Exception-Safe Coding

C++ Now! 2012 Talk by Jon Kalb

Website

http://exceptionsafecode.com

- Bibliography
- Video
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- Résumé

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Dedication

To the great teacher of Exception-Safe coding…

The Promise

- Easier to Read

  Easier to Understand and Maintain

- Easier to Write
- No time penalty
- 100% Robust

C++ 2003 C++ 2011

A Word on C++11

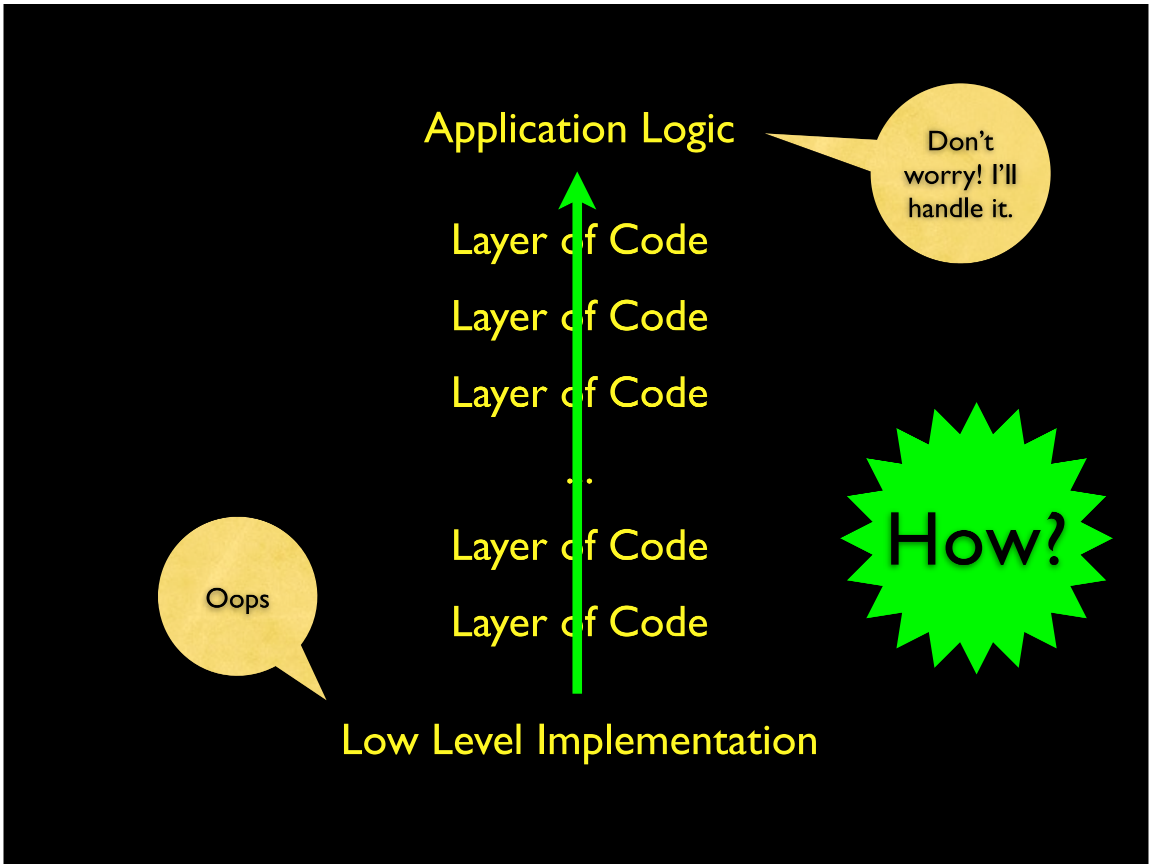
- I will cover both C++ 2003 and C++ 2011
  - Solid on classic C++
  - Some things still to learn about C++11
- No fundamental change in exception-safety
- Some new material
- Some material no longer necessary

Session Preview

- The problem
- Solutions that don't use exceptions
- Problems with exceptions as a solution
- How not to write Exception-Safe code
- Exception-Safe coding guidelines
- Implementation techniques

What's the Problem?

- Separation of Error Detection from Error Handling



Solutions without Exceptions

- Addressing the problem without exceptions
  - Error flagging
  - Return codes

Error Flagging

- errno
- "GetError" function

Error Flagging

```
errno = 0;
old_nice = getpriority(PRIO_PROCESS, 0);
/* check errno */
if (errno)
{
  /* handle error */
}
```

Problems with the Error Flagging Approach

- Errors can be ignored
  - Errors are ignored by default
- Ambiguity about which call failed
- Code is tedious to read and write

Return Codes

- Return values are error/status codes
  - (Almost) every API returns a code
  - Usually int or long
  - Known set of error/status values
  - Error codes relayed up the call chain

Problems with the Return Code Approach

- Errors can be ignored
  - Are ignored by default
  - If a single call "breaks the chain" by not returning an error, errors cases are lost
- Code is tedious to read and write
- Exception based coding addresses both of these issues…

… but has issues of its own.

The Dark Side

Broken error handling leads to bad states,

bad states lead to bugs,

bugs lead to suffering.

— Yoda

The Dark Side

Code using exceptions is no exception.


```
T& T::operator=(T const& x)
{
    if (this != &x)
    {
        this->~T(); // destroy in place
        new (this) T(x); // construct in place
    }
    return *this;
}
```

The Dark Side

Early adopters reluctant to embrace exceptions

The Dark Side

- Implementation issues are behind us
- Today's compilers:
  - Reliable, Performant, and Portable
- What causes concerns today?

Code Path Disruption

- Having error conditions that can't be ignored implies that the functions we are calling have unseen error returns.

" "

"Counter-intuitively, the hard part of coding exceptions is not the explicit throws and catches. The really hard part of using exceptions is to write all the intervening code in such a way that an arbitrary exception can propagate from its throw site to its handler, arriving safely and without damaging other parts of the program along the way."

