UCLA Stat 130D
Statistical Computing and Visualization in C++

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http://www.stat.ucla.edu/~dinov/courses_students.html

Introduction

- Errors can be dealt with at place error occurs
  - Easy to see if proper error checking implemented
  - Harder to read application itself and see how code works
- Exception handling
  - Makes clear, robust, fault-tolerant programs
  - C++ removes error handling code from "main line" of program
- Common failures
  - **new** not allocating memory
  - Out of bounds array subscript
  - Division by zero
  - Invalid function parameters

Introduction

- Exception handling - catch errors before they occur
  - Deals with synchronous errors (i.E., Divide by zero)
  - Does not deal with asynchronous errors - disk I/O completions, mouse clicks - use interrupt processing
  - Used when system can recover from error
    - Exception handler - recovery procedure
  - Typically used when error dealt with in different place than where it occurred
  - Useful when program cannot recover but must shut down cleanly
- Exception handling should not be used for program control
  - Not optimized, can harm program performance

Introduction

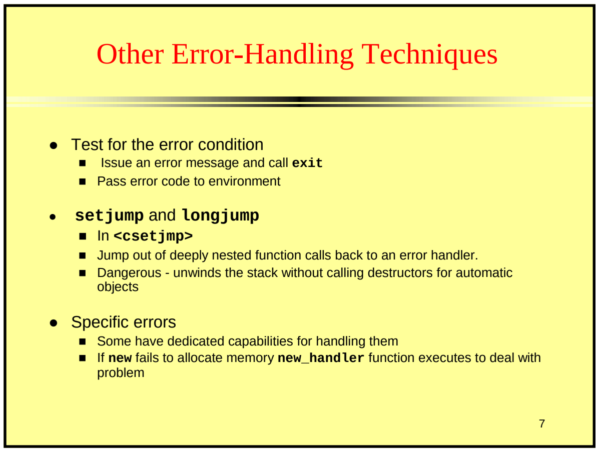
- Exception handling improves fault-tolerance
  - Easier to write error-processing code
  - Specify what type of exceptions are to be caught
- Most programs support only single threads
  - Techniques in this chapter apply for multithreaded OS as well (windows NT, OS/2, some UNIX)
- Exception handling another way to return control from a function or block of code

When To Use Exception Handling?

- Error handling should be used for
  - Processing exceptional situations
  - Processing exceptions for components that cannot handle them directly
  - Processing exceptions for widely used components (libraries, classes, functions) that should not process their own exceptions
  - Large projects that require uniform error processing

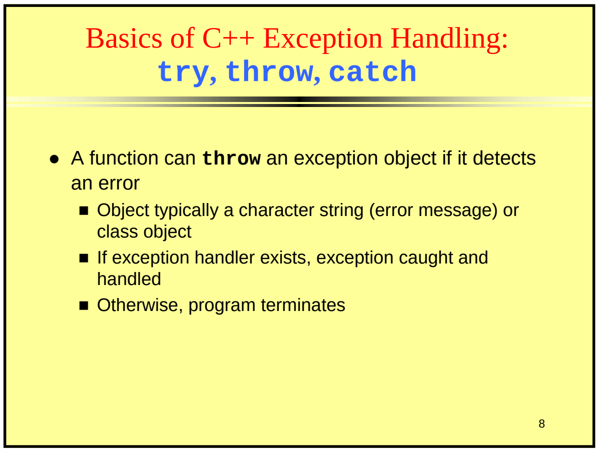
Other Error-Handling Techniques

- Use `assert`
  - If assertion `false`, the program terminates
- Ignore exceptions
  - Use this "technique" on casual, personal programs - not commercial!
- Abort the program
  - Appropriate for nonfatal errors give appearance that program functioned correctly
  - Inappropriate for mission-critical programs, can cause resource leaks
- Set some error indicator
  - Program may not check indicator at all points there error could occur



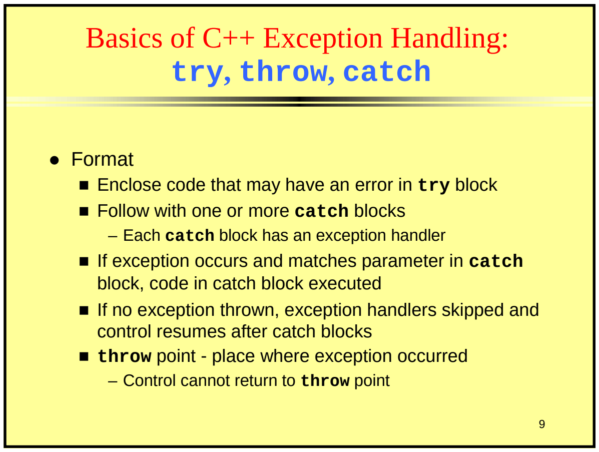
Other Error-Handling Techniques

- Test for the error condition
  - Issue an error message and call **exit**
  - Pass error code to environment
- **setjump** and **longjump**
  - In **<csetjmp>**
  - Jump out of deeply nested function calls back to an error handler.
  - Dangerous - unwinds the stack without calling destructors for automatic objects
- Specific errors
  - Some have dedicated capabilities for handling them
  - If **new** fails to allocate memory **new_handler** function executes to deal with problem



