CS11 Intro C++

Spring 2018 – Lecture 6

Copying Objects

- Last time, introduced a Complex class

```
class Complex {
    double re, im;
public:
    Complex(double re, double im);
    ...
};
```

- What if we want to make a copy of a specific object? i.e. initialize a Complex from another Complex

```
Complex c1{5, 2};
Complex c2{c1};  // Makes a copy!
```

- C++ automatically generates a **copy constructor** for every class

Copying Objects (2)

- The copy constructor is used when objects are passed by-value

  `double magnitude(Complex c);`

  - c is passed by value
  - A copy of c is made, and magnitude operates on the copy
  - The copy constructor is used
  - (This is why we want to pass objects by const-reference; to avoid the overhead of unnecessary copying)
- The default copy constructor generated by C++ simply copies the values of all members into the new object
  - Sometimes this causes problems…
- To write our own version of the copy constructor, implement this constructor:

  `Complex(const Complex &c); // Must pass by reference`

Assigning Objects

- Similarly, can use assignment on objects without any extra code

```
Complex c1{5, 2};
Complex c2;
...
c2 = c1;
```

- This is called the copy-assignment operator
- The default copy-assignment operator generated by C++ simply copies the values of all members from the RHS into the LHS
- To write our own version of the copy-assignment operator, implement this member operator-overload function:

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

  - Must return a non-const reference to the LHS of the assignment, in order to support operator-chaining, e.g. **`c3 = c2 = c1;`**

Allocating an Object on the Heap

- When you need a large chunk of memory, or you need to create objects that live beyond the lifetime of a specific function call, you can allocate memory from the heap

```
Complex *p = new Complex{3, 5};
```

  - p points to a Complex object allocated on the heap

- To access members of the object pointed to by p, must use -> operator

```
cout << p.real() << ", " << p.imag();      // ERROR
cout << p->real() << ", " << p->imag();    // OK!
```

- If your program allocates memory from the heap, your program must also take care to release it! Otherwise you will have a memory leak.

```
delete p;
```

  - p will still contain an address; don't use it after deleting the object!

Heap-Allocating Arrays of Objects

- Can also allocate arrays of objects on the heap

  `Complex *p = new Complex[1000];`

  - p points to an array of 1000 Complex objects, allocated on the heap
- Each element is initialized with the class' default constructor
  - Not possible to call a different constructor during array initialization
  - If your element type doesn't have default initialization, not possible to use in array allocations
- Can access array elements as usual, e.g. **`p[0].real()`**
  - Each element is a Complex object, so use . instead -> for member access
- Freeing arrays is slightly more complicated:

  `delete[] p;`

  - NOTE: Must use delete[] with new[], and delete with new! **Do not mix!!!**
  - The compiler will not stop you from mixing the two. The types do not indicate whether the allocation is an array or a single object.

Heap-Allocating Arrays of Primitives

- Can also allocate arrays of primitive values

```
double *array = new double[numValues];
```

- Primitive types do not have constructors or destructors. The values are uninitialized.
  - If there are random values in the memory area used for the allocation, the new array may contain garbage
  - *This doesn't always happen, but it will eventually!*
- <u>Always</u> initialize arrays of primitive values after allocating

```
for (int i = 0; i < numValues; i++)
    array[i] = 0;
```

- When finished, free with delete[] as usual

```
delete[] array;
```

Managing Heap-Allocated Memory

- Managing heap-allocated memory in C++ programs is difficult and bug-prone, particularly as program size grows
- Simple solution: Don't heap-allocate memory at all! ☺
  - When possible, use std::vector<T>, std::array<T>, std::string, etc.
- When you must heap-allocate memory, use the C++ class lifecycle to make memory management easier
- When an object goes out of scope, its destructor is called automatically…
- Strategy:
  - Heap-allocate memory in class constructor (and in a very few other places)
  - Free memory in destructor
  - The object manages memory for you – abstraction / encapsulation
- Pattern is called **Resource Acquisition Is Initialization** (RAII)

Array of Floats

- A class to manage an array of floats:

```
class FloatArray {
    int count;
    float *elems;
public:
    FloatArray(int n);
    ~FloatArray();
    ...
};
```

Array of Floats (2)

- Constructor:

```
FloatArray::FloatArray(int n) {
    count = n;
    elems = new float[count];
    for (int i = 0; i < count; i++)
        elems[i] = 0;
};
```

- Destructor:

```
FloatArray::~FloatArray() {
    delete[] elems;
};
```

Array of Floats (3)

