS required a minimum of 32, with C++26 the minimum will be 64.

Rationale: AVX-514 `simd<char>::size() == 64`. And also `long double` is not a vectorizable type anymore.

4.20 NO STD::HASH<SIMD>

No support for `std::hash<simd<T>>` was added.

Rationale: Is there a use case for `std::hash<simd<T>>`? In other words, is there a use case for using `basic_simd<T>` as a map key? Recall that we do not consider `basic_simd<T>` to be a product type [P0851R0]. If there's no use case for hashing a `basic_simd<T>` object as one, is there a use case for multiple look-ups into a map, parallelizing the lookup as much as possible?

Consider a hash map with `int` keys and the task of looking up multiple keys in arbitrary order (unordered). In this case, one might want to pass a `simd<int>`, compute the hashes of `simd<int>::size()` keys in parallel (using SIMD instructions), and potentially determine the addresses (or offsets in contiguous memory) of the corresponding values in parallel. The value lookup could then use a SIMD gather instruction.

If we consider this use case important (or at least interesting), is `std::hash<simd<T>>` the right interface to compute hashes element-wise? After all, `simd` operations act element-wise unless strong hints in the API suggest otherwise.

At this point we prefer to wait for concrete use cases of hashing `basic_simd` objects before providing any standard interface. Specifically, at this point *we do not want `std::hash` support for `basic_simd`*.

4.21 NO FREESTANDING SIMD

`simd` will not be enabled for freestanding.

Kernel code typically wants to have a small state for more efficient context switching. Therefore floating-point and SIMD registers are not used. However, we could limit `basic_simd` to integers and the scalar ABI for freestanding. The utility of such a crippled `basic_simd` is highly questionable. Note that freestanding is just the baseline requirement and embedded targets are still free to add `simd` support.

5 OPEN QUESTIONS / OUTLOOK

5.1 CORRECT PLACE FOR SIMD IN THE IS?

While `simd` is certainly very important for numerics and therefore fits into the “Numerics library” clause, it is also more than that. E.g. `simd` can be used for vectorization of text processing. In principle `simd` should be understood similar to fundamental types. Is the “General utilities library” clause a better place? Or rename “Concurrency support library” to “Parallelism and concurrency support library” and put it there? Alternatively, add a new library clause?

I am seeking feedback before making a recommendation.

5.2 ELEMENT_REFERENCE IS OVERSPECIFIED

`element_reference` is spelled out in a lot of detail. It may be better to define its requirements in a list of requirements or a table instead.

This change is not reflected in the wording, pending encouragement from WG21 (mostly LWG).

5.3 IMPLEMENTATION HINTS

We should consider the addition of a note recommending implementations let `basic_simd` and `basic_simd_mask` operations behave like operations of built-in types. Specifically, built-in operators are never function calls[2]. (cf. GCC PR108030)

5.4 CLEAN UP MATH FUNCTION OVERLOADS

The wording that produces `basic_simd` overloads misses a few cases and leaves room for ambiguity. There is also no explicit mention of integral overloads that are supported in `<cmath>` (e.g. `std::cos(1)` calling `std::cos(double)`). At the very least, `std::abs(basic_simd <`*`signed-integral`*`>)` should be specified.

Also, from implementation experience, “undefined behavior” for domain, pole, or range error is unnecessary. It could either be an unspecified result or even match the expected result of the function according to Annex F in the C standard. The latter could possibly be a recommendation, i.e. QoI. The intent is to avoid `errno` altogether, while still supporting floating-point exceptions (possibly depending on compiler flags).

---

[2] The exception may be soft-float?

This needs more work and is not reflected in the wording at this point.

5.5 INTEGRATION WITH RANGES

`simd` itself is not a container [P0851R0]. The value of a data-parallel object is not an array of elements but rather needs to be understood as a single opaque value that happens to have means for reading and writing element values. I.e. `simd<int> x = {};` does not start the lifetime of `int` objects. This implies that `simd` cannot model a contiguous range. But `simd` can trivially model `random_access_range`. However, in order to model `output_range`, the iterator of every non-const `simd` would have to return an `element_reference` on dereference. Without the ability of `element_reference` to decay to the element type (similar to how arrays decay to pointers on deduction), I would prefer to simply make `simd` model only `random_access_range`.

If `simd` is a range, then `std::vector<std::simd<float>> data` can be flattened trivially via `data | std::views::join`. This makes the use of “arrays of `simd<T>`” easier to integrate into existing interfaces the expect “array of `T`”.

I plan to pursue adding iterators and conversions to array and from random-access ranges, specifically `span` with static extent, in a follow-up paper. I believe it is not necessary to resolve this question before merging `simd` from the TS.

5.6 FORMATTING SUPPORT

If `simd` *is a* range, as suggested above and to be proposed in a follow-up paper, then `simd` will automatically be formatted as a range. This seems to be a good solution unless there is a demand to format `simd` objects differently from `random_access_range`.

6 CHANGES AFTER LEWG APPROVAL (FOR LEWG)

6.1 SIMD_SELECT OVERLOAD SET

P1928R6 presented the following overload set of the exposition-only hidden friend *`simd-select-impl`*:

```
template<class T, class Abi> class basic_simd {
  // [...]
  friend constexpr basic_simd simd-select-impl(
    const mask_type&, const basic_simd&, const basic_simd&) noexcept; // #1
};
// [...]
template<size_t Bytes, class Abi> class basic_simd_mask {
  // [...]
  friend constexpr basic_simd_mask simd-select-impl(
    const basic_simd_mask&, const basic_simd_mask&, const basic_simd_mask&) noexcept; // #2
  friend constexpr basic_simd_mask simd-select-impl(
```

```
    const basic_simd_mask&, bool, bool) noexcept; // #3
  template <class T0, class T1>
    friend constexpr basic_simd<see below, Abi>
      simd-select-impl(const basic_simd_mask&, const T0&, const T1&) noexcept; // #4
};
```

Given `std::simd_select(std::simd<double, 4>() == 0, 1, 2)`, the compiler would choose overload #3 because `int` is convertible to `bool` and #4 is constrained, requiring `sizeof(`*non-promoting-common-type*`<T0, T1>) == sizeof(double)`. That does not match the design intent. The intent was for non-boolean and non-simd arguments to pick overload #4 or fail to compile. This can be achieved either by replacing `bool` with a type that is convertible from `bool` only, or via `same_as<bool> auto` instead of `bool`. The former leads to puzzling error messages, because overload #4 is not mentioned in the resulting diagnostics. The latter will lead to a listing of all candidates and the reason why they were not viable.

Therefore, the wording for overload #3 was changed to say `same_as<bool> auto` instead of `bool`.

6.2 TIGHTEN SIMD_SPLIT SPECIFICATION

The reviewed wording (Varna 2023) for `simd_split` left the "epilogue" `basic_simd` object(s) unspecified. A user of `simd_split` therefore would have to cope with implementations returning one or more `basic_simd` objects for the otherwise same input parameters. Consider the case `simd_split<simd<int, 8>>(x)` with `simd<int, 15>`. One implementation might return
`tuple<simd<int, 8>, simd<int, 7>>`
while another implementation returns
`tuple<simd<int, 8>, simd<int, 4>, simd<int, 2>, simd<int, 1>>`
and yet another could choose to return
`tuple<simd<int, 8>, simd<int, 4>, simd<int, 3>>`. There are good reasons for either one of these. However, letting the implementation choose which one is best doesn't really help the user of the interface. Therefore, the wording was modified to return a single "epilogue" `basic_simd` object. In the example above, the user is thus returned a `simd<int, 7>` on every implementation and can choose to apply another `simd_split` to arrive at `tuple<simd<int, 4>, simd<int, 3>>` and so on.

6.3 RECONSIDER PRECONDITION ON MASK REDUCTIONS

As directed by LEWG, the precondition on `reduce_min_index` and `reduce_max_index` was removed from the latest wording. This required a specification of the return value for the missing case. The following results were chosen:

1. `reduce_min_index(simd_mask<int, 4>(false))` returns 4 (the SIMD width)
2. `reduce_max_index(simd_mask<int, 4>(false))` returns -1

3. `reduce_min_index(false)` returns 1
4. `reduce_max_index(false)` returns `-1`

6.3.1 NEW INFORMATION

It was always stated in LEWG discussions that removal of the precondition has no performance cost on modern processors. This is true for some cases but not in general. Consider `reduce_min_index(simd_mask<int, 4>(...))`: A reasonable x86 implementation will either already use a bit-mask (AVX512) or turn the vector-mask into a bit-mask (e.g. `movmskps`). `std::countr_zero` can be used to determine the position of the first non-zero bit in the bit-mask. If, however, the given mask was empty, then `countr_zero` will return the width of the given integer type, typically `32`. The correct answer for `reduce_min_index` needs to be `4`, though. So a fix-up is required. This could either be a branch on `32` or the implementation can unconditionally set the bit at index 4 before calling `countr_zero`. In any case, code size increases. In the branch-free implementation, the latency of the `reduce_min_index` call unconditionally increases by one clock cycle.

While avoiding UB is nice, the usefulness of returning `basic_simd_mask ::size()` or `-1` is questionable. How can these numbers be used other than for branching? Isn't it better to branch on `none_of(mask)` before calling `reduce_min_index`? If the goal is to avoid UB, then we need to consider whether the current state actually helps. Consider:

```
auto f(std::simd<float> x) {
  return x[std::reduce_min_index(x < 0.f)];
}
```

Here we see a precondition violation on subscripting `x`, unless at least one value in `x` is negative. Currently there are two possible solutions:

```
auto f(std::simd<float> x) {
  if (any_of(x < 0.f)
    return x[std::reduce_min_index(x < 0.f)];
  return 0.f;
}
```

or

```
auto f(std::simd<float> x) {
  int i = std::reduce_min_index(x < 0.f);
  if (i < x.size)
    return x[i];
  return 0.f;
}
```

The first solution is more efficient and, in my opinion, more readable. If unchecked use of `reduce_min_index/reduce_max_index` doesn't lead to UB, then it likely leads to logical errors.

In order to follow the "don't pay for whay you don't use" guideline, the precondition should be restored.

6.3.2 ALTERNATIVE

Instead of UB, the reduction functions could also return an unspecified value. Better even, an unspecified value outside of the range of valid subscript indices could be returned (e.g. 32 instead of 4). Maybe debug builds can be encouraged to diagnose calls with an empty mask[3].

