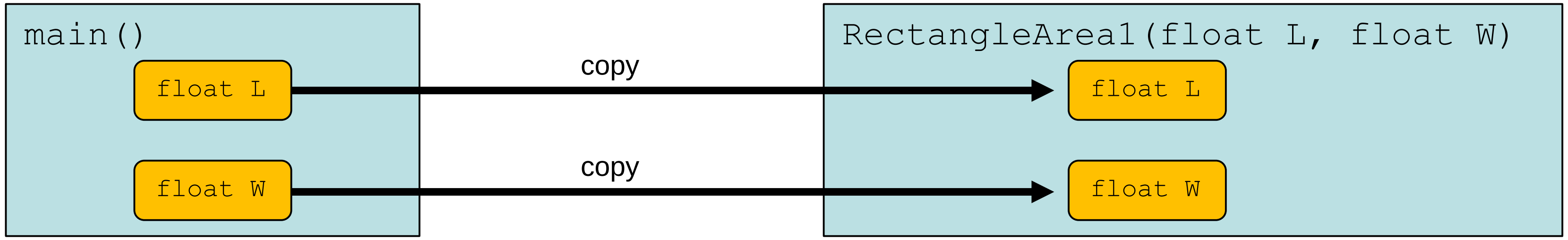
Introduction to C++: Part 2

BOSTON UNIVERSITY

Tutorial Outline: Part 2

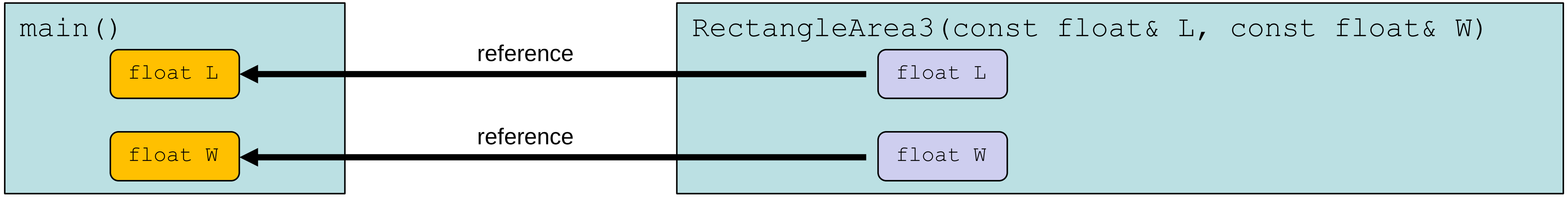
- References and Pointers
- The formal concepts in OOP
- More about C++ classes

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().

BOSTON UNIVERSITY

void does not return a value.

```
void RectangleArea4(const float& L, const float& W, float& area) {
    area= L*W ;
}
```

- 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.

- 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 Stroustrop

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:

```
#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

class keyword

Name of class

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

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

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

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.

```
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.

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

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

    return 0;
}
```

BOSTON UNIVERSITY

method Area does not take any arguments, it just returns the calculation based on the object members.

Methods are accessed just like members:

object.method(arguments)

```
class BasicRectangle
{
public:
    // width ;
    float W ;
    // length
    float L ;
    float Area() {
        return W * L ;
    }

};

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

    BasicRectangle rectangle ;
    rectangle.W = 21.0 ;
    rectangle.L = 2.0 ;

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

    return 0;
}
```

BOSTON UNIVERSITY

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.*

BOSTON UNIVERSITY

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() ;
```

BOSTON UNIVERSITY

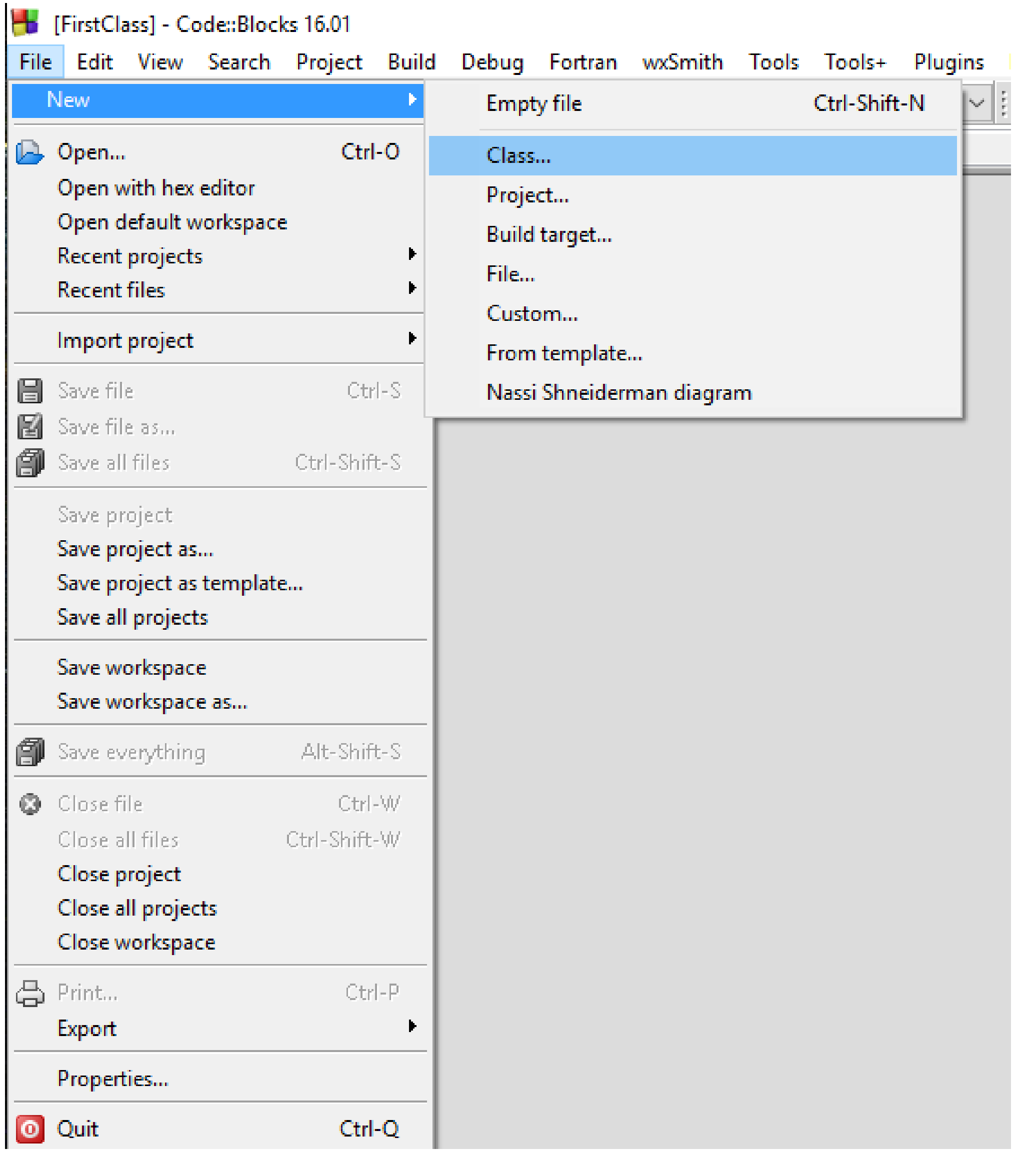
Now for a "real" class

- 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.

