Exception-Safe Coding

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Website

http://exceptionsafecode.com

- Bibliography
- Video
- Comments

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- Résumé

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Dedication

To the great teacher of Exception-Safe coding…

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?

What's the Problem?

- Separation of Error Detection from Error Handling

Application Logic

Low Level Implementation

Application Logic

Layer of Code

Layer of Code

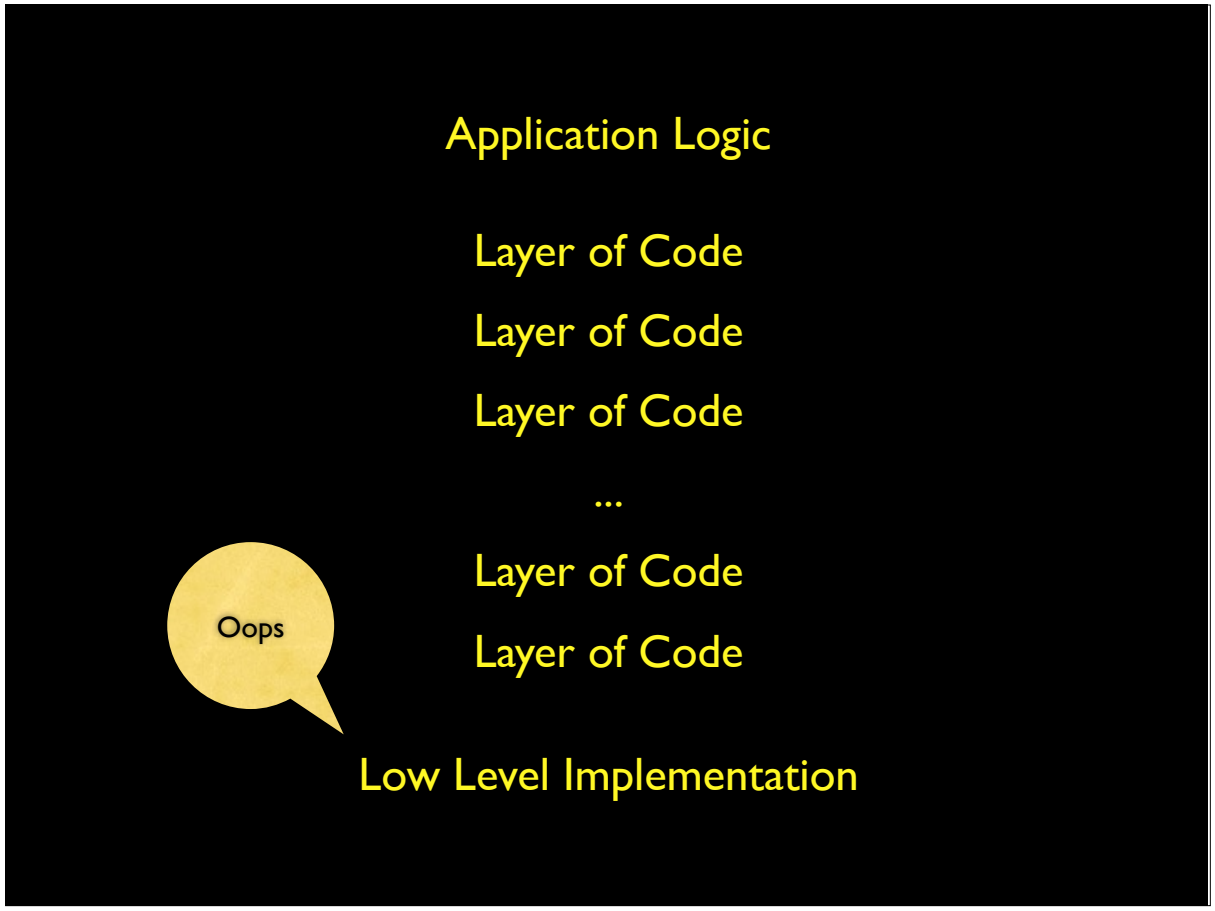
Layer of Code

...

