Copy Constructor, Destructor and Assignment Operator

In this Week

- Default Copy Constructor
- Overloaded Copy Constructor
- Deep Copy Vs Shallow Copy
- Destructor
- Default Assignment Operator
- Overloaded Assignment Operator

Default Copy Constructor

- Consider the **RationalNumber** class we have developed previously
- Now, observe the following C++ statements and determine its output:

```
RationalNumber r1(5, 8);      //Non default constructor
RationalNumber r2(r1);        //Construct r2 from a copy of r1
cout << "Originally, r1 = " << r1 << " and r2 = " << r2 << endl;
r2.setNumerator(1);           //Modify r2
cout << "Now, r1 = " << r1 << " and r2 = " << r2 << endl;
```

- Now, consider the second statement closely **RationalNumber r2(r1);**
- First of all, we ask the question: Is this a valid statement? Answer **YES!**

Default Copy Constructor

- The statement **RationalNumber r2(r1);** is valid because what is happening is that the new **RationalNumber** object **r2 is being constructed from a copy of r1**
- But we haven't provided a member function for copying an object!
- Indeed! But C++ provides a **default copy constructor**
- So what does the default copy constructor do?
- **The default copy constructor simply copies the VALUES of all the member variables of r1 to the corresponding member variables of r2**

Default Copy Constructor

- We may use the copy constructor in two ways
  - One way is as we showed

    RationalNumber r2(r1);
  - Another way is

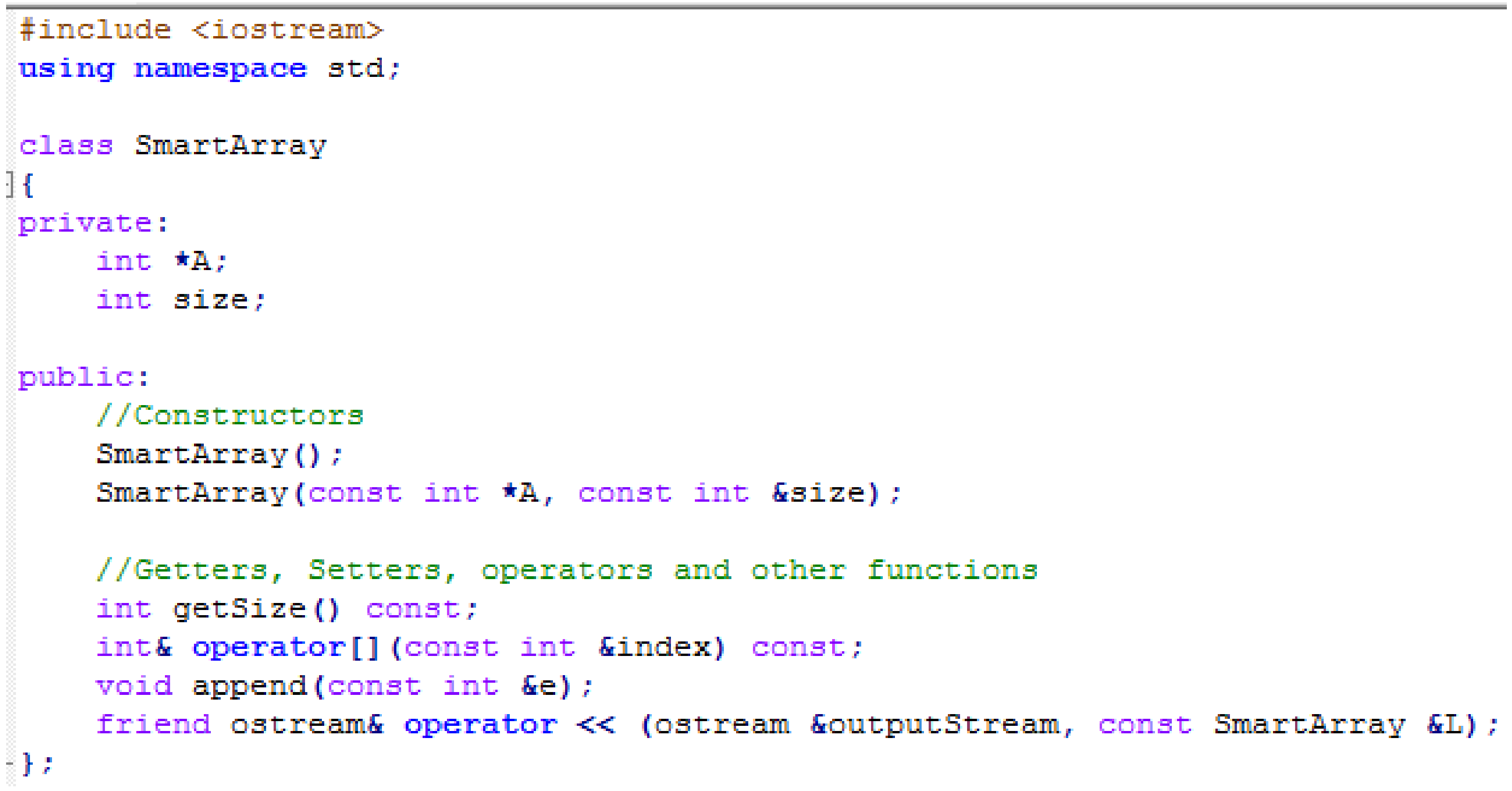
    RationalNumber r2 = r1;
- In both cases, r2 is being constructed from a copy of r1
- **Also we note that copy constructor is different from assignment operator: Copy constructor is invoked when a new object is constructed from a copy of an existing object**; but **an assignment operator is invoked when an existing object is assigned the value of another (or possibly the same) existing object**

Overloaded Copy Constructor

- Sometimes the default C++ copy constructor might not be enough to construct a new object from a copy of an existing object
- In such cases, we need to provide our own copy constructor member function in order to construct objects correctly
- When we provide our own copy constructor, we call it **overloaded copy constructor** because it will overload the default C++ copy constructor
- In order to appreciate why we need our own overloaded copy constructor, let us define a new class that has a dynamically allocated memory member variable and see what the default copy constructor will do in that case
- For demonstration purposes, let us design a class named **SmartArray** to represent arrays
- Our **SmartArray** class will represent dynamic arrays but also with more features as we will soon explore
- **A SmartArray class has two member variables: A dynamic array and the size of the array**

Overloaded Copy Constructor

- The declaration of the **SmartArray** class is therefore:



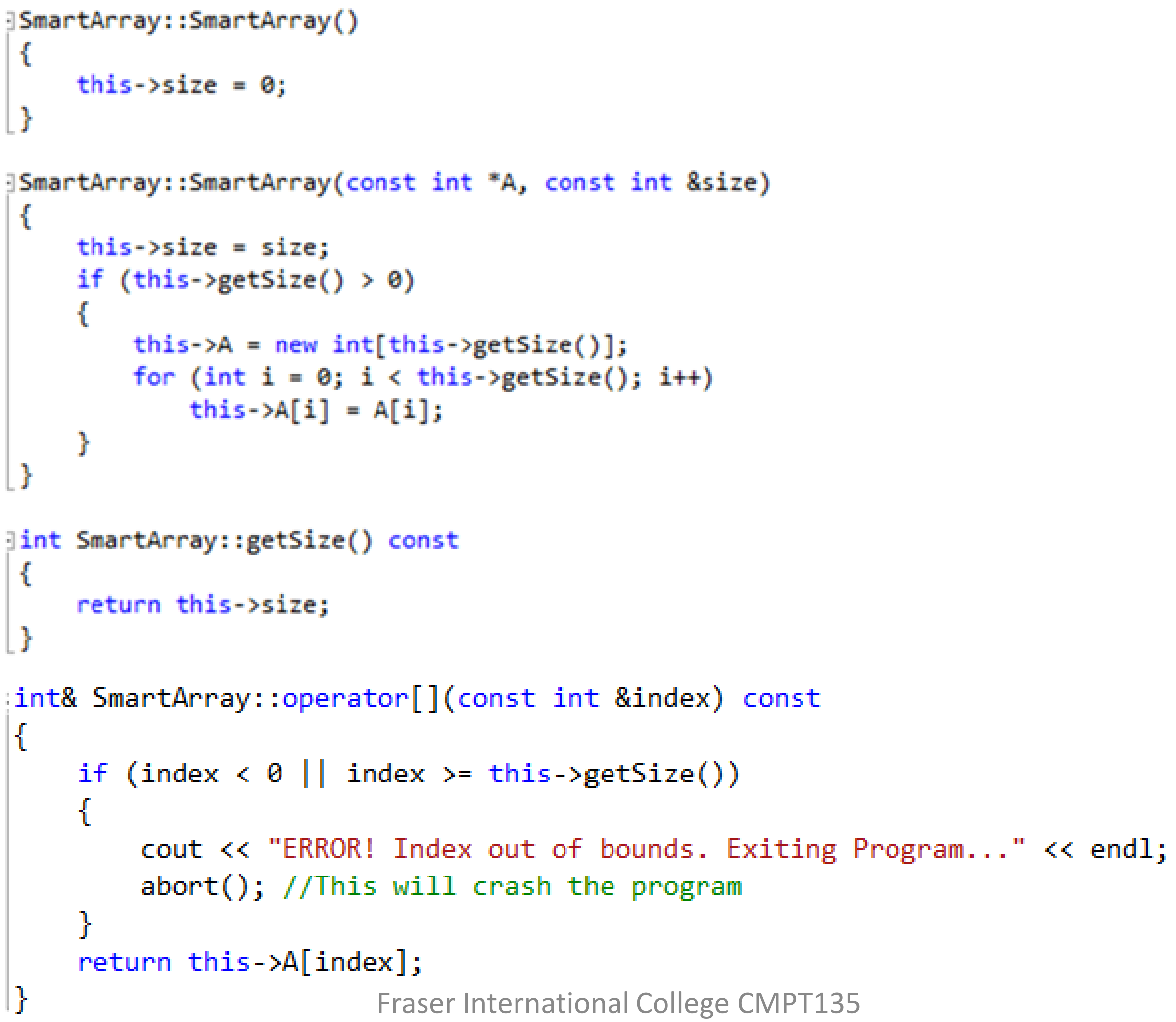
```
#include <iostream>
using namespace std;

class SmartArray
{
private:
    int *A;
    int size;

public:
    //Constructors
    SmartArray();
    SmartArray(const int *A, const int &size);

    //Getters, Setters, operators and other functions
    int getSize() const;
    int& operator[](const int &index) const;
    void append(const int &e);
    friend ostream& operator << (ostream &outputStream, const SmartArray &L);
};
```

