Module 37: Programming in C++

Exceptions (Error handling in C++): Part 2

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Slides taken from NPTEL course on Programming in Modern C++

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Module Objectives

- Understand the Error handling in C++

Module Outline

1. Exceptions in C++
   - `try-throw-catch`
   - Exception Scope (`try`)
   - Exception Arguments (`catch`)
   - Exception Matching
   - Exception Raise (`throw`)
   - Advantages
   - `std::exception`

2. Module Summary

Expectations

- Separate *Error-Handling code* from *Normal code*
- *Language Mechanism* rather than of the Library
- Compiler for *Tracking Automatic Variables*
- Schemes for *Destruction of Dynamic Memory*
- *Less Overhead* for the Designer
- *Exception Propagation* from the deepest of levels
- *Various Exceptions* handled by a single Handler

Error Handling Dynamics: C and C++

Header | **Caller** | **Callee**

C Scenario

Header

```
#include <stdio.h>
#include <stdbool.h>
#include <setjmp.h>
```

Caller

```
int main() {
    if (setjmp(jbuf) == 0) {
        printf("g() called\n");
        g();
        printf("g() returned\n");
    }
    else printf("g() failed\n"); // On longjmp
    return 0;
}
```

Callee

```
jmp_buf jbuf;
void g() {
    bool error = false;
    printf("g() started\n");
    if (error)
        longjmp(jbuf, 1);
    printf("g() ended\n");
    return;
}
```

C++ Scenario

Header

```
#include <iostream>
#include <exception>
using namespace std;
```

Caller

```
int main() {
    try {
        cout << "g() called\n";
        g();
        cout << "g() returned\n";
    }
    catch (Excp&) { cout << "g() failed\n"; }
    return 0;
}
```

Callee

```
class Excp: public exception {};
void g() {
    bool error = false;
    cout << "g() started\n";
    if (error)
        throw Excp();
    cout << "g() ended\n";
    return;
}
```

try-throw-catch

Caller

```
int main() {
    try {
        cout << "g() called\n";
        g();
        cout << "g() returned\n";
    }
    catch (Excp&) { cout << "g() failed\n"; }
    return 0;
}
```

(1) g() called

Callee

```
class Excp: public exception {};
void g() {
    bool error = false;
    cout << "g() started\n";
    if (error)
        throw Excp();
    cout << "g() ended\n";
    return;
}
```

(2) g() successfully returned

```
g() called
g() started
g() ended
g() returned
```

try-throw-catch

Caller

```
int main() {
    try {
        cout << "g() called\n";
        g();
        cout << "g() returned\n";
    }
    catch (Excp&) { cout << "g() failed\n"; }
    return 0;
}
```

Callee

```
class Excp: public exception {};
class A {};
void g() { A a;
    bool error = true;
    cout << "g() started\n";
    if (error)
        throw Excp();
    cout << "g() ended\n";
    return;
}
```

(1) g() called

(2) Exception raised
(3) Stack frame of g() unwinds and destructor of a called
(4) Remaining execution of g() and cout skipped

(5) Exception caught by catch clause
(6) Normal flow continues

```
g() called
g() started
g() failed
```

Exception Flow

```
#include <iostream>
#include <exception>
using namespace std;
class MyException: public exception { };
class MyClass { public: ~MyClass() { } };
void h() { MyClass h_a;
    //throw 1;              // Line 1
    //throw 2.5;            // Line 2
    //throw MyException();  // Line 3
    //throw exception();    // Line 4
    //throw MyClass();      // Line 5
}   // Stack unwind, h_a.~MyClass() called
    // Passes on all exceptions
void g() { MyClass g_a;
    try { h();
        bool okay = true; // Not executed
    }
    // Catches exception from Line 1
    catch (int) { cout << "int\n"; }
    // Catches exception from Line 2
    catch (double) { cout << "double\n"; }
    // Catches exception from Line 3-5 & passes on
    catch (...) { throw; }
}   // Stack unwind, g_a.~MyClass() called
```

```
void f() { MyClass f_a;
    try { g();
        bool okay = true; // Not executed
    }
    // Catches exception from Line 3
    catch (MyException) { cout << "MyException\n"; }
    // Catches exception from Line 4
    catch (exception) { cout << "exception\n"; }
    // Catches exception from Line 5 & passes on
    catch (...) { throw; }
}  // Stack unwind, f_a.~MyClass() called

int main() {
    try { f();
        bool okay = true; // Not executed
    }
    // Catches exception from Line 5
    catch (...) { cout << "Unknown\n"; }

    cout << "End of main()\n";
}
```

