New Iterator Concepts

Author: David Abrahams, Jeremy Siek, Thomas Witt
Contact: dave@boost-consulting.com, jsiek@osl.iu.edu, witt@styleadvisor.com
Organization: Boost Consulting, Indiana University Open Systems Lab, Zephyr Associates, Inc.
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Abstract: We propose a new system of iterator concepts that treat access and positioning independently. This allows the concepts to more closely match the requirements of algorithms and provides better categorizations of iterators that are used in practice.

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Motivation

The standard iterator categories and requirements are flawed because they use a single hierarchy of concepts to address two orthogonal issues: *iterator traversal* and *value access*. As a result, many algorithms with requirements expressed in terms of the iterator categories are too strict. Also, many real-world iterators can not be accurately categorized. A proxy-based iterator with random-access traversal, for example, may only legally have a category of "input iterator", so generic algorithms are unable to take advantage of its random-access capabilities. The current iterator concept hierarchy is geared towards iterator traversal (hence the category names), while requirements that address value access sneak in at various places. The following table gives a summary of the current value access requirements in the iterator categories.

Value Access Requirements in Existing Iterator Categories	
Output Iterator	`*i = a`
Input Iterator	`*i` is convertible to `T`
Forward Iterator	`*i` is `T&` (or `const T&` once issue 200 is resolved)
Random Access Iterator	`i[n]` is convertible to `T` (also `i[n] = t` is required for mutable iterators once issue 299 is resolved)

Because iterator traversal and value access are mixed together in a single hierarchy, many useful iterators can not be appropriately categorized. For example, `vector<bool>::iterator` is almost a random access iterator, but the return type is not `bool&` (see issue 96 and Herb Sutter's paper J16/99-0008 = WG21 N1185). Therefore, the iterators of `vector<bool>` only meet the requirements of input iterator and output iterator. This is so nonintuitive that the C++ standard contradicts itself on this point. In paragraph 23.2.4/1 it says that a `vector` is a sequence that supports random access iterators.

Another difficult-to-categorize iterator is the transform iterator, an adaptor which applies a unary function object to the dereferenced value of the some underlying iterator (see transform_iterator). For unary functions such as `times`, the return type of `operator*` clearly needs to be the `result_type` of the function object, which is typically not a reference. Because random access iterators are required to return lvalues from `operator*`, if you wrap `int*` with a transform iterator, you do not get a random access iterator as might be expected, but an input iterator.

A third example is found in the vertex and edge iterators of the Boost Graph Library. These iterators return vertex and edge descriptors, which are lightweight handles created on-the-fly. They must be returned by-value. As a result, their current standard iterator category is `input_iterator_tag`, which means that, strictly speaking, you could not use these iterators with algorithms like `min_element()`. As a temporary solution, the concept Multi-Pass Input Iterator was introduced to describe the vertex and edge descriptors, but as the design notes for the concept suggest, a better solution is needed.

In short, there are many useful iterators that do not fit into the current standard iterator categories. As a result, the following bad things happen:

- Iterators are often mis-categorized.
- Algorithm requirements are more strict than necessary, because they cannot separate the need for random access or bidirectional traversal from the need for a true reference return type.

Impact on the Standard

This proposal for TR1 is a pure extension. Further, the new iterator concepts are backward-compatible with the old iterator requirements, and old iterators are forward-compatible with the new iterator concepts. That is to say, iterators that satisfy the old requirements also satisfy appropriate concepts in the new system, and iterators modeling the new concepts will automatically satisfy the appropriate old requirements.

Possible (but not proposed) Changes to the Working Paper

The extensions in this paper suggest several changes we might make to the working paper for the next standard. These changes are not a formal part of this proposal for TR1.

Changes to Algorithm Requirements

The algorithms in the standard library could benefit from the new iterator concepts because the new concepts provide a more accurate way to express their type requirements. The result is algorithms that are usable in more situations and have fewer type requirements.

For the next working paper (but not for TR1), the committee should consider the following changes to the type requirements of algorithms. These changes are phrased as phrased as textual substitutions, listing the algorithms to which each textual substitution applies.

