# Creative Software Design

# 11 – Copy Constructor, Operator Overloading

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Fall 2023

# Midterm Exam

- Date & time: **Dec 19, AM 09:30 ~ 10:30**
- Place: **IT.BT 609**
- Scope: Lecture 8 ~ 13

- **You cannot leave until 30 minutes after the start of the exam** even if you finish the exam earlier.

- That means, **you cannot enter the room after 30 minutes from the start of the exam** (do not be late, never too late!).

- Please bring your **student ID card** to the exam.

- We will not accept questions unless the error in the problem is clearly evident. You should solve the problem based on the information provided in the question.

- Problem types: true/false, single choice, multiple choices, short answer, fill-in-blank, ...

# Schedule Updates

- Finish all lectures by Dec 5, and after that, only labs.

- Nov 28 (Tue): Lecture 11 (Today)
- Nov 29 (Wed): Lab 11-1
- **Nov 30 (Thu): Lecture 12**

- **Dec 5 (Tue): Lecture 13**
- **Dec 6 (Wed): Lab 12-1**
- **Dec 7 (Thu): Lab 13-1**

- **Dec 12 (Tue): Lab 11-2**
- **Dec 13 (Wed): Lab 12-2**
- **Dec 14 (Thu): Lab 13-2**

- Dec 19 (Tue): Final Exam

# Outline

- Copy constructor
- friend, static
- Operator overloading

# Copy constructor

- A copy constructor is a constructor that initializes an object using another object of the same class.

- The general form is:

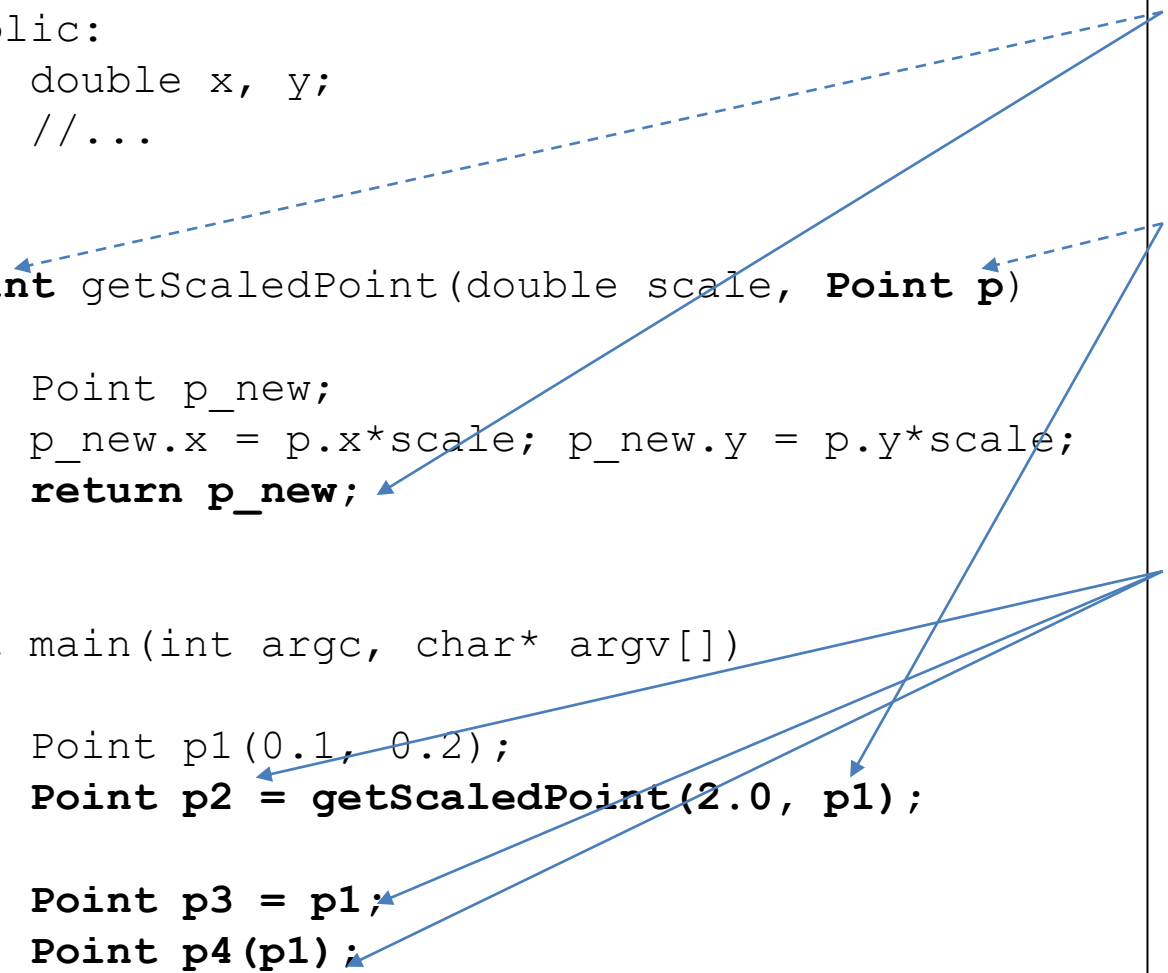
```
ClassName(const ClassName& src_obj);
```