try Block: Exception Scope

- try block
  - Consolidate areas that might throw exceptions
- function try block
  - Area for detection is the entire function body
- Nested try block
  - Semantically equivalent to nested function calls

Function try

```
void f()
    try {
        throw E();
    }
    catch (E& e) {
    }
```

Note: The usual curly braces for the function scope are not to be put here

Nested try

```
try {
    try { throw E(); }
    catch (E& e) { }
}
catch (E& e1) {
}
```

catch Block: Exception Arguments

- catch block
  - Name for the Exception Handler
  - Catching an Exception is like invoking a function
  - Immediately follows the try block
  - Unique Formal Parameter for each Handler
  - Can simply be a Type Name to distinguish its Handler from others

try-catch: Exception Matching

- **Exact Match**
  - The catch argument type matches the type of the thrown object
    - *No implicit conversion is allowed*
- **Generalization / Specialization**
  - The catch argument is a public base class of the thrown class object
- **Pointer**
  - Pointer types – convertible by standard conversion

try-catch: Exception Matching

- In the *order of appearance* with matching
- If Base Class `catch` block precedes Derived Class `catch` block
  - Compiler issues a warning and continues
  - Unreachable code (derived class handler) ignored
- `catch(...)` block must be the last `catch` block because it catches all exceptions
- If no matching Handler is found in the current scope, the search continues to find a matching handler in a dynamically surrounding `try` block
  - *Stack Unwinds*
- If eventually no handler is found, `terminate()` is called

`throw` *Expression*: Exception Raise

- *Expression* is treated the same way as
  - A *function argument* in a call or the *operand of a return* statement
- Exception Context
  - `class Exception { };`
- The *Expression*
  - Generate an Exception object to throw
    - ▷ `throw Exception();`
  - Or, Copies an existing Exception object to throw
    - ▷ `Exception ex;`
    - ▷ `...`
    - ▷ `throw ex; // Exception(ex);`
- *Exception object is created on the Free Store*

throw *Expression*: Restrictions

- For a UDT Expression
  - Copy Constructor and Destructor should be supported
- The type of Expression cannot be an incomplete type or a pointer to an incomplete type
  - No incomplete type like `void`, array of unknown size or of elements of incomplete type, Declared but not Defined `struct` / `union` / `enum` / `class` Objects or Pointers to such Objects
  - No pointer to an incomplete type, except `void*`, `const void*`, `volatile void*`, `const volatile void*`

(re)-throw: Throwing Again?

- Re-throw
  - catch may pass on the exception after handling
  - Re-throw is not same as throwing again!

Throws again

```
try { ... }
catch (Exception& ex) {
    // Handle and
    ...
    // Raise again
    throw ex;
// ex copied
// ex destructed
}
```

Re-throw

```
try { ... }
catch (Exception& ex) {
    // Handle and
    ...
    // Pass-on
    throw;
    // No copy
// No Destruction
}
```

Advantages

- **Destructor-savvy**:
  - Stack unwinds; Orderly destruction of Local-objects
- **Unobtrusive**:
  - Exception Handling is implicit and automatic
  - No clutter of error checks
- **Precise**:
  - Exception Object Type designed using semantics
- **Native and Standard**:
  - EH is part of the C++ language
  - EH is available in all standard C++ compilers