- FloatArray takes care of memory management, so we don't have to!

```
float getAverage() {
    int numFloats;
    cin >> numFloats;
    FloatArray f{numFloats};
    for (int i = 0; i < numFloats; i++) {
        float value;
        cin >> value;
        f.set(i, value);
    }
    return f.average();
};
```

f goes out of scope here

- When f goes out of scope, its destructor is called automatically
- Heap memory allocated within f is freed automatically

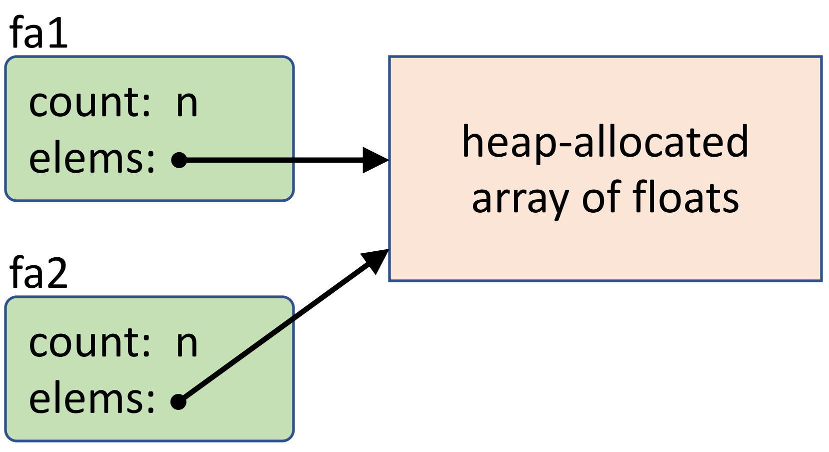
Copying Arrays of Floats

- What does this code do?

```
void f(int n) {
    FloatArray fa1{n};
    ... // populate fa1

    FloatArray fa2{fa1};  // Make a copy!
    ...
}
```

- Recall:
    - The default copy constructor generated by C++ simply copies the values of all members into the new object
- *Hmmmm….*



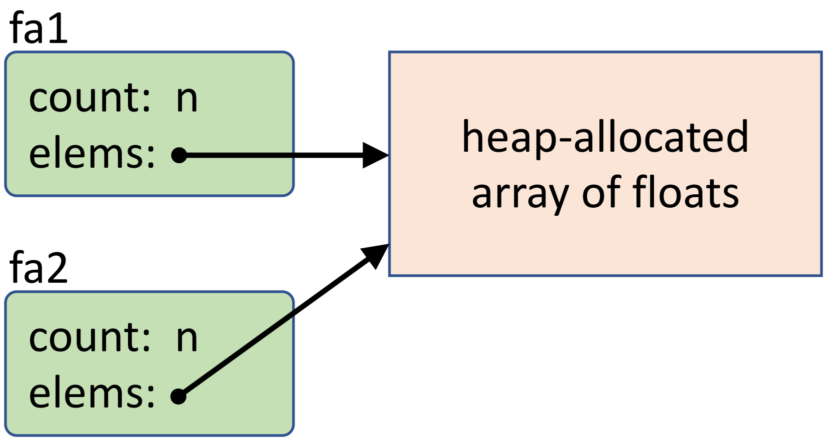
Copying Arrays of Floats (2)

- What does this code do?

```
void f(int n) {
    FloatArray fa1{n};
    ... // populate fa1

    FloatArray fa2{fa1};  // Make a copy!
    ...
}
```

- The default copy-constructor performs a **shallow copy**
- This code has several issues
  - Changes through fa1 will be visible through fa2, and vice versa
  - The code will likely crash with a double-free of the memory block



Custom Copy Constructors

- If your class dynamically allocates memory, you usually need to implement a custom copy-constructor that performs a deep copy
  - The object being initialized needs its own memory region!
- Updated code for FloatArray:

```
FloatArray::FloatArray(const FloatArray &f) {
    count = f.count;
    // Make a deep copy
    elems = new float[count];
    for (int i = 0; i < count; i++)
        elems[i] = f.elems[i];
}
```

- Note: Can directly access private members of f because we are still in the FloatArray code
  - Makes the implementation short and clean

Assigning Arrays of Floats

- What does this code do?

```
void f(int n) {
    FloatArray fa1{n};
    ... // populate fa1

    FloatArray fa2{10};
    ...
    fa2 = fa1;
}
```