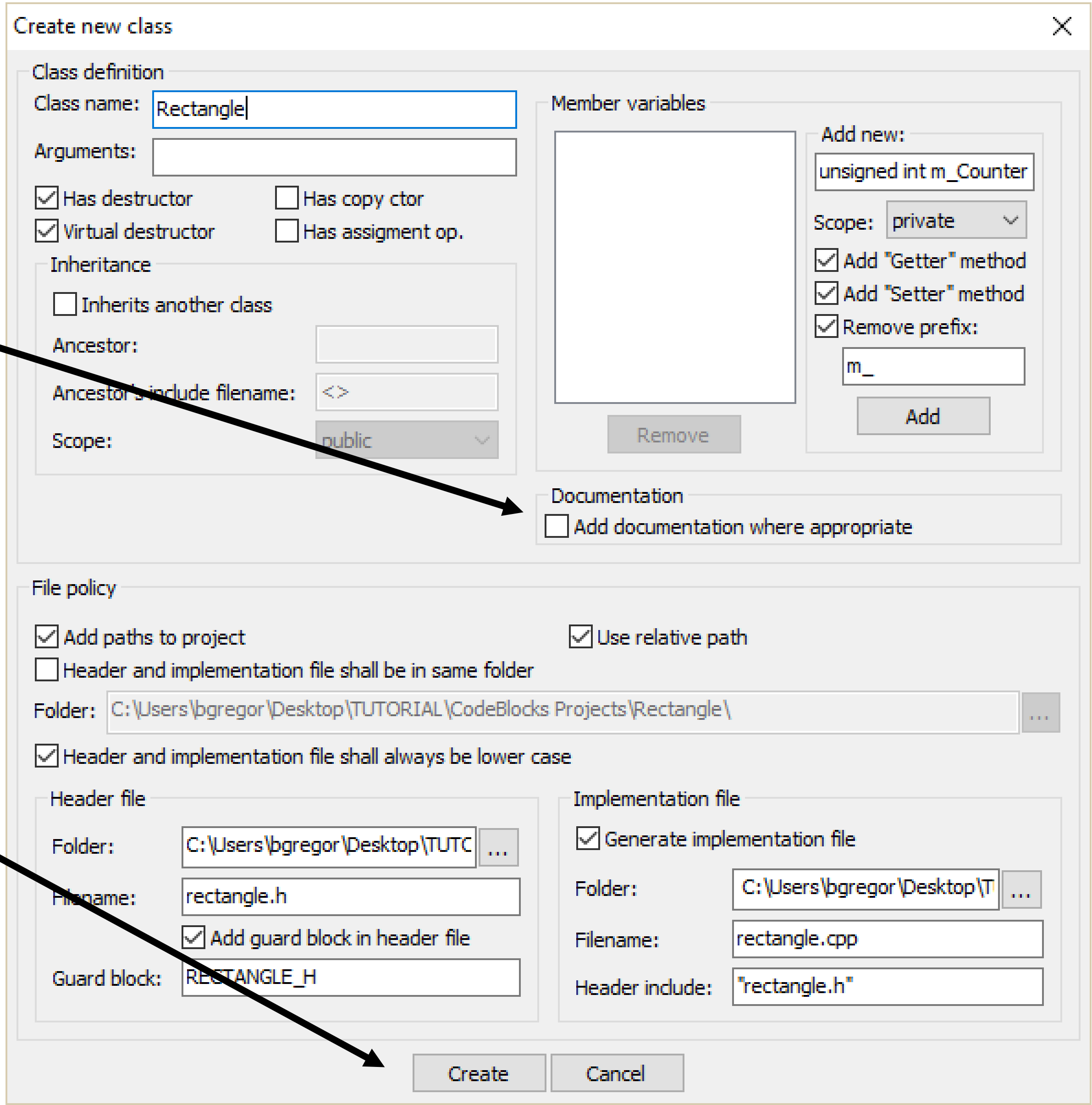
BOSTON UNIVERSITY

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!



BOSTON UNIVERSITY

rectangle.h

```cpp
#ifndef RECTANGLE_H
#define RECTANGLE_H


class Rectangle
{
    public:
        Rectangle();
        virtual ~Rectangle();

    protected:

    private:
};

#endif // RECTANGLE_H
```

rectangle.cpp

```cpp
#include "rectangle.h"

Rectangle::Rectangle()
{
    //ctor
}

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

- 2 files are automatically generated: rectangle.h and rectangle.h.cpp

BOSTON UNIVERSITY

Modify rectangle.h

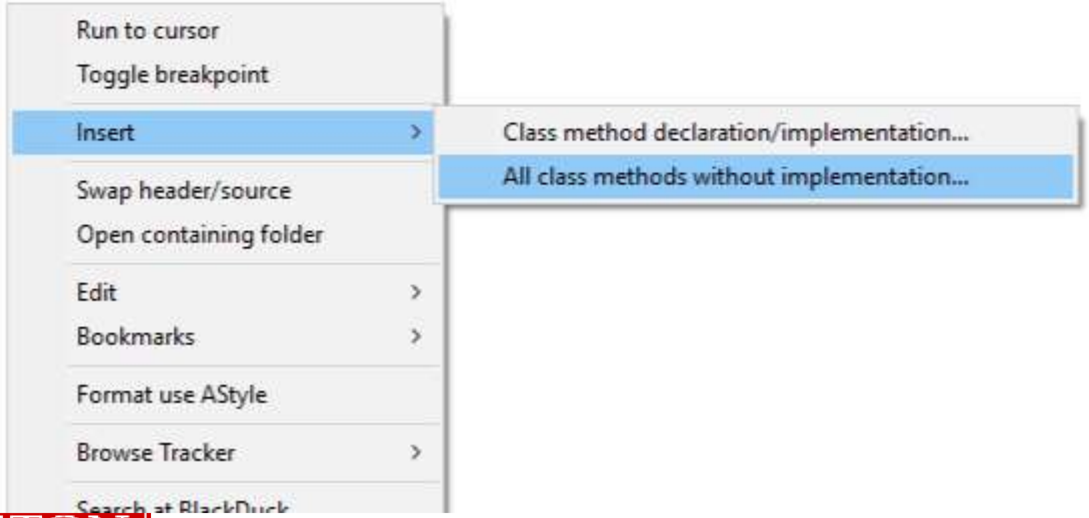
- As in the sample *BasicRectangle*, add storage for the length and width to the header file. Add a *declaration* for the Area method.
- The *protected* keyword will be discussed later.
- The *private* keyword declares anything following it (members, methods) to be visible only to code **in this class**.

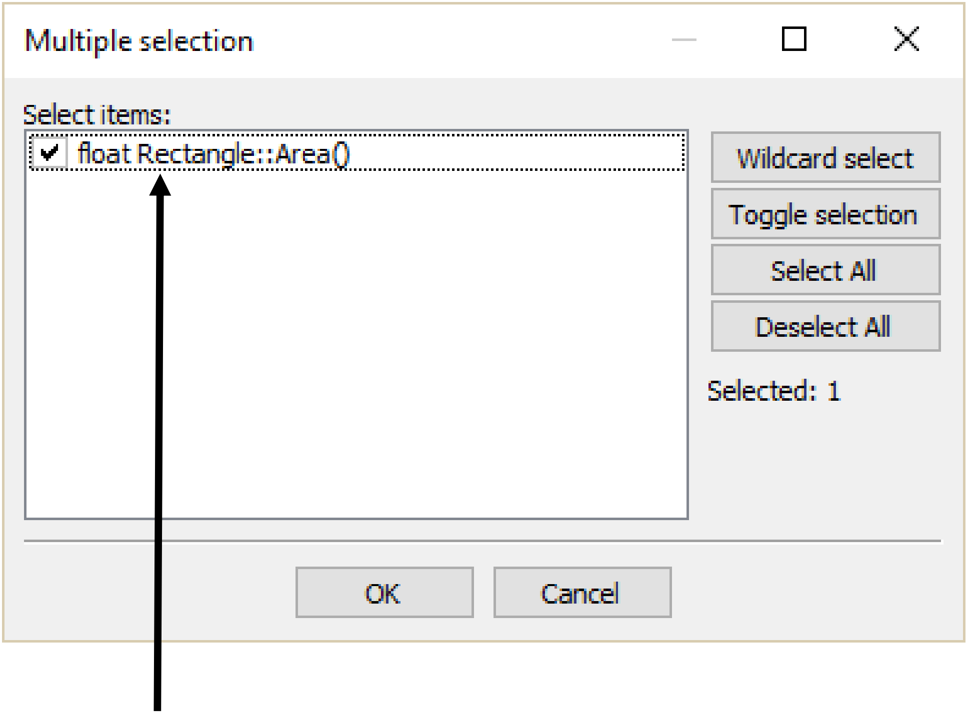
```
#ifndef RECTANGLE_H
#define RECTANGLE_H


class Rectangle
{
    public:
        Rectangle();
        virtual ~Rectangle();

        float m_length ;
        float m_width ;

        float Area() ;
    protected:

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

BOSTON UNIVERSITY

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.

rectangle.cpp

- 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

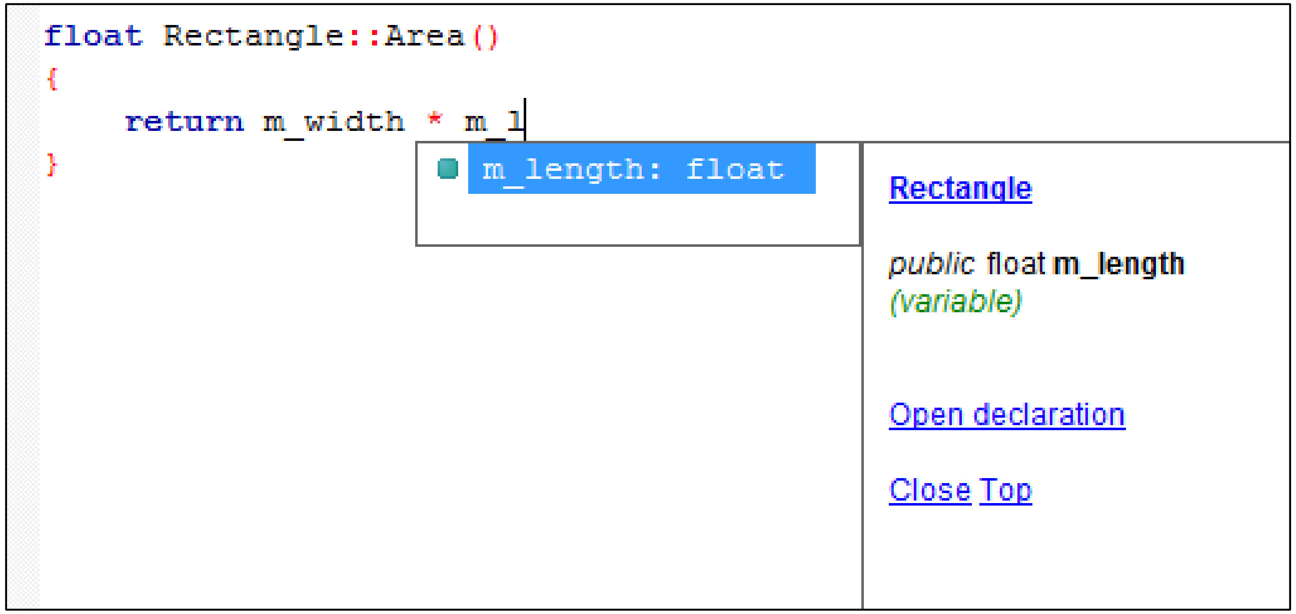
- Now take a few minutes to fill in the code for Area().
  - Hint – look at the code used in BasicRectangle...

```
#include "rectangle.h"

Rectangle::Rectangle()
{
    //ctor
}

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

float Rectangle::Area()
{

}
```

BOSTON UNIVERSITY

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.



