Object Oriented Programming in C++

Jan Faigl

Department of Computer Science
Faculty of Electrical Engineering
Czech Technical University in Prague

Lecture 12

PRG – Programming in C

Overview of the Lecture

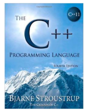
Part I

Part 1 – Object Oriented Programming

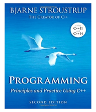
Resources Objects and Methods in C++ Relationship Inheritance Polymorphism Inheritance and Composition

Books

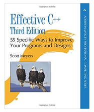
- The C++ Programming Language, *Bjarne Stroustrup*, Addison-Wesley Professional, 2013, ISBN 978-0321563842



- Programming: Principles and Practice Using C++, *Bjarne Stroustrup*, Addison-Wesley Professional, 2014, ISBN 978-0321992789



- Effective C++: 55 Specific Ways to Improve Your Programs and Designs, *Scott Meyers*, Addison-Wesley Professional, 2005, ISBN 978-0321334879



Example of Encapsulation

- Class Matrix encapsulates 2D matrix of double values

```
class Matrix {
   public:
      Matrix(int rows, int cols);
      Matrix(const Matrix &m);
      ~Matrix();

      inline int rows(void) const { return ROWS; }
      inline int cols(void) const { return COLS; }
      double getValueAt(int r, int c) const;
      void setValueAt(double v, int r, int c);
      void fillRandom(void);
      Matrix sum(const Matrix &m2);
      Matrix operator+(const Matrix &m2);
      Matrix& operator=(const Matrix &m);
   private:
      inline double& at(int r, int c) const { return vals[COLS * r + c]; }
   private:
      const int ROWS;
      const int COLS;
      double *vals;
};
std::ostream& operator<<(std::ostream& out, const Matrix& m);
```

lec12/matrix.h

Example – Matrix Subscripting Operator

- For a convenient access to matrix cells, we can implement operator () with two arguments *r* and *c* denoting the cell row and column

```
class Matrix {
   public:
      double& operator()(int r, int c);
      double operator()(int r, int c) const;
};

// use the reference for modification of the cell value
double& Matrix::operator()(int r, int c)
{
   return at(r, c);
}

// copy the value for the const operator
double Matrix::operator()(int r, int c) const
{
   return at(r, c);
}
```

For simplicity and better readability, we do not check range of arguments.

Example Matrix – Identity Matrix

- Implementation of the setIdentity() using the matrix subscripting operator

```
void setIdentity(Matrix& matrix)
{
   for (int r = 0; r < matrix.rows(); ++r) {
      for (int c = 0; c < matrix.cols(); ++c) {
         matrix(r, c) = (r == c) ? 1.0 : 0.0;
      }
   }
}

Matrix m1(2, 2);
std::cout << "Matrix m1 -- init values: " << std::endl << m1;
setIdentity(m1);
std::cout << "Matrix m1 -- identity: " << std::endl << m1;
```

- Example of output

```
Matrix m1 -- init values:
 0.0  0.0
 0.0  0.0
Matrix m1 -- identity:
 1.0  0.0
 0.0  1.0
```

lec12/demo-matrix.cc

Relationship between Objects

- Objects can be in relationship based on the
  - Inheritance – is the relationship of the type **is**

    *Object of descendant class **is** also the ancestor class*
    - One class is derived from the ancestor class

      Objects of the derived class extends the based class
    - Derived class contains all the field of the ancestor class

      However, some of the fields may be hidden
    - New methods can be implemented in the derived class

      *New implementation **override** the previous one*
    - Derived class (objects) are specialization of a more general ancestor (super) class
- An object can be part of the other objects – it is the **has** relation
  - Similarly to compound structures that contain other struct data types as their data fields, objects can also compound of other objects
  - We can further distinguish
    - **Aggregation** – an object is a part of other object
    - **Composition** – inner object exists only within the compound object

Example – Aggregation/Composition

- Aggregation – relationship of the type "**has**" or "**it is composed**
  - Let ***A*** be aggregation of ***B C***, then objects ***B*** and ***C*** are contained in ***A***
  - It results that ***B*** and ***C*** cannot survive without ***A***

In such a case, we call the relationship as composition

Example of implementation

```
class GraphComp { // composition
   private:
      std::vector<Edge> edges;
};

class GraphComp { // aggregation
   public:
      GraphComp(std::vector<Edge>& edges) : edges(
     edges) {}
   private:
      const std::vector<Edge>& edges;
};
```

```
struct Edge {
   Node v1;
   Node v2;
};

struct Node {
   Data data;
};
```


