ADVANCED C++ FEATURES

Bùi Tiến Lên

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KHOA CÔNG NGHỆ THÔNG TIN
TRƯỜNG ĐẠI HỌC KHOA HỌC TỰ NHIÊN

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C++ Is Software System

- C++ is a high-level general-purpose programming language created by Bjarne Stroustrup in 1985
- C++ developement

Year	C++ Standard	Informal name
1998	ISO/IEC 14882:1998	C++98
2003	ISO/IEC 14882:2003	C++03
2011	ISO/IEC 14882:2011	C++11
2014	ISO/IEC 14882:2014	C++14
2017	ISO/IEC 14882:2017	C++17
2020	ISO/IEC 14882:2020	C++20

Memory Management

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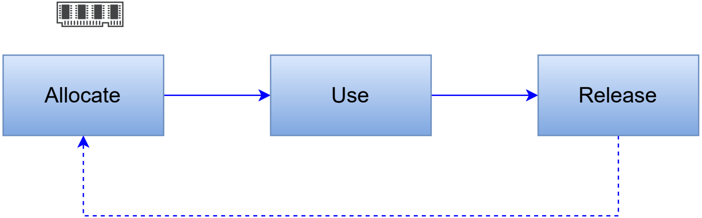
Overview

In C++,

- when we create variables, objects, or anything you can think of, the machine allocates memory for this
- when we don't need them, release them.



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The memory heap and stack

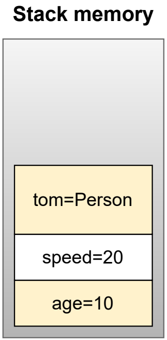
C++ uses two common places to store objects

- Stack memory
- Heap memory

Stack: Static memory allocation

- Stack memory is used to store static data such as local variables and parameters where C++ knows at compile time.

```
int age=10;
int speed=20;
Person tom = Person;
```



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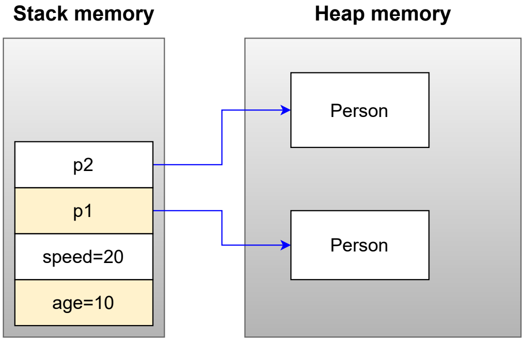
Heap: Dynamic memory allocation

- Heap memory is used to store dynamic data such as dynamic objects.

```
int age=10;
int speed=20;
Person *p1 = new Person;
Person *p2 = new Person;
```



Exception Handling

- Mechanism
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Introduction

Concept 1

Exception is unexpected something that has occurred or been detected

There are two types of exception:

- **Synchronous exceptions**
  - The exceptions which occur during the program execution due to some fault in the input data are known as synchronous exceptions.
  - For example: errors such as out of range, overflow, underflow.
- **Asynchronous exceptions**
  - The exceptions caused by events or faults unrelated (external) to the program and beyond the control of the program are called asynchronous exceptions.
  - For example: errors such as keyboard interrupts, hardware malfunctions, disk failure.

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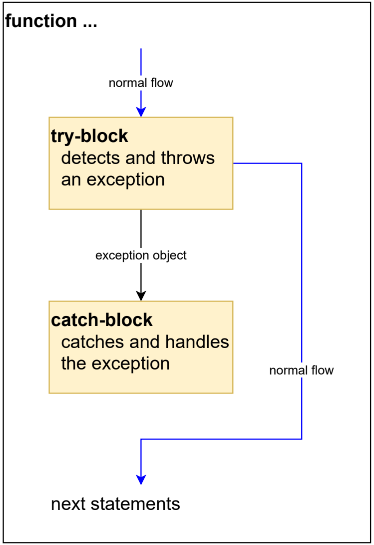
Exception Handling Mechanism

