Programmazione

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Error handling

- Error handling involves:
  - Detecting an error
  - Transmitting information about an error to some handler code
  - Preserve the state of a program in a valid state
  - Avoid resource leaks
- It is not possible to recover from all errors. We need a strategy to handle errors, especially if it is not possible to recover from them.

Exceptions

What are exceptions ?

- Exceptions are a mechanism for handling an error during execution.
- A function can indicate that an error has occurred by throwing an exception.
- The code that deals with the exception is said to handle it.

Why use exceptions ?

- Code where the error occurs and code to deal with the error can be separated
- Exceptions can be used with constructors and other functions/operators which can not return an error code
- Properly implemented exceptions lead to better code

How to use exceptions ?

- **try**
  - Try executing some block of code
  - See if an error occurs
- **throw**
  - An error condition occurred
  - Throw an exception to report the failure
- **catch**
  - Handle an exception thrown in a try block

How to use exceptions ?

- **try**
  - Try executing some block of code
  - See if an
- **throw**
  - An error condition occurred
  - Throw an exception to report the failure
- **catch**
  - Handle an exception thrown in a try block

An exception is an object that contains info about the problem

When to use exceptions ?

- Exceptions are meant to signal “exceptional” events and failures. Examples:
  - A precondition that cannot be met
  - A constructor that cannot construct an object (failure to establish its class's invariant)
  - An out-of-range error (e.g., `v[v.size()] = 7`)
  - Inability to acquire a resource (e.g., the network is down)
- In contrast, termination of an ordinary loop is not exceptional.
  - Do not use throw to return a method/function value !
  - Exceptions are for error handling only.

How exceptions work ?

- Normal program control flow is halted
  - At the point where an exception is thrown
- The program call stack “unwinds”
  - Stack frame of each function in call chain “pops”
  - Variables in each popped frame are destroyed
  - Goes until an enclosing try/catch scope is reached
- Control passes to first matching catch block
  - Can handle the exception and continue from there
  - Can free some resources and re-throw exception

What's right about exceptions

- Can't be silently ignored: if there is no applicable catch block for an exception the program terminates
- Automatically propagate across scopes (due to stack unwinding)
- Handling is out of main control flow, the code that implements the algorithm is not polluted

Exceptions syntax

C++ exceptions syntax

- Use `try-catch` blocks to catch an exception

```
try
{
    statement(s);
}
catch (ExceptionClass identifier)
{
    statement(s);
}
catch (ExceptionClass identifier)
{
    statement(s);
}
```

Place a statement(s) (function or method) that might throw an exception within a **try block**.

Appropriate code to handle the exception.

A try block **must** be followed by **one or more catch blocks**.

C++ exception flow

- When a statement (function or method) in a try block causes an exception:
  - Rest of try block is ignored.
  - Control passes to catch block corresponding to the exception.
  - After a catch block executes, control passes to statement after last catch block associated with the try block.

```
try
{
    ...
    statement;
    ...
}
catch (ExceptionClass identifier)
{
    statement(s);
}

statement(s);
```

Throw an exception

C++ exception flow - cont.

- A more complex example of exception flow:

```
void encodeChar(int i, string& str)
{
  ...
  str.replace(i, 1, 1, newChar);
}
```

Can throw the *out_of_range* exception.

```
void encodeString(int numChar, string& str)
{
  for(int i=numChar-1; i>=0; i--)
    encodeChar(i,str);
}
```

```
int main()
{
  string str1 = "NTU IM";
  encodeString(99, str1);
  return 0;
}
```

Abnormal program termination

Catching the exception

- Two examples on how to catch the exception:

```
void encodeChar(int i, string& str)
{
  try
  {
     ...
     str.replace(i, 1, 1, newChar);
   } catch (out_of_range e) {
     cout << "No character at " << i << endl;
   }
}
```

```
void encodeString(int numChar, string& str)
{
  for(int i=numChar-1; i>=0; i--)
    encodeChar(i,str);
}
```

```
int main()
{
  string str1 = "NTU IM";
  encodeString(99, str1);
  return 0;
}
```

