STL Algorithms @ O'Reilly

2. STL Algorithms

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2.1. Terminology

Terminology

Standard Library:

The *Standard Library* is the official collection of classes and functions described in and provided with the C++ standard. In parts, the STL is a subset of the Standard Library.

Alexander Stepanov

Andrew Koenig

Standard Template Library (STL):

The *STL* is a template-based C++ library developed in the 80s and 90s by Dave Musser, Alexander Stepanov and Meng Lee. Many concepts, ideas, classes, etc., were introduced into the C++ standard library.

2.2. Overview of the STL

The STL in a Nutshell

The STL consists of the following **six concepts**:

- **Containers**: Implementations of the classical data collections
- **Algorithms**: work on the data contained in containers
- **Iterators**: The glue between containers and algorithms
- **Functors**: Provide flexibility and customizability
- **Adapters**: Adapting the basic containers to special purposes
- **Allocators**: Generalization and customization of memory allocation

The STL in a Nutshell

2.3. Motivation

The Expert's View on the STL

"There was never any question that the [standard template] library represented a breakthrough in efficient and extensible design."

(Scott Meyers, Effective STL)

The Expert's Advice

"If you want to improve code quality in your organization, I would say, take all your coding guidelines and replace them with the one goal. That's how important I think this one goal is: No Raw Loops. This will make the biggest change in code quality within your organization."

(Sean Parent, C++ Seasoning, Going Native 2013)

2.4. STL Iterators

Iterators: Glue Between Containers and Algorithms

- The STL mechanism to decouple algorithms from containers
- Algorithms are parameterized by iterator types
- Pointers are iterators
- Containers provide iterators over their elements (begin and end)
- Iterator concepts form a hierarchy (no inheritance, but refinement)

Iterators: Glue Between Containers and Algorithms

All algorithms expect at least a pair of iterators specifying the range to work on:

[begin; end)

begin specifies the first element of the range.

end specifies the element after the last element of the range.

```
std::reverse( vec.begin(), vec.end() );
std::copy( vec.begin(), vec.end(), deque.begin() );
```

What are the advantages of this half-open interval concept? Discuss.

Iterator Guidelines

Guideline: Prefer using iterators with `[begin,end)` semantics.

Guideline: Remember that pointers, references, and iterators into a container with contiguous storage are invalidated when elements are added to this container.

Iterator Guidelines

Guideline: Prefer prefix increment and decrement to postfix increment and decrement for all iterator types.

```
std::vector<int> vec;
// ... Initialization
for(std::vector<int>::iterator it=vec.begin(); it!=vec.end(); it++)
{ /* ... */ }
```

~~it++~~

++it

Iterator Guidelines

Guideline: Prefer range-based `for` loops for the standard traversal of elements of a collection.

```
std::vector<int> vec;
// ... Initialization
for(auto& element : vec)
{ /* ... */ }
```

2.5. STL Algorithms

STL Algorithms

- Free functions, not member functions
- Operate on half open ranges
- Algorithms are decoupled from containers
- Provide an intuitive naming and parameter convention

```
namespace std {

template< class RandomIt >
void sort( RandomIt first, RandomIt last );

template< class InputIt, class OutputIt >
OutputIt copy( InputIt first, InputIt last, OutputIt d_first );

template< class InputIt, class UnaryPredicate >
InputIt find_if( InputIt first, InputIt last, UnaryPredicate p );

} // namespace std
```

STL Algorithms

Algorithms library

The algorithms library defines functions for a variety of purposes (e.g. searching, sorting, counting, manipulating) that operate on ranges of elements. Note that a range is defined as `[first, last)` where `last` refers to the element *past* the last element to inspect or modify.

Non-modifying sequence operations

Defined in header `<algorithm>`

`all_of` (C++11) `any_of` (C++11) `none_of` (C++11)	checks if a predicate is `true` for all, any or none of the elements in a range (function template)
`ranges::all_of` (C++20) `ranges::any_of` (C++20) `ranges::none_of` (C++20)	checks if a predicate is `true` for all, any or none of the elements in a range (niebloid)
`for_each`	applies a function to a range of elements (function template)
`ranges::for_each` (C++20)	applies a function to a range of elements (niebloid)
`for_each_n` (C++17)	applies a function object to the first n elements of a sequence (function template)
`ranges::for_each_n` (C++20)	applies a function object to the first n elements of a sequence (niebloid)
`count`	returns the number of elements satisfying specific criteria

Examples

- Copy from a vector to a deque

```
std::copy( vec.begin(), vec.end(), deq.begin() );
```

- Sort the elements in a vector

```
std::sort( vec.begin(), vec.end() );
```

- Reverse the order of elements

```
std::reverse( vec.begin(), vec.end() );
```

- Find the value 5 in a list

```
std::find( lst.begin(), lst.end(), 5 );
```

Examples

- Copy from a vector of integers to std::cout

```
std::copy( vec.begin(), vec.end()
         , std::ostream_iterator<int>( std::cout, "\n" ) );
```

- Removing all duplicates from a range

```
std::sort( vec.begin(), vec.end() );
vec.erase( std::unique( vec.begin(), vec.end() ), vec.end() );
```

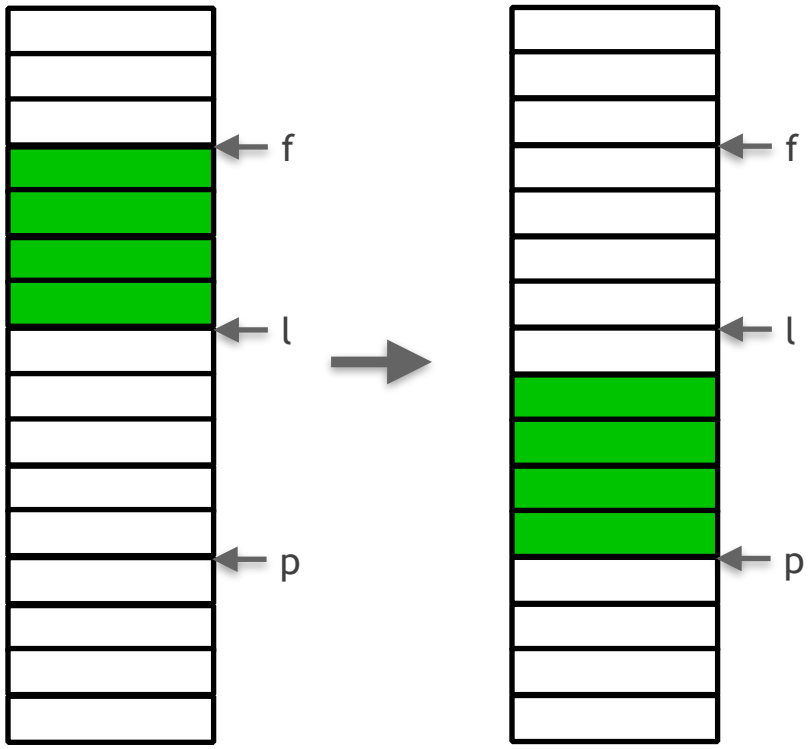
- Find the first odd integer in a list

```
struct IsOdd {
   bool operator()( int i ) const { return i & 0x1; }
};

std::find_if( lst.begin(), lst.end(), IsOdd{} );
```

Examples

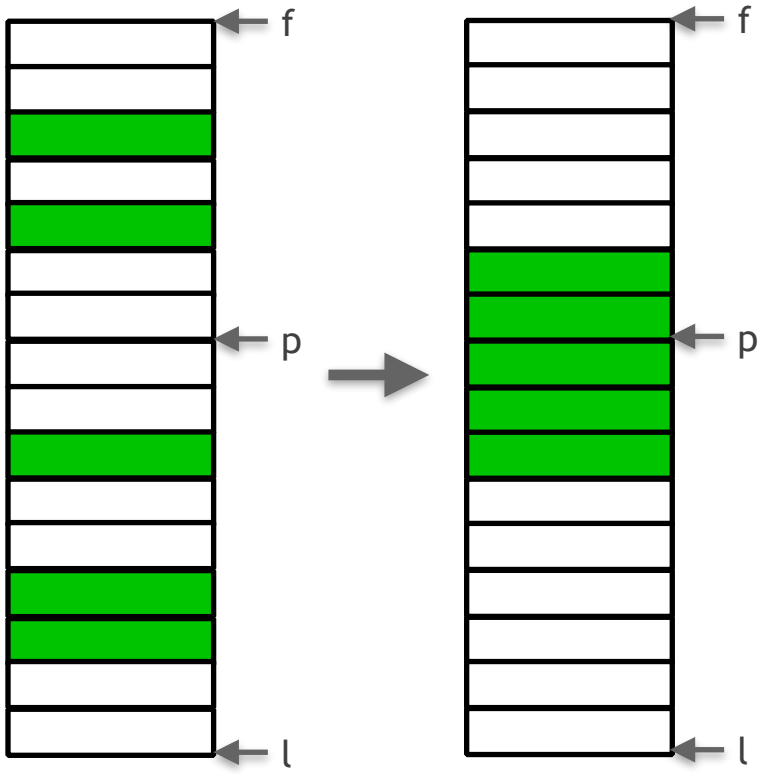
- Move a number of consecutive elements in a vector




```
std::rotate( f, l, p );
```