# When is a copy constructor called?

- When an object is returned by value.
- When an object is passed by value (not by address value) as a function argument.
- When an object is constructed based on another object of the same class.

# When is a copy constructor called?

```
class Point
{
public:
    double x, y;
    //...
};

Point getScaledPoint(double scale, Point p)
{
    Point p_new;
    p_new.x = p.x*scale; p_new.y = p.y*scale;
    return p_new;
}

int main(int argc, char* argv[])
{
    Point p1(0.1, 0.2);
    Point p2 = getScaledPoint(2.0, p1);

    Point p3 = p1;
    Point p4(p1);
    return 0;
}
```



- When an object is returned by value.
- When an object is passed by value (not by address value) as a function argument.
- When an object is constructed based on another object of the same class.

# Default copy constructor

- A default copy constructor is implicitly created by compiler if there is no user-defined copy constructor.

- It does a member-wise copy between objects,
  - where each member is copied by its own copy constructor.
  - This works fine in general, but does not work for some cases. We should define our own copy constructor for these cases.

# Default copy constructor: Example 1

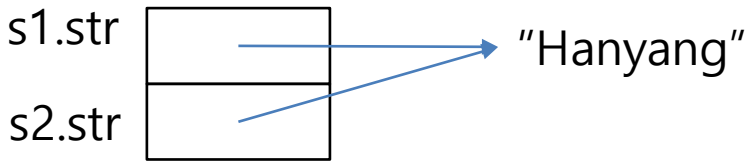
```
#include <iostream>
using namespace std;

class Point{
    private:
        int x, y;
    public:
        Point(int a=0): x(a), y(a) {}
        ~Point(){ cout << "bye " << x << " " << y << endl;}
        void Print(){ cout << x << " " << y << endl;}
};

int main()
{
    Point P1(3);
    Point P2 = P1;  // by default copy constructor
    Point P3(P2);   // by default copy constructor

    P1.Print();
    P2.Print();
    P3.Print();

    return 0;
}
```

- Default copy constructor copies each member of the object

# Default copy constructor: Example 2-1

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

class MyString{
private:
  int len;
  char *str;
public:
  MyString(const char *s = ""){
    len = strlen(s);
    str = new char[len+1];
    strcpy(str, s);
  }
  ~MyString(){delete[] str;}
  void Print() { cout << str << endl;}
};

int main(){

  MyString s1 = "Hanyang";
  MyString s2 = s1;  //copy constructor



  s1.Print();
  s2.Print();

  return 0;
}
```

→ runtime error: double free detected!



# Default copy constructor: Example 2-2

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

class MyString{
private:
  int len;
  char *str;
public:
  MyString(const char *s = ""){
    len = strlen(s);
    str = new char[len+1];
    strcpy(str, s);
  }
  ~MyString(){delete[] str;}
  void Print() { cout << str << endl;}
};

MyString GetString(void){
  MyString str("HY");
  return str;
}

int main(){

  MyString s2 = GetString();
  s2.Print();

  return 0;
}
```

//the space for "HY" is deallocatred

//the address to "HY" is copied

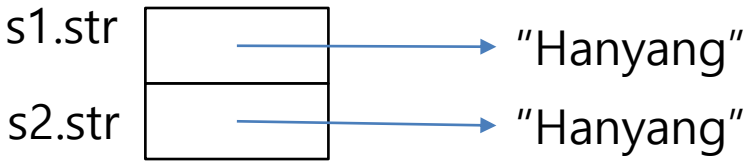
→ cout << (deleted pointer) << endl;

→ runtime error: double free detected!

