18

Exception Handling

OBJECTIVES

In this chapter you will learn:

- What exceptions are and when to use them.
- To use `try`, `catch` and `throw` to detect, handle and indicate exceptions, respectively.
- To process uncaught and unexpected exceptions.
- To declare new exception classes.
- How stack unwinding enables exceptions not caught in one scope to be caught in another scope.
- To handle `new` failures.
- To use `auto_ptr` to prevent memory leaks.
- To understand the standard exception hierarchy.

Outline

18.1 Introduction

- **Exceptions**
  - **Indicate problems that occur during a program's execution**
  - **Occur infrequently**
- **Exception handling**
  - **Can resolve exceptions**
    - **Allow a program to continue executing or**
    - **Notify the user of the problem and**
    - **Terminate the program in a controlled manner**
  - **Makes programs robust and fault-tolerant**

Error-Prevention Tip 18.1

Exception handling helps improve a program's fault tolerance.

Software Engineering Observation 18.1

Exception handling provides a standard mechanism for processing errors. This is especially important when working on a project with a large team of programmers.

18.2 Exception-Handling Overview

- **Intermixing program and error-handling logic**
  - **Pseudocode example**

```
Perform a task
If the preceding task did not execute correctly
   Perform error processing
Perform next task
If the preceding task did not execute correctly
   Perform error processing
…
```

  - **Makes the program difficult to read, modify, maintain and debug**

18.2 Exception-Handling Overview (Cont.)

- **Exception handling**
  - **Removes error-handling code from the program execution's "main line"**
  - **Programmers can handle any exceptions they choose**
    - **All exceptions,**
    - **All exceptions of a certain type or**
    - **All exceptions of a group of related types**

18.3 Example: Handling an Attempt to Divide by Zero

- Class `exception`
  - Is the standard C++ base class for all exceptions
  - Provides its derived classes with `virtual` function `what`
    - Returns the exception's stored error message

Outline

DivideByZeroException.h

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```
1  // Fig. 16.1: DivideByZeroException.h
2  // Class DivideByZeroException definition.
3  #include <stdexcept> // stdexcept header file contains runtime_error
4  using std::runtime_error; // standard C++ library class runtime_error
5
6  // DivideByZeroException objects should be thrown by functions
7  // upon detecting division-by-zero exceptions
8  class DivideByZeroException : public runtime_error
9  {
10 public:
11    // constructor specifies default error message
12    DivideByZeroException::DivideByZeroException()
13       : runtime_error( "attempted to divide by zero" ) {}
14 }; // end class DivideByZeroException
```

Outline

Fig18_02.cpp

(1 of 3)

```
1  // Fig. 16.2: Fig16_02.cpp
2  // A simple exception-handling example that checks for
3  // divide-by-zero exceptions.
4  #include <iostream>
5  using std::cin;
6  using std::cout;
7  using std::endl;
8
9  #include "DivideByZeroException.h" // DivideByZeroException class
10
11 // perform division and throw DivideByZeroException object if
12 // divide-by-zero exception occurs
13 double quotient( int numerator, int denominator )
14 {
15    // throw DivideByZeroException if trying to divide by zero
16    if ( denominator == 0 )
17       throw DivideByZeroException(); // terminate function
18
19    // return division result
20    return static_cast< double >( numerator ) / denominator;
21 } // end function quotient
22
23 int main()
24 {
25    int number1; // user-specified numerator
26    int number2; // user-specified denominator
27    double result; // result of division
28
29    cout << "Enter two integers (end-of-file to end): ";
```

Outline

Fig18_02.cpp

(2 of 3)

```
30
31    // enable user to enter two integers to divide
32    while ( cin >> number1 >> number2 )
33    {
34       // try block contains code that might throw exception
35       // and code that should not execute if an exception occurs
36       try
37       {
38          result = quotient( number1, number2 );
39          cout << "The quotient is: " << result << endl;
40       } // end try
41
42       // exception handler handles a divide-by-zero exception
43       catch ( DivideByZeroException &divideByZeroException )
44       {
45          cout << "Exception occurred: "
46             << divideByZeroException.what() << endl;
47       } // end catch
48
49       cout << "\nEnter two integers (end-of-file to end): ";
50    } // end while
51
52    cout << endl;
53    return 0; // terminate normally
54 } // end main
```