Examples

- Gather an arbitrary number of element at a specific position




```
using namespace std;

stable_partition(f, p, not1(s));
stable_partition(p, l, s);
```

Programming Task

Task (2_STL_Algorithms/STLintro): Solve the following tasks on a vector of integers by means of STL algorithms:

- Print the contents of the vector to the screen
- Reverse the order of elements in the vector
- Find the first element with the value 5
- Count the elements with the value 5
- Replace all 5s by 2s
- Sort the vector
- Determine the range of 2s

Hint: Use either of the following two web pages as reference.

www.cppreference.com

www.cplusplus.com

Programming Task

Task (2_STL_Algorithms/STLpro): Solve the following tasks on a vector of integers by means of STL algorithms:

- Compute the product of all elements in the vector
- Extract all numbers <= 5 from the vector
- Compute the (numerical) length of the vector
- Compute the ratios v[i+1]/v[i] for all elements v[i] in v
- Move the range [v[3], v[5]] to the beginning of the vector

Hint: Use either of the following two web pages as reference.

www.cppreference.com

www.cplusplus.com

Programming Task

Task (2_STL_Algorithms/Simpson): Implement the empty functions to perform the following operations on the Simpson characters:

- Print all persons to the screen
- Randomize their order
- Find the youngest person
- Order them by first name
- Order them by last name without affecting the order of first names
- Order them by age without affecting the order of first and last names
- Put all Simpsons first without affecting the general order of persons
- Compute the total age of all persons
- Put the last person first, moving all others by one position
- Determine the third oldest person as quickly as possible

Programming Task

Task (2_STL_Algorithms/SimpsonPro): Implement the empty functions to perform the following operations on the Simpson characters:

- Print all persons to the screen
- Randomize their order
- Find the youngest person
- Order them by last name without affecting the order of first names
- Highlight the last name of all persons with the given name
- Put all children first
- Compute the total length of all last names
- Check if two adjacent persons have the same age
- Compute the maximum age difference between two adjacent persons
- Determine the median age of all persons
- After ordering all persons by last name, find all the Simpsons

Programming Task

Task (2_STL_Algorithms/Accumulate):

Step 1: Implement the `accumulate()` algorithm. The algorithm should take a pair of iterators, an initial value for the reduction operation, and a binary operation that performs the elementwise reduction.

Step 2: Implement an overload of the `accumulate()` algorithm that uses `std::plus` as the default binary operation.

Step 3: Implement an overload of the `accumulate()` algorithm that uses the default of the underlying data type as initial value and `std::plus` as the default binary operation.

Step 4: Test your implementation with a custom binary operation (e.g. `Times`).

Programming Task

Task (2_STL_Algorithms/Partition): Implement the `partition()` algorithm that separates two groups of elements. The algorithm should take a pair of iterators and a predicate that identifies the elements of the first group.

Programming Task

Task (2_STL_Algorithms/SortSubrange): Implement the `sort_subrange()` algorithm in the following example. The algorithm should take four iterators, which specify the total range of elements and the subrange to be sorted.

Programming Task

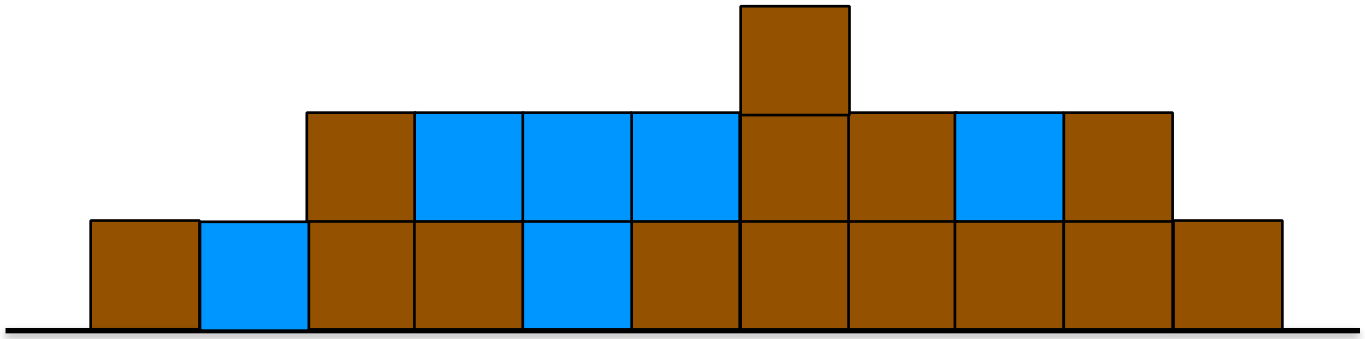
Task (2_STL_Algorithms/ExtractStrings): Implement the `extract_strings()` algorithm. The algorithm should extract all strings from a long string of space-separated words.

Programming Task

Task (2_STL_Algorithms/LongestStreak): Determine the longest streak of consecutive equal values in the given range of elements.

Programming Task

Task (2_STL_Algorithms/Trap): Implement the following `trap()` algorithm for a given vector of non-negative integers. The given vector represents an elevation map, where the width of each bar is 1. The `trap()` algorithm should compute how much water can be trapped in between the peaks.



```
vector<int> v{ 1,  0,  2,  1,  0,  1,  3,  2,  1,  2,  1 };
```

Programming Task

Task (2_STL_Algorithms/IsPalindrome):

Step 1: Implement the `is_palindrome()` algorithm in the following example. The algorithm should detect if the given range is the same when traversed forward and backward. The algorithm should return `true` only for true palindromes, and `false` for empty ranges and non-palindromes.

Step 2: Restrict the algorithm to bidirectional iterators by means of C++20 concepts.

Programming Task

Task (2_STL_Algorithms/AlgorithmPerformance1): Copy-and-paste the following code into godbolt.org. Compare the generated assembly code for the following three different solutions:

- an iterator-based manual for loop;
- the STL `accumulate()` algorithm;
- an index-based manual for loop.

Programming Task

Task (2_STL_Algorithms/AlgorithmPerformance2): Copy-and-paste the following code into quick-bench.com. Benchmark the time to sort a `std::vector` of integers.

Algorithm Guidelines

Guideline: “No raw loops” (Sean Parent)

Guideline: “Prefer to use algorithms or embed your raw loop in named functions” (Klaus Iglberger)

Guideline: Use algorithms to reduce duplication (DRY).

Guideline: Know the standard algorithms. They can handle all basic tasks elegantly and efficiently (zero cost abstraction).

Guideline: Use the right algorithm for the right task.

Algorithm Guidelines

Guideline: Consider the design of the STL: It follows SRP, OCP, DRY and builds on the Strategy and Command design patterns.

Core Guideline P.3: Express intent

Core Guideline T.40: Use function objects to pass operations to algorithms

Core Guideline T.141: Use an unnamed lambda if you need a simple function object in one place only

Limitations of STL Algorithms

Limitations of STL Algorithms - Example 1

Task (2_STL_Algorithms/BadCopy): Explain the error in the following program.

```
std::vector<int> vec;
std::list<int> lst;

// ... Initialization of lst

std::copy( lst.begin(), lst.end(), vec.begin() );
```

Limitations of STL Algorithms - Example 1

Task (2_STL_Algorithms/BadCopy): Explain the error in the following program.

```
std::vector<int> vec;
std::list<int> lst;

// ... Initialization of lst

std::copy( lst.begin(), lst.end(), vec.begin() );
```

- copy() assumes that the target holds enough elements for all elements to be copied
- Reasonable assumption since it is not possible to change the size of a container via the given iterators
- In case the target vector is empty, we enter the realm of undefined behavior

Limitations of STL Algorithms - Example 1

Either resize the `vector` accordingly ...

```
std::vector<int> vec;
std::list<int> lst;

// ... Initialization of lst

vec.resize( lst.size() );
std::copy( lst.begin(), lst.end(), vec.begin() );
```

Limitations of STL Algorithms - Example 1

... or use the following approach:

```
std::vector<int> vec;
std::list<int> lst;

// ... Initialization of lst

vec.reserve( lst.size() );  // Optional
std::copy( lst.begin(), lst.end(), std::back_inserter(vec) );
```

Limitations of STL Algorithms - Example 1

Guideline: Beware that algorithms cannot add new elements to a container.

