Tutorial Outline: Part 2

- References and Pointers
- The formal concepts in OOP
- More about C++ classes
Pass by Value

- C++ defaults to *pass by value* behavior when calling a function.
- The function arguments are *copied* when used in the function.
- Changing the value of L or W in the RectangleArea1 function does **not** effect their original values in the main() function.
- When passing objects as function arguments it is important to be aware that potentially large data structures are automatically copied!
Pass by Reference

- *Pass by reference* behavior is triggered when the `&` character is used to modify the type of the argument.
- This is the type of behavior you see in Fortran, Matlab, Python, and others.
- Pass by reference function arguments are **NOT** copied. Instead the compiler sends a *pointer* to the function that references the memory location of the original variable. The syntax of using the argument in the function does not change.
- Pass by reference arguments almost always act just like a pass by value argument when writing code **EXCEPT** that changing their value changes the value of the original variable!!
- The `const` modifier can be used to prevent changes to the original variable in `main()`.
In RectangleArea4 the pass by reference behavior is used as a way to return the result without the function returning a value.

The value of the area argument is modified in the main() routine by the function.

This can be a useful way for a function to return multiple values in the calling routine.

```c
void RectangleArea4(const float& L, const float& W, float& area) {
    area = L * W;
}
```
In C++ arguments to functions can be objects…which can contain any quantity of data you’ve defined!

- Example: Consider a string variable containing 1 million characters (approx. 1 MB of RAM).
  - Pass by value requires a copy – 1 MB.
  - Pass by reference requires 8 bytes!

Pass by value could potentially mean the accidental copying of large amounts of memory which can greatly impact program memory usage and performance.

When passing by reference, use the `const` modifier whenever appropriate to protect yourself from coding errors.

- Generally speaking – use `const` anytime you don’t want to modify function arguments in a function.

“C makes it easy to shoot yourself in the foot; C++ makes it harder, but when you do it blows your whole leg off.” – Bjarne Stroustrup
A first C++ class

- Start a new project. Call it `BasicRectangle`.
- In the `main.cpp`, we’ll define a class called `BasicRectangle`.
- First, just the basics: length and width.
- Enter the code on the right before the `main()` function in the `main.cpp` file (copy & paste is fine) and create a `BasicRectangle` object in `main.cpp`:

```cpp
#include <iostream>

using namespace std;

class BasicRectangle
{
public:
    // width
    float W ;
    // length
    float L ;
};

int main()
{
    cout << "Hello world!" << endl;

    BasicRectangle rectangle ;
    rectangle.W = 1.0 ;
    rectangle.L = 2.0 ;

    return 0;
}
```
Basic C++ Class Syntax

Curly braces at the beginning and end followed by a semi-colon

`class` keyword

Name of class

`public` keyword indicates everything following the keyword is accessible by any other code outside of this class.

Internal variables are called members

The class can now be used to declare an object named `rectangle`. The width and length of the rectangle can be set.

```cpp
class BasicRectangle
{
public:
    // width
    float W ;
    // length
    float L ;
};
```

```cpp
BasicRectangle rectangle ;
rectangle.W = 1.0 ;
rectangle.L = 2.0 ;
```
Accessing data in the class

- Public members in an object can be accessed (for reading or writing) with the syntax: `object.member`

- Next let’s add a function inside the object (called a `method`) to calculate the area.

```cpp
int main()
{
    cout << "Hello world!" << endl;
    BasicRectangle rectangle;
    rectangle.W = 1.0;
    rectangle.L = 2.0;
    return 0;
}
```
Methods are accessed just like members: `object.method(arguments)`

`method Area` does not take any arguments, it just returns the calculation based on the object members.
Basic C++ Class Summary

- C++ classes are defined with the keyword `class` and must be enclosed in a pair of curly braces plus a semi-colon:

  ```
  class ClassName { .... } ;
  ```

- The `public` keyword is used to mark members (variables) and methods (functions) as accessible to code outside the class.

- The combination of data and the functions that operate on it is the OOP concept of `encapsulation`. 
Encapsulation in Action

- In C – calculate the area of a few shapes...

  /* assume radius and width_square are assigned already */
  float a1 = AreaOfCircle(radius) ; // ok
  float a2 = AreaOfSquare(width_square) ; // ok
  float a3 = AreaOfCircle(width_square) ; // !! OOPS

- In C++ with Circle and Rectangle classes…not possible to miscalculate.
  - Well, provided the respective Area() methods are implemented correctly!