# User-defined copy constructor: Example

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

class MyString{
private:
  int len;
  char *str;
public:
  MyString(const char *s = ""){
    len = strlen(s);
    str = new char[len+1];
    strcpy(str, s);
  }
  MyString(const MyString &s){  //redefine copy constructor
    len = s.len;
    str = new char[len+1];
    strcpy(str, s.str);
  }
  ~MyString(){delete[] str;}
  void Print() { cout << str << endl;}
};

int main(){

  MyString s1 = "Hanyang";
  MyString s2 = s1;  //copy constructor

  s1.Print();
  s2.Print();

  return 0;
}
```

- The problem of deallocation by delete operator was resolved



# Default copy constructor & Default constructor

- Recall: A default constructor is implicitly created by compiler if there is no user-defined constructor.

- If you define a copy constructor, the complier doesn’t create the default constructor and default copy constructor.

# Copy constructor: Example

```
class Point
{
public:
    double x, y;
    Point(double x_, double y_):x(x_), y(y_) {}

    // The most general form.
    Point(const Point& p) { x = p.x; y = p.y; }

    // This form compiles as well.
    // In general, however, copy constructors are not expected
to modify the object passed in, so this form is not recommended
    Point(Point& p) { x = p.x; y = p.y; }

    // Compile error. If it were compiled, it would result in
infinite calling of copy constructor.
    Point(Point p) { x = p.x; y = p.y; }
};
```

# Quiz 1

- Go to https://www.slido.com/
- Join #**csd-ys**
- Click "Polls"

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

- Note that your quiz answer must be submitted **in the above format** to receive a quiz score!

# Friend Class and Function

- Functions or classes can be "friends" of another class (let's say ClassA).
  - If you declare them as "friends" in the definition of ClassA,
  - Then these "friends" can access all members of ClassA including priv ate members.

```
class ClassA {
 private:
  int var_;
  friend class ClassB;
  friend void DoSomething(const ClassA& a);
};

class ClassB {
  // ...
  void Function(const ClassA& a) { cout << a.var_; }  // OK.
};

void DoSomething(const ClassA& a) { cout << a.var_; }  // OK.
```

# Friend Class and Function

- "friend" should be used with caution.
  - Too many "friend" functions or classes may lessen the value of *encapsulation / data hiding*.
  - If "friends" are used properly, they can enhance *encapsulation / data hiding*.
    - For example, a LinkedList class may be allowed to access private members of Node class, but all other classes are not.

- Note that access specifiers have no effect on the meaning of friend declarations.
  - "friend" can appear in private, protected, or public sections, with no difference.
  - https://en.cppreference.com/w/cpp/language/friend

# Static Members

- Static member variables in a class are **shared by all the objects of the class.**
  - You **must explicitly define static member variables outside of the class**, in the global scope.
    - Because static member variables are not part of the individual class objects (they are treated similarly to global variables, and get initialized when the program starts),
- Static member functions **can only access static members**.
  - Static member functions cannot be virtual.
- Static members can be **accessed by class name** or object name.

# Static Members

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

class Point{
    private:
        int x, y;
        static int count;
    public:
        Point(int a=0, int b=0): x(a), y(b) {count++;}
        ~Point(){ cout << x << " " << y << endl;}
        static int GetCount() {return count;}
};
int Point::count = 0;

int main()
{
    cout << Point::GetCount() << endl;
    Point P1(1,2);
    cout << Point::GetCount() << endl;
    Point P2 =  Point(3,4);
    cout << P2.GetCount() << endl;
    return 0;
}
```

- If the class is defined in a header file, the static member definition is should be placed in a source file.
- If you put the static member definition in a header file, if that header file gets included more than once, you'll end up with multiple definitions, which will cause a linker error (much like a global variable).

# Recall: Function Overloading

- Use multiple functions sharing the same name
  - A family of functions that do the same thing but using different argument lists

```
void print(const char * str, int width);  // #1
void print(double d, int width);          // #2
void print(long l, int width);            // #3
void print(int i, int width);             // #4
void print(const char *str);              // #5


print("Pancakes", 15);          // use #1
print("Syrup");                 // use #5
print(1999.0, 10);              // use #2
print(1999, 12);                // use #4
print(1999L, 15);               // use #3
```

# Operator Overloading

- An operator function is a special function form to overload an operator
- operator*[op]*(arguments)
  - *[op]* is a valid C++ operator
  - e.g., operator+() overloads the + operator

- Note that C++ even allows redefining built-in operators such as +, -, *, ...