– Tom Cargill

Counter-intuitively,

this is true of any error handling system.

Cargill's Article

- "Exception Handling: A False Sense of Security"
- Analyzed a templated Stack class
- Found problems, but no solution

Cargill's Stumper

```
template <class T> T Stack<T>::pop()
{
  if( top < 0 )
    throw "pop on empty stack";
  return v[top--];
}
```


Standard's Solution

```
template <class T> T& stack<T>::top();

template <class T> void stack<T>::pop();
```

Cargill's Article

- Spread Fear, Uncertainty, and Doubt
- Some said, "Proves exceptions aren't safe"

Cargill's Conclusions

- Didn't say exceptions were unsafe
- Didn't say exceptions were too hard to use
- Did say he didn't have all the answers

Cargill's Conclusions

Abrahams' Conclusions

"Exception-handling isn't hard.
Error-handling is hard.
Exceptions make it easier!"

Joel on Software

"Making Wrong Code Look Wrong."
2005-05-11 Blog entry

Joel on Software

```
dosomething();
cleanup();
```

"…exceptions are extremely dangerous."
– Joel Spolsky

Joel on Software

```
dosomething();
cleanup();
```

"That code is wrong."

– Jon Kalb

First Steps

- Carefully check return values/error codes to detect and correct problems.
- Identify functions that can throw and think about what to do when they fail
- Use exception specifications so the compiler can help create safe code.
- Use try/catch blocks to control code flow

The Hard Way

- Carefully check return values/error codes to detect and correct problems.
- Identify functions that can throw and think about what to do when they fail
- Use exception specifications so the compiler can help create safe code.
- Use try/catch blocks to control code flow

The Wrong Way

- Carefully check return values/error codes to detect and correct problems.
- Identify functions that can throw and think about what to do when they fail
- Use exception specifications so the compiler can help create safe code.
- Use try/catch blocks to control code flow

“You must unlearn what you have learned.”

— Yoda

The Right Way

- Think structurally
- Maintain invariants

Exception-Safe!

- Guidelines for code that is Exception-Safe
  - Few enough to fit on one slide
  - Hard requirements
  - Sound advice

Exception-Safety Guarantees (Abrahams)

- Basic
  - invariants of the component are preserved, and no resources are leaked
- Strong
  - if an exception is thrown there are no effects
- No-Throw
  - operation will not emit an exception

Exception-Safety Guarantees (Abrahams)

- Basic
  - invariants of the component are preserved, and no resources are leaked
- Strong

  Yoda:

  "Do or do not."
- No-Throw
  - operation will not emit an exception

Exception-Safety Assumptions

- Basic guarantee
  - Cannot create robust code using functions that don't provide at least the Basic guarantee – fixing this is priority zero
- All code throws unless we know otherwise
  - We are okay with this

Mechanics

- How exceptions work in C++
  - → Error detection / throw
  - Error handling / catch
  - New in C++11

Error Detection

```
{
   /* A runtime error is detected. */
   ObjectType object;
   throw object;
}
```

Is object thrown?

Can we throw a pointer?

Can we throw a reference?

Error Detection

```
{
   std::string s("This is a local string.");
   throw ObjectType(constructor parameters);
}
```

Mechanics

- How exceptions work in C++
  - Error detection / throw
  - → Error handling / catch
  - New in C++11


```
try
{
  code_that_might_throw();
}
catch (A a)  <== works like a function argument
{
   error_handling_code_that_can_use_a(a);
}
catch (...) <== "catch all" handler
{
   more_generic_error_handling_code();
}
more_code();
```

```
...
catch (A a)
{
    ...
```

- Issues with catching by value
  - Slicing
  - Copying


```
...
catch (A& a)
{
    a.mutating_member();
    throw;
}
```

```
try
{
    throw A();
}
catch (B) {}        // if B is a public base class of A
catch (B&) {}
catch (B const&) {}
catch (B volatile&) {}
catch (B const volatile&) {}
catch (A) {}
catch (A&) {}
catch (A const&) {}
catch (A volatile&) {}
catch (A const volatile&) {}
catch (void*) {}  // if A is a pointer
catch (…) {}
```


Guideline

- Throw by value.
- Catch by reference.

Performance Cost of try/catch

- No throw — no cost.
- In the throw case…
  - Don't know. Don't care.

Function Try Blocks

```
void F(int a)
{
    try
    {
        int b;
        ...
    }
    catch (std::exception const& ex)
    {
        ... // Can reference a, but not b
        ... // Can throw, return, or end
    }
}
```

Function Try Blocks

```
void F(int a)
try
{
    int b;
    ...
}
catch (std::exception const& ex)
{
  ... // Can reference a, but not b
  ... // Can throw, but can't "return"
}
```


Function Try Blocks

- What good are they?
- Constructors
  - How do you catch exceptions from base class or data member constructors?

Function Try Block for a Constructor

```
Foo::Foo(int a)
try :
Base(a),
member(a)
{
}
catch (std::exception& ex)
{
... // Can reference a, but not Base or member
// Can modify ex or throw a different exception...
// but an exception will be thrown
}
```


Function Try Blocks

- Only use is to change the exception thrown by the constructor of a base class or data member constructor

C++ 2011

Mechanics

- How exceptions work in C++
  - Error detection / throw
  - Error handling / catch
  - New in C++11

C++ 2011

C++11 Supported Scenarios

- Moving exceptions between threads
- Nesting exceptions

C++ 2011

Moving Exceptions Between Threads

- Capture the exception
- Move the exception like any other object
- Re-throw whenever we want

C++ 2011

Moving Exceptions Between Threads

Capturing is easy

<exception> declares:

```
exception_ptr current_exception() noexcept;
```

C++ 2011

Moving Exceptions Between Threads

- std::exception_ptr is copyable
- The exception exists as long as any std::exception_ptr using to it does
- Can be copied between thread like any other data