Forward Iterator -> Forward Traversal Iterator and Readable Iterator

`find_end, adjacent_find, search, search_n, rotate_copy, lower_bound, upper_bound, equal_range, binary_search, min_element, max_element`

Forward Iterator (1) -> Single Pass Iterator and Readable Iterator, Forward Iterator (2) -> Forward Traversal Iterator and Readable Iterator

`find_first_of`

Forward Iterator -> Readable Iterator and Writable Iterator

`iter_swap`

Forward Iterator -> Single Pass Iterator and Writable Iterator

`fill, generate`

Forward Iterator -> Forward Traversal Iterator and Swappable Iterator

`rotate`

Forward Iterator (1) -> Swappable Iterator and Single Pass Iterator, Forward Iterator (2) -> Swappable Iterator and Incrementable Iterator

`swap_ranges`

Forward Iterator -> Forward Traversal Iterator and Readable Iterator and Writable Iterator `remove, remove_if, unique`

Forward Iterator -> Single Pass Iterator and Readable Iterator and Writable Iterator

`replace, replace_if`

Bidirectional Iterator -> Bidirectional Traversal Iterator and Swappable Iterator `reverse`

Bidirectional Iterator -> Bidirectional Traversal Iterator and Readable and Swappable Iterator `partition`

Bidirectional Iterator (1) -> Bidirectional Traversal Iterator and Readable Iterator, Bidirectional Iterator (2) -> Bidirectional Traversal Iterator and Writable Iterator

`copy_backwards`

Bidirectional Iterator -> Bidirectional Traversal Iterator and Swappable Iterator and Readable Iterator `next_permutation, prev_permutation`

Bidirectional Iterator -> Bidirectional Traversal Iterator and Readable Iterator and Writable Iterator `stable_partition, inplace_merge`

Bidirectional Iterator -> Bidirectional Traversal Iterator and Readable Iterator `reverse_copy`

Random Access Iterator -> Random Access Traversal Iterator and Readable and Writable Iterator `random_shuffle, sort, stable_sort, partial_sort, nth_element, push_heap, pop_heap make_heap, sort_heap`

Input Iterator (2) -> Incrementable Iterator and Readable Iterator `equal, mismatch`

Input Iterator (2) -> Incrementable Iterator and Readable Iterator `transform`

Deprecations

For the next working paper (but not for TR1), the committee should consider deprecating the old iterator tags, and std::iterator_traits, since it will be superceded by individual traits metafunctions.

`vector<bool>`

For the next working paper (but not for TR1), the committee should consider reclassifying `vector<bool>::iterator` as a Random Access Traversal Iterator and Readable Iterator and Writable Iterator.

Design

The iterator requirements are to be separated into two groups. One set of concepts handles the syntax and semantics of value access:

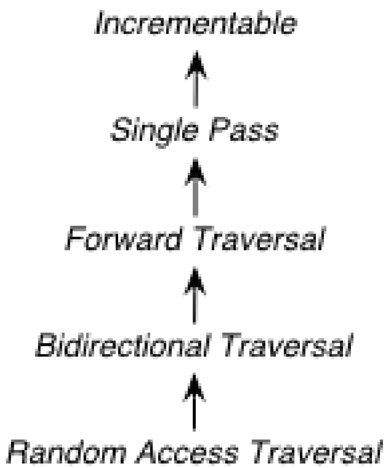
- Readable Iterator
- Writable Iterator
- Swappable Iterator
- Lvalue Iterator

The access concepts describe requirements related to `operator*` and `operator->`, including the `value_type`, `reference`, and `pointer` associated types.

The other set of concepts handles traversal:

- Incrementable Iterator
- Single Pass Iterator
- Forward Traversal Iterator
- Bidirectional Traversal Iterator
- Random Access Traversal Iterator

The refinement relationships for the traversal concepts are in the following diagram.

