

# Object Oriented Programming in C++

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Lecture 11

B3B36PRG – C Programming Language

## 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);
lec11/matrix.h
```

## 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

## Overview of the Lecture

- Part 1 – Object Oriented Programming (in C++)
  - Objects and Methods in C++
  - Relationship
  - Inheritance
  - Polymorphism
  - Inheritance and Composition
- Part 2 – Standard Template Library (in C++)
  - Templates
  - Standard Template Library (STL)

## 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 – 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;
};

struct Edge {
    Node v1;
    Node v2;
};

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

struct Node {
    Data data;
};
```

## Part I

## Part 1 – Object Oriented Programming

## Example Matrix – Identity Matrix

- Implementation of the function set the matrix to the identity 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
```

## 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 referring 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

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13 / 56

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

## 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

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16 / 56

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## 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

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20 / 56

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## 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 MatrixExt::operator*(const Matrix &m2)
{
    Matrix m3(rows(), m2.cols());
    for (int r = 0; r < rows(); ++r) {
        for (int c = 0; c < m2.cols(); ++c) {
            m3(r, c) = 0.0;
            for (int k = 0; k < cols(); ++k) {
                m3(r, c) += (*this)(r, k) * m2(k, c);
            }
        }
    }
    return m3;
}
```

lec11/matrix\_ext.cc

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14 / 56

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## 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

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17 / 56

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## 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

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21 / 56

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## 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" << 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

lec11/demo-matrix\_ext.cc

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15 / 56

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## 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**

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18 / 56

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## 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**

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22 / 56

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## 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

## 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 3/4

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

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

```
cout << "Using Base " << 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 – 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
```

## Example – Virtual Destructor 1/4

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

lec11/demo-virtual\_destructor.cc

## 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
Derived::~Derived -- release data2
Base::~Base -- release data
```

*Only the destructor of Base is called*

## 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
```

## Example – Virtual Destructor 2/4

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

lec11/demo-virtual\_destructor.cc

## 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 Extends Rectangle

- Class `Cuboid` extends the class `Rectangle` by the `depth`
  - `Cuboid` inherits data fields `width` and `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?

- 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*
  - 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)

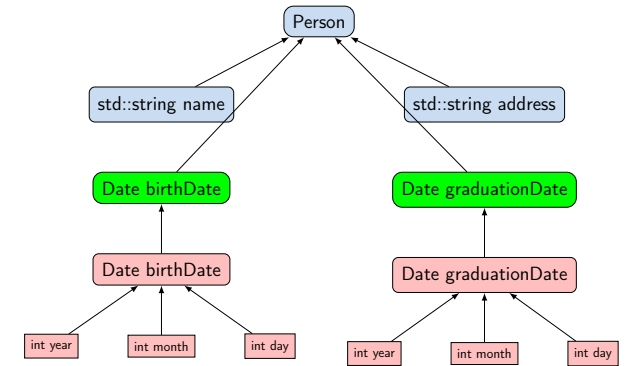
## Example – Composition 2/3

```
#include <string>

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

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

## 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 behaviour 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>
int T const & max(T const &a, T const &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 very useful data containers in STL is **vector** which behaves like C array but allows to add and remove 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;
}
leci1/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