SAFE ITERATOR FRAMEWORK FOR THE C++ STANDARD TEMPLATE LIBRARY

Norbert PATAKI
Department of Programming Languages and Compilers, Eötvös Loránd University,
Pázmány Péter sétány I/C H-1117 Budapest, Hungary,
e-mail: patakino@elte.hu

ABSTRACT

The C++ Standard Template Library is the flagship example for libraries based on the generic programming paradigm. The usage of this library is intended to minimize classical C/C++ errors, but does not warrant bug-free programs. Furthermore, many new kinds of errors may arise from the inaccurate use of the generic programming paradigm, like dereferencing invalid iterators or misunderstanding remove-like algorithms.

In this paper we present some typical scenarios that may cause undefined or weird behaviour. We present approaches that can be used for developing different safe iterators to avoid run-time errors. Some of these iterators are able to manipulate the container directly, hence they cannot result in undefined behaviour when an algorithm needs to add elements to the container or delete elements from the container. Our iterators are able to indicate if they are invalid. Algorithms’ preconditions are evaluated with our iterators.

Keywords: C++, STL, iterators, safety

1. INTRODUCTION

The C++ Standard Template Library (STL) was developed by generic programming approach. In this way containers are defined as class templates and many algorithms can be implemented as function templates. Furthermore, algorithms are implemented in a container-independent way, so one can use them with different containers. C++ STL is widely-used because it is a very handy, standard C++ library that contains beneficial containers (like list, vector, map, etc.), a lot of algorithms (like sort, find, count, etc.) among other utilities.

The STL was designed to be extensible. We can add new containers that can work together with existing algorithms. On the other hand, we can extend the set of algorithms with a new one that can work together with existing containers. Iterators bridge the gap between containers and algorithms. The expression problem is solved with this approach. STL also includes adaptor types which transform standard elements of the library for a different functionality. Adaptors can modify the interface of a container, transform streams into iterators, modify the behavior of functors etc.

However, the usage of C++ STL does not mean bugless or error-free code. Contrarily, incorrect application of the library may introduce new kinds of problems.

One of the problems is, that the error diagnostics are usually complex, and very hard to figure out the cause of a program error. Violation of the requirement of strict weak ordering in comparison functors also means strange bugs. This results in inconsistent containers at runtime.

Most of the properties are checked at compilation time. For example, the code does not compile if one uses sort algorithm with the standard list container, because the list’s iterators do not offer random accessibility. Other properties are checked at runtime. For example, the standard vector container offers an at method which tests if the index is valid and it raises an exception otherwise.

Unfortunately, there is still a large number of some properties are tested neither at compilation-time nor at run-time. Observance of these properties are in the charge of the programmers. Let us consider the following code snippet:

```cpp
std::vector<int> v;
int x;
//...
std::vector<int>::iterator i = std::lower_bound( v.begin(), v.end(), x );
```

The purpose of `lower_bound` is to find an element in an ordered range. It is a version of binary search, hence it has logarithmic complexity. We assume that we can find an element in a vector in logarithmic time because of the sortedness of the vector. However, it causes undefined result, if the vector is not ordered.

Implementations of these algorithms do not test if the range is sorted appropriately. Many STL algorithms expect ordered range: `equal_range`, `binary_search`, `set_difference`, etc.

Furthermore, sortedness of container is not enough. We must make sure that the same sorting function object is used for sorting and for searching. The following code snippet also results in undetermined behaviour:

```cpp
std::sort( v.begin(), v.end() );
```

Other typical STL-related mistakes are related to iterator invalidation. This problem occurs when a container that is being processed using an iterator has its shape changed during the process, for example anything that causes a vector’s reallocation (increase in the result of `capacity()`) will invalidate all iterators. When one use an invalid iterator also causes an undefined result. Let us consider the following code:

```cpp
std::vector<int> v;
```
from a container \[15\]. Let us consider the following code snippet:

```cpp
std::vector<int> v;


v.erase( std::remove( v.begin(), v.end(), 99 ), v.end() )
```