C++ 2011

Moving Exceptions Between Threads

```
std::exception_ptr ex(nullptr);
try {
...
}
catch(...) {
   ex = std::current_exception();
   ...
}
if (ex) {
...
```

C++ 2011

Moving Exceptions Between Threads

Re-throwing is easy

<exception> declares:

```
[[noreturn]] void rethrow_exception(exception_ptr p);
```


C++ 2011

Moving Exceptions Between Threads

A related scenario

```
int Func();  // might throw

std::future<int> f = std::async(Func());

int v(f.get());  // If Func() threw, it comes out here
```

C++ 2011

Nesting Exceptions

- Nesting the current exception
- Throwing a new exception with the nested one
- Re-throwing just the nested one

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Nesting Exceptions

Nesting the current exception is easy

<exception> declares:

```
class nested_exception;
```

Constructor implicitly calls current_exception() and holds the result.

C++ 2011

Nesting Exceptions

Throwing a new exception with the nested is easy <exception> declares:

```
[[noreturn]] template <class T>
void throw_with_nested(T&& t);
```

Throws a type that is inherited from both T and std:: nested_exception.

C++ 2011

Nesting Exceptions

```
try {
  try {
  ...
  } catch(...) {
    std::throw_with_nested(MyException());
  }
} catch (MyException&ex) {
  ... handle ex
  ... check if ex is a nested exception
  ... extract the contained exception
  ... throw the contained exception
}
```

C++ 2011

Nesting Exceptions

One call does all these steps

<exception> declares:

```
template <class E>
void rethrow_if_nested(E const& e);
```


C++ 2011

Nesting Exceptions

```
try {
   try {
   ...
   } catch(...) {
      std::throw_with_nested(MyException());
   }
} catch (MyException&ex) {
   ... handle ex
   ... check if ex is a nested exception
   ... extract the contained exception
   ... throw the contained exception
}
```

C++ 2011

Nesting Exceptions

```
try {
  try {
  ...
  } catch(...) {
    std::throw_with_nested(MyException());
  }
} catch (MyException&ex) {
  ... handle ex
  std::rethrow_if_nested(ex);
}
```


Standard Handlers

- The "Terminate" Handler
  - Calls std::abort()
  - We can write our own ...
    - …but it is too late.
- The "Unexpected" Handler
  - Calls the terminate handler
  - We can write our own ...
    - …but it is too late.

Standard Handlers

- The "Unexpected" Handler
  - Called when throwing an exception outside of (dynamic) exception specifications

73

C++ 2003

Exception Specifications

- Two flavors
  - C++ 2003
    - Exception Specifications
    - Now technically called *Dynamic* Exception Specifications

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C++ 2011

Exception Specifications

- Two flavors
  - C++ 2011
    - Introduces "noexcept" keyword
    - Deprecates Dynamic Exception Specifications

C++ 2003

Dynamic Exception Specifications

```
void F();  // may throw anything

void G() throw (A, B);  // may throw A or B

void H() throw ();  // may not throw anything
```

C++ 2003

Dynamic Exception Specifications

- Not checked at compile time.
- Enforced at run time.
  - By calling the "unexpected" handler and aborting.

C++ 2003

Guideline

- Do not use dynamic exception specifications.

C++ 2011

noexcept

- Two uses of “noexcept” keyword in C++11
  - noexcept specification (of a function)
  - noexcept operator

C++ 2011

noexcept

- As a noexcept exception specification

```
void F(); // may throw anything
void G() noexcept(Boolean constexpr);
void G() noexcept; // defaults to noexcept(true)
```

Destructors are noexcept by default.

C++ 2011

noexcept

- As an operator

```
static_assert(noexcept(2 + 3) , "");
static_assert(not noexcept(throw 23) , "");

inline int Foo() {return 0;}

static_assert(noexcept( Foo() ) , "");  // ???
```


C++ 2011

noexcept

- As an operator

```
static_assert(noexcept(2 + 3) , "");
static_assert(not noexcept(throw 23) , "");

inline int Foo() {return 0;}

static_assert(noexcept( Foo() ) , "");  // assert fails!
```

C++ 2011

noexcept

- As an operator

```
static_assert(noexcept(2 + 3) , "");
static_assert(not noexcept(throw 23) , "");

inline int Foo() noexcept {return 0;}

static_assert(noexcept( Foo() ) , "");  // true!
```


C++ 2011

noexcept

- How will noexcept be used?
- Operator form for no-throw based optimizations
  - move if no-throw, else do more expensive copying
- Unconditional form for simple user-defined types

```
struct Foo { Foo() noexcept {} };
```

- Conditional form for templates with operator form

```
template <typename T> struct Foo:T {
      Foo() noexcept( noexcept( T() ) ) {} };
```

C++ 2003 C++ 2011

Guideline

- Do not use dynamic exception specifications.
  - Do use noexcept.

C++ 2003 C++ 2011

Standard Handlers

- The “Terminate” Handler
  - Called when re-throw and there is no exception
  - Called when a “noexcept” function throws
  - Called when throwing when there is already an exception being thrown

C++ 2003 C++ 2011

How to not "Terminate"

- Don't re-throw outside of a catch block
  - ✔
- Don't throw from a "noexcept" function
  - ✔
- Don't throw when an exception is being thrown
  - When would that happen? After throw comes catch. What else happens?
    - Destructors!

Guideline

- Destructors must not throw.
  - Must deliver the No-Throw Guarantee.
  - Cleanup must always be safe.
  - May throw internally, but may not emit.

Safe Objects

- Exception-Safe Code is Built on Safe Objects

Object Lifetimes

- Order of construction:
  - Base class objects
    - As listed in the type definition, left to right
  - Data members
    - As listed in the type definition, top to bottom
    - Not as listed in the constructor's initializer list
  - Constructor body
- Order of destruction:
  - Exact reverse order of construction
- When does an object's lifetime begin?