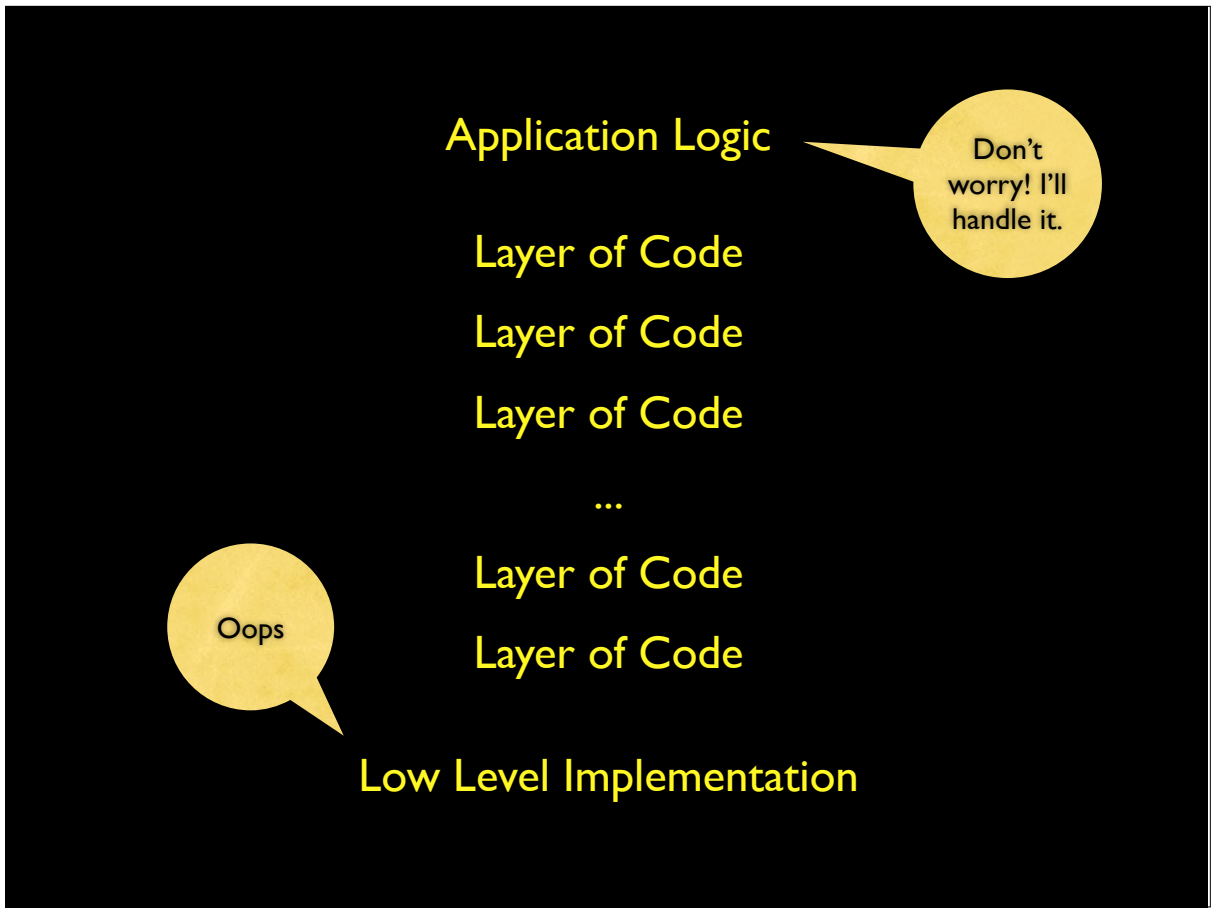
Layer of Code

Layer of Code

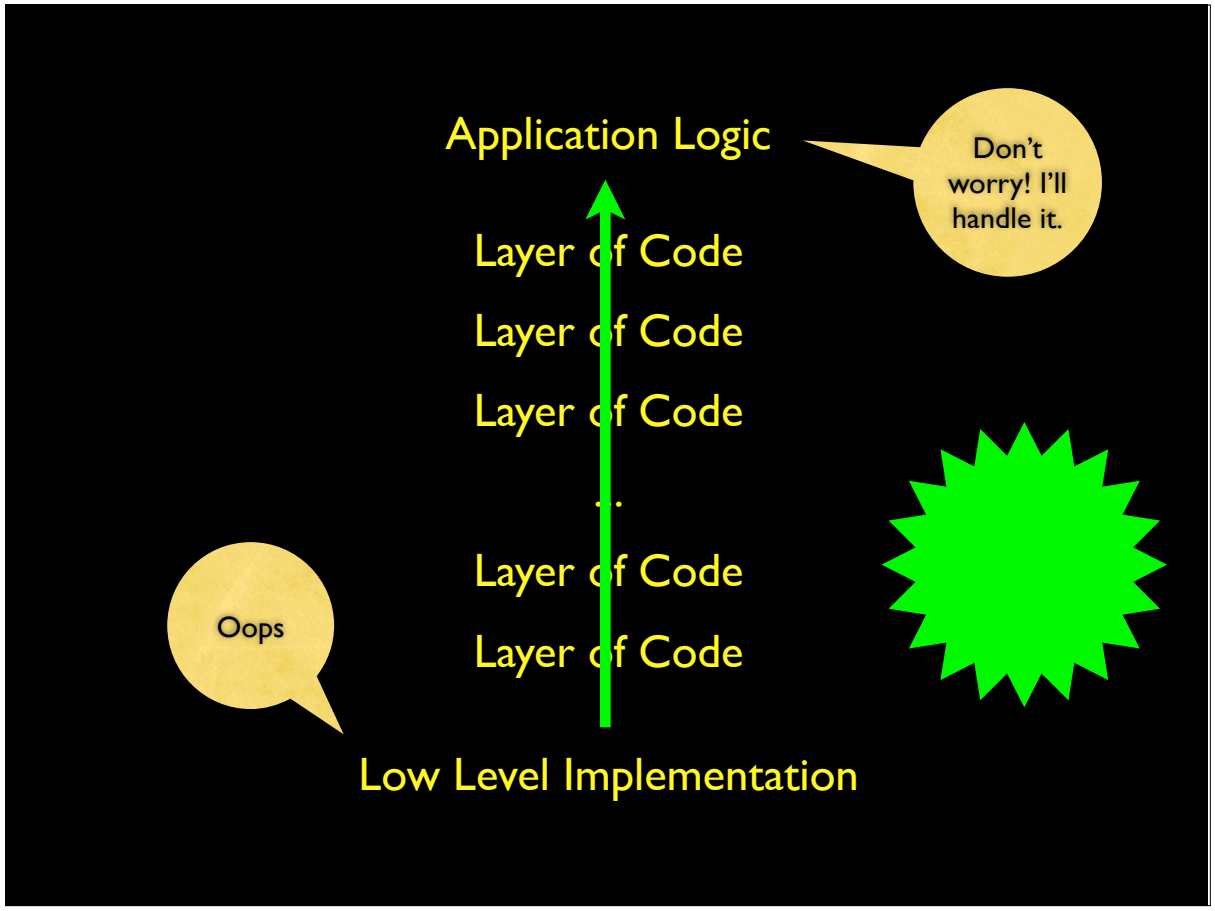
Low Level Implementation


Application Logic
Layer of Code
Layer of Code
Layer of Code
...
Layer of Code
Layer of Code
Oops
Low Level Implementation

9-3


Application Logic
Don't worry! I'll handle it.
Layer of Code
Layer of Code
Layer of Code
...
Layer of Code
Layer of Code
Oops
Low Level Implementation

9-4



9-5

Solutions without Exceptions

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

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Error Flagging

- errno
- “GetError” function

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Error Flagging

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

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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

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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

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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…

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

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Counter-intuitively,

this is true of any error handling system.