Inheritance

- Founding definition and implementation of one class on another existing class(es)
- Let class ***B*** be inherited from the class ***A***, then
  - Class ***B*** is subclass or the derived class of ***A***
  - Class ***A*** is superclass or the base class of ***B***
- The subclass ***B*** has two parts in general:
  - Derived part is inherited from ***A***
  - New incremental part contains definitions and implementation added by the class ***B***
- The inheritance is relationship of the type **is-a**
  - Object of the type ***B*** is also an instance of the object of the type ***A***
- Properties of ***B*** inherited from the ***A*** can be redefined
  - Change of field visibility (protected, public, private)
  - Overriding of the method implementation
- Using inheritance we can create hierarchies of objects

Implement general function in superclasses or creating abstract classes that are further specialized in the derived classes.

Example MatrixExt – Extension of the Matrix

- We will extend the existing class `Matrix` to have identity method and also multiplication operator
- We refer the superclass as the `Base` class using `typedef`
- We need to provide a constructor for the `MatrixExt`; however, we used the existing constructor in the base class

```
class MatrixExt : public Matrix {
   typedef Matrix Base; // typedef for refering the superclass

   public:
   MatrixExt(int r, int c) : Base(r, c) {} // base constructor

   void setIdentity(void);
   Matrix operator*(const Matrix &m2);
};
```

lec12/matrix_ext.h

Example MatrixExt – Identity and Multiplication Operator

- We can use only the `public` (or `protected`) methods of `Matrix` class

`Matrix` does not have any `protected` members

```
#include "matrix_ext.h"
void MatrixExt::setIdentity(void)
{
   for (int r = 0; r < rows(); ++r) {
      for (int c = 0; c < cols(); ++c) {
         (*this)(r, c) = (r == c) ? 1.0 : 0.0;
      }
   }
}
```

lec12/matrix_ext.cc

Example MatrixExt – Example of Usage 1/2

- Objects of the class `MatrixExt` also have the methods of the `Matrix`

```
#include <iostream>
#include "matrix_ext.h"

using std::cout;

int main(void)
{
   int ret = 0;
   MatrixExt m1(2, 1);
   m1(0, 0) = 3; m1(1, 0) = 5;

   MatrixExt m2(1, 2);
   m2(0, 0) = 1; m2(0, 1) = 2;

   cout << "Matrix m1:\n" << m1 << std::endl;
   cout << "Matrix m2:\n" << m2 << std::endl;
   cout << "m1 * m2 =\n" << m2 * m1 << std::endl;
   cout << "m2 * m1 =\n" << m1 * m2 << std::endl;
   return ret;
}
```

```
clang++ matrix.cc matrix_ext.cc demo-
     matrix_ext.cc &&     ./a.out
Matrix m1:
 3.0
 5.0

Matrix m2:
 1.0  2.0

m1 * m2 =
 13.0

m2 * m1 =
 3.0  6.0
 5.0 10.0
```

lec12/demo-matrix_ext.cc

Example MatrixExt – Example of Usage 2/2

- We may use objects of `MatrixExt` anywhere objects of `Matrix` can be applied.
- This is a result of the inheritance

And a first step towards polymorphism

```
void setIdentity(Matrix& matrix)
{
   for (int r = 0; r < matrix.rows(); ++r) {
      for (int c = 0; c < matrix.cols(); ++c) {
         matrix(r, c) = (r == c) ? 1.0 : 0.0;
      }
   }
}

MatrixExt m1(2, 1);
cout << "Using setIdentity for Matrix" << std::endl;
setIdentity(m1);
cout << "Matrix m1:\n" << m1 << std::endl;
```

lec12/demo-matrix_ext.cc

Categories of the Inheritance

- Strict inheritance – derived class takes all of the superclass and adds own methods and attributes. All members of the superclass are available in the derived class. It strictly follows the **is-a** hierarchy
- Nonstrict inheritance – the subclass derives from the a superclass only certain attributes or methods that can be further redefined
- Multiple inheritance – a class is derived from several superclasses

Inheritance – Summary

- Inheritance is a mechanism that allows
  - Extend data field of the class and modify them
  - Extend or modify methods of the class
- Inheritance allows to
  - Create hierarchies of classes
  - "Pass" data fields and methods for further extension and modification
  - Specialize (specify) classes
- The main advantages of inheritance are
  - It contributes essentially to the code reusability