- There are two ways of operator overloading:
- a) overload as a **class member function**
- b) overload as a **non-member function**.

# Operator overloading as member function

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

class Box {
  private:
     int x, y, z;
  public:
     Box(int a=0, int b=0, int c=0): x(a), y(b), z(c){}
     Box Sum(const Box box) {
        return Box(x+box.x, y+box.y, z+box.z);
     }
     void Print(){ cout << x << " " << y << " " << z << endl;
     }
};

int main(){
        Box B1(1,1,1);
        Box B2(2,2,2);
        Box B3 = B1.Sum(B2);
        B3.Print();

        return 0;
}
```

# Operator overloading as member function

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

class Box {
  private:
     int x, y, z;
  public:
     Box(int a=0, int b=0, int c=0): x(a), y(b), z(c){}
     Box operator+(const Box box) {
        return Box(x+box.x, y+box.y, z+box.z);
     }
     void Print(){ cout << x << " " << y << " " << z << endl;
     }
};

int main(){
        Box B1(1,1,1);
        Box B2(2,2,2);
        Box B3 = B1.operator+(B2);
        B3.Print();
        Box B4 = B1 + B2;
        B4.Print();

        return 0;
}
```

P1 + P2
→ **P1.operator+(P2)**

# Operator overloading as member function

- P1 + P2
- → **P1.operator+(P2)**
- That means, the overloaded operator member function gets invoked on the **first operand.**

- What if the **first operand is not a class type**, like double?
  - For example, 2.0 + P2 ?
- →You should overload a **non-member** operator function!

# Operator overloading as nonmember function

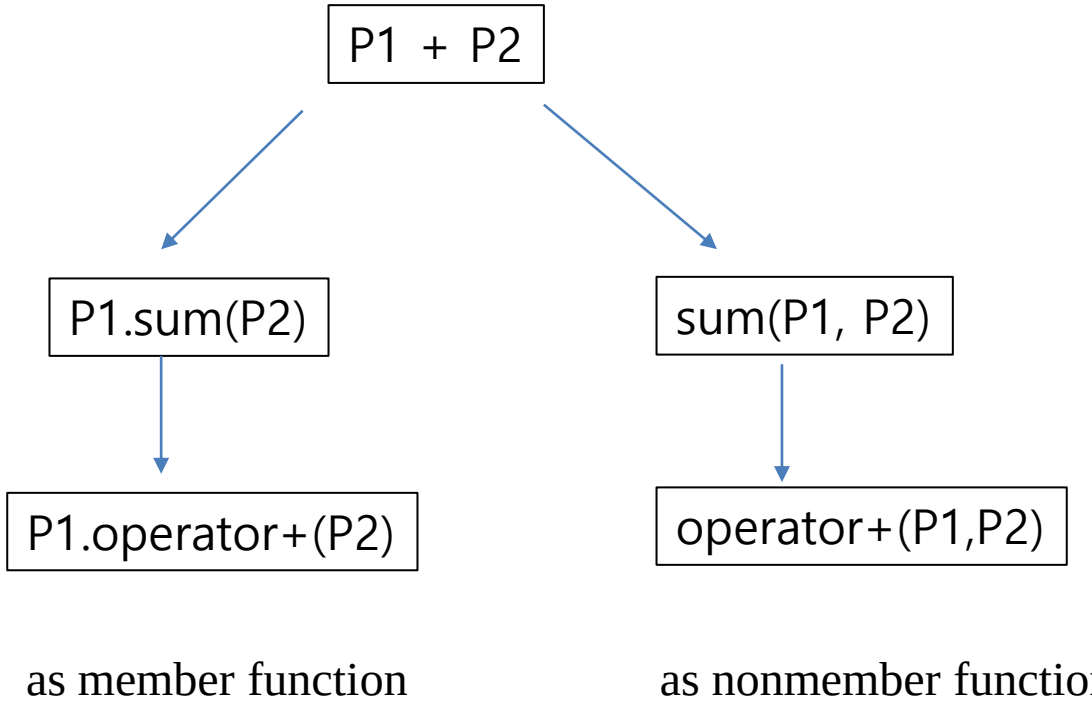
```
#include <iostream>
using namespace std;

class Point{
    int x, y;
public:
    Point(int a, int b): x(a), y(b){}
    void Print(){ cout << "(" << x << "," << y << ")" << endl;}
    friend Point operator+(int a, Point &Po);
};

Point operator+(int a, Point &Po){
    return Point(a + Po.x, a + Po.y);
}

int main(){

    Point P1(2, 2);
    int a = 2;

    Point P3 = a + P1;  // Point P3 = operator+(a, P1);
    P3.Print();

    return 0;
}
```