```
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): ^Z
```

Outline

Fig18_02.cpp

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18.3 Example: Handling an Attempt to Divide by Zero (Cont.)

- `try` Blocks
  - Keyword `try` followed by braces (`{}`)
  - Should enclose
    - Statements that might cause exceptions and
    - Statements that should be skipped in case of an exception

Software Engineering Observation 18.2

Exceptions may surface through explicitly mentioned code in a `try` block, through calls to other functions and through deeply nested function calls initiated by code in a `try` block.

18.3 Example: Handling an Attempt to Divide by Zero (Cont.)

- `catch` handlers
  - Immediately follow a `try` block
    - One or more `catch` handlers for each `try` block
  - Keyword `catch`
  - Exception parameter enclosed in parentheses
    - Represents the type of exception to process
    - Can provide an optional parameter name to interact with the caught exception object
  - Executes if exception parameter type matches the exception thrown in the `try` block
    - Could be a base class of the thrown exception's class

Common Programming Error 18.1

It is a syntax error to place code between a `try` block and its corresponding `catch` handlers.

Common Programming Error 18.2

Each `catch` handler can have only a single parameter—specifying a comma-separated list of exception parameters is a syntax error.

Common Programming Error 18.3

It is a logic error to catch the same type in two different `catch` handlers following a single `try` block.

Common Programming Error 18.4

Logic errors can occur if you assume that after an exception is handled, control will return to the first statement after the throw point.

Error-Prevention Tip 18.2

With exception handling, a program can continue executing (rather than terminating) after dealing with a problem. This helps ensure the kind of robust applications that contribute to what is called mission-critical computing or business-critical computing.

18.3 Example: Handling an Attempt to Divide by Zero (Cont.)

- **Throwing an exception**
  - **Use keyword `throw` followed by an operand representing the type of exception**
    - **The `throw` operand can be of any type**
      - **If the `throw` operand is an object, it is called an exception object**
  - **The `throw` operand initializes the exception parameter in the matching `catch` handler, if one is found**

Good Programming Practice 18.1

Associating each type of runtime error with an appropriately named exception object improves program clarity.

Software Engineering Observation 18.3

Incorporate your exception-handling strategy into your system from the design process's inception. Including effective exception handling after a system has been implemented can be difficult.

Software Engineering Observation 18.4

Exception handling provides a single, uniform technique for processing problems. This helps programmers working on large projects understand each other's error-processing code.

Software Engineering Observation 18.5

Avoid using exception handling as an alternate form of flow of control. These "additional" exceptions can "get in the way" of genuine error-type exceptions.

Software Engineering Observation 18.6

Exception handling simplifies combining software components and enables them to work together effectively by enabling predefined components to communicate problems to application-specific components, which can then process the problems in an application-specific manner.

Performance Tip 18.3

When no exceptions occur, exception-handling code incurs little or no performance penalties. Thus, programs that implement exception handling operate more efficiently than do programs that intermix error-handling code with program logic.

18.5 Rethrowing an Exception

- **Rethrowing an exception**
  - **Empty `throw;` statement**
  - **Use when a `catch` handler cannot or can only partially process an exception**
  - **Next enclosing `try` block attempts to match the exception with one of its `catch` handlers**

Common Programming Error 18.6

Executing an empty `throw` statement that is situated outside a `catch` handler causes a call to function terminate, which abandons exception processing and terminates the program immediately.

Outline

Fig18_03.cpp

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```
1  // Fig. 16.3: Fig16_03.cpp
2  // Demonstrating exception rethrowing.
3  #include <iostream>
4  using std::cout;
5  using std::endl;
6
7  #include <exception>
8  using std::exception;
9
10 // throw, catch and rethrow exception
11 void throwException()
12 {
13    // throw exception and catch it immediately
14    try
15    {
16       cout << "  Function throwException throws an exception\n";
17       throw exception(); // generate exception
18    } // end try
19    catch ( exception & ) // handle exception
20    {
21       cout << "  Exception handled in function throwException"
22          << "\n  Function throwException rethrows exception";
23       throw; // rethrow exception for further processing
24    } // end catch
25
26    cout << "This also should not print\n";
27 } // end function throwException
```