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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

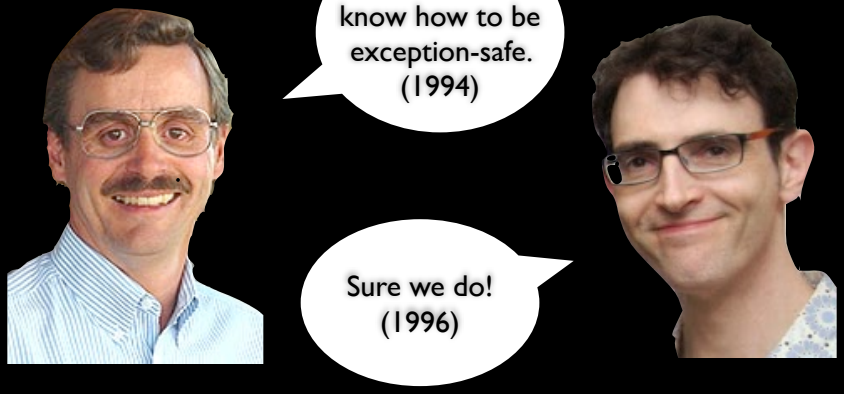
- Spread Fear, Uncertainty, and Doubt
- Some said, "Proves exceptions aren't safe"

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

Cargill's Conclusions



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Abrahams' Conclusions

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

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Joel on Software

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

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Joel on Software

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

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Joel on Software

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

"…exceptions are extremely dangerous."
– Joel Spolsky

Joel on Software

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

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.
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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

C++ 2011

Exception-Safety Guarantees (Abrahams)

- No-Throw Required
  - Cleanup (destructors)
  - swap()
  - move operations (C++11)

Exception-Safety Guarantees (Abrahams)

- Caller's Point-of-View
  - The No-Throw Required functions are the only functions that we need to be stronger than Basic.
  - We assume all other code throws unless we know otherwise. And we are okay with that.
  - This is a surprise to some!

Exception-Safety Guarantees (Abrahams)

- Implementor's Point-of-View
  - Always provide at least the Basic guarantee
  - Always provide No-Throw where Required
  - Document any stronger guarantees
  - Provide the Strong guarantee when it is "natural"

Exception-Safety Guarantees (Abrahams)

- What does it mean for the Strong guarantee to be "natural?"

```
template <typename T> struct vector
{
  ...
  void push_back(T const&);
  ...
};
```

Exception-Safety Guarantees (Abrahams)

- Case where size < capacity

```
void push_back(T const&t)
{
...
  new(&buffer[size]) T(t);
  ++size;
...
};
```


Exception-Safety Guarantees (Abrahams)

- Case where size == capacity

```
void push_back(T const&t)
  // allocate new buffer in temp ptr
  // copy existing items into new buffer
  // set new capacity
  new(&temp_buffer[size]) T(t);
  swap(temp_buffer, buffer);
  delete temp_buffer;
  ++size;
  ...
```

Exception-Safety Guarantees (Abrahams)

- For many functions, the Strong guarantee naturally comes "free" with the Basic guarantee

Exception-Safety Guarantees (Abrahams)

- When don't you give the strong guarantee
- Consider vector<>::insert()
  - Strong guarantee would require copying and inserting into the copy
  - The Standard does not promise the Strong guarantee

Mechanics

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

Mechanics

- How exceptions work in C++
  - Error detection / throw
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  - 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)
{
    ...
```



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

- Issues with catching by value
  - Slicing
  - Copying (might throw)

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



```
try
{
    throw A();
}
```

```
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 (…) {}
```

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Guideline

- Throw by value.
- Catch by reference.

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Performance Cost of try/catch

- No throw — no cost.
- In the throw case…

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,
    ... // Can't "return" in constructor try blocks
}
```