Overloaded Copy Constructor

- Let us first discuss the indexing operator [ ] overloading given by
  int& operator [ ] (const int &index) const;
- The indexing operator works with arrays as in A[k]
- Given an array A, element at index k is given by the indexing operator A[k]
- **In C++ indexing operator is interpreted as a binary operator** whose left hand side operand is the array and right hand side operand is the index
- Therefore the way we look at this operator is as follows
  A[k] is interpreted as **A [ ] k**
- When overloading this operator for our **SmartArray** class, the calling object (left hand side operand) will be a **SmartArray** object and the index will be an argument to the operator function (right hand side operand)
- Also remember that not only can we access element of an array A as A[k] but also we can assign the element a new value as A[k] = value
- This means this operator should return **not the literal R-value of the element at a given index**; but rather the memory location; which is why we are returning by reference. **Huh… but also it is a const function! How?**

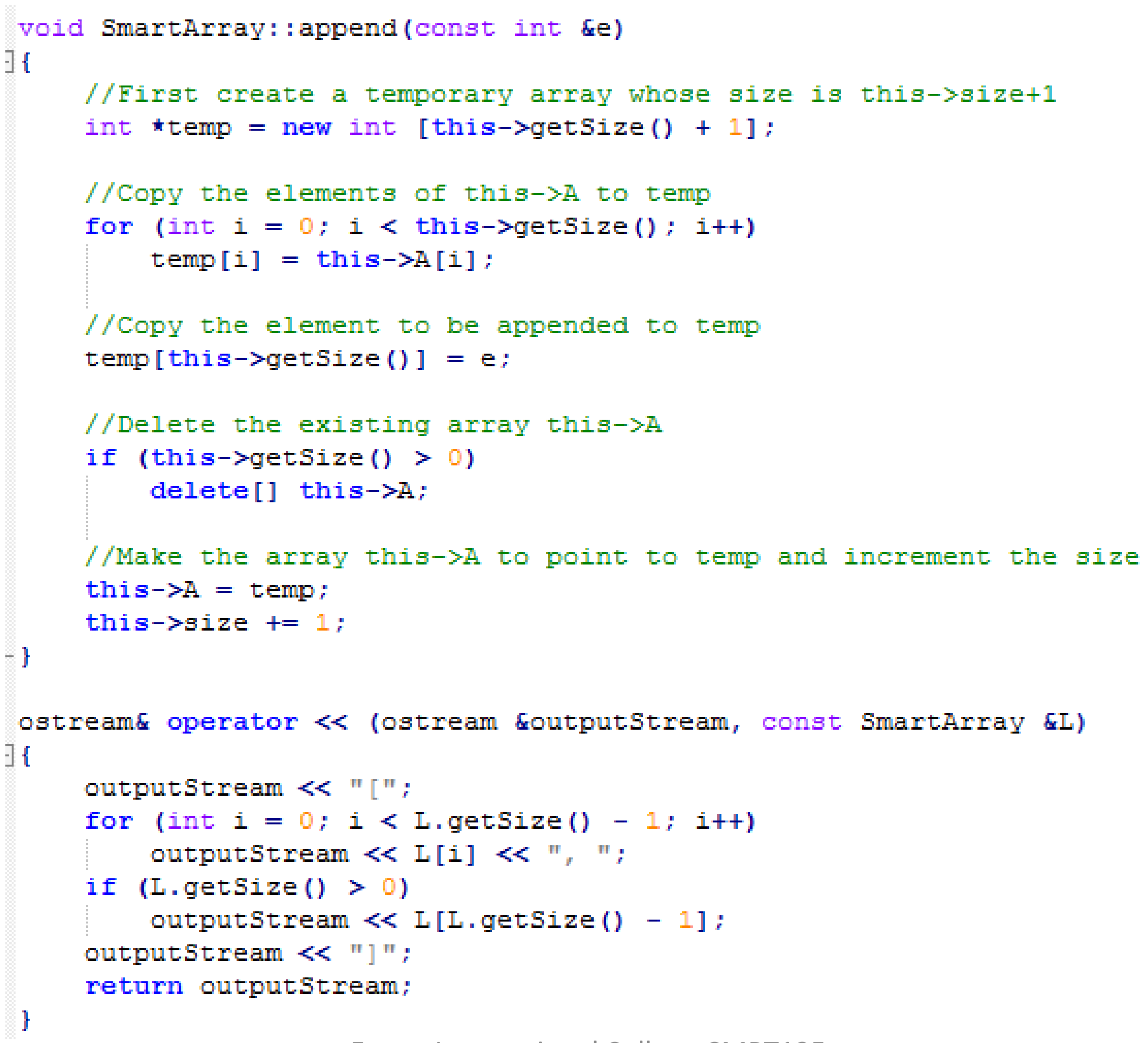
Overloaded Copy Constructor

- The implementation of the member functions will therefore be as follows:



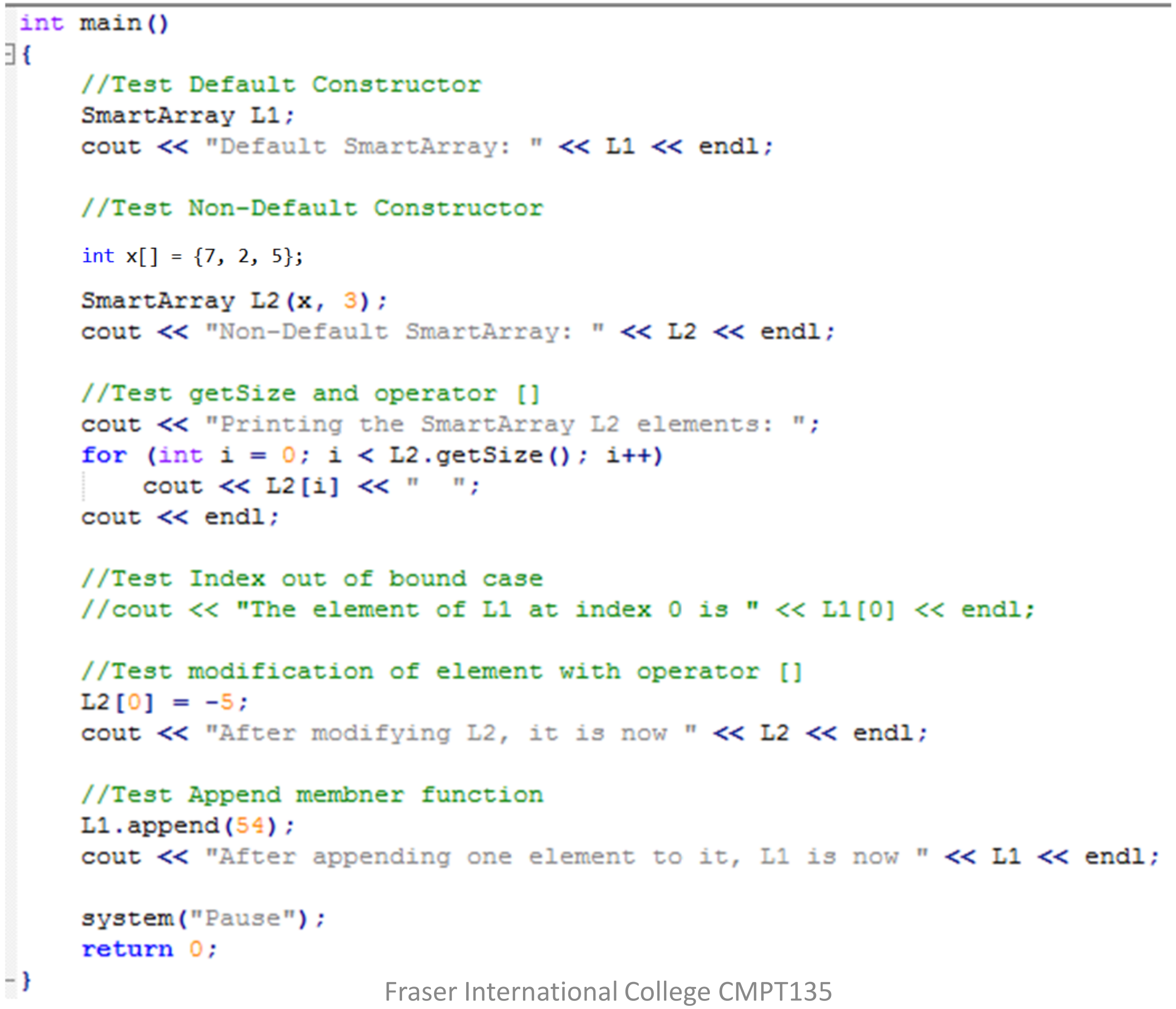
```
SmartArray::SmartArray()
{
    this->size = 0;
}

SmartArray::SmartArray(const int *A, const int &size)
{
    this->size = size;
    if (this->getSize() > 0)
    {
        this->A = new int[this->getSize()];
        for (int i = 0; i < this->getSize(); i++)
            this->A[i] = A[i];
    }
}

int SmartArray::getSize() const
{
    return this->size;
}

int& SmartArray::operator[](const int &index) const
{
    if (index < 0 || index >= this->getSize())
    {
        cout << "ERROR! Index out of bounds. Exiting Program..." << endl;
        abort(); //This will crash the program
    }
    return this->A[index];
}
```

