Programming in Modern C++

Module M14: Copy Constructor and Copy Assignment Operator

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All url's in this module have been accessed in September, 2021 and found to be functional

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Module M14

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Obj. & Outlines

Obj. Lifetime
String
Date
Rect
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CreditCard

Copy Constructor
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Signature
Data Members
Free Copy & Pitfall

Assignment Op.
Copy Objects
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Comparison

Class as Type

Module Summary

Module Recap

- Objects are initialized by Constructors that can be Parameterized and / or Overloaded
- Default Constructor does not take any parameter – necessary for arrays of objects
- Objects are cleaned-up by Destructors. Destructor for a class is unique
- Compiler provides *free* Default Constructor and Destructor, if not provides by the program
- Objects have a well-defined lifetime spanning from execution of the beginning of the body of a constructor to the execution till the end of the body of the destructor
- Memory for an object must be available before its construction and can be released only after its destruction

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Module Objectives

- More on Object Lifetime
- Understand Copy Construction
- Understand Copy Assignment Operator
- Understand Shallow and Deep Copy

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Module Outline

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Object Lifetime Examples

Program 14.01/02: Order of Initialization: Order of Data Members

```
#include <iostream>
using namespace std;
int init_m1(int m) { // Func. to init m1_
    cout << "Init m1_: " << m << endl;
    return m;
}
int init_m2(int m) { // Func. to init m2_
    cout << "Init m2_: " << m << endl;
    return m;
}
class X { int m1_; // Initialize 1st
          int m2_; // Initialize 2nd
public: X(int m1, int m2) :
        m1_(init_m1(m1)),  // Called 1st
        m2_(init_m2(m2))   // Called 2nd
        { cout << "Ctor: " << endl; }
    ~X() { cout << "Dtor: " << endl; } };
int main() { X a(2, 3); return 0; }
-----
Init m1_: 2
Init m2_: 3
Ctor:
Dtor:
```

```
#include <iostream>
using namespace std;
int init_m1(int m) { // Func. to init m1_
    cout << "Init m1_: " << m << endl;
    return m;
}
int init_m2(int m) { // Func. to init m2_
    cout << "Init m2_: " << m << endl;
    return m;
}
class X { int m2_; // Order of data members swapped
          int m1_;
public: X(int m1, int m2) :
        m1_(init_m1(m1)),  // Called 2nd
        m2_(init_m2(m2))   // Called 1st
        { cout << "Ctor: " << endl; }
    ~X() { cout << "Dtor: " << endl; } };
int main() { X a(2, 3); return 0; }
-----
Init m2_: 3
Init m1_: 2
Ctor:
Dtor:
```

- *Order of initialization does not depend on the order in the initialization list. It depends on the order of data members in the definition*

Program 14.03/04: A Simple String Class

C Style

```
#include <iostream>
#include <cstring>
#include <cstdlib>
using namespace std;
struct String { char *str_;   // Container
                size_t len_; // Length
};
void print(const String& s) {
    cout << s.str_ << ": "
         << s.len_ << endl;
}
int main() { String s;

    // Init data members
    s.str_ = strdup("Partha");
    s.len_ = strlen(s.str_);
    print(s);
    free(s.str);
}
-----
Partha: 6
```

C++ Style

```
#include <iostream>
#include <cstring>
#include <cstdlib>
using namespace std;
class String { char *str_;   // Container
               size_t len_; // Length
public: String(char *s) : str_(strdup(s)), // Uses malloc()
                          len_(strlen(str_))
    { cout << "ctor: "; print(); }
    ~String() { cout << "dtor: "; print();
        free(str_); // To match malloc() in strdup()
    }
    void print() { cout << "(" << str_ << ": "
                        << len_ << ")" << endl; }
    size_t len() { return len_; }
};
int main() { String s = "Partha"; // Ctor called
    s.print();
}
-----
ctor: (Partha: 6)
(Partha: 6)
dtor: (Partha: 6)
```

- *Note the order of initialization between `str_` and `len_`. What if we swap them?*

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Program 14.05: A Simple String Class: Fails for wrong order of data members