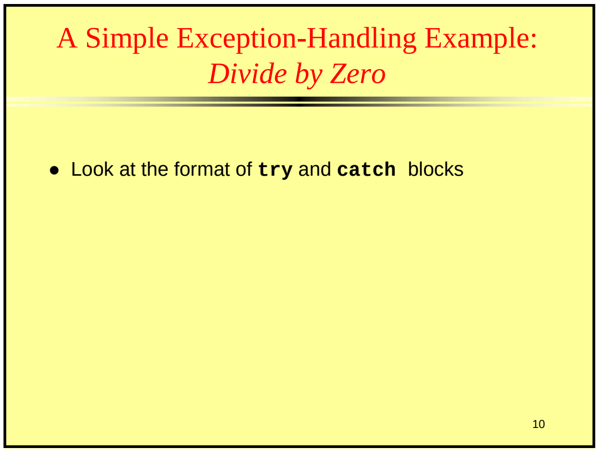
Basics of C++ Exception Handling: **try, throw, catch**

- A function can **throw** an exception object if it detects an error
  - Object typically a character string (error message) or class object
  - If exception handler exists, exception caught and handled
  - Otherwise, program terminates



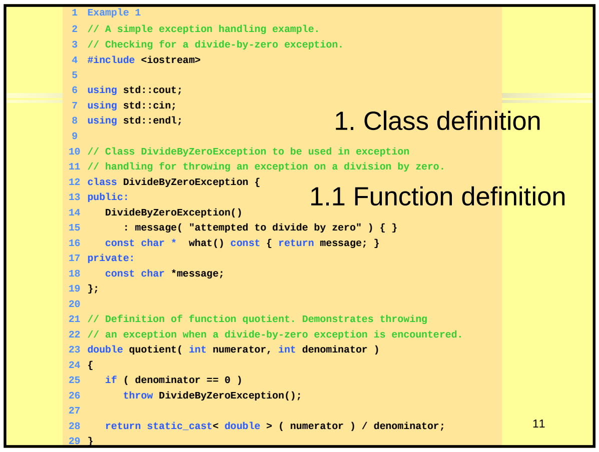
Basics of C++ Exception Handling: **try, throw, catch**

- Format
  - Enclose code that may have an error in **try** block
  - Follow with one or more **catch** blocks
    - Each **catch** block has an exception handler
  - If exception occurs and matches parameter in **catch** block, code in catch block executed
  - If no exception thrown, exception handlers skipped and control resumes after catch blocks
  - **throw** point - place where exception occurred
    - Control cannot return to **throw** point



A Simple Exception-Handling Example: *Divide by Zero*

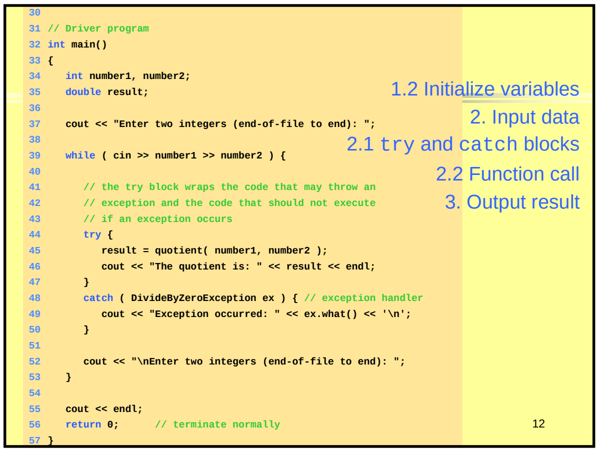
- Look at the format of **try** and **catch** blocks



```
Example 1
// A simple exception handling example.
// Checking for a divide-by-zero exception.
#include <iostream>

using std::cout;
using std::cin;
using std::endl;

// Class DivideByZeroException to be used in exception
// handling for throwing an exception on a division by zero.
class DivideByZeroException {
public:
   DivideByZeroException()
      : message( "attempted to divide by zero" ) { }
   const char *  what() const { return message; }
private:
   const char *message;
};

// Definition of function quotient. Demonstrates throwing
// an exception when a divide-by-zero exception is encountered.
double quotient( int numerator, int denominator )
{
   if ( denominator == 0 )
      throw DivideByZeroException();

   return static_cast< double > ( numerator ) / denominator;
}
```