Overloaded Copy Constructor



```cpp
void SmartArray::append(const int &e)
{
    //First create a temporary array whose size is this->size+1
    int *temp = new int [this->getSize() + 1];

    //Copy the elements of this->A to temp
    for (int i = 0; i < this->getSize(); i++)
        temp[i] = this->A[i];

    //Copy the element to be appended to temp
    temp[this->getSize()] = e;

    //Delete the existing array this->A
    if (this->getSize() > 0)
        delete[] this->A;

    //Make the array this->A to point to temp and increment the size
    this->A = temp;
    this->size += 1;
}

ostream& operator << (ostream &outputStream, const SmartArray &L)
{
    outputStream << "[";
    for (int i = 0; i < L.getSize() - 1; i++)
        outputStream << L[i] << ", ";
    if (L.getSize() > 0)
        outputStream << L[L.getSize() - 1];
    outputStream << "]";
    return outputStream;
}
```

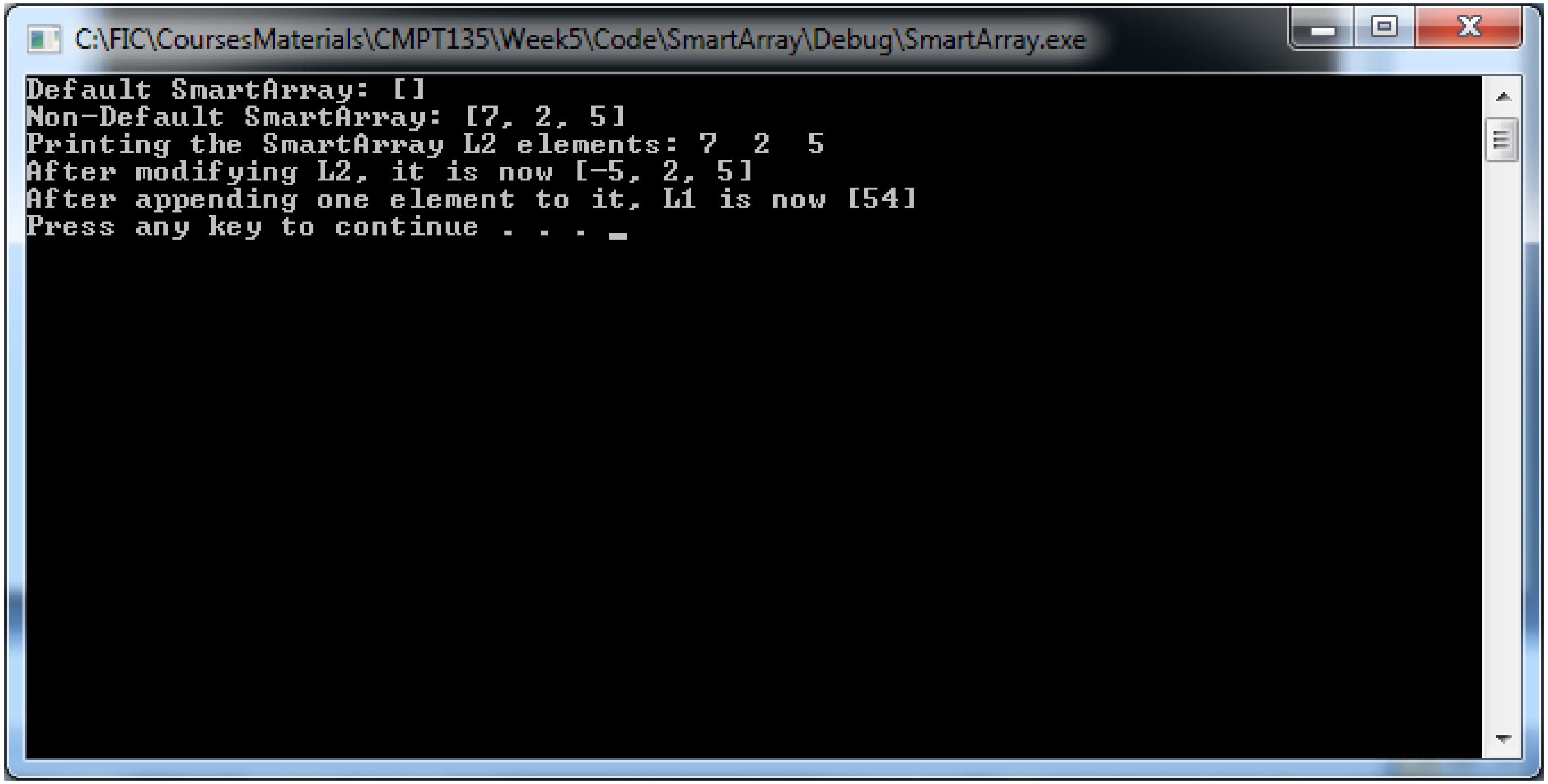
Overloaded Copy Constructor



```
int main()
{
    //Test Default Constructor
    SmartArray L1;
    cout << "Default SmartArray: " << L1 << endl;

    //Test Non-Default Constructor

    int x[] = {7, 2, 5};

    SmartArray L2(x, 3);
    cout << "Non-Default SmartArray: " << L2 << endl;

    //Test getSize and operator []
    cout << "Printing the SmartArray L2 elements: ";
    for (int i = 0; i < L2.getSize(); i++)
        cout << L2[i] << "  ";
    cout << endl;

    //Test Index out of bound case
    //cout << "The element of L1 at index 0 is " << L1[0] << endl;

    //Test modification of element with operator []
    L2[0] = -5;
    cout << "After modifying L2, it is now " << L2 << endl;

    //Test Append membner function
    L1.append(54);
    cout << "After appending one element to it, L1 is now " << L1 << endl;

    system("Pause");
    return 0;
}
```

Overloaded Copy Constructor

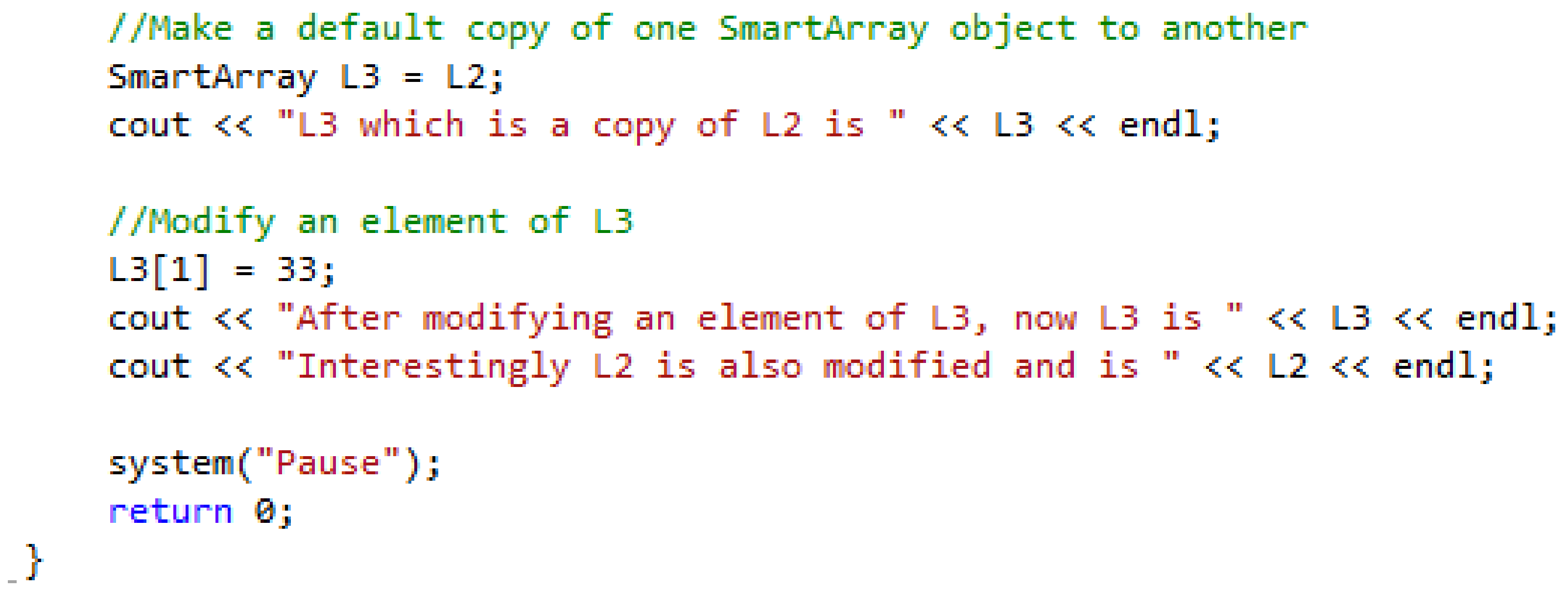
- The output of this main program will then be