P1 + P2
→ **operator+(P1, P2)**

# Operator overloading as nonmember function

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

class Box {
  private:
     int x, y, z;
  public:
     Box(int a=0, int b=0, int c=0): x(a), y(b), z(c){}

     friend Box operator+(const Box& box1, const Box& box2);
     void Print(){ cout << x << " " << y << " " << z << endl;}
};

Box operator+(const Box& box1, const Box& box2) {
     return Box(box1.x+box2.x, box1.y+box2.y, box1.z+box2.z);
}

int main(){
        Box B1(1,1,1);
        Box B2(2,2,2);


        Box B4 = operator+(B1,B2);   // Box B4 = B1 + B2;
        B4.Print();

        return 0;
}
```

# Operator function



# Quiz 2

- Go to https://www.slido.com/
- Join #**csd-ys**
- Click "Polls"

- Submit your answer in the following format:
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  - **e.g. 2017123456: 4)**

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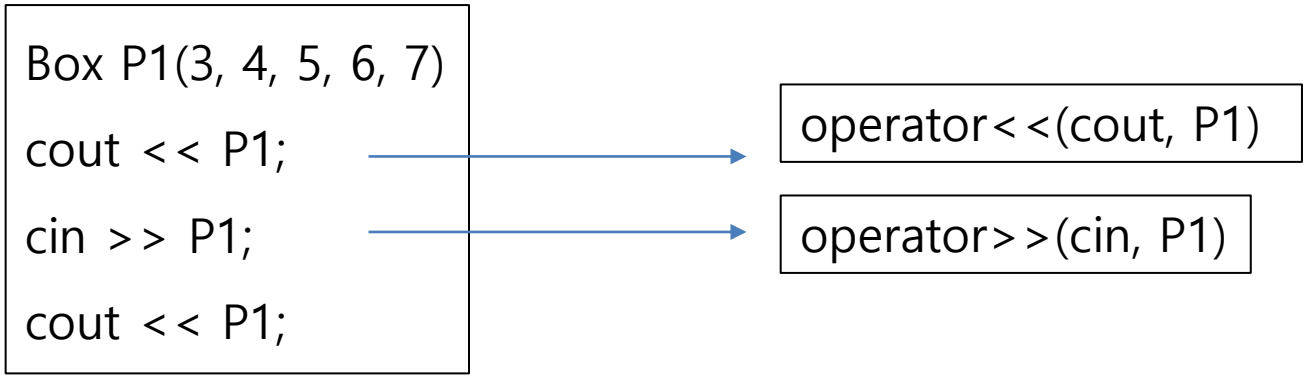
# Operator Overloading: <<, >> operator

- You should overload stream operators as non-member functions
  - because you cannot modify the first operand's class.




- Stream oprators are often declared as *friend* functions of the class.

# Operator Overloading: <<, >> operator

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

class Point{
private:
   int x, y;
public:
   Point(int a, int b): x(a), y(b){}
   void Print(){ cout << x << " " << y << endl;}
  friend ostream& operator<< (ostream& os, const Point& pt);
  friend istream& operator>> (istream& is, Point& pt);
};

ostream& operator<<(ostream& os, const Point& pt)
{
  os << pt.x << " " << pt.y << endl;
  return os;
}

istream& operator>>(istream& is, Point& pt)
{
  is >> pt.x >> pt.y;
  return is;
}


int main(){
        Point P1(2,2);
        P1.Print();
        cout << P1;
        cin >> P1;
        cout << P1;

        return 0;
}
```

# Assignment Operator(= operator) Overloading

- A default assignment operator is implicitly created by compiler if there is no user-defined assignment operator.

- It does a member-wise copy between objects.
  - where each member is copied by its own assignment operator.
  - Like default copy constructor, this works fine in general, but does not work for some cases.

