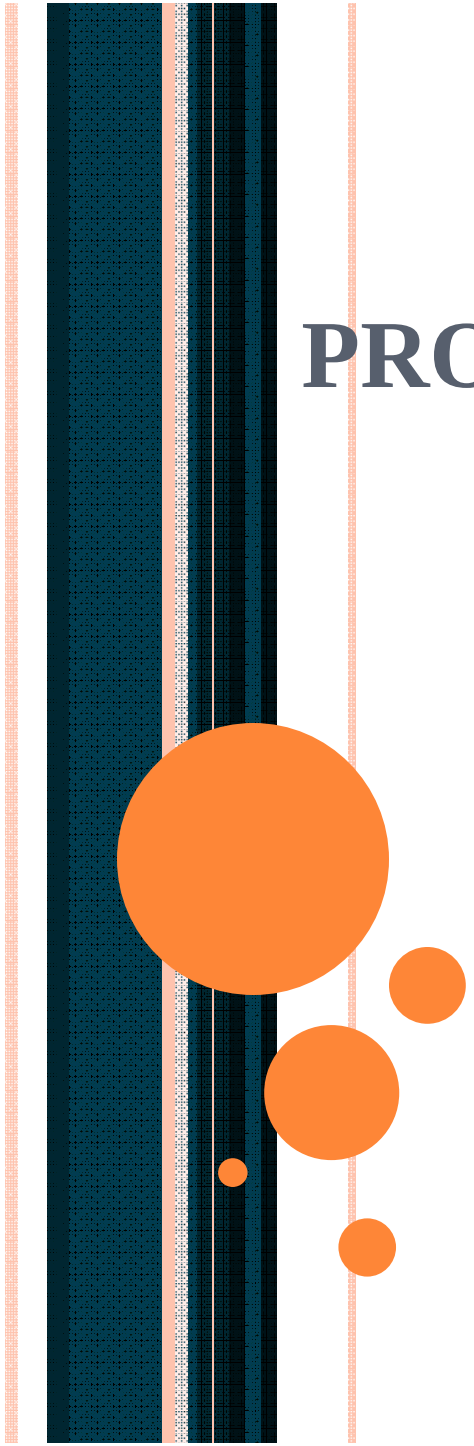


OBJECT ORIENTED PROGRAMMING USING C++

- Exception Handling

Outline

13.1 Introduction
13.2 When Exception Handling Should Be Used
13.3 Other Error-Handling Techniques
13.4 Basics of C++ Exception Handling: `try`, `throw`, `catch`
13.5 A Simple Exception-Handling Example: Divide by Zero
13.6 Throwing an Exception
13.7 Catching an Exception
13.8 Rethrowing an Exception
13.9 Exception Specifications
13.10 Processing Unexpected Exceptions
13.11 Stack Unwinding
13.12 Constructors, Destructors and Exception Handling
13.13 Exceptions and Inheritance
13.14 Processing `new` Failures
13.15 Class `auto_ptr` and Dynamic Memory Allocation
13.16 Standard Library Exception Hierarchy

13.1 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
- common failures
  - **new** not allocating memory
  - out of bounds array subscript
  - division by zero
  - invalid function parameters

13.1 Introduction (II)

- 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

13.1 Introduction (III)

- 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

13.2 When Exception Handling Should Be Used

- 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

13.3 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

13.3 Other Error-Handling Techniques (II)

- Test for the error condition
  - issue an error message and call **`exit`**
  - pass error code to environment

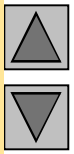
- **`setjump`** and **`longjump`**
  - in **`<csetjmp>`**
  - jump out of deeply nested function calls back to an error handler.
  - dangerous - unwinds the stack without calling destructors for automatic objects (more later)

13.4 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
- 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

13.5 A Simple Exception-Handling Example: Divide by Zero

- Look at the format of **`try`** and **`catch`** blocks
- Afterwards, we will cover specifics