Limitations of STL Algorithms - Example 2

Task (2_STL_Algorithms/BadTransform): Explain the error in the following program.

```
int transmogrify( int x );

std::vector<int> values;
// ... Put data into the vector

std::vector<int> results;

// Apply 'transmogrify' to each object in values,
// appending the return values to results
std::transform( values.begin(), values.end(),
                results.end(), transmogrify );
```

Limitations of STL Algorithms - Example 2

Task (2_STL_Algorithms/BadTransform): Explain the error in the following program.

```
int transmogrify( int x );

std::vector<int> values;
// ... Put data into the vector

std::vector<int> results;

// Apply 'transmogrify' to each object in values,
// appending the return values to results
std::transform( values.begin(), values.end(),
                results.end(), transmogrify );
```

Same problem as in the previous task: The target `vector` has not enough elements → undefined behavior.

Limitations of STL Algorithms - Example 2

Task (continued): Ok, now that we have repaired the access violation, there is an easy way to considerably improve performance. Show how this can be achieved.

```
int transmogrify( int x );

std::vector<int> values;
// ... Put data into the vector

std::vector<int> results;

// Apply 'transmogrify()' to each object in values,
// appending the return values to results
std::transform( values.begin(), values.end(),
                std::back_inserter(results), transmogrify );
```

Limitations of STL Algorithms - Example 2

If we turn the transmogrify function into a functor, the compiler can take advantage of the inline function definition and inline the function call. This is **not** possible in case of a function pointer.

```
struct Transmogrify {
   inline int operator()( int x ) const { return x * x; }
};

std::vector<int> values;
// ... Put data into the vector

std::vector<int> results;

// Apply 'Transmogrify' to each object in values,
// appending the return values to results
std::transform( values.begin(), values.end(),
                std::back_inserter(results), Transmogrify() );
```

Limitations of STL Algorithms - Example 2

Core Guideline T.40: Use function objects to pass operations to algorithms

Limitations of STL Algorithms - Example 3

Task (2_STL_Algorithms/BadAccumulate): Explain the error in the following program:

```
std::vector<double> vec;

// ... Adding elements to vec

const double sum =
   std::accumulate( vec.begin(), vec.end(), 0 );
```

Limitations of STL Algorithms - Example 3

Task (2_STL_Algorithms/BadAccumulate): Explain the error in the following program:

```
std::vector<double> vec;

// ... Adding elements to vec

const double sum =
   std::accumulate( vec.begin(), vec.end(), 0 );
```

- The type of the third parameter defines the type of the accumulator
- adding `double` values to an `int` strips away the floating point part
- the final result is wrong!

Limitations of STL Algorithms - Example 3

Make sure to use the right type for the `init` argument:

```
std::vector<double> vec;

// ... Adding elements to vec

const double sum =
   std::accumulate( vec.begin(), vec.end(), double{} );
```

Limitations of STL Algorithms - Example 3

Guideline: Beware the power of the third argument of `std::accumulate()`, `std::reduce()`, and similar algorithms.

Limitations of STL Algorithms - Example 4

Task (2_STL_Algorithms/BadRemove): Explain the error in the following program:

```
std::vector<int> vec{ 1, -3, 27, 42, 4, -8, 22, 42, 37, 4, 18, 9 };

const auto pos = std::max_element( begin(vec), end(vec) );

vec.erase( std::remove( begin(vec), end(vec), *pos ), end(vec) );
```

Limitations of STL Algorithms - Example 4

Task (2_STL_Algorithms/BadRemove): Explain the error in the following program:

```
std::vector<int> vec{ 1, -3, 27, 42, 4, -8, 22, 42, 37, 4, 18, 9 };

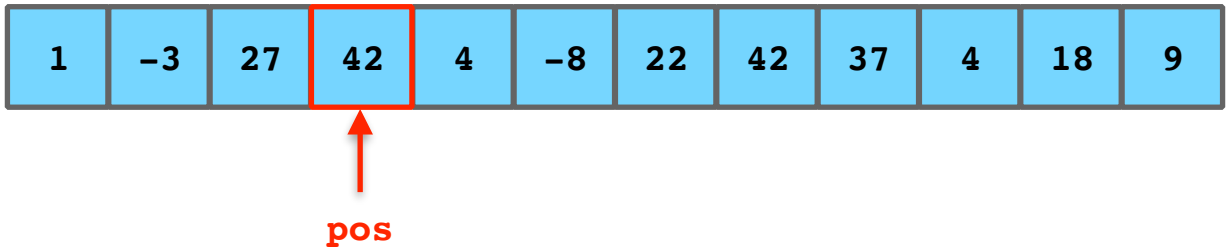
const auto pos = std::max_element( begin(vec), end(vec) );

vec.erase( std::remove( begin(vec), end(vec), *pos ), end(vec) );
```

- `std::remove()` takes its third argument by reference
- passing a reference to the value to be removed may result in aliasing effects
- In case of aliasing final result may be wrong!

Limitations of STL Algorithms - Example 4

```
std::vector<int> vec{ 1, -3, 27, 42, 4, -8, 22, 42, 37, 4, 18, 9 };
const auto pos = std::max_element( begin(vec), end(vec) );
vec.erase( std::remove( begin(vec), end(vec), *pos ), end(vec) );
```



Limitations of STL Algorithms - Example 4

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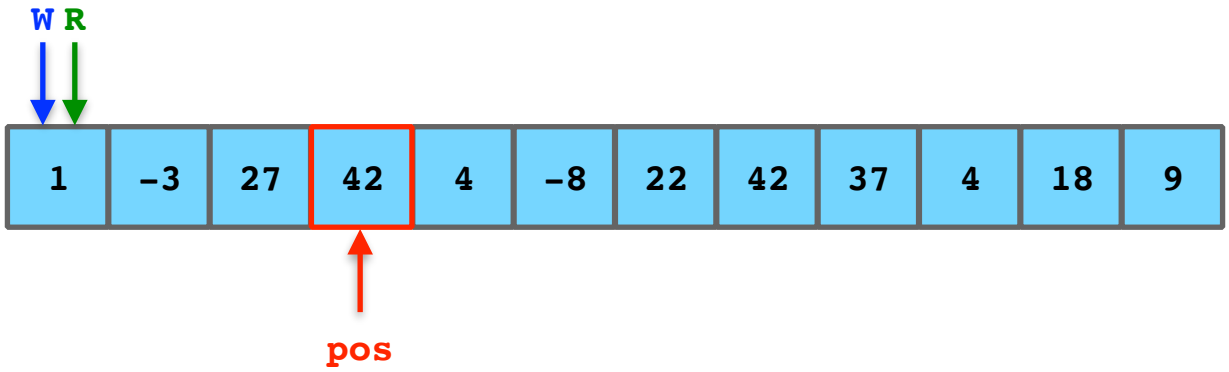

Limitations of STL Algorithms - Example 4

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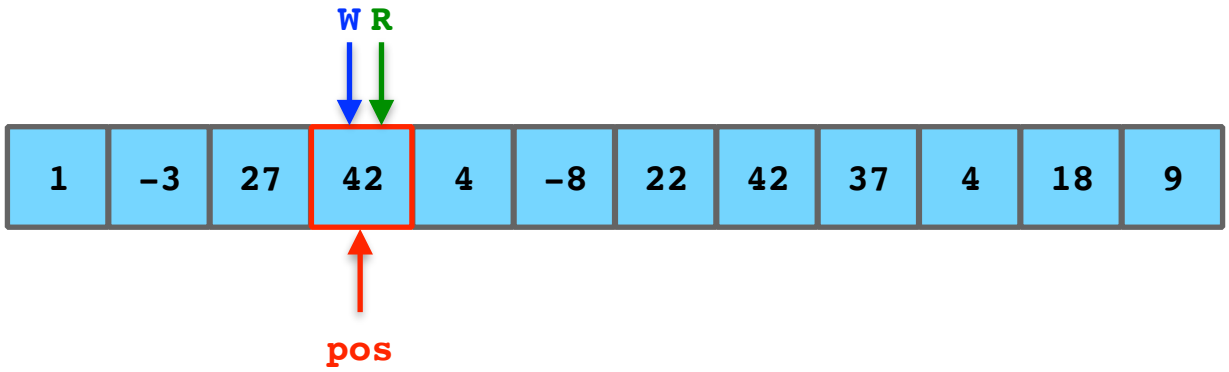