No character at 98
No character at 97
…

Catching the exception

- Two examples on how to catch the exception:

```
void encodeChar(int i, string& str)
{
   ...
   str.replace(i, 1, 1, newChar);
}
```

```
void encodeString(int numChar, string& str)
{
   try
   {
      for(int i=numChar-1; i>=0; i--)
         encodeChar(i,str);
   } catch (out_of_range e) {
      cout << "Something wrong" << endl;
   }
}
```

Something wrong

```
int main()
{
   string str1 = "NTU IM";
   encodeString(99, str1);
   return 0;
}
```

Handlers

- A handler may re-throw the exception that was passed:
  - it forwards the exception
  - Use: `throw; // no operand`
  - after the local handler cleanup it will exit the current handler
- A handler may throw an exception of a different type
  - it translates the exception

Catching multiple exceptions

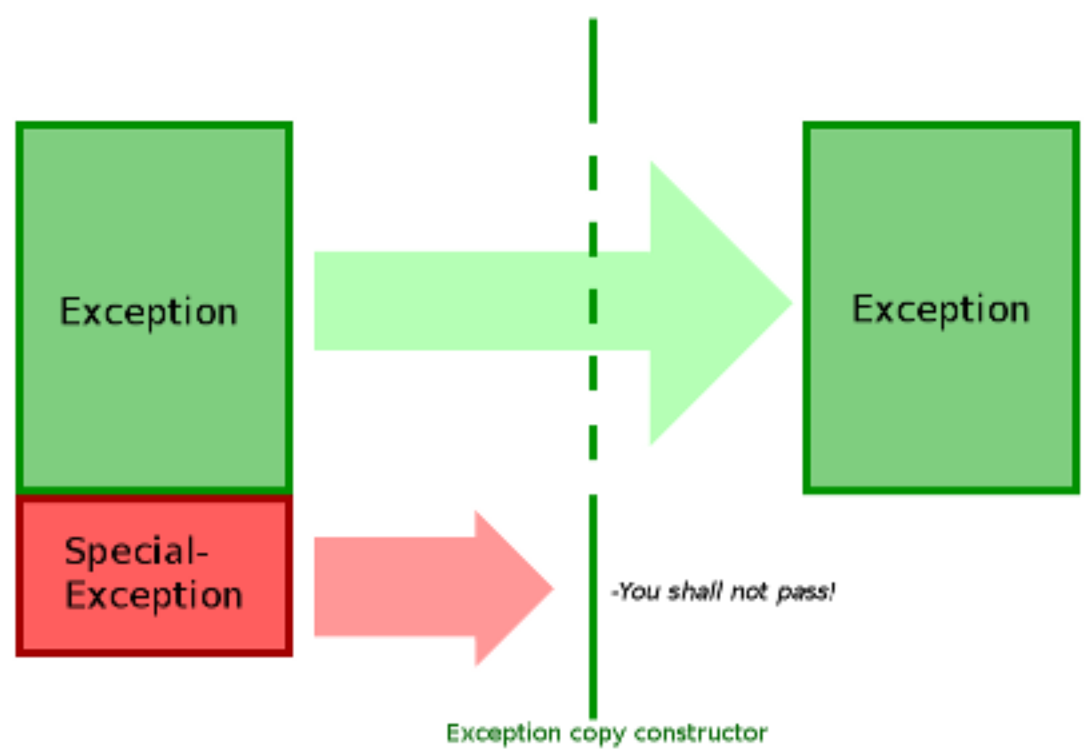
- The order of catch clauses is important:
  - Especially with inheritance-related exception classes
  - Put more specific catch blocks before more general ones
  - Put catch blocks for more derived exception classes before catch blocks for their respective base classes
- `catch(...)` catches any type

Catching multiple exceptions example

```
try {
  // can throw exceptions
} catch (DerivedExc &d) {
  // Do something
} catch (BaseExc &d) {
  // Do something else
} catch (...) {
  // Catch everything else
}
```

What to catch ?