C:\FIC\CoursesMaterials\CMPT135\Week5\Code\SmartArray\Debug\SmartArray.exe

```
Default SmartArray: []
Non-Default SmartArray: [7, 2, 5]
Printing the SmartArray L2 elements: 7  2  5
After modifying L2, it is now [-5, 2, 5]
After appending one element to it, L1 is now [54]
Press any key to continue . . .
```

Overloaded Copy Constructor

- Now, let us use the default copy constructor in order to copy one **SmartArray** object to another and see what happens

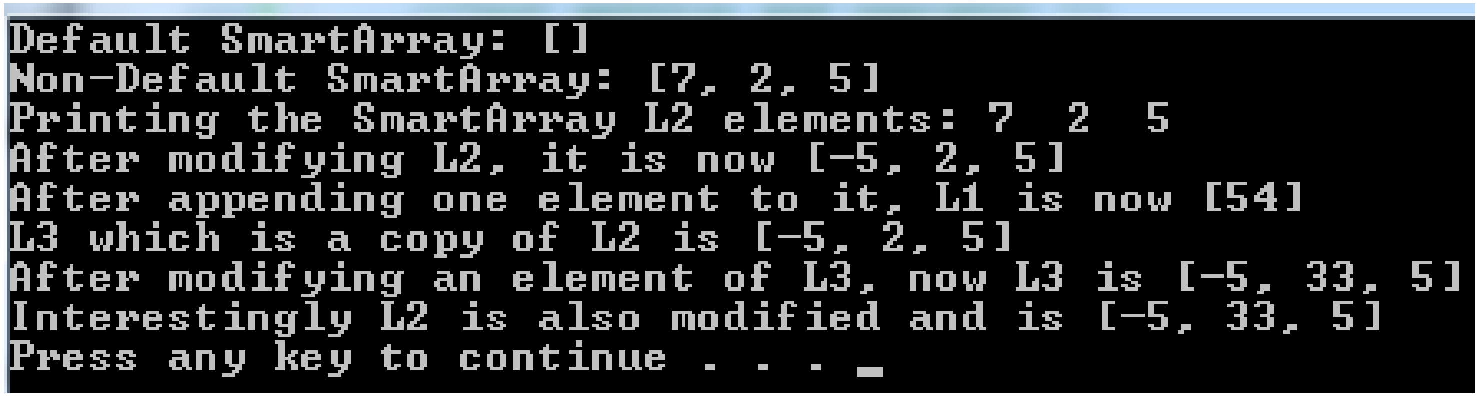


```
    //Make a default copy of one SmartArray object to another
    SmartArray L3 = L2;
    cout << "L3 which is a copy of L2 is " << L3 << endl;

    //Modify an element of L3
    L3[1] = 33;
    cout << "After modifying an element of L3, now L3 is " << L3 << endl;
    cout << "Interestingly L2 is also modified and is " << L2 << endl;

    system("Pause");
    return 0;
}
```

- **What is the output of this code?**

Overloaded Copy Constructor

- Surprisingly, or not surprisingly, the output will be as follows



```
Default SmartArray: []
Non-Default SmartArray: [7, 2, 5]
Printing the SmartArray L2 elements: 7  2  5
After modifying L2, it is now [-5, 2, 5]
After appending one element to it, L1 is now [54]
L3 which is a copy of L2 is [-5, 2, 5]
After modifying an element of L3, now L3 is [-5, 33, 5]
Interestingly L2 is also modified and is [-5, 33, 5]
Press any key to continue . . .
```

- Why? Because the default copy constructor copied the values of the member variables of L2 into the member variables of L3
- This means the value of the size of L2 was copied to the size of L3 and the value of the pointer variable A of L2 (which is a memory address) was copied to the pointer variable of L3.
- Therefore both L2 and L3 will point to the same consecutive memory on the heap and modifying element of L3 will also modify L2; and vice versa!!!

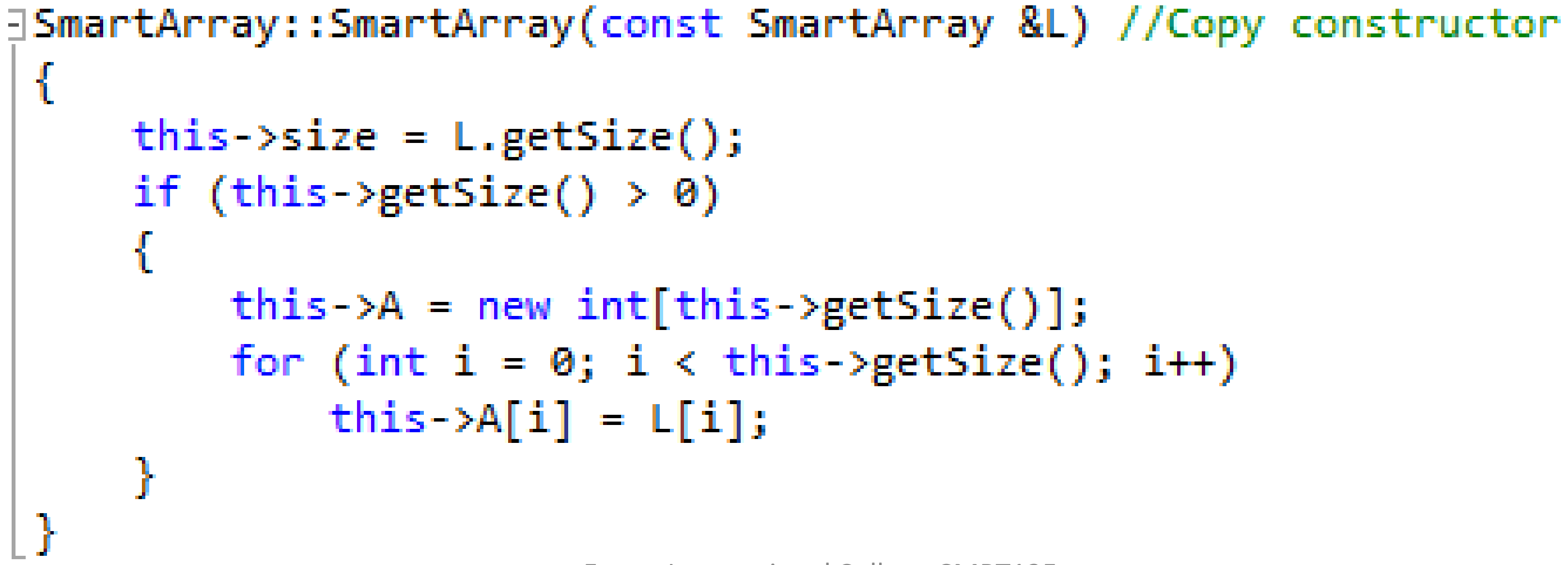
Overloaded Copy Constructor

- We conclude that the **default C++ copy constructor** does **Shallow Copy**
- That is, it does not know much about our class and therefore copies only at a high level
- It does not go deep to copy allocated memory
- This is very **dangerous**. For example, if we delete the allocated memory of L2, then automatically the memory of L3 is also deleted. Accessing L3 then will crash the program
- For this reason, it is important **we provide our own copy constructor that copies not the pointer value but rather creates a new dynamic memory and copies the elements**

Overloaded Copy Constructor

- The overloaded copy constructor of our own will look like
- **Declaration**

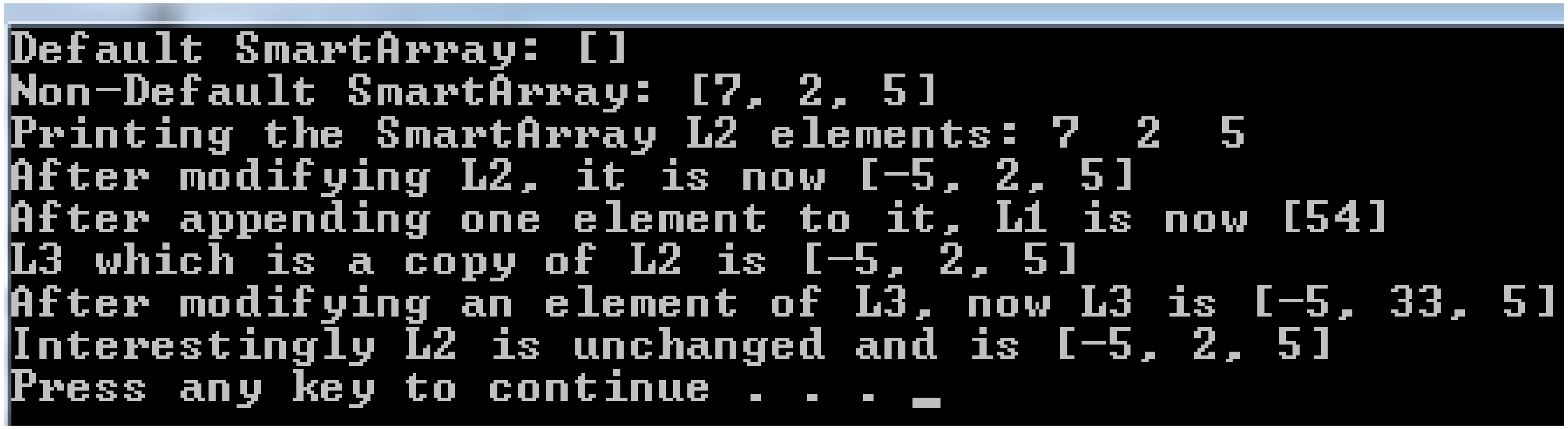
  SmartArray(const SmartArray &L);
- **Definition**



```
SmartArray::SmartArray(const SmartArray &L) //Copy constructor
{
    this->size = L.getSize();
    if (this->getSize() > 0)
    {
        this->A = new int[this->getSize()];
        for (int i = 0; i < this->getSize(); i++)
            this->A[i] = L[i];
    }
}
```