    Together with encapsulation!
  - Inheritance is foundation for the **polymorphism**

Polymorphism

- Polymorphism can be expressed as the ability to refer in a same way to different objects

  We can call the same method names on different objects
- We work with an object whose actual content is determined at the runtime
- Polymorphism of objects - Let the class ***B*** be a subclass of ***A***, then the object of the ***B*** can be used wherever it is expected to be an object of the class ***A***
- Polymorphism of methods requires dynamic binding, i.e., static vs. dynamic type of the class
  - Let the class ***B*** be a subclass of ***A*** and redefines the method `m()`
  - A variable `x` is of the static type ***B***, but its dynamic type can be ***A*** or ***B***
  - Which method is actually called for *x.m()* depends on the dynamic type

Example MatrixExt – Method Overriding 1/2

- In `MatrixExt`, we may override a method implemented in the base class `Matrix`, e.g., `fillRandom()` will also use negative values.

```
class MatrixExt : public Matrix {
   ...
   void fillRandom(void);
}

void MatrixExt::fillRandom(void)
{
   for (int r = 0; r < rows(); ++r) {
      for (int c = 0; c < cols(); ++c) {
         (*this)(r, c) = (rand() % 100) / 10.0;
         if (rand() % 100 > 50) {
            (*this)(r, c) *= -1.0; // change the sign
         }
      }
   }
}
```

lec12/matrix_ext.h, lec12/matrix_ext.cc

Example MatrixExt – Method Overriding 2/2

- We can call the method `fillRandom()` of the `MatrixExt`

```
MatrixExt *m1 = new MatrixExt(3, 3);
Matrix *m2 = new MatrixExt(3, 3);
m1->fillRandom(); m2->fillRandom();
cout << "m1: MatrixExt as MatrixExt:\n" << *m1 << std::endl;
cout << "m2: MatrixExt as Matrix:\n" << *m2 << std::endl;
delete m1; delete m2;
```

lec12/demo-matrix_ext.cc

- However, in the case of `m2` the `Matrix::fillRandom()` is called

```
m1: MatrixExt as MatrixExt:
-1.3  9.8  1.2
 8.7 -9.8 -7.9
-3.6 -7.3 -0.6

m2: MatrixExt as Matrix:
 7.9  2.3  0.5
 9.0  7.0  6.6
 7.2  1.8  9.7
```

We need a dynamic way to identity the object type at runtime for the **polymorphism of the methods**

Virtual Methods – Polymorphism and Inheritance

- We need a dynamic binding for polymorphism of the methods
- It is usually implemented as a **virtual method** in object oriented programming languages
- Override methods that are marked as **virtual** has a dynamic binding to the particular dynamic type

Example – Overriding without Virtual Method 1/2

```
#include <iostream>
using namespace std;
class A {
   public:
      void info()
      {
         cout << "Object of the class A" << endl;
      }
};
class B : public A {
   public:
      void info()
      {
         cout << "Object of the class B" << endl;
      }
};
A* a = new A(); B* b = new B();
A* ta = a; // backup of a pointer
a->info(); // calling method info() of the class A
b->info(); // calling method info() of the class B
a = b; // use the polymorphism of objects
a->info(); // without the dynamic binding, method of the class A is called
delete ta; delete b;
```

```
clang++ demo-novirtual.cc
./a.out
Object of the class A
Object of the class B
Object of the class A
```

lec12/demo-novirtual.cc

Example – Overriding with Virtual Method 2/2

```
#include <iostream>
using namespace std;
class A {
   public:
      virtual void info() // Virtual !!!
      {
         cout << "Object of the class A" << endl;
      }
};
class B : public A {
   public:
      void info()
      {
         cout << "Object of the class B" << endl;
      }
};
A* a = new A(); B* b = new B();
A* ta = a; // backup of a pointer
a->info(); // calling method info() of the class A
b->info(); // calling method info() of the class B
a = b; // use the polymorphism of objects
a->info(); // the dynamic binding exists, method of the class B is called
delete ta; delete b;
```

```
clang++ demo-virtual.cc
./a.out
Object of the class A
Object of the class B
Object of the class B
```

lec12/demo-virtual.cc

Derived Classes, Polymorphism, and Practical Implications

- Derived class inherits the methods and data fields of the superclass, but it can also add new methods and data fields
  - It can extend and specialize the class
  - It can modify the implementation of the methods
- An object of the derived class can be used instead of the object of the superclass, e.g.,
  - We can implement more efficient matrix multiplication without modification of the whole program

