Exception-Safety Issues and Techniques
-- By Herb Sutter

Writing Exception-Safe Code

Exception handling and templates are two of C++'s most powerful features. Writing exception-safe code, however, can be difficult—especially in a template, when you may have no idea when (or what) a certain function might throw your way.

We'll begin where creating a safe version of the Stack template. Later on, we'll significantly improve the Stack container by reducing the requirements on T, the contained type, and show advanced techniques for managing resources exception-safely. Along the way, we'll find the answers to such questions as:

* What are the different "levels" of exception safety?
* Can or should generic containers be fully exception-neutral?
* Are the standard library containers exception-safe or exception-neutral?
* Does exception safety affect the design of your container's public interface?
* Should generic containers use exception specifications?

Here is the declaration of the Stack template. Your mission: Make Stack exception-safe and exception-neutral. That is, Stack objects should always be in a correct and consistent state, regardless of any exceptions that might be thrown in the course of executing Stack's member functions. If any exceptions are thrown, they should be propagated seamlessly through to the caller, who can deal with them as he pleases, because he knows the context of T and we don't.

```
template <class T> class Stack
{
public:
 Stack();
 ~Stack();

   /*...*/

private:
  T*     v_;      // ptr to a memory area big
  size_t vsize_;  //  enough for 'vsize_' T's
  size_t vused_;  // #  of T's actually in use
};
```

Write the Stack default constructor and destructor in a way that is demonstrably exception-safe (works properly in the presence of exceptions) and exception-neutral (propagates all exceptions to the caller, without causing integrity problems in a Stack object).

Solution

Right away, we can see that Stack is going to have to manage dynamic memory resources. Clearly, one key is going to be avoiding leaks, even in the presence of exceptions thrown by T operations and standard memory allocations. For now, we'll manage these memory resources within each Stack

member function. Later on in this miniseries, we'll improve on this by using a private base class to encapsulate resource ownership.

Default Construction

First, consider one possible default constructor:

```
// Is this safe?

template<class T>
Stack<T>::Stack()
: v_(0),
  vsize_(10),
  vused_(0)        // nothing used yet
{
  v_ = new T[vsize_]; // initial allocation
}
```

Is this constructor exception-safe and exception-neutral? To find out, consider what might throw. In short, the answer is: any function. So the first step is to analyze this code and determine which functions will actually be called, including both free functions and constructors, destructors, operators, and other member functions.

This Stack constructor first sets vsize_ to 10, then attempts to allocate some initial memory using new T[vsize_]. The latter first tries to call operator new[]() (either the default operator new[]() or one provided by T) to allocate the memory, then tries to call T::T a total of vsize_ times. There are two operations that might fail. First, the memory allocation itself, in which case operator new[]() will throw a bad_alloc exception. Second, T's default constructor, which might throw anything at all, in which case any objects that were constructed are destroyed and the allocated memory is automatically guaranteed to be deallocated via operator delete[]().

Hence the above function is fully exception-safe and exception-neutral, and we can move on to the next…what? Why is the function fully robust, you ask? All right, let's examine it in a little more detail.

1. We're exception-neutral. We don't catch anything, so if the new throws, then the exception is correctly propagated up to our caller as required.

Guideline If a function isn't going to handle (or translate or deliberately absorb) an exception, it should allow the exception to propagate up to a caller who can handle it.

2. We don't leak. If the operator new[]() allocation call exited by throwing a bad_alloc exception, then no memory was allocated to begin with, so there can't be a leak. If one of the T constructors threw, then any T objects that were fully constructed were properly destroyed and, finally, operator delete[]() was automatically called to release the memory. That makes us leakproof, as advertised.

I'm ignoring for now the possibility that one of the T destructor calls might throw during the cleanup, which would call terminate() and simply kill the program altogether and leave events well out of your control anyway.

3. We're in a consistent state whether or not any part of the new throws. Now one might think that

if the new throws, then vsize_ has already been set to 10 when, in fact, nothing was successfully allocated. Isn't that inconsistent? Not really, because it's irrelevant. Remember, if the new throws, we propagate the exception out of our own constructor, right? And, by definition, "exiting a constructor by means of an exception" means our Stack proto-object never actually got to become a completely constructed object at all. Its lifetime never started, so its state is meaningless because the object never existed. It doesn't matter what the memory that briefly held vsize_ was set to, any more than it matters what the memory was set to after we leave an object's destructor. All that's left is raw memory, smoke, and ashes.

Guideline Always structure your code so that resources are correctly freed and data is in a consistent state even in the presence of exceptions.

All right, I'll admit it: I put the new in the constructor body purely to open the door for that third discussion. What I'd actually prefer to write is:

```
template<class T>
Stack<T>::Stack()
  : v_(new T[10]),  // default allocation
    vsize_(10),
    vused_(0)       // nothing used yet
{
}
```

Both versions are practically equivalent. I prefer the latter because it follows the usual good practice of initializing members in initializer lists whenever possible.

Destruction
The destructor looks a lot easier, once we make a (greatly) simplifying assumption.

```
template<class T>
Stack<T>::~Stack()
{
  delete[] v_;      // this can't throw
}
```

Why can't the delete[] call throw? Recall that this invokes T::~T for each object in the array, then calls operator delete[]() to deallocate the memory. We know that the deallocation by operator delete[]() may never throw, because the standard requires that its signature is always one of the following:[2]

[2] As Scott Meyers pointed out in private communication, strictly speaking this doesn't prevent someone from providing an overloaded operator delete[] that does throw, but any such overload would violate this clear intent and should be considered defective.

```
void operator delete[]( void* ) throw();
void operator delete[]( void*, size_t ) throw();
```

Hence, the only thing that could possibly throw is one of the T::~T calls, and we're arbitrarily going to have Stack require that T::~T may not throw. Why? To make a long story short, we just can't implement the Stack destructor with complete exception safety if T::~T can throw, that's why.

However, requiring that T::~T may not throw isn't particularly onerous, because there are plenty of other reasons why destructors should never be allowed to throw at all.[3] Any class whose destructor can throw is likely to cause you all sorts of other problems sooner or later, and you can't even reliably new[] or delete[] an array of them. More on that as we continue in this miniseries.

[3] Frankly, you won't go far wrong if you habitually write throw() after the declaration of every destructor you ever write. Even if exception specifications cause expensive checks under your current compiler, at least write all your destructors as though they were specified as throw()—that is, never allow exceptions to leave destructors.

Guideline Observe the canonical exception safety rules: Never allow an exception to escape from a destructor or from an overloaded operator delete() or operator delete[](); write every destructor and deallocation function as though it had an exception specification of "throw()". More on this as we go on; this is an important theme.

Now that we have the default constructor and the destructor under our belts, we might be tempted to think that all the other functions will be about the same. Well, writing exception-safe and exception-neutral copy and assignment code presents its own challenges, as we shall now see.