- Catch by reference not by value:
  - it's faster (no copying)
  - it's safer: no slicing in case of exception inheritance
- Most handlers do not modify their exception so catch const references



Throwing exceptions

- When you detect an error within a method, you can throw an exception by using a throw statement.
- The remaining code within the function does not execute.
- Syntax: `throw ExceptionClass(stringArgument);`

  type of the exception — more detailed information

```
void myMethod(int x) throw(MyException)
{
    if (...)
        throw MyException("MyException: …");
    ...
}   // end myMethod
```

Throwing exceptions - cont.

- The exception is propagated back to the point where the function was called.

```
try
{
    ...
    myMethod(int x);
    ...
}
catch (ExceptionClass identifier)
{
    statement(s);
}
```

back to here!!

What to throw

- Always throw by value, not by pointer:
  - `throw Exception(); // OK`
  - `throw new Exception(); // Bad`

1. You want to throw an exception, not a pointer.
2. There is no point in allocating on the heap if you don't have to.
3. You force to clean up memory for you when catching.

Specifying exceptions

- Functions that throw an exception have a throw clause, to restrict the exceptions that a function can throw.
  - Allow stronger type checking enforced by the compiler
  - By default, a function can throw anything it wants
- A throw clause in a function's signature
  - Limits what can be thrown
  - A promise to calling function
- A throw clause with no types
  - Says nothing will be thrown
- Can list multiple types, comma separated

Specifying exceptions examples

These are four alternative declarations

```
// can throw anything
void Foo::bar();

// promises not to throw
void Foo::bar() noexcept; //C++11

// promises to only throw int
void Foo::bar() throw(int);

// throws only char or int
void Foo::bar() throw(char,int);
```

Specifying exceptions examples

These are four alternative declarations

```
// can throw anything
void Foo::bar();

// promises not to throw
```

Old (deprecated): `void Foo::bar() throw();`

```
// promises to only throw int
void Foo::bar() throw(int);

// throws only char or int
void Foo::bar() throw(char,int);
```

Specifying exceptions examples

```
// can throw anything
void Foo::bar();
```

Also throw specifications have been deprecated in C++11. In general simply use `noexcept` or nothing at all.

The rationale for this change is that if a function throws an exception different from the specified ones then the program is terminated.
So just throw whatever must be thrown and catch it at the appropriate level.

noexcept

- Use `noexcept` if a function surely won't throw (e.g. all its operations do not throw) or…
- if it's unacceptable to throw an exception, e.g. we are not willing or able to handle the situation, so crashing the program is acceptable
  - Many standard-library functions are noexcept including all the standard-library functions from the C Standard Library.

Destructors and exceptions

Destructors and exceptions

- Prevent exceptions from leaving destructors: premature program termination or undefined behaviour can result from destructors emitting exceptions
  - during the stack unwinding resulting from the processing of the exception are called the destructors of local objects, and one may trigger another exception

How to behave: example

```
class DBConnection {
public:
  //...

  // return a DBConnection object
  static DBConnection create();

  void close(); // close connection and
                // throws exception if
                // closing fails
};
```

```
// class to manage DBConnection
class DBConnMgr {
public:
  //...
  DBConnMgr(DBConnection dbc);
  ~DBConnMgr() {
    db.close(); // we're sure it
                // gets closed
  }

private:
  DBConnection db;
};
```

```
// client code
{
  DBConnMgr dbc( DBConnection::create() );
  //... use DBConnection through DBConnMgr interface
} // DBConnMgr obj is automatically destroyed, calling the close
```

How to behave: example

```
class DBConnection {
public:
  //...

  // return a DBConnection object
  static DBConnection create();

  void close(); // close connection and
                // throws exception if
                // closing fails
};
```

```
// class to manage DBConnection
class DBConnMgr {
public:
  //...
  DBConnMgr(DBConnection dbc);
  ~DBConnMgr() {
    db.close(); // we're sure it
                // gets closed
  }

private:
  DBConnection db;
```