  Circle c1 ;
  Rectangle r1 ;
  // ... assign radius and width ...
  float a1 = c1.Area() ;
  float a2 = r1.Area() ;
Now for a “real” class

- Defining a class in the main.cpp file is not typical.
- Two parts to a C++ class:
  - Header file (my_class.h)
    - Contains the interface (definition) of the class – members, methods, etc.
    - The interface is used by the compiler for type checking, enforcing access to private or protected data, and so on.
    - Also useful for programmers when using a class – no need to read the source code, just rely on the interface.
  - Source file (my_class.cc)
    - Compiled by the compiler.
    - Contains implementation of methods, initialization of members.
    - In some circumstances there is no source file to go with a header file.
Create a new class in C::B

- Using an IDE is especially convenient in C++ to keep the details straight when defining a class
  - Typically header and source files are needed
  - Some default methods are created to save you some typing
- Create another project in C::B, call it Shapes.
- Once open, go the File menu, click New, then click Class.
- This opens a wizard GUI that helps get things started.
- This will create the header and source files for you.
- Name the class *Rectangle*

- Uncheck the Documentation option
  - This will just confuse things for now

- Click Create!
2 files are automatically generated: rectangle.h and rectangle.h.cpp
Modify rectangle.h

- As in the sample BasicRectangle, add storage for the length and width to the header file. Add a *declaration* for the Area method.

- The *protected* keyword will be discussed later.

- The *private* keyword declares anything following it (members, methods) to be visible only to code *in this class*.
Modify rectangle.cpp

- This will now contain the code for the Area() method.
- Use the C::B environment to help out here!
- Open rectangle.cpp (under Sources/src)
- Right-click and choose Insert/All class methods without implementation

- The Area() method is automatically found from the header file.
- Click OK.
The Area() method now has a basic definition added.
The syntax:
```
class::method
tells the compiler that this is the code for the Area() method declared in rectangle.h
```
Now take a few minutes to fill in the code for Area().
- Hint – look at the code used in BasicRectangle...
More C::B assistance

- You may have noticed C::B trying to help when entering the code for Area()
- Press the Tab key to accept the suggestion
- It will offer up variable names, member names, class names, etc. that match what you’re typing when appropriate to save you effort.
  - This can be a *huge* convenience when dealing with large code bases.
Last Step

- Go to the main.cpp file
- Add an include statement for “rectangle.h”
- Create a Rectangle object in main()
- Add a length and width
- Print out the area using cout.

- Hint: just like the BasicRectangle example…
Solution

- You should have come up with something like this:

```cpp
#include <iostream>

using namespace std;

#include "rectangle.h"

int main()
{
    Rectangle rT;
    rT.m_width = 1.0;
    rT.m_length = 2.0;

    cout << rT.Area() << endl;

    return 0;
}
```
Part 1 introduced the concept of passing by reference when calling functions.
- Selected by using the & character in function argument types: `int add (int &a, int b)`

References hold a memory address of a value.
- `int add (int &a, int b)` → `a` has the value of a memory address, `b` has an integer value.
- Used like regular variables and C++ automatically fills in the value of the reference when needed:
  ```
  int c = a + b ;  // “retrieve the value of a and add it to the value of b”
  ```

From C there is another way to deal with the memory address of a variable: via `pointer` types.

Similar syntax in functions except that the & is replaced with a *:
- `int add (int *a, int b)`

To get a value a pointer requires manual intervention by the programmer:
- `int c = *a + b ;  // “retrieve the value of a and add it to the value of b”`
<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>Pointer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Declaration</td>
<td>int &amp;ref ;</td>
<td>int *ptr ;</td>
</tr>
<tr>
<td>Set memory address to something in memory</td>
<td>int a = 0 ; int &amp;ref = a ;</td>
<td>int a = 0 ; int *ptr = &amp;a ;</td>
</tr>
<tr>
<td>Fetch value of thing in memory</td>
<td>cout &lt;&lt; ref ;</td>
<td>cout &lt;&lt; *ptr ;</td>
</tr>
<tr>
<td>Can refer/point to nothing (null value)?</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Can change address that it refers to/points at?</td>
<td>No. int a = 0 ; int b = 1 ; int &amp;ref = a ; ref = b ; // value of a is now 1!</td>
<td>Yes int a = 0 ; int b = 1 ; int *ptr = &amp;a ; ptr = &amp;b ; // ptr now points at b</td>
</tr>
<tr>
<td>Object member/method syntax</td>
<td>MyClass obj ; MyClass &amp;ref = obj ; ref.member ; ref.method() ;</td>
<td>MyClass obj ; MyClass *ptr = obj ; ptr-&gt;member ; ptr-&gt;method() ; // OR (*ptr).member ; (*ptr).method() ;</td>
</tr>
</tbody>
</table>

```cpp
int a = 0 ;
int &ref = a ;
int *ptr = &a ;
```

Value stored in ref: 0xAABBFF
Value stored in ptr: 0xAABBFF

int a: 4 bytes in memory at address 0xAAAABBBFF with a value of 0.
When to use a reference or a pointer

- Both references and pointers can be used to refer to objects in memory in methods, functions, loops, etc.
- Avoids copying due to default call-by-value C++ behavior
  - Could lead to memory/performance problems.
  - Or cause issues with open files, databases, etc.
- If you need to:
  - Hold a null value (i.e. point at nothing), use a pointer.
  - Re-assign the memory address stored, use a pointer.
- Otherwise, use a reference.
  - References are much easier to use, no funky C-style pointer syntax.
  - Same benefits as a pointer, with less chance for error.
  - Also no need to check if a reference has a null value…since they can’t hold one!