6.3.3 SUGGESTED POLLS

Poll: Restore the precondition on `reduce_min_index(empty_mask)` and `reduce_max_index(empty_mask)` (TS status quo).

SF	F	N	A	SA

Poll: Return an unspecified value on `reduce_min_index(empty_mask)` and `reduce_max_index(empty_mask)`.

SF	F	N	A	SA

Poll: Return an unspecified value outside of the range of valid subscript indices on `reduce_min_index(empty_mask)` and `reduce_max_index(empty_mask)`.

SF	F	N	A	SA

7 WORDING: ADD SECTION 9 OF N4808 WITH MODIFICATIONS

The following section presents the wording to be applied against the C++ working draft.

In [version.syn], add

```
#define __cpp_lib_simd YYYYMML // also in <simd>
```

Adjust the placeholder value as needed so as to denote this proposal's date of adoption.

Add a new subclause after §28.8 [numbers]

(7.1) 28.9 Data-Parallel Types [simd]

---

[3] I guess Contracts would only trigger for a real precondition, a.k.a. UB?

(7.1.1) 28.9.1 General [simd.general]

1 The simd subclause defines data-parallel types and operations on these types. A data-parallel type consists of elements of an underlying vectorizable type, called the *element type*. The number of elements is a constant for each data-parallel type and called the *width* of that type.

2 The term *data-parallel type* refers to all *supported* (28.9.6.1) specializations of the `basic_simd` and `basic_simd_mask` class templates. A *data-parallel object* is an object of *data-parallel type*.

3 The set of *vectorizable types* comprises all cv-unqualified arithmetic types other than `bool` and `long double`.

4 An *element-wise operation* applies a specified operation to the elements of one or more data-parallel objects. Each such application is unsequenced with respect to the others. A *unary element-wise operation* is an element-wise operation that applies a unary operation to each element of a data-parallel object. A *binary element-wise operation* is an element-wise operation that applies a binary operation to corresponding elements of two data-parallel objects.

5 Given a `basic_simd_mask<Bytes, Abi>` object `mask`, the *selected indices* signify the integers $i \in \{j \in \mathbb{N}_0 | j <$ `mask.size()` $\wedge$ `mask[`j`]`$\}$. Given an additional object `data` of type `basic_simd<T, Abi>` or `basic_simd_mask<Bytes, Abi>`, the *selected elements* signify the elements `data[`i`]` for all selected indices i.

6 The conversion from vectorizable type `U` to vectorizable type `T` is *value-preserving* if all possible values of `U` can be represented with type `T`.

7 [*Note:* The intent is to support acceleration through data-parallel execution resources, such as SIMD registers and instructions or execution units driven by a common instruction decoder. If such execution resources are unavailable, the interfaces support a transparent fallback to sequential execution. — *end note*]

(7.1.2) 28.9.2 Header `<simd>` synopsis [simd.syn]

```
namespace std {
  using simd-size-type = see below; // exposition only
  template <class T> constexpr size_t mask-element-size = see below; // exposition only
  template <size_t Bytes> using integer-from = see below; // exposition only

  template <class T>
    concept constexpr-wrapper-like =                     // exposition only
      convertible_to<T, decltype(T::value)> &&
      equality_comparable_with<T, decltype(T::value)> &&
      bool_constant<T() == T::value>::value &&
      bool_constant<static_cast<decltype(T::value)>(T()) == T::value>::value;

  // 28.9.3, simd ABI tags
  template<class T> using native-abi = see below; // exposition only
  template<class T, simd-size-type N> using deduce-t = see below; // exposition only

  // 28.9.4, simd type traits
  template<class T, class U = typename T::value_type> struct simd_alignment;
  template<class T, class U = typename T::value_type>
    inline constexpr size_t simd_alignment_v = simd_alignment<T,U>::value;

  template<class T, class V> struct rebind_simd { using type = see below; };
  template<class T, class V> using rebind_simd_t = typename rebind_simd<T, V>::type;
```

```
template<simd-size-type N, class V> struct resize_simd { using type = see below; };
template<simd-size-type N, class V> using resize_simd_t = typename resize_simd<N, V>::type;

// 28.9.5, Load and store flags
template <class... Flags> struct simd_flags;
inline constexpr simd_flags<> simd_flag_default{};
inline constexpr simd_flags<see below> simd_flag_convert{};
inline constexpr simd_flags<see below> simd_flag_aligned{};
template<size_t N> requires (has_single_bit(N))
  inline constexpr simd_flags<see below> simd_flag_overaligned{};

// 28.9.6, Class template basic_simd
template<class T, class Abi = native-abi<T>> class basic_simd;
template<class T, simd-size-type N = basic_simd<T>::size()>
  using simd = basic_simd<T, deduce-t<T, N>>;

// 28.9.8, Class template basic_simd_mask
template<size_t Bytes, class Abi = native-abi<T>> class basic_simd_mask;
template<class T, simd-size-type N = basic_simd_mask<sizeof(T)>::size()>
  using simd_mask = basic_simd_mask<sizeof(T), deduce-t<T, N>>;

// 28.9.7.6, basic_simd and basic_simd_mask creation
template<class V, class Abi>
  constexpr auto
    simd_split(const basic_simd<typename V::value_type, Abi>& x) noexcept;
template<class M, class Abi>
  constexpr auto
    simd_split(const basic_simd_mask<mask-element-size<M>, Abi>& x) noexcept;

template<class T, class... Abis>
  constexpr basic_simd<T, deduce-t<T, (basic_simd<T, Abis>::size + ...)>>
    simd_cat(const basic_simd<T, Abis>&...) noexcept;
template<size_t Bs, class... Abis>
  constexpr constexpr basic_simd_mask<Bs, deduce-t<integer-from<Bs>,
                                            (basic_simd_mask<Bs, Abis>::size() + ...)>>
    simd_cat(const basic_simd_mask<Bs, Abis>&...) noexcept;

// 28.9.9.5, basic_simd_mask reductions
template<size_t Bs, class Abi>
  constexpr bool all_of(const basic_simd_mask<Bs, Abi>&) noexcept;
template<size_t Bs, class Abi>
  constexpr bool any_of(const basic_simd_mask<Bs, Abi>&) noexcept;
template<size_t Bs, class Abi>
  constexpr bool none_of(const basic_simd_mask<Bs, Abi>&) noexcept;
template<size_t Bs, class Abi>
  constexpr simd-size-type reduce_count(const basic_simd_mask<Bs, Abi>&) noexcept;
```

```
template<size_t Bs, class Abi>
  constexpr simd-size-type reduce_min_index(const basic_simd_mask<Bs, Abi>&) noexcept;
template<size_t Bs, class Abi>
  constexpr simd-size-type reduce_max_index(const basic_simd_mask<Bs, Abi>&) noexcept;

constexpr bool all_of(same_as<bool> auto) noexcept;
constexpr bool any_of(same_as<bool> auto) noexcept;
constexpr bool none_of(same_as<bool> auto) noexcept;
constexpr simd-size-type reduce_count(same_as<bool> auto) noexcept;
constexpr simd-size-type reduce_min_index(same_as<bool> auto) noexcept;
constexpr simd-size-type reduce_max_index(same_as<bool> auto) noexcept;

// 28.9.7.5, basic_simd reductions
template<class T, class Abi, class BinaryOperation = plus<>>
  constexpr T reduce(const basic_simd<T, Abi>&, BinaryOperation = {});
template<class T, class Abi, class BinaryOperation>
  constexpr T reduce(const basic_simd<T, Abi>& x,
    const typename basic_simd<T, Abi>::mask_type& mask, T identity_element,
    BinaryOperation binary_op);
template<class T, class Abi>
  constexpr T reduce(const basic_simd<T, Abi>& x,
    const typename basic_simd<T, Abi>::mask_type& mask, plus<> binary_op = {}) noexcept;
template<class T, class Abi>
  constexpr T reduce(const basic_simd<T, Abi>& x,
    const typename basic_simd<T, Abi>::mask_type& mask, multiplies<> binary_op) noexcept;
template<class T, class Abi>
  constexpr T reduce(const basic_simd<T, Abi>& x,
    const typename basic_simd<T, Abi>::mask_type& mask, bit_and<> binary_op) noexcept;
template<class T, class Abi>
  constexpr T reduce(const basic_simd<T, Abi>& x,
    const typename basic_simd<T, Abi>::mask_type& mask, bit_or<> binary_op) noexcept;
template<class T, class Abi>
  constexpr T reduce(const basic_simd<T, Abi>& x,
    const typename basic_simd<T, Abi>::mask_type& mask, bit_xor<> binary_op) noexcept;

template<class T, class Abi>
  constexpr T reduce_min(const basic_simd<T, Abi>&) noexcept;
template<class T, class Abi>
  constexpr T reduce_min(const basic_simd<T, Abi>&,
                         const typename basic_simd<T, Abi>::mask_type&) noexcept;
template<class T, class Abi>
  constexpr T reduce_max(const basic_simd<T, Abi>&) noexcept;
template<class T, class Abi>
  constexpr T reduce_max(const basic_simd<T, Abi>&,
                         const typename basic_simd<T, Abi>::mask_type&) noexcept;
```

```
    // 28.9.7.7, Algorithms
    template<class T, class Abi>
      constexpr basic_simd<T, Abi>
        min(const basic_simd<T, Abi>& a, const basic_simd<T, Abi>& b) noexcept;
    template<class T, class Abi>
      constexpr basic_simd<T, Abi>
        max(const basic_simd<T, Abi>& a, const basic_simd<T, Abi>& b) noexcept;
    template<class T, class Abi>
      constexpr pair<basic_simd<T, Abi>, basic_simd<T, Abi>>
        minmax(const basic_simd<T, Abi>& a, const basic_simd<T, Abi>& b) noexcept;
    template<class T, class Abi>
      constexpr basic_simd<T, Abi>
        clamp(const basic_simd<T, Abi>& v, const basic_simd<T, Abi>& lo,
              const basic_simd<T, Abi>& hi);

    template<class T, class U>
      constexpr auto simd_select(bool c, const T& a, const U& b)
      -> remove_cvref_t<decltype(c ? a : b)>;
    template<size_t Bytes, class Abi, class T, class U>
      constexpr auto simd_select(const basic_simd_mask<Bytes, Abi>& c, const T& a, const U& b)
      noexcept -> decltype(simd-select-impl(c, a, b));
  }
```

1 The header `<simd>` defines class templates, tag types, trait types, and function templates for element-wise operations on data-parallel objects.