1. Class definition

1.1 Function definition



```

// Driver program
int main()
{
   int number1, number2;
   double result;

   cout << "Enter two integers (end-of-file to end): ";

   while ( cin >> number1 >> number2 ) {

      // the try block wraps the code that may throw an
      // exception and the code that should not execute
      // if an exception occurs
      try {
         result = quotient( number1, number2 );
         cout << "The quotient is: " << result << endl;
      }
      catch ( DivideByZeroException ex ) { // exception handler
         cout << "Exception occurred: " << ex.what() << '\n';
      }

      cout << "\nEnter two integers (end-of-file to end): ";
   }

   cout << endl;
   return 0;      // terminate normally
}
```

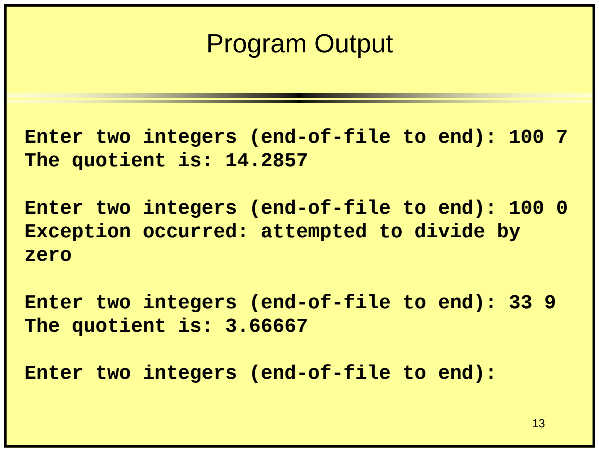
1.2 Initialize variables

2. Input data

2.1 `try` and `catch` blocks

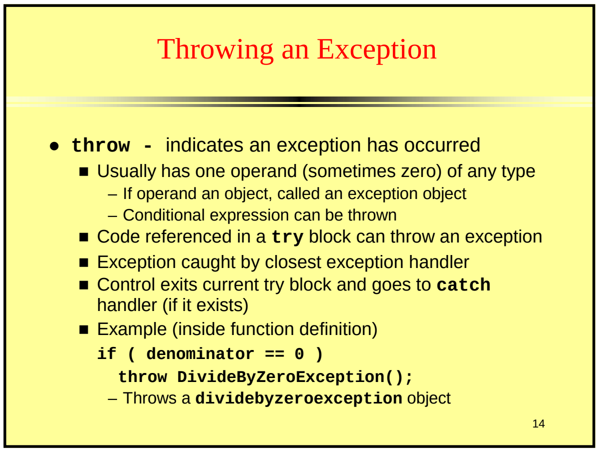
2.2 Function call

3. Output result



Program Output

```
Enter two integers (end-of-file to end): 100 7
The quotient is: 14.2857

Enter two integers (end-of-file to end): 100 0
Exception occurred: attempted to divide by
zero

Enter two integers (end-of-file to end): 33 9
The quotient is: 3.66667

Enter two integers (end-of-file to end):
```

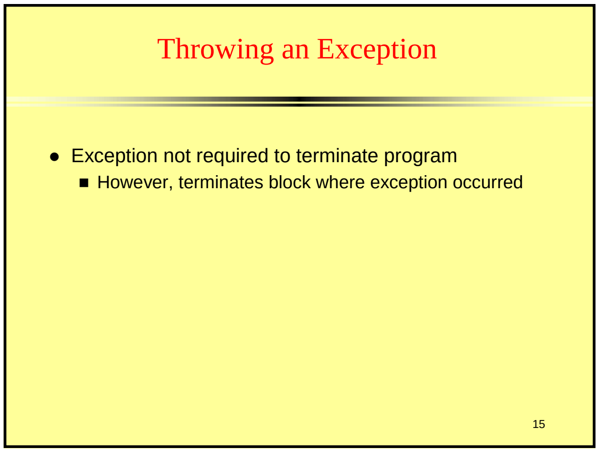


Throwing an Exception

- **`throw` -** indicates an exception has occurred
  - Usually has one operand (sometimes zero) of any type
    - If operand an object, called an exception object
    - Conditional expression can be thrown
  - Code referenced in a **`try`** block can throw an exception
  - Exception caught by closest exception handler
  - Control exits current try block and goes to **`catch`** handler (if it exists)
  - Example (inside function definition)