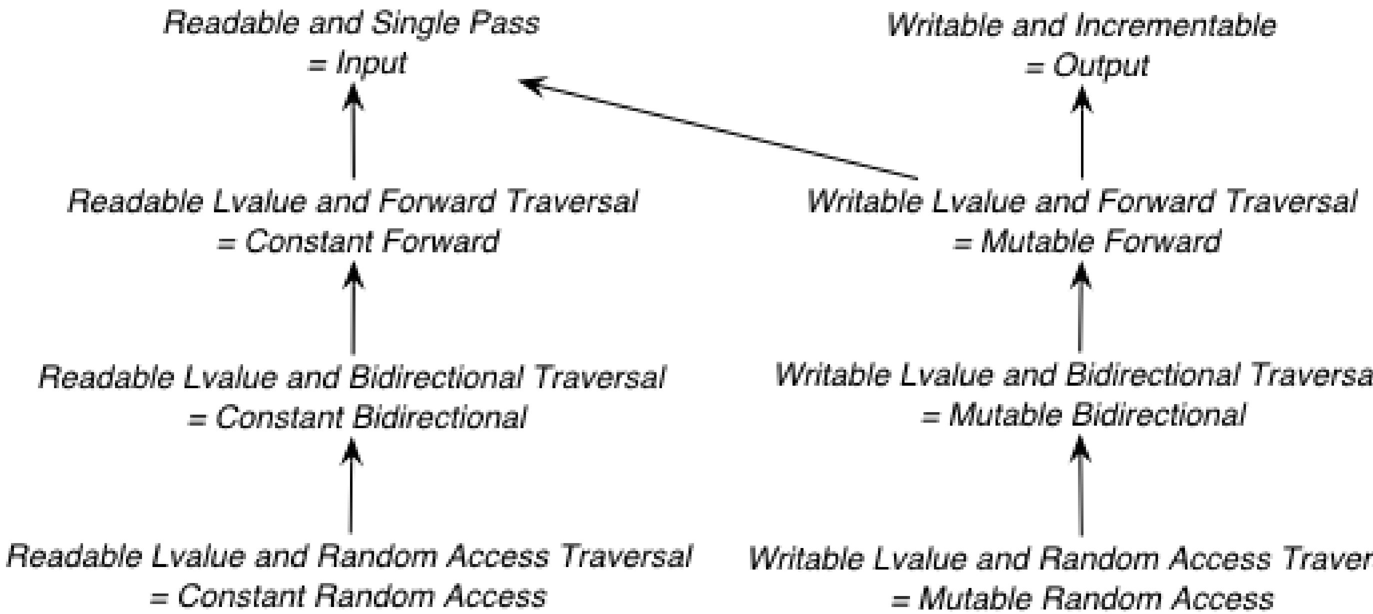


In addition to the iterator movement operators, such as `operator++`, the traversal concepts also include requirements on position comparison such as `operator==` and `operator<`. The reason for the fine grain slicing of the concepts into the Incrementable and Single Pass is to provide concepts that are exact matches with the original input and output iterator requirements.

This proposal also includes a concept for specifying when an iterator is interoperable with another iterator, in the sense that `int*` is interoperable with `int const*`.

- Interoperable Iterators

The relationship between the new iterator concepts and the old are given in the following diagram.



Like the old iterator requirements, we provide tags for purposes of dispatching based on the traversal concepts. The tags are related via inheritance so that a tag is convertible to another tag if the concept associated with the first tag is a refinement of the second tag.

Our design reuses `iterator_traits<Iter>::iterator_category` to indicate an iterator's traversal capability. To specify capabilities not captured by any old-style iterator category, an iterator designer can use an `iterator_category` type that is convertible to both the the most-derived old iterator category tag which fits, and the appropriate new iterator traversal tag.

We do not provide tags for the purposes of dispatching based on the access concepts, in part because we could not find a way to automatically infer the right access tags for old-style iterators. An iterator's writability may be dependent on the assignability of its `value_type` and there's no known way to detect whether an arbitrary type is assignable. Fortunately, the need for dispatching based on access capability is not as great as the need for dispatching based on traversal capability.