Rethrow the exception

Outline

Fig18_03.cpp

(2 of 2)

```
28
29 int main()
30 {
31    // throw exception
32    try
33    {
34       cout << "\nmain invokes function throwException\n";
35       throwException();
36       cout << "This should not print\n";
37    } // end try
38    catch ( exception & ) // handle exception
39    {
40       cout << "\n\nException handled in main\n";
41    } // end catch
42
43    cout << "Program control continues after catch in main\n";
44    return 0;
45 } // end main
```

Catch rethrown exception

```
main invokes function throwException
  Function throwException throws an exception
  Exception handled in function throwException
  Function throwException rethrows exception

Exception handled in main
Program control continues after catch in main
```

18.6 Exception Specifications

- **Exception specifications (a.k.a. `throw` lists)**
  - **Keyword `throw`**
  - **Comma-separated list of exception classes in parentheses**
  - **Example**
    - ```
      int someFunction( double value )
         throw ( ExceptionA, ExceptionB,
                 ExceptionC )
      {
         …
      }
      ```
      - **Indicates `someFunction` can throw exceptions of types `ExceptionA`, `ExceptionB` and `ExceptionC`**


      ```

Common Programming Error 18.7

Throwing an exception that has not been declared in a function's exception specification causes a call to function `unexpected`.

Error-Prevention Tip 18.3

The compiler will not generate a compilation error if a function contains a `throw` expression for an exception not listed in the function's exception specification. An error occurs only when that function attempts to throw that exception at execution time. To avoid surprises at execution time, carefully check your code to ensure that functions do not throw exceptions not listed in their exception specifications.

18.7 Processing Unexpected Exceptions

- Function `unexpected`
  - Called when a function `throw`s an exception not in its exception specification
  - Calls the function registered with function `set_unexpected`
  - Function `terminate` is called by default
- Function `set_unexpected` of `<exception>`
  - Takes as argument a pointer to a function with no arguments and a `void` return type
  - Returns a pointer to the last function called by `unexpected`
    - Returns `0` the first time

18.7 Processing Unexpected Exceptions (Cont.)

- Function `terminate`
  - Called when
    - No matching `catch` is found for a thrown exception
    - A destructor attempts to `throw` an exception during stack unwinding
    - Attempting to rethrow an exception when no exception is being handled
    - Calling function `unexpected` before registering a function with function `set_unexpected`
  - Calls the function registered with function `set_terminate`
  - Function `abort` is called by default

18.7 Processing Unexpected Exceptions (Cont.)

- Function `set_terminate`
  - Takes as argument a pointer to a function with no arguments and a `void` return type
  - Returns a pointer to the last function called by `terminate`
    - Returns `0` the first time
- Function `abort`
  - Terminates the program without calling destructors for automatic or static storage class objects
    - Could lead to resource leaks

18.8 Stack Unwinding

- **Stack unwinding**
  - **Occurs when a thrown exception is not caught in a particular scope**
  - **Unwinding a function terminates that function**
    - **All local variables of the function are destroyed**
    - **Control returns to the statement that invoked the function**
  - **Attempts are made to `catch` the exception in outer `try...catch` blocks**
  - **If the exception is never caught, function `terminate` is called**

Outline

Fig18_04.cpp

(1 of 3)

```
1  // Fig. 16.4: Fig16_04.cpp
2  // Demonstrating stack unwinding.
3  #include <iostream>
4  using std::cout;
5  using std::endl;
6
7  #include <stdexcept>
8  using std::runtime_error;
9
10 // function3 throws run-time error
11 void function3() throw ( runtime_error )
12 {
13    cout << "In function 3" << endl;
14
15    // no try block, stack unwinding occur, return control to function2
16    throw runtime_error( "runtime_error in function3" );
17 } // end function3
18
19 // function2 invokes function3
20 void function2() throw ( runtime_error )
21 {
22    cout << "function3 is called inside function2" << endl;
23    function3(); // stack unwinding occur, return control to function1
24 } // end function2
```