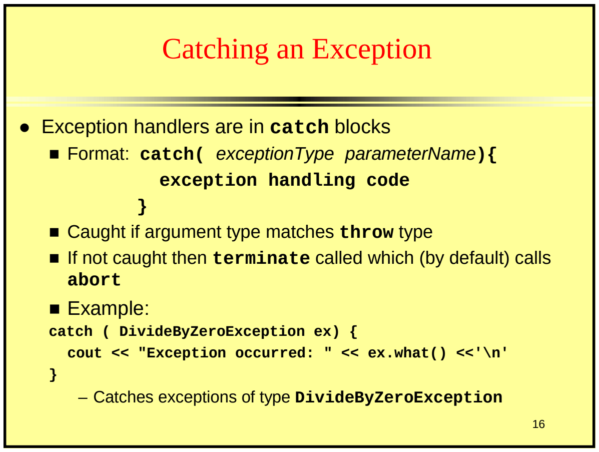
```
if ( denominator == 0 )
   throw DivideByZeroException();
```

    - Throws a **`dividebyzeroexception`** object



Throwing an Exception

- Exception not required to terminate program
  - However, terminates block where exception occurred



Catching an Exception

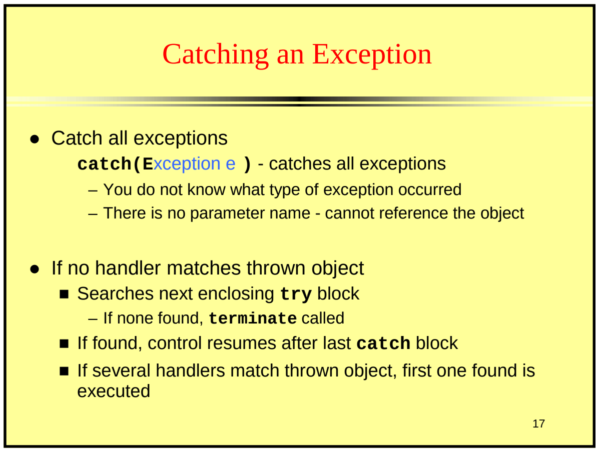
- Exception handlers are in **`catch`** blocks
  - Format: **`catch(`** *exceptionType parameterName* **`){`**

```
         exception handling code
      }
```

  - Caught if argument type matches **`throw`** type
  - If not caught then **`terminate`** called which (by default) calls **`abort`**
  - Example:

```
catch ( DivideByZeroException ex) {
  cout << "Exception occurred: " << ex.what() <<'\n'
}
```

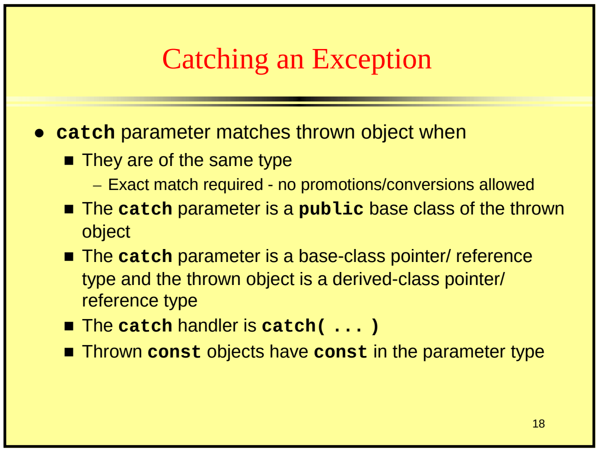
    - Catches exceptions of type **`DivideByZeroException`**



Catching an Exception

- Catch all exceptions
  - **`catch(E`**xception e **`)`** - catches all exceptions
    - You do not know what type of exception occurred
    - There is no parameter name - cannot reference the object

- If no handler matches thrown object
  - Searches next enclosing **`try`** block
    - If none found, **`terminate`** called
  - If found, control resumes after last **`catch`** block
  - If several handlers match thrown object, first one found is executed



Catching an Exception

- **`catch`** parameter matches thrown object when
  - They are of the same type
    - Exact match required - no promotions/conversions allowed
  - The **`catch`** parameter is a **`public`** base class of the thrown object
  - The **`catch`** parameter is a base-class pointer/ reference type and the thrown object is a derived-class pointer/ reference type
  - The **`catch`** handler is **`catch( ... )`**
  - Thrown **`const`** objects have **`const`** in the parameter type

Catching an Exception (IV)

- Unreleased resources
  - Resources may have been allocated when exception thrown
  - **`catch`** handler should **`delete`** space allocated by **`new`** and close any opened files
- **`catch`** handlers can throw exceptions
  - Exceptions can only be processed by outer **`try`** blocks

Rethrowing an Exception

- Rethrowing exceptions
  - Used when an exception handler cannot process an exception
  - Rethrow exception with the statement:

    `throw;`
    - No arguments
    - If no exception thrown in first place, calls **`terminate`**
  - Handler can always rethrow exception, even if it performed some processing
  - Rethrown exception detected by next enclosing **`try`** block

```
// Example
// Demonstration of rethrowing an exception.
#include <iostream>

using std::cout;
using std::endl;

#include <exception>

using std::exception;

void throwException()
{
   // Throw an exception and immediately catch it.
   try {
      cout << "Function throwException\n";
      throw exception();  // generate exception
   }
   catch( exception e )
   {
      cout << "Exception handled in function throwException\n";
```

1. Load header

1.1 Function prototype

```
      throw;  // rethrow exception for further processing
   }

   cout << "This also should not print\n";
}

int main()
{
   try {
      throwException();
      cout << "This should not print\n";
   }
   catch ( exception e )
   {
      cout << "Exception handled in main\n";
   }

   cout << "Program control continues after catch in main"
        << endl;
   return 0;
}
```

2. Function call

3. Output

```
Function throwException
Exception handled in function throwException
Exception handled in main
Program control continues after catch in main
```

Exception Specifications

- Exception specification (**`throw`** list)
  - Lists exceptions that can be thrown by a function

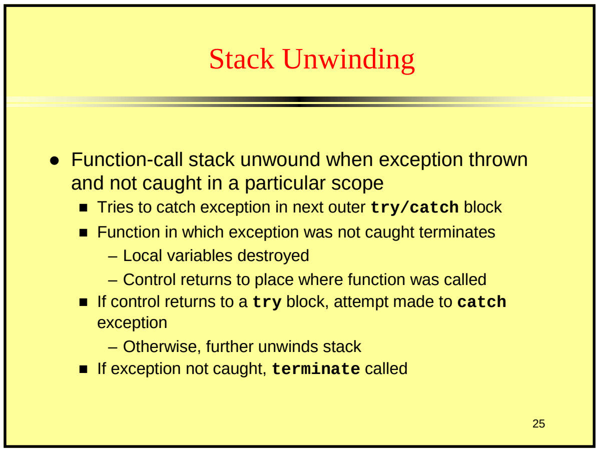
Example:

```
int g( double h ) throw ( a, b, c )
  {
     // function body
  }
```

- Function can throw listed exceptions or derived types
- If other type thrown, function **`unexpected`** called
- **`throw()`** (i.e., no **`throw`** list) states that function will not throw any exceptions
  - In reality, function can still throw exceptions, but calls **`unexpected`** (more later)
- If no **`throw`** list specified, function can **`throw`** any exception

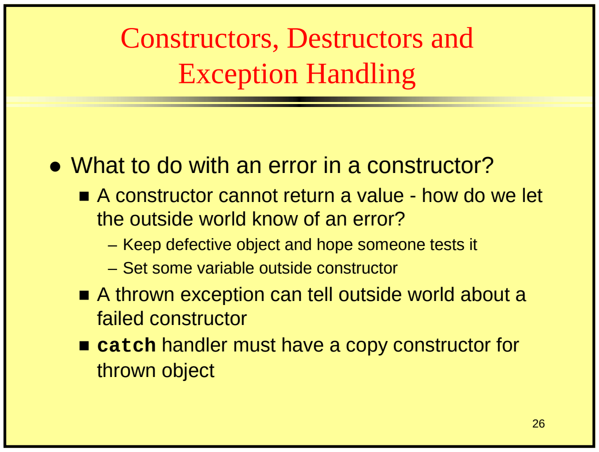
Processing Unexpected Exceptions

- Function **`unexpected`**
  - Calls the function specified with **`set_unexpected`**
    - Default: **`terminate`**
- Function **`terminate`**
  - Calls function specified with **`set_terminate`**
    - Default: **`abort`**
- **`set_terminate`** and **`set_unexpected`**
  - Prototypes in **`<exception>`**
  - Take pointers to functions (i.e., Function name)
    - Function must return **`void`** and take no arguments
  - Returns pointer to last function called by **`terminate`** or **`unexpected`**



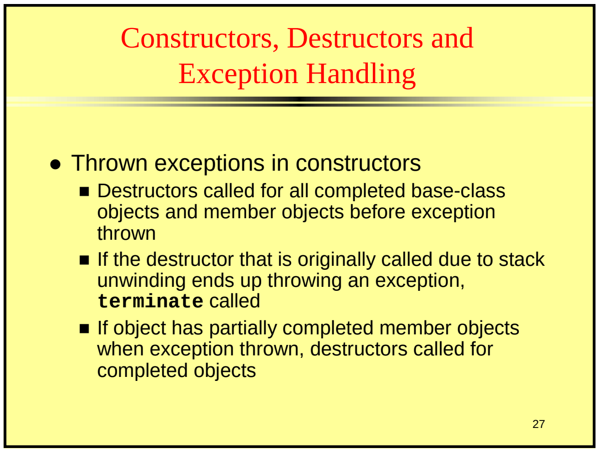
Stack Unwinding

- Function-call stack unwound when exception thrown and not caught in a particular scope
  - Tries to catch exception in next outer **`try/catch`** block
  - Function in which exception was not caught terminates
    - Local variables destroyed
    - Control returns to place where function was called
  - If control returns to a **`try`** block, attempt made to **`catch`** exception
    - Otherwise, further unwinds stack
  - If exception not caught, **`terminate`** called