Consider again Stack template:

```
template <class T> class Stack
{
public:
  Stack();
  ~Stack();
  Stack(const Stack&);
  Stack& operator=(const Stack&);
  /*...*/
private:
  T*     v_;      // ptr to a memory area big
  size_t vsize_;  //  enough for 'vsize_' T's
  size_t vused_;  // # of T's actually in use
};
```

Now write the Stack copy constructor and copy assignment operator so that both are demonstrably exception-safe (work properly in the presence of exceptions) and exception-neutral (propagate all exceptions to the caller, without causing integrity problems in a Stack object).

Solution

To implement the copy constructor and the copy assignment operator, let's use a common helper function, NewCopy, to manage allocating and growing memory. NewCopy takes a pointer to (src) and size of (srcsize) an existing T buffer, and returns a pointer to a new and possibly larger copy of the buffer, passing ownership of the new buffer to the caller. If exceptions are encountered, NewCopy correctly releases all temporary resources and propagates the exception in such a way that nothing is leaked.

```
template<class T>
```

```
T* NewCopy( const T* src,
            size_t   srcsize,
            size_t   destsize )
{
  assert( destsize >= srcsize );
  T* dest = new T[destsize];
  try
  {
    copy( src, src+srcsize, dest );
  }
  catch(...)
  {
    delete[] dest; // this can't throw
    throw;         // rethrow original exception
  }
  return dest;
}
```

Let's analyze this one step at a time.

1. In the new statement, the allocation might throw bad_alloc or the T::T's may throw anything. In either case, nothing is allocated and we simply allow the exception to propagate. This is both leak-free and exception-neutral.
2. Next, we assign all the existing values using T::operator=(). If any of the assignments fail, we catch the exception, free the allocated memory, and rethrow the original exception. This is again both leak-free and exception-neutral. However, there's an important subtlety here: T::operator=() must guarantee that if it does throw, then the assigned-to T object must be destructible.[4]

[4] As we progress, we'll arrive at an improved version of Stack that does not rely on T::operator=.

3. If the allocation and copy both succeed, then we return the pointer to the new buffer and relinquish ownership (that is, the caller is responsible for the buffer from here on out). The return simply copies the pointer value, which cannot throw.

Copy Construction

With NewCopy in hand, the Stack copy constructor is easy to write.

```
template<class T>
Stack<T>::Stack( const Stack<T>& other )
  : v_(NewCopy( other.v_,
                other.vsize_,
                other.vsize_ )),
    vsize_(other.vsize_),
    vused_(other.vused_)
{
}
```

The only possible exception is from NewCopy, which manages its own resources.
Copy Assignment

Next, we tackle copy assignment.

```
template<class T>
Stack<T>&
Stack<T>::operator=( const Stack<T>& other )
{
  if( this != &other )
  {
    T* v_new = NewCopy( other.v_,
                        other.vsize_,
                        other.vsize_ );
    delete[] v_;  // this can't throw
    v_ = v_new;   // take ownership
    vsize_ = other.vsize_;
    vused_ = other.vused_;
  }
  return *this;   // safe, no copy involved
}
```

Again, after the routine weak guard against self-assignment, only the NewCopy call might throw. If it does, we correctly propagate that exception, without affecting the Stack object's state. To the caller, if the assignment throws then the state is unchanged, and if the assignment doesn't throw, then the assignment and all its side effects are successful and complete.

What we see here is the following very important exception-safety idiom.

Guideline Observe the canonical exception-safety rules: In each function, take all the code that might emit an exception and do all that work safely off to the side. Only then, when you know that the real work has succeeded, should you modify the program state (and clean up) using only nonthrowing operations.

Are you getting the hang of exception safety? Well, then, it must be time to throw you a curve ball. So get ready, and don't swing too soon.

Now for the final piece of original Stack template.

```
template <class T> class Stack
{
public:
  Stack();
  ~Stack();
  Stack(const Stack&);
  Stack& operator=(const Stack&);
size_t Count() const;
void  Push(const T&);
T    Pop(); // if empty, throws exception
```

```
private:
  T*     v_;      // ptr to a memory area big
  size_t vsize_;  //  enough for 'vsize_' T's
  size_t vused_;  // # of T's actually in use
};
```

Write the final three Stack functions: Count(), Push(), and Pop(). Remember, be exception-safe and exception-neutral!

Count()

The easiest of all Stack's members to implement safely is Count, because all it does is copy a builtin that can never throw.

```
template<class T>
size_t Stack<T>::Count() const
{
  return vused_;  // safe, builtins don't throw
}
```

No problem.

Push()

On the other hand, with Push, we need to apply our now-usual duty of care.

```
template<class T>
void Stack<T>::Push( const T& t )
{
  if( vused_ == vsize_ )  // grow if necessary
  {                       // by some grow factor
    size_t vsize_new = vsize_*2+1;
    T* v_new = NewCopy( v_, vsize_, vsize_new );
    delete[] v_;  // this can't throw
    v_ = v_new;   // take ownership
    vsize_ = vsize_new;
  }
  v_[vused_] = t;
  ++vused_;
}
```

If we have no more space, we first pick a new size for the buffer and make a larger copy using NewCopy. Again, if NewCopy throws, then our own Stack's state is unchanged and the exception propagates through cleanly. Deleting the original buffer and taking ownership of the new one involves only operations that are known not to throw, so the entire if block is exception-safe.

After any required grow operation, we attempt to copy the new value before incrementing our vused_ count. This way, if the assignment throws, the increment is not performed and our Stack's state is unchanged. If the assignment succeeds, the Stack's state is changed to recognize the presence of the new value, and all is well.

Guideline Observe the canonical exception-safety rules: In each function, take all the code that might emit an exception and do all that work safely off to the side; only then, when you know that the real work has succeeded, should you modify the program state (and clean up) using only nonthrowing operations.

Pop() Goes the Weasel

Only one function left. That wasn't so hard, was it? Well, don't get too happy yet, because it turns out that Pop is the most problematic of these functions to write with complete exception safety. Our initial attempt might look something like this:

```
// Hmmm... how safe is it really?

template<class T>
T Stack<T>::Pop()
{
  if( vused_ == 0)
  {
    throw "pop from empty stack";
  }
  else
  {
    T result = v_[vused_-1];
    --vused_;
    return result;
  }
}
```

If the stack is empty, we throw an appropriate exception. Otherwise, we create a copy of the T object to be returned, update our state, and return the T object. If the initial copy from v_[vused_-1] fails, the exception is propagated and the state of the Stack is unchanged, which is what we want. If the initial copy succeeds, our state is updated and the Stack is in its new consistent state, which is also what we want.

So this works, right? Well, kind of. There is a subtle flaw here that's completely outside the purview of Stack::Pop(). Consider the following client code:

```
string s1(s.Pop());
string s2;
s2 = s.Pop();
```

Note that above we talked about "the initial copy" (from v_[vused_-1]). That's because there is another copy[5] to worry about in either of the above cases—namely, the copy of the returned temporary into the destination. If that copy construction or copy assignment fails, then the Stack has completed its side effect (the top element has been popped off), but the popped value is now lost forever, because it never reached its destination (oops). This is bad news. In effect, it means that any version of Pop() that is written to return a temporary like this—and that therefore is responsible for two side effects—cannot be made completely exception-safe, because even though the function's implementation itself may look technically exception-safe, it forces clients of Stack to write exception-unsafe code. More generally,

mutator functions should not return T objects by value.