2 *`simd-size-type`*is an exposition-only alias for a signed integer type.

3 *`mask-element-size`*`<basic_simd_mask<Bytes, Abi>>` has the value `Bytes`.

4 *`integer-from`*`<Bytes>` is an alias for a signed integer type `T` so that `sizeof(T) == Bytes`.

(7.1.3) 28.9.3 `simd` ABI tags [simd.abi]

```
  template<class T> using native-abi = see below; // exposition only
  template<class T, \simdsizetype N> using deduce-t = see below; // exposition only
```

1 An *ABI tag* is a type that indicates a choice of size and binary representation for objects of data-parallel type. [*Note:* The intent is for the size and binary representation to depend on the target architecture. — *end note*] The ABI tag, together with a given element type implies a number of elements. ABI tag types are used as the second template argument to `basic_simd` and `basic_simd_mask`.

2 [*Note:* The ABI tag is orthogonal to selecting the machine instruction set. The selected machine instruction set limits the usable ABI tag types, though (see 28.9.6.1). The ABI tags enable users to safely pass objects of data-parallel type between translation unit boundaries (e.g. function calls or I/O). — *end note*]

3 An implementation defines ABI tag types as necessary for the following exposition-only aliases.

4 The exposition-only alias *`deduce-t`*`<T, N>` results in a substitution failure if

- `T` is not a vectorizable type, or
- `N` is larger than an implementation-defined maximum.

The implementation-defined maximum for `N` is no smaller than 64.

5 Where present, the exposition-only alias *`deduce-t`*`<T, N>` names an ABI tag type that satisfies

- `basic_simd<T, deduce-t<T, N>>::size == N`, and
- `basic_simd<T, deduce-t<T, N>>` is default constructible (see 28.9.6.1).

6 `native-abi<T>` is an implementation-defined alias for an ABI tag. [*Note:* The intent is to use the ABI tag producing the most efficient data-parallel execution for the element type `T` that is supported on the currently targeted system. For target architectures with ISA extensions, compiler flags may change the type of the `native-abi<T>` alias. — *end note*] [*Example:* Consider a target architecture supporting the ABI tags `__simd128` and `__simd256`, where hardware support for `__simd256` only exists for floating-point types. The implementation therefore defines `native-abi<T>` as an alias for

- `__simd256` if `T` is a floating-point type, and
- `__simd128` otherwise.

— *end example*]

7 The type of `deduce-t<T, N>` in TU1 differs from the type of `deduce-t<T, N>` in TU2 iff the type of `native-abi<T>` in TU1 differs from the type of `native-abi<T>` in TU2.

(7.1.4) 28.9.4 `simd` type traits [simd.traits]

`template<class T, class U = typename T::value_type> struct simd_alignment { see below };`

1 `simd_alignment<T, U>` shall have a member `value` if and only if

- `T` is a specialization of `basic_simd_mask` and `U` is `bool`, or
- `T` is a specialization of `basic_simd` and `U` is a vectorizable type.

2 If `value` is present, the type `simd_alignment<T, U>` is a `BinaryTypeTrait` with a base characteristic of `integral_constant<size_t, N>` for some implementation-defined `N` (see 28.9.6.5 and 28.9.8.3). [*Note:* `value` identifies the alignment restrictions on pointers used for (converting) loads and stores for the give type `T` on arrays of type `U`. — *end note*]

3 The behavior of a program that adds specializations for `simd_alignment` is undefined.

`template<class T, class V> struct rebind_simd { using type = see below; };`

4 The member `type` is present if and only if

- `V` is either `basic_simd<U, Abi0>` or `basic_simd_mask<UBytes, Abi0>`, where `U`, `UBytes`, and `Abi0` are deduced from `V`, and
- `T` is a vectorizable type, and
- `simd_abi::deduce<T, basic_simd<U, Abi0>::size, Abi0>` has a member type `type`.

5 Let `Abi1` denote the type `deduce_t<T, basic_simd<U, Abi0>::size, Abi0>`. Where present, the member typedef `type` names `basic_simd<T, Abi1>` if `V` is `basic_simd<U, Abi0>` or `basic_simd_mask<sizeof(T), Abi1>` if `V` is `basic_simd_mask<UBytes, Abi0>`.

`template<simd-size-type N, class V> struct resize_simd { using type = see below; };`

6 The member `type` is present if and only if

- `V` is either `basic_simd<T, Abi0>` or `basic_simd_mask<Bytes, Abi0>`, where `T`, `Bytes`, and `Abi0` are deduced from `V`, and
- `simd_abi::deduce<T, N, Abi0>` has a member type `type`.

7 Let `Abi1` denote the type `deduce_t<T, N, Abi0>`. Where present, the member typedef `type` names `basic_simd<T, Abi1>` if `V` is `basic_simd<T, Abi0>` or `basic_simd_mask<Bytes, Abi1>` if `V` is `basic_simd_mask<Bytes, Abi0>`.

(7.1.5) 28.9.5 Load and store flags [simd.flags]

```
inline constexpr simd_flags<see below> simd_flag_convert{};
inline constexpr simd_flags<see below> simd_flag_aligned{};
template<size_t N> requires (has_single_bit(N))
  inline constexpr simd_flags<see below> simd_flag_overaligned{};
```

1 The template arguments to `simd_flags` are unspecified types used by the implementation to identify the different load and store flags.

2 There may be additional implementation-defined load and store flags.

(7.1.5.1) 28.9.5.1 Class template `simd_flags` overview [simd.flags.overview]

```
template <class... Flags> struct simd_flags {
  // 28.9.5.2, simd_flags operators
  template <class... Other>
    friend consteval auto operator|(simd_flags, simd_flags<Other...>);
};
```

1 The class template `simd_flags` acts like a integer bit-flag for types.

2 *Constraints*: Every type in `Flags` is a valid template argument to one of `simd_flag_convert`, `simd_flag_aligned`, `simd_flag_overaligned`, or to one of the implementation-defined load and store flags.

(7.1.5.2) 28.9.5.2 `simd_flags` operators [simd.flags.oper]

```
template <class... Other>
  friend consteval auto operator|(simd_flags a, simd_flags<Other...> b);
```

1 *Returns:* A specialization of `simd_flags` identifying all load and store flags identified either by `a` or `b`.

(7.1.6) 28.9.6 Class template `basic_simd` [simd.class]

(7.1.6.1) 28.9.6.1 Class template `basic_simd` overview [simd.overview]

```
template<class T, class Abi> class basic_simd {
public:
  using value_type = T;
  using reference = see below;
```

```
using mask_type = basic_simd_mask<sizeof(T), Abi>;
using abi_type = Abi;

static constexpr integral_constant<simd-size-type, see below> size;

constexpr basic_simd() noexcept = default;

// 28.9.6.4, basic_simd constructors
template<class U> constexpr basic_simd(U&& value) noexcept;
template<class U, class UAbi>
  constexpr explicit(see below) basic_simd(const basic_simd<U, UAbi>&) noexcept;
template<class G> constexpr explicit basic_simd(G&& gen) noexcept;
template<class It, class... Flags>
  constexpr basic_simd(It first, simd_flags<Flags...> = {});
template<class It, class... Flags>
  constexpr basic_simd(It first, const mask_type& mask, simd_flags<Flags...> = {});

// 28.9.6.5, basic_simd copy functions
template<class It, class... Flags>
  constexpr void copy_from(It first, simd_flags<Flags...> f = {});
template<class It, class... Flags>
  constexpr void copy_from(It first, const mask_type& mask, simd_flags<Flags...> f = {});
template<class Out, class... Flags>
  constexpr void copy_to(Out first, simd_flags<Flags...> f = {}) const;
template<class Out, class... Flags>
  constexpr void copy_to(Out first, const mask_type& mask, simd_flags<Flags...> f = {}) const;

// 28.9.6.6, basic_simd subscript operators
constexpr reference operator[](simd-size-type) &;
constexpr value_type operator[](simd-size-type) const&;

// 28.9.6.7, basic_simd unary operators
constexpr basic_simd& operator++() noexcept;
constexpr basic_simd operator++(int) noexcept;
constexpr basic_simd& operator--() noexcept;
constexpr basic_simd operator--(int) noexcept;
constexpr mask_type operator!() const noexcept;
constexpr basic_simd operator~() const noexcept;
constexpr basic_simd operator+() const noexcept;
constexpr basic_simd operator-() const noexcept;

// 28.9.7.1, basic_simd binary operators
friend constexpr basic_simd operator+(const basic_simd&, const basic_simd&) noexcept;
friend constexpr basic_simd operator-(const basic_simd&, const basic_simd&) noexcept;
friend constexpr basic_simd operator*(const basic_simd&, const basic_simd&) noexcept;
friend constexpr basic_simd operator/(const basic_simd&, const basic_simd&) noexcept;
```

```
    friend constexpr basic_simd operator%(const basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd operator&(const basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd operator|(const basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd operator^(const basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd operator<<(const basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd operator>>(const basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd operator<<(const basic_simd&, simd-size-type) noexcept;
    friend constexpr basic_simd operator>>(const basic_simd&, simd-size-type) noexcept;

    // 28.9.7.2, basic_simd compound assignment
    friend constexpr basic_simd& operator+=(basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd& operator-=(basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd& operator*=(basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd& operator/=(basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd& operator%=(basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd& operator&=(basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd& operator|=(basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd& operator^=(basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd& operator<<=(basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd& operator>>=(basic_simd&, const basic_simd&) noexcept;
    friend constexpr basic_simd& operator<<=(basic_simd&, simd-size-type) noexcept;
    friend constexpr basic_simd& operator>>=(basic_simd&, simd-size-type) noexcept;

    // 28.9.7.3, basic_simd compare operators
    friend constexpr mask_type operator==(const basic_simd&, const basic_simd&) noexcept;
    friend constexpr mask_type operator!=(const basic_simd&, const basic_simd&) noexcept;
    friend constexpr mask_type operator>=(const basic_simd&, const basic_simd&) noexcept;
    friend constexpr mask_type operator<=(const basic_simd&, const basic_simd&) noexcept;
    friend constexpr mask_type operator>(const basic_simd&, const basic_simd&) noexcept;
    friend constexpr mask_type operator<(const basic_simd&, const basic_simd&) noexcept;

    // 28.9.7.4, basic_simd conditional operators
    friend constexpr basic_simd simd-select-impl(
      const mask_type&, const basic_simd&, const basic_simd&) noexcept;
  };
```

1 The class template `basic_simd` is a data-parallel type. The width of a given `basic_simd` specialization is a constant expression, determined by the template parameters.