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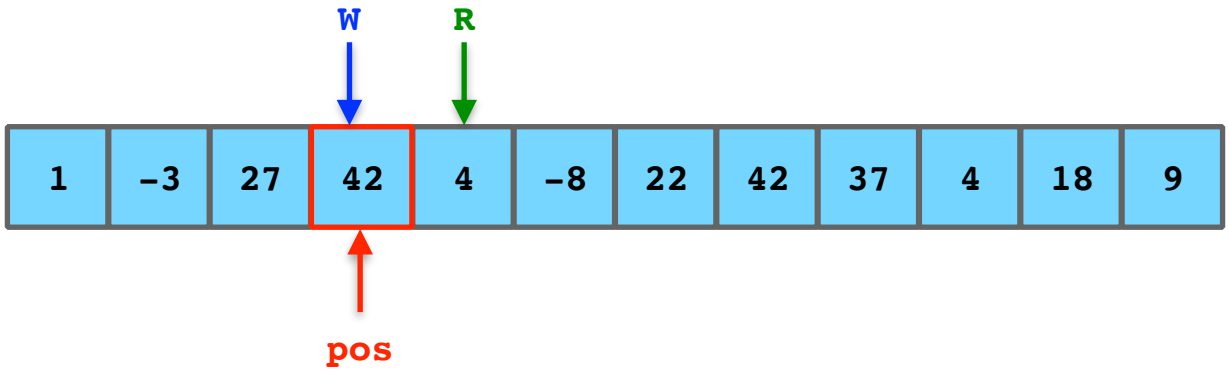
```



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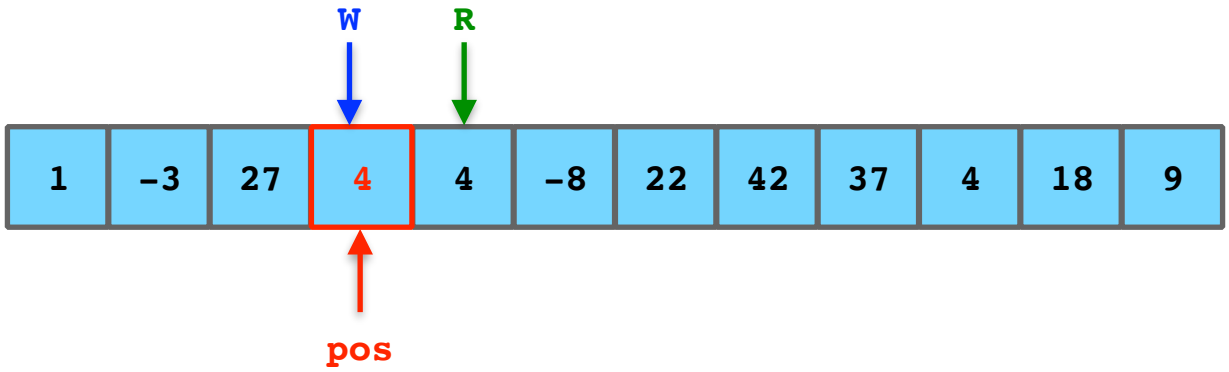

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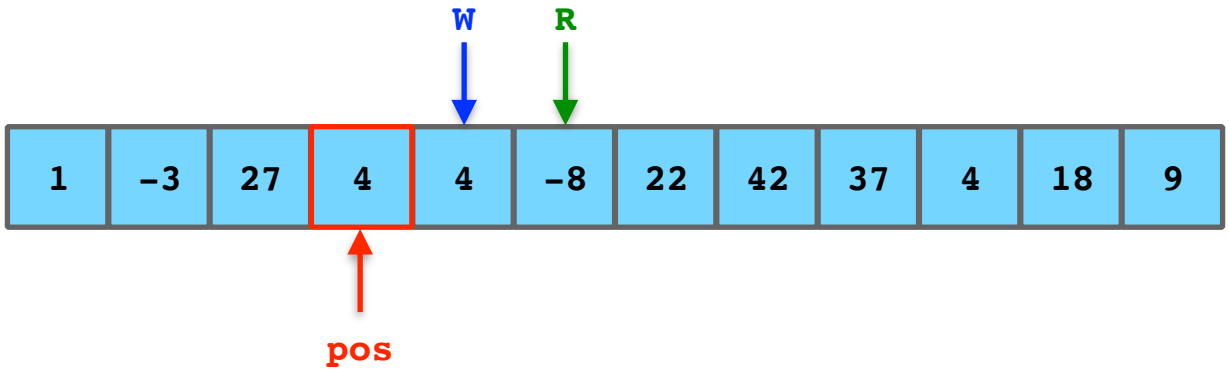

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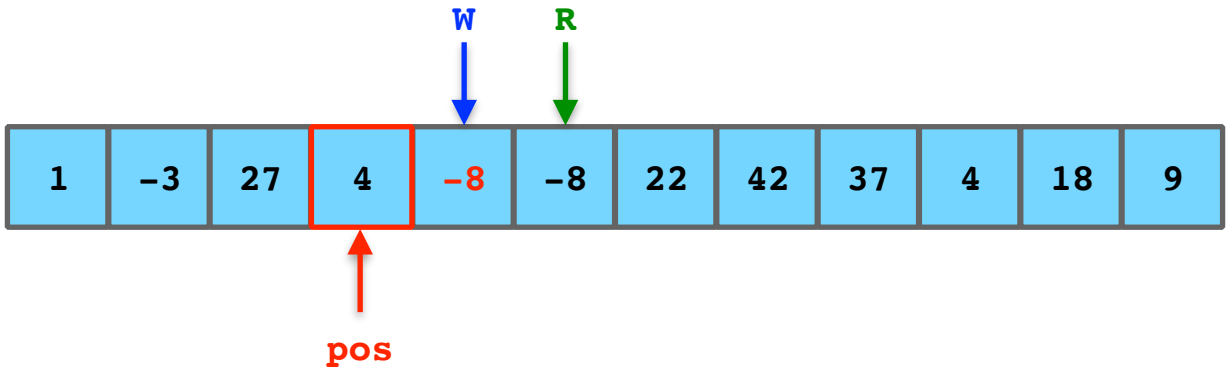

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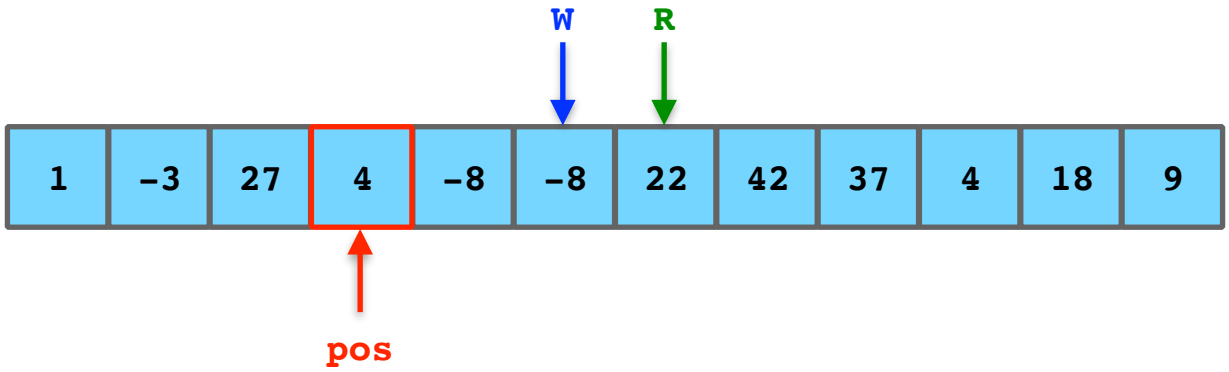

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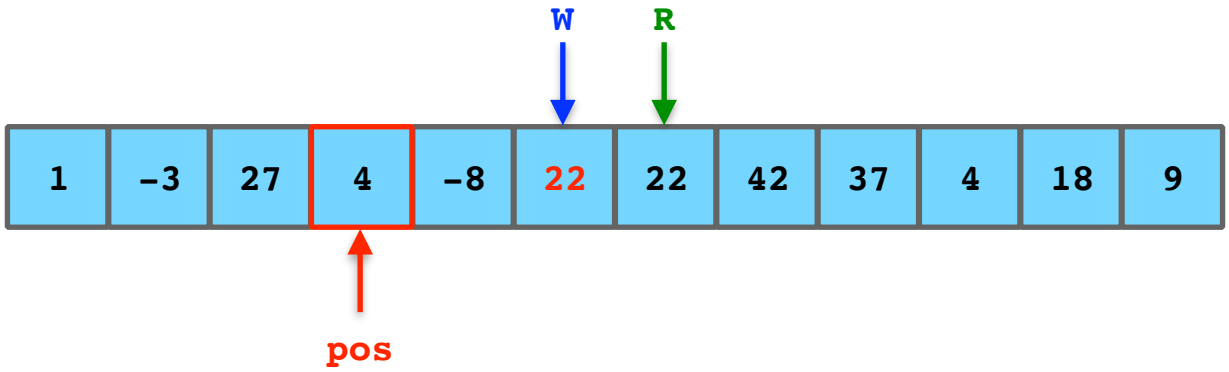

Limitations of STL Algorithms - Example 4

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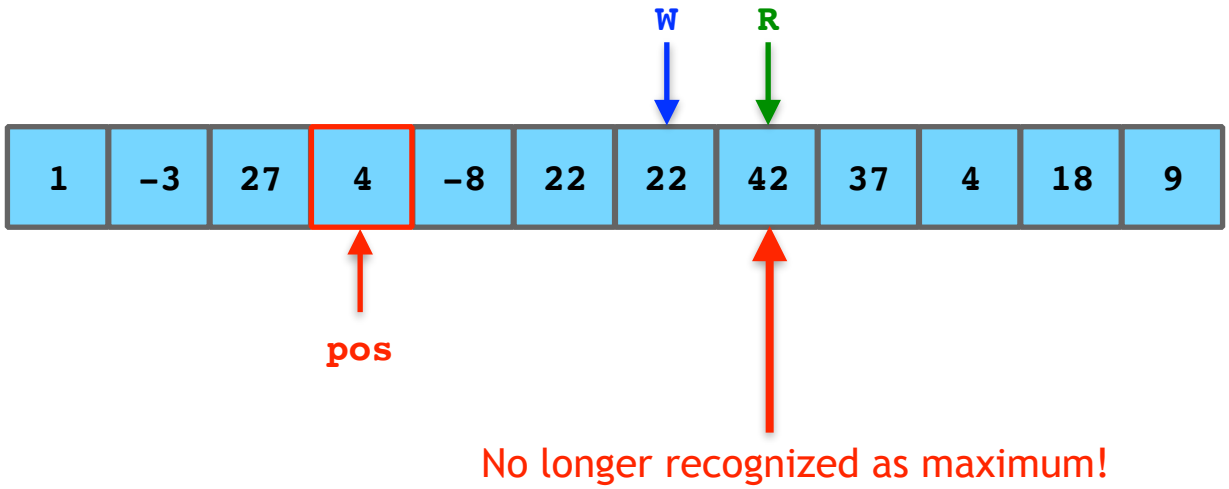

Limitations of STL Algorithms - Example 4

