STANDARDIZATION

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.

CONTENTS

1 Changelog
   1.1 Changes from revision 0 ............................................ 1
   1.2 Changes from revision 1 ............................................ 2
   1.3 Changes from revision 2 ............................................ 2
   1.4 Changes from revision 3 ............................................ 3
   1.5 Changes from revision 4 ............................................ 4
   1.6 Changes from revision 5 ............................................ 4
   1.7 Changes from revision 6 ............................................ 5
   1.8 Changes from revision 7 ............................................ 6
2 Straw Polls
   2.1 SG1 at Kona 2022 .................................................... 6
   2.2 LEWG at Issaquah 2023 ............................................ 7
   2.3 LEWG at Varna 2023 ............................................ 9
3 Introduction
   3.1 Related papers ...................................................... 12
## Changes after TS feedback

### 4.1 Improve ABI tags

### 4.2 basic_simd_mask<sizeof, ABI>

### 4.3 Simplify/generalize casts

### 4.4 Add simd_mask generator constructor

### 4.5 Default load/store flags to element_aligned

### 4.6 Contiguous iterators for loads and stores

### 4.7 constexpr everything

### 4.8 Specify simd::size as integral_constant

### 4.9 Replace where facilities

### 4.10 Make use of int and size_t consistent

### 4.11 Add lvalue-qualifier to non-const subscript

### 4.12 Rename simd_mask reductions

### 4.13 Rename hmin and hmax

### 4.14 Added constraints on operators and functions to match their underlying element types

### 4.15 Rename alignment flags and extend load/store flags for opt-in to conversions

### 4.16 Reduce overloads and rename split and concat

### 4.17 Remove int exception from broadcast conversion rules

### 4.18 Remove long double from vectorizable types

### 4.19 Increase minimum supported width to 64

### 4.20 No std::hash<simd>

### 4.21 No freestanding SIMD

## Open questions / Outlook

### 5.1 Correct place for simd in the IS?

### 5.2 element_reference is overspecified

### 5.3 Implementation hints

### 5.4 Clean up math function overloads

### 5.5 Integration with ranges

### 5.6 Formatting support

## Changes after LEWG approval (for LEWG)

### 6.1 simd_select overload set

### 6.2 Tighten simd_split specification

### 6.3 Reconsider precondition on mask reductions

## Wording: Add Section 9 of N4808 with modifications

### 28.9 Data-Parallel Types [simd] (7.1.0)

## Acknowledgments
B Bibliography

Contents

60
1 CHANGEOLOG

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 $\texttt{simd\_abi::fixed\_size}$.
- Remove $\texttt{ simd\_abi::compatible}$.
- Add (but ask for removal) $\texttt{simd\_abi::abi\_stable}$.
- 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 $\texttt{simd\_mask}$ 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 $\texttt{element\_aligned}$.
- Generalize casts: conditionally $\texttt{explicit}$ 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 ([simd.unary], [simd.binary]).
• 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 ([simd ctor], [simd copy], [simd mask ctor], [simd mask copy]).
• Respecify basic_simd reductions to use a basic_simd_mask argument instead of const_...where_expression ([simd reductions]).
• Add basic_simd_mask operators returning a basic_simd ([simd mask unary], [simd mask conv])
• Add conditional operator overloads as hidden friends to basic_simd and basic_simd_mask ([simd cond], [simd mask cond]).
• Discuss std::hash for basic_simd (Section 4.20).
• Constrain some functions (e.g., min, max, clamp) to be totally_ordered ([simd reductions], [simd alg]).
• 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 ([simd ctor]).
• Add relational operators to basic_simd_mask as directed by LEWG ([simd.mask.comparison]).
• 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 ([simd.reductions]).
1.8 CHANGES FROM REVISION 7

Previous revision: P1928R7

- Include `std::optional` return value from `reduce_min_index` and `reduce_max_index` in the exploration.
- Fix \LaTeX markup errors.
- Remove repetitive mention of “exposition-only” before `deduce-t`.
- Replace “TU” with “translation unit”.
- Reorder first paragraphs in the wording, especially reducing the note on compiling down to SIMD instructions.
- Replace cv-unqualified arithmetic types with a more precise list of types.
- Move the place where “supported” is defined.

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)

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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.)

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
2.2 **LEWG at Issaquah 2023**

Poll: Change the default SIMD ABI tag to `simd::abi::native` instead of `simd::abi::compatible`.