Whereas C++ STL is pre- eminent in a sequential realm, it is not aware of multicore environment \[18\]. For example, the Cilk++ language aims at multicore programming. This language extends C++ with new keywords and one can write programs for multicore architectures easily. However, the language does not contain an efficient multicore library, just the C++ STL only which is an efficiency bottleneck in multicore environment. We develop a new STL implementation for Cilk++ to cope with the challenges of multicore architectures \[25\]. This new implementation can be a safer solution, too. Hence, our safety extensions will be included in the new implementation. However, the techniques presented in this paper concern to the original C++ STL, too.

In this paper we present extensions of the C++ STL, that is able to check iterators' validness at runtime. We also describe a technique that can use generic algorithms on sorted intervals in a safer way. Erasable and copy-safe iterators are introduced in order to overcome some typical mistakes.

This paper is organized as follows. In section \[2\] a modification in the related traits type is advised to be taken advantage of the following sections. We provide an approach for checking algorithms' preconditions in section \[3\]. We argue for a solution to the iterator invalidation in section \[4\]. Erasable iterators are introduced and present in section \[5\]. We provide our copy-safe iterators in section \[6\]. Finally, this paper concludes in section \[7\].

## 2. Extension of Iterator Traits

In this paper we argue for some new kinds of iterators that subserve the correct usage of the STL. This requires new traits to make the compilers able to make decisions about iterators' usage. The following empty types describe if an iterator is erasable and precondition-safe.

```cpp
struct erasable{};
struct unerasable{};
struct precondition_safe{};
struct precondition_unsafe{};
```

Next, two new traits added to \texttt{iterator_traits}. A similar approach is available \[18\]. The first traits specifies if an iterator is erasable, the second one specifies if an iterator is precondition-safe. The default \texttt{iterator_traits} is the following:

```cpp
template <class T>
struct iterator_traits
{
  typedef typename T::iterator_category iterator_category;
}
```

In contrast to the name of the algorithm, the size of the container is unchanged. The remaining elements have been moved to front of the container, but the tail is also unchanged. The result of this algorithm may be counter-intuitive at first time. The proper usage of the remove is called \textit{erase-remove idiom}:

```cpp
v.erase( std::remove( v.begin(), v.end(), 99 ), v.end() );
```
typedef typename T::value_type
  value_type;
typedef typename T::difference_type
  difference_type;
typedef typename T::pointer
  pointer;
typedef typename T::reference
  reference;
typedef unerasable
  erasability;
typedef typename T::precond_safety
  precond_safety;
};

The new kind of traits is defined as erasability and precond_safety type synonyms. As the default case shows, the ordinary iterators are not erasable and not precondition-safe. These traits can be set by the trivially modified iterator base class. In the case of erasable iterators, the erasibility tag must be set to erasable, and in the case of precondition safe iterators, the precondition safety property must be set to precond_safe. In every other case it must be set to the default.

3. PRECONDITIONS OF ALGORITHMS

The STL algorithms work well only if its preconditions are satisfied. Typically, the algorithm which require sorted input, check if the input is sorted neither at compilation-time nor at run-time. If this requirement is violated the result of algorithm is undefined.

We provide precondition-safe iterator adaptor to overcome this situation. The implementation is the following:

```cpp
template <class T>
struct Precond_safe: T
{
  Precond_safe( T t ): T( t ) { }

  typedef precond_safe precond_safety;
};
```

The adaptor is based on the mixin technique, the type of the base class is the iterator type itself [23]. Thus, Precond_safe provides all the properties and operations just like the original iterator only the safety type is defined to precond_safe. Algorithms can be overloaded on this type information. The following template method can be used to deduce the parameter:

```cpp
template <class T>
Precond_safe<T> Precond( T t )
{
  return Precond_safe<T>( t );
}
```