Aborted Construction

- How?
  - Throw from constructor of base class, constructor of data member, constructor body
- What do we need to clean up?
  - Base class objects?
  - Data members?
  - Constructor body?
    - We need to clean up anything we do here because the destructor will ***not*** be called.
- What about new array?
- What about the object's memory?

Aborted Construction

- Throwing from a constructor
- Leaking object memory
- Placement new

Placement New

- Any use of new passing additional parameter
- Standard has “original placement new”
- Overload for “newing” an object in place

```
Object* obj = new(&buffer) Object;
```

- “Placement” can be misleading

Aborted Construction

- Throwing from a constructor
- Leaking object memory
- Placement new
- *Effective* C++, 3rd Ed.
  - Item 52:
    - Write placement `delete` if you write placement `new`.

Placement Delete

- We can’t pass parameters to the delete operator
- Only called if constructor throws during the “corresponding” placement new
- Not an error if not defined
  - It’s just a hard to find bug

RAII

- Resource Acquisition Is Initialization

RAII Examples

- Most smart pointers
- Many wrappers for
  - memory
  - files
  - mutexes
  - network sockets
  - graphic ports

RAII Examples

```
template <typename U> struct ArrayRAII
{
    ArrayRAII(int size): array_(new U[size]) {}
    ~ArrayRAII() {delete [] array_;}
    U* array() {return array_;}
    ...

private:
    // Cannot be default constructed or copied.
    ArrayRAII();
    ArrayRAII(ArrayRAII const&);
    ArrayRAII& operator=(ArrayRAII const&);

    U* array_;
};
```

What happens to the object if acquisition fails?

- Nothing

What happens to the object if acquisition fails?

- The object never exists.
- If you have the object, you have the resource.
- If the attempt to get the resource failed, then the constructor threw and we don't have the object.

RAII Cleanup

- Destructors have resource release responsibility.
- Some objects may have a “release” member function.
- Cleanup cannot throw
  - Destructors cannot throw

Design Guideline

- Each item (function or type) does just one thing.
- No object should manage more than one resource.

Every Resource in a Object

- If it isn't in an object, it isn't going to be cleaned up in a destructor and it may leak.
- Smart Pointers are your friend.

C++ 2003 C++ 2011

shared_pointer

- The smart pointer
  - From Boost
  - Was in the TR1
  - Is in C++ 2011
- Ref-counted
- Supports custom deleters

Smart Pointer "Gotcha"

- Is this safe?

```
FooBar(smart_ptr<Foo>(new Foo(f)),
          smart_ptr<Bar>(new Bar(b)));
```

"There's many a slip twixt the cup and the lip"

Smart Pointer "Gotcha"

- What is the rule?

"No more than one new in any statement."

```
a = FooBar(smart_ptr<Foo>(new Foo(f))) + Bar();
```

where we assume Bar() can throw

(Why do we assume Bar() can throw?)

Smart Pointer "Gotcha"

- What is the rule?

"Never incur a responsibility as part of an expression that can throw."

```
smart_ptr<T> t(new T);
```

Does both, but never at the same time.

Smart Pointer "Gotcha"

- But what about this?

```
smart_ptr<Foo> t(new Foo( F() ));
```

Does it violate the rule?

It is safe.

Smart Pointer "Gotcha"

- What is the rule?

> Assign ownership of every resource, immediately upon allocation, to a named manager object that manages no other resources.

Dimov's rule

Smart Pointer "Gotcha"

- A better way

```
auto r(std::make_shared<Foo>(f));
auto s(sutter::make_unique<Foo>(f));
```

- More efficient.
- Safer

Smart Pointer "Gotcha"

- Is this safe?

```
FooBar(std::make_shared<Foo>(f),
       std::make_shared<Bar>(b));
```

Yes!

Smart Pointer "Gotcha"

- A better rule

"Don't call new."

Smart Pointer "Gotcha"

- A better rule

  "~~Don't call new.~~"
  "Avoid calling new."

Lesson Learned

- Keep your resources on a short leash to not go leaking wherever they want.

Manage State Like a Resource

- Use objects to manage state in the same way that we use objects to manage any other resource.

RAII

- Resource Acquisition Is Initialization

RAII

- ~~Resource~~ Acquisition Is Initialization
  - “Resource” includes too much
  - “Resource” includes too little
- *Responsibility* Acquisition Is Initialization
  - *Responsibility* leaks
  - *Responsibility* management

Guideline

- Use RAII.
  - Responsibility Acquisition Is Initialization.
- Every responsibility is an object
- One responsibility per object

Cleanup Code

- Don’t write cleanup code that isn’t being called by a destructor.
- Destructors must cleanup all of an object’s outstanding responsibilities.
- Be suspicious of cleanup code not called by a destructor.

Joel on Software

```
dosomething();
cleanup();
```

“…exceptions are extremely dangerous.”
– Joel Spolsky

Jon on Software

```
{
    CleanupType   cleanup;
    dosomething();
}
```

"…Exception-Safe code is exceptionally safe."
– Jon Kalb

Guideline

- All cleanup code is called from a destructor.
- An object with such a destructor must be put on the stack as soon as calling the cleanup code become a responsibility.

The Cargill Widget Example

```
class Widget
{
  Widget& operator=(Widget const& );
      // Strong Guarantee ???
  // ...
private:
  T1 t1_;
  T2 t2_;
};
```


The Cargill Widget Example

```
Widget& Widget::operator=(Widget const& rhs) {
    T1 original(t1_);
    t1_ = rhs.t1_;
    try {
        t2_ = rhs.t2_;
    } catch (...) {
        t1_ = original;
        throw;
    }
}
```

The Cargill Widget Example

```
Widget& Widget::operator=(Widget const& rhs) {
   T1 original(t1_);
   t1_ = rhs.t1_;
   try {
      t2_ = rhs.t2_;
   } catch (...) {
      t1_ = original; <<=== can throw
      throw;
   }
}
```


The Cargill Widget Example

- Cargill's Points
  - Exception-safety is harder than it looks.
  - It can't be "bolted on" after the fact.
    - It need to be designed in from the beginning.
- Cargill's answer to the challenge:
  - No, it can't be done.
- Jon's answer:
  - Yes, it can.