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>8</td>
<td>7</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Option</th>
<th>Votes</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>where(u &gt; 0, v).copy_from(ptr)</code></td>
<td>12</td>
</tr>
<tr>
<td><code>v.copy_from_if(u &gt; 0, ptr)</code></td>
<td>1</td>
</tr>
<tr>
<td><code>v.copy_from_if(ptr, u &gt; 0)</code></td>
<td>2</td>
</tr>
<tr>
<td><code>v.copy_from(ptr, u &gt; 0)</code></td>
<td>14</td>
</tr>
<tr>
<td><code>v.copy_from(u &gt; 0, ptr)</code></td>
<td>3</td>
</tr>
<tr>
<td><code>v.copy_from_where(u &gt; 0, ptr)</code></td>
<td>4</td>
</tr>
<tr>
<td><code>v.copy_from_where(ptr, u &gt; 0)</code></td>
<td>11</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Option</th>
<th>Votes</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>where(u &gt; 0, v).copy_from(ptr)</code></td>
<td>5</td>
</tr>
<tr>
<td><code>v.copy_from(ptr, u &gt; 0)</code></td>
<td>12</td>
</tr>
<tr>
<td><code>v.copy_from_where(ptr, u &gt; 0)</code></td>
<td>6</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>9</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>10</td>
<td>6</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>
Poll: 2 * simd<float> should produce simd<double> (status quo: simd<float>).

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>5</td>
<td>9</td>
<td>6</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>9</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>7</td>
<td>0</td>
<td>5</td>
</tr>
</tbody>
</table>

Poll: simd should be a range.

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>9</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>12</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>8</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

Poll: Rename popcount to reduce_count.

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>9</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Poll: Rename find_first_set/find_last_set to reduce_min_index/reduce_max_index.

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>7</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>
2.3 lewg at varna 2023

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

<table>
<thead>
<tr>
<th>Option</th>
<th>Votes</th>
</tr>
</thead>
<tbody>
<tr>
<td>conditional_operator</td>
<td>10</td>
</tr>
<tr>
<td>ternary</td>
<td>12</td>
</tr>
<tr>
<td>inline_if</td>
<td>0</td>
</tr>
<tr>
<td>iif</td>
<td>1</td>
</tr>
<tr>
<td>blend</td>
<td>2</td>
</tr>
<tr>
<td>select</td>
<td>14</td>
</tr>
<tr>
<td>choose</td>
<td>4</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Option</th>
<th>Votes</th>
</tr>
</thead>
<tbody>
<tr>
<td>conditional_operator</td>
<td>2</td>
</tr>
<tr>
<td>ternary</td>
<td>8</td>
</tr>
<tr>
<td>select</td>
<td>10</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>0</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>9</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>8</td>
<td>9</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
The conditional operator facility should be called (vote once for your favorite):

<table>
<thead>
<tr>
<th>Option</th>
<th>Votes</th>
</tr>
</thead>
<tbody>
<tr>
<td>simd_ternary</td>
<td>4</td>
</tr>
<tr>
<td>simd_bland</td>
<td>6</td>
</tr>
<tr>
<td>simd_select</td>
<td>12</td>
</tr>
<tr>
<td>simd_choose</td>
<td>0</td>
</tr>
</tbody>
</table>

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>>

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>11</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

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).

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>9</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Poll: Rename split to simd_split and concat to simd_cat.

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>11</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
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
```

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
```

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
```

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

```
SF | F | N | A | SA
---|---|---|---|---
   | 1 | 9 | 3 | 2
```

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
```

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

```
SF | F | N | A | SA
---|---|---|---|---
   | 12| 3 | 1 | 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
```
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. \texttt{simd<T0, A0>} is implicitly convertible to \texttt{simd<T1, A1>} if, additionally,
   - the conversion \texttt{T0} to \texttt{T1} is value-preserving, and
   - if both \texttt{T0} and \texttt{T1} are integral types, the integer conversion rank of \texttt{T1} is greater than or equal to the integer conversion rank of \texttt{T0}, and
   - if both \texttt{T0} and \texttt{T1} are floating-point types, the floating-point conversion rank of \texttt{T1} is greater than or equal to the floating-point conversion rank of \texttt{T0}.

3. \texttt{simd\_mask<T0, A0>} is convertible to \texttt{simd\_mask<T1, A1>} if \texttt{simd\_size\_v<T0, A0> == simd\_size\_v<T1, A1>}.

4. \texttt{simd\_mask<T0, A0>} is implicitly convertible to \texttt{simd\_mask<T1, A1>} if, additionally, \texttt{sizeof(T0) == sizeof(T1)}. (This point is irrelevant if Section 4.2 is accepted.)