Outline

Fig18_04.cpp

(2 of 3)

```
25
26 // function1 invokes function2
27 void function1() throw ( runtime_error )
28 {
29    cout << "function2 is called inside function1" << endl;
30    function2(); // stack unwinding occur, return control to main
31 } // end function1
32
33 // demonstrate stack unwinding
34 int main()
35 {
36    // invoke function1
37    try
38    {
39       cout << "function1 is called inside main" << endl;
40       function1(); // call function1 which throws runtime_error
41    } // end try
42    catch ( runtime_error &error ) // handle run-time error
43    {
44       cout << "Exception occurred: " << error.what() << endl;
45       cout << "Exception handled in main" << endl;
46    } // end catch
47
48    return 0;
49 } // end main
```

```
function1 is called inside main
function2 is called inside function1
function3 is called inside function2
In function 3
Exception occurred: runtime_error in function3
Exception handled in main
```

Outline

Fig18_04.cpp

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18.9 Constructors, Destructors and Exception Handling

- **Exceptions and constructors**
  - **Exceptions enable constructors, which cannot return values, to report errors to the program**
  - **Exceptions thrown by constructors cause any already-constructed component objects to call their destructors**
    - **Only those objects that have already been constructed will be destructed**
- **Exceptions and destructors**
  - **Destructors are called for all automatic objects in the terminated `try` block when an exception is thrown**
    - **Acquired resources can be placed in local objects to automatically release the resources when an exception occurs**
  - **If a destructor invoked by stack unwinding throws an exception, function `terminate` is called**

Error-Prevention Tip 18.4

When an exception is thrown from the constructor for an object that is created in a `new` expression, the dynamically allocated memory for that object is released.

18.10 Exceptions and Inheritance

- **Inheritance with exception classes**
  - **New exception classes can be defined to inherit from existing exception classes**
  - **A catch handler for a particular exception class can also catch exceptions of classes derived from that class**

18.11 Processing new Failures

- new failures
  - Some compilers throw a bad_alloc exception
    - Compliant to the C++ standard specification
  - Some compilers return 0
    - C++ standard-compliant compilers also have a version of new that returns 0
      - Use expression new(nothrow), where nothrow is of type nothrow_t
  - Some compilers throw bad_alloc if <new> is included

Outline

Fig18_05.cpp

(1 of 2)

```
1  // Fig. 16.5: Fig16_05.cpp
2  // Demonstrating pre-standard new returning 0 when memory
3  // is not allocated.
4  #include <iostream>
5  using std::cerr;
6  using std::cout;
7
8  int main()
9  {
10    double *ptr[ 50 ];
11
12    // allocate memory for ptr
13    for ( int i = 0; i < 50; i++ )
14    {
15       ptr[ i ] = new double[ 50000000 ];
16
17       if ( ptr[ i ] == 0 ) // did new fail to allocate memo
18       {
19          cerr << "Memory allocation failed for ptr[ " << i << " ]\n";
20          break;
21       } // end if
22       else // successful memory allocation
23          cout << "Allocated 50000000 doubles in ptr[ " << i << " ]\n";
24    } // end for
25
26    return 0;
27 } // end main
```

Allocate **50000000 double** values

new will have returned **0** if the memory allocation operation failed

```
Allocated 50000000 doubles in ptr[ 0 ]
Allocated 50000000 doubles in ptr[ 1 ]
Allocated 50000000 doubles in ptr[ 2 ]
Memory allocation failed for ptr[ 3 ]
```

Outline

Fig18_03.cpp

(2 of 2)