C++ 2003

Fundamental Object Functions

- Construction
  - Default
  - Copy
- Destruction
- (Copy) Assignment operator
  - Value class
- The Rule of Three
- The Rule of Four
  - One more fundamental operator…

C++ 2003

The Swapperator

- swap()
- No-Throw swapping is a key exception-safety tool
- swap() is defined in std, but...
  - std::swap<>() not No-Throw (in classic C++)
- swap() for types we define can (almost) always be written as No-Throw

C++ 2003

The Swapperator

- Spelled “swap()”
- Write a one-parameter member function and two-parameter free function in the “std” namespace
  - If your type is a template, do not it put in “std”
- Both take parameters by (non-const) reference
- Does not throw!
- Is not written like this: swap() throw ()
  - Do not use dynamic exception specifications

C++ 2003

Swapperator Examples

```
struct BigInt {
    …
        void swap(BigInt&); // No Throw
          // swap bases, then members
    …
};
namespace std {
    template <> void swap<BigInt>(BigInt&a, BigInt&b)
    {a.swap(b);}
}
```

C++ 2003

Swapperator Examples

```
template <typename T>
struct CircularBuffer {
    ...
    void swap(CircularBuffer<T>&); // No Throw
    // Implementation will swap bases then members.
    ...
};
// not in namespace std
template <typename T>
void swap(CircularBuffer<T>&a, CircularBuffer<T>&b)
{a.swap(b);}
```


C++ 2003

Why No-Throw?

- That is the whole point
- std::swap<>() is always an option
  - But it doesn't promise No-Throw
    - It does three copies–Copies can fail!
- Our custom swaps can be No Throw
  - Don't use non-swapping base / member classes
  - Don't use const or reference data members
    - These are not swappable

C++ 2003

Guideline

- Create swapperator for value classes.
  - Must deliver the No-Throw guarantee.

C++ 2011

The Swapperator

- Swappertor new and improved for C++11
- std::swap() now with moves!
- can be noexcept...
  - for objects with noexcept move opertions

C++ 2011

The Swapperator

- To define swap() or not to define swap()
  - Not needed for exception-safety
    - noexcept move operators are enough
  - May be wanted for performance
  - If defined, declared as noexcept

C++ 2011

The Swapperator

- New rules for move operations
  - Kind of based on Rule of Three
    - If we create copy operations we must create our own move operations
- How to know we've done it right?
  - Call Jon!
    - (925) 890...

C++ 2011

The Swapperator

esc::check_swap() will verify at compile time that its argument's swapperator is declared noexcept

```
#include "esc.hpp"

template <typename T>
  void check_swap(T* = 0);
```

(Safe, but useless, in C++ 2003)

C++ 2011

The Swapperator

```
#include "esc.hpp"

{
   std::string a;
   esc::check_swap(&a);
   esc::check_swap<std::vector<int>>();
}
```

C++ 2011

The Swapperator

```
#include "esc.hpp"
struct MyType…
{
    …
    void AnyMember() {esc::check_swap(this); …}
    …
}
```


C++ 2011

The Swapperator

```
template <typename T> void check_swap(T* const t = 0)
{
    static_assert(noexcept(delete t), "msg...");
    static_assert(noexcept(T(std::move(*t))), "msg...");
    static_assert(noexcept(*t = std::move(*t)), "msg...");
    using std::swap;
    static_assert(noexcept(swap(*t, *t)), "msg...");
}
```

C++ 2011

The Swapperator

```
template <typename T> void check_swap(T* const t = 0)
{
    ...
    static_assert(
      std::is_nothrow_move_constructible<T>::value, "msg...");
    static_assert(
      std::is_nothrow_move_assignable<T>::value, "msg...");
   ...
}
```


Calling swap in a template

```
template…
{
    …
    using std::swap;
    swap(a, b);
    …
}
```

Calling swap in a template (alternative)

```
#include "boost/swap.hpp"

boost::swap(a, b);
```


C++ 2003

Guideline

- Create swapperator for value classes.
  - Must deliver the No-Throw guarantee.

C++ 2003

Guideline

- ~~Create~~ swapperator for value classes.
  - Must deliver the No-Throw guarantee.

C++ 2003 C++ 2011

Guideline

- Support swapperator for value classes.
  - Must deliver the No-Throw guarantee.

Guideline

- Support swapperator for value classes.
  - Must deliver the No-Throw guarantee.

C++ 2003 C++ 2011

Guideline

- Do not use dynamic exception specifications.
  - Do use noexcept.
    - Cleanup
      - Destructors are noexcept by default
    - Move/swap
    - Where else?
      - Wherever we can?

C++ 2003 | C++ 2011

Guideline

- Do not use dynamic exception specifications.
  - Do use noexcept.
    - Cleanup
      - Destructors are noexcept by default
    - Move/swap
    - Where else?
      - Wherever it is "natural" and free?

C++ 2003 | C++ 2011

Guideline

- Do not use dynamic exception specifications.
  - Do use noexcept.
    - Cleanup
      - Destructors are noexcept by default
    - Move/swap
    - Where else?
      - No where!