- This doesn't invoke the copy-constructor, because it isn't part of a variable-initialization statement
- Rather, it invokes the **copy-assignment operator**

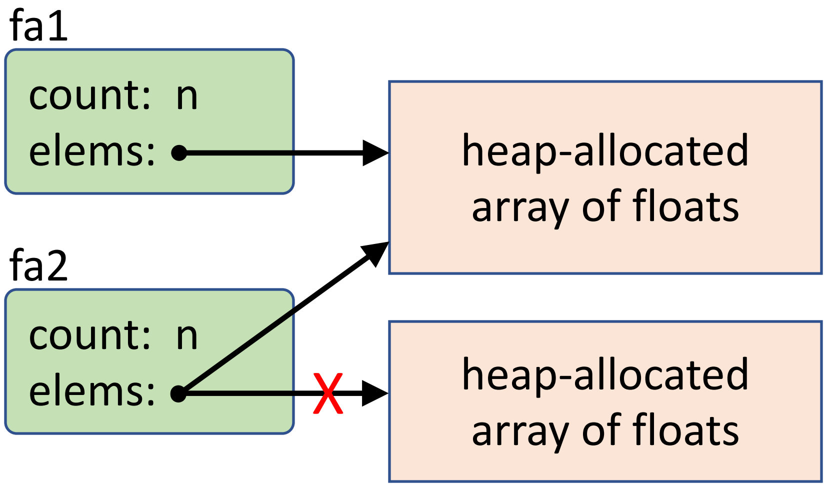
  FloatArray & FloatArray::operator=(const FloatArray &f)

Assigning Arrays of Floats (2)

- What does this code do?

```
void f(int n) {
    FloatArray fa1{n};
    ... // populate fa1

    FloatArray fa2{10};
    ...
    fa2 = fa1;
}
```



- C++ also generates a default copy-assignment operator for you
- The default copy-assignment operator generated by C++ simply copies the values of all members from the RHS into the LHS
- *We have the same problems as before, but we <u>also</u> leak memory!*

Custom Copy-Assignment Operators

- Previous observation:
  - If your class dynamically allocates memory, you usually need to implement a custom copy-constructor that performs a deep copy
  - The object being initialized needs its own memory region
- Similarly:
  - If your class dynamically allocates memory, you usually need to implement a custom copy-assignment operator that cleans up any existing allocation, and also performs a deep copy
  - The object being assigned to may already hold some memory, which needs to be freed
  - The object being assigned to needs its own memory region

The Rule of Three

- **The Rule Of Three:** If your class defines any of the following:
  - A destructor
  - A copy-constructor
  - A copy-assignment operator
- It probably needs to define <u>all three</u>.
- (There is also a **Rule of Five** – we will discuss in a future lecture)

- Aside: We would avoid needing to do this if we simply used a std::vector<T> or std::array<T> !
  - These classes already manage heap-allocated memory properly for us
- Gives rise to our favorite rule: **The Rule of Zero**
  - Write classes in such a way that you can rely on the default behavior of operations like the destructor, copy-constructor, copy-assignment, etc.

Custom Copy-Assignment Operator

- Copy-assignment operator must follow specific rules
  - Make sure to release any dynamically-allocated resources, then allocate new resources to receive the values from the RHS (i.e. do a deep copy)
  - Return a non-const reference to the LHS of the assignment
- Example FloatArray implementation, take 1:

```
FloatArray & FloatArray::operator=(const FloatArray &f) {
    delete[] elems;             // Release old memory
    count = f.count;
    elems = new float[count];   // Allocate new memory
    for (int i = 0; i < count; i++)
        elems[i] = f.elems[i];

    // Return non-const reference to myself
    return *this;
}
```

Custom Copy-Assignment Operator (2)

- Example FloatArray implementation, take 1:

```
FloatArray & FloatArray::operator=(const FloatArray &f) {
    delete[] elems;              // Release old memory
    count = f.count;
    elems = new float[count];   // Allocate new memory
    for (int i = 0; i < count; i++)
        elems[i] = f.elems[i];
    return *this;
}
```

- What happens if we write this code?

```
FloatArray f{1000};
... // Populate f

f = f;
```

f is both LHS and RHS of the assignment. First step is to delete the internal array of data… ☹

Custom Copy-Assignment Operator (3)