BOSTON UNIVERSITY

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…

BOSTON UNIVERSITY

Solution

- You should have come up with something like this:

```
#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;
}
```

References and Pointers

- 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 *:

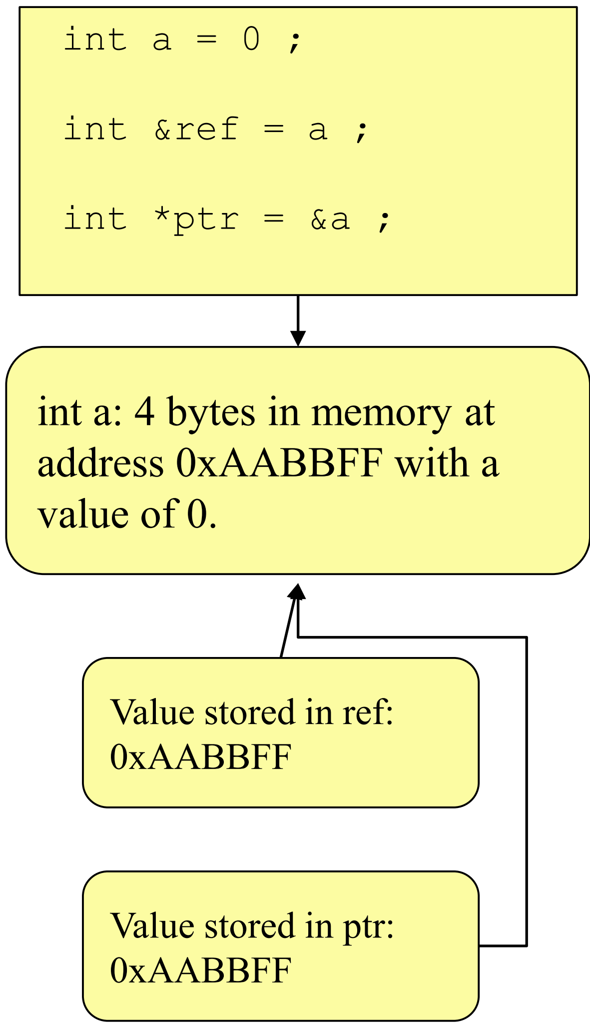
```
int add (int *a, int b)
```

- 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"

	Reference	Pointer
Declaration	int &ref ;	int *ptr ;
Set memory address to something in memory	int a = 0 ; int &ref = a ;	int a = 0 ; int *ptr = &a ;
Fetch value of thing in memory	cout << ref ;	cout << *ptr ;
Can refer/point to nothing (null value)?	No	Yes
Can change address that it refers to/points at?	No. int a = 0 ; int b = 1 ; int &ref = a ; ref = b ; // value of a is now 1!	Yes int a = 0 ; int b = 1 ; int *ptr = &a ; ptr = &b ; // ptr now points at b

Object member/method syntax	MyClass obj ;
	MyClass &ref = obj ;
	
	ref.member ;
	ref.method();
		MyClass obj ;
		MyClass *ptr = obj ;
		ptr->member ;
		ptr->method();
		
		// OR
		(*ptr).member ;
		(*ptr).method() ;



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 ;
```

BOSTON UNIVERSITY

Null Value Checking

```
//  Pointer version
void add(const int *a, const int b, int *c)
{
   if (a && c) { // check for null pointer
     *c = *a + b ;
   }
}

// a && c  → this means if a AND c are not
//            null
```

```
//  Reference version
void add(const int &a, const int b, int &c)
{
   c = a + b ;
}
```

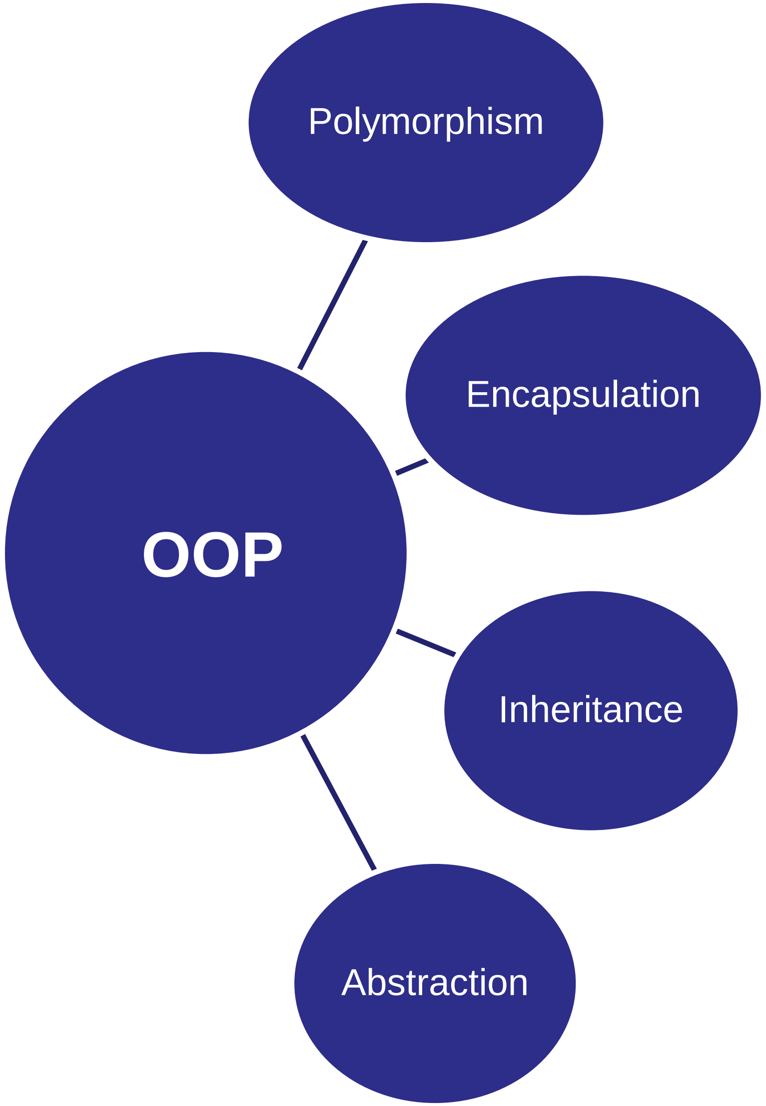
- A null value means the pointer is not currently pointing at anything.
  - It’s a good idea to check before accessing the value they point at.

- References cannot be null, so the code on the right does not need checking.

BOSTON UNIVERSITY

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



BOSTON UNIVERSITY

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)

```
#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
```

BOSTON UNIVERSITY

Encapsulation

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

BOSTON UNIVERSITY

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:

```
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.

BOSTON UNIVERSITY

When an object is instantiated…

- The rT object is created in memory.
- When it is created its *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 *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.

```
#include "rectangle.h"

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

```
#include "rectangle.h"

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

Note the constructor has no return type!

BOSTON UNIVERSITY

A second constructor

rectangle.h

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

   /* etc */
};
```

```
#include "rectangle.h"

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

OR

rectangle.cpp

```
#include "rectangle.h"

/* 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:

Colon goes here

```
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.

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.

```
#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;
}
```

BOSTON UNIVERSITY

Default values

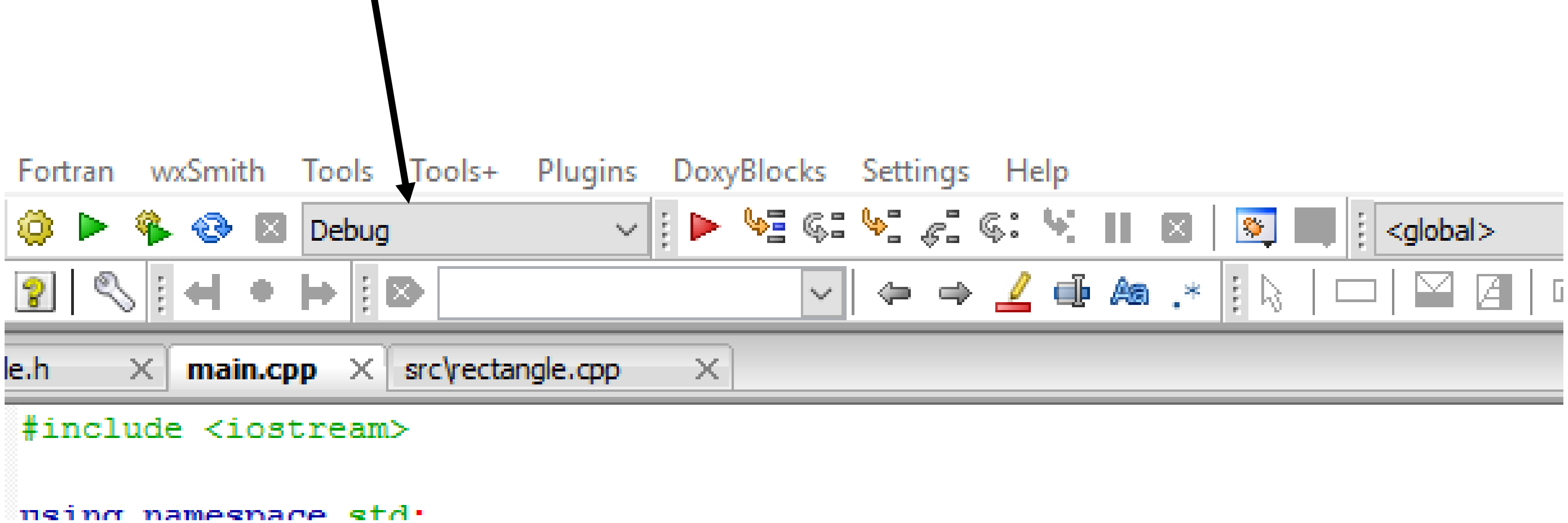
- C++11 added the ability to define default values in headers in an intuitive way.
- Pre-C++11 default values would have been coded into constructors.
- If members with default values get their value set in constructor than the default value is ignored.
  - i.e. no “double setting” of the value.

```
#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
```