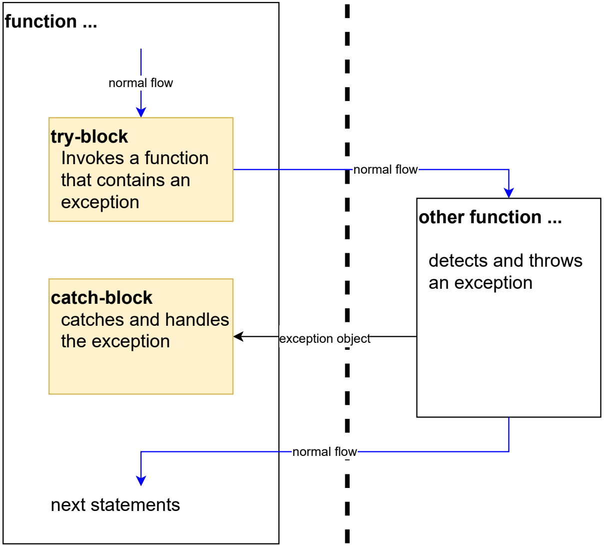
The exception handling mechanism is built upon three keywords:

- `try`-block
  A try block is used to preface a block of statements which may generate exceptions.
- `catch`-block
  A catch block catches the exception thrown by the throw statement in the try block and handles it appropriately.
  One/multiple catch blocks can be associated with a try block
- `throw`
  When an exception is detected, it is thrown using a throw statement.

Exception Thrown Inside



Exception Thrown by Other Function



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Exceptions – Flow of Control

1. If the function which is called from within a try block throws an exception, the function terminates and the try block is immediately exited.
   - If **automatic objects** were created in the try block and an exception is thrown, they are **destroyed**.
2. A catch block to process the exception is searched for in the source code immediately following the try block.
3. If a catch block is found that matches the exception thrown, it is executed. If no catch block that matches the exception is found, the program terminates.

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Try/Catch Syntax

- try/catch block

```
try {
    ...
}
catch( ) {
    ...
}
```

- nested try/catch blocks

```
try {
    ...
    try {
        ...
    }
    catch( ) {
        ...
    }
    ...
}
catch( ) {
    ...
}
```

Function-try-block

Concept 2

Function-try-block establishes an exception handler around the body of a function and the member initializer list (if used in a constructor) as well.

```
class Person {
private:
   ...
   Date dob;
public
   Person(int d, int m, int y)
   try : dob(d, m, y)
   { ... }
   catch (...)
   { ... }
};
```

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Throwing Exception

- When an exception is desired to be handled is detected, it is thrown using the throw statement.
- Throw statement has one of the following forms:

```
throw (exception);
throw exception;
throw;
```

- The operand object exception may be of any type, including constants.

Exception classes

- One of the major problems with using basic data types (such as `int`) as exception types is that they are inherently vague.
- One way to solve this problem is to use exception classes. An exception class is just a normal class that is designed specifically to be thrown as an exception.

```
class MyException {
private:
  string msg;
public:
  MyException(string msg) {
    this->msg = msg;
  }
  string getInfo() {
    return msg;
  }
};
```

```
void main() {
  try {
    ...
    if(b == 0)
      throw MyException("Divided by zero");
    cout << "a/b=" << a/b;
  }
  catch(MyException& ex) {
    cout << ex.getInfo();
  }
}
```

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Catching Exception

- A catch block looks like a function definition:

```
catch(type exception) { // catch by value
    // statements for handling exceptions.
}
catch(type& exception) { // catch by reference
    // statements for handling exceptions.
}
```

  - The type indicates the type of exception that catch block handles.
  - The catch statement catches an exception whose type matches with the type of catch argument.

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Catching Exception (cont.)

- Catch exceptions by reference in order to:
  - avoid copying
  - avoid slicing
  - allow exception object to be modified and then rethrown
- A catch statement can also force to catch all exceptions instead of a certain type alone.

```
catch(...) {
    // statements for handling all exceptions.
}
```

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Re-throwing an Exception

- A handler can re-throw the exception caught without processing it.
- This can be done using `throw` without any arguments.
- Every time when an exception is re-thrown it will not be caught by the same catch statements rather it will be caught by the catch statements outside the try/catch block.