The Critical Line

- Implementing the Strong Guarantee
- Deferring the commit until success is guaranteed


```
struct ResourceOwner
{
        // …
        ResourceOwner& operator=(ResourceOwner const&rhs)
        {
            delete mResource;
            mResource = new Resource(*rhs.mResource);
            return *this;
        }
        // …
    private:
        // …
        Resource* mResource;
};
```

```
struct ResourceOwner
{
        // ...
        ResourceOwner& operator=(ResourceOwner const&rhs)
        {
            if (this != &rhs)
            {
                delete mResource;
                mResource = new Resource(*rhs.mResource);
                return *this;
            }
        }
        // ...
    private:
        // ...
        Resource* mResource;
};
```



```
struct ResourceOwner
{
        // ...
        ResourceOwner& operator=(ResourceOwner const&rhs)
        {
            if (this != &rhs)
            {
                Resource temp(*rhs.mResource);
                temp.swap(*mResource);
                return *this;
            }
        }
        // ...
    private:
        // ...
        Resource* mResource;
};
```

```
struct ResourceOwner
{
        // …
        ResourceOwner& operator=(ResourceOwner const&rhs)
        {
            Resource temp(*rhs.mResource);
            temp.swap(*mResource);
            return *this;
        }
        // …
    private:
        // …
        Resource* mResource;
};
```



```
void FunctionWithStrongGuarantee()
{
    // Code That Can Fail

    ObjectsThatNeedToBeModified.MakeCopies(OriginalObjects);
    ObjectsThatNeedToBeModified.Modify();
```

The Critical Line

```
    // Code That Cannot Fail (Has a No-Throw Guarantee)

    ObjectsThatNeedToBeModified.swap(OriginalObjects);
}
```

```
struct ResourceOwner
{
        // …
        ResourceOwner& operator=(ResourceOwner const&rhs)
        {
            Resource temp(*rhs.mResource);
```

The Critical Line

```
            temp.swap(*mResource);
            return *this;
        }
        // …
    private:
        // …
        Resource* mResource;
};
```



```
struct ResourceOwner
{
        // …
        void swap(ResourceOwner&); // No Throw
        ResourceOwner& operator=(ResourceOwner rhs)
        {
            swap(rhs);
            return *this;
        }
        // …
    private:
        // …
        Resource* mResource;
};
```

C++ 2003

```
struct ResourceOwner
{
        // ...
        void swap(ResourceOwner&); // No Throw
        ResourceOwner& operator=(ResourceOwner rhs)
        {
            swap(rhs);
            return *this;
        }
        // ...
    private:
        // ...
        Resource* mResource;
};
```


C++ 2011

```
struct ResourceOwner
{
        // ...
        void swap(ResourceOwner&) noexcept;
        ResourceOwner& operator=(ResourceOwner rhs);
        ResourceOwner& operator=(ResourceOwner&& rhs) noexcept;



        // ...
    private:
        // ...
        Resource* mResource;
};
```

C++ 2011

```
struct ResourceOwner
{
        // …
        void swap(ResourceOwner&) noexcept;
        ResourceOwner& operator=(ResourceOwner const&rhs);
        ResourceOwner& operator=(ResourceOwner&& rhs) noexcept;



        // …
    private:
        // …
        Resource* mResource;
};
```


C++ 2011

```
struct ResourceOwner
{
        // …
        void swap(ResourceOwner&) noexcept;
        ResourceOwner& operator=(ResourceOwner const&rhs)
        {
            ResourceOwner temp(rhs);
            swap(temp);
            return *this;
        }
    private:
        // …
        Resource* mResource;
};
```

Guideline

- Use "Critical Lines" for Strong Guarantees.

The Cargill Widget Example

```
Widget& Widget::operator=(Widget const& rhs) {
   T1 tempT1(rhs.t1_);
   T2 tempT2(rhs.t2_);
   t1_.swap(tempT1);
   t2_.swap(tempT2);
}
```

The Cargill Widget Example

```
Widget& Widget::operator=(Widget const& rhs) {
    T1 tempT1(rhs.t1_);
    T2 tempT2(rhs.t1_);
    The Critical Line
    t1_.swap(tempT1);
    t2_.swap(tempT2);
}

// Strong Guarantee achieved!
```


swap()

- The Force is strong in this one. — Yoda

Where to try/catch

- Switch
- Strategy
- Some success

Switch

- Anywhere that we need to switch our method of error reporting.

Switch Cases

- Anywhere that we support the No-Throw Guarantee
  - Destructors & Cleanup
  - Swapperator & Moves
- C-API
- OS Callbacks
- UI Reporting
- Converting to other exception types
- Threads

Strategy

- Anywhere that we have a way of dealing with an error such as an alternative or fallback method.

Some Success

- Anywhere that partial failure is acceptable.

Using ReadRecord() which throws when the database block is corrupt.

```
void DisplayContact(Database const& db, RecordID rID)
{
    ContactPtr contact(db.ReadRecord(rID));
    ContactWindowPtr contactWindow(CreateContactWindow());
    contactWindow->LoadContactData(contact);
    …
}
```

Using ReadRecord() which throws when the database block is corrupt.

```
void ScavengeDatabaseRecords(Database const& src, Database& dest)
{
    Recs recs(src.GetAllRecordIDs());
    for (Recs::const_iterator b(recs.begin()), e(recs.end()); b != e; ++b)
    {
        try
        {
            RecordPtr record(src.ReadRecord(*b));
            dest.WriteRecord(record);
        }
        catch (...) { /* possibly log that we failed to read this record. */ }
    }
}
```


Guideline

- Know where to catch.
    - Switch
    - Strategy
    - Some Success

“Most Important Design Guideline”

- Scott Meyers Known for C++ Advice
- Universal Design Principle
  - Not controversial

“Most Important Design Guideline”

Make interfaces easy to use correctly and hard to use incorrectly.