2 Every specialization of `basic_simd` is a complete type. The specialization `basic_simd<T, Abi>` is supported if `T` is a vectorizable type and

- `Abi` is `simd_abi::scalar`, or
- `Abi` is `simd_abi::fixed_size<N>`, with `N` constrained as defined in 28.9.3.

It is implementation-defined whether `basic_simd<T, Abi>` is supported. [*Note:* The intent is for implementations to decide on the basis of the currently targeted system. — *end note*]

If `basic_simd<T, Abi>` is not supported, the specialization shall have a deleted default constructor, deleted destructor, deleted copy constructor, and deleted copy assignment. Otherwise, the following are true:

- `is_nothrow_move_constructible_v<basic_simd<T, Abi>>`, and
- `is_nothrow_move_assignable_v<basic_simd<T, Abi>>`, and
- `is_nothrow_default_constructible_v<basic_simd<T, Abi>>`.

[*Example:* Consider an implementation that defines the ABI tags `__simd_x` and `__gpu_y`. When the compiler is invoked to translate to a machine that has support for the `__simd_x` ABI tag for all arithmetic types other than `long double` and no support for the `__gpu_y` ABI tag, then:

- `basic_simd<T, simd_abi::__gpu_y>` is not supported for any `T` and has a deleted constructor.
- `basic_simd<long double, simd_abi::__simd_x>` is not supported and has a deleted constructor.
- `basic_simd<double, simd_abi::__simd_x>` is supported.
- `basic_simd<long double, simd_abi::scalar>` is supported.

— *end example*]

3 Default initialization performs no initialization of the elements; value-initialization initializes each element with `T()`. [*Note:* Thus, default initialization leaves the elements in an indeterminate state. — *end note*]

4 Implementations should enable explicit conversion from and to implementation-defined types. This adds one or more of the following declarations to class `basic_simd`:

```
constexpr explicit operator implementation-defined() const;
constexpr explicit basic_simd(const implementation-defined& init);
```

[*Example:* Consider an implementation that supports the type `__vec4f` and the function `__vec4f _vec4f_addsub(__vec4f, __vec4f)` for the currently targeted system. A user may require the use of `_vec4f_addsub` for maximum performance and thus writes:

```
using V = basic_simd<float, simd_abi::__simd128>;
V addsub(V a, V b) {
  return static_cast<V>(_vec4f_addsub(static_cast<__vec4f>(a), static_cast<__vec4f>(b)));
}
```

— *end example*]

(7.1.6.2) 28.9.6.2 `basic_simd` width [simd.width]

```
static constexpr integral_constant<simd-size-type, see below> size;
```

1 `size` is an `integral_constant<@simd-size-type@, N>` with `N` equal to the number of elements in a `basic_simd` object.

2 [*Note:* This member is present even if the particular `basic_simd` specialization is not supported. — *end note*]

(7.1.6.3) 28.9.6.3 Element references [simd.reference]

1 A `reference` is an object that refers to an element in a `basic_simd` or `basic_simd_mask` object. `reference::value_type` is the same type as `simd::value_type` or `simd_mask::value_type`, respectively.

2 Class `reference` is for exposition only. An implementation is permitted to provide equivalent functionality without providing a class with this name.

```
class reference // exposition only
{
public:
  reference() = delete;
  reference(const reference&) = delete;

  constexpr operator value_type() const noexcept;

  template<class U> constexpr reference operator=(U&& x) && noexcept;

  template<class U> constexpr reference operator+=(U&& x) && noexcept;
  template<class U> constexpr reference operator-=(U&& x) && noexcept;
  template<class U> constexpr reference operator*=(U&& x) && noexcept;
  template<class U> constexpr reference operator/=(U&& x) && noexcept;
  template<class U> constexpr reference operator%=(U&& x) && noexcept;
  template<class U> constexpr reference operator|=(U&& x) && noexcept;
  template<class U> constexpr reference operator&=(U&& x) && noexcept;
  template<class U> constexpr reference operator^=(U&& x) && noexcept;
  template<class U> constexpr reference operator<<=(U&& x) && noexcept;
  template<class U> constexpr reference operator>>=(U&& x) && noexcept;

  constexpr reference operator++() && noexcept;
  constexpr value_type operator++(int) && noexcept;
  constexpr reference operator--() && noexcept;
  constexpr value_type operator--(int) && noexcept;

  friend constexpr void swap(reference&& a, reference&& b) noexcept;
  friend constexpr void swap(value_type& a, reference&& b) noexcept;
  friend constexpr void swap(reference&& a, value_type& b) noexcept;
};
```

`constexpr operator value_type() const noexcept;`

3 *Returns:* The value of the element referred to by `*this`.

`template<class U> constexpr reference operator=(U&& x) && noexcept;`

4 *Constraints*: `declval<value_type&>() = std::forward<U>(x)` is well-formed.

5 *Effects*: Replaces the referred to element in `basic_simd` or `basic_simd_mask` with `static_cast<value_type>(std::forward<U>(x))`.

6 *Returns:* A copy of `*this`.

```
template<class U> constexpr reference operator+=(U&& x) && noexcept;
template<class U> constexpr reference operator-=(U&& x) && noexcept;
template<class U> constexpr reference operator*=(U&& x) && noexcept;
template<class U> constexpr reference operator/=(U&& x) && noexcept;
```

```
template<class U> constexpr reference operator%=(U&& x) && noexcept;
template<class U> constexpr reference operator|=(U&& x) && noexcept;
template<class U> constexpr reference operator&=(U&& x) && noexcept;
template<class U> constexpr reference operator^=(U&& x) && noexcept;
template<class U> constexpr reference operator<<=(U&& x) && noexcept;
template<class U> constexpr reference operator>>=(U&& x) && noexcept;
```

7 *Constraints*: `declval<value_type&>() @= std::forward<U>(x)` (where `@=` denotes the indicated compound assignment operator) is well-formed.

8 *Effects*: Applies the indicated compound operator to the referred to element in `basic_simd` or `basic_simd_mask` and `std::forward<U>(x)`.

9 *Returns:* A copy of `*this`.

```
constexpr reference operator++() && noexcept;
constexpr reference operator--() && noexcept;
```

10 *Constraints*: The indicated operator can be applied to objects of type `value_type`.

11 *Effects*: Applies the indicated operator to the referred to element in `basic_simd` or `basic_simd_mask`.

12 *Returns:* A copy of `*this`.

```
constexpr value_type operator++(int) && noexcept;
constexpr value_type operator--(int) && noexcept;
```

13 *Remarks:* The indicated operator can be applied to objects of type `value_type`.

14 *Effects*: Applies the indicated operator to the referred to element in `basic_simd` or `basic_simd_mask`.

15 *Returns:* A copy of the referred to element before applying the indicated operator.

```
friend constexpr void swap(reference&& a, reference&& b) noexcept;
friend constexpr void swap(value_type& a, reference&& b) noexcept;
friend constexpr void swap(reference&& a, value_type& b) noexcept;
```

16 *Effects*: Exchanges the values `a` and `b` refer to.

(7.1.6.4) 28.9.6.4 `basic_simd` constructors [simd.ctor]

```
template<class U> constexpr basic_simd(U&&) noexcept;
```

1 Let `From` denote the type `remove_cvref_t<U>`.

2 *Constraints*: `From` satisfies `convertible_to<value_type>`, and either

- `From` satisfies *`constexpr-wrapper-like`* (28.9.2) and the actual value of `From::value` after conversion to `value_type` will fit into `value_type` and will produce the original value when converted back to `decltype(From::value)`, or
- `From` is a vectorizable type and the conversion from `From` to `value_type` is value-preserving (28.9.1), or

  - `From` is not an arithmetic type and does not satisfy *`constexpr-wrapper-like`*.

3 *Effects*: Constructs an object with each element initialized to the value of the argument after conversion to `value_type`.

```
template<class U, class UAbi> constexpr explicit(see below)
  basic_simd(const basic_simd<U, UAbi>& x) noexcept;
```

4 *Constraints*: `basic_simd<U, UAbi>::size == size()`.

5 *Effects*: Constructs an object where the i^{th} element equals `static_cast<T>(x[`*`i`*`])` for all i in the range of `[0, size())`.

6 *Remarks:* The constructor is `explicit`

- if the conversion from `U` to `value_type` is not value-preserving, or
- if both `U` and `value_type` are integral types and the integer conversion rank ([conv.rank]) of `U` is greater than the integer conversion rank of `value_type`, or
- if both `U` and `value_type` are floating-point types and the floating-point conversion rank ([conv.rank]) of `U` is greater than the floating-point conversion rank of `value_type`.

```
template<class G> constexpr basic_simd(G&& gen) noexcept;
```

7 *Constraints*: `basic_simd(gen(integral_constant<`*`simd-size-type`*`, i>()))` is well-formed for all i in the range of `[0, size())`.

8 *Effects*: Constructs an object where the i^{th} element is initialized to `gen(integral_constant<`*`simd-size-type`*`, i>())`.

9 The calls to `gen` are unsequenced with respect to each other. Vectorization-unsafe standard library functions may not be invoked by `gen` ([algorithms.parallel.exec]). `gen` is invoked exactly once for each i.

```
template<class It, class... Flags>
  constexpr basic_simd(It first, simd_flags<Flags...> = {});
```

10 *Constraints*:

- `iter_value_t<It>` is a vectorizable type, and
- `It` satisfies `contiguous_iterator`.

11 *Mandates*: If the template parameter pack `Flags` does not contain the type identifying `simd_flag_convert`, then the conversion from `iter_value_t<It>` to `value_type` is value-preserving.