A difficult design decision concerned the `operator[]`. The direct approach for specifying `operator[]` would have a return type of `reference`; the same as `operator*`. However, going in this direction would mean that an iterator satisfying the old Random Access Iterator requirements would not necessarily be a model of Readable or Writable Lvalue Iterator. Instead we have chosen a design that matches the preferred resolution of issue 299: `operator[]` is only required to return something convertible to the `value_type` (for a Readable Iterator), and is required to support assignment `i[n] = t` (for a Writable Iterator).

Proposed Text

Addition to [lib.iterator.requirements]

Iterator Value Access Concepts [lib.iterator.value.access]

In the tables below, `X` is an iterator type, `a` is a constant object of type `X`, `R` is `std::iterator_traits<X>::reference`, `T` is `std::iterator_traits<X>::value_type`, and `v` is a constant object of type `T`.

Readable Iterators [lib.readable.iterators]

A class or built-in type `X` models the *Readable Iterator* concept for value type `T` if, in addition to `X` being Assignable and Copy Constructible, the following expressions are valid and respect the stated semantics. `U` is the type of any specified member of type `T`.

Readable Iterator Requirements (in addition to Assignable and Copy Constructible)		
Expression	**Return Type**	**Note/Precondition**
`iterator_traits<X>::value_type`	`T`	Any non-reference, non-cv-qualified type
`*a`	Convertible to `T`	**pre: `a` is dereferenceable. If `a == b` then `*a` is** equivalent to `*b`.

Readable Iterator Requirements (in addition to Assignable and Copy Constructible)		
Expression	**Return Type**	**Note/Precondition**
`a->m`	`U&`	pre: `pre:` `(*a).m` is well-defined. Equivalent to `(*a).m`.

Writable Iterators [lib.writable.iterators]

A class or built-in type `X` models the *Writable Iterator* concept if, in addition to `X` being Copy Constructible, the following expressions are valid and respect the stated semantics. Writable Iterators have an associated *set of value types*.

Writable Iterator Requirements (in addition to Copy Constructible)		
Expression	**Return Type**	**Precondition**
`*a = o`		pre: The type of `o` is in the set of value types of `X`

Swappable Iterators [lib.swappable.iterators]

A class or built-in type `X` models the *Swappable Iterator* concept if, in addition to `X` being Copy Constructible, the following expressions are valid and respect the stated semantics.

Swappable Iterator Requirements (in addition to Copy Constructible)		
Expression	**Return Type**	**Postcondition**
`iter_swap(a, b)`	`void`	the pointed to values are exchanged

[***Note:*** **An iterator that is a model of the *Readable* and *Writable Iterator* concepts** is also a model of *Swappable Iterator*. *–end note*]

Lvalue Iterators [lib.lvalue.iterators]

The *Lvalue Iterator* concept adds the requirement that the return type of `operator*` type be a reference to the value type of the iterator.

Lvalue Iterator Requirements		
Expression	**Return Type**	**Note/Assertion**
`*a`	`T&`	`T` is *cv* `iterator_traits<X>::value_type` where *cv* is an optional cv-qualification. pre: `a` is dereferenceable. If `a == b` then `*a` is equivalent to `*b`.

Iterator Traversal Concepts [lib.iterator.traversal]

In the tables below, `X` is an iterator type, `a` and `b` are constant objects of type `X`, `r` and `s` are mutable objects of type `X`, `T` is `std::iterator_traits<X>::value_type`, and `v` is a constant object of type `T`.

Incrementable Iterators [lib.incrementable.iterators]

A class or built-in type `X` models the *Incrementable Iterator* concept if, in addition to `X` being Assignable and Copy Constructible, the following expressions are valid and respect the stated semantics.

Incrementable Iterator Requirements (in addition to Assignable, Copy Constructible)		
Expression	**Return Type**	**Assertion/Semantics**
`++r`	`X&`	`&r == &++r`

Incrementable Iterator Requirements (in addition to Assignable, Copy Constructible)		
Expression	**Return Type**	**Assertion/Semantics**
`r++`	`X`	`{ X tmp = r; ++r; return tmp; }`
`iterator_traversal<X>::type`	Convertible to `incrementable_traversal_tag`	

Single Pass Iterators [lib.single.pass.iterators]

A class or built-in type `X` models the *Single Pass Iterator* concept if the following expressions are valid and respect the stated semantics.