Overloaded Copy Constructor

- Now, we provide the same main program and its output to see the impact of our copy constructor
- We say, our own copy constructor does a DEEP copy and avoids the entanglement of L2 and L3



```
Default SmartArray: []
Non-Default SmartArray: [7, 2, 5]
Printing the SmartArray L2 elements: 7  2  5
After modifying L2, it is now [-5, 2, 5]
After appending one element to it, L1 is now [54]
L3 which is a copy of L2 is [-5, 2, 5]
After modifying an element of L3, now L3 is [-5, 33, 5]
Interestingly L2 is unchanged and is [-5, 2, 5]
Press any key to continue . . . _
```

Destructor Member Function

- Recall that whenever we create a dynamic array, we need to delete it in order to free the memory we had allocated
- This means, in the previous example, when the program terminates the memories allocated to L1, L2 and L3 are still not freed
- **Question**: How do we free dynamically allocated memory inside objects?
- **Proposal:** Can we delete the allocated memories of L1, L2 and L3 from within the main program? **No!** Because the pointer member variable of the SmartArray class is a private member variable and thus can not be accessed from outside the class
- **Answer**: We use a special member function called **destructor**!

Destructor Member Function

- The destructor member function looks like:
- **Destructor: Declaration**

```
~SmartArray();
```

- **Destructor: Definition**

```
 SmartArray ::~ SmartArray()
{
        if (this->getSize() > 0)
        {
                delete[] this->A;
                this->size= 0;
        }
}
```

- **Remark: Check if memory was allocated before deleting**

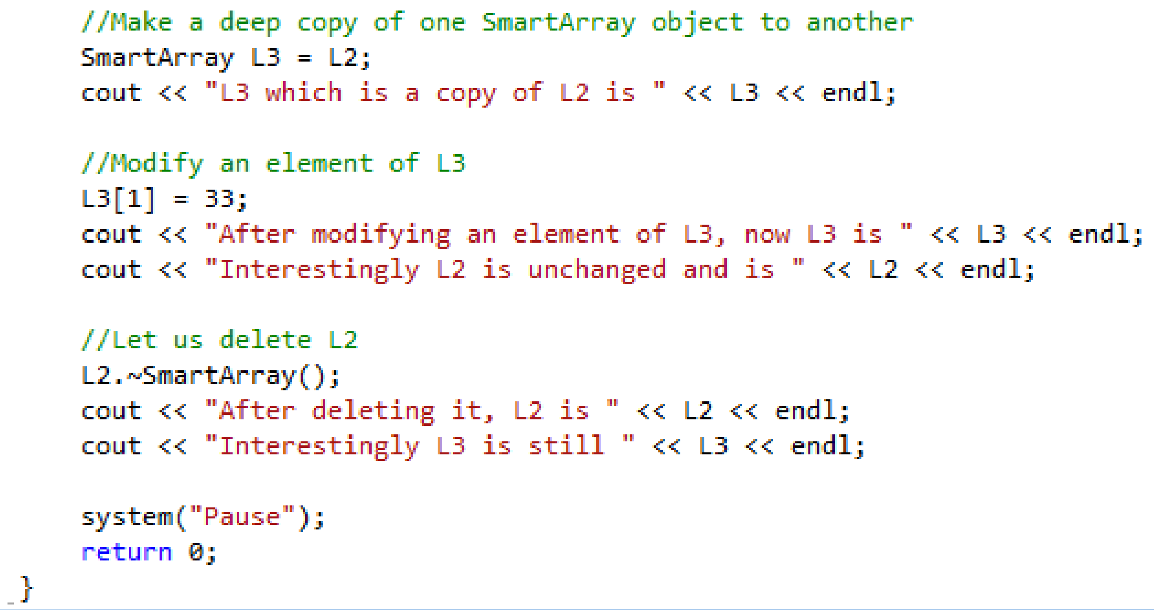
Destructor Member Function

- The destructor is important because it is automatically called every time an object goes out of scope and therefore its memory automatically deleted
- While objects with destructor member function will automatically be deleted when they go out of scope, sometimes we may need to delete objects before they go out of scope
- For example, in order to delete object L1, we proceed as follows:

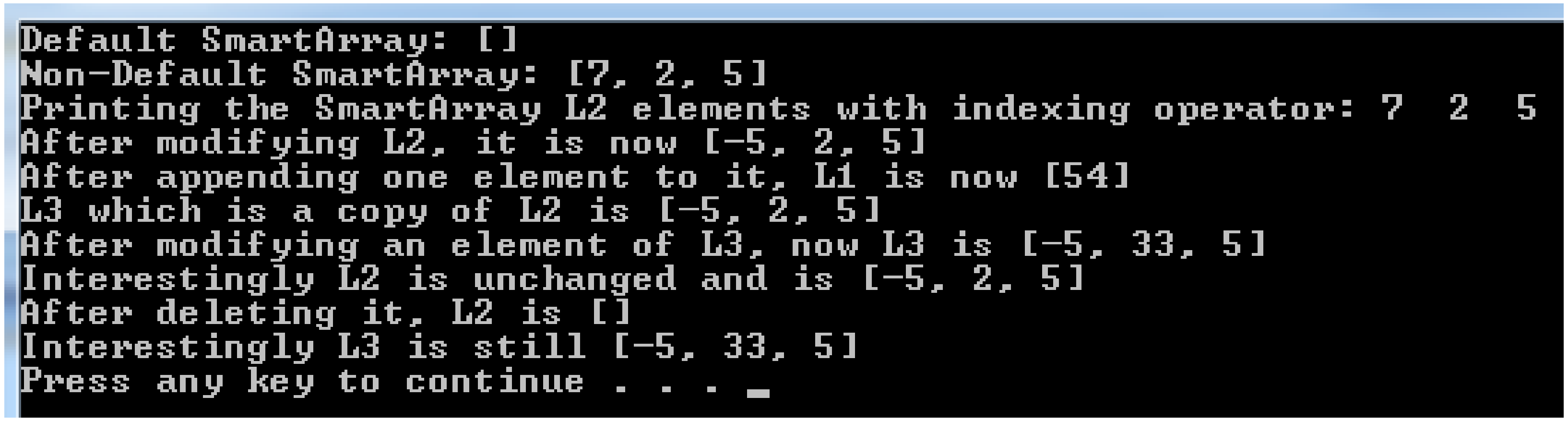
```
L1.~SmartArray();
```

- The main program demonstrating this follows…

Deleting Objects



```
    //Make a deep copy of one SmartArray object to another
    SmartArray L3 = L2;
    cout << "L3 which is a copy of L2 is " << L3 << endl;

    //Modify an element of L3
    L3[1] = 33;
    cout << "After modifying an element of L3, now L3 is " << L3 << endl;
    cout << "Interestingly L2 is unchanged and is " << L2 << endl;

    //Let us delete L2
    L2.~SmartArray();
    cout << "After deleting it, L2 is " << L2 << endl;
    cout << "Interestingly L3 is still " << L3 << endl;

    system("Pause");
    return 0;
}
```



```
Default SmartArray: []
Non-Default SmartArray: [7, 2, 5]
Printing the SmartArray L2 elements with indexing operator: 7  2  5
After modifying L2, it is now [-5, 2, 5]
After appending one element to it, L1 is now [54]
L3 which is a copy of L2 is [-5, 2, 5]
After modifying an element of L3, now L3 is [-5, 33, 5]
Interestingly L2 is unchanged and is [-5, 2, 5]
After deleting it, L2 is []
Interestingly L3 is still [-5, 33, 5]
Press any key to continue . . .
```

Deleting Objects

- In order to appreciate the overloaded copy constructor, now do the following and explain what happened:
  - Comment out your copy constructor declaration
  - Comment out your copy constructor definition
  - Run the same main program you have in the previous page
  - Not only will your program print garbage data for L3 but also your program will **crash after the program ends!!!** Explain why!
- Afterwards uncomment the copy constructor so that to have a correct class to work with in the following sections

The Default Assignment Operator

- Now, consider the statements

```
SmartArray L4;    //Default constructor
L4 = L3;  //This is NOT copy constructor!
```

- What does the last statement **L4 = L3;** do?
- It does **NOT** call copy constructor! Because copy constructor is called only when object is **constructed by copying from another**; that is **copy constructor is called only when there is declaration of a new object and initialized** to another object as in like

```
SmartArray L3 = L2;       //Copy Constructor
```