To present this technique the safe implementation of lower_bound is shown. The following is the type of exception to indicate the erroneous usage of the algorithm:

```cpp
class not_sorted{};
```

The standard algorithm implementation checks if the iterator is precondition-safe:

```cpp
template <class It, class T>
It lower_bound( It first,
  It last,
  const T& t )
{
  return lower_bound(
    first,
    last,
    t,
    typename
    iterator_traits<It>::
    precond_safety() );
}
```

The precondition-safe version checks the precondition. An exception is raised if the precondition fails, otherwise calls the original implementation:

```cpp
template <class Iterator, class T>
Iterator lower_bound( Iterator first,
  Iterator last,
  const T& t,
  precond_safe )
{
  if ( !std::is_sorted(first, last) )
  {
    throw not_sorted();
  }

  return lower_bound( first,
    last,
    t,
    precond_unsafe() );
}
```

The original version is the precondition-unsafe one:

```cpp
template <class Iterator, class T>
Iterator lower_bound( Iterator first,
  Iterator last,
  const T& t,
  precond_unsafe )
{
  // original implementation...
}
```

If the adapter is in-use, the safe implementation works. The conversion trivially works:

```cpp
std::vector<int> v;
int x;
// ...
std::vector<int>::iterator i =
  std::lower_bound( Precond( v.begin() ),
  Precond( v.end() ),
  x );
```
The user-defined predicated version is straightforward, just an other template parameter must be used. This technique is able to check arbitrary precondition of arbitrary algorithm.

4. INVALID ITERATORS

In this section we present a technique that can be used to avoid the undefined behaviour of invalid iterators’ usage. The technique is adaptable for all standard and nonstandard containers. Different containers invalidate iterators in different ways, however, this technique can be transformed to list, deque or other third party defined containers too. In a more sophisticated solution the invalidation behaviour should be parametrized. We present the technique as an extension of STL’s vector template.

In our implementation the vector objects keep tracks their iterators which have a member to describe if the iterator is valid. When the vector reallocates itself, it sends a message to its iterators that they become invalid. If one accesses an element via an invalid iterator, then an exception is raised. Since STL always creates copies from the iterators, we have to keep them on the heap memory. We use the shared_ptr to avoid memory-leaks which is the part of the C++11, and it is the part of Boost library [15].

Let us consider the following code snippet:

```cpp
template <class T, class Alloc = std::allocator<T>, bool debug = false>
class vector {
    typedef ItCont
        std::list<shared_ptr<iterator_impl> >;
    T* p;
    int cap, s;
    ItCont iterators;

    public:
        struct iterator_impl {
            private:
                bool isvalid;
                T* curr;
            public:
                iterator_impl( T* c ) : curr(c),
                isvalid( true ) {}

                T& operator*() {
                    if ( !isdebug )
                        return *curr;
                    if( isvalid )
                        return *curr;
                }
                iterator_impl& operator++() {
                    ++curr;
                    return *this;
                }
                iterator_impl operator++( int ) {
                    iterator_impl tmp( *this );
                    ++curr;
                    return tmp;
                }

                // ...
            };

        public:
            struct iterator:
                std::iterator<
                    std::random_access_iterator_tag,
                    T>
            {
                iterator_impl* p;
            // delegates
            // iterator_impl's operations
            };

        private:
            void realloc() {
                cap*=2;
                T* t = new T[cap];
                std::copy( p, p + s, t );
                delete [] p;
                p = t;
            }

            void invalid() {
                for( typename ItCont::iterator it =
                    iterators.begin();
                    it != iterators.end();
                    ++it)
                {
                    (*it)->isvalid = false;
                }
            }

            public:
                vector(): cap( 1 ), s( 0 ) {
                p = new T[cap];
            }
        }
    }
```
vector()
{
    delete [] p;
}

void push_back( const T& a )
{
    if ( s < cap )
        p[ s++ ] = a;
    else
    {
        realloc();
        invalid();
        push_back( a );
    }
}

iterator begin()
{
    iterator_impl* x =
        new iterator_impl( p );
    iterators.push_back( x );
    return iterator( x );
}

iterator end()
{
    iterator_impl* x =
        new iterator_impl( p + s );
    iterators.push_back( x );
    return iterator( x );
}