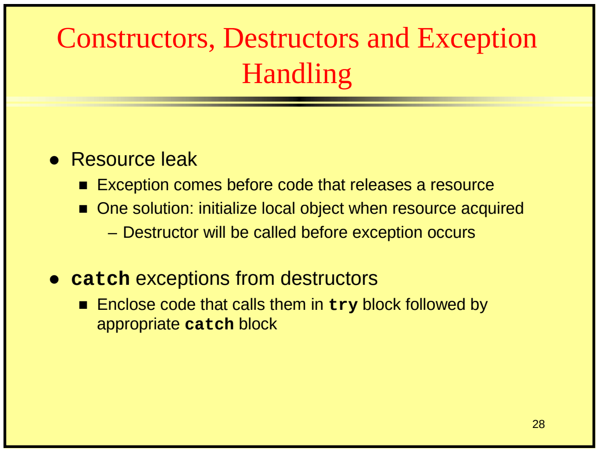
Constructors, Destructors and Exception Handling

- What to do with an error in a constructor?
  - A constructor cannot return a value - how do we let the outside world know of an error?
    - Keep defective object and hope someone tests it
    - Set some variable outside constructor
  - A thrown exception can tell outside world about a failed constructor
  - **`catch`** handler must have a copy constructor for thrown object



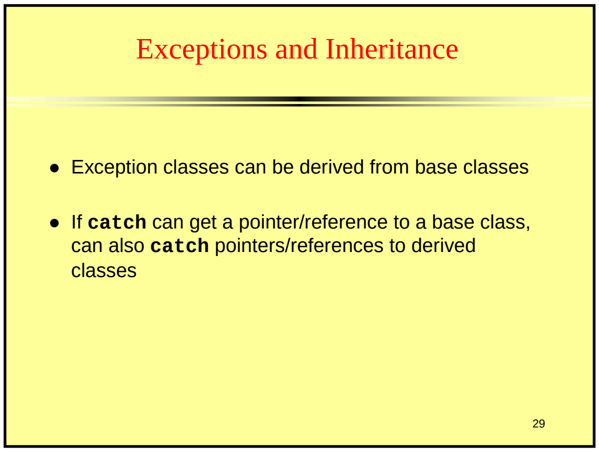
Constructors, Destructors and Exception Handling

- Thrown exceptions in constructors
  - Destructors called for all completed base-class objects and member objects before exception thrown
  - If the destructor that is originally called due to stack unwinding ends up throwing an exception, **`terminate`** called
  - If object has partially completed member objects when exception thrown, destructors called for completed objects



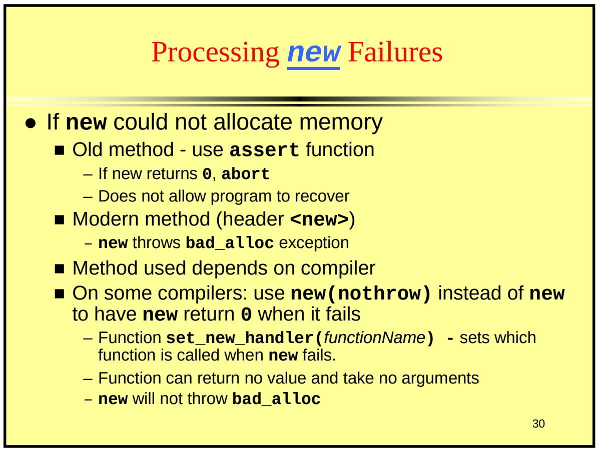
Constructors, Destructors and Exception Handling

- Resource leak
  - Exception comes before code that releases a resource
  - One solution: initialize local object when resource acquired
    - Destructor will be called before exception occurs
- **`catch`** exceptions from destructors
  - Enclose code that calls them in **`try`** block followed by appropriate **`catch`** block



Exceptions and Inheritance

- Exception classes can be derived from base classes
- If **`catch`** can get a pointer/reference to a base class, can also **`catch`** pointers/references to derived classes