Single Pass Iterator Requirements (in addition to Incrementable Iterator and Equality Comparable)		
Expression	**Return Type**	**Assertion/Semantics / Pre-/Post-condition**
`++r`	`X&`	pre: `r` is dereferenceable; post: `r` is dereferenceable or `r` is past-the-end
`a == b`	convertible to `bool`	`==` is an equivalence relation over its domain
`a != b`	convertible to `bool`	`!(a == b)`
`iterator_traversal<X>::type`	Convertible to `single_pass_traversal_tag`	

Forward Traversal Iterators [lib.forward.traversal.iterators]

A class or built-in type `X` models the *Forward Traversal Iterator* concept if, in addition to `X` meeting the requirements of Default Constructible and Single Pass Iterator, the following expressions are valid and respect the stated semantics.

Forward Traversal Iterator Requirements (in addition to Default Constructible and Single Pass Iterator)		
Expression	**Return Type**	**Assertion/Note**
`X u;`	`X&`	note: `u` may have a singular value.
`++r`	`X&`	`r == s` and `r` is dereferenceable implies `++r == ++s.`
`iterator_traits<X>::difference_type`	A signed integral type representing the distance between iterators	
`iterator_traversal<X>::type`	Convertible to `forward_traversal_tag`	

Bidirectional Traversal Iterators [lib.bidirectional.traversal.iterators]

A class or built-in type `X` models the *Bidirectional Traversal Iterator* concept if, in addition to `X` meeting the requirements of Forward Traversal Iterator, the following expressions are valid and respect the stated semantics.

Bidirectional Traversal Iterator Requirements (in addition to Forward Traversal Iterator)		
Expression	**Return Type**	**Assertion/Semantics / Pre-/Post-condition**
`--r`	`X&`	pre: there exists `s` such that `r == ++s`. post: `s` is dereferenceable. `--(++r) == r`. `--r == --s` implies `r == s`. `&r == &--r`.
`r--`	convertible to `const X&`	`{ X tmp = r; --r; return tmp; }`

Bidirectional Traversal Iterator Requirements (in addition to Forward Traversal Iterator)		
Expression	**Return Type**	**Assertion/Semantics / Pre-/Post-condition**
`iterator_traversal<X>::type`	Convertible to `bidirectional_traversal_tag`	

Random Access Traversal Iterators [lib.random.access.traversal.iterators]

A class or built-in type `X` models the *Random Access Traversal Iterator* concept if the following expressions are valid and respect the stated semantics. In the table below, `Distance` is `iterator_traits<X>::difference_type` and `n` represents a constant object of type `Distance`.

Random Access Traversal Iterator Requirements (in addition to Bidirectional Traversal Iterator)			
Expression	**Return Type**	**Operational Semantics**	**Assertion/ Pre-condition**
`r += n`	`X&`	`{ Distance m = n; if (m >= 0) while (m--) ++r; else while (m++) --r; return r; }`	
`a + n, n + a`	`X`	`{ X tmp = a; return tmp += n; }`	
`r -= n`	`X&`	`return r += -n`	
`a - n`	`X`	`{ X tmp = a; return tmp -= n; }`	
`b - a`	`Distance`	`a < b ? distance(a,b) : -distance(b,a)`	pre: there exists a value `n` of `Distance` such that `a + n == b`. `b == a + (b - a)`.
`a[n]`	convertible to T	`*(a + n)`	pre: a is a readable iterator
`a[n] = v`	convertible to T	`*(a + n) = v`	pre: a is a writable iterator
`a < b`	convertible to `bool`	`b - a > 0`	`<` is a total ordering relation
`a > b`	convertible to `bool`	`b < a`	`>` is a total ordering relation
`a >= b`	convertible to `bool`	`!(a < b)`	
`a <= b`	convertible to `bool`	`!(a > b)`	
`iterator_traversal<X>::type`	Convertible to `random_access_traversal_tag`		

Interoperable Iterators [lib.interoperable.iterators]

A class or built-in type `X` that models Single Pass Iterator is *interoperable with* a class or built-in type `Y` that also models Single Pass Iterator if the following expressions are valid and respect the stated semantics. In the tables below, `x` is an object of type `X`, `y` is an object of type `Y`, `Distance` is `iterator_traits<Y>::difference_type`, and `n` represents a constant object of type `Distance`.