Outline

Fig18_06.cpp

(1 of 2)

```
1  // Fig. 16.6: Fig16_06.cpp
2  // Demonstrating standard new throwing bad_alloc when memory
3  // cannot be allocated.
4  #include <iostream>
5  using std::cerr;
6  using std::cout;
7  using std::endl;
8
9  #include <new> // standard operator new
10 using std::bad_alloc;
11
12 int main()
13 {
14    double *ptr[ 50 ];
15
16    // allocate memory for ptr
17    try
18    {
19       // allocate memory for ptr[ i ]; new throws bad_alloc on failure
20       for ( int i = 0; i < 50; i++ )
21       {
22          ptr[ i ] = new double[ 50000000 ]; // may throw exception
23          cout << "Allocated 50000000 doubles in ptr[ " << i << " ]\n";
24       } // end for
25    } // end try
```

Allocate **50000000** **double** values

```
26
27    // handle bad_alloc exception
28    catch ( bad_alloc &memoryAllocationException )
29    {
30       cerr << "Exception occurred: "
31          << memoryAllocationException.what() << endl;
32    } // end catch
33
34    return 0;
35 } // end main
```

```
Allocated 50000000 doubles in ptr[ 0 ]
Allocated 50000000 doubles in ptr[ 1 ]
Allocated 50000000 doubles in ptr[ 2 ]
Exception occurred: bad allocation
```

new throws a **bad_alloc** exception if the memory allocation operation failed

Outline

Fig18_06.cpp

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18.13 Standard Library Exception Hierarchy

- **Exception hierarchy classes**
  - **Base-class `exception`**
    - **Contains `virtual` function `what` for storing error messages**
    - **Exception classes derived from `exception`**
      - **`bad_alloc` – thrown by `new`**
      - **`bad_cast` – thrown by `dynamic_cast`**
      - **`bad_typeid` – thrown by `typeid`**
      - **`bad_exception` – thrown by `unexpected`**
        - **Instead of terminating the program or calling the function specified by `set_unexpected`**
        - **Used only if `bad_exception` is in the function's `throw` list**

Common Programming Error 18.8

Placing a `catch` handler that catches a base-class object before a `catch` that catches an object of a class derived from that base class is a logic error. The base-class `catch` catches all objects of classes derived from that base class, so the derived-class `catch` will never execute.