[5] For you experienced readers, yes, it's actually "zero or one copies," because the compiler is free to optimize away the second copy if the return value optimization applies. The point is that there can be a copy, so you have to be ready for it.

The bottom line—and it's significant—is this: Exception safety affects your class's design. In other words, you must design for exception safety from the outset, and exception safety is never "just an implementation detail."

Common Mistake

Never make exception safety an afterthought. Exception safety affects a class's design. It is never "just an implementation detail."

The Real Problem

One alternative—in fact, the minimum possible change[6]—is to respecify Pop as follows:

[6] The minimum possible acceptable change, that is. You could always simply change the original version to return T& instead of T (this would be a reference to the popped T object, because for the time being the popped object happens to still physically exist in your internal representation), and then the caller could still write exception-safe code. But this business of returning references to "I no longer consider it there" resources is purely evil. If you change your implementation in the future, this may no longer be possible! Don't go there.

```
template<class T>
void Stack<T>::Pop( T& result )
{
  if( vused_ == 0)
  {
    throw "pop from empty stack";
  }
  else
  {
    result = v_[vused_-1];
    --vused_;
  }
}
```

This ensures that the Stack's state is not changed unless the copy safely arrives in the caller's hands.

But the real problem is that, as specified, Pop() has two responsibilities—namely, to pop the top-most element and to return the just-popped value.

Guideline Prefer cohesion. Always endeavor to give each piece of code—each module, each class, each function—a single, well-defined responsibility.

So another option (and preferable, in my opinion) is to separate the functions of "querying the top-most

value" and "popping the top-most value off the stack." We do this by having one function for each.

```
template<class T>
T& Stack<T>::Top()
{
  if( vused_ == 0)
  {
    throw "empty stack";
  }
  return v_[vused_-1];
}

template<class T>
void Stack<T>::Pop()
{
  if( vused_ == 0)
  {
    throw "pop from empty stack";
  }
  else
  {
    --vused_;
  }
}
```

Incidentally, have you ever grumbled at the way the standard library containers' pop functions (for example, list::pop_back, stack::pop, etc.) don't return the popped value? Well, here's one reason to do this: It avoids weakening exception safety.

In fact, you've probably noticed that the above separated Top and Pop now match the signatures of the top and pop members of the standard library's stack<> adapter. That's no coincidence. We're actually only two public member functions away from the stack<> adapter's full public interface—namely:

```
template<class T>
const T& Stack<T>::Top() const
{
  if( vused_ == 0)
  {
    throw "empty stack";
  }
  else
  {
    return v_[vused_-1];
  }
}
```

to provide Top for const Stack objects, and:

```
template<class T>
```

```
bool Stack<T>::Empty() const
{
  return( vused_ == 0 );
}
```

Of course, the standard stack<> is actually a container adapter that's implemented in terms of another container, but the public interface is the same and the rest is just an implementation detail.

There's just one more fundamental point I want to drive home. I'll leave the following with you to ponder.

Common Mistake

"Exception-unsafe" and "poor design" go hand in hand. If a piece of code isn't exception-safe, that's generally okay and can simply be fixed. But if a piece of code cannot be made exception-safe because of its underlying design, that almost always is a signal of its poor design. Example 1: A function with two different responsibilities is difficult to make exception-safe. Example 2: A copy assignment operator that is written in such a way that it must check for self-assignment is probably not strongly exception-safe either

You will see Example 2 demonstrated very soon in this miniseries. Note that copy assignment operators may well elect to check for self-assignment even if they don't have to—for example, they might do so for efficiency. But a copy assignment operator that has to check for self-assignment (and else would not work correctly for self-assignment) is probably not strongly exception-safe.

Mid-series interlude: What have we accomplished so far?

Now that we have implemented an exception-safe and exception-neutral Stack<T>, answer these questions as precisely as possible:

1. What are the important exception-safety guarantees?
2. For the Stack<T> that was just implemented, what are the requirements on T, the contained type?

Solution

Just as there's more than one way to skin a cat (I have a feeling I'm going to get enraged e-mail from animal lovers), there's more than one way to write exception-safe code. In fact, there are two main alternatives we can choose from when it comes to guaranteeing exception safety. These guarantees were first set out in this form by Dave Abrahams.

1. Basic guarantee: Even in the presence of exceptions thrown by T or other exceptions, Stack objects don't leak resources. Note that this also implies that the container will be destructible and usable even if an exception is thrown while performing some container operation. However, if an exception is thrown, the container will be in a consistent, but not necessarily predictable, state. Containers that support the basic guarantee can work safely in some settings.
2. Strong guarantee: If an operation terminates because of an exception, program state will remain unchanged. This always implies commit-or-rollback semantics, including that no references or iterators

into the container be invalidated if an operation fails. For example, if a Stack client calls Top and then attempts a Push that fails because of an exception, then the state of the Stack object must be unchanged and the reference returned from the prior call to Top must still be valid. For more information on these guarantees, see Dave Abrahams's documentation of the SGI exception-safe standard library adaptation at: http://www.gotw.ca/publications/xc++/da_stlsafety.htm.

Probably the most interesting point here is that when you implement the basic guarantee, the strong guarantee often comes along for free.[7] For example, in our Stack implementation, almost everything we did was needed to satisfy just the basic guarantee—and what's presented above very nearly satisfies the strong guarantee, with little or no extra work.[8] Not half bad, considering all the trouble we went to.

[7] Note that I said "often," not "always." In the standard library, for example, vector is a well-known counter-example in which satisfying the basic guarantee does not cause the strong guarantee to come along for free.

[8] There is one subtle way in which this version of Stack still falls short of the strong guarantee. If Push() is called and has to grow its internal buffer, but then its final v_[vused_] = t; assignment throws, the Stack is still in a consistent state, but its internal memory buffer has moved—which invalidates any previously valid references returned from Top(). This last flaw in Stack::Push() can be fixed fairly easily by moving some code and adding a try block. For a better solution, however, see the Stack presented in the second half of this miniseries. That Stack does not have the problem, and it does satisfy the strong commit-or-rollback guarantee.

In addition to these two guarantees, there is one more guarantee that certain functions must provide in order to make overall exception safety possible:

3. Nothrow guarantee: The function will not emit an exception under any circumstances. Overall exception safety isn't possible unless certain functions are guaranteed not to throw. In particular, we've seen that this is true for destructors; later in this miniseries, we'll see that it's also needed in certain helper functions, such as Swap().

Guideline Understand the basic, strong, and nothrow exception-safety guarantees.

Now we have some points to ponder. Note that we've been able to implement Stack to be not only exception-safe but fully exception-neutral, yet we've used only a single try/catch. As we'll see next time, using better encapsulation techniques can get rid of even this try block. That means we can write a strongly exception-safe and exception-neutral generic container, without using try or catch—very natty, very elegant.