# Copy Constructor vs. Assignment Operator

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

class Point
{
private:
    double x, y;
public:
    Point(double x_, double y_):x(x_), y(y_) {}

    Point(const Point& p)
    { x = p.x; y = p.y; cout << "copy constructor" << endl; }

    Point& operator=(const Point& p)
    { x = p.x; y = p.y; cout << "assignment operator" << endl; return *this;
}
};

int main()
{
    Point p1(1,2);

    Point p2(p1);   // "copy constructor"
    Point p3 = p1;  // "copy constructor"

    Point p4(2,3);
    p4 = p1;        // "assignment operator"

    return 0;
}
```

# Return Type of Assignment Operator

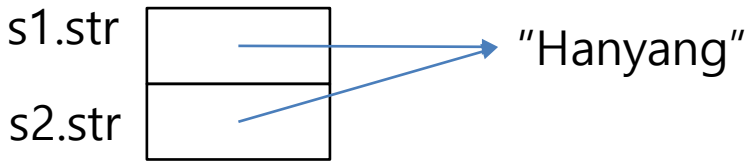
```
#include <iostream>
using namespace std;

class Point
{
private:
    double x, y;
public:
    Point():x(0.0), y(0.0) {}
    Point(double x_, double y_):x(x_), y(y_) {}

    // inconsistent behavior with default assignment operator & assignments for primitive types
    Point operator=(const Point& p)
    { x = p.x; y = p.y; return Point(*this); }

    // same behavior as default assignment operator & assignments for primitive types-> use this!
    Point& operator=(const Point& p)
    { x = p.x; y = p.y; return *this; }

    friend ostream& operator<<(ostream& os, const Point& p);
};

ostream& operator<<(ostream& os, const Point& p)
{
    os << "(" << p.x << ", " << p.y << ")";
    return os;
}

int main()
{
    Point p1(1,2);
    Point p2, p3;
    (p3 = p2) = p1;

    cout << p1 << p2 << p3 << endl;
    return 0;
}
```

# Default assignment operator: Example

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

class MyString{
private:
  int len;
  char *str;
public:
  MyString(const char *s = ""){
    len = strlen(s);
    str = new char[len+1];
    strcpy(str, s);
  }
  ~MyString(){delete[] str;}
  void Print() { cout << str << endl;}
};

int main(){

  MyString s1("Hanyang");
  MyString s2("University");

  s2 = s1;

  s1.Print();
  s2.Print();

  return 0;
}
```

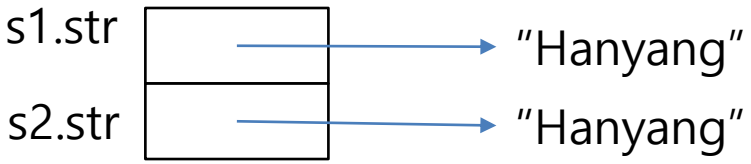
Is it OK?

= operator copies the address



# User-defined assignment operator: Example

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

class MyString{
private:
  int len;
  char *str;
public:
  MyString(const char *s = ""){
    len = strlen(s);
    str = new char[len+1];
    strcpy(str, s);
  }
  MyString &operator=(const MyString &string){
    delete[] str;
    len = string.len;
    str = new char[len+1];
    strcpy(str, string.str);
    return(*this);
  }
  ~MyString(){delete[] str;}
  void Print() { cout << str << endl;}
};

int main(){

  MyString s1("Hanyang");
  MyString s2("University");

  s2 = s1;

  s1.Print();
  s2.Print();

  return 0;
}
```



# Operator Overloading: negation operator

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

class Point{
private:
   int x, y;
public:
   Point(int a, int b): x(a), y(b){}
   Point operator-() { return Point(-x, -y); }
   Point& operator-() { x=-x; y=-y; return *this;}
   void Print(){ cout << x << " " << y << endl;}
};

int main(){
        Point P1(2,2);
        P1.Print();
        Point P2 = -P1;
        P1.Print();
        P2.Print();



        return 0;
}
```

1)

2)

**1) is consistent with primitive types.**

1)

```
2 2
2 2
-2 -2
```

2)

```
2 2
-2 -2
-2 -2
```

# Operator Overloading: increment operator

- Prefix increment operator: `++var`
  - the value of `var` is incremented by 1; then it returns the value.

- Postfix increment operator: `var++`
  - the original value of `var` is returned first; then `var` is incremented by 1.