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

class String {
    size_t len_; // Swapped members cause garbage to be printed or program crash (unhandled exception)
    char *str_;
public:
    String(char *s) : str_(strdup(s)), len_(strlen(str_)) { cout << "ctor: "; print(); }
    ~String() { cout << "dtor: "; print(); free(str_); }
    void print() { cout << "(" << str_ << ": " << len_ << ")" << endl; }
};
int main() { String s = "Partha";
    s.print();
}
----- // May produce garbage or crash
ctor: (Partha: 20)
(Partha: 20) // Garbage
dtor: (Partha: 20)
```

- **`len_` precedes `str_` in list of data members**
- **`len_(strlen(str_))` is executed before `str_(strdup(s))`**
- **When `strlen(str_)` is called `str_` is still uninitialized**
- **May causes the program to crash**

Practice: Program 14.06: A Simple Date Class


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

char monthNames[][4]={ "Jan", "Feb", "Mar", "Apr", "May", "Jun", "Jul", "Aug", "Sep", "Oct", "Nov", "Dec" };
char dayNames[][10] ={ "Monday", "Tuesday", "Wednesday", "Thursday", "Friday", "Saturday", "Sunday" };
class Date {
    enum Month { Jan = 1, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec };
    enum Day { Mon, Tue, Wed, Thr, Fri, Sat, Sun };
    typedef unsigned int UINT;
    UINT date_; Month month_; UINT year_;
public:
    Date(UINT d, UINT m, UINT y) : date_(d), month_((Month)m), year_(y) { cout << "ctor: "; print(); }
    ~Date() { cout << "dtor: "; print(); }
    void print() { cout << date_ << "/" << monthNames[month_ - 1] << "/" << year_ << endl; }
    bool validDate() { /* Check validity */ return true; } // Not implemented
    Day day() { /* Compute day from date using time.h */ return Mon; } // Not implemented
};
int main() {
    Date d(30, 7, 1961);
    d.print();
}
-----
ctor: 30/Jul/1961
30/Jul/1961
dtor: 30/Jul/1961
```

Practice: Program 14.07: Point and Rect Classes: Lifetime of Data Members or Embedded Objects


```
#include <iostream>
using namespace std;
class Point { int x_; int y_; public:
    Point(int x, int y):
        x_(x), y_(y)
    { cout << "Point ctor: ";
      print(); cout << endl; }
    ~Point() { cout << "Point dtor: ";
                 print(); cout << endl; }
    void print() { cout << "(" << x_ << ", "
                      << y_ << ")"; }
};

int main() {
    Rect r (0, 2, 5, 7);

    cout << endl; r.print(); cout << endl;

    cout << endl;
}
```

```
class Rect { Point TL_; Point BR_; public:
    Rect(int tlx, int tly, int brx, int bry):
        TL_(tlx, tly), BR_(brx, bry)
    { cout << "Rect ctor: ";
      print(); cout << endl; }
    ~Rect() { cout << "Rect dtor: ";
                 print(); cout << endl; }
    void print() { cout << "["; TL_.print();
           cout << " "; BR_.print(); cout << "]"; }
};
-----
Point ctor: (0, 2)
Point ctor: (5, 7)
Rect ctor: [(0, 2) (5, 7)]

[(0, 2) (5, 7)]

Rect dtor: [(0, 2) (5, 7)]
Point dtor: (5, 7)
Point dtor: (0, 2)
```

- Attempt is to construct a Rect object
- That, in turn, needs constructions of Point data members (or embedded objects) – TL_ and BR_ respectively
- Destruction, initiated at the end of scope of destructor's body, naturally follows a reverse order

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Practice: Program 14.08: Name & Address Classes


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

#include "String.h" // Containing class String from slide 14.7
#include "Date.h"

class Name { String firstName_, lastName_;
public: Name(char* fn, char* ln) : firstName_(fn), lastName_(ln)
    { cout << "Name ctor: "; print(); cout << endl; }
    ~Name() { cout << "Name dtor: "; print(); cout << endl; }
    void print() { firstName_.print(); cout << " "; lastName_.print(); }
};
class Address { unsigned int houseNo_;
    String street_, city_, pin_;
public: Address(unsigned int hn, char* sn, char* cn, char* pin) :
        houseNo_(hn), street_(sn), city_(cn), pin_(pin)
    { cout << "Address ctor: "; print(); cout << endl; }
    ~Address() { cout << "Address dtor: "; print(); cout << endl; }
    void print() {
        cout << houseNo_ << " ";
        street_.print(); cout << " ";
        city_.print(); cout << " ";
        pin_.print();
    }
};
```

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Practice: Program 14.08: CreditCard Class


```
class CreditCard { typedef unsigned int UINT;
    char cardNumber_[17]; // 16-digit (character) card number as C-string
    Name holder_; Address addr_;
    Date issueDate_, expiryDate_;
    UINT cvv_;
public:
    CreditCard(char* cNumber, char* fn, char* ln, unsigned int hn, char* sn, char* cn, char* pin,
        UINT issueMonth, UINT issueYear, UINT expiryMonth, UINT expiryYear, UINT cvv) :
        holder_(fn, ln), addr_(hn, sn, cn, pin),
        issueDate_(1, issueMonth, issueYear),
        expiryDate_(1, expiryMonth, expiryYear), cvv_(cvv)
        { strcpy(cardNumber_, cNumber); cout << "CC ctor: "; print(); cout << endl; }
    ~CreditCard() { cout << "CC dtor: "; print(); cout << endl; }
    void print() {
        cout << cardNumber_ << " "; holder_.print(); cout << " "; addr_.print(); cout << " ";
        issueDate_.print(); cout << " "; expiryDate_.print(); cout << " "; cout << cvv_;
    }
};
int main() {
    CreditCard cc("5321711934640027", "Sharlock", "Holmes",
                  221, "Baker Street", "London", "NW1 6XE", 7, 2014, 12, 2016, 811);
    cout << endl; cc.print(); cout << endl << endl;;
}
```

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Practice: Program 14.08: CreditCard Class: Lifetime Chart