For the template as we've seen it so far, Stack requires its instantiation type to have all of the following:

* Default constructor (to construct the v_ buffers)
* Copy constructor (if Pop returns by value)
* Nonthrowing destructor (to be able to guarantee exception-safety)
* Exception-safe copy assignment (To set the values in v_, and if the copy assignment throws, then it must guarantee that the target object is still a valid T. Note that this is the only T member function that must be exception-safe in order for our Stack to be exception-safe.)

In the second half of this miniseries, we'll also see how to reduce even these requirements, without compromising exception safety. Along the way, we'll get an even more-detailed look at the standard operation of the statement delete[] x;.

All right, you've had enough rest—roll up your sleeves, and get ready for a wild ride.

Now we're ready to delve a little deeper into the same example, and write not just one but two new-and-improved versions of Stack. Not only is it, indeed, possible to write exception-safe generic containers, but by the time this miniseries is over, we'll have created no fewer than three complete solutions to the exception-safe Stack problem.

Along the way, we'll also discover the answers to several more interesting questions:

* How can we use more-advanced techniques to simplify the way we manage resources and get rid of the last try/catch into the bargain?
* How can we improve Stack by reducing the requirements on T, the contained type?
* Should generic containers use exception specifications?
* What do new[] and delete[] really do?

The answer to the last question may be quite different from what one might expect. Writing exception-safe containers in C++ isn't rocket science; it just requires significant care and a good understanding of how the language works. In particular, it helps to develop a habit of eyeing with mild suspicion anything that might turn out to be a function call—including user-defined operators, user-defined conversions, and silent temporary objects among the more subtle culprits—because any function call might throw.[9]

[9] Except for functions declared with an exception specification of throw() or certain functions in the standard library that are documented to never throw.

One way to greatly simplify an exception-safe container like Stack is to use better encapsulation. Specifically, we'd like to encapsulate the basic memory management work. Most of the care we had to take while writing our original exception-safe Stack was needed just to get the basic memory allocation right, so let's introduce a simple helper class to put all that work in one place.

```
template <class T> class StackImpl
{
/*????*/:
  StackImpl(size_t size=0);
  ~StackImpl();
  void Swap(StackImpl& other) throw();

  T*     v_;      // ptr to a memory area big
  size_t vsize_;  //  enough for 'vsize_' T's
  size_t vused_;  // # of T's actually in use

private:
  // private and undefined: no copying allowed
  StackImpl( const StackImpl& );
  StackImpl& operator=( const StackImpl& );
```

```
};
```

Note that StackImpl has all the original Stack's data members so that we've essentially moved the original Stack's representation entirely into StackImpl. StackImpl also has a helper function named Swap, which exchanges the guts of our StackImpl object with those of another StackImpl.

Your tasks:

1. Implement all three member functions of StackImpl, but not just any old way. Assume that at any time, the v_ buffer must contain exactly as many constructed T objects as there are T objects in the container, no more, no less. In particular, unused space in the v_ buffer should not contain constructed T objects.
2. Describe StackImpl's responsibilities. Why does it exist?
3. What should /*????*/ be? How does the choice affect how StackImpl will be used? Be as specific as possible.

Solution

We won't spend much time analyzing why the following functions are fully exception-safe (work properly in the presence of exceptions) and exception-neutral (propagate all exceptions to the caller), because the reasons are pretty much the same as those we discussed in detail in the first half of this miniseries. But do take a few minutes now to analyze these solutions, and note the commentary.

Constructor

The constructor is fairly straightforward. We'll use operator new() to allocate the buffer as raw memory. (Note that if we used a new-expression like new T[size], then the buffer would be initialized to default-constructed T objects, which was explicitly disallowed in the problem statement.)

```
template <class T>
StackImpl<T>::StackImpl( size_t size )
  : v_( static_cast<T*>
        ( size == 0
          ? 0
          : operator new(sizeof(T)*size) ) ),
    vsize_(size),
    vused_(0)
{
}
```

Destructor

The destructor is the easiest of the three functions to implement. Again, remember what we learned about operator delete() earlier in this miniseries. (See "Some Standard Helper Functions" for full details about functions such as destroy() and swap() that appear in the next few pieces of code.)

```
template <class T>
StackImpl<T>::~StackImpl()
{
    destroy( v_, v_+vused_ ); // this can't throw
    operator delete( v_ );
```

```
}
```

We'll see what destroy() is in a moment.

Some Standard Helper Functions

The Stack and StackImpl presented in this solution use three helper functions, one of which (swap()) also appears in the standard library: construct(), destroy(), and swap(). In simplified form, here's what these functions look like:

```
// construct() constructs a new object in
// a given location using an initial value
//
template <class T1, class T2>
void construct( T1* p, const T2& value )
{
  new (p) T1(value);
}
```

The above form of new is called "placement new," and instead of allocating memory for the new object, it just puts it into the memory pointed at by p. Any object new'd in this way should generally be destroyed by calling its destructor explicitly (as in the following two functions), rather than by using delete.

```
// destroy() destroys an object or a range
// of objects
//
template <class T>
void destroy( T* p )
{
  p->~T();
}
template <class FwdIter>
void destroy( FwdIter first, FwdIter last )
{
  while( first != last )
  {
    destroy( &*first );
    ++first;
  }
}
// swap() just exchanges two values
//
template <class T>
void swap( T& a, T& b )
{
  T temp(a); a = b; b = temp;
}
```

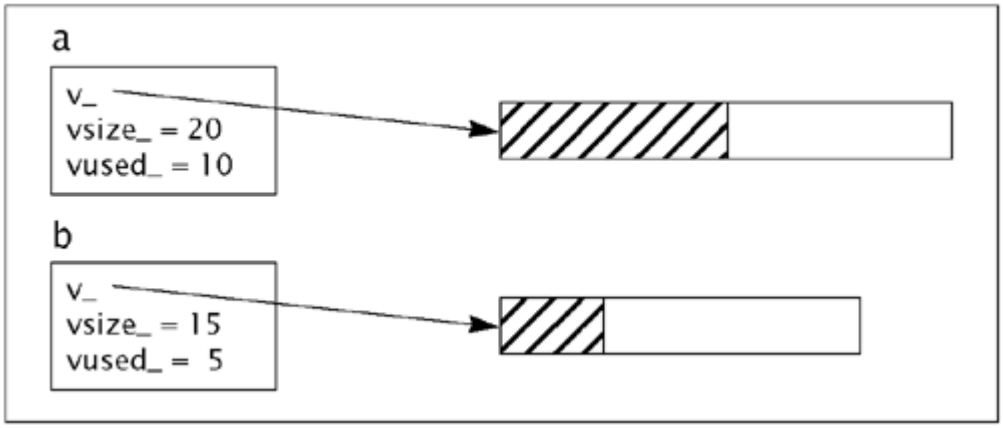
Of these, destroy(first,last) is the most interesting. We'll return to it a little later in the main miniseries; it illustrates more than one might think!
Swap

Finally, a simple but very important function. Believe it or not, this is the function that is instrumental in making the complete Stack class so elegant, especially its operator=(), as we'll see soon.

```
template <class T>
void StackImpl<T>::Swap(StackImpl& other) throw()
{
   swap( v_,     other.v_ );
   swap( vsize_, other.vsize_ );
   swap( vused_, other.vused_ );
}
```