5. \texttt{simd<T0, A0>} can be bit\_casted to \texttt{simd<T1, A1>} if \texttt{sizeof(simd<T0, A0>) == sizeof(simd<T1, A1>)}.

6. \texttt{simd\_mask<T0, A0>} can be bit\_casted to \texttt{simd\_mask<T1, A1>} if \texttt{sizeof(simd\_mask<T0, A0>) == sizeof(simd\_mask<T1, A1>)}.

### 4.4 Add \texttt{simd\_mask} generator constructor

This constructor was added:

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

For a discussion, see P1928R3 Section 4.3.

### 4.5 Default load/store flags to \texttt{element\_aligned}

Different to the TS, load/store flags default to \texttt{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 \texttt{contiguous\_iterator} instead of pointers. For a discussion, see P1928R3 Section 4.5.

### 4.7 \texttt{constexpr} everything

The merge adds \texttt{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 re-
placed 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
Changes after TS feedback

- `basic_simd_mask simd-select-impl(const basic_simd_mask& bool, bool) noexcept`
- `simd<const 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 Changes after TS feedback

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.

<table>
<thead>
<tr>
<th>TS</th>
<th>P1928R8</th>
</tr>
</thead>
<tbody>
<tr>
<td>std::experimental::element_aligned</td>
<td>std:: simd_flag_default</td>
</tr>
<tr>
<td>std::experimental::vector_aligned</td>
<td>std:: simd_flag_aligned</td>
</tr>
<tr>
<td>std::experimental::overaligned&lt;N&gt;</td>
<td>std:: simd_flag_overaligned&lt;N&gt;</td>
</tr>
<tr>
<td>implicit</td>
<td>std:: simd_flag_convert</td>
</tr>
</tbody>
</table>

Table 1: Load/store flag changes

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.

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

TS

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

P1928R8

```cpp
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.

¹ same as simd<float, 4>.
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.

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
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?

TODO: LWG prefers to append "Data-parallel types" to the "Numerics library".

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)

**TODO:** Left completely to QoI. No new note.

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).

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.

---

\(^2\) The exception may be soft-float?
6 Changes after LEWG approval (for LEWG)

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`:

```cpp
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:

```cpp
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:

```cpp
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

```cpp
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 what you don’t use” guideline, the precondition should be restored. Or:

6.3.2 ALTERNATIVE 1

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.  

6.3.3 ALTERNATIVE 2

The functions could also return `std::optional<simd-size-type>`. Exploration results using GCC 13 below. The current state of how GCC optimizes the `std::optional` case is really good, but still more expensive on average than the solution returning an unspecified value. Note the `unspecified_value_nocheck` solution which optimizes even further by dropping the compare instruction, reducing execution latency even more. (This is valid because `vmovmskps` extracts the sign bits into the `eax` register.)

---

3 I guess Contracts would only trigger for a real precondition, a.k.a. UB?
Personally, I’m also bothered by the “out of place” need to call `.value()` or add a `*`. This introduces an inconsistency in how a very similar set of functions needs to be used.

Considering the typical use (that the code branches before calling `reduce_min_index`) and our ability to avoid UB I recommend to return any unspecified value if `none_of(mask)`.

```cpp
int unspecified_value(std::simd<int> x)
{
    if (any_of(x < 0))
        return reduce_min_index(x < 0);
    return -1;
}

int unspecified_value_nocheck(std::simd<int> x)
{
    x[1] = -1;
    return reduce_min_index(x < 0);
}

int opt1(std::simd<int> x)
{
    if (any_of(x < 0))
        return reduce_min_index_opt(x < 0).value();
    return -1;
}
```
opt1(std::basic_simd<int, std::experimental::parallelism_v2::simd_abi::_VecBuiltIn<32>>):
  vmovdqa ymm1, ymm0
  vpxor xmm0, xmm0, xmm0
  vpcmpgt d ymm0, ymm0, ymm1
  vptest ymm0, ymm0
  je .L13
  vmovmskps eax, ymm0
  tzcnt eax, eax
  ret

.L13:
  mov eax, -1
  ret

int opt2(std::simd<int> x)
{
  auto opt = reduce_min_index_opt(x < 0);
  return opt.value_or(-1);
}

opt2(std::basic_simd<int, std::experimental::parallelism_v2::simd_abi::_VecBuiltIn<32>>):
  vmovdqa ymm1, ymm0
  vpxor xmm0, xmm0, xmm0
  xor edx, edx
  vpcmpgt d ymm0, ymm0, ymm1
  vptest ymm0, ymm0
  vmovmskps eax, ymm0
  sete dl
  tzcnt eax, eax
  test edx, edx
  mov edx, -1
  cmovne eax, edx
  ret

int opt_nocheck(std::simd<int> x)
{
  x[1] = -1;
  return reduce_min_index_opt(x < 0).value();
}

opt_nocheck(std::basic_simd<int, std::experimental::parallelism_v2::simd_abi::_VecBuiltIn<32>>):
  mov eax, -1
  vpinsrd xmm1, xmm0, eax, 1
  vinserti128 ymm0, ymm0, xmm1, 0x0
  vpxor xmm1, xmm1, xmm1

---------------------------------------------
6.3.4 SUGGESTED POLLS

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
</table>

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

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
</table>

Poll: Return `std::optional<simd-size-type>` from `reduce_min_index` and `reduce_max_index`.

<table>
<thead>
<tr>
<th>SF</th>
<th>F</th>
<th>N</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
</table>

7 WORDING: ADD SECTION 9 OF N4808 WITH MODIFICATIONS

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