```
typedef unsigned int UINT;
class CreditCard { char cardNumber_[17];
    Name holder_; Address addr_;
    Date issueDate_, expiryDate_; UINT cvv_; };
class Name { String firstName_, lastName_; };
class Address { unsigned int houseNo_;
    String street_, city_, pin_; };
class Date { enum Month;
    UINT date_; Month month_; UINT year_; };
```

Construction of Objects

```
        String: Sharlock
        String: Holmes
    Name: Sharlock Holmes
        String: Baker Street
        String: London
        String: NW1 6XE
    Address: 221 Baker Street London NW1 6XE
    Date: 1/Jul/2014
    Date: 1/Dec/2016
CC: 5321711934640027 Sharlock Holmes 221 Baker Street London NW1 6XE 1/Jul/2014 1/Dec/2016 811
```

Use of Object

```
5321711934640027 Sharlock Holmes 221 Baker Street London NW1 6XE 1/Jul/2014 1/Dec/2016 811
```

Destruction of Objects

```
~CC: 5321711934640027 Sharlock Holmes 221 Baker Street London NW1 6XE 1/Jul/2014 1/Dec/2016 811
    ~Date: 1/Dec/2016
    ~Date: 1/Jul/2014
    ~Address: 221 Baker Street London NW1 6XE
        ~String: NW1 6XE
        ~String: London
        ~String: Baker Street
    ~Name: Sharlock Holmes
        ~String: Holmes
        ~String: Sharlock
```

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Copy Constructor

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Copy Constructor

Copy Constructor

- We know:

  `Complex c1(4.2, 5.9);`

  invokes

  `Constructor Complex::Complex(double, double);`

- Which constructor is invoked for?

  `Complex c2(c1);`

  Or for?

  `Complex c2 = c1;`

- It is the **Copy Constructor** that takes an object of the same type and constructs a copy:

  `Complex::Complex(const Complex &);`

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Program 14.09: Complex: Copy Constructor


```cpp
#include <iostream>
#include <cmath>
using namespace std;
class Complex { double re_, im_; public:
    // Constructor
    Complex(double re, double im):
        re_(re), im_(im)
    { cout << "Complex ctor: "; print(); }
    // Copy Constructor
    Complex(const Complex& c):
        re_(c.re_), im_(c.im_)
    { cout << "Complex copy ctor: "; print(); }
    // Destructor
    ~Complex()
    { cout << "Complex dtor: "; print(); }
    double norm() { return sqrt(re_*re_ + im_*im_); }
    void print() { cout << "|" << re_ << "+j" << im_ << "| = " << norm() << endl; }
};
int main() {
    Complex c1(4.2, 5.3), // Constructor - Complex(double, double)
            c2(c1),       // Copy Constructor - Complex(const Complex&)
            c3 = c2;      // Copy Constructor - Complex(const Complex&)

    c1.print(); c2.print(); c3.print();
}
```

```
-----
Complex ctor: |4.2+j5.3| = 6.7624      // Ctor: c1
Complex copy ctor: |4.2+j5.3| = 6.7624 // CCtor: c2 of c1
Complex copy ctor: |4.2+j5.3| = 6.7624 // CCtor: c3 of c2
|4.2+j5.3| = 6.7624                    // c1
|4.2+j5.3| = 6.7624                    // c2
|4.2+j5.3| = 6.7624                    // c3
Complex dtor: |4.2+j5.3| = 6.7624      // Dtor: c3
Complex dtor: |4.2+j5.3| = 6.7624      // Dtor: c2
Complex dtor: |4.2+j5.3| = 6.7624      // Dtor: c1
```

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Why do we need Copy Constructor?

- Consider the **function call mechanisms** in C++:
  - *Call-by-reference*: Set a reference to the actual parameter as a formal parameter. Both the formal parameter and the actual parameter share the same location (object). *No copy is needed*
  - *Return-by-reference*: Set a reference to the computed value as a return value. Both the computed value and the return value share the same location (object). *No copy is needed*
  - *Call-by-value*: Make a *copy* or *clone* of the actual parameter as a formal parameter. This needs a **Copy Constructor**
  - *Return-by-value*: Make a *copy* or *clone* of the computed value as a return value. This needs a **Copy Constructor**
- **Copy Constructor** is needed for *initializing the data members* of a UDT from an existing value

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Program 14.10: Complex: Call by value

```
#include <iostream>
#include <cmath>
using namespace std;
class Complex { double re_, im_; public:
    Complex(double re, double im): re_(re), im_(im)   // Constructor
    { cout << "ctor: "; print(); }
    Complex(const Complex& c): re_(c.re_), im_(c.im_) // Copy Constructor
    { cout << "copy ctor: "; print(); }
    ~Complex() { cout << "dtor: "; print(); }
    double norm() { return sqrt(re_*re_ + im_*im_); }
    void print() { cout << "|" << re_ << "+j" << im_ << "| = " << norm() << endl; }
};
void Display(Complex c_param) { // Call by value
    cout << "Display: "; c_param.print();
}
int main() { Complex c(4.2, 5.3);     // Constructor - Complex(double, double)