// Pointer to a null value
int *a = NULL; // C-style
int *b = nullptr; // C++11 style.

// Reference to a null value
// won't compile.
int &c = nullptr;
Null Value Checking

- A null value means the pointer is not currently pointing at anything.
  - It’s a good idea to check before accessing the value they point at.

- References cannot be null, so the code on the right does not need checking.
The formal concepts in OOP

- **Object-oriented programming (OOP):**
  - Defines *classes* to represent data and logic in a program. Classes can contain members (data) and methods (internal functions).
  - Creates *instances* of classes, aka *objects*, and builds the programs out of their interactions.

- **The core concepts in addition to classes and objects are:**
  - Encapsulation
  - Inheritance
  - Polymorphism
  - Abstraction
Core Concepts

- **Encapsulation**
  - As mentioned while building the C++ class in the last session.
  - Bundles related data and functions into a class

- **Inheritance**
  - Builds a relationship between classes to share class members and methods

- **Abstraction**
  - The hiding of members, methods, and implementation details inside of a class.

- **Polymorphism**
  - The application of the same code to multiple data types
  - There are 3 kinds, all of which are supported in C++. However only 1 is actually called polymorphism in C++ jargon (!)
C++ Classes

- Open the **Part 2 Shapes** project in C::B
- In the Rectangle class C::B generated two methods automatically.
  - *Rectangle()* is a *constructor*. This is a method that is called when an object is instantiated for this class.
    - Multiple constructors per class are allowed
  - ~*Rectangle()* is a *destructor*. This is called when an object is removed from memory.
    - Only one destructor per class is allowed!
    - (ignore the *virtual* keyword for now)

```cpp
#ifndef RECTANGLE_H
#define RECTANGLE_H

class Rectangle
{
    public:
        Rectangle();
        virtual ~Rectangle();
        float m_length ;
        float m_width ;
        float Area() ;

    protected:

    private:
};
#endif // RECTANGLE_H
```
Encapsulation

- Bundling the data and area calculation for a rectangle into a single class is an example of the concept of *encapsulation*. 
Construction and Destruction

- The *constructor* is called when an object is created.

- This is used to initialize an object:
  - Load values into member variables
  - Open files
  - Connect to hardware, databases, networks, etc.

- The *destructor* is called when an object goes *out of scope*.

- Example:

```c
void function() {
    ClassOne c1;
}
```

- Object c1 is created when the program reaches the first line of the function, and destroyed when the program leaves the function.
When an object is instantiated...

- The rT object is created in memory.
- When it is created its \textit{constructor} is called to do any necessary initialization.
  - Here the constructor is empty so nothing is done.
- The constructor can take any number of arguments like any other function but it \textit{cannot} return any values.
  - Essentially the return value is the object itself!
- What if there are multiple constructors?
  - The compiler chooses the correct one based on the arguments given.

```cpp
#include "rectangle.h"

int main()
{
    Rectangle rT;
    rT.m_width = 1.0;
}
```

```cpp
#include "rectangle.h"

Rectangle::Rectangle()
{
    //ctor
}
```

Note the constructor has no return type!
A second constructor

```cpp
#include "rectangle.h"

/* OK to do this */
Rectangle::Rectangle(float width, float length)
{
    m_width = width;
    m_length = length;
}

/* Better to do this */
Rectangle::Rectangle(float width, float length) :
    m_width(width), m_length(length) { } 
```

- Two styles of constructor. Above is the C++11 member initialization list style. At the top is the old way. C++11 is preferred.
- With the old way the empty constructor is called automatically even though it does nothing – it still adds a function call.
- Same rectangle.h for both styles.
Member Initialization Lists

- Syntax:

```cpp
MyClass(int A, OtherClass &B, float C):
    m_A(A),
    m_B(B),
    m_C(C) {
        /* other code can go here */
    }
```

Members assigned and separated with commas. Note: order doesn’t matter.

Colon goes here

Additional code can be added in the code block.
And now use both constructors

- Both constructors are now used. The new constructor initializes the values when the object is created.
- Constructors are used to:
  - Initialize members
  - Open files
  - Connect to databases
  - Etc.

```cpp
#include <iostream>
using namespace std;
#include "rectangle.h"

int main()
{
    Rectangle rT;
    rT.m_width = 1.0;
    rT.m_length = 2.0;
    cout << rT.Area() << endl;

    Rectangle rT_2(2.0, 2.0);
    cout << rT_2.Area() << endl;

    return 0;
}
```
C++11 added the ability to define default values in headers in an intuitive way.