```cpp
#define __cpp_lib_simd YYYYMM
// also in <simd>
```

Adjust the placeholder value as needed so as to denote this proposal’s date of adoption.
(7.1) 28.9 Data-Parallel Types

(7.1.1) 28.9.1 General

1. The simd subclause defines data-parallel types and operations on these types. [Note: The intent is to support acceleration through data-parallel execution resources where available, such as SIMD registers and instructions or execution units driven by a common instruction decoder. —end note]

2. A data-parallel type consists of one or more 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. The sequence of elements contained in a data-parallel-type

3. The term data-parallel type refers to all supported ([simd.overview]) specializations of the basic_simd and basic simd_mask class templates. A data-parallel object is an object of data-parallel type.

4. The set of vectorizable types comprises all standard integer types, character types, and the types float and double ([basic.fundamental]). In addition, if __STDCPP_FLOAT16_T__ is defined, std::float16_t is a vectorizable type; if __STDCPP_FLOAT32_T__ is defined, std::float32_t is a vectorizable type; if __STDCPP_FLOAT64_T__ is defined, std::float64_t is a vectorizable type ([basic.extended.fp]).

5. 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.

6. Given a basic_simd_mask<Bytes, Abi> object mask, the selected indices signify the integers \(i \in \{j \in \mathbb{N}_0 | j < \text{mask.size()} \land \text{mask}[j]\}\). 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 \(i\).

7. The conversion from vectorizable type \(U\) to vectorizable type \(T\) is value-preserving if all possible values of \(U\) can be represented with type \(T\).

(7.1.2) 28.9.2 Header <simd> synopsis

```cpp
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;