Outline

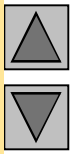
1. Class definition

1.1 Function definition

```
1  // Fig. 13.1: fig13_01.cpp
2  // A simple exception handling example.
3  // Checking for a divide-by-zero exception.
4  #include <iostream>
5
6  using std::cout;
7  using std::cin;
8  using std::endl;
9
10 // Class DivideByZeroException to be used in exception
11 // handling for throwing an exception on a division by zero.
12 class DivideByZeroException {
13 public:
14    DivideByZeroException()
15       : message( "attempted to divide by zero" ) { }
16    const char *what() const { return message; }
17 private:
18    const char *message;
19 };
20
21 // Definition of function quotient. Demonstrates throwing
22 // an exception when a divide-by-zero exception is encountered.
23 double quotient( int numerator, int denominator )
24 {
25    if ( denominator == 0 )
26       throw DivideByZeroException();
27
28    return static_cast< double > ( numerator ) / denominator;
29 }
```

The function is defined to throw an exception object if **`denominator == 0`**

```
30
31 // Driver program
32 int main()
33 {
34    int number1, number2;
35    double result;
36
37    cout << "Enter two integers (end-of-file to end): ";
38
39    while ( cin >> number1 >> number2 ) {
40
41       // the try block wraps the code that may throw an
42       // exception and the code that should not execute
43       // if an exception occurs
44       try {
45          result = quotient( number1, number2 );
46          cout << "The quotient is: " << result << endl;
47       }
48       catch ( DivideByZeroException ex ) { // exception handler
49          cout << "Exception occurred: " << ex.what() << '\n';
50       }
51
52       cout << "\nEnter two integers (end-of-file t
53    }
54
55    cout << endl;
56    return 0;      // terminate normally
57 }
```



Outline

1.2 Initialize variables

2. Input data

2.1 `try` and `catch`

3. Output result

`try` block encloses code that may throw an exception, along with code that should not execute if an exception occurs.

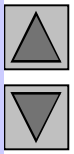
`catch` block follows **`try`** block, and contains exception-handling code.

```
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):
```



Outline

Program Output

13.6 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
- Exception not required to terminate program
  - however, terminates block where exception occurred

13.7 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`**
- Catch all exceptions

  `catch(...)` - catches all exceptions
  - you do not know what type of exception occurred
  - there is no parameter name - cannot reference the object

13.7 Catching an Exception (II)

- 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
- **`catch`** parameter matches thrown object when
  - they are of the same type
    - exact match required - no 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

13.7 Catching an Exception (III)

- 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

13.8 Rethrowing an Exception

- Rethrowing exceptions
  - used when an exception handler cannot process an exception
  - rethrow exception with the statement:

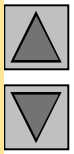
    ```
    throw;
    ```

    - 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

```
1  // Fig. 13.2: fig13_02.cpp
2  // Demonstration of rethrowing an exception.
3  #include <iostream>
4
5  using std::cout;
6  using std::endl;
7
8  #include <exception>
9
10 using std::exception;
11
12 void throwException()
13 {
14    // Throw an exception and immediately catch it.
15    try {
16       cout << "Function throwException\n";
17       throw exception();  // generate exception
18    }
19    catch( exception e )
20    {
21       cout << "Exception handled in function throwException\n";
```

Header file **<exception>** has class **exception**

When called, **throwException** throws an exception then catches it.



Outline

1. Load header

1.1 Function prototype

```
22       throw;  // rethrow exception for further processing
23    }
24
25    cout << "This also should not print\n";
26 }
27
28 int main()
29 {
30    try {
31       throwException();
32       cout << "This should not print\n";
33    }
34    catch ( exception e )
35    {
36       cout << "Exception handled in main\n";
37    }
38
39    cout << "Program control continues after catch in main"
40         << endl;
41    return 0;
42 }
```

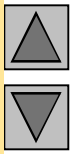
The exception is rethrown

This line not executed because control leaves the throw point and the function ends

Line not executed because of rethrown exception. Control exits **`try`** block and goes to appropriate **`catch`** block.

Catch the rethrown exception

Control returns to first statement after the **`catch`** block.