    We may further need a mechanism to create new object based on the dynamic type, i.e., using the `newInstance` *virtual method*
- **Virtual** methods are important for the **polymorphism**
  - It is crucial to use a virtual **destructor** for a proper destruction of the object

    E.g., when a derived class allocate additional memory

Example – Virtual Destructor 1/4

```
#include <iostream>
class Base {
   public:
      Base(int capacity) {
         std::cout << "Base::Base -- allocate data" << std::endl;
         data = new int[capacity];
      }
      virtual ~Base() { // virtual destructor is important
         std::cout << "Base::~Base -- release data" << std::endl;
         delete[] data;
      }
   protected:
      int *data;
};
```

lec12/demo-virtual_destructor.cc

Example – Virtual Destructor 2/4

```
class Derived : public Base {
   public:
      Derived(int capacity) : Base(capacity) {
         std::cout << "Derived::Derived -- allocate data2" << std::endl;
         data2 = new int[capacity];
      }
      ~Derived() {
         std::cout << "Derived::~Derived -- release data2" << std::endl;
         delete[] data2;
      }
   protected:
      int *data2;
};
```

lec12/demo-virtual_destructor.cc

Example – Virtual Destructor 3/4

- Using `virtual` destructor all allocated data are properly released

```
std::cout << "Using Derived " << std::endl;
Derived *object = new Derived(1000000);
delete object;
std::cout << std::endl;

std::cout << "Using Base" << std::endl;
Base *object = new Derived(1000000);
delete object;
```

lec12/demo-virtual_destructor.cc

```
clang++ demo-virtual_destructor.cc && ./a.out
```

```
Using Derived
Base::Base -- allocate data
Derived::Derived -- allocate data2
Derived::~Derived -- release data2
Base::~Base -- release data
```

```
Using Base
Base::Base -- allocate data
Derived::Derived -- allocate data2
Derived::~Derived -- release data2
Base::~Base -- release data
```

Both desctructors `Derived` and `Base` are called

Example – Virtual Destructor 4/4

- Without `virtual` destructor, e.g,,

```
class Base {
   ...
   ~Base(); // without virtualdestructor
};
Derived *object = new Derived(1000000);
delete object;
Base *object = new Derived(1000000);
delete object;
```

- Only both constructors are called, but only destructor of the `Base` class in the second case `Base *object = new Derived(1000000);`

```
Using Derived
Base::Base -- allocate data
Derived::Derived -- allocate data2
Derived::~Derived -- release data2
Base::~Base -- release data
```

```
Using Base
Base::Base -- allocate data
Derived::Derived -- allocate data2
Base::~Base -- release data
```

Only the desctructor of `Base` is called

Inheritance and Composition

- A part of the object oriented programming is the object oriented design (OOD)
  - It aims to provide "a plan" how to solve the problem using objects and their relationship
  - An important part of the design is identification of the particular objects
  - their generalization to the classes
  - and also designing a class hierarchy
- Sometimes, it may be difficult to decides
  - What is the common (general) object and what is the specialization, which is important step for class hierarchy and applying the inheritance
  - It may also be questionable when to use composition
- Let show the inheritance on an example of geometrical objects

Example – Is Cuboid Extended **Rectangle**? 1/2

```
class Rectangle {
   public:
      Rectangle(double w, double h) : width(w), height(h) {}
      inline double getWidth(void) const { return width; }
      inline double getHeight(void) const { return height; }
      inline double getDiagonal(void) const
      {
         return sqrt(width*width + height*height);
      }

   protected:
      double width;
      double height;
};
```


Example – Is Cuboid Extended **Rectangle**? 2/2

```
class Cuboid : public Rectangle {
   public:
      Cuboid(double w, double h, double d) :
         Rectangle(w, h), depth(d) {}
      inline double getDepth(void) const { return depth; }
      inline double getDiagonal(void) const
      {
         const double tmp = Rectangle::getDiagonal();
         return sqrt(tmp * tmp + depth * depth);
      }

   protected:
      double depth;
};
```


Example – Inheritance Cuboid Extend Rectangle

- Class `Cuboid` extends the class `Rectangle` by the `depth`
  - `Cuboid` inherits data fields `width` a `height`
  - `Cuboid` also inherits „getters" `getWidth()` and `getHeight()`
  - Constructor of the `Rectangle` is called from the `Cuboid` constructor
- The descendant class `Cuboid` extends (override) the `getDiagonal()` methods

  It actually uses the method `getDiagonal()` *of the ancestor* `Rectangle::getDiagonal()`

- We create a "specialization" of the `Rectangle` as an extension `Cuboid` class

Is it really a suitable extension?