  // [simd.abi], 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
}
```
// [simd.traits], 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;

// [simd.flags], Load and store flags
template <class... Flags> struct simd_flags;
inline constexpr simd_flags<> simd_flag_default{};
inline constexpr simd_flags<> simd_flag_convert{};
inline constexpr simd_flags<> simd_flag_aligned{};
template<simd-size-type N> requires (has_single_bit(N))
    inline constexpr simd_flags<> simd_flag_overaligned{};

// [simd.class], 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>>;

// [simd.mask.class], 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>>;

// [simd.creation], 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 basic_simd_mask<Bs, deduce-t<integer-from<Bs>>,
        (basic_simd_mask<Bs, Abis>::size() + ...)>>
        simd_cat(const basic_simd_mask<Bs, Abis>&...) noexcept;

// [simd.mask.reductions], 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 ;

// [simd.reductions], basic_simd reductions
template<class T, class Abi, class BinaryOperation = plus<>>
    constexpr T reduce (const basic_simd<T, Abi>&) noexcept ;
template<class T, class Abi, class BinaryOperation>
    constexpr T reduce (const basic_simd<T, Abi>& x, BinaryOperation = { }) noexcept ;
template<class T, class Abi, class BinaryOperation>
    constexpr T reduce (const basic_simd<T, Abi>& x, BinaryOperation binary_op) noexcept ;
template<class T, class Abi, class BinaryOperation>
    constexpr T reduce (const basic_simd<T, Abi>& x, BinaryOperation binary_op = {}) noexcept ;

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

// [simd.alg]. 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

template<class T> using native-abi = see below; // exposition only

template<class T, simd-size-type 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 [simd.overview]). 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 \texttt{deduce-t\langle T, N\rangle} 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, \texttt{deduce-t\langle T, N\rangle} names an ABI tag type that satisfies

- \texttt{basic_simd\langle T, deduce-t\langle T, N\rangle\rangle::size == N}, and
- \texttt{basic_simd\langle T, deduce-t\langle T, N\rangle\rangle} is default constructible (see \cite{simd.overview}).

6 \texttt{native-abi\langle T\rangle} is an implementation-defined alias for an ABI tag. \textit{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 \texttt{native-abi\langle T\rangle} alias. \textit{— end note}\] [\textit{Example:} Consider a target architecture supporting the ABI tags \texttt{__simd128} and \texttt{__simd256}, where hardware support for \texttt{__simd256} only exists for floating-point types. The implementation therefore defines \texttt{native-abi\langle T\rangle} as an alias for

- \texttt{__simd256} if \( T \) is a floating-point type, and
- \texttt{__simd128} otherwise. \textit{— end example}\]

7 The type of \texttt{deduce-t\langle T, N\rangle} in translation unit 1 differs from the type of \texttt{deduce-t\langle T, N\rangle} in translation unit 2 iff the type of \texttt{native-abi\langle T\rangle} in translation unit 1 differs from the type of \texttt{native-abi\langle T\rangle} in translation unit 2.

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

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

// 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.

1 If value is present, the type simd_alignment\langle T, U\rangle is a BinaryTypeTrait with a base characteristic of integral_constant\langle size_t, N\rangle for some implementation-defined \( N \) (see \cite{simd.copy} and \cite{simd.mask.copy}). [\textit{Note:} value identifies the alignment restrictions on pointers used for (converting) loads and stores for the give type \( T \) on arrays of type \( U \). \textit{— 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\langle U, Abi0\rangle or basic_simd_mask\langle UBytes, Abi0\rangle, where \( U, UBytes, \) and \( Abi0 \) are deduced from \( V \), and
- \( T \) is a vectorizable type, and
- simd_abi::deduce\langle T, basic_simd\langle U, Abi0\rangle::size, Abi0\rangle has a member type type.
\end{verbatim}
Let \( \text{Abi1} \) denote the type \( \text{deduce_t<T, basic\_simd<U, \text{Abi0}}>::\text{size, Abi0}} \). 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<Bytes, Abi0>.

```cpp
template<\text{simd\_size\_type} N, \text{class} V> \text{struct resize\_simd} \{ \text{using type = see below; } \};
```

The member type is present if and only if

1. \( V \) is either basic\_simd<T, Abi0> or basic\_simd\_mask<Bytes, Abi0>, where \( T, \text{Bytes, and Abi0} \) are deduced from \( V \), and
2. \( \text{simd\_abi}\_\text{\_deduce<T, N, Abi0}} \) has a member typedef type.

Let \( \text{Abi1} \) denote the type \( \text{deduce_t<T, N, Abi0}} \). 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

```cpp
\text{inline constexpr simd\_flags<see below> simd\_flag\_convert{}; }
\text{inline constexpr simd\_flags<see below> simd\_flag\_aligned{}; }
\text{template<size_t N> requires (has\_single\_bit(N))}
\text{inline constexpr simd\_flags<see below> simd\_flag\_overaligned{}; }
```

1. The template arguments to \( \text{simd\_flags} \) 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 \( \text{simd\_flags} \) overview

```cpp
\text{template <class... Flags> \text{struct simd\_flags} \{ }
\text{// [simd\_flags\_oper], simd\_flags\_operators}
\text{template <class... Other> }
\text{friend constexpr auto operator|(simd\_flags a, simd\_flags<Other...> b); }
```

1. The class template \( \text{simd\_flags} \) acts like a integer bit-flag for types.
2. Constraints: Every type in Flags is a valid template argument to one of \( \text{simd\_flag\_convert}, \text{simd\_flag\_aligned}, \text{simd\_flag\_overaligned} \), or to one of the implementation-defined load and store flags.

(7.1.5.2) 28.9.5.2 simd\_flags operators

```cpp
\text{template <class... Other> }
\text{friend constexpr auto operator|(simd\_flags a, simd\_flags<Other...> b); }
```

1. Returns: A specialization of \( \text{simd\_flags} \) identifying all load and store flags identified either by \( a \) or \( b \).
7.1.6.1 Class template basic_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;

  // [simd ctor], basic_simd constructors
  template<class U> constexpr basic_simd(U& value) noexcept
    : 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...> = {});

  // [simd copy], basic_simd 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 mask_type & 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 mask_type & mask, simd_flags<Flags...> = {} const);

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

  // [simd unary], 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;

// [simd.binary], 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;

// [simd.cassign], 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;

// [simd.comparison], 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;

// [simd.cond], basic_simd conditional operators
friend constexpr basic_simd simd-select-impl(
    const mask_type &, const basic_simd &, const basic_simd &) noexcept;

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.

TODO: basic_simd is not a data-parallel type. Only its supported specializations are.
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 [simd.abi].

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]

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]

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

```cpp
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:

```cpp
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]
size is an integral_constant<@simd-size-type@>, \( N \) with \( N \) equal to the number of elements in a basicsimd object.

[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

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.

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

```cpp
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;

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

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

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;

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

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

Returns: A copy of `*this`.