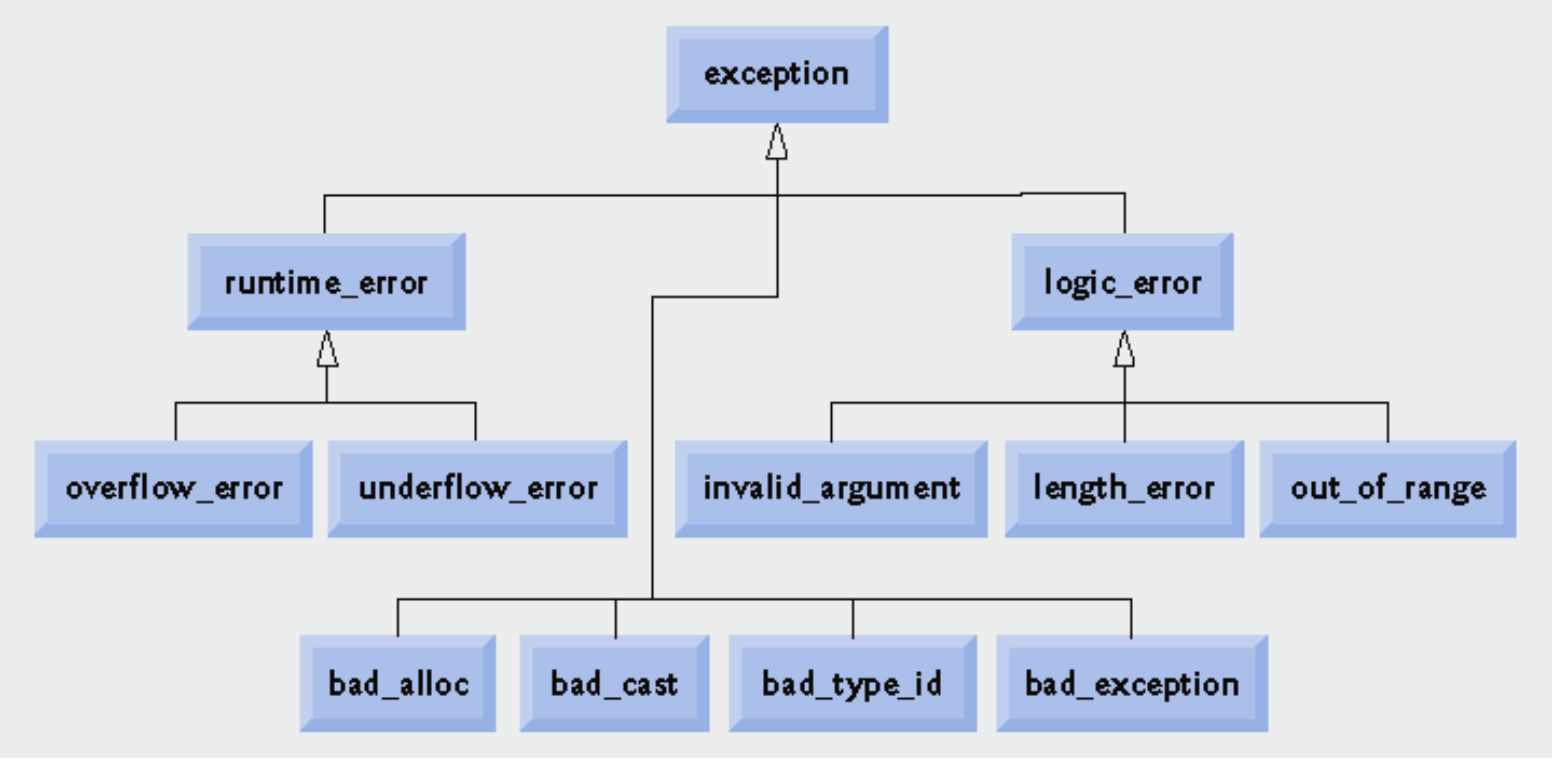

Fig. 18.11 | Standard Library exception classes.

18.13 Standard Library Exception Hierarchy (Cont.)

- **Exception hierarchy classes (Cont.)**
  - Class `logic_error`, derived from `exception`
    - Indicates errors in program logic
    - Exception classes derived from `logic_error`
      - `invalid_argument`
        - Indicates an invalid argument to a function
      - `length_error`
        - Indicates a length larger than the maximum size for some object was used
      - `out_of_range`
        - Indicates a value, such as an array subscript, exceeded its allowed range

18.13 Standard Library Exception Hierarchy (Cont.)

- **Exception hierarchy classes (Cont.)**
  - **Class `runtime_error`, derived from `exception`**
    - **Indicates execution-time errors**
    - **Exception classes derived from `runtime_error`**
      - `overflow_error`
        - **Indicates an arithmetic overflow error – an arithmetic result is larger than the largest storable number**
      - `underflow_error`
        - **Indicates an arithmetic underflow error – an arithmetic result is smaller than the smallest storable number**

Common Programming Error 18.9

Programmer-defined exception classes need not be derived from class `exception`. Thus, writing `catch( exception anyException )` is not guaranteed to `catch` all exceptions a program could encounter.

Error-Prevention Tip 18.6

To `catch` all exceptions potentially thrown in a `try` block, use `catch(...)`. One weakness with catching exceptions in this way is that the type of the caught exception is unknown at compile time. Another weakness is that, without a named parameter, there is no way to refer to the exception object inside the exception handler.

Software Engineering Observation 18.10

The standard `exception` hierarchy is a good starting point for creating exceptions. Programmers can build programs that can `throw` standard exceptions, `throw` exceptions derived from the standard exceptions or `throw` their own exceptions not derived from the standard exceptions.

Software Engineering Observation 18.11

Use `catch(...)` to perform recovery that does not depend on the exception type (e.g., releasing common resources). The exception can be rethrown to alert more specific enclosing `catch` handlers.