What is the cuboid area? What is the cuboid circumference?

Example – Inheritance – Rectangle is a Special **Cuboid** 1/2

- Rectangle is a cuboid with zero depth

```
class Cuboid {
   public:
      Cuboid(double w, double h, double d) :
         width(w), height(h), depth(d) {}

      inline double getWidth(void) const { return width; }
      inline double getHeight(void) const { return height; }
      inline double getDepth(void) const { return depth; }

      inline double getDiagonal(void) const
      {
         return sqrt(width*width + height*height + depth*depth);
      }
   protected:
      double width;
      double height;
      double depth;
};
```

Example – Inheritance – Rectangle is a Special **Cuboid** 2/2

```
class Rectangle : public Cuboid {
   public:
      Rectangle(double w, double h) : Cuboid(w, h, 0.0) {}
};
```

- Rectangle is a "cuboid" with zero depth
- `Rectangle` inherits all data fields: `with`, `height`, and `depth`
- It also inherits all methods of the ancestor

  Accessible can be only particular ones
- The constructor of the `Cuboid` class is accessible and it used to set data fields with the zero `depth`
- Objects of the class `Rectangle` can use all variable and methods of the `Cuboid` class

Should be Rectangle Descendant of Cuboid or Cuboid be Descendant of Rectangle?

1. Cuboid is descendant of the rectangle
   - "Logical" addition of the depth dimensions, but methods valid for the rectangle do not work of the cuboid

     E.g., area of the rectangle
2. Rectangle as a descendant of the cuboid
   - Logically correct reasoning on specialization

     "All what work for the cuboid also work for the cuboid with zero depth"
   - Inefficient implementation – every rectangle is represented by 3 dimensions

Specialization is correct

*Everything what hold for the **ancestor** have to be valid for the **descendant***

However, in this particular case, usage of the inheritance is questionable.

Relationship of the Ancestor and Descendant is of the type "**is-a**"

- Is a straight line segment descendant of the point?
  - Straight line segment does not use any method of a point

    is-a?: segment is a point ? → **NO** → segment is not descendant of the point
- Is rectangle descendant of the straight line segment?

  is-a?: **NO**
- Is rectangle descendant of the square, or vice versa?
  - Rectangle "extends" square by one dimension, but it is not a square
  - Square is a rectangle with the width same as the height

    Set the width and height in the constructor!

Substitution Principle

- Relationship between two derived classes
- Policy
  - Derived class is a specialization of the superclass

    *There is the **is-a** relationship*
  - Wherever it is possible to sue a class, it must be possible to use the descendant in such a way that a user cannot see any difference

    Polymorphism
  - Relationship **is-a** must be permanent

Composition of Objects

- If a class contains data fields of other object type, the relationship is called **composition**
- Composition creates a hierarchy of objects, but not by inheritance

  Inheritance creates hierarchy of relationship in the sense of descendant / ancestor
- Composition is a relationship of the objects – **aggregation** – **consists** / **is compound**
- It is a relationship of the type "**has**"

Example – Composition 1/3

- Each person is characterized by attributes of the `Person` class
  - `name` (string)
  - `address` (string)
  - `birthDate` (date)
  - `graduationDate` (date)
- Date is characterized by three attributes Datum (class `Date`)
  - `day` (`int`)
  - `month` (`int`)
  - `year` (`int`)

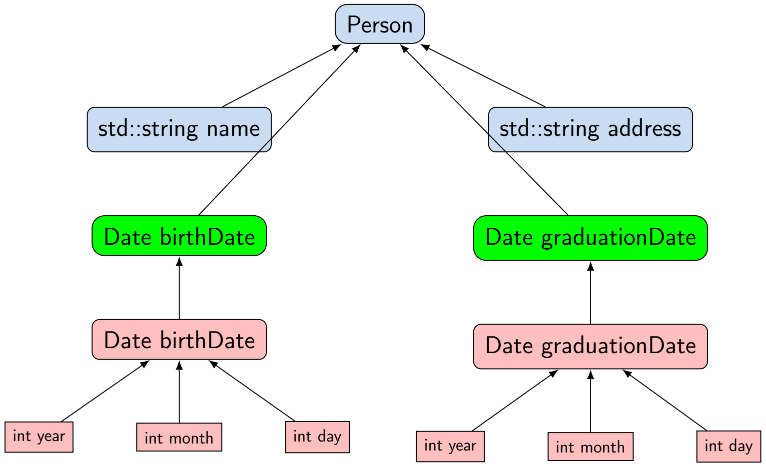
Example – Composition 2/3

```
#include <string>

class Person {
   public:
   std::string name;
   std::string address;
   Date birthDate;
   Date graduationDate;
};
```

```
class Date {
   public:
      int day;
      int month;
      int year;
};
```