Listing 1

```
int gcd(int a, int b) {
  if(a <= 0 || b <= 0)
    throw string("error");

  while(a != b)
    if(a > b) a -= b;
    else b -= a;

  return a;
}
```

```
void main() {
  ...
  try {
    u = gcd(a, b);
    cout << u;
  }
  catch(string ex) {
    cout << ex;
  }
}
```

Exception and Inheritance

- Consider the following program

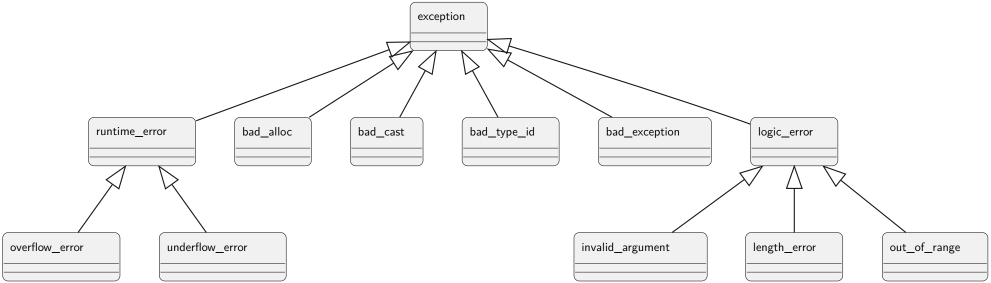
```
class Base {};
class Derived: public Base {};
void main() {
    try {
        throw Derived();
    }
    catch (Base &base) {
        cout << "caught Base";
    }
    catch (Derived &derived) {
        cout << "caught Derived";
    }
}
```

Standard Exception Classes

- All exception classes in standard library derived (directly or indirectly) from `std::exception` class
- Exception classes derived from `std::exception` class

Type	Description
`logic_error`	faulty logic in program
`runtime_error`	error caused by circumstances beyond scope of program
`bad_type_id`	invalid operand for typeid operator
`bad_cast`	invalid expression for `dynamic_cast`
`bad_weak_ptr`	bad `weak_ptr` given
`bad_function_call`	*function* has no target
`bad_alloc`	storage allocation failure
`bad_exception`	use of invalid exception type in certain contexts
`bad_variant_access`	*variant* accessed in invalid way

Standard Exception Classes (cont.)



Listing 2

```
#include <iostream>
#include <exception>  // include this to catch exception bad_alloc
using namespace std;
int main() {
   cout << "Enter number of integers you wish to reserve: ";
   try    {
      int Input = 0;
      cin >> Input;
      // Request memory space and then return it
      int* pReservedInts = new int [Input];
      delete[] pReservedInts;
   }
   catch (std::bad_alloc& exp)    {
      cout << "Exception encountered: " << exp.what() << endl;
      cout << "Got to end, sorry!" << endl;
   }
   catch(...)    {
      cout << "Exception encountered. Got to end, sorry!" << endl;
   }
   return 0;
}
```

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Exception and Resource

- Consider the following function

```
int fibo(int n) {
  int *a = new int[n+2];
  if(n > 46) throw "overflow";
  a[0] = 1;
  a[1] = 1;
  for(int i=2; i<=n; i++) a[i] = a[i-1] + a[i-2];
  int re = a[n];
  delete[] a;
  return re;
}
```

- It leaks the memory if `n > 46`

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Exception and Resource (cont.)

Solution

1. Rewrite the function or
2. Use *Resource Acquisition Is Initialization*

Resource Acquisition Is Initialization

Resource Acquisition Is Initialization (RAII), a C++ programming technique proposed by Bjarne Stroustrup

- encapsulate each resource (allocated heap memory, thread of execution, open socket, open file, locked mutex, disk space, database connection) into a class, where
  - **the constructor acquires** the resource and establishes all class invariants or throws an exception if that cannot be done
  - **the destructor releases** the resource and never throws exceptions
- **it binds** the life cycle of a resource to the lifetime of an object; always use the resource via an instance of a RAII-class that either
  - has automatic storage duration or temporary lifetime itself, or
  - has lifetime that is bounded by the lifetime of an automatic or temporary object

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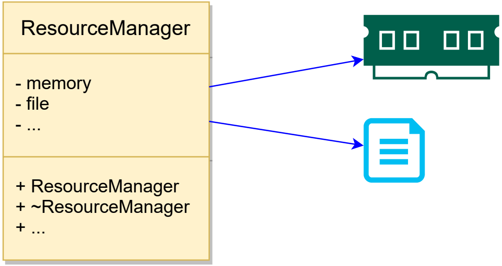
Resource Acquisition Is Initialization (cont.)