BOSTON UNIVERSITY

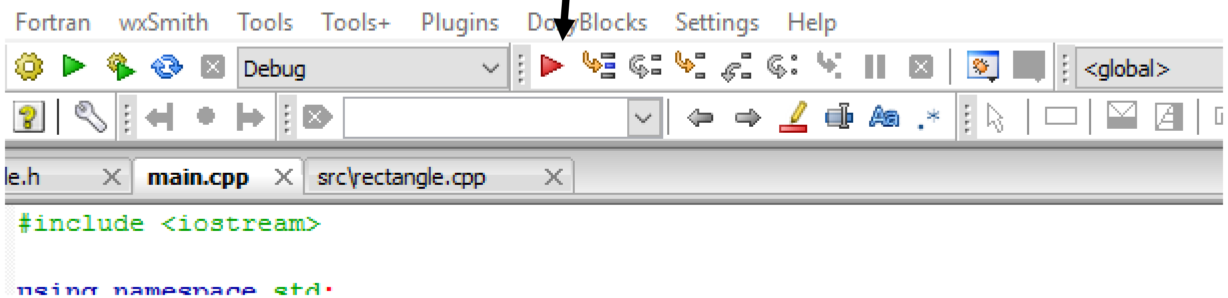
Using the C::B Debugger

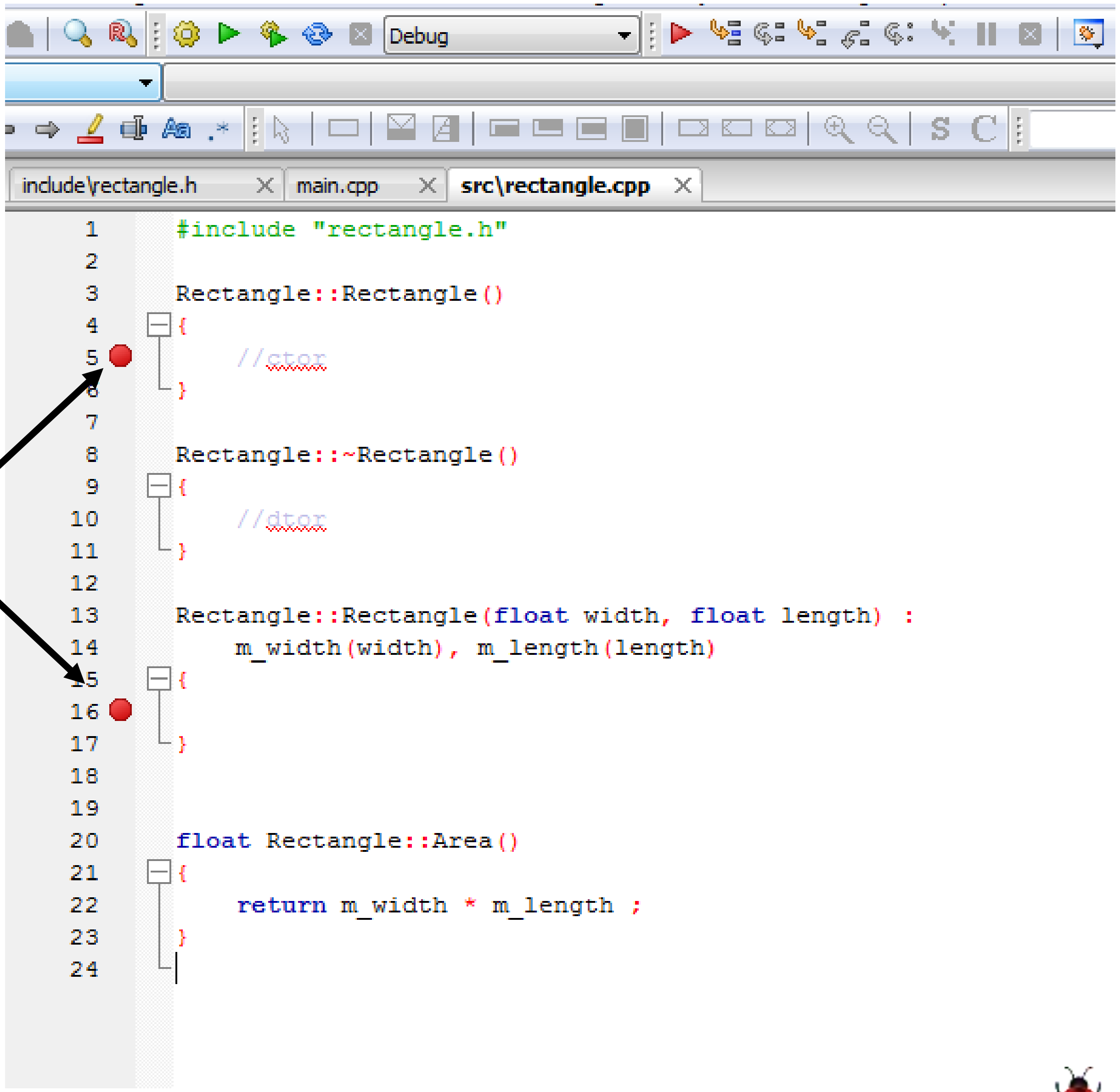
- To show how this works we will use the C::B interactive debugger to step through the program line-by-line to follow the constructor calls.
- Make sure you are running in *Debug* mode. This turns off compiler optimizations and has the compiler include information in the compiled code for effective debugging.



Add a Breakpoint

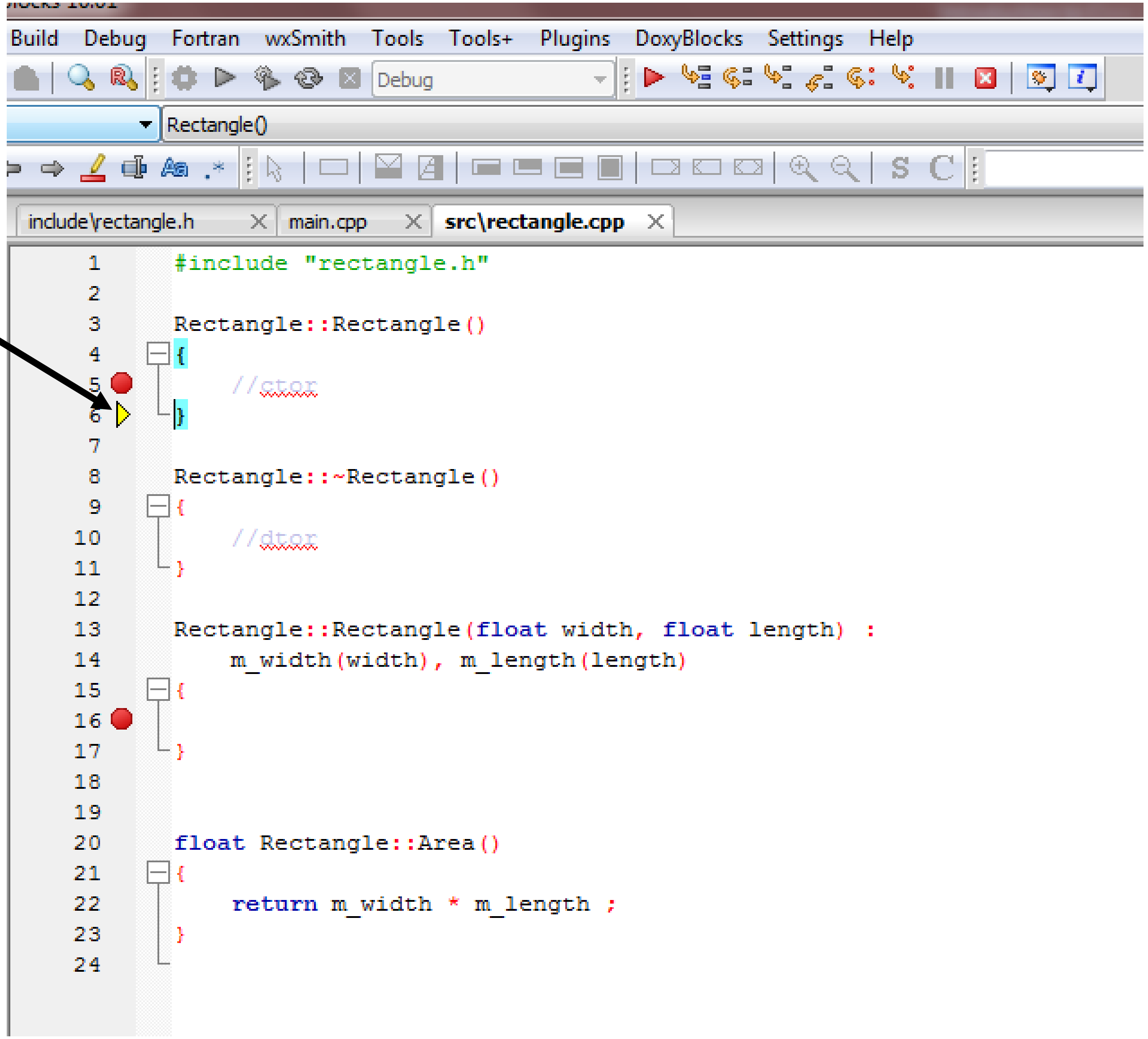
- Breakpoints tell the debugger to halt at a particular line so that the state of the program can be inspected.
- In rectangle.cpp, double click to the left of the lines in the constructors to set a pair of breakpoints. A red dot will appear.
- Click the red arrow to start the code in the debugger.