Pre-C++11 default values would have been coded into constructors.

If members with default values get their value set in constructor than the default value is ignored.
  - i.e. no “double setting” of the value.

```cpp
#ifndef RECTANGLE_H
#define RECTANGLE_H

class Rectangle
{
    public:
        Rectangle();
        virtual ~Rectangle();
        // could do:
        float m_length = 0.0;
        float m_width = 0.0;

        float Area() ;
    protected:
    }

private:
};
#endif // RECTANGLE_H
```
Using the C::B Debugger

- To show how this works we will use the C::B interactive debugger to step through the program line-by-line to follow the constructor calls.
- Make sure you are running in *Debug* mode. This turns off compiler optimizations and has the compiler include information in the compiled code for effective debugging.
Add a Breakpoint

- Breakpoints tell the debugger to halt at a particular line so that the state of the program can be inspected.
- In rectangle.cpp, double click to the left of the lines in the constructors to set a pair of breakpoints. A red dot will appear.
- Click the red arrow to start the code in the debugger.
• The program has paused at the first breakpoint in the default constructor.
• Use the Next Line button to go back to the main() routine.
• Press the red arrow to continue execution – stops at the next breakpoint.
Default constructors and destructors

- The two methods created by C::B automatically are explicit versions of the default C++ constructors and destructors.
- Every class has them – if you don’t define them then empty ones that do nothing will be created for you by the compiler.
  - If you really don’t want the default constructor you can delete it with the `delete` keyword.
  - Also in the header file you can use the `default` keyword if you like to be clear that you are using the default.

```cpp
class Foo {
    public:
    Foo() = delete; // Another constructor // must be defined!
    Foo(int x);
};

class Bar {
    public:
    Bar() = default;
};
```
Custom constructors and destructors

- You must define your own constructor when you want to initialize an object with arguments.

- A custom destructor is always needed when internal members in the class need special handling.
  - Examples: manually allocated memory, open files, hardware drivers, database or network connections, custom data structures, etc.
Destructors

- Destructors are called when an object is destroyed.
- There is only one destructor allowed per class.
- Objects are destroyed when they go out of scope.
- Destructors are never called explicitly by the programmer. Calls to destructors are inserted automatically by the compiler.

Note the destructor has no return type and is named with a ~. This class just has 2 floats as members which are automatically removed from memory by the compiler.

```cpp
Rectangle::~Rectangle()
{
    // dtor
}
```

~House() destructor

House object
Destructors

Example:

class Example {
    public:
        Example() = delete;
        Example(int count);

        virtual ~Example();

    // A pointer to some memory
    // that will be allocated.
    float *values = nullptr;
};

Example::Example(int count) {
    // Allocate memory to store "count"
    // floats.
    values = new float[count];
}

Example::~Example() {
    // The destructor must free this
    // memory. Only do so if values is not
    // null.
    if (values) {
        delete[] values;
    }
}
Scope

- Scope is the region where a variable is valid.
- Constructors are called when an object is created.
- Destructors are only ever called implicitly.

```c
int main() { // Start of a code block
    // in main function scope
    float x; // No constructors for built-in types
    ClassOne c1; // c1 constructor ClassOne() is called.
    if (1){ // Start of an inner code block
        // scope of c2 is this inner code block
        ClassOne c2; // c2 constructor ClassOne() is called.
        } // c2 destructor ~ClassOne() is called.
    ClassOne c3; // c3 constructor ClassOne() is called.
} // leaving program, call destructors for c3 and c1 ~ClassOne()
// variable x: no destructor for built-in type
```
Copy, Assignment, and Move Constructors

- The compiler will automatically create constructors to deal with copying, assignment, and moving.
  - Moving occurs, for example, when an object is created and added to a list in a loop.
  - Moving is an optimization feature that’s part of C++11.
- Dealing with the details of these constructors is outside of the scope of this tutorial.
- How do you know if you need to write one?
  - When you move, assign, or copy an object in your code and the code won’t compile!
  - OR you move, assign, or copy an object, it compiles, but unexpected things happen when running.
- You may require custom code when...
  - dealing with open files inside an object
  - The class manually allocated memory
  - Hardware resources (a serial port) opened inside an object
  - Etc.

```cpp
Rectangle rT_1(1.0, 2.0); // Now use the copy constructor
Rectangle rT_2(rT_1);    // Do an assignment, with the
                         // default assignment operator
rT_2 = rT_1;
```
So Far…

- Define a C++ class
  - Adding members and methods

- Use separate header and source files for a C++ class.
- Class constructors & destructors

- OOP concept: Encapsulation
The formal concepts in OOP

- Next up: Inheritance
Inheritance

- Inheritance is the ability to form a hierarchy of classes where they share common members and methods.
  - Helps with: code re-use, consistent programming, program organization

- This is a powerful concept!
Inheritance

- The class being derived *from* is referred to as the **base**, **parent**, or **super** class.