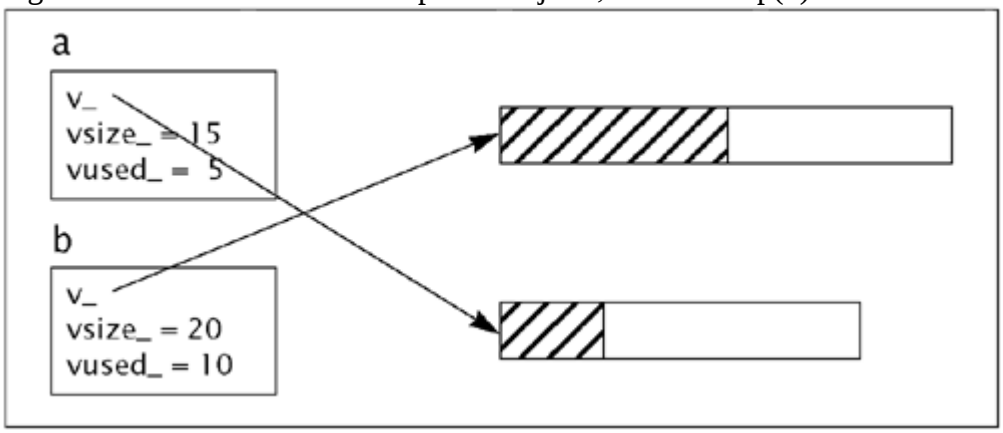
To picture how Swap() works, say that you have two StackImpl<T> objects a and b, as shown in Figure 1.

Figure 1. Two StackImpl<T> objects a and b



Then executing a.Swap(b) changes the state to that shown in Figure 2.

Figure 2. The same two StackImpl<T> objects, after a.Swap(b)



Note that Swap() supports the strongest exception guarantee of all—namely, the nothrow guarantee; Swap() is guaranteed not to throw an exception under any circumstances. It turns out that this feature of Swap() is essential, a linchpin in the chain of reasoning about Stack's own exception safety.

Why does StackImpl exist? Well, there's nothing magical going on here: StackImpl is responsible for simple raw memory management and final cleanup, so any class that uses it won't have to worry about those details.

Guideline Prefer cohesion. Always endeavor to give each piece of code—each module, each class, each function—a single, well-defined responsibility.

So what access specifier would you write in place of the comment "/*????*/"? Hint: The name StackImpl itself hints at some kind of "implemented-in-terms-of " relationship, and there are two main ways to write that kind of relationship in C++.

Technique 1: Private Base Class.The missing /*????*/ access specifier must be either protected or public. (If it were private, no one could use the class.) First, consider what happens if we make it protected.

Using protected means that StackImpl is intended to be used as a private base class. So Stack will be "implemented in terms of " StackImpl, which is what private inheritance means, and we have a clear division of responsibilities. The StackImpl base class will take care of managing the memory buffer and destroying all remaining T objects during Stack destruction, while the Stack derived class will take care of constructing all T objects within the raw memory. The raw memory management takes place pretty much entirely outside Stack itself, because, for example, the initial allocation must fully succeed before any Stack constructor body can be entered.

Technique 2: Private Member. Next, consider what happens if StackImpl's missing /*????*/ access specifier is public.

Using public hints that StackImpl is intended to be used as a struct by some external client, because its data members are public. So again, Stack will be "implemented in terms of " StackImpl, only this time using a HAS-A containment relationship instead of private inheritance. We still have the same clear division of responsibilities. The StackImpl object will take care of managing the memory buffer and destroying all T objects remaining during Stack destruction, and the containing Stack will take care of constructing T objects within the raw memory. Because data members are initialized before a class's constructor body is entered, the raw memory management still takes place pretty much entirely outside Stack, because, for example, the initial allocation must fully succeed before any Stack constructor body can be entered.

As we'll see when we look at the code, this second technique is only slightly different from the first.

And now for an even better Stack, with fewer requirements on T—not to mention a very elegant operator=().

Imagine that the /*????*/ comment in StackImpl stood for protected. Implement all the member functions of the following version of Stack, which is to be implemented in terms of StackImpl by using

StackImpl as a private base class.

```
template <class T>
class Stack : private StackImpl<T>
{
public:
  Stack(size_t size=0);
  ~Stack();
  Stack(const Stack&);
  Stack& operator=(const Stack&);
  size_t Count() const;
  void   Push(const T&);
  T&     Top();   // if empty, throws exception
  void   Pop();   // if empty, throws exception
};
```

As always, remember to make all the functions exception-safe and exception-neutral.

(Hint: There's a very elegant way to implement a fully safe operator=(). Can you spot it?)

Solution
The Default Constructor

Using the private base class method, our Stack class will look something like this (the code is shown inlined for brevity):

```
template <class T>
class Stack : private StackImpl<T>
{
public:
  Stack(size_t size=0)
    : StackImpl<T>(size)
  {
  }
```

Stack's default constructor simply calls the default constructor of StackImpl, that just sets the stack's state to empty and optionally performs an initial allocation. The only operation here that might throw is the new done in StackImpl's constructor, and that's unimportant when considering Stack's own exception safety. If it does happen, we won't enter the Stack constructor body and there will never have been a Stack object at all, so any initial allocation failures in the base class don't affect Stack.

Note that we slightly changed Stack's original constructor interface to allow a starting "hint" at the amount of memory to allocate. We'll make use of this in a minute when we write the Push function.

Guideline Observe the canonical exception-safety rules: Always use the "resource acquisition is initialization" idiom to isolate resource ownership and management.

The Destructor

Here's the first elegance: We don't need to provide a Stack destructor. The default compiler-generated Stack destructor is fine, because it just calls the StackImpl destructor to destroy any objects that were constructed and actually free the memory. Elegant.

The Copy Constructor

Note that the Stack copy constructor does not call the StackImpl copy constructor. (See the previous solution for a discussion of what construct() does.)

```
Stack(const Stack& other)
  : StackImpl<T>(other.vused_)
{
  while( vused_ < other.vused_ )
  {
    construct( v_+vused_, other.v_[vused_] );
    ++vused_;
  }
}
```

Copy construction is now efficient and clean. The worst that can happen here is that a T constructor could fail, in which case the StackImpl destructor will correctly destroy exactly as many objects as were successfully created and then deallocate the raw memory. One big benefit derived from StackImpl is that we could add as many more constructors as we want without putting clean-up code inside each one.

Elegant Copy Assignment

The following is an incredibly elegant and nifty way to write a completely safe copy assignment operator. It's even cooler if you've never seen the technique before.

```
Stack& operator=(const Stack& other)
{
  Stack temp(other); // does all the work
  Swap( temp );      // this can't throw
  return *this;
}
```

Do you get it? Take a minute to think about it before reading on.

This function is the epitome of a very important guideline that we've seen already.

Guideline Observe the canonical exception-safety rules: In each function, take all the code that might emit an exception and do all that work safely off to the side. Only then, when you know that the real work has succeeded, should you modify the program state (and clean up) using only nonthrowing operations.