# Operator Overloading: increment operator

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

class Point{
private:
   int x, y;
public:
   Point(int a, int b): x(a), y(b){}
   Point &operator++(){x++; y++;  return *this;}
   void Print(){ cout << x << " " << y << endl;}
};

int main(){
        Point P1(2,2);
        P1.Print();
        Point P2 = ++P1;
        P1.Print();
        (++P1).Print();

        return 0;
}
```

(++P1) → P1.operator++()

# Operator Overloading: increment operator

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

class Point{
private:
   int x, y;
public:
   Point(int a, int b): x(a), y(b){}
   //Point &operator++(int a){Point temp = (*this); x++; y++;  return temp;}
   Point operator++(int a){Point temp = (*this); x++; y++;  return temp;}
   void Print(){ cout << x << " " << y << endl;}
};

int main(){
        Point P1(2,2);
        P1.Print();
        Point P2 = P1++;
        P1.Print();
        P2.Print();

        return 0;
}
```

(++P1) → P1.operator++()
(P1++) → P1.operator++(0)

Reference: https://www.learncpp.com/cpp-tutorial/97-overloading-the-increment-and-decrement-operators/

# Operator Overloading: []

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

class Point{
private:
  int x,y,z;
public:
  Point(int a = 0, int b = 0, int c = 0): x(a), y(b), z(c){}
  int& operator[](int index){
    if (index == 0) return x;
    else if (index == 1) return y;
    else if (index == 2) return z;
}
  void Print(){cout << x << " " << y << " " << z << endl;}
};

int main(){
  Point P1(1,1,1);
  P1[0] = 2;
  P1[1] = 3;
  P1[2] = 4;
  P1.Print();
  return 0;
}
```

# Quiz 3

- Go to https://www.slido.com/
- Join #**csd-ys**
- Click "Polls"

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

- Note that your quiz answer must be submitted **in the above format** to receive a quiz score!

# Operator Overloading: Summary

- In general, an operator whose result is ...
- New value: Returns the new value by value
  - e.g. +, -, postfix ++, ...

- Existing value, but modified: Returns a reference to the modified value.
  - e.g. =, +=, prefix ++, ...

# Operator Overloading: Summary

```
class A {                              // A a0, a1;
  A& operator =(const A& a);           // a0 = a1;
  A operator +(const A& a) const;      // a0 + a1
  A operator +() const;                // +a0
  A& operator +=(const A& a);          // a0 += a1;
  A& operator ++();                    // ++a0
  A operator ++(int);                 // a0++
};

A operator +(const A& a0, const A& a1);  // a0 + a1
A operator +(const A& a0);               // +a0
A& operator +=(A& a0, const A& a1);      // a0 += a1;
A& operator ++(A& a0);                   // ++a0
A operator ++(A& a0, int);              // a0++

std::ostream& operator <<(std::ostream& out, const A& a);   // cout << a0;
```

# Operator Overloading: Summary

- The C++ language rarely puts constraints on operator overloading such as
  - what the overloaded operators do
  - what should be the return type

- But in general, overloaded operators *are expected to behave as similar as possible to the* ***built-in operators***:
  - operator+ is expected to add, rather than multiply its arguments,
  - operator= is expected to assign
  - Assignment operators return by reference to make it possible to write a = b = c = d, because the built-in operators allow that.

# Operator Overloading: Summary

- Most commonly overloaded operators are
  - Arithmetic operators : +, -, *, / …
  - Assignment operators : =, +=, -=, *= …
  - Comparison operators : <, >, <=, >=, ==, != …
  - For array or containers : [], () …
  - Rarely : ->, new, delete, ...
- Operator overloading must be used very carefully, since it can hamper the readability seriously.

# Operator that can be overloaded

| | | | | | |
|---|---|---|---|---|---|
| + | - | * | / | % | ^ |
| & | \| | ~ | ! | = | < |
| > | += | -= | *= | /= | %= |
| ^= | &= | \|= | << | >> | >>= |
| <<= | == | != | <= | >= | && |
| \|\| | ++ | -- | , | ->* | -> |
| () | [] | new | delete | new [] | delete [] |

# Example 1

```
class Time
{
private:
    int hours;
    int minutes;
public:
    Time();
    Time(int h, int m = 0);
    void AddMin(int m);
    void AddHr(int h);
    void Reset(int h = 0, int m = 0);
    Time operator+(const Time & t) const;
    void Show() const;
};
```