- The class being derived is the **derived**, **child**, or **sub** class.

- For consistency, we’ll use superclass and subclass in this tutorial. A base class is the one at the top of the hierarchy.
Inheritance in Action

- Streams in C++ are series of characters – the C+ I/O system is based on this concept.

- **cout** is an object of the class **ostream**. It is a write-only series of characters that prints to the terminal.

- There are two subclasses of ostream:
  - **ofstream** – write characters to a file
  - **ostringstream** – write characters to a string

- Writing to the terminal is straightforward:

  ```
  cout << some_variable;
  ```

- How might an object of class **ofstream** or **ostringstream** be used if we want to write characters to a file or to a string?
Inheritance in Action

- For `ofstream` and `ofstringstream` the `<<` operator is inherited from `ostream` and behaves the same way for each from the programmer’s point of view.

- The `ofstream` class adds a constructor to open a file and a `close()` method.

- `ofstringstream` adds a method to retrieve the underlying string, `str()`

- If you wanted a class to write to something else, like a USB port…
  - Maybe look into inheriting from `ostream`!
  - Or its underlying class, `basic_ostream` which handles types other than characters…
Inheritance in Action

```cpp
#include <iostream>  // cout
#include <fstream>   // ofstream
#include <sstream>   // ostringstream

using namespace std;
void some_func(string msg) {
    cout << msg;  // to the terminal
    // The constructor opens a file for writing
    ofstream my_file("filename.txt");
    // Write to the file.
    my_file << msg;
    // close the file.
    my_file.close();
    ostringstream oss;
    // Write to the stringstream
    oss << msg;
    // Get the string from stringstream
    cout << oss.str();
}
```
Public, protected, private

- These keywords were added by C::B to our Rectangle class.
- These are used to control access to different parts of the class during inheritance by other pieces of code.

```cpp
class Rectangle
{
    public:
        Rectangle();
        Rectangle(float width, float length);
        virtual ~Rectangle();

        float m_width;
        float m_length;

        float Area();

    protected:

    private:
};
```

“There are only two things wrong with C++: The initial concept and the implementation.”
– Bertrand Meyer (inventor of the Eiffel OOP language)
C++ Access Control and Inheritance

- A summary of the accessibility of members and methods:

<table>
<thead>
<tr>
<th>Access</th>
<th>public</th>
<th>protected</th>
<th>private</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same class</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Subclass</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Outside classes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

```cpp
class Super {
public:
    int i;
protected:
    int j;
private:
    int k;
};

class Sub : public Super {
    // in methods, could access
    // i and j from Parent only.
};

Sub myobj;
Myobj.i = 10; // ok
Myobj.j = 3; // Compiler error
```
Inheritance

- With inheritance subclasses have access to private and protected members and methods all the way back to the base class.
- Each subclass can still define its own public, protected, and private members and methods along the way.
Single vs Multiple Inheritance

- C++ supports creating relationships where a subclass inherits data members and methods from a single superclass: single inheritance
- C++ also support inheriting from multiple classes simultaneously: Multiple inheritance
- This tutorial will only cover single inheritance.
- Generally speaking…
  - Multiple inheritance requires a large amount of design effort
  - It’s an easy way to end up with overly complex, fragile code
  - Java, C#, and Python (all came after C++) exclude multiple inheritance on purpose to avoid problems with it.

With multiple inheritance a hierarchy like this is possible to create. This is nicknamed the **Deadly Diamond of Death** as it creates ambiguity in the code.
Abstraction

- Having private (internal) data and methods separated from public ones is the OOP concept of *abstraction*.
C++ Inheritance Syntax

- Inheritance syntax pattern:
  ```
  class SubclassName : public SuperclassName
  ```

- Here the `public` keyword is used.
  - Methods implemented in class Sub can access any public or protected members and methods in Super but cannot access anything that is private.

- Other inheritance types are `protected` and `private`.
It is now time to inherit

- The C::B program will help with the syntax when defining a class that inherits from another class.
- With the **Shapes** project open, click on File → New → Class
- Give it the name Square and check the “Inherits another class” option.
- Enter Rectangle as the superclass and the include as “rectangle.h” (note the lowercase r)
- Click Create!
2 files are automatically generated: square.h and square.cpp

Class Square inherits from class Rectangle

- Note that subclasses are free to add any number of new methods or members, they are not limited to those in the superclass.
A new constructor is needed.