Processing ***new*** Failures

- If **`new`** could not allocate memory
  - Old method - use **`assert`** function
    - If new returns **`0`**, **`abort`**
    - Does not allow program to recover
  - Modern method (header **`<new>`**)
    - **`new`** throws **`bad_alloc`** exception
  - Method used depends on compiler
  - On some compilers: use **`new(nothrow)`** instead of **`new`** to have **`new`** return **`0`** when it fails
    - Function **`set_new_handler(`***functionName***`)`** - sets which function is called when **`new`** fails.
    - Function can return no value and take no arguments
    - **`new`** will not throw **`bad_alloc`**

Processing **new** Failures

- **new**
  - Loop that tries to acquire memory
- A **new** handler function should either:
  - Make more memory available by deleting other dynamically allocated memory and return to the loop in operator **new**
  - Throw an exception of type **bad_alloc**
  - Call function **abort** or **exit** (header **<cstdlib>**) to terminate the program

```
// Example.cpp
// Demonstrating new throwing bad_alloc
// when memory is not allocated
#include <iostream>

using std::cout;
using std::endl;

#include <new>

using std::bad_alloc;

int main()
{
   double *ptr[ 50 ];

   try {
      for ( int i = 0; i < 50; i++ ) {
         ptr[ i ] = new double[ 5000000 ];
         cout << "Allocated 5000000 doubles in ptr[ "
              << i << " ]\n";
      }
   }
   catch ( bad_alloc exception ) {
      cout << "Exception occurred: "
           << exception.what() << endl;
   }

   return 0;
}
```

1. Load headers

1.1 Function definition

1.2 Initialize large arrays

2. Use all available memory

3. Output

```
Allocated 5000000 doubles in ptr[ 0 ]
Allocated 5000000 doubles in ptr[ 1 ]
Allocated 5000000 doubles in ptr[ 2 ]
Allocated 5000000 doubles in ptr[ 3 ]
Exception occurred: Allocation Failure
```

Program Output

```
// Example.cpp
// Demonstrating set_new_handler
#include <iostream>

using std::cout;
using std::cerr;

#include <new>
#include <cstdlib>

using std::set_new_handler;

void customNewHandler()
{
   cerr << "customNewHandler was called";
   abort();
}

int main()
{
   double *ptr[ 50 ];
   set_new_handler( customNewHandler );

   for ( int i = 0; i < 50; i++ ) {
      ptr[ i ] = new double[ 5000000 ];

      cout << "Allocated 5000000 doubles in ptr[ "
           << i << " ]\n";
   }

   return 0;
}
```

1. Load headers

1.1 Function definition

1.2 Initialize large arrays

2. Use all available memory

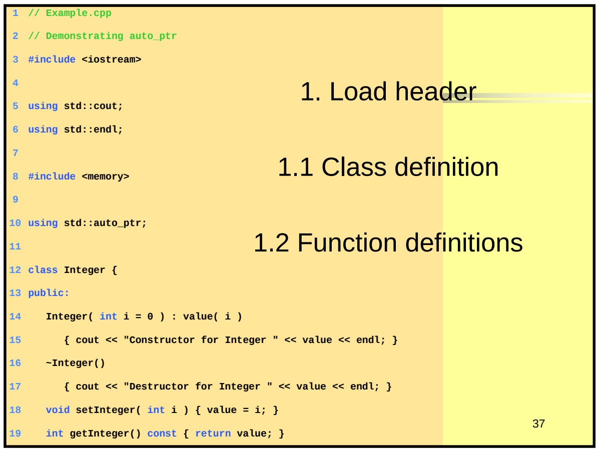
3. Output

```
Allocated 5000000 doubles in ptr[ 0 ]
Allocated 5000000 doubles in ptr[ 1 ]
Allocated 5000000 doubles in ptr[ 2 ]
Allocated 5000000 doubles in ptr[ 3 ]
customNewHandler was called
```

Program Output

Class `auto_ptr` and Dynamic Memory Allocation

- Pointers to dynamic memory
  - Memory leak can occur if exceptions happens before **delete** command
  - Use class template **auto_ptr** (header **<memory>**) to resolve this
  - **auto_ptr** objects act just like pointers
    - Automatically deletes what it points to when it is destroyed (leaves scope)
    - Can use ***** and **->** like normal pointers