Outline

2. Function call

Program Output

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

13.9 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

13.10 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`**

13.11 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

13.12 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
- Thrown exceptions in destructors
  - 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

13.12 Constructors, Destructors and Exception Handling (II)

- resource leak
  - exception comes before code that releases a resource

- **`catch`** exceptions from destructors
  - enclose code that calls them in **`try`** block followed by appropriate **`catch`** block

13.13 Exceptions and Inheritance

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

13.14 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**

13.14 Processing new Failures (II)

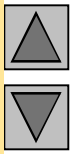
- **new**
  - loop that tries to acquire memory

- 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

```
1  // Fig. 13.5: fig13_05.cpp
2  // Demonstrating new throwing bad_alloc
3  // when memory is not allocated
4  #include <iostream>
5
6  using std::cout;
7  using std::endl;
8
9  #include <new>
10
11 using std::bad_alloc;
12
13 int main()
14 {
15    double *ptr[ 50 ];
16
17    try {
18       for ( int i = 0; i < 50; i++ ) {
19          ptr[ i ] = new double[ 5000000 ];
20          cout << "Allocated 5000000 doubles in ptr[ "
21               << i << " ]\n";
22       }
23    }
24    catch ( bad_alloc exception ) {
25       cout << "Exception occurred: "
26            << exception.what() << endl;
27    }
28
29    return 0;
30 }
```

Create large arrays until the computer runs out of memory

catch the **bad_alloc** exception thrown by **new** when it fails to allocate memory. Call member function **what** to print what the exception was.



Outline

1. Load headers

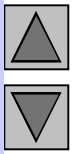
1.1 Function definition

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
```



Outline

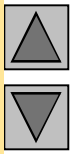
Program Output

```
1  // Fig. 13.6: fig13_06.cpp
2  // Demonstrating set_new_handler
3  #include <iostream>
4
5  using std::cout;
6  using std::cerr;
7
8  #include <new>
9  #include <cstdlib>
10
11 using std::set_new_handler;
12
13 void customNewHandler()
14 {
15    cerr << "customNewHandler was called";
16    abort();
17 }
18
19 int main()
20 {
21    double *ptr[ 50 ];
22    set_new_handler( customNewHandler );
23
24    for ( int i = 0; i < 50; i++ ) {
25       ptr[ i ] = new double[ 5000000 ];
26
27       cout << "Allocated 5000000 doubles in ptr[ "
28            << i << " ]\n";
29    }
30
31    return 0;
32 }
```

Custom function to be called instead of the default.

Set **customNewHandler** to be called when new fails.

Create large arrays until the computer runs out of memory



Outline

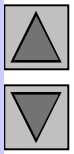
1. Load headers

1.1 Function definition

1.2 Initialize large arrays

ailable memory

```
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
```



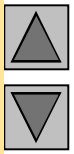
Outline

Program Output

13.15 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

```
1  // Fig. 13.7: fig13_07.cpp
2  // Demonstrating auto_ptr
3  #include <iostream>
4
5  using std::cout;
6  using std::endl;
7
8  #include <memory>
9
10 using std::auto_ptr;
11
12 class Integer {
13 public:
14    Integer( int i = 0 ) : value( i )
15       { cout << "Constructor for Integer " << value << endl; }
16    ~Integer()
17       { cout << "Destructor for Integer " << value << endl; }
18    void setInteger( int i ) { value = i; }
19    int getInteger() const { return value; }
```



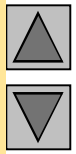
Outline

1. Load header

1.1 Class definition

1.2 Function definitions

```
20 private:
21    int value;
22 };
23
24 int main()
25 {
26    cout << "Creating an auto_ptr object that points "
27         << "to an Integer\n";
28
29    auto_ptr< Integer > ptrToInteger( new Integer( 7 ) );
30
31    cout << "Using the auto_ptr to manipulate the Integer\n";
32    ptrToInteger->setInteger( 99 );
33    cout << "Integer after setInteger: "
34         << ( *ptrToInteger ).getInteger()
35         << "\nTerminating program" << endl;
36
37    return 0;
38 }
```



Outline

1.3 Initialize `auto_ptr` pointer

2. Manipulate values

3. Output

A memory leak is avoided because pointers of type **`auto_ptr`** automatically destroy the object they point to when they leave scope.

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
```

13.16 Standard Library Exception Hierarchy

- 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

13.16 Standard Library Exception Hierarchy (II)

- 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`** (Chapter 21)
    - **`typeid - bad_typeid`** (Chapter 21)
  - put **`std::bad_exception`** in **`throw`** list
    - **`unexpected()`** will **`throw bad_exception`** instead of calling function set by **`set_unexpected`**