```
std::vector<int> vec{ 1, -3, 27, 42, 4, -8, 22, 42, 37, 4, 18, 9 };
const auto pos = std::max_element( begin(vec), end(vec) );
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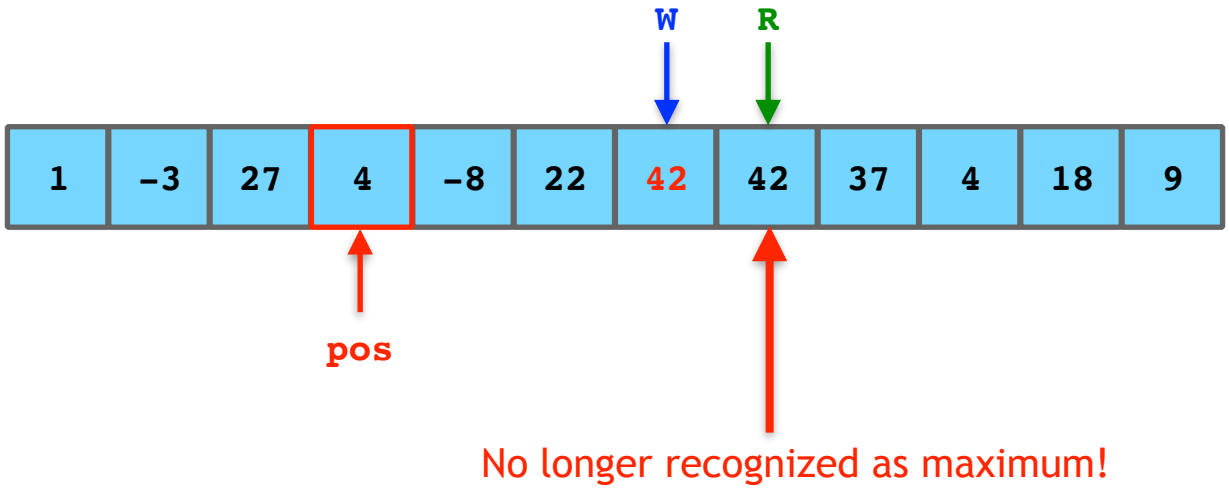

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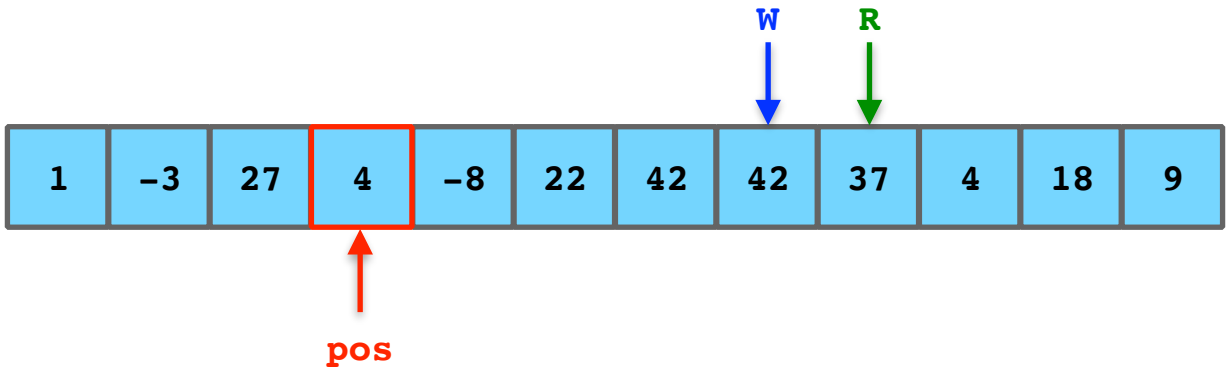

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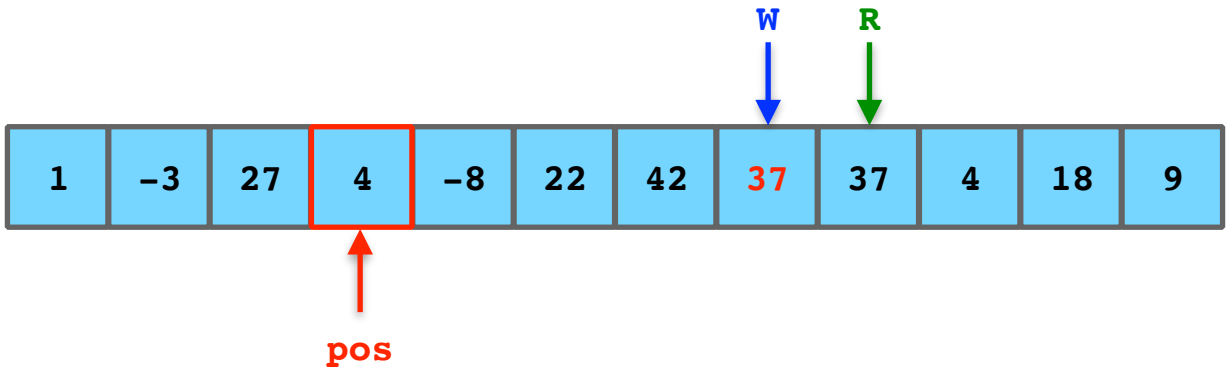