- Most smart pointers
- Many wrappers for
  - memory
  - files
  - mutexes
  - network sockets
  - graphic ports



Smart Pointers

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Introduction

Concept 3

A smart pointer in C++ is a class with overloaded operators, which behaves like a **conventional pointer**.

- C++ supplies full flexibility to the programmer in memory allocation, deallocation, and management. Unfortunately, this flexibility is a double-edged sword.
- It can memory-related problems, such as memory leaks, when dynamically allocated objects are not correctly released.

The Problem with Using Conventional Pointers

In the following line of code, there is no obvious way to tell whether the memory pointed to by `pData`

- Was allocated on the `heap`, and therefore eventually needs to be `deallocated`?
- Is the responsibility of the caller to `deallocate`?
- Will automatically be destroyed by the object's `destructor`?

```
CData *pData = mObject.GetData();
/*
Questions: Is object pointed by pData dynamically allocated
    using new?
Who will perform delete: caller or the called?
Answer: No idea!
*/
pData->Display();
```

How Do Smart Pointers Help?

- The programmer can choose a smarter way to allocate and manage dynamic data by adopting the use of smart pointers in his programs:

```
smart_pointer<CData> spData = mObject.GetData();

// Use a smart pointer like a conventional pointer!
spData->Display();
(*spData).Display();

// Don't have to worry about de-allocation
// (the smart pointer's destructor does it for you)
```

- Smart pointers behave like conventional pointers but supply useful features via their *overloaded operators* and *destructors* to ensure that dynamically allocated data is destroyed in a timely manner.

How Are Smart Pointers Implemented?

```
template <typename T>
class smart_pointer {
private:
    T* m_pRawPointer;
public:
    // constructor
    smart_pointer (T* pData) : m_pRawPointer (pData) {}
    // destructor
    ~smart_pointer () {delete pData;}
    // copy constructor
    smart_pointer (const smart_pointer & anotherSP) {...}
    // copy assignment operator
    smart_pointer& operator= (const smart_pointer& anotherSP) {...}
    T& operator* () const {        // dereferencing operator
        return *(m_pRawPointer);
    }
    T* operator-> () const {       // member selection operator
        return m_pRawPointer;
    }
};
```

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Types of Smart Pointers

Classification of smart pointers is actually a classification of their memory resource management strategies. These are

- Deep copy
- Copy on Write (COW)
- Reference counted
- Reference linked
- Destructive copy

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Deep Copy

- In a smart pointer that implements deep copy, every smart pointer instance holds a complete copy of the object that is being managed.
- Whenever the smart pointer is copied, the object pointed to is also copied (thus, deep copy).
- When the smart pointer goes out of scope, it releases the memory it points to (via the destructor).

Listing 3

```
template <typename T>
class deepcopy_smart_pointer {
private:
    T* m_pObject;
public:
    // ... other functions
    // copy constructor of the deepcopy pointer
    deepcopy_smart_pointer (const deepcopy_smart_pointer& source)     {
        // Clone() is virtual: ensures deep copy of Derived class object
        m_pObject = source->Clone ();
    }
    // copy assignment operator
    deepcopy_smart_pointer& operator= (const deepcopy_smart_pointer& source) {
        if (m_pObject)
            delete m_pObject;
        m_pObject = source->Clone ();
    }
};
```

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Copy on Write Mechanism

- *Copy on Write* (COW as it is popularly called) attempts to optimize the performance of deep-copy smart pointers by sharing pointers until the first attempt at writing to the object is made.
- On the first attempt at invoking a non-`const` function, a COW pointer typically creates a copy of the object on which the non-`const` function is invoked, whereas other instances of the pointer continue sharing the source object.
- COW has its fair share of fans. For those that swear by COW, implementing operators (`*`) and (`->`) in their `const` and non-`const` versions is key to the functionality of the COW pointer. The latter creates a copy.

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Reference-Counted Smart Pointers

- Reference counting in general is a mechanism that keeps a count of the number of users of an object.
- When the count reduces to zero, the object is released.
- So, reference counting makes a very good mechanism for sharing objects without having to copy them.
- Reference counting suffers from the problem caused by cyclic dependency.