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

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

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

Returns: A copy of `*this`.

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

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

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

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;

Effects: Exchanges the values `a` and `b` refer to.
template<class U> constexpr basic_simd(U&&) noexcept;

Let From denote the type remove_cvref_t<U>.

Constraints: From satisfies convertible_to<value_type>, and either

- From satisfies constexpr-unsafe ([simd.syn]) 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 ([simd.general]), or
- From is not an arithmetic type and does not satisfy constexpr-unsafe.

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;

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

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

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;

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

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

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...> = {});

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

Preconditions:
- \([\text{first}, \text{first} + \text{size())}]\) 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.

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, \text{size())}].

Throws: Nothing.

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

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

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.

Preconditions:
- For all selected indices \(i\), \([\text{first}, \text{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.

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, \text{size())}].

Throws: Nothing.

(7.1.6.5) 28.9.6.5 basic_simd copy functions

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

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

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.

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

Throws: Nothing.

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

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

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.

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.

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

Throws: Nothing.

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

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

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.

Preconditions:
- \([\text{first, first} + \text{size()}]\) is a valid range.
- \text{Out} models contiguous\_iterator.
- \text{Out} models indirectly\_writable<value\_type>.
- If the template parameter pack \text{Flags} contains the type identifying \text{simd\_flag\_aligned}, \text{addressof(*first)} shall point to storage aligned by \text{simd\_alignment\_v<basic\_simd, iter\_value\_t<Out>}}.
- If the template parameter pack \text{Flags} contains the type identifying \text{simd\_flag\_overaligned<N>}, \text{addressof(*first)} shall point to storage aligned by \(N\).

\text{Effects}: Copies all basic\_simd elements as if \text{first}[i] = static\_cast<iter\_value\_t<Out>>(\operator[](i)) for all \(i\) in the range of \([0, \text{size()}]\).

\text{Throws}: Nothing.

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

\text{Constraints}:
- \text{iter\_value\_t<Out>} is a vectorizable type, and
- \text{Out} satisfies contiguous\_iterator, and
- \text{Out} satisfies indirectly\_writable<value\_type>.

\text{Mandates}: If the template parameter pack \text{Flags} does not contain the type identifying \text{simd\_flag\_convert}, then the conversion from value\_type to iter\_value\_t<Out> is value\_preserving.

\text{Preconditions}:
- For all selected indices \(i\), \([\text{first, first} + i]\) is a valid range.
- \text{Out} models contiguous\_iterator.
- \text{Out} models indirectly\_writable<value\_type>.
- If the template parameter pack \text{Flags} contains the type identifying \text{simd\_flag\_aligned}, \text{addressof(*first)} shall point to storage aligned by \text{simd\_alignment\_v<basic\_simd, iter\_value\_t<Out>}}.
- If the template parameter pack \text{Flags} contains the type identifying \text{simd\_flag\_overaligned<N>}, \text{addressof(*first)} shall point to storage aligned by \(N\).

\text{Effects}: Copies the selected elements as if \text{first}[i] = static\_cast<iter\_value\_t<Out>>(\operator[](i)) for all selected indices \(i\).

\text{Throws}: Nothing.

\text{(7.1.6.6) 28.9.6.6 basic\_simd subscript operators}

\begin{verbatim}
    constexpr reference operator[](simd\_size\_type i) &;
\end{verbatim}

\text{Preconditions}: \(i < \text{size()}\).

\text{Returns}: A reference (see [simd.reference]) referring to the \(i\)th element.

\text{Throws}: Nothing.

\begin{verbatim}
    constexpr value\_type operator[](simd\_size\_type i) const&;
\end{verbatim}
Preconditions: \( i < \text{size()} \).

Returns: The value of the \( i \)th element.

Throws: Nothing.

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

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

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

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

Effects: Increments every element by one.

Returns: *this.

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

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

Effects: Increments every element by one.

Returns: A copy of *this before incrementing.

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

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

Effects: Decrements every element by one.