    Display(c); // Copy Constructor called to copy c to c_param
}
-----
ctor: |4.2+j5.3| = 6.7624          // Ctor of c in main()
copy ctor: |4.2+j5.3| = 6.7624     // Ctor c_param as copy of c, call Display()
Display: |4.2+j5.3| = 6.7624       // c_param
dtor: |4.2+j5.3| = 6.7624          // Dtor c_param on exit from Display()
dtor: |4.2+j5.3| = 6.7624          // Dtor of c on exit from main()
```

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Signature of Copy Constructors

- Signature of a *Copy Constructor* can be one of:

```
MyClass(const MyClass& other);           // Common
                                         // Source cannot be changed
MyClass(MyClass& other);                 // Occasional
                                         // Source needs to change. Like in smart pointers
MyClass(volatile const MyClass& other);  // Rare
MyClass(volatile MyClass& other);        // Rare
```

- None of the following are copy constructors, though they can copy:

```
MyClass(MyClass* other);
MyClass(const MyClass* other);
```

- *Why the parameter to a copy constructor must be passed as Call-by-Reference?*

```
MyClass(MyClass other);
```

The above is an infinite recursion of copy calls as the call to copy constructor itself needs to make copy for the Call-by-Value mechanism

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Program 14.11: Point and Rect Classes: Embedded Objects Default, Copy and Overloaded Constructors

```
#include <iostream>
using namespace std;
class Point { int x_; int y_; public:
    Point(int x, int y): x_(x), y_(y) { cout << "Point ctor: "; print(); cout << endl; }          // Ctor
    Point(): x_(0), y_(0) { cout << "Point ctor: "; print(); cout << endl; }                      // DCtor
    Point(const Point& p): x_(p.x_), y_(p.y_) { cout << "Point cctor: "; print(); cout << endl; } // CCtor
    ~Point() { cout << "Point dtor: "; print(); cout << endl; }                                   // Dtor
    void print() { cout << "(" << x_ << ", " << y_ << ")"; } };  // Class Point
class Rect { Point TL_; Point BR_; public:
    Rect(int tlx, int tly, int brx, int bry): TL_(tlx, tly), BR_(brx, bry) // Ctor of Rect: 4 coords
    { cout << "Rect ctor: "; print(); cout << endl; }                       // Uses Ctor for Point
    Rect(const Point& p_tl, const Point& p_br): TL_(p_tl), BR_(p_br)       // Ctor of Rect: 2 Points
    { cout << "Rect ctor: "; print(); cout << endl; }                       // Uses CCtor for Point
    Rect(const Point& p_tl, int brx, int bry): TL_(p_tl), BR_(brx, bry)    // Ctor of Rect: Point + 2 coords
    { cout << "Rect ctor: "; print(); cout << endl; }                       // Uses CCtor for Point
    Rect() { cout << "Rect ctor: "; print(); cout << endl; }                // DCtor of Rect: // DCtor Point
    Rect(const Rect& r): TL_(r.TL_), BR_(r.BR_)                            // CCtor of Rect
    { cout << "Rect cctor: "; print(); cout << endl; }                      // Uses CCtor for Point
    ~Rect() { cout << "Rect dtor: "; print(); cout << endl; }               // Dtor
    void print() { cout << "["; TL_.print(); cout << " "; BR_.print(); cout << "]"; } }; // Class Rect
```

- When parameter `(tlx, tly)` is set to `TL_` by `TL_(tlx, tly)`: parameterized **Ctor** of Point is invoked
- When parameter `p_tl` is set to `TL_` by `TL_(p_tl)`: **CCtor** of Point is invoked
- When `TL_` is set by default in **DCtor** of Rect: **DCtor** of Point is invoked
- When member `r.TL_` is set to `TL_` by `TL_(r.TL_)` in **CCtor** of Rect: **CCtor** of Point is invoked

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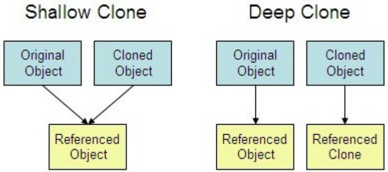
Practice: Program 14.11: Rect Class: Trace of Object Lifetimes

Code	Output	Lifetime	Remarks
`int main() {`			
`Rect r1(0, 2, 5, 7);`	Point ctor: (0, 2)	Point r1.TL_	
`//Rect(int, int, int, int)`	Point ctor: (5, 7)	Point r1.BR_	
	Rect ctor: [(0, 2) (5, 7)]	Rect r1	
`Rect r2(Point(3, 5),`	Point ctor: (6, 9)	Point t1	Second parameter
`Point(6, 9));`	Point ctor: (3, 5)	Point t2	First parameter
`//Rect(Point&, Point&)`	Point cctor: (3, 5)	r2.TL_ = t2	Copy to `r2.TL_`
	Point cctor: (6, 9)	r2.BR_ = t1	Copy to `r2.BR_`
	Rect ctor: [(3, 5) (6, 9)]	Rect r2	
	Point dtor: (3, 5)	~Point t2	First parameter
	Point dtor: (6, 9)	~Point t1	Second parameter
`Rect r3(Point(2, 2), 6, 4);`	Point ctor: (2, 2)	Point t3	First parameter
`//Rect(Point&, int, int)`	Point cctor: (2, 2)	r3.TL_ = t3	Copy to `r3.TL_`
	Point ctor: (6, 4)	Point r3.BR_	
	Rect ctor: [(2, 2) (6, 4)]	Rect r3	
	Point dtor: (2, 2)	~Point t3	First parameter
`Rect r4;`	Point ctor: (0, 0)	Point r4.TL_	
`//Rect()`	Point ctor: (0, 0)	Point r4.BR_	
	Rect ctor: [(0, 0) (0, 0)]	Rect r4	
`return 0;`	Rect dtor: [(0, 0) (0, 0)]	~Rect r4	
`}`	Point dtor: (0, 0)	~Point r4.BR_	
	Point dtor: (0, 0)	~Point r4.TL_	
	Rect dtor: [(2, 2) (6, 4)]	~Rect r3	
	Point dtor: (6, 4)	~Point r3.BR_	
	Point dtor: (2, 2)	~Point r3.TL_	
	Rect dtor: [(3, 5) (6, 9)]	~Rect r2	
	Point dtor: (6, 9)	~Point r2.BR_	
	Point dtor: (3, 5)	~Point r2.TL_	
	Rect dtor: [(0, 2) (5, 7)]	~Rect r1	
	Point dtor: (5, 7)	~Point r1.BR_	
	Point dtor: (0, 2)	~Point r1.TL_	

Free Copy Constructor

- If no copy constructor is provided by the user, the compiler supplies a *free* one
- *Free* copy constructor cannot initialize the object to proper values. It performs *Shallow Copy*
- **Shallow Copy** aka *bit-wise copy*, *field-by-field copy*, *field-for-field copy*, or *field copy*
  - An object is created by simply *copying the data of all variables* of the original object
  - Works well if *none of the variables of the object are defined in heap / free store*
  - For dynamically created variables, the *copied object refers to the same memory location*
  - Creates *ambiguity* (changing one changes the copy) and *run-time errors* (dangling pointer)
- **Deep Copy** or its variants *Lazy Copy* and *Copy-on-Write*
  - An object is created by copying data of all variables except the ones on heap
  - Allocates similar memory resources with the same value to the object
  - **Need to explicitly define the copy constructor and assign dynamic memory as required**
  - **Required to dynamically allocate memory to the variables in the other constructors**



Pitfalls of Bit-wise Copy: Shallow Copy

- Consider a class:

```
class A { int i_;      // Non-pointer data member
          int* p_;     // Pointer data member
public:
    A(int i, int j) : i_(i), p_(new int(j)) { } // Init. with pointer to dynamically created object
    ~A() { cout << "Destruct " << this << ": ";                            // Object identity
        cout << "i_ = " << i_ << " p_ = " << p_ << " *p = " << *p_ << endl; // Object state
        delete p_;                                                         // Release resource
    }
};
```

- As no copy constructor is provided, the implicit copy constructor does a bit-wise copy. So when an A object is copied, p_ is copied and continues to point to the same dynamic int:

```
int main() { A a1(2, 3); A a2(a1); // Construct a2 as a copy of a1. Done by bit-wise copy
    cout << "&a1 = " << &a1 << " &a2 = " << &a2 << endl;
}
```

- The output is wrong, as a1.p_ = a2.p_ points to the same int location. Once a2 is destructed, a2.p_ is released, and a1.p_ becomes dangling. The program may print garbage or crash:

```
&a1 = 008FF838 &a2 = 008FF828                       // Identities of objects
Destruct 008FF828: i_ = 2 p_ = 00C15440 *p = 3         // Dtor of a2. Note that a2.p_ = a1.p_
Destruct 008FF838: i_ = 2 p_ = 00C15440 *p = -17891602 // Dtor of a1. a1.p_=a2.p_ points to garbage
```

- The bit-wise copy of members is known as **Shallow Copy**

Pitfalls of Bit-wise Copy: Deep Copy

- Now suppose we provide a user-defined copy constructor:

```
class A { int i_;      // Non-pointer data member
          int* p_;     // Pointer data member
public:
    A(int i, int j) : i_(i), p_(new int(j)) { } // Init. with pointer to dynamically created object
    A(const A& a) : i_(a.i_),          // Copy Constructor
        p_(new int(*a.p_)) { }         // Allocation done and value copied - Deep Copy
    ~A() { cout << "Destruct " << this << ": ";                               // Object identity
        cout << "i_ = " << i_ << " p_ = " << p_ << " *p = " << *p_ << endl; // Object state
        delete p_;                                                             // Release resource
    }
};
```

- The output now is correct, as a1.p_ $\neq$ a2.p_ points to the different int locations with the values *a1.p_ = *a2.p_ properly copied:

```
&a1 = 00B8F9E0 &a2 = 00B8F9D0                   // Identities of objects
Destruct 00B8F9D0: i_ = 2 p_ = 00C95480 *p = 3  // Dtor of a2. a2.p_ is different from a1.p_
Destruct 00B8F9E0: i_ = 2 p_ = 00C95440 *p = 3  // Dtor of a1. Works correctly!
```

- This is known as **Deep Copy** where every member is copied properly. Note that:
  - In every class, provide copy constructor to adopt to deep copy which is always safe
  - Naturally, shallow copy is cheaper than deep copy. So some languages support variants as *Lazy Copy* or *Copy-on-Write* for efficiency

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Practice: Program 14.12: Complex: Free Copy Constructor

```
#include <iostream>
#include <cmath>
using namespace std;
class Complex { double re_, im_; public:
    Complex(double re, double im) : re_(re), im_(im) { cout << "ctor: "; print(); } // Ctor
 // Complex(const Complex& c) : re_(c.re_), im_(c.im_) { cout<<"copy ctor: "; print(); } // CCtor: Free only
    ~Complex() { cout << "dtor: "; print(); }                                         // Dtor
    double norm() { return sqrt(re_*re_ + im_*im_); }
    void print() { cout << "|" << re_ << "+j" << im_ << "| = " << norm() << endl; }
};
void Display(Complex c_param) { cout << "Display: "; c_param.print(); }
int main() { Complex c(4.2, 5.3);  // Constructor - Complex(double, double)
    Display(c);                     // Free Copy Constructor called to copy c to c_param
}
```

User-defined CCtor	Free CCtor
ctor: |4.2+j5.3| = 6.7624	ctor: |4.2+j5.3| = 6.7624
copy ctor: |4.2+j5.3| = 6.7624	No message from free CCtor
Display: |4.2+j5.3| = 6.7624	Display: |4.2+j5.3| = 6.7624
dtor: |4.2+j5.3| = 6.7624	dtor: |4.2+j5.3| = 6.7624
dtor: |4.2+j5.3| = 6.7624	dtor: |4.2+j5.3| = 6.7624

- User has provided *no copy constructor*
- Compiler provides *free copy constructor*
- Compiler-provided copy constructor *performs bit-wise copy* - hence there is no message
- *Correct in this case* as members are of built-in type and there is no dynamically allocated data

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Practice: Program 14.13: String: User-defined Copy Constructor


```
#include <iostream>
#include <cstdlib>
#include <cstring>
using namespace std;
class String { public: char *str_; size_t len_;
    String(char *s) : str_(strdup(s)), len_(strlen(str_)) { }        // Ctor
    String(const String& s) : str_(strdup(s.str_)), len_(s.len_) { } // CCtor: User provided
    ~String() { free(str_); }                                         // Dtor
    void print() { cout << "(" << str_ << ": " << len_ << ")" << endl; }
};
void strToUpper(String a) { // Make the string uppercase
    for (int i = 0; i < a.len_; ++i) { a.str_[i] = toupper(a.str_[i]); }
    cout << "strToUpper: "; a.print();
} // a.~String() is invoked releasing a.str_. s.str_ remains intact
int main() { String s = "Partha"; s.print(); strToUpper(s); s.print(); }
---
(Partha: 6)
strToUpper: (PARTHA: 6)
(Partha: 6)
```

- User has *provided copy constructor*. So Compiler *does not provide free copy constructor*
- When actual parameter `s` is copied to formal parameter `a`, space is allocated for `a.str_` and then it is copied from `s.str_`. On exit from `strToUpper`, `a` is destructed and `a.str_` is deallocated. But in `main`, `s` remains intact and access to `s.str_` is valid.
- **Deep Copy**: While copying the object, the pointed object is copied in a fresh allocation. *This is safe*

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Practice: Program 14.14: String: Free Copy Constructor

```
#include <iostream>
#include <cstring>
#include <cstdlib>
using namespace std;
class String { public: char *str_; size_t len_;
    String(char *s) : str_(strdup(s)), len_(strlen(str_)) { }              // Ctor
    // String(const String& s) : str_(strdup(s.str_)), len_(s.len_) { } // CCtor: Free only
    ~String() { free(str_); }                                              // Dtor
    void print() { cout << "(" << str_ << ": " << len_ << ")" << endl; }
};
void strToUpper(String a) { // Make the string uppercase
    for (int i = 0; i < a.len_; ++i) { a.str_[i] = toupper(a.str_[i]); } cout<<"strToUpper: "; a.print();
} // a.~String() is invoked releasing a.str_ and invalidating s.str_ = a.str_
int main() { String s = "Partha"; s.print(); strToUpper(s); s.print(); } // Last print fails
```

User-defined CCtor	**Free CCtor**
(Partha: 6)	(Partha: 6)
strToUpper: (PARTHA: 6)	strToUpper: (PARTHA: 6)
(Partha: 6)	(????????????????????????????: 6)

- User has provided *no copy constructor*. Compiler provides *free copy constructor*
- Free copy constructor performs *bit-copy* - hence no allocation is done for `str_` when actual parameter `s` is copied to formal parameter `a`. `s.str_` is merely copied to `a.str_` and both continue to point to the same memory. On exit from `strToUpper`, `a` is destructed and `a.str_` is deallocated. Hence in `main` access to `s.str_` is dangling. Program prints garbage and / or crashes
- **Shallow Copy**: With bit-copy, only the pointer is copied - not the pointed object. *This is risky*

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Copy Assignment Operator

Copy Assignment Operator

- We can copy an existing object to another existing object as