Expression	**Return Type**	**Assertion/Precondition/Postcondition**
`y = x`	`Y`	post: `y == x`
`Y(x)`	`Y`	post: `Y(x) == x`
`x == y`	convertible to `bool`	`==` is an equivalence relation over its domain.
`y == x`	convertible to `bool`	`==` is an equivalence relation over its domain.
`x != y`	convertible to `bool`	`bool(a==b) != bool(a!=b)` over its domain.

Expression	Return Type	Assertion/Precondition/Postcondition
`y != x`	convertible to `bool`	`bool(a==b) != bool(a!=b)` over its domain.

If `X` and `Y` both model Random Access Traversal Iterator then the following additional requirements must be met.

Expression	Return Type	Operational Semantics	Assertion/ Precondition
`x < y`	convertible to `bool`	`y - x > 0`	`<` is a total ordering relation
`y < x`	convertible to `bool`	`x - y > 0`	`<` is a total ordering relation
`x > y`	convertible to `bool`	`y < x`	`>` is a total ordering relation
`y > x`	convertible to `bool`	`x < y`	`>` is a total ordering relation
`x >= y`	convertible to `bool`	`!(x < y)`	
`y >= x`	convertible to `bool`	`!(y < x)`	
`x <= y`	convertible to `bool`	`!(x > y)`	
`y <= x`	convertible to `bool`	`!(y > x)`	
`y - x`	`Distance`	`distance(Y(x),y)`	pre: there exists a value `n` of `Distance` such that `x + n == y`. `y == x + (y - x)`.
`x - y`	`Distance`	`distance(y,Y(x))`	pre: there exists a value `n` of `Distance` such that `y + n == x`. `x == y + (x - y)`.

Addition to [lib.iterator.synopsis]

```
// lib.iterator.traits, traits and tags
template <class Iterator> struct is_readable_iterator;
template <class Iterator> struct iterator_traversal;

struct incrementable_traversal_tag { };
struct single_pass_traversal_tag : incrementable_traversal_tag { };
struct forward_traversal_tag : single_pass_traversal_tag { };
struct bidirectional_traversal_tag : forward_traversal_tag { };
struct random_access_traversal_tag : bidirectional_traversal_tag { };
```

Addition to [lib.iterator.traits]

The `is_readable_iterator` class template satisfies the UnaryTypeTrait requirements.

Given an iterator type `X`, `is_readable_iterator<X>::value` yields `true` if, for an object `a` of type `X`, `*a` is convertible to `iterator_traits<X>::value_type`, and `false` otherwise.

`iterator_traversal<X>::type` is

```
category-to-traversal(iterator_traits<X>::iterator_category)
```

where *category-to-traversal* is defined as follows

```
category-to-traversal(C) =
    if (C is convertible to incrementable_traversal_tag)
        return C;
    else if (C is convertible to random_access_iterator_tag)
        return random_access_traversal_tag;
    else if (C is convertible to bidirectional_iterator_tag)
        return bidirectional_traversal_tag;
    else if (C is convertible to forward_iterator_tag)
        return forward_traversal_tag;
    else if (C is convertible to input_iterator_tag)
        return single_pass_traversal_tag;
    else if (C is convertible to output_iterator_tag)
        return incrementable_traversal_tag;
```

```
else
    the program is ill-formed
```

Footnotes

The UnaryTypeTrait concept is defined in n1519; the LWG is considering adding the requirement that specializations are derived from their nested `::type`.