BOSTON UNIVERSITY

- 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.



BOSTON UNIVERSITY

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.

```
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.

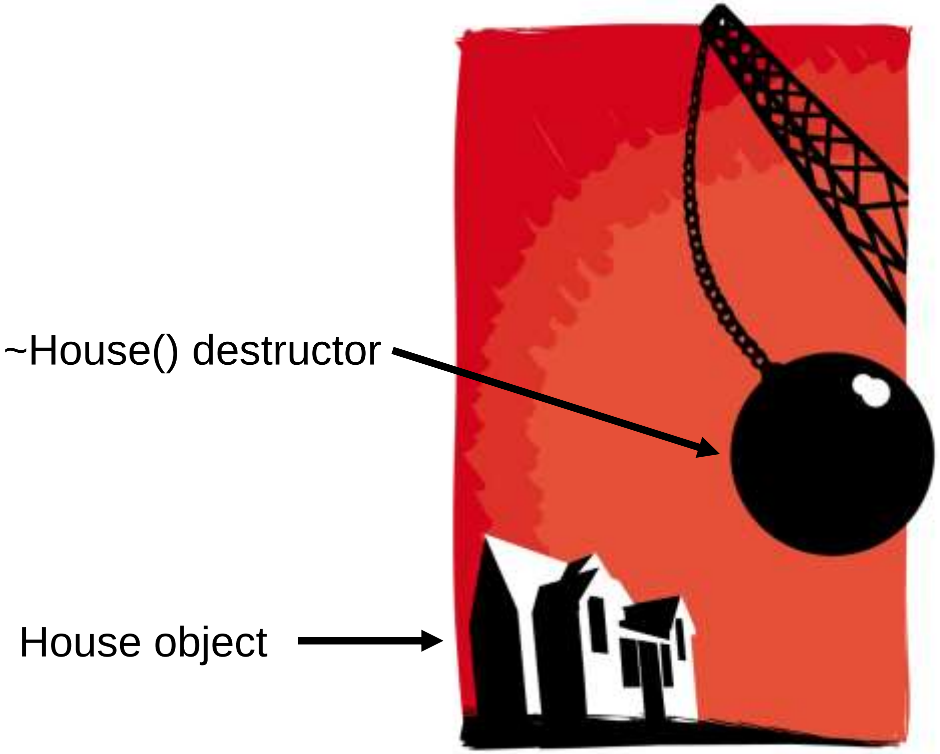
- A custom destructor is **always** needed when internal members in the class need special handling.
  - Examples: manually allocated memory, open files, hardware drivers, database or network connections, custom data structures, etc.

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.

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



BOSTON UNIVERSITY

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.