```
Complex c1 = (4.2, 5.9), c2(5.1, 6.3);

c2 = c1;     // c1 becomes { 4.2, 5.9 }
```

  This is like normal assignment of built-in types and overwrites the old value with the new value

- It is the **Copy Assignment** that takes an object of the same type and overwrites into an existing one, and returns that object:

```
Complex::Complex& operator= (const Complex &);
```

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Program 14.15: Complex: Copy Assignment

```
#include <iostream>
#include <cmath>
using namespace std;
class Complex { double re_, im_; public:
    Complex(double re, double im) : re_(re), im_(im) { cout << "ctor: "; print(); }    // Ctor
    Complex(const Complex& c) : re_(c.re_), im_(c.im_) { cout << "cctor: "; print(); } // CCtor
    ~Complex() { cout << "dtor: "; print(); }                                          // Dtor
    Complex& operator=(const Complex& c)  // Copy Assignment Operator
    { re_ = c.re_; im_ = c.im_; cout << "copy: "; print(); return *this; } // Return *this for chaining
    double norm() { return sqrt(re_*re_ + im_*im_); }
    void print() { cout << "|" << re_ << "+j" << im_ << "| = " << norm() << endl; } }; // Class Complex
int main() { Complex c1(4.2, 5.3), c2(7.9, 8.5); Complex c3(c2); // c3 Copy Constructed from c2
    c1.print(); c2.print(); c3.print();
    c2 = c1; c2.print();                               // Copy Assignment Operator
    c1 = c2 = c3; c1.print(); c2.print(); c3.print(); // Copy Assignment Chain
}
```

```
ctor: |4.2+j5.3| = 6.7624    // c1 - ctor
ctor: |7.9+j8.5| = 11.6043   // c2 - ctor
cctor: |7.9+j8.5| = 11.6043 // c3 - ctor
|4.2+j5.3| = 6.7624          // c1
|7.9+j8.5| = 11.6043         // c2
|7.9+j8.5| = 11.6043         // c3
copy: |4.2+j5.3| = 6.7624    // c2 <- c1
|4.2+j5.3| = 6.7624          // c2
```

```
copy: |7.9+j8.5| = 11.6043   // c2 <- c3
copy: |7.9+j8.5| = 11.6043   // c1 <- c2
|7.9+j8.5| = 11.6043         // c1
|7.9+j8.5| = 11.6043         // c2
|7.9+j8.5| = 11.6043         // c3
dtor: |7.9+j8.5| = 11.6043   // c3 - dtor
dtor: |7.9+j8.5| = 11.6043   // c2 - dtor
dtor: |7.9+j8.5| = 11.6043   // c1 - dtor
```

- Copy assignment operator should *return the object to make chain assignments possible*

Program 14.16: String: Copy Assignment


```
#include <iostream>
#include <cstring>
#include <cstdlib>
using namespace std;
class String { public: char *str_; size_t len_;
    String(char *s) : str_(strdup(s)), len_(strlen(str_)) { }         // Ctor
    String(const String& s) : str_(strdup(s.str_)), len_(s.len_) { } // CCtor
    ~String() { free(str_); }                                        // Dtor
    String& operator=(const String& s) {                             // Copy Assignment Operator
        free(str_);            // Release existing memory
        str_ = strdup(s.str_); // Perform deep copy
        len_ = s.len_;         // Copy data member of built-in type
        return *this;          // Return object for chain assignment
    }
    void print() { cout << "(" << str_ << ": " << len_ << ")" << endl; }
};
int main() { String s1 = "Football", s2 = "Cricket"; s1.print(); s2.print(); s2 = s1; s2.print(); }
---
(Football: 8)
(Cricket: 7)
(Football: 8)
```

- In copy assignment operator, `str_ = s.str_` should not be done for two reasons:
  1) Resource held by `str_` will *leak*
  2) *Shallow copy* will result with its related issues
- What happens if a self-copy `s1 = s1` is done?

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Program 14.17: String: Self Copy

```
#include <iostream>
#include <cstring>
#include <cstdlib>
using namespace std;
class String { public: char *str_; size_t len_;
    String(char *s) : str_(strdup(s)), len_(strlen(str_)) { }        // Ctor
    String(const String& s) : str_(strdup(s.str_)), len_(s.len_) { } // CCtor
    ~String() { free(str_); }                                        // Dtor
    String& operator=(const String& s) {                             // Copy Assignment Operator
        free(str_);            // Release existing memory
        str_ = strdup(s.str_); // Perform deep copy
        len_ = s.len_;         // Copy data member of built-in type
        return *this;          // Return object for chain assignment
    }
    void print() { cout << "(" << str_ << ": " << len_ << ")" << endl; }
};
int main() { String s1 = "Football", s2 = "Cricket"; s1.print(); s2.print(); s1 = s1; s1.print(); }
---
(Football: 8)
(Cricket: 7)
(????????: 8) // Garbage is printed. May crash too
```

- For self-copy

- Hence, `free(str_)` first releases the memory, and then `strdup(s.str_)` tries to copy from released memory
- **This may crash or produce garbage values**
- **Self-copy must be detected and guarded**

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Program 14.18: String: Self Copy: Safe