- A square is, of course, just a rectangle with equal length and width.
- The area can be calculated the same way as a rectangle.
- Our Square class therefore needs just one value to initialize it and it can re-use the Rectangle.Area() method for its area.
- Go ahead and try it:
  - Add an argument to the default constructor in square.h
  - Update the constructor in square.cpp to do…?
  - Remember Square can access the public members and methods in its superclass
Solution 1

Square can access the public members in its superclass.
Its constructor can then just assign the length of the side to the Rectangle m_width and m_length.
This is unsatisfying – while there is nothing wrong with this it’s not the OOP way to do things.
Why re-code the perfectly good constructor in Rectangle?

```cpp
#ifndef SQUARE_H
#define SQUARE_H
#include "rectangle.h"

class Square : public Rectangle {
    public:
        Square(float width);
        virtual ~Square();

    protected:

    private:
};
#endif // SQUARE_H

#include "square.h"

Square::Square(float length) {
    m_width = width;
    m_length = length;
}
```
The delegating constructor

- C++11 added a new constructor type called the delegating constructor.
- Using member initialization lists you can call one constructor from another.
- Even better: with member initialization lists C++ can call superclass constructors!

Reference:
Solution 2

Square can directly call its superclass constructor and let the Rectangle constructor make the assignment to m_width and m_float.

This saves typing, time, and reduces the chance of adding bugs to your code.

The more complex your code, the more compelling this statement is.

Code re-use is one of the prime reasons to use OOP.
Trying it out in main()

- What happens behind the scenes when this is compiled….

```cpp
#include <iostream>
using namespace std;
#include "square.h"

int main()
{
    Square sQ(4);
    // Uses the Rectangle Area() method!
    cout << sQ.Area() << endl;
    return 0;
}
```

Square class does not implement Area() so compiler looks to superclass

Finds Area() in Rectangle class.

Inserts call to Rectangle.Area() method in compiled code.
More on Destructors

- When a subclass object is removed from memory, its destructor is called as it is for any object.

- Its superclass destructor is also called.

- Each subclass should only clean up its own problems and let superclasses clean up theirs.
The formal concepts in OOP

- Next up: Polymorphism
Using subclasses

- A function that takes a superclass argument can *also* be called with a subclass as the argument.

- The reverse is **not** true – a function expecting a subclass argument cannot accept its superclass.

- Copy the code to the right and add it to your main.cpp file.

```cpp
void PrintArea(Rectangle &rT) {
    cout << rT.Area() << endl ;
}

int main() {
    Rectangle rT(1.0,2.0) ;
    Square sQ(3.0) ;
    PrintArea(rT) ;
    PrintArea(sQ) ;
}
```

The `PrintArea` function can accept the `Square` object `sQ` because `Square` is a subclass of `Rectangle`. 
Overriding Methods

- Sometimes a subclass needs to have the same interface to a method as a superclass with different functionality.
- This is achieved by *overriding* a method.
- Overriding a method is simple: just re-implement the method with the same name and arguments in the subclass.

```cpp
class Super {
public:
    void PrintNum() {
        cout << 1 << endl;
    }
};

class Sub : public Super {
public:
    // Override
    void PrintNum() {
        cout << 2 << endl;
    }
};

Super sP;
sP.PrintNum(); // Prints 1
Sub sB;
sB.PrintNum(); // Prints 2
```

In C::B open project:
CodeBlocks Projects → Part 2 → Virtual Method Calls
Overriding Methods

- Seems simple, right?

- To quote from slide 10 in Part 1 of this tutorial, C++: “Includes all the subtleties of C and adds its own”

- Overriding methods is one of those subtleties.
How about in a function call…

- Given the class definitions, what is happening in this function call?
- Using a single function to operate on different types is **polymorphism**.

```
#include <iostream>

class Super {
public:
    void PrintNum() {
        cout << 1 << endl;  
    }
};

class Sub : public Super {
public:
    // Override
    void PrintNum() {
        cout << 2 << endl;  
    }
};

void FuncRef(Super &sP) {
    sP.PrintNum();
}

Super sP;
Func(sP); // Prints 1
Sub sB;
Func(sB); // Hey!! Prints 1!!
```

“C++ is an insult to the human brain”
– Niklaus Wirth (designer of Pascal)
Type casting

- The Func function passes the argument as a reference (Super &sP).
  - What’s happening here is dynamic type casting, the process of converting from one type to another at runtime.
  - Same mechanism as the dynamic_cast function

- The incoming object is treated as though it were a superclass object in the function.

- When methods are overridden and called there are two points where the proper version of the method can be identified: either at compile time or at runtime.
Virtual methods

- When a method is labeled as virtual and overridden the compiler will generate code that will check the type of an object at runtime when the method is called.

- The type check will then result in the expected version of the method being called.