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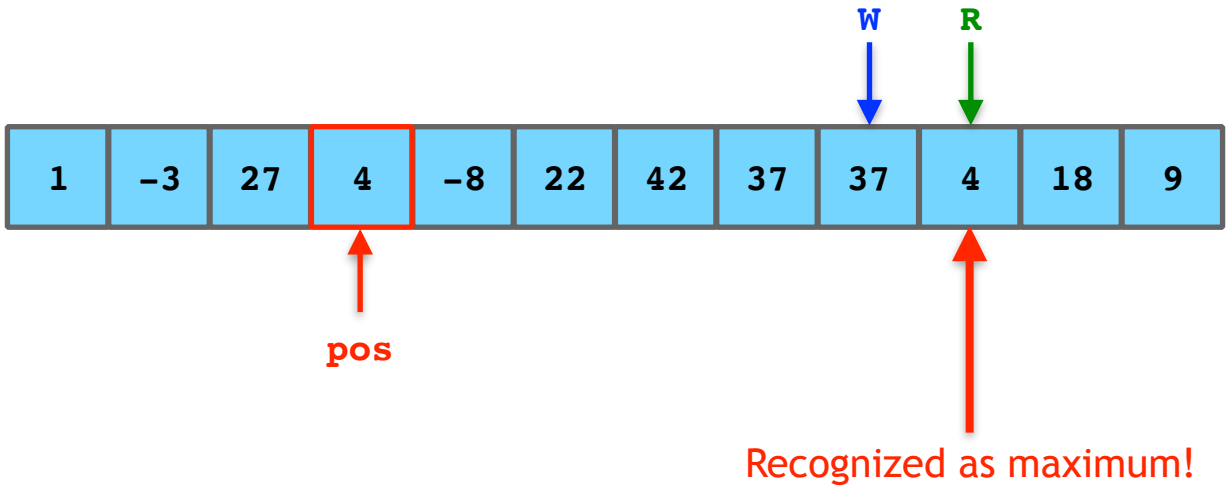

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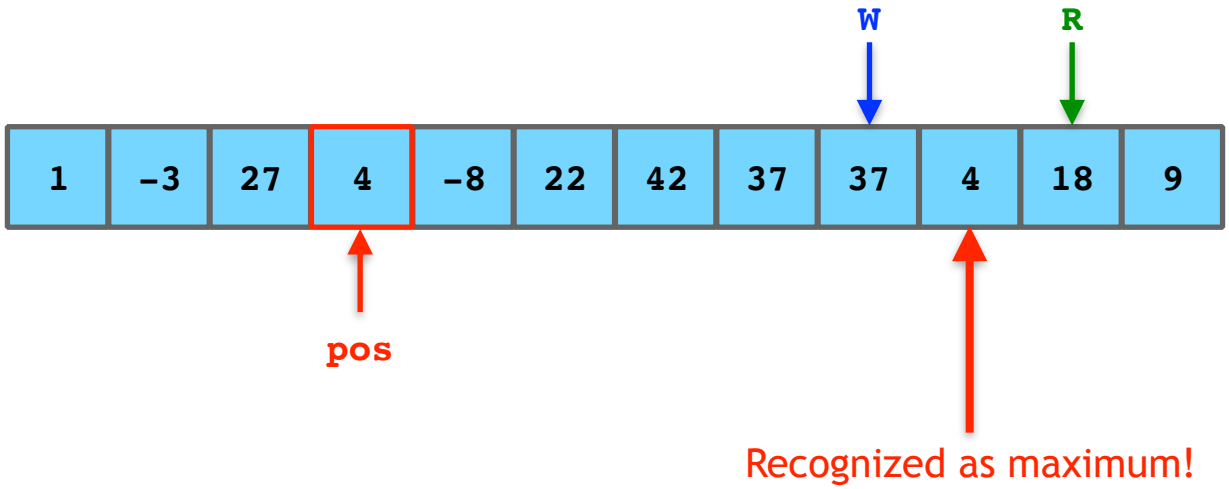

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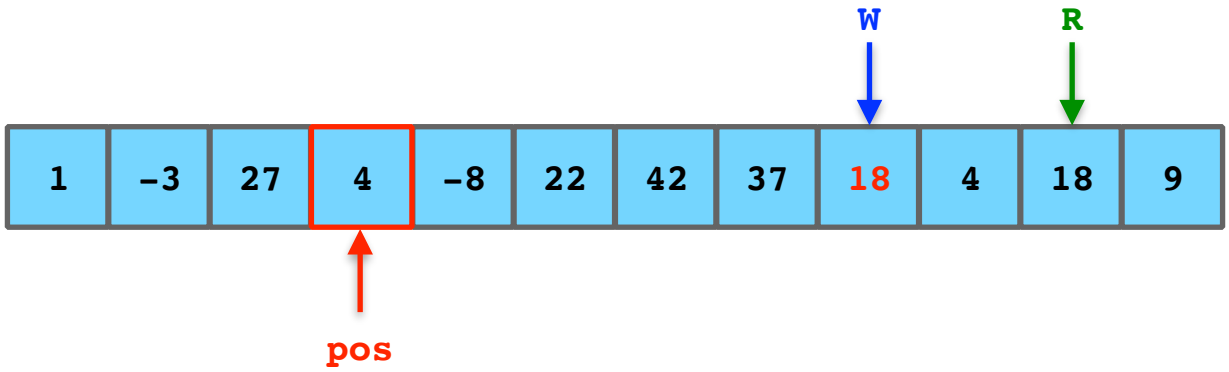

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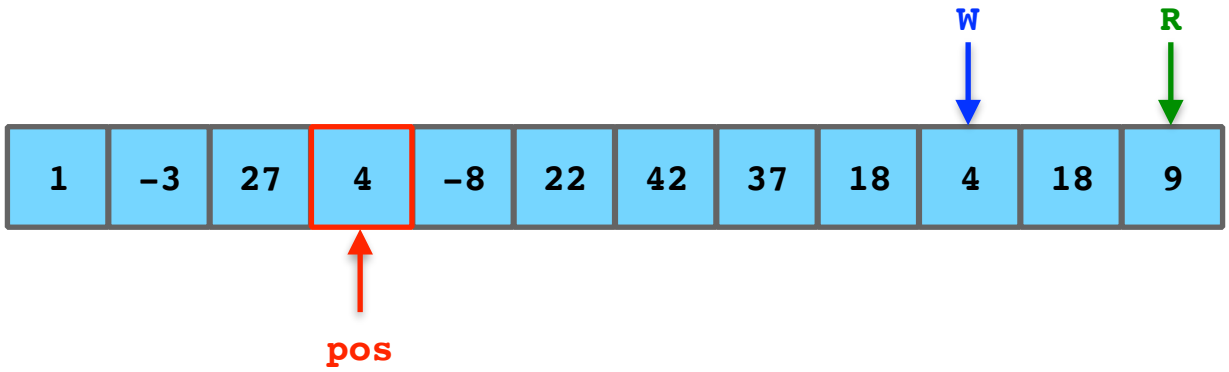

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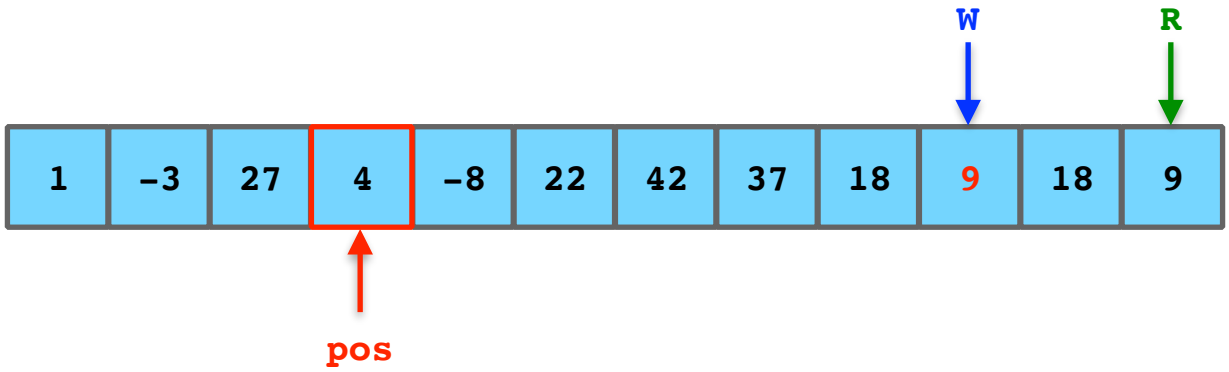