There are at least two popular ways to keep this count:

- Reference count maintained in the object being pointed to
- Reference count maintained by the pointer class in a shared object

Reference-Linked Smart Pointers

- *Reference-linked* smart pointers are ones that don't proactively count the number of references using the object; rather, they just need to know when the number comes down to zero so that the object can be released.
- They are called *reference-linked* because their implementation is based on a double-linked list.
- When a new smart pointer is created by copying an existing one, it is appended to the list.
- When a smart pointer goes out of scope or is destroyed, the destructor de-indexes the smart pointer from this list.
- Reference linking also suffers from the problem caused by cyclic dependency, as applicable to reference-counted pointers.

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Destructive Copy

- *Destructive copy* is a mechanism where a smart pointer, when copied, transfers complete ownership of the object being handled to the destination and resets itself.

Listing 4

```
template <typename T>
class destructivecopy_pointer {
private:
   T* pObject;
public:
   destructivecopy_pointer(T* pInput):pObject(pInput) {}
   ~destructivecopy_pointer() { delete pObject; }
   // copy constructor
   destructivecopy_pointer(destructivecopy_pointer& source) {
      // Take ownership on copy
      pObject = source.pObject;
      // destroy source
      source.pObject = 0;
   }
   // copy assignment operator
   destructivecopy_pointer& operator= (destructivecopy_pointer& rhs) {
      if (pObject != source.pObject) {
         delete pObject;
         pObject = source.pObject;
         source.pObject = 0;
      }
   }
};
```

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Introduction

- Since C++ 11, we can use smart pointers to dynamically allocate memory and not worry about deleting the memory when we are finished using it.
- Must `#include` the memory header file

```
#include <memory>
```

- Three types of smart pointer

```
unique_ptr
shared_ptr
weak_ptr
```

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Listing 5

```
#include <iostream>
#include <memory>  // include this to use std::unique_ptr
using namespace std;
class Fish {
public:
    Fish() {cout << "Fish: Constructed!" << endl;}
    ~Fish() {cout << "Fish: Destructed!" << endl;}
    void Swim() const {cout << "Fish swims in water" << endl;}
};
void MakeFishSwim(const unique_ptr<Fish>& inFish) {
   inFish->Swim();
}
int main() {
   unique_ptr<Fish> smartFish (new Fish);
   smartFish->Swim();
   MakeFishSwim(smartFish); // OK, as MakeFishSwim accepts reference
   unique_ptr<Fish> copySmartFish;
   // copySmartFish = smartFish; // error: operator= is private
   return 0;
}
```

Move Constructor and Move Assignment Operator

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Concept 4

The **move constructor** and the **move assignment operators** are performance optimization features that have become a part of the standard in C++11, ensuring that **temporary values** (**rvalues** that don't exist beyond the statement) are not unnecessarily copied.

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The Problem of Unwanted Copy Steps

```
class MyString {
  ...
  MyString operator+ (const MyString& AddThis) {
    MyString NewString;
    if (AddThis.Buffer != NULL) {
      // copy into NewString
    }
    return NewString;
  }
  ...
}
```

The Problem of Unwanted Copy Steps (cont.)

```
1 MyString Hello("Hello ");
2 MyString World("World ");
3 MyString CPP("of C++");
4 MyString sayHello(Hello + World + CPP);
5 MyString sayHelloAgain("overwrite this");
6 sayHelloAgain = Hello + World + CPP;
```

- Line 4: `operator+`, copy constructor
- Line 6: `operator+`, copy constructor, copy assignment `operator=`

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Declaring a Move Constructor and Move Assignment Operator

Syntax

```
class ClassName
    // move constructor
    ClassName(ClassName&& moveSource);
    // move assignment operator
    ClassName& operator= (ClassName&& moveSource);
```

Listing 5

```
#include <iostream>
using namespace std;
class MyString {
private:
   char* Buffer;
   // private default constructor
   MyString(): Buffer(NULL) {
      cout << "Default constructor called" << endl;
   }
public:
   // Destructor
   ~MyString() {
      if (Buffer != NULL)
         delete [] Buffer;
   }
   int GetLength() {
      return strlen(Buffer);
   }
   operator const char*() {
      return Buffer;
   }
   MyString operator+ (const MyString& AddThis) {
      cout << "operator+ called: " << endl;
      MyString NewString;
      if (AddThis.Buffer != NULL) {
         NewString.Buffer = new char[GetLength() + strlen(AddThis.Buffer) + 1];
```