- When overriding a virtual method in a subclass, it’s a good idea to label the method as virtual in the subclass as well.
  - ...just in case this gets subclassed again!

```cpp
class SuperVirtual
{
public:
    virtual void PrintNum()
    {
        cout << 1 << endl;
    }
};

class SubVirtual : public SuperVirtual
{
public:
    // Override
    virtual void PrintNum()
    {
        cout << 2 << endl;
    }
};

void Func(SuperVirtual &sP)
{
    sP.PrintNum();
}

SuperVirtual sP;
Func(sP); // Prints 1
SubVirtual sB;
Func(sB); // Prints 2!!
```
Early (static) vs. Late (dynamic) binding

- What is going on here?
- Leaving out the virtual keyword on a method that is overridden results in the compiler deciding \textit{at compile time} which version (subclass or superclass) of the method to call.
- This is called early or static \textit{binding}.  
- At compile time, a function that takes a superclass argument will only call the \textbf{non-virtual} superclass method under early binding.

- Making a method virtual adds code behind the scenes (that you, the programmer, never interact with directly)
  - Lookups in a hidden table (the vtable are done to figure out what override of the virtual method should be run.
- This is called late or dynamic binding.
- There is a small performance penalty for late binding due to the vtable lookup.
- \textbf{This only applies when an object is referred to by a reference or pointer.}
Behind the scenes – vptr and vtable

- C++ classes have a hidden pointer (vptr) generated that points to a table of virtual methods associated with a class (vtable).

- When a virtual class method (base class or its subclasses) is called by reference (or pointer) when the programming is running the following happens:
  - The object’s class vptr is followed to its class vtable
  - The virtual method is looked up in the vtable and is then called.
  - One vptr and one vtable per class so minimal memory overhead
  - If a method override is non-virtual it won’t be in the vtable and it is selected at compile time.

```
Func(SuperVirtual &sP)
```

sP is a reference to a...

```
SuperVirtual
SuperVirtual’s vptr
Vtable & SuperVirtual::PrintNum()
```

```
SubVirtual
SubVirtual’s vptr
Vtable & SubVirtual::PrintNum()
```
Let’s run this through the debugger

- Open the project: Parts 2-3/Virtual Method Calls.
- Everything here is implemented in one big main.cpp
- Place a breakpoint at the first line in main() and in the two implementations of Func()
When to make methods virtual

- If a method will be (or might be) overridden in a subclass, make it virtual
  - There is a *minor* performance penalty. Will that even matter to you?
    - i.e. Have you profiled and tested your code to show that virtual method calls are a performance issue?
  - When is this true?
    - Almost always! Who knows how your code will be used in the future?

- Constructors are **never** virtual in C++.
- Destructors in a base class should always be virtual.
  - Also – if any method in a class is virtual, make the destructor virtual
  - These are important when dealing with objects via reference and it avoids some subtleties when manually allocating memory.
Why all this complexity?

- Late binding allows for code libraries to be updated for new functionality. As methods are identified at runtime the executable does not need to be updated.
- This is done *all the time!* Your C++ code may be, for example, a plugin to an existing simulation code.
- Greater flexibility when dealing with multiple subclasses of a superclass.
- Most of the time this is the behavior you are looking for when building class hierarchies.

```cpp
void FuncEarly(SuperVirtual &sP)
{
    sP.PrintNum();
}

void FuncLate(SuperVirtual sP)
{
    sP.PrintNum();
}
```

- Called by reference – late binding to PrintNum()
- Called by value – early binding to PrintNum even though it’s virtual!
Remember the Deadly Diamond of Death? Let’s explain.

Look at the class hierarchy on the right.
- Square and Circle inherit from Shape
- Squircle inherits from both Square and Circle
- Syntax:
  
  ```
  class Squircle : public Square, public Circle
  ```

The Shape class implements an empty Area() method. The Square and Circle classes override it. Squircle does not.

Under late binding, which version of Area is accessed from Squircle? Square.Area() or Circle.Area()?
Interfaces

- Another pitfall of multiple inheritance: the *fragile base class* problem.
  - If many classes inherit from a single base (super) class then changes to methods in the base class can have unexpected consequences in the program.
  - This can happen with single inheritance but it’s much easier to run into with multiple inheritance.

- Interfaces are a way to have your classes share behavior without them sharing actual code.
- Gives much of the benefit of multiple inheritance without the complexity and pitfalls

- Example: for debugging you’d like each class to have a Log() method that would write some info to a file.
  - But each class has different types of information to print!
  - With multiple inheritance each subclass might implement its own Log() method (or not). If an override is left out in a subclass it may call the Log() method on a superclass and print unexpected information.
Interfaces

- An interface class in C++ is called a pure virtual class.
- It contains virtual methods only with a special syntax. Instead of {} the function is set to 0.
  - Any subclass needs to implement the methods!
- Modified square.h shown.
- What happens when this is compiled?

```cpp
#ifndef SQUARE_H
#define SQUARE_H

#include "rectangle.h"

class Log {
  virtual void LogInfo() = 0;
};

class Square : public Rectangle, Log {
  public:
    Square(float length);
    virtual ~Square();
    // virtual void LogInfo() {} // virtual void LogInfo() {}
  protected:
  private:
};
#endif // SQUARE_H
```

- Once the LogInfo() is uncommented it will compile.