Of course, the testing can depend on a preprocessor
macro or something else. Legacy STL-based codes can be
easily transformed to use this vector container with extra
checks. Just an extra parameter should be passed to the
vector type. However, there is no trivial assignment and
copy between an untested and tested vector container, but a
special template copy constructor and assignment operator
can be added.

Naturally, we can create a specialization for the safe and
unsafe versions. This makes our implementation faster.

Similarly, we can create a safe iterator implementation
that is able to pursue the vector’s pointer. In this case, an
exception is thrown when an iterator is referred which point
at an erased element.

It is also should be considered if invalidation includes
the end iterators. Also causes runtime problems if end iter-
ators are dereferenced. It can be handled in an orthogonal
way.

5. ERASABLE ITERATORS

In this section we present our approach to develop it-
erators that are able manipulate the container and remove
elements from it [4].

First, we add a new inner class to the vector container.
This class is called erasable_iterator: this is quite sim-
ilar to the standard iterator class, but it has a pointer
to the container and a new member function called erase.
This method accesses the member functions of the con-
tainer via the pointer. Only point is that the method has
to avoid invalidation of the iterator. The container’s mem-
ber function ebegin returns an erasable iterator to the first
element, and its method einend returns an erasable iterator to
the end of the sequence, respectively.

typedef
    std::random_access_iterator_tag
ran_acc_tag;

template <class T,
    class Alloc = std::alloc<T> >
class vector
{
    T* p;
    int s, cap;
    // usual vector's members, typedefs,
    // classes, operators

public:

    class iterator:
        public
            std::iterator<ran_acc_tag,
                          T>
{
    protected:
        T* p;
    // usual operators...
};

class erasable_iterator: public iterator
{
    vector<T, Alloc>* v;

public:
    erasable_iterator( iterator i,
                       vector<T, Alloc>* vt ) :
        iterator( i ), v( vt ) {};

    void erase()
    {
        T* tmp = iterator::p + 1;
        v->erase( *this );
        iterator::p = tmp;
    }
};

erasable_iterator ebegin()
{
    return erasable_iterator( begin(), this );
}

erasable_iterator einend()
{
    return erasable_iterator( end(), this );
}
This technique can be transformed to other containers, too.
However, the standard algorithms of the STL do not
know the notation of erasable iterators. Thus, we have to
write new algorithms that take advantage of this new kind
of iterators. An algorithm can be decide if it uses erasable
iterator based on the extended traits. In the case of erasable
iterators the algorithm is able to use the erase method.

\[
\text{template } \langle\text{class It, class T}\rangle \\
\text{It remove( It first,} \\
\text{It last,} \\
\text{const T& t )} \\
\text{\{} \\
\text{\return remove( first,} \\
\text{last,} \\
\text{t,} \\
\text{typename} \\
\text{std::iterator_traits<It> \::erasability() \);} \\
\text{\}) \\
\text{\}
\]

The erasable version can be implemented in the follow-
ing way:

\[
\text{template } \langle\text{class Iter, class T}\rangle \\
\text{void remove( Iter first,} \\
\text{Iter last,} \\
\text{const T& t,} \\
\text{erasable } \rangle \\
\text{\{} \\
\text{\while( first != last )} \\
\text{\{} \\
\text{\if ( t == *first )} \\
\text{\{} \\
\text{\first.erase();} \\
\text{\}\} \\
\text{\else} \\
\text{\{} \\
\text{\++first;} \\
\text{\}\} \\
\text{\}\} \\
\text{\return first;} \\
\text{\}
\]

The version that uses unerasable iterators is the same as
the original implementation.