12 *Preconditions*:

- `[first, first + size())` is a valid range.
- `It` models `contiguous_iterator`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd, iter_value_t<It>>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

13 *Effects*: Constructs an object where the i^{th} element is initialized to `static_cast<T>(first[i])` for all i in the range of `[0, size())`.

14 *Throws:* Nothing.

```
template<class It, class... Flags>
  constexpr basic_simd(It first, const mask_type& mask, simd_flags<Flags...> = {});
```

15 *Constraints*:

- `iter_value_t<It>` is a vectorizable type, and
- `It` satisfies `contiguous_iterator`.

16 *Mandates*: If the template parameter pack `Flags` does not contain the type identifying `simd_flag_convert`, then the conversion from `iter_value_t<It>` to `value_type` is value-preserving.

17 *Preconditions*:

- For all selected indices i, `[first, first + i)` is a valid range.
- `It` models `contiguous_iterator`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd, iter_value_t<It>>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

18 *Effects*: Constructs an object where the i^{th} element is initialized to `mask[i] ? static_cast<T>(first[i]) : T()` for all i in the range of `[0, size())`.

19 *Throws:* Nothing.

(7.1.6.5) 28.9.6.5 `basic_simd` copy functions [simd.copy]

```
template<class It, class... Flags>
  constexpr void copy_from(It first, simd_flags<Flags...> f = {});
```

1 *Constraints*:

- `iter_value_t<It>` is a vectorizable type, and
- `It` satisfies `contiguous_iterator`.

2 *Mandates*: If the template parameter pack `Flags` does not contain the type identifying `simd_flag_convert`, then the conversion from `iter_value_t<It>` to `value_type` is value-preserving.

3 *Preconditions*:

- `[first, first + size())` is a valid range.
- `It` models `contiguous_iterator`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd, iter_value_t<It>>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

4 *Effects*: Replaces the elements of the `basic_simd` object such that the i^{th} element is assigned with `static_cast<T>(first[`i`])` for all i in the range of `[0, size())`.

5 *Throws:* Nothing.

```
template<class It, class... Flags>
  constexpr void copy_from(It first, const mask_type& mask, simd_flags<Flags...> f = {});
```

6 *Constraints*:

- `iter_value_t<It>` is a vectorizable type, and
- `It` satisfies `contiguous_iterator`.

7 *Mandates*: If the template parameter pack `Flags` does not contain the type identifying `simd_flag_convert`, then the conversion from `iter_value_t<It>` to `value_type` is value-preserving.

8 *Preconditions*:

- For all selected indices i, `[first, first + `i`)` is a valid range.
- `It` models `contiguous_iterator`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd, iter_value_t<It>>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

9 *Effects*: Replaces the selected elements of the `basic_simd` object such that the i^{th} element is replaced with `static_cast<T>(first[`i`])` for all selected indices i.

10 *Throws:* Nothing.

```
template<class Out, class... Flags>
  constexpr void copy_to(Out first, simd_flags<Flags...> f = {}) const;
```

11 *Constraints*:

- `iter_value_t<Out>` is a vectorizable type, and
- `Out` satisfies `contiguous_iterator`, and
- `Out` satisfies `indirectly_writable<value_type>`.

12 *Mandates*: If the template parameter pack `Flags` does not contain the type identifying `simd_flag_convert`, then the conversion from `value_type` to `iter_value_t<Out>` is value-preserving.

13 *Preconditions*:

- `[first, first + size())` is a valid range.
- `Out` models `contiguous_iterator`.
- `Out` models `indirectly_writable<value_type>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd, iter_value_t<Out>>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

14 *Effects*: Copies all `basic_simd` elements as if `first[`i`] = static_cast<iter_value_t<Out>>(operator[](`i`))` for all i in the range of `[0, size())`.

15 *Throws:* Nothing.

```
template<class Out, class... Flags>
  constexpr void copy_to(Out first, const mask_type& mask, simd_flags<Flags...> f = {}) const;
```

16 *Constraints*:

- `iter_value_t<Out>` is a vectorizable type, and
- `Out` satisfies `contiguous_iterator`, and
- `Out` satisfies `indirectly_writable<value_type>`.

17 *Mandates*: If the template parameter pack `Flags` does not contain the type identifying `simd_flag_convert`, then the conversion from `value_type` to `iter_value_t<Out>` is value-preserving.

18 *Preconditions*:

- For all selected indices i, `[first, first + `i`)` is a valid range.
- `Out` models `contiguous_iterator`.
- `Out` models `indirectly_writable<value_type>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd, iter_value_t<Out>>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

19 *Effects*: Copies the selected elements as if `first[`i`] = static_cast<iter_value_t<Out>>(operator[](`i`))` for all selected indices i.

20 *Throws:* Nothing.

(7.1.6.6) 28.9.6.6 `basic_simd` subscript operators [simd.subscr]

```
constexpr reference operator[](simd-size-type i) &;
```

1 *Preconditions*: `i < size()`.

2 *Returns:* A `reference` (see 28.9.6.3) referring to the i^{th} element.

3 *Throws:* Nothing.

```
constexpr value_type operator[](simd-size-type i) const&;
```

4 *Preconditions*: `i < size()`.

5 *Returns:* The value of the i^{th} element.

6 *Throws:* Nothing.

(7.1.6.7) 28.9.6.7 `basic_simd` unary operators [simd.unary]

1 Effects in this subclause are applied as unary element-wise operations.

```
constexpr basic_simd& operator++() noexcept;
```

2 *Constraints*: Application of unary `++` to objects of type `value_type` is well-formed.

3 *Effects*: Increments every element by one.

4 *Returns:* `*this`.

```
constexpr basic_simd operator++(int) noexcept;
```

5 *Constraints*: Application of unary `++` to objects of type `value_type` is well-formed.

6 *Effects*: Increments every element by one.

7 *Returns:* A copy of `*this` before incrementing.

```
constexpr basic_simd& operator--() noexcept;
```

8 *Constraints*: Application of unary `--` to objects of type `value_type` is well-formed.

9 *Effects*: Decrements every element by one.

10 *Returns:* `*this`.

```
constexpr basic_simd operator--(int) noexcept;
```

11 *Constraints*: Application of unary `--` to objects of type `value_type` is well-formed.

12 *Effects*: Decrements every element by one.

13 *Returns:* A copy of `*this` before decrementing.

```
constexpr mask_type operator!() const noexcept;
```

14 *Constraints*: Application of unary `!` to objects of type `value_type` is well-formed.

15 *Returns:* A `basic_simd_mask` object with the i^{th} element set to `!operator[](`i`)` for all i in the range of `[0, size())`.

```
constexpr basic_simd operator~() const noexcept;
```

16 *Constraints*: Application of unary `~` to objects of type `value_type` is well-formed.

17 *Returns:* A `basic_simd` object where each bit is the inverse of the corresponding bit in `*this`.

```
constexpr basic_simd operator+() const noexcept;
```

18 *Constraints*: Application of unary `+` to objects of type `value_type` is well-formed.

19 *Returns:* `*this`.

```
constexpr basic_simd operator-() const noexcept;
```

20 *Constraints*: Application of unary `-` to objects of type `value_type` is well-formed.

21 *Returns:* A `basic_simd` object where the i^{th} element is initialized to `-operator[](`i`)` for all i in the range of `[0, size())`.

(7.1.7) 28.9.7 `basic_simd` non-member operations [simd.nonmembers]

(7.1.7.1) 28.9.7.1 `basic_simd` binary operators [simd.binary]

```
friend constexpr basic_simd operator+(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd operator-(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd operator*(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd operator/(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd operator%(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd operator&(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd operator|(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd operator^(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd operator<<(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd operator>>(const basic_simd& lhs, const basic_simd& rhs) noexcept;
```

1 *Constraints*: Application of the indicated operator to objects of type `value_type` is well-formed.

2 *Returns:* A `basic_simd` object initialized with the results of applying the indicated operator to `lhs` and `rhs` as a binary element-wise operation.

```
friend constexpr basic_simd operator<<(const basic_simd& v, simd-size-type n) noexcept;
friend constexpr basic_simd operator>>(const basic_simd& v, simd-size-type n) noexcept;
```

3 *Constraints*: Application of the indicated operator to objects of type `value_type` is well-formed.

4 *Returns:* A `basic_simd` object where the i^{th} element is initialized to the result of applying the indicated operator to `v[`i`]` and `n` for all i in the range of `[0, size())`.

(7.1.7.2) 28.9.7.2 `basic_simd` compound assignment [simd.cassign]

```
friend constexpr basic_simd& operator+=(basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd& operator-=(basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd& operator*=(basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd& operator/=(basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd& operator%=(basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd& operator&=(basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd& operator|=(basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd& operator^=(basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd& operator<<=(basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr basic_simd& operator>>=(basic_simd& lhs, const basic_simd& rhs) noexcept;
```

1 *Constraints*: Application of the indicated operator to objects of type `value_type` is well-formed.

2 *Effects*: These operators apply the indicated operator to `lhs` and `rhs` as an element-wise operation.

3 *Returns:* `lhs`.

```
friend constexpr basic_simd& operator<<=(basic_simd& lhs, simd-size-type n) noexcept;
friend constexpr basic_simd& operator>>=(basic_simd& lhs, simd-size-type n) noexcept;
```

4 *Constraints*: Application of the indicated operator to objects of type `value_type` is well-formed.

5 *Effects*: Equivalent to: `return operator@=(lhs, basic_simd(n));`

(7.1.7.3) 28.9.7.3 `basic_simd` compare operators [simd.comparison]

```
friend constexpr mask_type operator==(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr mask_type operator!=(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr mask_type operator>=(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr mask_type operator<=(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr mask_type operator>(const basic_simd& lhs, const basic_simd& rhs) noexcept;
friend constexpr mask_type operator<(const basic_simd& lhs, const basic_simd& rhs) noexcept;
```

1 *Constraints*: Application of the indicated operator to objects of type `value_type` is well-formed.

2 *Returns:* A `basic_simd_mask` object initialized with the results of applying the indicated operator to `lhs` and `rhs` as a binary element-wise operation.

(7.1.7.4) 28.9.7.4 `basic_simd` conditional operators [simd.cond]

```
friend constexpr basic_simd
simd-select-impl(const mask_type& mask, const basic_simd& a, const basic_simd& b) noexcept;
```

1 *Returns:* A `basic_simd` object where the i^{th} element equals `mask[i] ? a[i] : b[i]` for all i in the range of `[0, size())`.