Returns: *this.

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

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

Effects: Decrements every element by one.

Returns: A copy of *this before decrementing.

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

Constraints: Application of unary \(!\) to objects of type value_type is well-formed.

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

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

Constraints: Application of unary \(~\) to objects of type value_type is well-formed.

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

```cpp
constexpr basic_simd operator+() const noexcept;
```
Constraints: Application of unary + to objects of type value_type is well-formed.

Returns: *this.

constexpr basic_simd operator-() const noexcept;

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

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

(7.1.7) 28.9.7 basic_simd non-member operations

(7.1.7.1) 28.9.7.1 basic_simd binary operators

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

Returns: A basic_simd object initialized with the results of applying the indicated operator to \( \text{lhs} \) and \( \text{rhs} \) as a binary element-wise operation.

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

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

(7.1.7.2) 28.9.7.2 basic_simd compound assignment

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

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

Constraints: Application of the indicated operator to objects of type value_type is well-formed.
Effects: These operators apply the indicated operator to lhs and rhs as an element-wise operation.
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 ;

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

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

Constraints: Application of the indicated operator to objects of type value_type is well-formed.
Returns: A basic_simd_mask object where the ith 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]

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 = {});
Constraints: BinaryOperation satisfies invocable<simd<T>, 1>, simd<T, 1>>.

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.

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

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, 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 ;

Constraints: is_integral_v<T> is true.

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 ;

Constraints: T satisfies totally_ordered.

Preconditions: T models totally_ordered.

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 ;

Constraints: T satisfies totally_ordered.

Preconditions: T models totally_ordered.

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 ;

Constraints: T satisfies totally_ordered.

Preconditions: T models totally_ordered.

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_max(
    const basic_simd<T, Abi>&, const typename basic_simd<T, Abi>::mask_type&) noexcept ;

Constraints: T satisfies totally_ordered.

Preconditions: T models totally_ordered.

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

Constraints:
• For the first overload T is a specialization of basic_simd.
• For the second overload T is a specialization of basic_simd_mask.

Let \( N \) be \( x.\text{size()} / V.\text{size()} \).

Returns:
• If \( x.\text{size()} \% V.\text{size()} == 0 \), an array of \( N \) objects of type \( T \) 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 \( i + j \times V.\text{size()} \).
• Otherwise, a tuple of \( N \) objects of type \( T \) and one object of type \( \text{resize_simd_t}<x.\text{size()} \% V.\text{size()}, T> \). 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 \( i + j \times V.\text{size()} \). The \( i \)-th basic_simd or basic_simd_mask element of the \( N \)-th tuple element is initialized to the value of the element in \( x \) with index \( i + N \times V.\text{size()} \).

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;

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 \( i + \text{the sum of the width of the first } j \text{ parameters in the } xs \text{ pack} \).

(7.1.7.7) 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;

Constraints: \( T \) satisfies totally_ordered.

Preconditions: \( T \) models totally_ordered.

Returns: The result of the element-wise application of \( \text{std::min}(a[i], b[i]) \) for all \( i \) in the range of \( [0, \text{size()}()] \).

template<class T, class Abi>
constexpr basic_simd<T, Abi> max(const basic_simd<T, Abi>& a, const basic_simd<T, Abi>& b) noexcept;
Constraints: T satisfies totally_ordered.

Preconditions: T models totally_ordered.

Returns: The result of the element-wise application of std::max(a[i], b[i]) for all i in the range of \([0, \text{size}())\).

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;

Constraints: T satisfies totally_ordered.

Preconditions: T models totally_ordered.

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 \([0, \text{size}())\) 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 \([0, \text{size}())\) 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);

Constraints: T satisfies totally_ordered.

Preconditions: T models totally_ordered.

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

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

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

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));

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

(7.1.7.8) 28.9.7.8 basic_simd math library

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.
// [simd.mask.copy], 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;

// [simd.mask.subscr], basic_simd_mask subscript operators
constexpr reference operator[](simd-size-type) &;
constexpr value_type operator[](simd-size-type) const&;

// [simd.mask.unary], 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;

// [simd.mask.conv], basic_simd_mask conversion operators
template <class U, class A>
  constexpr explicit(sizeof(U) != Bytes) operator basic_simd<U, A>() const noexcept;

// [simd.mask.binary], 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;

// [simd.mask.cassign], 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;

// [simd.mask.comparison], 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 ;

// [simd.mask.cond], 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 ([simd.abi]).