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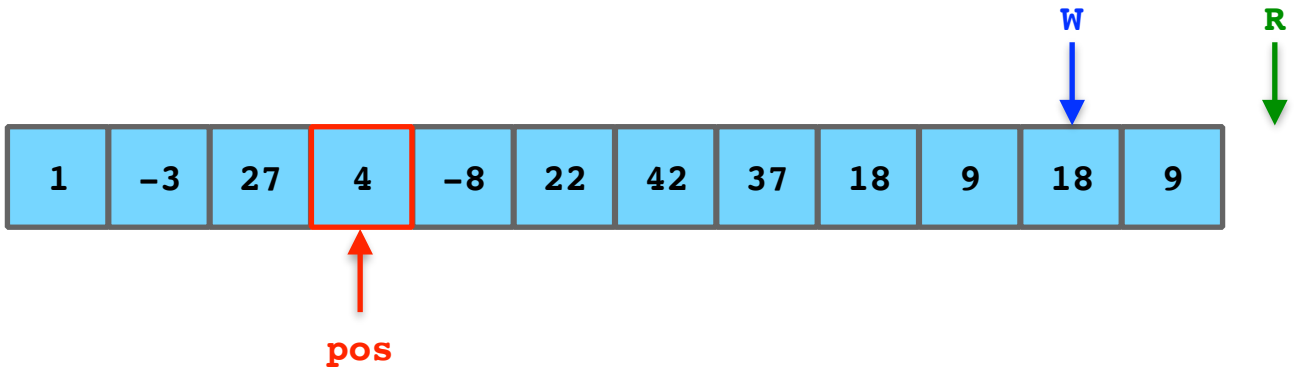

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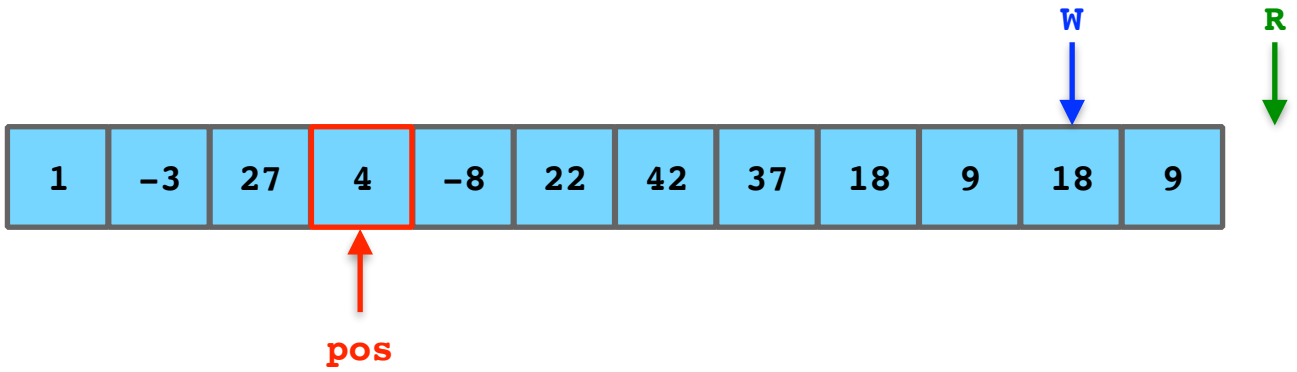

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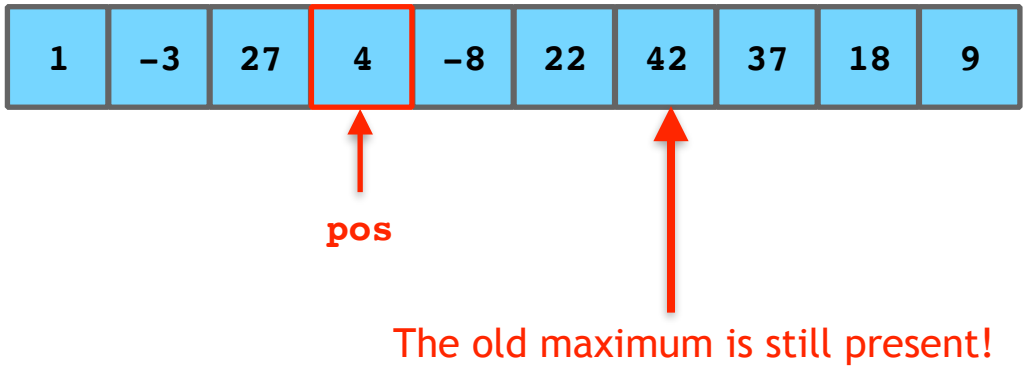
```



Limitations of STL Algorithms - Example 4

Make sure to evaluate the value in case there is aliasing:

```
std::vector<int> vec{ 1, -3, 27, 42, 4, -8, 22, 42, 37, 4, 18, 9 };
const auto pos = std::max_element( begin(vec), end(vec) );
vec.erase( std::remove( begin(vec), end(vec), int{*pos} ), end(vec) );
```

Limitations of STL Algorithms - Example 4

Guideline: Beware the few reference arguments in the STL.

Limitations of STL Algorithms - Example 5

Task (2_STL_Algorithms/Simpson): Consider the following implementation for the Simpson `order_by_lastname()` function:

```
std::stable_sort( std::begin(table), std::end(table),
   std::not_fn( []( const Person& lhs, const Person& rhs ) {
      return lhs.lastname < rhs.lastname;
   } ) );
```

Explain the error in the implementation.

Limitations of STL Algorithms - Example 5

Task (2_STL_Algorithms/Simpson): Consider the following implementation for the Simpson `order_by_lastname()` function:

```
std::stable_sort( std::begin(table), std::end(table),
   std::not_fn( []( const Person& lhs, const Person& rhs ) {
      return lhs.lastname < rhs.lastname;
   } ) );
```

Explain the error in the implementation.

- All sorting algorithms (including `std::nth_element`) are based on equivalence (`!(a<b) && !(b<a)`), not on equality (`a == b`)
- The negation of the lambda result in a `>=` comparison (including equality!)
- That comparison does not adhere to the sorting requirements: Undefined behavior!

Limitations of STL Algorithms - Example 5

Possible output:

```
Enter command: r
Bart        Simpson     10
Marge       Simpson     34
Hans        Moleman     33
Ralph       Wiggum       8
Montgomery  Burns      104          // Random order of characters after
Homer       Simpson     38          // a call to std::shuffle
Lisa        Simpson      8
Maggie      Simpson      1
Jeff        Albertson   45

Enter command: l
Ralph       Wiggum       8
Maggie      Simpson      1
Lisa        Simpson      8
Homer       Simpson     38          // Order of characters after a call to
Marge       Simpson     34          // std::stable_sort. The order of equal
Bart        Simpson     10          // elements is NOT preserved!
Hans        Moleman     33
Montgomery  Burns      104
Jeff        Albertson   45
```

Limitations of STL Algorithms - Example 6

Task (2_STL_Algorithms/BadFind): Explain the problem in the following program.

```
std::set<int> s{ /*...*/ };

const auto pos = std::find( std::begin(s), std::end(s), 42 );
```

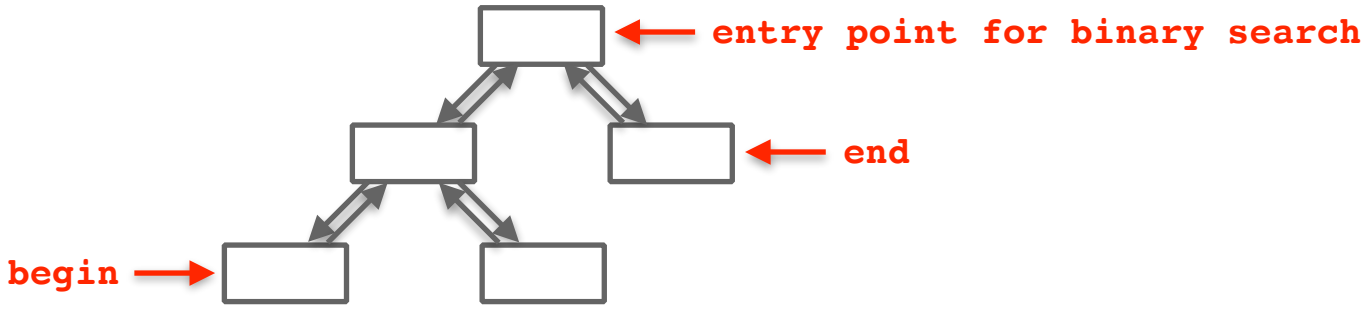
Limitations of STL Algorithms - Example 6

Task (2_STL_Algorithms/BadFind): Explain the problem in the following program.