```
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
```

BOSTON UNIVERSITY

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.

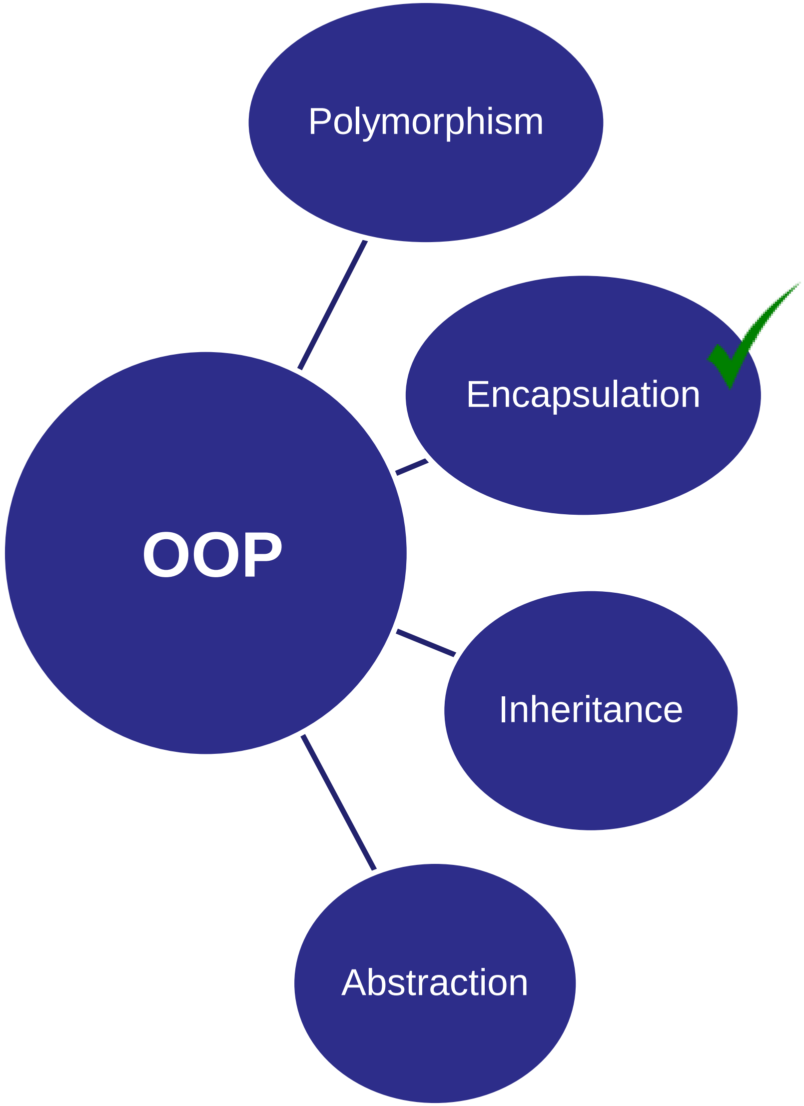
```
Rectangle rT_1(1.0,2.0) ;
// Now use the copy constructor
Rectangle rT_2(rT_1) ;
// Do an assignment, with the
// default assignment operator
rT_2 = rT_1 ;
```

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

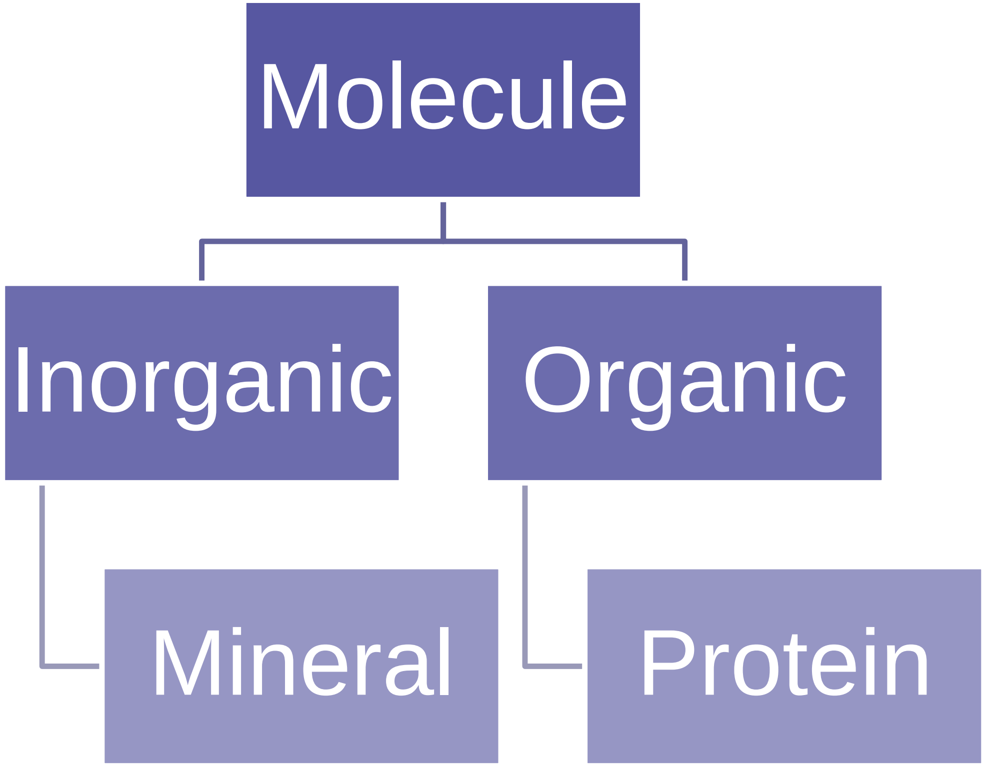


BOSTON UNIVERSITY

Inheritance

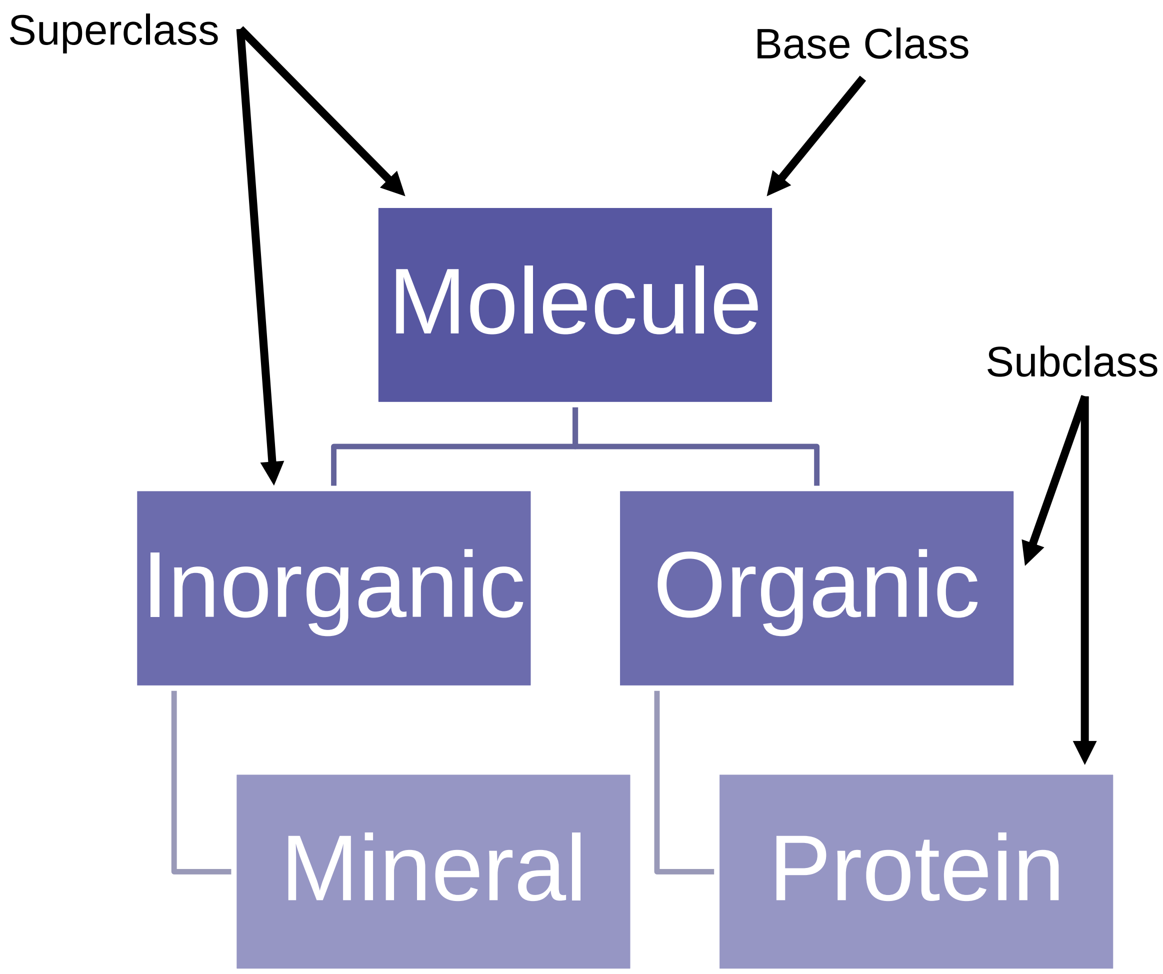
- Inheritance is the ability to form a hierarchy of classes where they share common members and methods.
  - Helps with: code re-use, consistent programming, program organization

- This is a powerful concept!

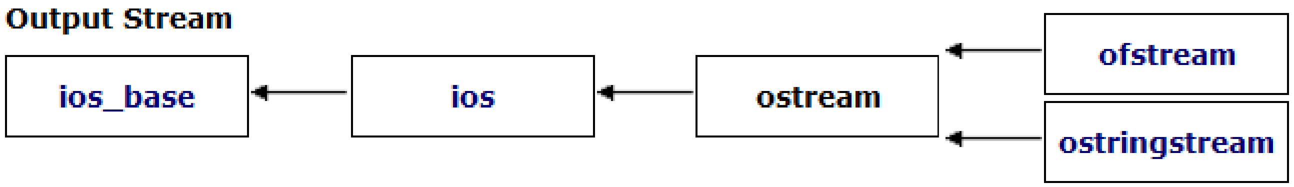


Inheritance

- 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

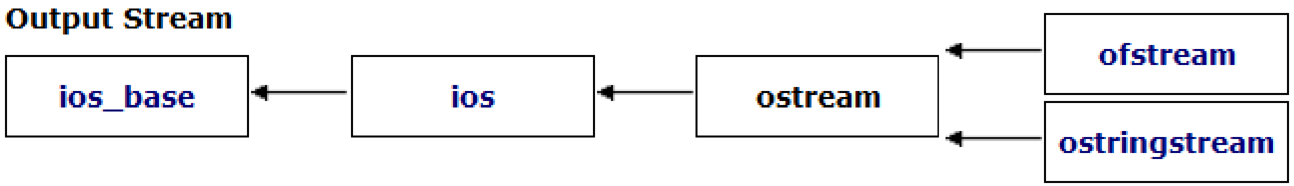


- Streams in C++ are series of characters – the C+ I/O system is based on this concept.
- **cout** is an object of the class *ostream*. It is a write-only series of characters that prints to the terminal.
- There are two subclasses of ostream:
  - *ofstream* – write characters to a file
  - *ostringstream* – 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



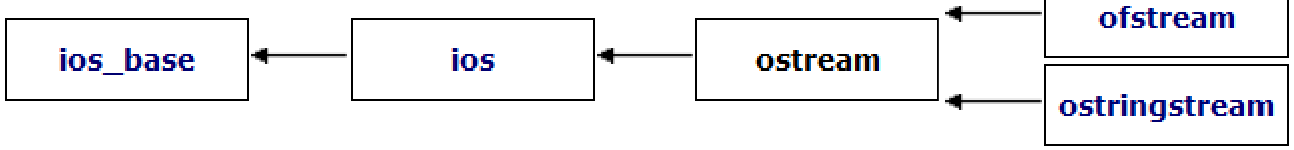
- For *ofstream* and *ofstringstream* the << operator is inherited from *ostream* and behaves the same way for each from the programmer's point of view.

- 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

Output Stream




```
#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()  ;
}
```

BOSTON UNIVERSITY

Public, protected, private

> "There are only two things wrong with C++: The initial concept and the implementation."
> – Bertrand Meyer (inventor of the Eiffel OOP language)

- 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.

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

        float m_width ;
        float m_length ;

        float Area() ;

    protected:

    private:
};
```

C++ Access Control and Inheritance

- A summary of the accessibility of members and methods:

Access	public	protected	private
Same class	Yes	Yes	Yes
Subclass	Yes	Yes	No
Outside classes	Yes	No	No