   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);
The member type reference has the same interface as basic_simd<T, Abi>::reference, except its value_type is bool. ([simd.reference])

(7.1.8.2) **28.9.8.2 basic_simd_mask constructors**

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

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

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

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

**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())`.

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

**Constraints:**

- `static_cast<bool>(gen(integral_constant< simd-size-type, i>())` is well-formed for all `i` in the range of `[0, size())`.
- Constructs an object where the `i`th element is initialized to `gen(integral_constant< simd-size-type, i>())`.
- 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]).

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

**Constraints:**

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

**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`.

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

**Throws:** Nothing.

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

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

Preconditions:

- For all selected indices $i$, $[\text{first}, \text{first} + i)$ is a valid range.
- It models contiguous_iterator.
- If the template parameter pack Flags contains the type identifying simd_flag_aligned, addressof($*\text{first}$) 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($*\text{first}$) shall point to storage aligned by N.

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()).

Throws: Nothing.

(7.1.8.3) 28.9.8.3 basic_simd_mask copy functions

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

Constraints:

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

Preconditions:

- $[\text{first}, \text{first} + \text{size}())$ is a valid range.
- It models contiguous_iterator.
- If the template parameter pack Flags contains the type identifying simd_flag_aligned, addressof($*\text{first}$) 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($*\text{first}$) shall point to storage aligned by N.

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()).

Throws: Nothing.

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

Constraints:

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

Preconditions:

- For all selected indices $i$, $[\text{first}, \text{first} + i)$ is a valid range.
It models contiguous_iterator.

If the template parameter pack Flags contains the type identifying simd_flagAligned, 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_flagOveraligned<N>, addressof(*first) shall point to storage aligned by N.

**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.

**Throws:** Nothing.

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

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

**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_flagAligned, 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_flagOveraligned<N>, addressof(*first) shall point to storage aligned by N.

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

**Throws:** Nothing.

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

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

**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_flagAligned, 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.

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

**Throws:** Nothing.

### 28.9.8.4 basic_simd_mask subscript operators

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

1. **Preconditions:** i < size().
2. **Returns:** A reference (see [simd.reference]) referring to the i
3. **Throws:** Nothing.

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

4. **Preconditions:** i < size().
5. **Returns:** The value of the i
6. **Throws:** Nothing.

### 28.9.8.5 basic_simd_mask unary operators

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

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

```cpp
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).

### 28.9.8.6 basic_simd_mask conversion operators

```cpp
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
3. **element is initialized to static_cast<U>(operator[](i)).

### 28.9.9 Non-member operations

### 28.9.9.1 basic_simd_mask binary operators
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;

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;

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

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;

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;

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

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

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

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;

    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.

    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()>>.

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

    (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;

    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;

    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;

    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;
Returns: The number of boolean elements in \( k \) that are true.

\[
\text{template<\text{size}_t \text{Bytes}, \text{class } \text{Abi}>}
\]
\[
\text{constexpr simd-size-type reduce_min_index(const basic_simd_mask<\text{Bytes}, \text{Abi}>& \text{k}) noexcept ;}
\]

Returns: If \( \text{none_of} (\text{k}) \) is true, size(), otherwise the lowest element index \( i \) where \( \text{k}[i] \) is true.

\[
\text{template<\text{size}_t \text{Bytes}, \text{class } \text{Abi}>}
\]
\[
\text{constexpr simd-size-type reduce_max_index(const basic_simd_mask<\text{Bytes}, \text{Abi}>& \text{k}) noexcept ;}
\]

Returns: If \( \text{none_of} (\text{k}) \) is true, -1, otherwise the greatest element index \( i \) where \( \text{k}[i] \) is true.

\[
\text{constexpr bool all_of (same_as <bool> auto) noexcept ;}
\]
\[
\text{constexpr bool any_of (same_as <bool> auto) noexcept ;}
\]
\[
\text{constexpr bool none_of (same_as <bool> auto) noexcept ;}
\]
\[
\text{constexpr simd-size-type reduce_count(same_as <bool> auto x) noexcept ;}
\]
\[
\text{constexpr simd-size-type reduce_min_index(same_as <bool> auto y) noexcept ;}
\]
\[
\text{constexpr simd-size-type reduce_max_index(same_as <bool> auto z) noexcept ;}
\]

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 \( \neg y \); reduce_max_index returns \( -\neg z \).

---

A

ACKNOWLEDGMENTS

Thanks to Daniel Towner, Ruslan Arutyunyan, Jonathan Müller, Jeff Garland, and Nicolas Morales for discussions and/or pull requests on this/previous paper(s).

B

BIBLIOGRAPHY