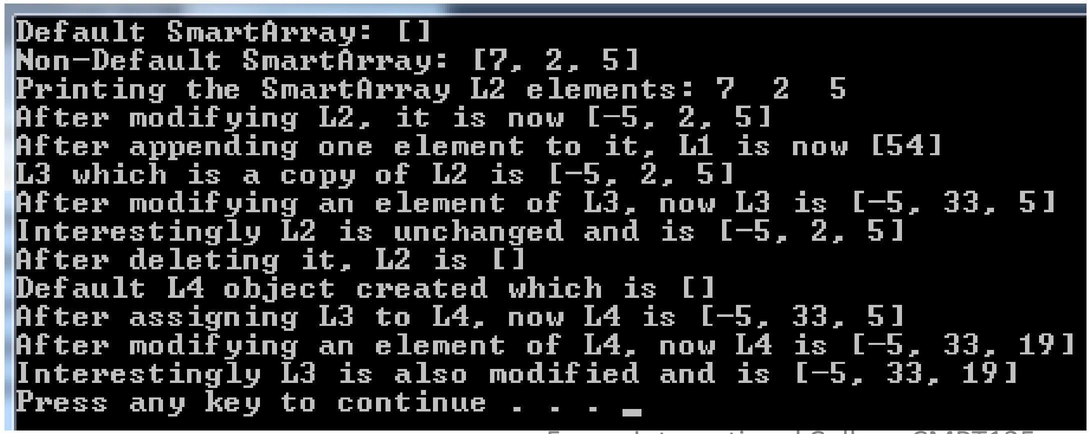
The Default Assignment Operator

- So what does the statement **L4 = L3;** do?
- **Answer**: It calls the **DEFAULT C++ ASSIGNMENT OPERATOR** to assign L3 to L4
- The default assignment operator copies the **VALUES** of all member variables of L3 onto L4
- This means pointers will be copied but not their allocated memory

The Default Assignment Operator

- Consider the following program and analyze its output

```
        //Make a default assignment of one SmartArray object to another
        SmartArray L4;
        cout << "Default L4 object created which is " << L4 << endl;
        L4 = L3;
        cout << "After assigning L3 to L4, now L4 is " << L4 << endl;

        //Modify an element of L4
        L4[2] = 19;
        cout << "After modifying an element of L4, now L4 is " << L4 << endl;
        cout << "Interestingly L3 is also modified and is " << L3 << endl;

        system("Pause");
        return 0;
}
```



```
Default SmartArray: []
Non-Default SmartArray: [7, 2, 5]
Printing the SmartArray L2 elements: 7  2  5
After modifying L2, it is now [-5, 2, 5]
After appending one element to it, L1 is now [54]
L3 which is a copy of L2 is [-5, 2, 5]
After modifying an element of L3, now L3 is [-5, 33, 5]
Interestingly L2 is unchanged and is [-5, 2, 5]
After deleting it, L2 is []
Default L4 object created which is []
After assigning L3 to L4, now L4 is [-5, 33, 5]
After modifying an element of L4, now L4 is [-5, 33, 19]
Interestingly L3 is also modified and is [-5, 33, 19]
Press any key to continue . . .
```

This program will crash at the end!!!

The Default Assignment Operator

- Again, both L4 and L3 will have pointers pointing to the same allocated memory on the heap
- Therefore changing any element in L4 changes the element in L3 and vice versa
- But **worse still**, when L3 or L4 goes out of scope or is manually deleted, then its allocated memory to which both L3 and L4 point to will be deleted
- This means the remaining object will have its memory deleted too! **Dangerous!!!**

Overloaded Assignment Operator

- In order to avoid any memory entanglement during assignment operation, we therefore need to overload the default assignment operator whenever our class has a pointer member variable
- Also recall that chain assignment is allowed in C++ as follows:

```
int x, y, z;
z = x = y = 3;
```

- This assigns the value 3 to the variable y. Next it assigns the returned value of the assignment operation y = 3 to the variable x
- This means the assignment operator returns a value!
- So what does it return? It returns the assigned value (or object) by reference! **Why by reference? This is mainly for speed reasons**
- In the next section, we write our own assignment operator to overload the default C++ operator

Overloaded Assignment Operator

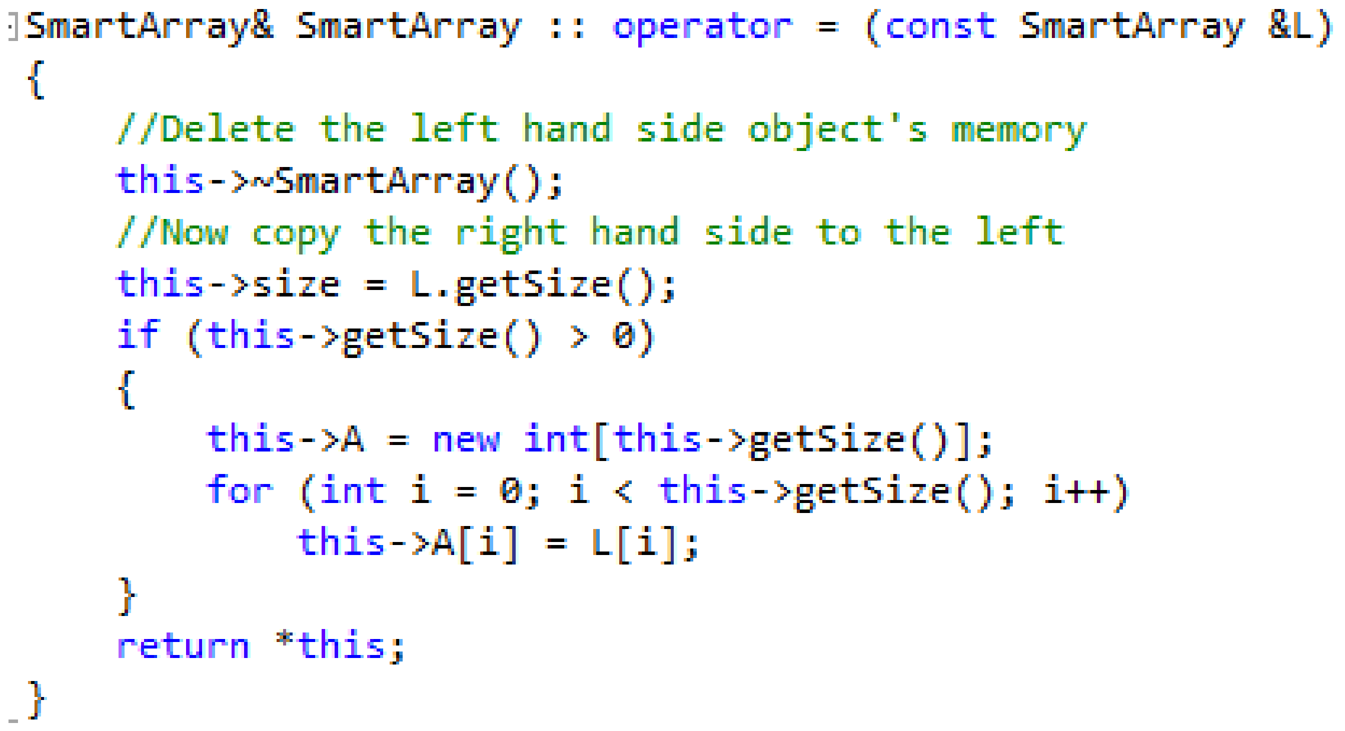
- The overloaded assignment operator will have the declaration given by

```
SmartArray& operator = (const SmartArray& L);
```

- The overloaded assignment operator is a binary operator and has a function name given by **operator =**
- The calling object of the operator is the left hand side operand of the assignment operator
- It takes one argument which is the right hand side operand of the assignment operator
- It returns a **reference** to the calling object

Overloaded Assignment Operator

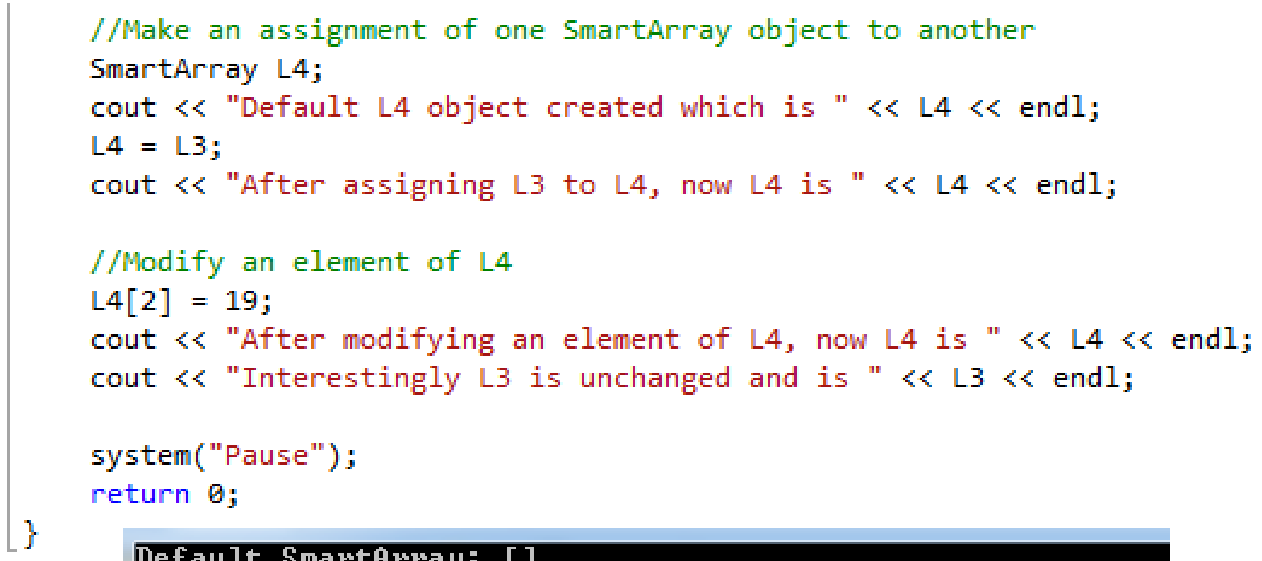
- The implementation of the operator member function will then look like:



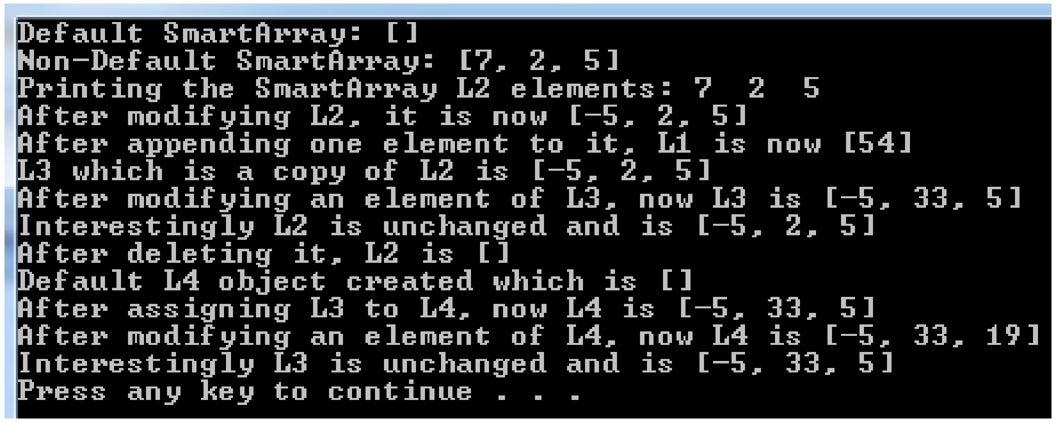
```
SmartArray& SmartArray :: operator = (const SmartArray &L)
{
    //Delete the left hand side object's memory
    this->~SmartArray();
    //Now copy the right hand side to the left
    this->size = L.getSize();
    if (this->getSize() > 0)
    {
        this->A = new int[this->getSize()];
        for (int i = 0; i < this->getSize(); i++)
            this->A[i] = L[i];
    }
    return *this;
}
```

Overloaded Assignment Operator

- Now, we can see the same main program and its output



```
    //Make an assignment of one SmartArray object to another
    SmartArray L4;
    cout << "Default L4 object created which is " << L4 << endl;
    L4 = L3;
    cout << "After assigning L3 to L4, now L4 is " << L4 << endl;

    //Modify an element of L4
    L4[2] = 19;
    cout << "After modifying an element of L4, now L4 is " << L4 << endl;
    cout << "Interestingly L3 is unchanged and is " << L3 << endl;

    system("Pause");
    return 0;
}
```



```
Default SmartArray: []
Non-Default SmartArray: [7, 2, 5]
Printing the SmartArray L2 elements: 7  2  5
After modifying L2, it is now [-5, 2, 5]
After appending one element to it, L1 is now [54]
L3 which is a copy of L2 is [-5, 2, 5]
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Default L4 object created which is []
After assigning L3 to L4, now L4 is [-5, 33, 5]
After modifying an element of L4, now L4 is [-5, 33, 19]
Interestingly L3 is unchanged and is [-5, 33, 5]
Press any key to continue . . .
```

Overloaded Assignment Operator

- This looks good so far. But it has a very fundamental problem
- Consider the following assignment operation

```
//Assign L4 to L4 and see what happens
L4 = L4;
cout << "After assigning L4 to L4, now L4 is " << L4 << endl;
```

- What will be the output of this code?
- You might think it will give the following output

  After assigning L4 to L4, now L4 is [-5, 33, 19]

- But it does **NOT** give such output. Rather it gives the following output

  After assigning L4 to L4, now L4 is [ ]

- **Why?**

Overloaded Assignment Operator

- Why does it give empty array?
- To see why, we need to look at our overloaded assignment operator
- Observe that the first statement in our overloaded assignment operator function is

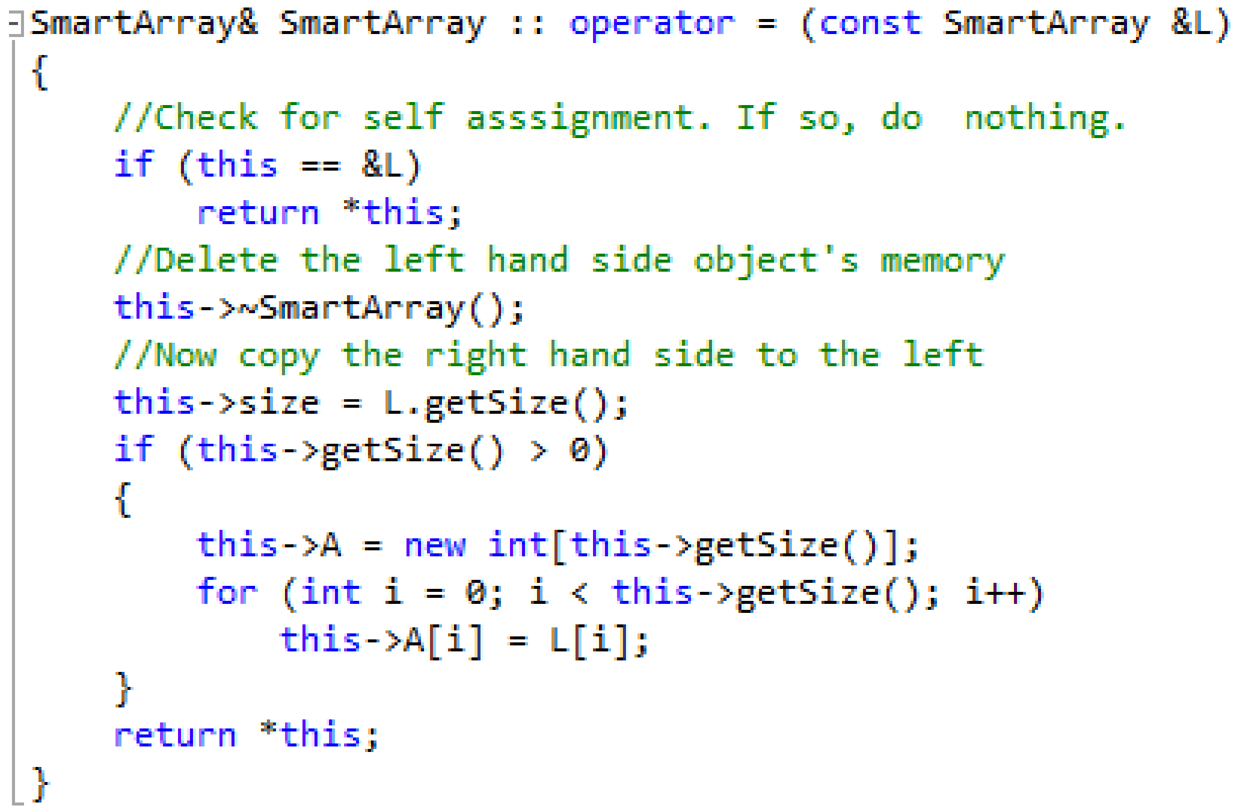
  this->~SmartArray();
- When the **same object is on both sides of the assignment operator**, this will delete the data and setting the size to zero.
- After that we will not create any new memory for the data because the size is zero. Neither will we execute the for loop block for the same reason
- This means the data pointer will completely lose the original data
- So practically we have deleted the elements and got empty array.

Overloaded Assignment Operator

- What should we do then to avoid this problem?
- **Answer:-** We must first check for self assignment; that is when an object is assigned to itself
- How do we do that?
- **We check if the memory address of the left hand side operand is the same as the memory address of the right hand side operand**
- Alternatively, we could compare if the values of the member variables (that is, the **size** and the **elements of the data array**) of the right hand side operand are equal to the values on the left side