It's beautifully elegant, if a little subtle. We just construct a temporary object from other, then call Swap to swap our own guts with temp's, and, finally, when temp goes out of scope and destroys itself, it automatically cleans up our old guts in the process, leaving us with the new state.

Note that when operator=() is made exception-safe like this, a side effect is that it also automatically

handles self-assignment (for example, Stack s; s = s;) correctly without further work. (Because self-assignment is exceedingly rare, I omitted the traditional if(this != &other) test, which has its own subtleties.)

Note that because all the real work is done while constructing temp, any exceptions that might be thrown (either by memory allocation or T copy construction) can't affect the state of our object. Also, there won't be any memory leaks or other problems from the temp object, because the Stack copy constructor is already strongly exception-safe. Once all the work is done, we simply swap our object's internal representation with temp's, which cannot throw (because Swap has a throw() exception specification, and because it does nothing but copy builtins), and we're done.

Note especially how much more elegant this is than the exception-safe copy assignment we implemented early. This version also requires much less care to ensure that it's been made properly exception-safe.

If you're one of those folks who like terse code, you can write the operator=() canonical form more compactly by using pass-by-value to create the temporary:

```
Stack& operator=(Stack temp)
{
  Swap( temp );
  return *this;
}
```

Stack<T>::Count()

Yes, Count() is still the easiest member function to write.

```
size_t Count() const
{
  return vused_;
}
```

Stack<T>::Push()

Push() needs a little more attention. Study it for a moment before reading on.

```
void Push( const T& t )
{
  if( vused_ == vsize_ )  // grow if necessary
  {
    Stack temp( vsize_*2+1 );
    while( temp.Count() < vused_ )
    {
      temp.Push( v_[temp.Count()] );
    }
    temp.Push( t );
    Swap( temp );
  }
```

```
  else
  {
    construct( v_+vused_, t );
    ++vused_;
  }
}
```

First, consider the simple else case: If we already have room for the new object, we attempt to construct it. If the construction succeeds, we update our vused_ count. This is safe and straightforward.

Otherwise, like last time, if we don't have enough room for the new element, we trigger a reallocation. In this case, we simply construct a temporary Stack object, push the new element onto that, and finally swap out our original guts to it to ensure they're disposed of in a tidy fashion.

But is this exception-safe? Yes. Consider:

* If the construction of temp fails, our state is unchanged and no resources have been leaked, so that's fine.
* If any part of the loading of temp's contents (including the new object's copy construction) fails by throwing an exception, temp is properly cleaned up when its destructor is called as temp goes out of scope.
* In no case do we alter our state until all the work has already been completed successfully.

Note that this provides the strong commit-or-rollback guarantee, because the Swap() is performed only if the entire reallocate-and-push operation succeeds. Any references returned from Top(), or iterators if we later chose to provide them, would never be invalidated (by a possible internal grow operation) if the insertion is not completely successful.

Stack<T>::Top()

Top() hasn't changed at all.

```
T& Top()
{
  if( vused_ == 0 )
  {
    throw "empty stack";
  }
  return v_[vused_-1];
}
```

Stack<T>::Pop()

Neither has Pop(), save the new call to destroy().

```
void Pop()
{
  if( vused_ == 0 )
    {
      throw "pop from empty stack";
```

```
    }
    else
    {
      --vused_;
      destroy( v_+vused_ );
    }
  }
};
```

In summary, Push() has been simplified, but the biggest benefit of encapsulating the resource ownership in a separate class was seen in Stack's constructor and destructor. Thanks to StackImpl, we can go on to write as many more constructors as we like, without having to worry about clean-up code, whereas last time each constructor would have had to know about the clean-up itself.

You may also have noticed that even the lone try/catch we had to include in the first version of this class has now been eliminated—that is, we've written a fully exception-safe and exception-neutral generic container without writing a single try! (Who says writing exception-safe code is trying?)

Only a slight variant—of course, operator=() is still very nifty.

Imagine that the /*????*/ comment in StackImpl stood for public. Implement all the member functions of the following version of Stack, which is to be implemented in terms of StackImpl by using a StackImpl member object.

```
template <class T>
class Stack
{
public:
  Stack(size_t size=0);
  ~Stack();
  Stack(const Stack&);
  Stack& operator=(const Stack&);
  size_t Count() const;
  void   Push(const T&);
  T&     Top();   // if empty, throws exception
  void   Pop();   // if empty, throws exception
private:
  StackImpl<T> impl_;  // private implementation
};
```

Don't forget exception safety.

Solution

This implementation of Stack is only slightly different from the last. For example, Count() returns impl_.vused_ instead of just an inherited vused_.

Here's the complete code:

```
template <class T>
class Stack
{
public:
  Stack(size_t size=0)
    : impl_(size)
  {
  }

  Stack(const Stack& other)
    : impl_(other.impl_.vused_)
  {
    while( impl_.vused_ < other.impl_.vused_ )
    {
      construct( impl_.v_+impl_.vused_,
                 other.impl_.v_[impl_.vused_] );
      ++impl_.vused_;
    }
  }

  Stack& operator=(const Stack& other)
  {
    Stack temp(other);
    impl_.Swap(temp.impl_); // this can't throw
    return *this;
  }

  size_t Count() const
  {
    return impl_.vused_;
  }

  void Push( const T& t )
  {
    if( impl_.vused_ == impl_.vsize_ )
    {
      Stack temp( impl_.vsize_*2+1 );
      while( temp.Count() < impl_.vused_ )
      {
        temp.Push( impl_.v_[temp.Count()] );
      }
      temp.Push( t );
      impl_.Swap( temp.impl_ );
    }
    else
    {
      construct( impl_.v_+impl_.vused_, t );
      ++impl_.vused_;
```

```
  }
 }

 T& Top()
 {
  if( impl_.vused_ == 0 )
  {
   throw "empty stack";
  }
  return impl_.v_[impl_.vused_-1];
 }

 void Pop()
 {
  if( impl_.vused_ == 0 )
  {
   throw "pop from empty stack";
  }
  else
  {
   --impl_.vused_;
   destroy( impl_.v_+impl_.vused_ );
  }
 }

private:
 StackImpl<T> impl_; // private implementation
};
```

Whew. That's a lot of impl_'s. Which brings us to the final question in this miniseries.

That's it—this is the final leg of the miniseries. The end of the line is a good place to stop and reflect, and that's just what we'll do for these last three problems.

1. Which technique is better—using StackImpl as a private base class, or as a member object?
2. How reusable are the last two versions of Stack? What requirements do they put on T, the contained type? (In other words, what kinds of T can our latest Stack accept? The fewer the requirements are, the more reusable Stack will be.)
3. Should Stack provide exception specifications on its functions?

Solution
Let's answer the questions one at a time.

1. Which technique is better—using StackImpl as a private base class, or as a member object?

Both methods give essentially the same effect and nicely separate the two concerns of memory management and object construction/destruction.