“Most Important Design Guideline”

ErrorCode SomeCall(...);

void SomeCall(...); // throws

Guideline

- Prefer Exceptions to Error Codes

Prefer Exceptions to Error Codes

- Throwing exceptions should be mostly about resource availability
- When possible, provide defined behavior and/or use strong pre-conditions instead of failure cases
- Don't use exceptions for general flow control
  - Exceptions getting thrown during normal execution is usually an indication of a design flaw

Exception-Safety Guidelines

- Throw by value. Catch by reference.
- No dynamic exception specifications. Use noexcept.
- Destructors that throw are evil.
- Use RAII. (Every responsibility is an object. One per.)
- All cleanup code called from a destructor
- Support swapperator (With No-Throw Guarantee)
- Draw "Critical Lines" for the Strong Guarantee
- Know where to catch (Switch/Strategy/Some Success)
- Prefer exceptions to error codes.

Implementation Techniques

- on_scope_exit
- Lippincott Functions
- boost::exception
- Transitioning from legacy code
- Before and After

on_scope_exit

- Creating a struct just to do one-off cleanup can be tedious.
- That is why we have on_scope_exit.

```
void CTableLabelBase::TrackMove( ... )  // This function
    // needs to set the cursor to the grab hand while it
{
    //   executes and set it back to the open hand afterwards.
    ...

    esc::on_scope_exit handRestore(&UCursor::SetOpenHandCursor);

    UCursor::SetGrabHandCursor();
    ...
}
```



```
Handle FillNewHandleFromDataFork( ... )  // This function needs to create a
    // Handle and fill it with the data from a file. If we fail in the read, we need to
    // dispose of the Handle
{
    Handle newHandle(::NewHandle( ... ));
    esc::on_scope_exit handleDisposer(bind(&::DisposeHandle, newHandle));
        ...
    if ( ... successful ... )
    {
        handleDisposer.release();    // Any code path that doesn't go through
                                     // here, will result in the Handle being
    }                                // handle being disposed of.
        ...
}
```

```
void JoelsFunction()
{
    dosomething();
    cleanup();
}
```


C++ 2011

```
void JoelsFunction()
{
    esc::on_scope_exit clean(cleanup);
    dosomething();
}
```

```
struct on_scope_exit
{
        typedef function<void(void)> exit_action_t;

        on_scope_exit(exit_action_t action): action_(action) {}
        ~on_scope_exit() {if (action_) action_();}
      void set_action(exit_action_t action = 0) {action_ = action;}
      void release() {set_action();}

   private:
        on_scope_exit();
        on_scope_exit(on_scope_exit const&);
      on_scope_exit& operator=(on_scope_exit const&rhs);
      exit_action_t action_;
};
```



```
... :: ... ( ... )    // This member function needs to do things that would
              // normally trigger notifications, but for the duration of
{             // this call we don't want to generate notifications.
              // We can temporarily suppress these notifications by
              // setting a data member to false but we need to remember
              // to reset the value no matter how we leave the function.
   ...

   esc::on_scope_exit
      resumeNotify(esc::revert_value(mSendNotifications));

   mSendNotifications = false;
   ...
}
```

```
template <typename T>
void set_value(T&t, T value) {t = value;}

template <typename T>
on_scope_exit::exit_action_t revert_value(T&t)
{
    return bind(set_value<T>, ref(t), t);
}
```


on_scope_exit source

- Source for esc namespace code (check_swap and on_scope_exit) is available at

  http://exceptionsafecode.com

Lippincott Functions

- A technique for factoring exception handling code.
- Example in *The C++ Standard Library* 2nd Ed. by Nicolai M. Josuttis page 50


```
C_APIStatus C_APIFunctionCall()
{
    C_APIStatus result(kC_APINoError);
    try
    {
        CodeThatMightThrow();
    }
    catch (FrameworkException const& ex)
    {result = ex.GetErrorCode();}
    catch (Util::OSStatusException const&ex)
    {result = ex.GetStatus();}
    catch (std::exception const&)
    {result = kC_APIUnknownError;}
    catch (...)
    {result = kC_APIUnknownError;}
    return result;
}
```

```
C_APIStatus C_APIFunctionCall()
{
    C_APIStatus result(kC_APINoError);
    try
    {
        CodeThatMightThrow();
    }
    catch (…)
    {
        result = ErrorFromException();
    }
    return result;
}
```



```
C_APIStatus ErrorFromException()
{
    C_APIStatus result(kC_APIUnknownError);
    try
    { throw; } // rethrows the exception caught in the caller's catch block.
    catch (FrameworkException const& ex)
    { result = ex.GetErrorCode(); }
    catch (Util::OSStatusException const&ex)
    { result = ex.GetStatus(); }
    catch (std::exception const&) { /* already kC_APIUnknownError */ }
    catch (...) { /* already kC_APIUnknownError */ }
    if (result == noErr) { result = kC_APIUnknownError; }
    return result;
}
```

boost::exception

- An interesting implementation to support enhanced trouble-shooting.
- Error detecting code may not have enough information for good error reporting.
- boost::exception supports layers adding information to an exception and re-throwing
- An exception to Switch/Strategy/Some Success?

Legacy Code

- Transitioning from pre-exception/exception-unsafe legacy code
  - Does not handle code path disruption gracefully
- Sean Parent's **Iron Law of Legacy Refactoring**
  - ***Existing contracts cannot be broken!***

Sean's Rules

1. All new code is written to be exception safe
2. Any ***new*** interfaces are free to throw an exception
3. When working on existing code, the interface to that code must be followed - *if it wasn't throwing exceptions before, it can't start now*
   a. Consider implementing a parallel call and re-implementing the old in terms of the new

Refactoring Steps

a. Consider implementing a parallel call and re-implementing the old in terms of the new

Refactoring Steps

1. Implement a parallel call following exception safety guidelines
2. Legacy call now calls new function wrapped in try/catch (...)
   a. Legacy API unchanged / doesn't throw
3. New code can always safely call throwing code
4. Retire wrapper functions as appropriate

Refactoring Steps

- Moving an large legacy code base still a big chore
- Can be done in small bites
  - Part of regular maintenance
  - No need to swallow an elephant
- Can move forward with confidence
  - Code base is never at risk!