If close() throws the destructor propagates the exception

```
// client code
{
  DBConnMgr dbc( DBConnection::create() );
  //... use DBConnection through DBConnMgr interface
} // DBConnMgr obj is automatically destroyed, calling the close
```

(Not so good) solutions

- Terminate the program:

```
DBConnMgr::~DBConnMgr() {
  try{ db.close(); }
  catch (...) {
    // log failure and...
    std::abort();
  }
}
```

- Swallow the exception:

```
DBConnMgr::~DBConnMgr() {
  try{ db.close() }
  catch (...) {
    // just log the error
  }
}
```

(Not so good) solutions

- Terminate the program:

```
DBConnMgr::~DBConnMgr() {
  try{ db.close(); }
  catch (...) {
    // log failure and...
    std::abort();
  }
}
```

- Swallow the exception:

```
DBConnMgr::~DBConnMgr() {
  try{ db.close() }
  catch (...) {
    // just log the error
  }
}
```

With this solution we’re just hiding the problem

A better strategy

```
// class to manage DBConnection
class DBConnMgr {
public:
  //...
  DBConnMgr(DBConnection dbc);
  void close() {
    db.close();
    closed = true;
  }
  ~DBConnMgr() { // we're sure it gets closed
    if( !closed ) {
      try {
        db.close();
      } catch (...) {
        // log and... terminate or swallow
      }
    }
  }

private:
  DBConnection db;
  bool closed;
};
```

A better strategy

```
// class to manage DBConnection
class DBConnMgr {
public:
  //...
  DBConnMgr(DBConnection dbc);
  void close() {
    db.close();
    closed = true;
  }
  ~DBConnMgr() { // we're sure it gets closed
    if( !closed ) {
      try {
        db.close();
      } catch (...) {
        // log and... terminate or swallow
      }
    }
  }

private:
  DBConnection db;
  bool closed;
};
```

Client code should use this method...

A better strategy

```
// class to manage DBConnection
class DBConnMgr {
public:
  //...
  DBConnMgr(DBConnection dbc);
  void close() {
    db.close();
    closed = true;
  }
  ~DBConnMgr() { // we're sure it gets closed
    if( !closed ) {
      try {
        db.close();
      } catch (...) {
        // log and... terminate or swallow
      }
    }
  }

private:
  DBConnection db;
  bool closed;
};
```

Client code should use this method...

...but if it doesn't there's the destructor

Defining exceptions classes

Syntax and example

Defining exceptions classes

- C++ Standard Library supplies a number of exception classes.
  - E.g., `exception`, `out_of_range`, … etc.
- You may also want to define your own exception class.
  - Should inherit from those pre-defined exception classes for a standardized exception working interface.
- Syntax:

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

Purpose-designed user-defined exceptions

- It is a good practice to use purpose-designed user-defined types as exceptions:
  - They do not clash with other people's exceptions
  - Clear intent of the code
- Standard-library exceptions should be used as base classes or for exceptions requiring "generic handling"

BAD

```
void my_code() {
  // ...
  throw runtime_error{"moon in
            the 4th quarter"};
    // ...
}

void your_code() {
  try {
    // ...
    my_code();
    // ...
  }
  catch(const runtime_error&) {
    // runtime_error means
    // "input buffer too small"
    // ...
  }
}
```

GOOD

```
void my_code() {
  // ...
  throw Moonphase_error{};
  // ...
}

void your_code() {
  try {
    // ...
    my_code();
    // ...
  }
  catch(const
      Bufferpool_exhausted&) {
      // ...
  }
}
```

Defining exceptions classes example

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

class MyException : public exception
{
public:
   MyException(const string & Message = "")
        : exception(Message.c_str()) {}
} // end class
```