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

Inheritance

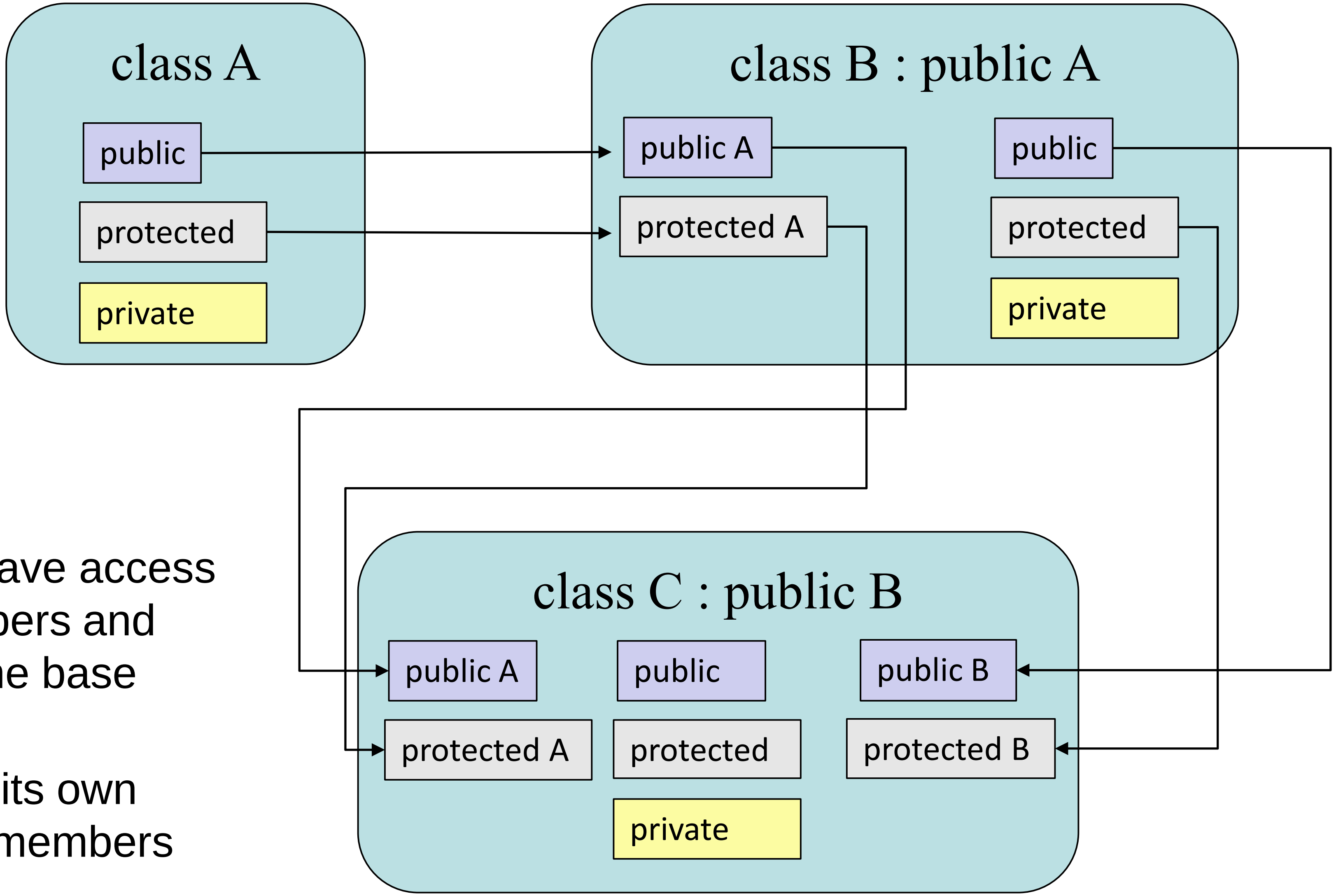
```
class Sub : public Super {
// in methods, could access
// i and j from Parent only.
};
```

Outside code

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

BOSTON UNIVERSITY

Inheritance

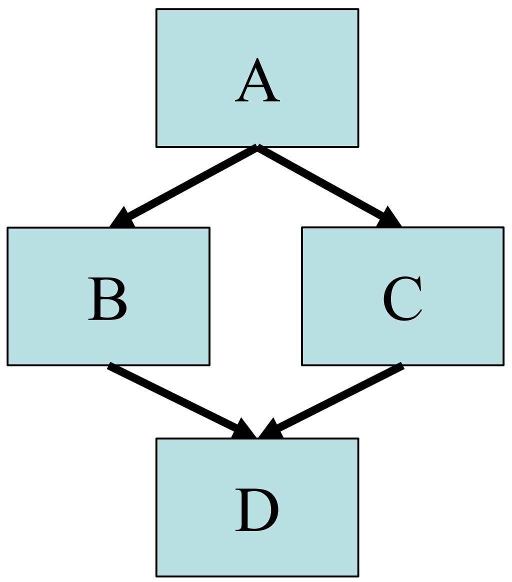


- With inheritance subclasses have access to private and protected members and methods all the way back to the base class.
- Each subclass can still define its own public, protected, and private members and methods along the way.

BOSTON UNIVERSITY

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*.

BOSTON UNIVERSITY

C++ Inheritance Syntax

- Inheritance syntax pattern:

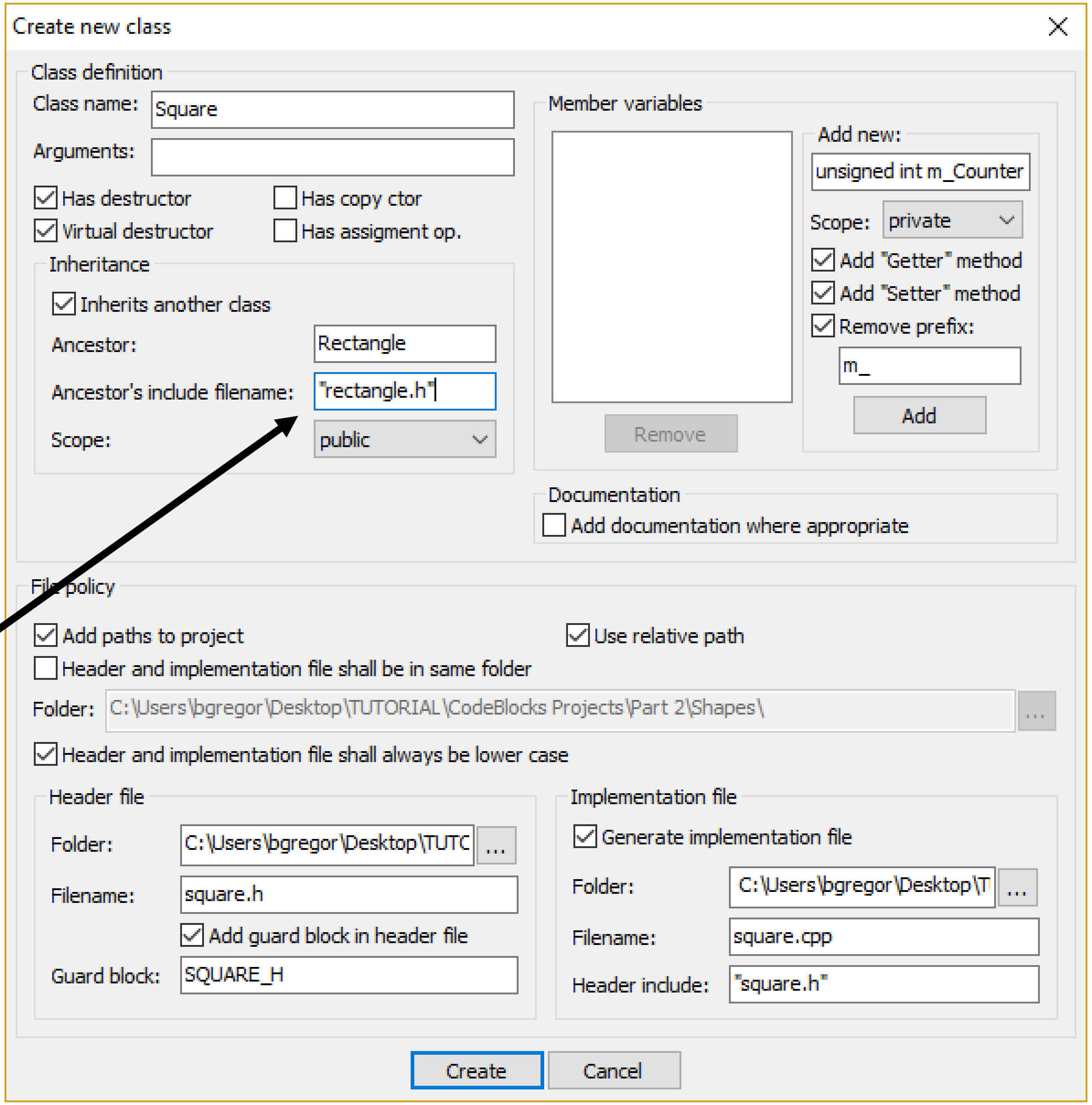
```
class SubclassName : public SuperclassName
```

- 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.*

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

class Sub : public Super {
// ...
};
```

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!



square.h

```cpp
#ifndef SQUARE_H
#define SQUARE_H

#include "rectangle.h"


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

    protected:

    private:
};

#endif // SQUARE_H
```

square.cpp

```cpp
#include "square.h"

Square::Square()
{
    //ctor
}

Square::~Square()
{
    //dtor
}
```

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

- 2 files are automatically generated: square.h and square.cpp
- Class Square inherits from class Rectangle

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

```
#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 ;
}
```

- 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?

BOSTON UNIVERSITY

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!