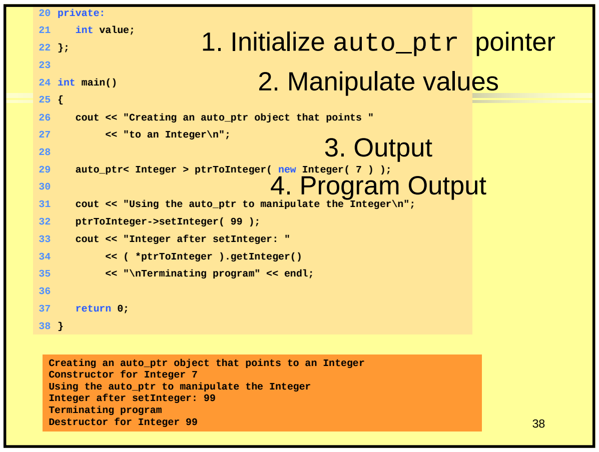


```
// Example.cpp
// Demonstrating auto_ptr
#include <iostream>

using std::cout;
using std::endl;

#include <memory>

using std::auto_ptr;

class Integer {
public:
   Integer( int i = 0 ) : value( i )
      { cout << "Constructor for Integer " << value << endl; }
   ~Integer()
      { cout << "Destructor for Integer " << value << endl; }
   void setInteger( int i ) { value = i; }
   int getInteger() const { return value; }
```

1. Load header

1.1 Class definition

1.2 Function definitions



```
private:
   int value;
};

int main()
{
   cout << "Creating an auto_ptr object that points "
        << "to an Integer\n";

   auto_ptr< Integer > ptrToInteger( new Integer( 7 ) );

   cout << "Using the auto_ptr to manipulate the Integer\n";
   ptrToInteger->setInteger( 99 );
   cout << "Integer after setInteger: "
        << ( *ptrToInteger ).getInteger()
        << "\nTerminating program" << endl;

   return 0;
}
```

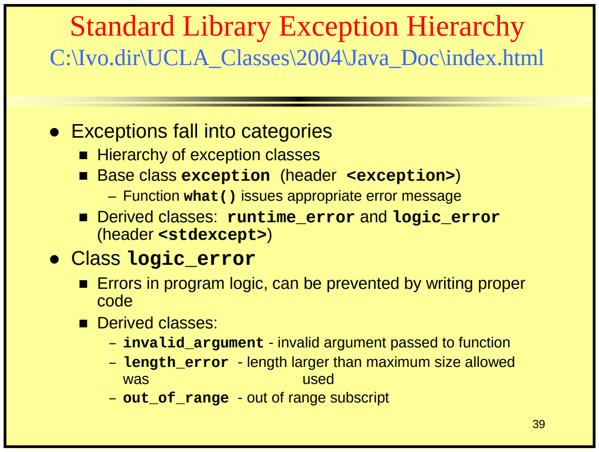
1. Initialize `auto_ptr` pointer

2. Manipulate values

3. Output

4. Program Output

```
Creating an auto_ptr object that points to an Integer
Constructor for Integer 7
Using the auto_ptr to manipulate the Integer
Integer after setInteger: 99
Terminating program
Destructor for Integer 99
```



Standard Library Exception Hierarchy

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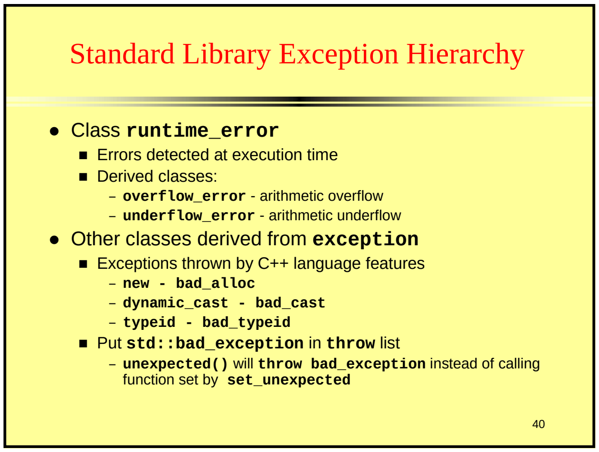
- Exceptions fall into categories
  - Hierarchy of exception classes
  - Base class **`exception`** (header **`<exception>`**)
    - Function **`what()`** issues appropriate error message
  - Derived classes: **`runtime_error`** and **`logic_error`** (header **`<stdexcept>`**)
- Class **`logic_error`**
  - Errors in program logic, can be prevented by writing proper code
  - Derived classes:
    - **`invalid_argument`** - invalid argument passed to function
    - **`length_error`** - length larger than maximum size allowed was used
    - **`out_of_range`** - out of range subscript



Standard Library Exception Hierarchy

- Class **`runtime_error`**
  - Errors detected at execution time
  - Derived classes:
    - **`overflow_error`** - arithmetic overflow
    - **`underflow_error`** - arithmetic underflow
- Other classes derived from **`exception`**
  - Exceptions thrown by C++ language features
    - **`new - bad_alloc`**
    - **`dynamic_cast - bad_cast`**
    - **`typeid - bad_typeid`**
  - Put **`std::bad_exception`** in **`throw`** list
    - **`unexpected()`** will **`throw bad_exception`** instead of calling function set by **`set_unexpected`**