(7.1.7.5) 28.9.7.5 `basic_simd` reductions [simd.reductions]

1 In this subclause, `BinaryOperation` shall be a binary element-wise operation.

```
template<class T, class Abi, class BinaryOperation = plus<>>
  constexpr T reduce(const basic_simd<T, Abi>& x, BinaryOperation binary_op = {});
```

2 *Constraints*: `BinaryOperation` satisfies `invocable<simd<T, 1>, simd<T, 1>>`.

3 *Mandates*: `binary_op` can be invoked with two arguments of type `basic_simd<T, A1>` returning `basic_simd<T, A1>` for every `A1` that is an ABI tag type.

4 *Returns:* `GENERALIZED_SUM(binary_op, x.data[i], ...)` for all i in the range of `[0, size())`([numerics.defns]).

5 *Throws:* Any exception thrown from `binary_op`.

```
template<class T, class Abi, class BinaryOperation>
  constexpr T reduce(const basic_simd<T, Abi>& x, const typename basic_simd<T, Abi>::mask_type& mask,
                     T identity_element, BinaryOperation binary_op);
```

6 *Constraints*: `BinaryOperation` satisfies `invocable<simd<T, 1>, simd<T, 1>>`.

7 *Mandates*: `binary_op` can be invoked with two arguments of type `basic_simd<T, A1>` returning `basic_simd<T, A1>` for every `A1` that is an ABI tag type.

8 *Preconditions*: The results of `all_of(x == binary_op(basic_simd<T, A1>(identity_element), basic_simd<T, A1>(x)))` and `all_of(basic_simd<T, A1>(x) == binary_op(x, basic_simd<T, A1>(identity_element)))` shall be `true` for every `A1` that is an ABI tag type and for all finite values `x` representable by `T`.

9 *Returns:* If `none_of(mask)`, returns `identity_element`. Otherwise, returns `GENERALIZED_SUM(binary_op, x[i], ...)` for all selected indices i.

10 *Throws:* Any exception thrown from `binary_op`.

```
template<class T, class Abi>
  constexpr T reduce(const basic_simd<T, Abi>& x, const typename basic_simd<T, Abi>::mask_type& mask,
                     plus<> binary_op = {}) noexcept;
```

11 *Returns:* If `none_of(mask)`, returns `T()`. Otherwise, returns `GENERALIZED_SUM(binary_op, x[i], ...)` for all selected indices i.

```
template<class T, class Abi>
  constexpr T reduce(const basic_simd<T, Abi>& x, const typename basic_simd<T, Abi>::mask_type& mask,
                     multiplies<> binary_op) noexcept;
```

12 *Returns:* If `none_of(x)`, returns `1`. Otherwise, returns `GENERALIZED_SUM(binary_op, x[i], ...)` for all selected indices i.

```
template<class T, class Abi>
  constexpr T reduce(const basic_simd<T, Abi>& x, const typename basic_simd<T, Abi>::mask_type& mask,
                     bit_and<> binary_op) noexcept;
```

13 *Constraints*: `is_integral_v<T>` is `true`.

14 *Returns:* If `none_of(mask)`, returns `~T()`. Otherwise, returns `GENERALIZED_SUM(binary_op, x[i], ...)` for all selected indices i.

```
template<class T, class Abi>
  constexpr T reduce(const basic_simd<T, Abi>& x, const typename basic_simd<T, Abi>::mask_type& mask,
                     bit_or<> binary_op) noexcept;
template<class T, class Abi>
  constexpr T reduce(const basic_simd<T, Abi>& x, const typename basic_simd<T, Abi>::mask_type& mask,
                     bit_xor<> binary_op) noexcept;
```

15 *Constraints*: `is_integral_v<T>` is `true`.

16 *Returns:* If `none_of(mask)`, returns `T()`. Otherwise, returns `GENERALIZED_SUM(binary_op, x[i], ...)` for all selected indices i.

```
template<class T, class Abi> constexpr T reduce_min(const basic_simd<T, Abi>& x) noexcept;
```

17 *Constraints*: `T` satisfies `totally_ordered`.

18 *Preconditions*: `T` models `totally_ordered`.

19 *Returns:* The value of an element `x[j]` for which `x[i] < x[j]` is `false` for all i in the range of `[0, size())`.

```
template<class T, class Abi>
  constexpr T reduce_min(
    const basic_simd<T, Abi>&, const typename basic_simd<T, Abi>::mask_type&) noexcept;
```

20 *Constraints*: `T` satisfies `totally_ordered`.

21 *Preconditions*: `T` models `totally_ordered`.

22 *Returns:* If `none_of(mask)`, returns `numeric_limits<T>::max()`. Otherwise, returns the value of a selected element `x[j]` for which `x[i] < x[j]` is `false` for all selected indices i.

```
template<class T, class Abi> constexpr T reduce_max(const basic_simd<T, Abi>& x) noexcept;
```

23 *Constraints*: `T` satisfies `totally_ordered`.

24 *Preconditions*: `T` models `totally_ordered`.

25 *Returns:* The value of an element `x[j]` for which `x[j] < x[i]` is `false` for all i in the range of `[0, size())`.

```
template<class T, class Abi>
  constexpr T reduce_max(
    const basic_simd<T, Abi>&, const typename basic_simd<T, Abi>::mask_type&) noexcept;
```

26 *Constraints*: `T` satisfies `totally_ordered`.

27 *Preconditions*: `T` models `totally_ordered`.

28 *Returns:* If `none_of(mask)`, returns `numeric_limits<V::value_type>::lowest()`. Otherwise, returns the value of a selected element `x.data[j]` for which `x.data[j] < x.data[i]` is `false` for all selected indices i.

(7.1.7.6) 28.9.7.6 `basic_simd` and `basic_simd_mask` creation [simd.creation]

```
template<class T, class Abi>
  constexpr auto simd_split(const basic_simd<typename V::value_type, Abi>& x) noexcept;
template<class T, class Abi>
  constexpr auto simd_split(const basic_simd_mask<mask-element-size<T>, Abi>& x) noexcept;
```

1 *Constraints*:

- For the first overload `T` is a specialization of `basic_simd`.
- For the second overload `T` is a specialization of `basic_simd_mask`.

2 Let N be `x.size() / V::size()`.

3 *Returns:*

- If `x.size() % V::size() == 0`, an `array<T, N>` with the i^{th} `basic_simd` or `basic_simd_mask` element of the j^{th} `array` element initialized to the value of the element in `x` with index `i + j * V::size()`.

- Otherwise, a `tuple` of N objects of type `T` and one object of type `resize_simd_t<x.size() % V::size(), T>`. The i^{th} `basic_simd` or `basic_simd_mask` element of the j^{th} `tuple` element of type `T` is initialized to the value of the element in `x` with index i `+` j `*` `V::size()`. The i^{th} `basic_simd` or `basic_simd_mask` element of the `N`$^{\text{th}}$ `tuple` element is initialized to the value of the element in `x` with index i `+` N `*` `V::size()`.

```
template<class T, class... Abis>
  constexpr simd<T, (basic_simd<T, Abis>::size + ...)>
    simd_cat(const basic_simd<T, Abis>&... xs) noexcept;
template<size_t Bytes, class... Abis>
  constexpr simd_mask<deduce-t<integer-from<Bytes>, (basic_simd_mask<Bytes, Abis>::size() + ...)>
    simd_cat(const basic_simd_mask<Bytes, Abis>&... xs) noexcept;
```

4 *Returns:* A data-parallel object initialized with the concatenated values in the `xs` pack of data-parallel objects: The i^{th} `basic_simd`/`basic_simd_mask` element of the j^{th} parameter in the `xs` pack is copied to the return value's element with index i + the sum of the width of the first j parameters in the `xs` pack.

(7.1.7.7) 28.9.7.7 Algorithms [simd.alg]

```
template<class T, class Abi>
  constexpr basic_simd<T, Abi> min(const basic_simd<T, Abi>& a, const basic_simd<T, Abi>& b) noexcept;
```

1 *Constraints*: `T` satisfies `totally_ordered`.

2 *Preconditions*: `T` models `totally_ordered`.

3 *Returns:* The result of the element-wise application of `std::min(a[`i`], b[`i`])` for all i in the range of `[0, size())`.

```
template<class T, class Abi>
  constexpr basic_simd<T, Abi> max(const basic_simd<T, Abi>& a, const basic_simd<T, Abi>& b) noexcept;
```

4 *Constraints*: `T` satisfies `totally_ordered`.

5 *Preconditions*: `T` models `totally_ordered`.

6 *Returns:* The result of the element-wise application of `std::max(a[`i`], b[`i`])` for all i in the range of `[0, size())`.

```
template<class T, class Abi>
  constexpr pair<basic_simd<T, Abi>, basic_simd<T, Abi>>
  minmax(const basic_simd<T, Abi>& a, const basic_simd<T, Abi>& b) noexcept;
```

7 *Constraints*: `T` satisfies `totally_ordered`.

8 *Preconditions*: `T` models `totally_ordered`.

9 *Returns:* A `pair` initialized with

- the result of element-wise application of `std::min(a[`i`], b[`i`])` for all i in the range of `[0, size())` in the `first` member, and

- the result of element-wise application of `std::max(a[i], b[i])` for all i in the range of `[0, size())` in the `second` member.

```
template<class T, class Abi>
  constexpr basic_simd<T, Abi> clamp(
    const basic_simd<T, Abi>& v, const basic_simd<T, Abi>& lo, const basic_simd<T, Abi>& hi);
```

10 *Constraints*: `T` satisfies `totally_ordered`.

11 *Preconditions*: `T` models `totally_ordered`.

12 *Preconditions*: No element in `lo` shall be greater than the corresponding element in `hi`.

13 *Returns:* The result of element-wise application of `std::clamp(v[i], lo[i], hi[i])` for all i in the range of `[0, size())`.

```
template<class T, class U>
  constexpr auto simd_select(bool c, const T& a, const U& b)
  -> remove_cvref_t<decltype(c ? a : b)>;
```

14 *Returns:* As-if `c ? a : b`.

```
template<size_t Bytes, class Abi, class T, class U>
  constexpr auto simd_select(const basic_simd_mask<Bytes, Abi>& c, const T& a, const U& b)
  noexcept -> decltype(simd-select-impl(c, a, b));
```

15 *Returns:* As-if `simd-select-impl(c, a, b)`.