- Copy-assignment operator must follow specific rules
  - Make sure to release any dynamically-allocated resources, then allocate new resources to receive the values from the RHS (i.e. do a deep copy)
  - Return a non-const reference to the LHS of the assignment
  - **Properly identify and handle self-assignment!**
- An easy way to detect self-assignment: compare the address of the LHS and RHS of the assignment
  - If they are the same address, can safely assume it's self-assignment

Custom Copy-Assignment Operator (4)

- A correct FloatArray implementation of copy-assignment:

```
FloatArray & FloatArray::operator=(const FloatArray &f) {
    // Detect and handle self-assignment
    if (this == &f)
        return *this;

    delete[] elems;               // Release old memory
    count = f.count;
    elems = new float[count];  // Allocate new memory
    for (int i = 0; i < count; i++)
        elems[i] = f.elems[i];

    // Return non-const reference to myself
    return *this;
}
```

The **`bool`** Type and Comparisons

- C++ has a **`bool`** type to use for representing Boolean values
  - Two values: **`true`** and **`false`**
- If you write code that keeps track of flags, or returns true/false based on a condition, use the **`bool`** type, not **`int`**!
- Example: Comparison operators

```
bool operator==(const MyClass &c1, const MyClass &c2) {
    ...
}
```

- Easiest to implement != in terms of ==

```
bool operator!=(const MyClass &c1, const MyClass &c2) {
    return !(c1 == c2);
}
```

  - Ensures that != is truly the inverse of ==

C++ Inline Functions

- In C++, can provide the definition of functions as part of the declaration

```
class Complex {
    double re, im;
public:
    ...
    double real() const {
        return re;
    }

    double imag() const {
        return im;
    }
};
```

- These are called **inline functions**

C++ Inline Functions (2)

- Due to its object-oriented nature, C++ encourages a high level of encapsulation and modularity in code
  - Make data-members private, and provide public member functions to access this state
- Problem: Function-invocations aren't free
  - Must pass arguments, set up stack frame, jump to function code, jump back
  - The approach of the language encourages a lot of extra function invocations
- Solution: If a function is short and simple, the compiler can simply replace the function-invocation with the function's body
- Example:

```
complex c = ...;
cout << c.real() << ", " << c.imag();
// Compiles into:  cout << c.re << ", " << c.im;
```

C++ Inline Functions (3)

- Any function you define (i.e. write code for) in a class declaration is a candidate to be inlined…
- **The compiler will not blindly inline functions!** It will evaluate whether it makes sense to do so, or not
  - If a function is recursive, it usually won’t be inlined
  - If a function is large and complex, and will cause significant bloat in the binary file, it usually won’t be inlined
  - Inlining is primarily for short, simple functions
- asdf

C++ Inline Functions (4)

- Providing the definition of member-functions inline, *inside of* a class declaration, requires no additional syntax
- Example: a file **`complex.h`**

```
class Complex {
    double re, im;
public:
    ...
    double real() const {
        return re;
    }

    double imag() const {
        return im;
    }
};
```

- No need to define Complex::real() or Complex::imag() in the complex.cpp file if they are defined in the complex.h file

C++ Inline Functions (5)

- If you wish to define a top-level function (i.e. not a member-function in a class) in the header file, you must use the **`inline`** keyword
- Example: still inside the file **`complex.h`**

```
inline bool operator==(const Complex& c1,
                       const Complex & c2) {
    return c1.real() == c2.real() &&
           c1.imag() == c2.imag();
}
```

- Without the **`inline`** keyword, you will likely encounter “multiple definition” errors at compilation and link time ☹

This Week's Assignment

- This week's assignment will be to implement a 2D integer **`Matrix`** class whose dimensions can be specified to the constructor
- In C/C++, best approach to represent a 2D matrix/array is to map the 2D (row, column) coordinates into a 1D array
  - Numerous reasons for this, including performance, ease of maintenance, etc.
- Given a matrix of size *rows* x *cols*, how to map a given 2D (r, c) coordinate into the corresponding 1D cell?
  - index = r * cols + c (row-major order)
  - index = c * rows + r (column-major order)
- **Row-major order** means that column-values in the same row are physically adjacent to each other in memory
- C/C++ multidimensional arrays use row-major order
  - A few other languages (e.g. Fortran, MATLAB, R) use column-major order

This Week's Assignment (2)

- Because the **`Matrix`** class dynamically allocates memory, it needs a destructor, a copy-constructor, and a copy-assignment operator
    - Follow the **Rule of Three**!

- As usual, write Doxygen-style comments, and write a Makefile

- Tests are provided! ☺