Listing 5 (cont.)

```
        strcpy(NewString.Buffer, Buffer);
        strcat(NewString.Buffer, AddThis.Buffer);
    }
    return NewString;
}
// constructor
MyString(const char* InitialInput) {
    cout << "Constructor called for: " << InitialInput << endl;
    if(InitialInput != NULL) {
        Buffer = new char [strlen(InitialInput) + 1];
        strcpy(Buffer, InitialInput);
    }
    else
        Buffer = NULL;
}
// Copy constructor
MyString(const MyString& CopySource) {
    cout<<"Copy constructor to copy from: "<<CopySource.Buffer<<endl;
    if(CopySource.Buffer != NULL) {
        // ensure deep copy by first allocating own buffer
        Buffer = new char [strlen(CopySource.Buffer) + 1];
        // copy from the source into local buffer
        strcpy(Buffer, CopySource.Buffer);
    }
    else
        Buffer = NULL;
```

Listing 5 (cont.)

```
}
// Copy assignment operator
MyString& operator= (const MyString& CopySource) {
   cout<<"Copy assignment operator to copy from: "<<CopySource.Buffer<< endl;
   if ((this != &CopySource) && (CopySource.Buffer != NULL)) {
      if (Buffer != NULL)
       delete[] Buffer;
      // ensure deep copy by first allocating own buffer
      Buffer = new char [strlen(CopySource.Buffer) + 1];
      // copy from the source into local buffer
      strcpy(Buffer, CopySource.Buffer);
   }
  return *this;
}
// move constructor
MyString(MyString&& MoveSource) {
   cout << "Move constructor to move from: " << MoveSource.Buffer << endl;
   if(MoveSource.Buffer != NULL) {
      Buffer = MoveSource.Buffer; // take ownership i.e.  'move'
      MoveSource.Buffer = NULL;   // free move source
   }
 }
// move assignment operator
MyString& operator= (MyString&& MoveSource) {
  cout<<"Move assignment operator to move from: "<<MoveSource.Buffer<<endl;
  if((MoveSource.Buffer != NULL) && (this != &MoveSource)) {
```

Listing 5 (cont.)

```
        delete Buffer; // release own buffer
        Buffer = MoveSource.Buffer; // take ownership i.e.  'move'
        MoveSource.Buffer = NULL;   // free move source
      }
      return *this;
    }
};
int main() {
   MyString Hello("Hello ");
   MyString World("World");
   MyString CPP(" of C++");
   MyString sayHelloAgain("overwrite this");
   sayHelloAgain = Hello + World + CPP;
   return 0;
}
```

Workshop

Quiz

1. What is `std::exception`?

2. What type of exception is thrown when an allocation using `new` fails?

3. Is it alright to allocate a million integers in an exception handler (`catch` block) to back up existing data for instance?

Memory Management
Exception Handling
Mechanism
Function-try-block
Throwing Exception
Catching Exception
Standard Exception Classes
Exception and Resource
Smart Pointers
Types of Smart Pointers
Standard Smart Pointers
Move Constructor and Move Assignment Operator
Workshop

Quiz (cont.)

4. How would you catch an exception object of type `class MyException` that inherits from `std::exception`?

   ....
   ....
   ....

5. Would a smart pointer slow down your application significantly?

   ....
   ....
   ....

6. Where can reference-counted smart pointers hold the reference count data?

   ....
   ....
   ....

Exercises

1. Point out the bug in this code:

```
std::auto_ptr<SampleClass> pObject (new SampleClass ());
std::auto_ptr<SampleClass> pAnotherObject (pObject);
pObject->DoSomething ();
pAnotherObject->DoSomething();
```

2. Use the unique_ptr class to instantiate a Carp that inherits from Fish. Pass the object as a Fish pointer and comment on slicing, if any.
3. Point out the bug in this code:

```
std::unique_ptr<Tuna> myTuna (new Tuna);
unique_ptr<Tuna> copyTuna;
copyTuna = myTuna;
```

References

Deitel, P. (2016).
C++: How to program.
Pearson.

Gaddis, T. (2014).
Starting Out with C++ from Control Structures to Objects.
Addison-Wesley Professional, 8th edition.

Jones, B. (2014).
Sams teach yourself C++ in one hour a day.
Sams.