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 (can't "return")
}
```

Function Try Blocks

Function Try Blocks

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

Function Try Blocks

- Only use is to change the exception thrown by the constructor of a base class or data member constructor
- (Except see esc.hpp on http://exceptionsafecode.com)

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

C++ 2011

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
}
```

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C++ 2011

Nesting Exceptions

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

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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

C++ 2003

Exception Specifications

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

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() ) ) {} };
```

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C++ 2003 C++ 2011

Guideline

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

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C++ 2003 C++ 2011

Standard Handlers

- The "Terminate" Handler
  - Called for unhandled exceptions
  - Called when re-throw and there is no exception
    - or rethrow_exception() with null_ptr
  - 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"

C++ 2003 C++ 2011

How to not "Terminate"

- Put a try/catch block in main

C++ 2003 C++ 2011

How to not "Terminate"

- Put a try/catch block in main
  - ✔
- Don't re-throw outside of a catch block

C++ 2003 C++ 2011

How to not "Terminate"

- Put a try/catch block in main
  - ✔
- Don't re-throw outside of a catch block
  - ✔
- Don't throw from a "noexcept" function

C++ 2003 C++ 2011

How to not "Terminate"

- Put a try/catch block in main
  - ✔
- 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

C++ 2003 C++ 2011

How to not "Terminate"

- Put a try/catch block in main
  - ✔
- 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?

C++ 2003 C++ 2011

How to not "Terminate"

- Put a try/catch block in main
  - ✔
- 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.

Guideline

- Destructors must not throw.
  - Must deliver the No-Throw Guarantee.
  - Cleanup must always be safe.
  - May throw internally, but may not emit.
  - But see C++ Next blog

Safe Objects

- Exception-Safe Code is Built on Safe Objects

Object Lifetimes

- Order of construction:

Object Lifetimes

- Order of construction:
  - Base class objects

Object Lifetimes

- Order of construction:
  - Base class objects
    - As listed in the type definition, left to right

Object Lifetimes

- Order of construction:
  - Base class objects
    - As listed in the type definition, left to right
  - Data members

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

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

Object Lifetimes

- Order of construction:
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  - Constructor body

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- Order of destruction:

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- Order of destruction:
  - Exact reverse order of construction

Object Lifetimes

- Order of construction:
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    - 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?

Aborted Construction

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Aborted Construction

- How?
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  - Base class objects?
  - Data members?
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- What about new array?

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

Aborted Construction

- Throwing from a constructor

Aborted Construction

- Throwing from a constructor
- Leaking object 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

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

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

What happens to the object if acquisition fails?

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.

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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.

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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)));
```

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."

Smart Pointer "Gotcha"

- What is the rule?

"No more than one new in any statement."

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 Pointer "Gotcha"

- What is the rule?

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

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

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?

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));
```

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

RAII

- ~~Resource~~ Acquisition Is Initialization
  - "Resource" includes too much

RAII

- ~~Resource~~ Acquisition Is Initialization
  - "Resource" includes too much
  - "Resource" includes too little

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;
   }
}
```

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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;
   }
}
```

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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.

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.

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

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?

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!

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...

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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.

C++ 2003 C++ 2011

Guideline

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

C++ 2003 C++ 2011

Guideline

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

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?

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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?

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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;
};
```

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

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

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

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```
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);
}
```

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

The Critical Line

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

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

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C++ 2003

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

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C++ 2011

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



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

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C++ 2011

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



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

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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

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.

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Guideline

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

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"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();
    ...
}
```

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

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

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```
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_;
};
```

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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;
}
```

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

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```
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;
}
```

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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?

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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!

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Example Code

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

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```
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;
}
```

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Example Code

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

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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();
}
```

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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

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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.


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```

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

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  jonkalb@a9.com

Exception-Safe Coding

Questions?

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