6. COPY-SAFE ITERATORS

In this section we present our implementation of copy-

This iterator type is also similar to iterator type of
the container. This kind of iterator also has a pointer
to the container. When a safe pointer is dereferenced
(ie. its operator* is called, it can invoke the container’s
push_back method and add new element to the vector if
necessary. Hence, if this kind of iterators is in use it causes
no runtime problems if someone copies elements into an
empty vector. Our implementation is able to detect if the
client uses problematic iterators for copying ranges [18].
The container’s member function cbegin returns a copy-
safe iterator to the first element, and its method cend re-
turns a copy-safe iterator to the end of the sequence, re-
spectively.

\[
\text{template } \langle\text{class T,} \\
\text{class Alloc = std::allocator<T> } \rangle \\
\text{class vector} \\
\text{\{} \\
\text{\// usual members, methods, typedefs, etc.} \\
\text{\}
\]

\text{class copy_safe_iterator: public iterator} \\
\text{\{} \\
\text{\vector<T, Alloc>* v;} \\
\text{\public:} \\
\text{\copy_safe_iterator( iterator i,} \\
\text{\vector<T, Alloc>* vt ) :} \\
\text{\iterator( i ), v( vt ) \{ \}} \\
\text{\}} \\
\text{T& operator*() \{ \\
\text{\if ( *this == v->end() )} \\
\text{\{ \\
\text{\v->push_back( T() );} \\
\text{\iterator::p = & ( v->back() );} \\
\text{\}\} \\
\text{\return iterator::operator*();} \\
\text{\}} \\
\text{\}
\]

\text{copy_safe_iterator csbegin() \{} \\
\text{\return copy_safe_iterator( begin(), this );} \\
\text{\}} \\
\text{copy_safe_iterator csend() \{} \\
\text{\return copy_safe_iterator( end(), this );} \\
\text{\}} \\
\text{\}

This technique can be transformed to other containers,
too.

Modification of any algorithms is not necessary because
these iterators can be work with standard copying algo-
rithms, such as copy or transform. For instance, the fol-
lowing code snippet shows the usage that cannot be imple-
mented in the original STL way:

\[
\text{std::vector<int> vi;} \\
\text{// ...} \\
\text{std::list<int> li;} \\
\text{// ...} \\
\text{std::copy( li.begin(),} \\
\text{li.end(), vi.csbegin() );}
\]
This invocation of copy algorithm overwrites all the existing elements in the vector, and added more new elements to the vector, if necessary. To achieve this goal without copy-safe iterators is much more harder.

However, limitations can be mentioned with this approach. However, vector does not offer push_front method, the copy_iterator should be parametrized with strategy of adding new element to container. Function objects (also known as functors) make the library much more flexible without significant runtime overhead. They parametrize user-defined algorithms in the library, for example, they determine the comparison in the ordered containers or define a predicate to find.

The iterator always executes a check when it is dereferenced, it has runtime overhead. However, it guarantees safety, and original non-copier iterators are available, too. The runtime overhead should be measured [20].

7. CONCLUSION

STL is the most widely-used library based on the generic programming paradigm. STL increases efficacy of C++ programmers mightily because it consists of expedient containers and algorithms. It is efficient and convenient, but the incorrect usage of the library results in weird or undefined behaviour.

In this paper we present some examples that can be compiled, but at runtime their usage is defective. We argue for some new extensions to overcome these risky situations. New kind of iterators are presented as a solution. The limitations of these iterators are also discussed.

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REFERENCES

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BIOGRAPHY

Norbert Pataki was born on 26. 2. 1982. In 2006 he graduated (MSc) at the department of Eötvös Loránd University (ELTE), Budapest. He takes part many industrial projects during his PhD. In 2009 he has become assistant professor at Eötvös Loránd University. His research area includes programming languages (especially the C++ programming language), multicore programming, software metrics, and generative programming.