When deciding between private inheritance and containment, my rule of thumb is always to prefer the latter and use inheritance only when absolutely necessary. Both techniques mean "is implemented in terms of," and containment forces a better separation of concerns because the using class is a normal client with access to only the used class's public interface. Use private inheritance instead of containment only when absolutely necessary, which means when:

* You need access to the class's protected members, or
* You need to override a virtual function, or
* The object needs to be constructed before other base subobjects[10]

[10] Admittedly, in this case it's tempting to use private inheritance anyway for syntactic convenience so that we don't have to write "impl_." in so many places.

2. How reusable are the last two versions of Stack? What requirements do they put on T, the contained type?

When writing a templated class, particularly something as potentially widely useful as a generic container, always ask yourself one crucial question: How reusable is my class? Or, to put it a different way: What constraints have I put upon users of the class, and do those constraints unduly limit what those users might want to reasonably do with my class?

These Stack templates have two major differences from the first one we built. We've discussed one of the differences already. These latest Stacks decouple memory management from contained object construction and destruction, which is nice, but doesn't really affect users. However, there is another important difference. The new Stacks construct and destroy individual objects in place as needed, instead of creating default T objects in the entire buffer and then assigning them as needed.

This second difference turns out to have significant benefits: better efficiency and reduced requirements on T, the contained type. Recall that our original Stack required T to provide four operations:

* Default constructor (to construct the v_ buffers)
* Copy constructor (if Pop returns by value)
* Nonthrowing destructor (to be able to guarantee exception safety)
* Exception-safe copy assignment (To set the values in v_, and if the copy assignment throws, then it must guarantee that the target object is still a valid T. Note that this is the only T member function that must be exception-safe in order for our Stack to be exception-safe.)

Now, however, no default construction is needed, because the only T construction that's ever performed is copy construction. Further, no copy assignment is needed, because T objects are never assigned within Stack or StackImpl. On the other hand, we now always need a copy constructor. This means that the new Stacks require only two things of T:

* Copy constructor
* Nonthrowing destructor (to be able to guarantee exception safety)

How does this measure up to our original question about usability? Well, while it's true that many classes have both default constructors and copy assignment operators, many useful classes do not. (In fact, some objects simply cannot be assigned to, such as objects that contain reference members, because they cannot be reseated.) Now even these can be put into Stacks, whereas in the original version they could not. That's definitely a big advantage over the original version, and one that quite a few users are likely to appreciate as Stack gets reused over time.

Guideline Design with reuse in mind.

3. Should Stack provide exception specifications on its functions?

In short: No, because we, the authors of Stack, don't know enough, and we still probably wouldn't want to even if we did know enough. The same is true in principle for any generic container.

First, consider what we, as the authors of Stack, do know about T, the contained type: precious little. In particular, we don't know in advance which T operations might throw or what they might throw. We could always get a little totalitarian about it and start dictating additional requirements on T, which would certainly let us know more about T and maybe add some useful exception specifications to Stack's member functions. However, doing that would run completely counter to the goal of making Stack widely reusable, and so it's really out of the question.

Next, you might notice that some container operations (for example, Count()) simply return a scalar value and are known not to throw. Isn't it possible to declare these as throw()? Yes, but there are two good reasons why you probably wouldn't.

* Writing throw() limits you in the future in case you want to change the underlying implementation to a form that could throw. Loosening an exception specification always runs some risk of breaking existing clients (because the new revision of the class breaks an old promise), so your class will be inherently more resistant to change and therefore more brittle. (Writing throw() on virtual functions can also make classes less extensible, because it greatly restricts people who might want to derive from your classes. It can make sense, but such a decision requires careful thought.)
* Exception specifications can incur a performance overhead whether an exception is thrown or not, although many compilers are getting better at minimizing this. For widely-used operations and general-purpose containers, it may be better not to use exception specifications in order to avoid this overhead.

How well do you understand the innocuous expression delete[] p? What are its implications when it comes to exception safety?

And now, for the topic you've been waiting for: "Destructors That Throw and Why They're Evil."

Consider the expression delete[] p;, where p points to a valid array on the free store, which was properly allocated and initialized using new[].

1. What does delete[] p; really do?
2. How safe is it? Be as specific as possible.

Solution
This brings us to a key topic, namely the innocent looking delete[] p;. What does it really do? And how safe is it?
Destructors That Throw and Why They're Evil

First, recall our standard destroy helper function:

```
template <class FwdIter>
void destroy( FwdIter first, FwdIter last )
```

```
{
  while( first != last )
  {
    destroy( &*first ); // calls "*first"'s destructor
    ++first;
  }
}
```

This was safe in our example above, because we required that T destructors never throw. But what if a contained object's destructor were allowed to throw? Consider what happens if destroy is passed a range of five objects. If the first destructor throws, then as it is written now, destroy will exit and the other four objects will never be destroyed. This is obviously not a good thing.

"Ah," you might interrupt, "but can't we clearly get around that by writing destroy to work properly in the face of T's whose destructors are allowed to throw?" Well, that's not as clear as one might think. For example, you'd probably start writing something like this:

```
template <class FwdIter>
void destroy( FwdIter first, FwdIter last )
{
  while( first != last )
  {
    try
    {
      destroy( &*first );
    }
    catch(...)
    {
      /* what goes here? */
    }
    ++first;
  }
}
```

The tricky part is the "what goes here?" There are really only three choices: the catch body rethrows the exception, it converts the exception by throwing something else, or it throws nothing and continues the loop.

1. If the catch body rethrows the exception, then the destroy function nicely meets the requirement of being exception-neutral, because it does indeed allow any T exceptions to propagate out normally. However, it still doesn't meet the safety requirement that no resources be leaked if exceptions occur. Because destroy has no way of signaling how many objects were not successfully destroyed, those objects can never be properly destroyed, so any resources associated with them will be unavoidably leaked. Definitely not good.
2. If the catch body converts the exception by throwing something else, we've clearly failed to meet both the neutrality and the safety requirements. Enough said.
3. If the catch body does not throw or rethrow anything, then the destroy function nicely meets the safety requirement that no resources be leaked if an exception is thrown.[11]

[11] True, if a T destructor could throw in a way that its resources might not be completely released, then there could still be a leak. However, this isn't destroy's problem...this just means that T itself is not exception-safe. But destroy is still properly leak-free in that it doesn't fail to release any resources that it should (namely the T objects themselves).

However, it obviously fails to meet the neutrality requirement that T exceptions be allowed to pass through because exceptions are absorbed and ignored (as far as the caller is concerned, even if the catch body does attempt to do some sort of logging).

I've seen people suggest that the function should catch the exception and "save" it while continuing to destroy everything else, then rethrow it at the end. That too isn't a solution—for example, it can't correctly deal with multiple exceptions should multiple T destructors throw (even if you save them all until the end, you can end by throwing only one of them and the others are silently absorbed). You might be thinking of other alternatives, but trust me, they all boil down to writing code like this somewhere, because you have a set of objects and they all need to be destroyed. Someone, somewhere, is going to end up writing exception-unsafe code (at best) if T destructors are ever allowed to throw.

Which brings us to the innocent-looking new[] and delete[].