Example Code

- First example I found
- Apple's FSCreateFileAndOpenForkUnicode sample code
- CreateReadOnlyForCurrentUserACL()
- "mbr_" and "acl_" APIs return non-zero error codes on error


```
static acl_t CreateReadOnlyForCurrentUserACL(void)
{
    acl_t  theACL = NULL;
    uuid_t  theUUID;
    int    result;

    result =  mbr_uid_to_uuid(geteuid(), theUUID);  // need the uuid for the ACE
    if (result == 0)
    {
        theACL = acl_init(1);  // create an empty ACL
        if (theACL)
        {
            Boolean freeACL = true;
            acl_entry_t newEntry;
            acl_permset_t newPermSet;

            result = acl_create_entry_np(&theACL, &newEntry, ACL_FIRST_ENTRY);
            if (result == 0)
            {  // allow
                result = acl_set_tag_type(newEntry, ACL_EXTENDED_ALLOW);
                if (result == 0)
                {  // the current user
                    result = acl_set_qualifier(newEntry, (const void *)theUUID);
                    if (result == 0)
                    {
                        result = acl_get_permset(newEntry, &newPermSet);
                        if (result == 0)
                        {  // to read data
                            result = acl_add_perm(newPermSet, ACL_READ_DATA);
                            if (result == 0)
                            {
                                result = acl_set_permset(newEntry, newPermSet);
                                if (result == 0)
                                    freeACL = false;  // all set up and ready to go
                            }
                        }
                    }
                }
            }
            if (freeACL)
            {
                acl_free(theACL);
                theACL = NULL;
            }
        }
    }
    return theACL;
}
```

Example Code

- Rewrite Assumptions
  - All “mbr_” and “acl_” APIs throw
  - acl_t RAII Wrapper Class

Example Rewrite

- Two versions of re-writes
  - intermediate.cpp
    - Does not throw
  - after.cpp
    - throws instead of returning a code

```
static acl_t CreateReadOnlyForCurrentUserACL()
{
   acl_t result(0);
   try
   {
      ACL    theACL(1);
      acl_entry_t newEntry;
      acl_create_entry_np(&theACL.get(), &newEntry, ACL_FIRST_ENTRY);

      // allow
      acl_set_tag_type(newEntry, ACL_EXTENDED_ALLOW);

      // the current user
      uuid_t    theUUID;
      mbr_uid_to_uuid(geteuid(), theUUID);  // need the uuid for the ACE
      acl_set_qualifier(newEntry, (const void *)theUUID);
      acl_permset_t newPermSet;
      acl_get_permset(newEntry, &newPermSet);

      // to read data
      acl_add_perm(newPermSet, ACL_READ_DATA);
      acl_set_permset(newEntry, newPermSet);

      // all set up and ready to go
      result = theACL.release();
   }
   catch (...) {}
   return result;
}
```



```
static acl_t CreateReadOnlyForCurrentUserACL()
{
   ACL    theACL(1);
   acl_entry_t newEntry;
   acl_create_entry_np(&theACL.get(), &newEntry, ACL_FIRST_ENTRY);

   // allow
   acl_set_tag_type(newEntry, ACL_EXTENDED_ALLOW);

   // the current user
   uuid_t    theUUID;
   mbr_uid_to_uuid(geteuid(), theUUID);  // need the uuid for the ACE
   acl_set_qualifier(newEntry, (const void *)theUUID);
   acl_permset_t newPermSet;
   acl_get_permset(newEntry, &newPermSet);

   // to read data
   acl_add_perm(newPermSet, ACL_READ_DATA);
   acl_set_permset(newEntry, newPermSet);

   // all set up and ready to go
   return theACL.release();
}
```

Before & After Example

- Advantages
  - More white space
  - 50% fewer lines
  - 100% fewer braces
  - 100% fewer control structures
- Easier to write and read, faster, and 100% robust

What does Exception-Safe Code look like?

- There is no “try.” — Yoda

The Coder's Fantasy

- Writing code without dealing with failure.

The Success Path

- The power of the Exception-Safe coding guidelines is the focus on the success path.

```
static acl_t CreateReadOnlyForCurrentUserACL()
{
    ACL    theACL(1);
    acl_entry_t newEntry;
    acl_create_entry_np(&theACL.get(), &newEntry, ACL_FIRST_ENTRY);

    // allow
    acl_set_tag_type(newEntry, ACL_EXTENDED_ALLOW);

    // the current user
    uuid_t    theUUID;
    mbr_uid_to_uuid(geteuid(), theUUID);  // need the uuid for the ACE
    acl_set_qualifier(newEntry, (const void *)theUUID);
    acl_permset_t newPermSet;
    acl_get_permset(newEntry, &newPermSet);

    // to read data
    acl_add_perm(newPermSet, ACL_READ_DATA);
    acl_set_permset(newEntry, newPermSet);

    // all set up and ready to go
    return theACL.release();
}
```


The Promise

- Easier to Read

  Easier to Understand and Maintain
- Easier to Write
- No time penalty
- 100% Robust

The Promise

- Why easier to read and write?
  - Many fewer lines of code
    - No error propagation code
  - Focus on the success path only

The Promise

- Why no time penalty?
  - As fast as if errors handling is ignored!
    - No return code checking
  - Compiler knows error handling code
    - catch blocks can be appropriately (de)optimitized

The Promise

- Why 100% robust?
  - Errors are never ignored
  - Errors do not leave us in bad states
  - No leaks

Thank you

- Visit:

  http://exceptionsafecode.com
- Send me hate mail or good reviews:

  jon@exceptionsafecode.com
- Please Follow me on Twitter:

  @JonathanKalb
- Send me your résumé:

  jonkalb@a9.com

Exception-Safe Coding

Questions?

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