Example – Composition 3/3



Inheritance vs Composition

- Inheritance objects:
  - Creating a derived class (descendant, subclass, derived class)
  - Derived class is a specialization of the superclass
    - May add variables (data fields) *Or overlapping variables (names)*
    - Add or modify methods
  - Unlike composition, inheritance changes the properties of the objects
    - New or modified methods
    - Access to variables and methods of the ancestor (base class, superclass)

      If access is allowed (public/protected)
- Composition of objects is made of attributes (data fields) of the object type

  It consists of objects
- A distinction between composition an inheritance
  - „Is" test – a symptom of inheritance (**is-a**)
  - „Has" test – a symptom of composition (**has**)

Inheritance and Composition – Pitfalls

- Excessive usage of composition and also inheritance in cases it is not needed leads to complicated design
- Watch on literal interpretations of the relationship is-a and has, sometimes it is not even about the inheritance, or composition

  E.g., Point2D and Point3D or Circle and Ellipse
- Prefer composition and not the inheritance

  One of the advantages of inheritance is the ***polymorphism***
- Using inheritance violates the **encapsulation**

  Especially with the access rights set to the `protected`

Part II

Part 2 – Standard Template Library (STL)

Templates

- Class definition may contain specific data fields of a particular type
- The data type itself does not change the behavior of the object, e.g., typically as in
  - Linked list or double linked list
  - Queue, Stack, etc.
  - *data containers*
- Definition of the class for specific type would be identical except the data type
- We can use **templates** for later specification of the particular data type, when the instance of the class is created
- Templates provides `compile-time polymorphism`

  In constrast to the run-time polymorphism realized by virtual methods.

Example – Template Class

- The template class is defined by the **template** keyword with specification of the type name

```
template <typename T>
class Stack {
   public:
      bool push(T *data);
      T* pop(void);
};
```

- An object of the template class is declared with the specified particular type

```
Stack<int> intStack;
Stack<double> doubleStack;
```


Example – Template Function

- Templates can also be used for functions to specify particular type and use type safety and typed operators

```
template <typename T>
const T & max(const T &a, const T &b)
{
   return a < b ? b : a;
}

double da, db;
int ia, ib;

std::cout << "max double: " << max(da, db) << std::endl;

std::cout << "max int: " << max(ia, ib) << std::endl;

//not allowed such a function is not defined
std::cout << "max mixed " << max(da, ib) << std::endl;
```


STL

- Standard Template Library (STL) is a library of the standard C++ that provides efficient implementations of the data **containers**, algorithms, functions, and iterators
- High efficiency of the implementation is achieved by templates with compile-type polymorphism
- Standard Template Library Programmer's Guide – https://www.sgi.com/tech/stl/

std::vector – Dynamic "C" like array

- One of the very useful data containers in the STL is `vector` that behaves like C array but allows adding and removing elements.

```
#include <iostream>
#include <vector>

int main(void)
{
   std::vector<int> a;

   for (int i = 0; i < 10; ++i) {
      a.push_back(i);
   }

   for (int i = 0; i < a.size(); ++i) {
      std::cout << "a[" << i << "] = " << a[i] << std::endl;
   }

   std::cout << "Add one more element" << std::endl;
   a.push_back(0);

   for (int i = 5; i < a.size(); ++i) {
      std::cout << "a[" << i << "] = " << a[i] << std::endl;
   }
   return 0;
}
```

lec12/stl-vector.cc

Summary of the Lecture

Topics Discussed

- Objects and Methods in C++ – example of 2D matrix encapsulation
  - Subscripting operator
- Relationship between objects
  - Aggregation
  - Composition
- Inheritance – properties and usage in C++
- Polymorphism – dynamic binding and virtual methods
- Inheritance and Composition
- Templates and STL