```
#include <iostream>
#include <cstring>
#include <cstdlib>
using namespace std;
class String { public: char *str_; size_t len_;
    String(char *s) : str_(strdup(s)), len_(strlen(str_)) { }        // Ctor
    String(const String& s) : str_(strdup(s.str_)), len_(s.len_) { } // CCtor
    ~String() { free(str_); }                                         // Dtor
    String& operator=(const String& s) {                              // Copy Assignment Operator
        if (this != &s) { // Check if the source and destination are same
            free(str_);
            str_ = strdup(s.str_);
            len_ = s.len_;
        }
        return *this;
    }
    void print() { cout << "(" << str_ << ": " << len_ << ")" << endl; }
};
int main() { String s1 = "Football", s2 = "Cricket"; s1.print(); s2.print(); s1 = s1; s1.print(); }
---
(Football: 8)
(Cricket: 7)
(Football: 8)
```

- Check for se

- In case of self-copy, do nothing

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Signature and Body of Copy Assignment Operator

- For class `MyClass`, typical copy assignment operator will be:

```
MyClass& operator=(const MyClass& s) {
    if (this != &s) { // Check if the source and destination are same
                      // Release resources held by *this
                      // Copy members of s to members of *this
    }
    return *this;     // Return object for chain assignment
}
```

- Signature of a *Copy Assignment Operator* can be one of:

```
MyClass& operator=(const MyClass& rhs); // Common. No change in Source
MyClass& operator=(MyClass& rhs);       // Occasional. Change in Source
```

- The following *Copy Assignment Operator*s are occasionally used:

```
MyClass& operator=(MyClass rhs);
const MyClass& operator=(const MyClass& rhs);
const MyClass& operator=(MyClass& rhs);
const MyClass& operator=(MyClass rhs);
MyClass operator=(const MyClass& rhs);
MyClass operator=(MyClass& rhs);
MyClass operator=(MyClass rhs);
```

Free Assignment Operator

- If no copy assignment operator is provided / overloaded by the user, the compiler supplies a *free* one
- *Free* copy assignment operator cannot copy the object with proper values. It performs *Shallow Copy*
- In every class, provide copy assignment operator to adopt to deep copy which is always safe

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Comparison of Copy Constructor and Copy Assignment Operator

Comparison of Copy Constructor and Copy Assignment Operator

Copy Constructor	Copy Assignment Operator
• An overloaded constructor	• An operator overloading
• Initializes a new object with an existing object	• Assigns the value of one existing object to another existing object
• Used when a new object is created with some existing object	• Used when we want to assign existing object to another object
• Needed to support call-by-value and return-by-value	
• Newly created object use new memory location	• Memory location of destination object is reused with pointer variables being released and reallocated
	• Care is needed for self-copy
• If not defined in the class, the compiler provides one with bitwise copy	• If not overloaded, the compiler provides one with bitwise copy

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Class as a Data-type

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Class as a Data-type

Class as a Data-type

- We add the copy construction and assignment to a class being a composite data type in C++

`// declare i to be of int type` `int i;`	`// declare c to be of Complex type` `Complex c;`

`// initialise i`
`int i = 5;`
`int j = i;`
`int k(j);`
	`// initialise the real and imaginary components of c`
	`Complex c = (4, 5); // Ctor`
	`Complex c1 = c;     // CCtor`
	`Complex c2(c1);     // CCtor`

`// print i`
`cout << i;`
	`// print the real and imaginary components of c`
	`cout << c.re << c.im;`
	`OR c.print(); // Method Complex::print() defined for printing`
	`OR cout << c; // operator<<() overloaded for printing`

`// add two ints`
`int i = 5, j = 6;`
`i+j;`
	`// add two Complex objects`
	`Complex c1 = (4, 5), c2 = (4, 6);`
	`c1.add(c2); // Method Complex::add() defined to add`
	`OR c1+c2; // operator+() overloaded to add`

`// copy value of i to j`
`int i = 5, j;`
`j = i;`
	`// copy value of one Complex object to another`
	`Complex c1 = (4, 5), c2 = (4, 6);`
	`c2 = c1; // c2.re <- c1.re and c2.im <- c1.im by copy assignment`

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Module Summary

- **Copy Constructors**
  - A new object is created
  - The new object is initialized with the value of data members of another object
- **Copy Assignment Operator**
  - An object is already existing (and initialized)
  - The members of the existing object are replaced by values of data members of another object
  - Care is needed for self-copy
- **Deep and Shallow Copy for Pointer Members**
  - Deep copy allocates new space for the contents and copies the pointed data
  - Shallow copy merely copies the pointer value – hence, the new copy and the original pointer continue to point to the same data

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