```
void Time::AddMin(int m)
{
    minutes += m;
    hours += minutes / 60;
    minutes %= 60;
}

void Time::AddHr(int h)
{
    hours += h;
}

void Time::Reset(int h, int m)
{
    hours = h;
    minutes = m;
}
```

```
Time Time::operator+(const Time & t) const
{
    Time sum;
    sum.minutes = minutes + t.minutes;
    sum.hours = hours + t.hours + sum.minutes / 60;
    sum.minutes %= 60;
    return sum;
}
```

# Converting Constructor & Operator Overloading

- Basically, constructors can convert some type (the parameter type) to another type (the class belonging the constructor).

- This can affect the behavior of overloaded operators.

- See the following Example 2.

# Example 2

```
class Complex {
 public:
  Complex() : real(0.0), imag(0.0) {}
  Complex(double r, double i) : real(r), imag(i) {}
  Complex(const Complex& c) : real(c.real), imag(c.imag) {}

  Complex operator+(const Complex& c) const {
    return Complex(real + c.real, imag + c.imag);
  }
 private:
  double real, imag;
};
void Test() {
  Complex a(1.0, 2.0), b(2.0, 5.0);
  Complex c(a + b);
  c = c + a;
}
```

# Example 2

```
class Complex {
 public:
  Complex() : real(0.0), imag(0.0) {}
  Complex(double r, double i) : real(r), imag(i) {}
  Complex(const Complex& c) : real(c.real), imag(c.imag) {}

  Complex operator+(const Complex& c) const;
 private:
  double real, imag;
};
void Test() {
  Complex a(1.0, 2.0), b(2.0, 5.0), c;
  c = a + b;     // OK.
  c = a + 3.0;   // Error.
  c = 2.0 + b;   // Error.
}
```

# Example 2

```
class Complex {
 public:
  Complex() : real(0.0), imag(0.0) {}
  Complex(double v) : real(v), imag(0.0){}//Constructor for a
single v.
  Complex(double r, double i) : real(r), imag(i) {}
  Complex(const Complex& c) : real(c.real), imag(c.imag) {}

  Complex operator+(const Complex& c) const;
 private:
  double real, imag;
};
void Test() {
  Complex a(1.0, 2.0), b(2.0, 5.0), c;
  c = a + b;     // OK.
  c = a + 3.0; // OK.
  c = 2.0 + b;  // Error.
}
```

# Example 2

```
class Complex {
 public:
  Complex() : real(0.0), imag(0.0) {}
  Complex(double v) : real(v), imag(0.0) {} // Constructor for a single v.
  Complex(double r, double i) : real(r), imag(i) {}
  Complex(const Complex& c) : real(c.real), imag(c.imag) {}

  Complex& operator=(const Complex& c);
 private:
  double real, imag;
  friend Complex operator+(const Complex& lhs, const Complex& rhs);
};
Complex operator+(const Complex& lhs, const Complex& rhs) {
  return Complex(lhs.real + rhs.real, lhs.imag + rhs.imag);
}
void Test() {
  Complex a(1.0, 2.0), b(2.0, 5.0), c;
  c = a + b;    // OK.
  c = a + 3.0;  // OK.
  c = 2.0 + b;  // OK.}
```

```
class Complex {
 public:
  Complex() : real(0.0), imag(0.0) {}
  Complex(double v) : real(v), imag(0.0) {}
  Complex(double r, double i) : real(r), imag(i) {}
  Complex(const Complex& c) : real(c.real), imag(c.imag) {}

  Complex& operator=(const Complex& c) {          // Complex a(1.0, 0.0), c;
    real = c.real, imag = c.imag;                 // c = a;
    return *this;
  }

  Complex operator+() const { return *this; }                    // c = +a;
  Complex operator-() const { return Complex(-real, -imag); }    // c = -a;

  double& operator[](int i) { return i == 0 ? real : imag; }     // i = c[0];
  const double& operator[](int i) const { return i == 0 ? real : imag; }

 private:
  double real, imag;

  friend Complex operator+(const Complex& lhs, const Complex& rhs);
  friend bool operator<(const Complex& lhs, const Complex& rhs);
};

Complex operator+(const Complex& lhs, const Complex& rhs) const {  // c + a
  return Complex(lhs.real + rhs.real, lhs.imag + rhs.imag);
}
bool operator<(const Complex& lhs, const Complex& rhs) {  // if (c < a)
  return lhs.real < rhs.real && lhs.imag < rhs.imag;
}
```

# Next Time

- Labs for this lecture:
  - **Lab1: Assignment 11-1 (tomorrow)**
  - Lab2: Assignment 11-2 (later)

- Next lecture:
  - **12 - Template (the day after tomorrow, Nov 30)**