- C++ offers another fix for the diamond problem, Virtual inheritance. See: https://en.wikipedia.org/wiki/Virtual_inheritance
Putting it all together

- Now let’s revisit our Shapes project.
- In the directory of C::B Part 2 projects, open the “Shapes with Circle” project.
  - This has a Shape base class with a Rectangle and a Square
- Add a Circle class to the class hierarchy in a sensible fashion.

- Hint: Think first, code second.
New pure virtual Shape class

- Slight bit of trickery:
  - An empty constructor is defined in shape.h
  - No need to have an extra shape.cpp file if these functions do nothing!

- Q: How much code can be in the header file?
  - A: Most of it with some exceptions.
    - .h files are not compiled into .o files so a header with a lot of code gets re-compiled every time it’s referenced in a source file.
Give it a try

- Add inheritance from Shape to the Rectangle class
- Add a Circle class, inheriting from wherever you like.
- Implement Area() for the Circle

- If you just want to see a solution, open the project “Shapes with Circle solved”
A Potential Solution

- A Circle has one dimension (radius), like a Square.
  - Would only need to override the Area() method
- But…
  - Would be storing the radius in the members m_width and m_length. This is not a very obvious to someone else who reads your code.
- Maybe:
  - Change m_width and m_length names to m_dim_1 and m_dim_2?
    - Just makes everything more muddled!
A Better Solution

- Inherit separately from the Shape base class
  - Seems logical, to most people a circle is not a specialized form of rectangle…
- Add a member \texttt{m\_radius} to store the radius.
- Implement the \texttt{Area()} method
- Makes more sense!
- Easy to extend to add an Oval class, etc.
New Circle class

- Also inherits from Shape
- Adds a constant value for $\pi$
  - Constant values can be defined right in the header file.
  - If you accidentally try to change the value of PI the compiler will throw an error.

```cpp
#ifndef CIRCLE_H
#define CIRCLE_H

#include "shape.h"

class Circle : public Shape {
public:
    Circle();
    Circle(float radius);
    virtual ~Circle();
    virtual float Area();
    const float PI = 3.14;
    float m_radius;

protected:

private:
};

#endif // CIRCLE_H
```
#include "circle.h"

Circle::Circle()
{
   // ctor
}

Circle::~Circle()
{
   // dtor
}

// Use a member initialization list.
Circle::Circle(float radius) : m_radius{radius}
{
}

float Circle::Area()
{
   // Quiz: what happens if this line is
   // uncommented and then compiled:
   // PI=3.14159 ;
   return m_radius * m_radius * PI ;
}
Quiz time!

- What happens behind the scenes when the function `PrintArea` is called?
- How about if `PrintArea`’s argument was instead:

```cpp
void PrintArea(Shape &shape) {
    cout << "Area: " << shape.Area() << endl;
}

int main() {
    Square sQ(4);
    Circle circ(3.5);
    Rectangle rT(21, 2);

    // Print everything
    PrintArea(sQ);
    PrintArea(rT);
    PrintArea(circ);
    return 0;
}
```
Quick mention…

- Aside from overriding functions it is also possible to override operators in C++.
  - As seen in the C++ string. The + operator concatenates strings:
    ```cpp
    string str = "ABC" ;
    str = str + "DEF" ;
    // str is now "ABCDEF"
    ```
  - It’s possible to override +,-,=,<,>, brackets, parentheses, etc.

- Syntax:
  ```cpp
  MyClass operator*(const MyClass& mC) {...}
  ```

- Recommendation:
  - Generally speaking, avoid this. This is an easy way to generate very confusing code.
  - A well-named function will almost always be easier to understand than an operator.

- Exceptions:
  - Assignment: operator=
  - For certain special functions: operator()
Summary

- C++ classes can be created in hierarchies via inheritance, a core concept in OOP.
- Classes that inherit from others can make use of the superclass’ public and protected members and methods
  - You write less code!
- Virtual methods should be used whenever methods will be overridden in subclasses.
- Avoid multiple inheritance, use interfaces instead.
- Subclasses can override a superclass method for their own purposes and can still explicitly call the superclass method.
- Abstraction means hiding details when they don’t need to be accessed by external code.
  - Reduces the chances for bugs.
- While there is a lot of complexity here – in terms of concepts, syntax, and application – keep in mind that OOP is a highly successful way of building programs!