```
try
{
   ...
}
catch (MyExceptoin e)
{    cout << e.what();
}
```

```
throw MyException("more detailed information");
```

A full example

- An ADT List implementation using exceptions:
  - out-of-bound list index.
  - attempt to insert into a full list.

Define two exception classes

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

class ListIndexOutOfRangeException : public out_of_range {
public:
  ListIndexOutOfRangeException(const string& message = “”)
        : out_of_range(message.c_str()) {}
}; // end ListException

class ListException : public logic_error {
public:
  ListException(const string & message = “”)
         : logic_error(message.c_str()) {}
}; // end ListException
```

Declare the throw

```
#include "MyListExceptions.h"
 . . .
class List
{
public:
   . . .
   void insert(int index, const ListItemType& newItem)

        throw(ListIndexOutOfRangeException,
              ListException);
   . . .
}  // end List
```

Method implementation

```
void List::insert(int index, const ListItemType& newItem)
   throw(ListIndexOutOfRangeException, ListException) {
   if (size >= MAX_LIST)
      throw ListException("ListException: List full on insert");
   if (index >= 1 && index <= size+1)   {
       for (int pos = size; pos >= index; --pos)
         items[translate(pos+1)] = items[translate(pos)];
      // insert new item
      items[translate(index)] = newItem;
      ++size;  // increase the size of the list by one
   } else  // index out of range
      throw ListIndexOutOfRangeException(
       "ListIndexOutOfRangeException: Bad index on insert");
}  // end insert
```

Good Programming Style with C++ Exceptions

- Don’t use exceptions for normal program flow
  - Only use where normal flow isn’t possible
- Don’t let exceptions leave destructors
  - If during stack unwinding one more exception is thrown then the program is terminated.
- Always throw some type
  - So the exception can be caught
- ~~Use exception specifications widely~~ (deprecated)
  - Helps caller know possible exceptions to catch

Constructors and exceptions

- Constructors can throw exceptions, but:
  - if a constructor throws an exception, the object's destructor is not run.
  - If your object has already done something that needs to be undone (such as allocating some memory, etc.), this must be undone:
    - using smart pointers is a solution, since their destruction will free the resource.
    - handling the resource in the constructor before leaving it

Constructors and exceptions

```
class Foo {
public:
    Foo() {
      try{
          p = new p;
          throw /* something */;
      }
      catch (.. .) {
         delete p;
         throw; //rethrow. no memory leak
      }
    }
private:
    int *p;
};
```

Where to catch an exception ?

- Don't try to catch every exception in every function
  - Catching an exception in a function that cannot take a meaningful recovery action leads to complexity and waste.
  - Let an exception propagate until it reaches a function that can handle it.

Exception-safe functions

- Exception-safe functions offer one of three guarantees:
  - **basic guarantee**: if an exception is thrown, everything in the program remains in a valid state
  - **strong guarantee**: if an exception is thrown, the state of the program is unchanged. The call to the function is atomic
  - **nothrow guarantee**: promise to never throw exception: they always do what they promise. All operations on built-in types are nothrow.

Exception-safe code

- When an exception is thrown, exception safe functions:
  - leak no resource (e.g. new-ed objects, handles, etc.)
  - don't allow data structures to become corrupted (e.g. a pointer that had to point to a new object was left pointing to nowhere)

Reading material

- M. Bertini, "Programmazione Object-Oriented in C++", parte I, cap. 5
- B. Stroustrup, "C++, Linguaggio, libreria standard, principi di programmazione", cap. 13
- B. Stroustrup, "C++, guida essenziale per programmatori" - pp. 27-28
- L.J. Aguilar, "Fondamenti di programmazione in C++. Algoritmi, strutture dati e oggetti" - cap. 14

Credits

- These slides are based on the material of:
  - Dr. Walter E. Brown, Fermi Lab
  - Dr. Chien Chin Chen, National Taiwan University
  - Dr. Jochen Lang, University of Ottawa
  - Fred Kuhns, Washington University
  - Scott Meyers, "Effective C++", 3rd ed.