

Object Oriented Programming in C++

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Lecture 11

PRG(A) – Programming in C

Overview of the Lecture

- Part 1 – Object Oriented Programming (in C++)

 - Resources

 - Objects and Methods in C++

 - Relationship

 - Inheritance

 - Polymorphism

 - Inheritance and Composition

- Part 2 – Standard Template Library (in C++)

 - Templates

 - Standard Template Library (STL)

Part I

Part 1 – Object Oriented Programming

Books



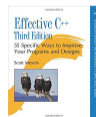
The C++ Programming Language,
Bjarne Stroustrup, Addison-Wesley Professional, 2013, ISBN
978-0321563842



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);
```

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
```

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);  
};
```

`lec11/matrix_ext.h`

Example MatrixExt – Identity and Multiplication Operator

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

```
#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;  
        }  
    }  
}
```

Matrix does not have any protected members

lec11/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" << m1 * m2 << std::endl;
    cout << "m2 * m1 =\n" << m2 * m1 << 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
```

lec11/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;
```

`lec11/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
 - Inheritance is foundation for the **polymorphism**

Together with encapsulation!

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
            }
        }
    }
}
```

`lec11/matrix_ext.h, lec11/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;
```

[lec11/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 identify 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
```

lec11/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
```

lec11/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;
};
```

lec11/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;
};
```

lec11/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;
```

[lec11/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 destructors `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: **width**, **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`)

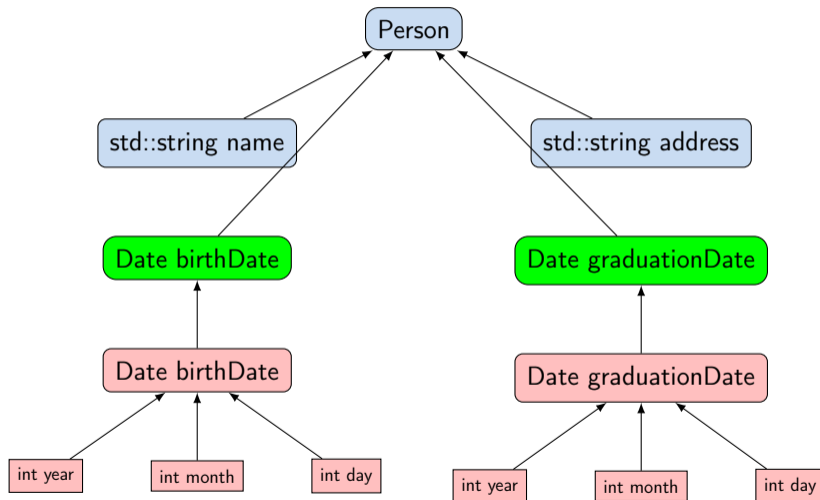
Example – Composition 2/3

```
#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 and 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 contrast 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;
}
```

lec11/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