```
std::set<int> s{ /*...*/ };

const auto pos = std::find( std::begin(s), std::end(s), 42 );
```

- All find() algorithm cannot exploit the tree structure of the `std::set` due to the `begin` and `end` iterators



- This results in a linear search instead of a binary search

Guidelines

Guideline: If available, prefer member functions to general algorithms (`find()`, `lower_bound()`, `upper_bound()`, …).

Wait a Second…

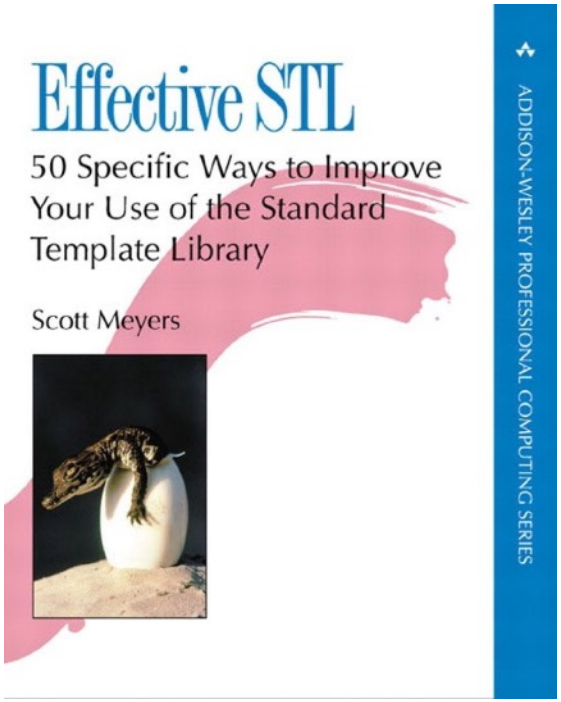
Can’t I overload the free `find()` algorithm to call the member function?

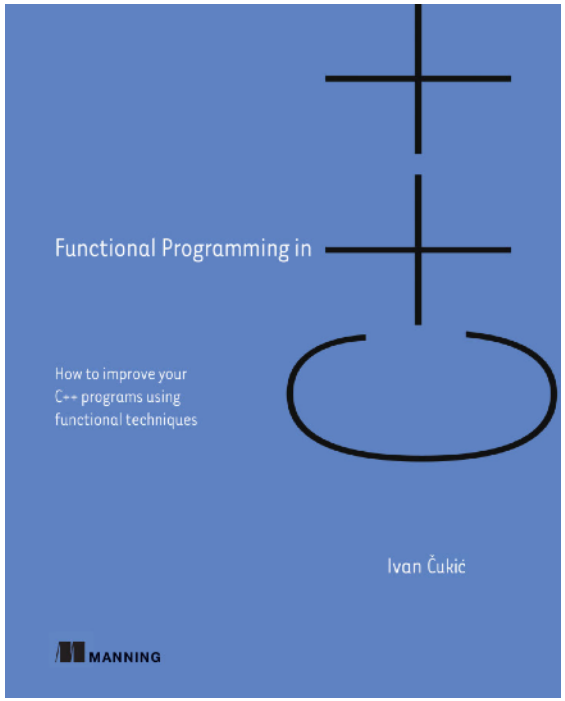
No, unfortunately not. You would need a reference to the container to call the member function, but the algorithm is only given iterators. However, it is possible in C++20 😀

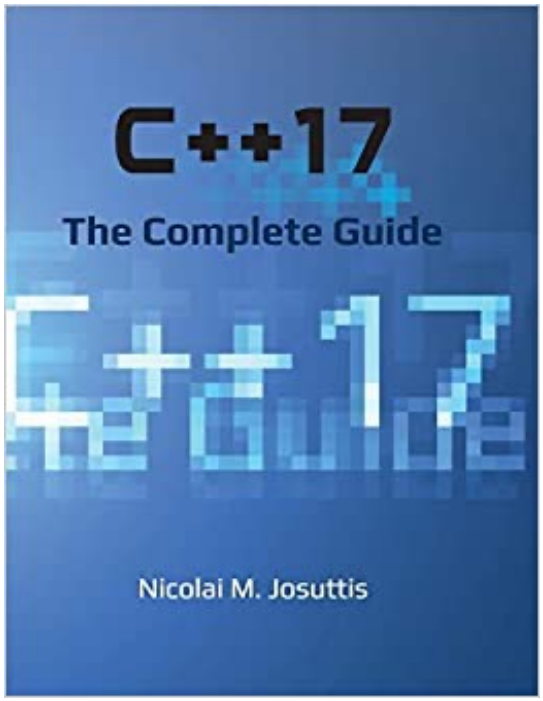
Things to Remember

- Familiarize yourself with the STL and STL-style code
- Prefer algorithms over handwritten loops
- Remember the conventions and possible pitfalls of algorithms

Literature


Effective STL
50 Specific Ways to Improve Your Use of the Standard Template Library
Scott Meyers
ADDISON-WESLEY PROFESSIONAL COMPUTING SERIES


Functional Programming in C++
How to improve your C++ programs using functional techniques
Ivan Čukić
MANNING


C++17
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Nicolai M. Josuttis

References

- Sean Parent, “C++ Seasoning”, GoingNative 2013 (https://channel9.msdn.com/Events/GoingNative/2013/Cpp-Seasoning)
- Chandler Carruth, “Efficiency with Algorithms, Performance with Data Structures”. cppcon 2014 (https://www.youtube.com/watch?v=fHNmRkzxHWs)
- Michael VanLoon, “STL Algorithms in Action”. CppCon 2015 (https://www.youtube.com/watch?v=eidEEmGLQcU)
- Eric Niebler, “Ranges for the Standard Library”. CppCon 2015 (https://www.youtube.com/watch?v=mFUXNMfaciE)
- Ben Deane, “std::accumulate: Exploring an Algorithmic Empire”. CppCon 2016 (https://www.youtube.com/watch?v=B6twozNPUoA)
- Jonathan Boccara, “105 STL Algorithms in Less Than An Hour”. CppCon 2018 (https://www.youtube.com/watch?v=2olsGf6JIkU)
- Frederic Tingaud, “A Little Order: Delving into the STL sorting algorithms”. CppCon 2018 (https://www.youtube.com/watch?v=-0tO3Eni2uo)
- Conor Hoekstra, “Algorithm Intuition (Part 1 of 2)”. CppCon 2019 (https://www.youtube.com/watch?v=pUEnO6SvAMo)
- Arthur O’Dwyer, “Back to Basics: Lambdas from Scratch”. CppCon 2019 (https://www.youtube.com/watch?v=3jCOwajNch0)

Online Resources

- Working Draft, Standard for Programming Language C++: http://eel.is/c++draft/
- C++ Reference: www.cppreference.com
- C++ Core Guidelines: isocpp.github.io/CppCoreGuidelines/CppCoreGuidelines
- Stackoverflow: www.stackoverflow.com
- Compiler Explorer: www.godbolt.org
- Quick-Bench: www.quick-bench.com
- C++ Insights: www.cppinsights.io
- Build-Bench: www.build-bench.com
- C++ Shell: cpp.sh
- Wandbox: wandbox.org
- repl.it: repl.it
- Intel Intrinsics Guide: software.intel.com/sites/landingpage/IntrinsicsGuide
- x86/x64 SIMD Instruction List: https://www.officedaytime.com/simd512e/

Additional Online Resources

- C++ Bestiary: http://videocortex.io/2017/Bestiary/
- More C++ Idioms: https://en.wikibooks.org/wiki/More_C%2B%2B_Idioms
- Codewars: https://www.codewars.com
- CodeKata: http://codekata.com

email: klaus.iglberger@gmx.de

LinkedIn: linkedin.com/in/klaus-iglberger-2133694/

Xing: xing.com/profile/Klaus_Iglberger/cv