The issue with both of these is that they have fundamentally the same problem we just described for destroy. For example, consider the following code:

```
T* p = new T[10];
delete[] p;
```

Looks like normal, harmless C++, doesn't it? But have you ever wondered what new[] and delete[] do if a T destructor throws? Even if you have wondered, you can't know the answer for the simple reason that there is none. The standard says you get undefined behavior if a T destructor throws anywhere in this code, which means that any code that allocates or deallocates an array of objects whose destructors could throw can result in undefined behavior. This may raise some eyebrows, so let's see why this is so.

First, consider what happens if the constructions all succeed and, then, during the delete[] operation, the fifth T destructor throws. Then delete[], has the same catch-22 problem[12] outlined above for destroy. It can't allow the exception to propagate because then the remaining T objects would be irretrievably undestroyable, but it also can't translate or absorb the exception because then it wouldn't be exception-neutral.

[12] Pun intended.

Second, consider what happens if the fifth constructor throws. Then the fourth object's destructor is invoked, then the third's, and so on until all the T objects that were successfully constructed have again been destroyed, and the memory is safely deallocated. But what if things don't go so smoothly? In particular, what if, after the fifth constructor throws, the fourth object's destructor throws? And, if that's ignored, the third's? You can see where this is going.

If destructors may throw, then neither new[] nor delete[] can be made exception-safe and exception-neutral.

The bottom line is simply this: Don't ever write destructors that can allow an exception to escape.[13]

If you do write a class with such a destructor, you will not be able to safely even new[] or delete[] an array of those objects. All destructors should always be implemented as though they had an exception specification of throw()—that is, no exceptions must ever be allowed to propagate.

[13] As of the London meeting in July of 1997, the draft makes the blanket statement: "No destructor operation defined in the C++ Standard Library will throw an exception." Not only do all the standard classes have this property, but in particular it is not permitted to instantiate a standard container with a type whose destructor does throw. The rest of the guarantees I'm going to outline were fleshed out at the following meeting (Morristown, N.J., November 1997, which was the meeting at which the completed standard was voted out).

Guideline Observe the canonical exception safety rules: Never allow an exception to escape from a destructor or from an overloaded operator delete() or operator delete[](); write every destructor and deallocation function as though it had an exception specification of "throw()."

Granted, some may feel that this state of affairs is a little unfortunate, because one of the original reasons for having exceptions was to allow both constructors and destructors to report failures (because they have no return values). This isn't quite true, because the intent was mainly for constructor failures (after all, destructors are supposed to destroy, so the scope for failure is definitely less). The good news is that exceptions are still perfectly useful for reporting construction failures, including array and array-new[] construction failures, because there they can work predictably, even if a construction does throw.
Safe Exceptions

The advice "be aware, drive with care" certainly applies to writing exception-safe code for containers and other objects. To do it successfully, you do have to meet a sometimes significant extra duty of care. But don't get unduly frightened by exceptions. Apply the guidelines outlined above—that is, isolate your resource management, use the "update a temporary and swap" idiom, and never write classes whose destructors can allow exceptions to escape—and you'll be well on your way to safe and happy production code that is both exception-safe and exception-neutral. The advantages can be both concrete and well worth the trouble for your library and your library's users.

For your convenience (and, hopefully, your future review), here is the "exception safety canonical form" summarized in one place.

Guideline Observe the canonical exception-safety rules: (1) Never allow an exception to escape from a destructor or from an overloaded operator delete() or operator delete[](); write every destructor and deallocation function as though it had an exception specification of "throw()." (2) Always use the "resource acquisition is initialization" idiom to isolate resource ownership and management. (3) In each function, take all the code that might emit an exception and do all that work safely off to the side. Only then, when you know that the real work has succeeded, should you modify the program state (and clean up) using only nonthrowing operations.

The end—at last. Thank you for considering this miniseries. I hope you've enjoyed it.

At this point, you're probably feeling a little drained and more than a little tired. That's understandable. So here's a final question as a parting gift—it's designed to make everyone remember the equally (if not more) tired people who had to figure this stuff out on their own from first principles and then scrambled hard to get reasonable exception-safety guarantees put into the standard library at the last minute. It's appropriate at this time to repeat public thanks to Dave Abrahams, Greg Colvin, Matt

Austern, and all the other "exceptional" people who helped get the current safety guarantees into the standard library—and who managed to complete the job literally days before the standard was frozen in November 1997, at the ISO WG21 / ANSI J16 meeting at Morristown, N.J., USA.

Is the C++ standard library exception-safe?
Explain.

Solution

Exception Safety and the Standard Library

Are the standard library containers exception-safe and exception-neutral? The short answer is: Yes.[14]

[14] Here, I'm focusing my attention on the containers and iterators portion of the standard library. Other parts of the library, such as iostreams and facets, are specified to provide at least the basic exception-safety guarantee.

* All iterators returned from standard containers are exception-safe and can be copied without throwing an exception.
* All standard containers must implement the basic guarantee for all operations: They are always destructible, and they are always in a consistent (if not predictable) state even in the presence of exceptions.
* To make this possible, certain important functions are required to implement the nothrow guarantee (are required not to throw)—including swap (the importance of which was illustrated by the example in the previous Item), allocator<T>::deallocate (the importance of which was illustrated by the discussion of operator delete() at the beginning of this miniseries) and certain operations of the template parameter types themselves (especially, the destructor, the importance of which was illustrated in Item 16 by the discussion headed "Destructors That Throw and Why They're Evil").
* All standard containers must also implement the strong guarantee for all operations (with two exceptions). They always have commit-or-rollback semantics so that an operation such as an insert either succeeds completely or else does not change the program state at all. "No change" also means that failed operations do not affect the validity of any iterators that happened to be already pointing into the container.
* There are only two exceptions to this point. First, for all containers, multi-element inserts ("iterator range" inserts) are never strongly exception-safe. Second, for vector<T> and deque<T> only, inserts and erases (whether single- or multi-element) are strongly exception-safe as long as T's copy constructor and assignment operator do not throw. Note the consequences of these particular limitations. Unfortunately, among other things, this means that inserting into and erasing from a vector<string> or a vector<vector<int> >, for example, are not strongly exception-safe.
* Why these particular limitations? Because to roll back either kind of operation isn't possible without extra space/time overhead, and the standard did not want to require that overhead in the name of exception safety. All other container operations can be made strongly exception-safe without overhead. So if you ever insert a range of elements into a container, or if T's copy constructor or assignment operator can throw and you insert into or erase from a vector<T> or a deque<T>, the container will not necessarily have predictable contents afterward and iterators into it may have been invalidated.

What does this mean for you? Well, if you write a class that has a container member and you perform range insertions, or you write a class that has a member of type vector<T> or deque<T>, and T's copy

constructor or assignment operator can throw, then you are responsible for doing the extra work to ensure that your own class's state is predictable if exceptions do occur. Fortunately, this "extra work" is pretty simple. Whenever you want to insert into or erase from the container, first take a copy of the container, then perform the change on the copy. Finally, use swap to switch over to using that new version after you know that the copy-and-change steps have succeeded.