(7.1.7.8) 28.9.7.8 `basic_simd` math library [simd.math]

1 For each set of overloaded functions within `<cmath>`, there shall be additional overloads sufficient to ensure that if any argument corresponding to a `double` parameter has type `basic_simd<T, Abi>`, where `is_floating_point_v<T>` is `true`, then:

- All arguments corresponding to `double` parameters shall be convertible to `basic_simd<T, Abi>`.
- All arguments corresponding to `double*` parameters shall be of type `basic_simd<T, Abi>*`.
- All arguments corresponding to parameters of integral type `U` shall be convertible to `simd<U, basic_simd<T, Abi>::size>`.
- All arguments corresponding to `U*`, where `U` is integral, shall be of type `simd<U, basic_simd<T, Abi>::size>*`.
- If the corresponding return type is `double`, the return type of the additional overloads is `basic_simd<T, Abi>`. Otherwise, if the corresponding return type is `bool`, the return type of the additional overload is `basic_simd_mask<T, Abi>`. Otherwise, the return type is `simd<R, basic_simd<T, Abi>::size>`, with `R` denoting the corresponding return type.

It is unspecified whether a call to these overloads with arguments that are all convertible to `basic_simd<T, Abi>` but are not of type `basic_simd<T, Abi>` is well-formed.

2 Each function overload produced by the above rules applies the indicated `<cmath>` function element-wise. For the mathematical functions, the results per element only need to be approximately equal to the application of the function which is overloaded for the element type.

3 The result is unspecified if a domain, pole, or range error occurs when the input argument(s) are applied to the indicated `<cmath>` function. [*Note:* Implementations are encouraged to follow the C specification (especially Annex F). — *end note*]

4 TODO: Allow `abs(basic_simd`<signed-integral>`)`.

5 If `abs` is called with an argument of type `basic_simd<X, Abi>` for which `is_unsigned_v<X>` is `true`, the program is ill-formed.

(7.1.8) 28.9.8 Class template `basic_simd_mask` [simd.mask.class]

(7.1.8.1) 28.9.8.1 Class template `basic_simd_mask` overview [simd.mask.overview]

```
template<size_t Bytes, class Abi> class basic_simd_mask {
public:
  using value_type = bool;
  using reference = see below;
  using abi_type = Abi;

  static constexpr auto size = basic_simd<integer-from<Bytes>, Abi>::size;

  constexpr basic_simd_mask() noexcept = default;

  // 28.9.8.2, basic_simd_mask constructors
  constexpr explicit basic_simd_mask(value_type) noexcept;
  template<size_t UBytes, class UAbi>
    constexpr explicit basic_simd_mask(const basic_simd_mask<UBytes, UAbi>&) noexcept;
  template<class G> constexpr explicit basic_simd_mask(G&& gen) noexcept;
  template<class It, class... Flags>
    constexpr basic_simd_mask(It first, Flags = {});
  template<class It, class... Flags>
    constexpr basic_simd_mask(It first, const basic_simd_mask& mask, simd_flags<Flags...> = {});

  // 28.9.8.3, basic_simd_mask copy functions
  template<class It, class... Flags>
    constexpr void copy_from(It first, simd_flags<Flags...> = {});
  template<class It, class... Flags>
    constexpr void copy_from(It first, const basic_simd_mask& mask, simd_flags<Flags...> = {});
  template<class Out, class... Flags>
    constexpr void copy_to(Out first, simd_flags<Flags...> = {}) const;
  template<class Out, class... Flags>
    constexpr void copy_to(Out first, const basic_simd_mask& mask, simd_flags<Flags...> = {}) const;

  // 28.9.8.4, basic_simd_mask subscript operators
  constexpr reference operator[](simd-size-type) &;
```

```
constexpr value_type operator[](simd-size-type) const&;

// 28.9.8.5, basic_simd_mask unary operators
constexpr basic_simd_mask operator!() const noexcept;
constexpr basic_simd<integer-from<Bytes>, Abi> operator+() const noexcept;
constexpr basic_simd<integer-from<Bytes>, Abi> operator-() const noexcept;
constexpr basic_simd<integer-from<Bytes>, Abi> operator~() const noexcept;

// 28.9.8.6, basic_simd_mask conversion operators
template <class U, class A>
  constexpr explicit(sizeof(U) != Bytes) operator basic_simd<U, A>() const noexcept;

// 28.9.9.1, basic_simd_mask binary operators
friend constexpr basic_simd_mask
  operator&&(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator||(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator&(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator|(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator^(const basic_simd_mask&, const basic_simd_mask&) noexcept;

// 28.9.9.2, basic_simd_mask compound assignment
friend constexpr basic_simd_mask&
  operator&=(basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask&
  operator|=(basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask&
  operator^=(basic_simd_mask&, const basic_simd_mask&) noexcept;

// 28.9.9.3, basic_simd_mask comparisons
friend constexpr basic_simd_mask
  operator==(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator!=(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator>=(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator<=(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator>(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator<(const basic_simd_mask&, const basic_simd_mask&) noexcept;
```

```
    // 28.9.9.4, basic_simd_mask conditional operators
    friend constexpr basic_simd_mask simd-select-impl(
      const basic_simd_mask&, const basic_simd_mask&, const basic_simd_mask&) noexcept;
    friend constexpr basic_simd_mask simd-select-impl(
      const basic_simd_mask&, same_as<bool> auto, same_as<bool> auto) noexcept;
    template <class T0, class T1>
      friend constexpr simd<see below, size()>
        simd-select-impl(const basic_simd_mask&, const T0&, const T1&) noexcept;
  };
```

1 The class template `basic_simd_mask` is a data-parallel type with the element type `bool`. The width of a given `basic_simd_mask` specialization is a constant expression, determined by the template parameters. Specifically, `basic_simd_mask<T, Abi>::size() == basic_simd<T, Abi>::size()`.

2 Every specialization of `basic_simd_mask` is a complete type. The specialization `basic_simd_mask<T, Abi>` is supported if `T` is a vectorizable type and

- `Abi` is `simd_abi::scalar`, or
- `Abi` is `simd_abi::fixed_size<N>`, with `N` constrained as defined in (28.9.3).

It is implementation-defined whether `basic_simd_mask<T, Abi>` is supported. [*Note:* The intent is for implementations to decide on the basis of the currently targeted system. — *end note*]

If `basic_simd_mask<Bytes, Abi>` is not supported, the specialization shall have a deleted default constructor, deleted destructor, deleted copy constructor, and deleted copy assignment. Otherwise, the following are true:

- `is_nothrow_move_constructible_v<basic_simd_mask<Bytes, Abi>>`, and
- `is_nothrow_move_assignable_v<basic_simd_mask<Bytes, Abi>>`, and
- `is_nothrow_default_constructible_v<basic_simd_mask<Bytes, Abi>>`.

3 Default initialization performs no initialization of the elements; value-initialization initializes each element with `false`. [*Note:* Thus, default initialization leaves the elements in an indeterminate state. — *end note*]

4 Implementations should enable explicit conversion from and to implementation-defined types. This adds one or more of the following declarations to class `basic_simd_mask`:

```
  constexpr explicit operator implementation-defined() const;
  constexpr explicit basic_simd_mask(const implementation-defined& init);
```

5 The member type `reference` has the same interface as `basic_simd<T, Abi>::reference`, except its `value_type` is `bool`. (28.9.6.3)

(7.1.8.2) 28.9.8.2 `basic_simd_mask` constructors [simd.mask.ctor]

```
constexpr explicit basic_simd_mask(value_type x) noexcept;
```

1 *Effects*: Constructs an object with each element initialized to `x`.

```
template<size_t UBytes, class UAbi>
  constexpr explicit basic_simd_mask(const basic_simd_mask<UBytes, UAbi>& x) noexcept;
```

2 *Constraints*: `simd_size_v<U, UAbi> == size()`.

3 *Effects*: Constructs an object of type `basic_simd_mask` where the i^{th} element equals `x[`i`]` for all i in the range of `[0, size())`.

```
template<class G> constexpr explicit basic_simd_mask(G&& gen) noexcept;
```

4 *Constraints*: `static_cast<bool>(gen(integral_constant<`*`simd-size-type`*`, i>()))` is well-formed for all i in the range of `[0, size())`.

5 *Effects*: Constructs an object where the i^{th} element is initialized to `gen(integral_constant<`*`simd-size-type`*`, i>())`.

6 The calls to `gen` are unsequenced with respect to each other. Vectorization-unsafe standard library functions may not be invoked by `gen` ([algorithms.parallel.exec]).

```
template<class It, class... Flags>
  constexpr basic_simd_mask(It first, simd_flags<Flags...> = {});
```

7 *Constraints*:

- `iter_value_t<It>` is of type `bool`, and
- `It` satisfies `contiguous_iterator`.

8 *Preconditions*:

- `[first, first + size())` is a valid range.
- `It` models `contiguous_iterator`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd_mask>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

9 *Effects*: Constructs an object where the i^{th} element is initialized to `first[`i`]` for all i in the range of `[0, size())`.

10 *Throws:* Nothing.

```
template<class It, class... Flags>
  constexpr basic_simd_mask(It first, const basic_simd_mask& mask, simd_flags<Flags...> = {});
```

11 *Constraints*:

- `iter_value_t<It>` is of type `bool`, and
- `It` satisfies `contiguous_iterator`.

12 *Preconditions*:

- For all selected indices i, `[first, first + `i`)` is a valid range.
- `It` models `contiguous_iterator`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd_mask>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

13 *Effects*: Constructs an object where the i^{th} element is initialized to `mask[`i`] ? first[`i`] : false` for all i in the range of `[0, size())`.

14 *Throws:* Nothing.

(7.1.8.3) 28.9.8.3 `basic_simd_mask` copy functions [simd.mask.copy]

```
template<class It, class... Flags>
  constexpr void copy_from(It first, simd_flags<Flags...> = {});
```

1 *Constraints*:

- `iter_value_t<It>` is of type `bool`, and
- `It` satisfies `contiguous_iterator`.