Overloaded Assignment Operator

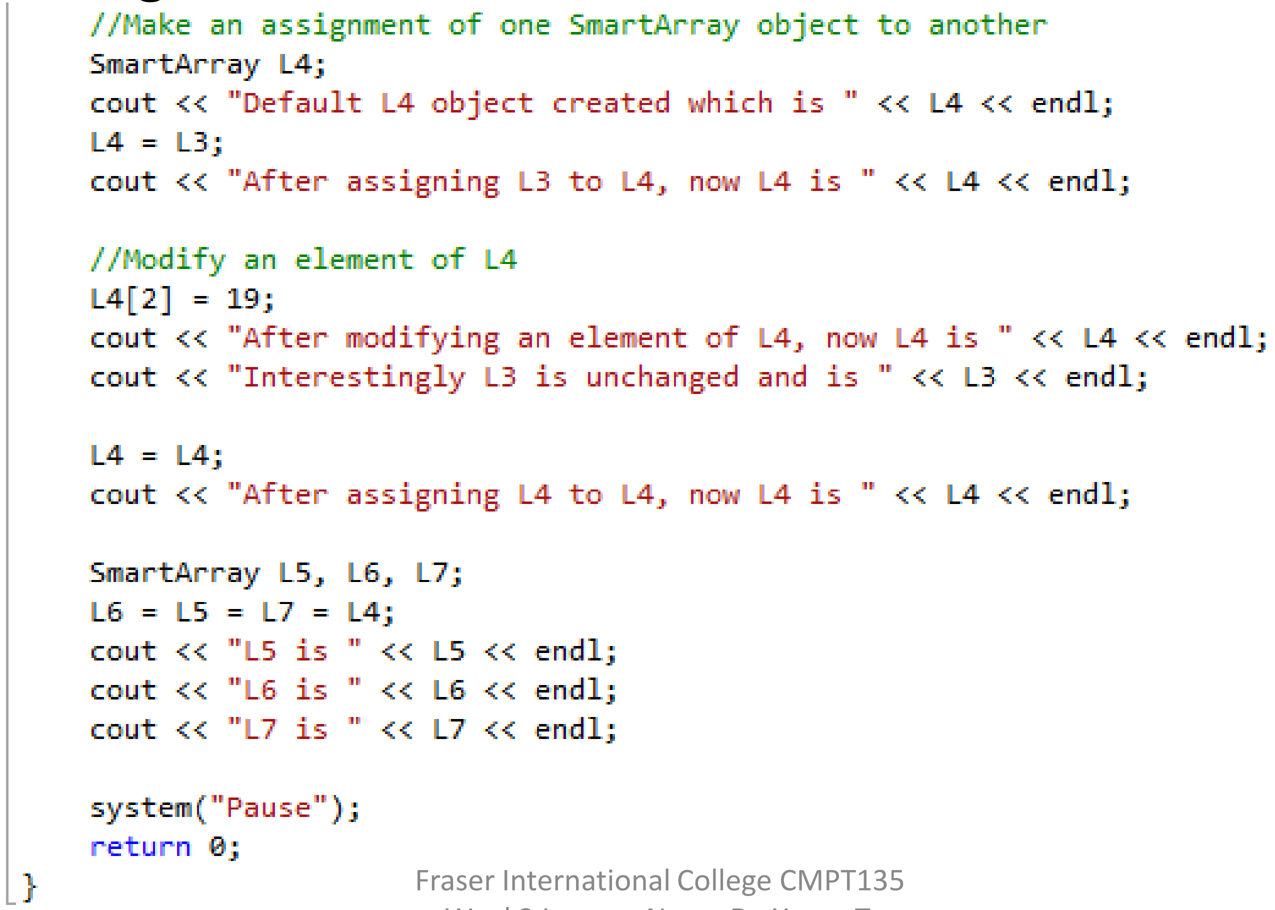
- Since the memory address check is more efficient, we will use that approach to do self assignment check as shown below



```
SmartArray& SmartArray :: operator = (const SmartArray &L)
{
    //Check for self asssignment. If so, do  nothing.
    if (this == &L)
        return *this;
    //Delete the left hand side object's memory
    this->~SmartArray();
    //Now copy the right hand side to the left
    this->size = L.getSize();
    if (this->getSize() > 0)
    {
        this->A = new int[this->getSize()];
        for (int i = 0; i < this->getSize(); i++)
            this->A[i] = L[i];
    }
    return *this;
}
```

Overloaded Assignment Operator

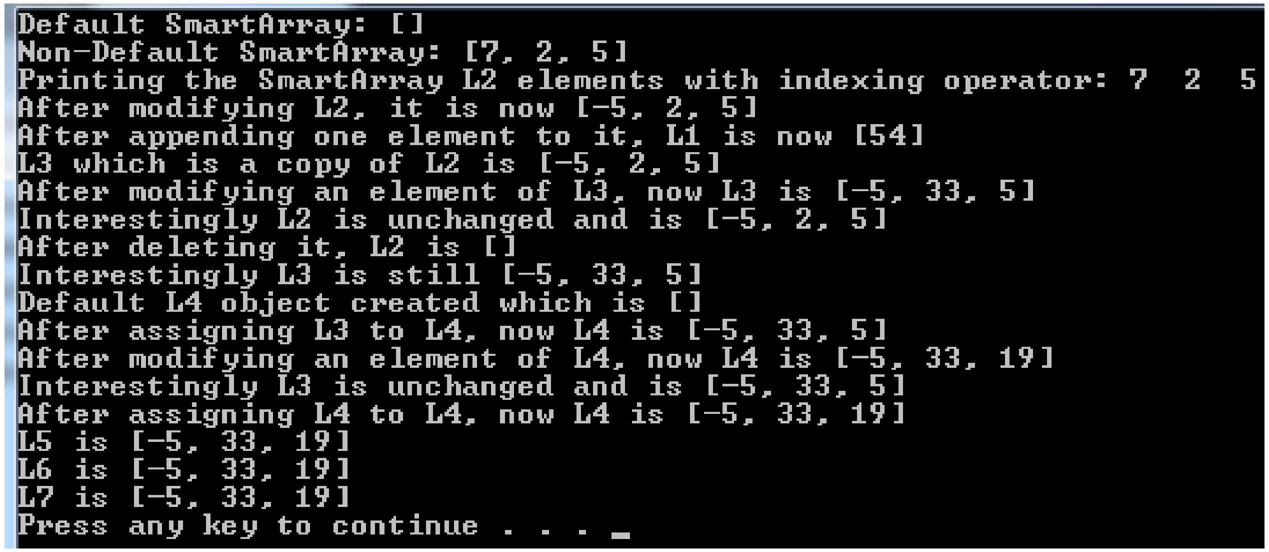
- The following program demonstrates self assignment and chain assignment



```cpp
    //Make an assignment of one SmartArray object to another
    SmartArray L4;
    cout << "Default L4 object created which is " << L4 << endl;
    L4 = L3;
    cout << "After assigning L3 to L4, now L4 is " << L4 << endl;

    //Modify an element of L4
    L4[2] = 19;
    cout << "After modifying an element of L4, now L4 is " << L4 << endl;
    cout << "Interestingly L3 is unchanged and is " << L3 << endl;

    L4 = L4;
    cout << "After assigning L4 to L4, now L4 is " << L4 << endl;

    SmartArray L5, L6, L7;
    L6 = L5 = L7 = L4;
    cout << "L5 is " << L5 << endl;
    cout << "L6 is " << L6 << endl;
    cout << "L7 is " << L7 << endl;

    system("Pause");
    return 0;
}
```

Overloaded Assignment Operator

- The output of the program will be



```
Default SmartArray: []
Non-Default SmartArray: [7, 2, 5]
Printing the SmartArray L2 elements with indexing operator: 7  2  5
After modifying L2, it is now [-5, 2, 5]
After appending one element to it, L1 is now [54]
L3 which is a copy of L2 is [-5, 2, 5]
After modifying an element of L3, now L3 is [-5, 33, 5]
Interestingly L2 is unchanged and is [-5, 2, 5]
After deleting it, L2 is []
Interestingly L3 is still [-5, 33, 5]
Default L4 object created which is []
After assigning L3 to L4, now L4 is [-5, 33, 5]
After modifying an element of L4, now L4 is [-5, 33, 19]
Interestingly L3 is unchanged and is [-5, 33, 5]
After assigning L4 to L4, now L4 is [-5, 33, 19]
L5 is [-5, 33, 19]
L6 is [-5, 33, 19]
L7 is [-5, 33, 19]
Press any key to continue . . . _
```

- **Note that we can NOT have a statement like**

  SmartArray L5 = L6 = L7 = L4;

  because the chain operation is possible only on existing objects. That is, our overloaded function that allows chain operations is assignment operator (but not copy constructor)

Concluding Remarks

- In C++, given a class (example the **SmartArray** class), the statement

```
        SmartArray L2 = L1;          //Assuming L1 was already constructed, OR
        SmartArray L2(L1);           //Assuming L1 was already constructed
```

  calls the **copy constructor**; while the statement

```
        L2 = L1;   //assuming L1 and L2 were already constructed
```

  calls the **assignment operator**
- In order to avoid shallow copy and perform a deep copy during copy constructor or assignment operator, we need to provide our own copy constructor and assignment operator member functions that overload the default C++ default copy constructor and assignment operator
- A class can have several constructors, but it has only one destructor
- Destructor is automatically invoked every time an object goes out of scope
- While it is good for overloaded assignment operator to return the calling object so that to allow chain assignment; it is not a MUST for the overloaded assignment operator to return anything. It can return by value, by reference or be void as well.

Working with Objects

- Having the copy constructor, assignment operator, and destructor member variables allow us to treat any object including container objects such as SmarterArray objects just like simple data type variables and work with them seamlessly
- For example, given two SmarterArray objects A1 and A2 already populated with some elements, we can swap these objects in exactly the same way we did with simple data types as follows:

```
SmarterArray temp = A1;
A1 = A2;
A2 = temp;
```

- How? This is possible because the copy constructor will perform a deep copy of A1 to temp, the assignment operator will perform a memory cleanup of A1 and then perform a deep copy of A2 to A1, and finally the assignment operator will perform a memory cleanup of A2 and then perform a deep copy of temp to A2
- In addition, we don't need to worry about memory spaces used by objects because they will be automatically freed when objects go out scope thanks to the destructor member function

Working with Objects

- We may also have pointers to container objects such as

  ```
  SmarterArray *p = new SmarterArray();
  ```

- This constructs a SmarterArray object on the heap memory that is pointed to by the pointer variable p
- The pointer variable **p** may invoke any member function of the SmarterArray class using `(*p).` or `p->`
- For example, we may print an element using `(*p)[index]` or `p->operator[](index)`
- The SmarterArray object on the heap memory needs to be deleted once it is not needed which is achieved by the same way we delete heap momories for any simple data types as shown below

  delete p;

- The delete operator here will first automatically invoke the destructor member function in order to free the heap memory used by the elements of the SmarterArray object and after that will delete the heap memory used by the object itself