Advantages

- **Scalable**:
  - Each function can have multiple try blocks
  - Each try block can have a single Handler or a group of Handlers
  - Each Handler can catch a single type, a group of types, or all types
- **Fault-tolerant**:
  - Functions can specify the exception types to throw; Handlers can specify the exception types to catch
  - Violation behavior of these specifications is predictable and user-configurable

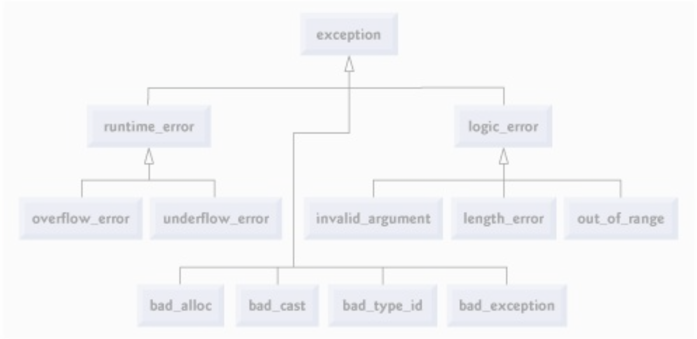
Exceptions in Standard Library: `std::exception`

All objects thrown by components of the standard library are derived from this class. Therefore, all standard exceptions can be caught by catching this type by reference.

```
class exception {
public:
    exception() throw();
    exception(const exception&) throw();
    exception& operator=(const exception&) throw();
    virtual ~exception() throw();
    virtual const char* what() const throw();
}
```

Sources: `std::exception` and `std::exception in C++11, C++14, C++17 & C++20`

Exceptions in Standard Library: std::exception



Sources: Standard Library Exception Hierarchy

Exceptions in Standard Library: `std::exception`

- `logic_error`: Faulty logic like violating logical preconditions or class invariants (may be preventable)
  - `invalid_argument`: An argument value has not been accepted
  - `domain_error`: Situations where the inputs are outside of the domain for an operation
  - `length_error`: Exceeding implementation defined length limits for some object
  - `out_of_range`: Attempt to access elements out of defined range
- `runtime_error`: Due to events beyond the scope of the program and can not be easily predicted
  - `range_error`: Result cannot be represented by the destination type
  - `overflow_error`: Arithmetic overflow errors (Result is too large for the destination type)
  - `underflow_error`: Arithmetic underflow errors (Result is a subnormal floating-point value)
- `bad_typeid`: Exception thrown on typeid of null pointer
- `bad_cast`: Exception thrown on failure to dynamic cast
- `bad_alloc`: Exception thrown on failure allocating memory
- `bad_exception`: Exception thrown by unexpected handler

Sources: `std::exception` and `std::exception in C++11, C++14, C++17 & C++20`

Exceptions in Standard Library: std::exception: C++98, C++11, C++14, C++17 & C++20

- logic_error
  - invalid_argument
  - domain_error
  - length_error
  - out_of_range
  - future_error (C++11)
- bad_optional_access (C++17)
- runtime_error
  - range_error
  - overflow_error
  - underflow_error
  - regex_error (C++11)
  - system_error (C++11)
    - ios_base::failure (C++11)
    - filesystem::filesystem_error (C++17)
  - txtion (TM TS)
  - nonexistent_local_time (C++20)
  - ambiguous_local_time (C++20)
  - format_error (C++20)
- bad_typeid
- bad_cast
  - bad_any_cast (C++17)
- bad_weak_ptr (C++11)
- bad_function_call (C++11)
- bad_alloc
  - bad_array_new_length (C++11)
- bad_exception
- ios_base::failure (until C++11)
- bad_variant_access (C++17)

Module Summary

- Discussed exception (error) handling in C++
- Illustrated `try-throw-catch` feature in C++ for handling errors
- Demonstrated with examples