2 *Preconditions*:

- `[first, first + size())` is a valid range.
- `It` models `contiguous_iterator`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd_mask>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

3 *Effects*: Replaces the elements of the `basic_simd_mask` object such that the i^{th} element is replaced with `first[`i`]` for all i in the range of `[0, size())`.

4 *Throws:* Nothing.

```
template<class It, class... Flags>
  constexpr void copy_from(It first, const basic_simd_mask& mask, simd_flags<Flags...> = {});
```

5 *Constraints*:

- `iter_value_t<It>` is of type `bool`, and
- `It` satisfies `contiguous_iterator`.

6 *Preconditions*:

- For all selected indices i, `[first, first + `i`)` is a valid range.
- `It` models `contiguous_iterator`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd_mask>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

7 *Effects*: Replaces the selected elements of the `basic_simd_mask` object such that the i^{th} element is replaced with `first[`i`]` for all selected indices i.

8 *Throws:* Nothing.

```
template<class Out, class... Flags>
  constexpr void copy_to(Out first, simd_flags<Flags...> = {}) const;
```

9 *Constraints*:

- `iter_value_t<Out>` is of type `bool`, and

- `Out` satisfies `contiguous_iterator`, and
- `Out` satisfies `indirectly_writable<value_type>`.

10 *Preconditions*:

- `[first, first + size())` is a valid range.
- `Out` models `contiguous_iterator`.
- `Out` models `indirectly_writable<value_type>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd_mask>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

11 *Effects*: Copies all `basic_simd_mask` elements as if `first[`*i*`] = operator[](`*i*`)` for all i in the range of `[0, size())`.

12 *Throws:* Nothing.

```
template<class Out, class... Flags>
  constexpr void copy_to(Out first, const basic_simd_mask& mask, simd_flags<Flags...> = {}) const;
```

13 *Constraints*:

- `iter_value_t<Out>` is of type `bool`, and
- `Out` satisfies `contiguous_iterator`, and
- `Out` satisfies `indirectly_writable<value_type>`.

14 *Preconditions*:

- For all selected indices i, `[first, first + `*i*`)` is a valid range.
- `Out` models `contiguous_iterator`.
- `Out` models `indirectly_writable<value_type>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_aligned`, `addressof(*first)` shall point to storage aligned by `simd_alignment_v<basic_simd_mask>`.
- If the template parameter pack `Flags` contains the type identifying `simd_flag_overaligned<N>`, `addressof(*first)` shall point to storage aligned by `N`.

15 *Effects*: Copies the selected elements as if `first[`*i*`] = operator[](`*i*`)` for all selected indices i.

16 *Throws:* Nothing.

(7.1.8.4) 28.9.8.4 `basic_simd_mask` subscript operators [simd.mask.subscr]

```
constexpr reference operator[](simd-size-type i) &;
```

1 *Preconditions*: `i < size()`.

2 *Returns:* A `reference` (see 28.9.6.3) referring to the i^{th} element.

3 *Throws:* Nothing.

```
constexpr value_type operator[](simd-size-type i) const&;
```

4 *Preconditions*: `i < size()`.

5 *Returns:* The value of the i^{th} element.

6 *Throws:* Nothing.

(7.1.8.5) 28.9.8.5 `basic_simd_mask` unary operators [simd.mask.unary]

```
constexpr basic_simd_mask operator!() const noexcept;
```

1 *Returns:* The result of the element-wise application of `operator!`.

```
constexpr basic_simd<integer-from<Bytes>, Abi> operator+() const noexcept;
constexpr basic_simd<integer-from<Bytes>, Abi> operator-() const noexcept;
constexpr basic_simd<integer-from<Bytes>, Abi> operator~() const noexcept;
```

2 *Constraints*: Application of the indicated unary operator to objects of type `T` is well-formed.

3 *Returns:* The result of applying the indicated operator to `static_cast<simd_type>(*this)`.

(7.1.8.6) 28.9.8.6 `basic_simd_mask` conversion operators [simd.mask.conv]

```
template <class U, class A>
  constexpr explicit(sizeof(U) != Bytes) operator basic_simd<U, A>() const noexcept;
```

1 *Constraints*: `simd_size_v<U, A> == simd_size_v<T, Abi>`.

2 *Returns:* An object where the i^{th} element is initialized to `static_cast<U>(operator[](`i`))`.

(7.1.9) 28.9.9 Non-member operations [simd.mask.nonmembers]

(7.1.9.1) 28.9.9.1 `basic_simd_mask` binary operators [simd.mask.binary]

```
friend constexpr basic_simd_mask
  operator&&(const basic_simd_mask& lhs, const basic_simd_mask& rhs) noexcept;
friend constexpr basic_simd_mask
  operator||(const basic_simd_mask& lhs, const basic_simd_mask& rhs) noexcept;
friend constexpr basic_simd_mask
  operator& (const basic_simd_mask& lhs, const basic_simd_mask& rhs) noexcept;
friend constexpr basic_simd_mask
  operator| (const basic_simd_mask& lhs, const basic_simd_mask& rhs) noexcept;
friend constexpr basic_simd_mask
  operator^ (const basic_simd_mask& lhs, const basic_simd_mask& rhs) noexcept;
```

1 *Returns:* A `basic_simd_mask` object initialized with the results of applying the indicated operator to `lhs` and `rhs` as a binary element-wise operation.

(7.1.9.2) 28.9.9.2 `basic_simd_mask` compound assignment [simd.mask.cassign]

```
friend constexpr basic_simd_mask&
  operator&=(basic_simd_mask& lhs, const basic_simd_mask& rhs) noexcept;
friend constexpr basic_simd_mask&
  operator|=(basic_simd_mask& lhs, const basic_simd_mask& rhs) noexcept;
friend constexpr basic_simd_mask&
  operator^=(basic_simd_mask& lhs, const basic_simd_mask& rhs) noexcept;
```

1 *Effects*: These operators apply the indicated operator to `lhs` and `rhs` as a binary element-wise operation.

2 *Returns:* `lhs`.

(7.1.9.3) 28.9.9.3 `basic_simd_mask` comparisons [simd.mask.comparison]

```
friend constexpr basic_simd_mask
  operator==(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator!=(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator>=(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator<=(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator>(const basic_simd_mask&, const basic_simd_mask&) noexcept;
friend constexpr basic_simd_mask
  operator<(const basic_simd_mask&, const basic_simd_mask&) noexcept;
```

1 *Returns:* A `basic_simd_mask` object initialized with the results of applying the indicated operator to `lhs` and `rhs` as a binary element-wise operation.

(7.1.9.4) 28.9.9.4 `basic_simd_mask` conditional operators [simd.mask.cond]

```
friend constexpr basic_simd_mask simd-select-impl(
  const basic_simd_mask& mask, const basic_simd_mask& a, const basic_simd_mask& b) noexcept;
```

1 *Returns:* A `basic_simd_mask` object where the i^{th} element equals `mask[`i`] ? a[`i`] : b[`i`]` for all i in the range of `[0, size())`.

```
friend constexpr basic_simd_mask
simd-select-impl(const basic_simd_mask& mask, same_as<bool> auto a, same_as<bool> auto b) noexcept;
```

2 *Returns:* A `basic_simd_mask` object where the i^{th} element equals `mask[`i`] ? a : b` for all i in the range of `[0, size())`.

```
template <class T0, class T1>
  friend constexpr simd<see below, size()>
    simd-select-impl(const basic_simd_mask& mask, const T0& a, const T1& b) noexcept;
```

3 Let `U` be the common type of `T0` and `T1` without applying integral promotions on integral types with integer conversion rank less than the rank of `int`.

4 *Constraints*:

- `U` is a vectorizable type, and
- `sizeof(U) == Bytes`, and
- `T0` satisfies `convertible_to<simd<U, size()>>`, and
- `T1` satisfies `convertible_to<simd<U, size()>>`.

5 *Returns:* A `basic_simd<U, Abi>` object where the i^{th} element equals `mask[`i`] ? a : b` for all i in the range of `[0, size())`.

(7.1.9.5) 28.9.9.5 `basic_simd_mask` reductions [simd.mask.reductions]

```
template<size_t Bytes, class Abi>
  constexpr bool all_of(const basic_simd_mask<Bytes, Abi>& k) noexcept;
```

1 *Returns:* `true` if all boolean elements in `k` are `true`, `false` otherwise.

```
template<size_t Bytes, class Abi>
  constexpr bool any_of(const basic_simd_mask<Bytes, Abi>& k) noexcept;
```

2 *Returns:* `true` if at least one boolean element in `k` is `true`, `false` otherwise.

```
template<size_t Bytes, class Abi>
  constexpr bool none_of(const basic_simd_mask<Bytes, Abi>& k) noexcept;
```

3 *Returns:* `true` if none of the one boolean elements in `k` is `true`, `false` otherwise.

```
template<size_t Bytes, class Abi>
  constexpr simd-size-type reduce_count(const basic_simd_mask<Bytes, Abi>& k) noexcept;
```

4 *Returns:* The number of boolean elements in `k` that are `true`.

```
template<size_t Bytes, class Abi>
  constexpr simd-size-type reduce_min_index(const basic_simd_mask<Bytes, Abi>& k) noexcept;
```

5 *Returns:* If `none_of(k)` is `true`, `size()`, otherwise the lowest element index i where `k[`i`]` is `true`.

```
template<size_t Bytes, class Abi>
  constexpr simd-size-type reduce_max_index(const basic_simd_mask<Bytes, Abi>& k) noexcept;
```

6 *Returns:* If `none_of(k)` is `true`, `-1`, otherwise the greatest element index i where `k[`i`]` is `true`.

```
constexpr bool all_of(same_as<bool> auto) noexcept;
constexpr bool any_of(same_as<bool> auto) noexcept;
constexpr bool none_of(same_as<bool> auto) noexcept;
constexpr simd-size-type reduce_count(same_as<bool> auto x) noexcept;
constexpr simd-size-type reduce_min_index(same_as<bool> auto y) noexcept;
constexpr simd-size-type reduce_max_index(same_as<bool> auto z) noexcept;
```

7 *Returns:* `all_of` and `any_of` return their arguments; `none_of` returns the negation of its argument; `reduce_count` returns the integral representation of `x`; `reduce_min_index` returns the integral representation of `!y`; `reduce_max_index` returns `-!z`.

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