```
class class_c {
public:
    int max;
    int min;
    int middle;

    class_c(int my_max) {
        max = my_max > 0 ? my_max : 10;
    }
    class_c(int my_max, int my_min) : class_c(my_max) {
        min = my_min > 0 && my_min < max ? my_min : 1;
    }
    class_c(int my_max, int my_min, int my_middle) :
            class_c (my_max, my_min){
        middle = my_middle < max &&
               my_middle > min ? my_middle : 5;
}
};
```

```
Square::Square(float length) :
       Rectangle(length,length)
{
  // other code could go here.
}
```

Reference:

https://msdn.microsoft.com/en-us/library/dn387583.aspx

BOSTON UNIVERSITY

Solution 2

```
#ifndef SQUARE_H
#define SQUARE_H

#include "rectangle.h"


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

    protected:

    private:
};

#endif // SQUARE_H
```

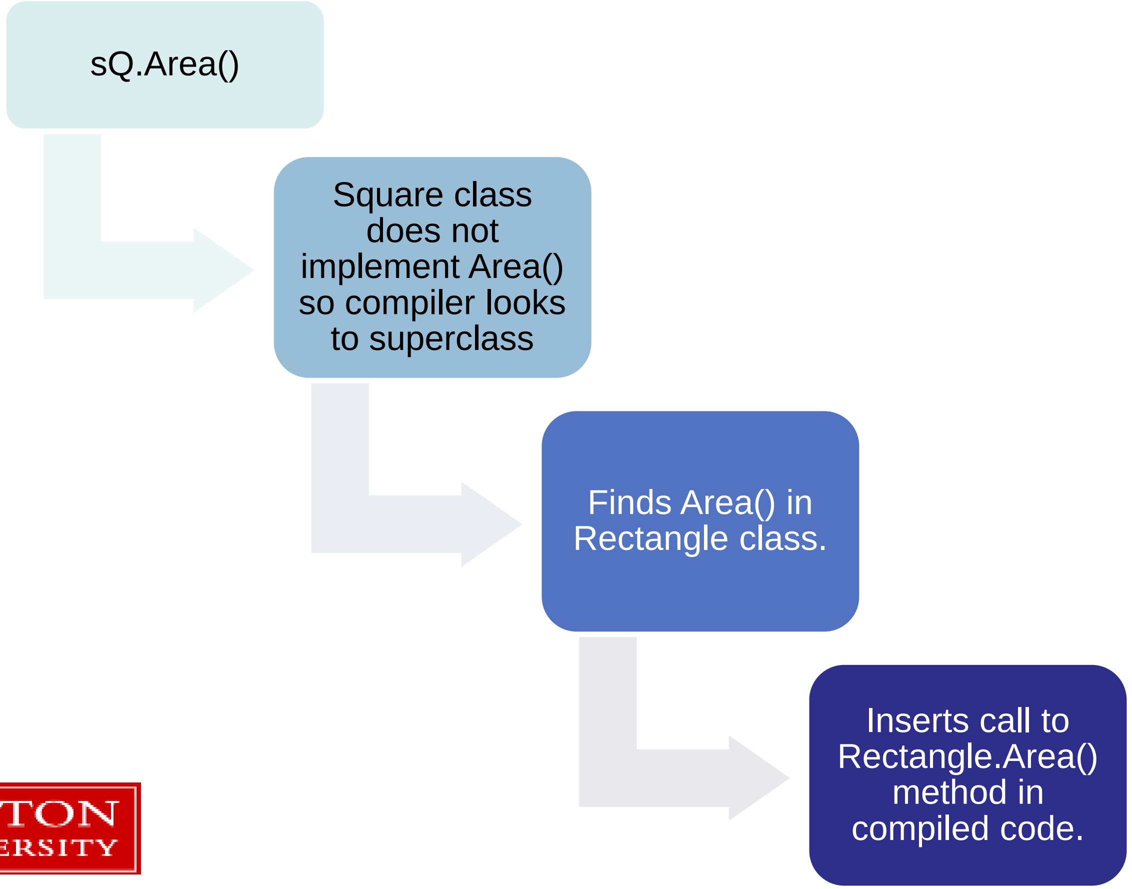
```
#include "square.h"

Square::Square(float length) :
     Rectangle(length, length) {}
```

- 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.

BOSTON UNIVERSITY

Trying it out in main()

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

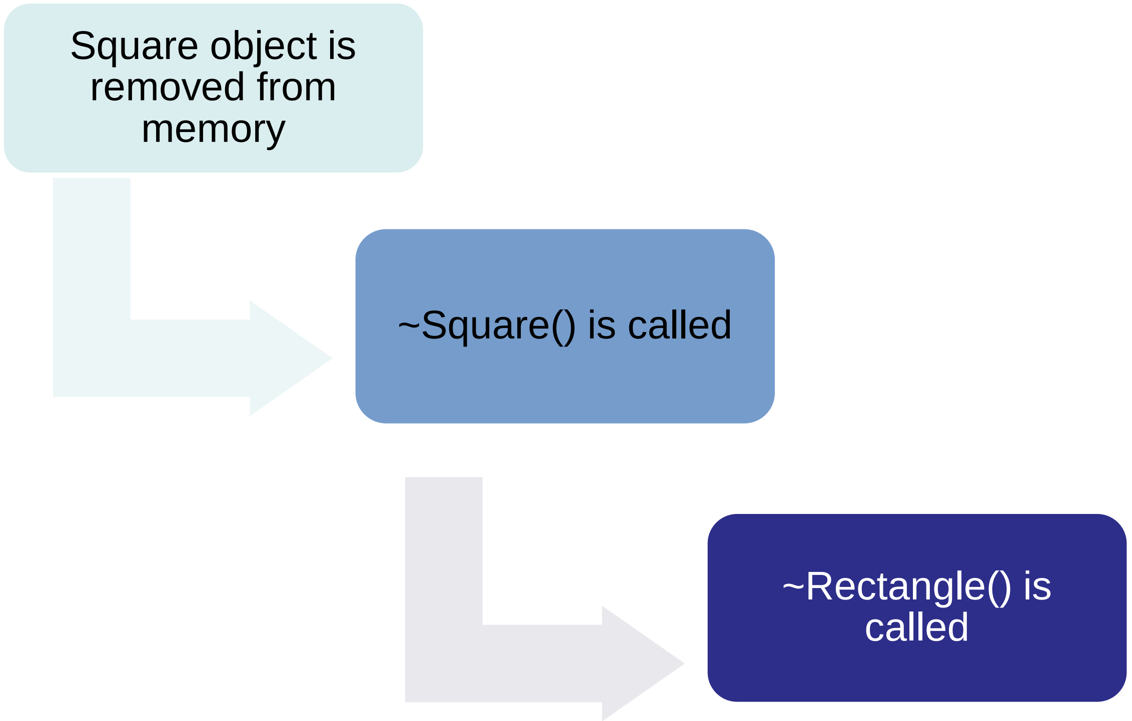



```
#include <iostream>

using namespace std;

#include "square.h"

int main()
{
    Square sQ(4) ;

    // Uses the Rectangle Area() method!
    cout << sQ.Area() << endl ;

    return 0;
}
```

BOSTON UNIVERSITY

More on Destructors

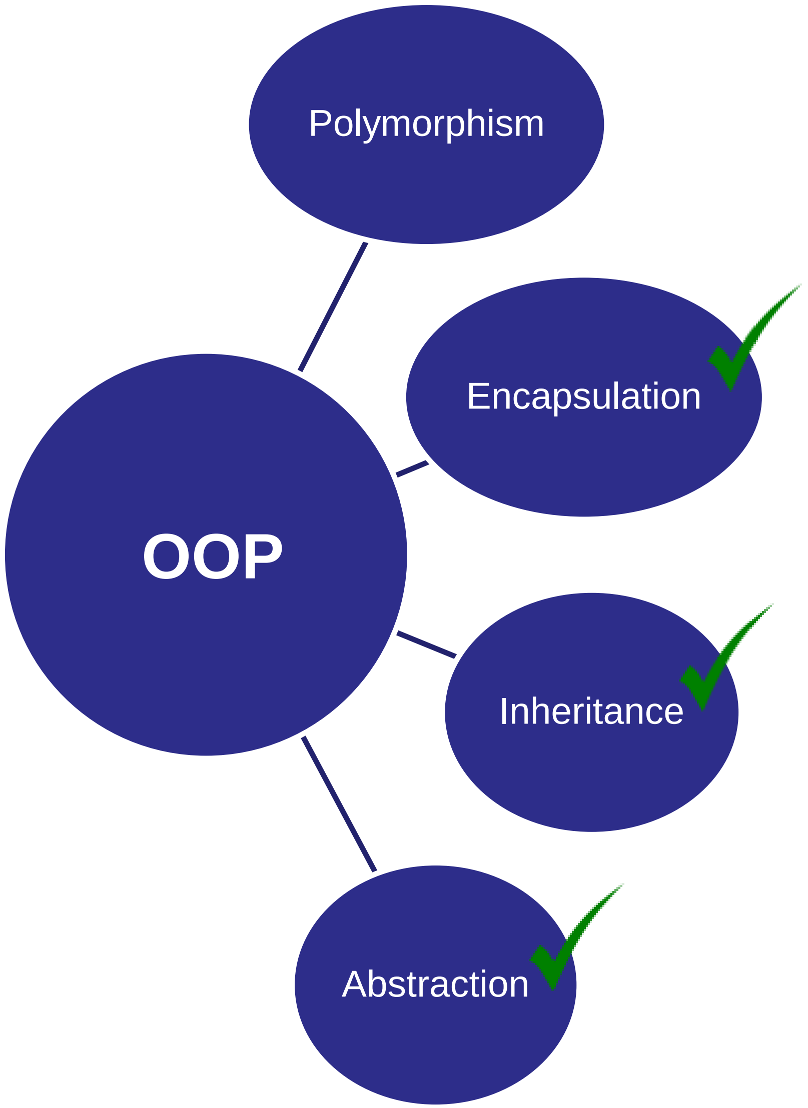
- When a subclass object is removed from memory, its destructor is called as it is for any object.
- Its superclass destructor is than *also* called .
- Each subclass should only clean up its own problems and let superclasses clean up theirs.



BOSTON UNIVERSITY

The formal concepts in OOP

- Next up: Polymorphism



BOSTON UNIVERSITY

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.

```
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.

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

```
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
```

BOSTON UNIVERSITY

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.

```
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
```

BOSTON UNIVERSITY

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.*

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

```
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!!
```

BOSTON UNIVERSITY

Type casting

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

- 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.

BOSTON UNIVERSITY

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

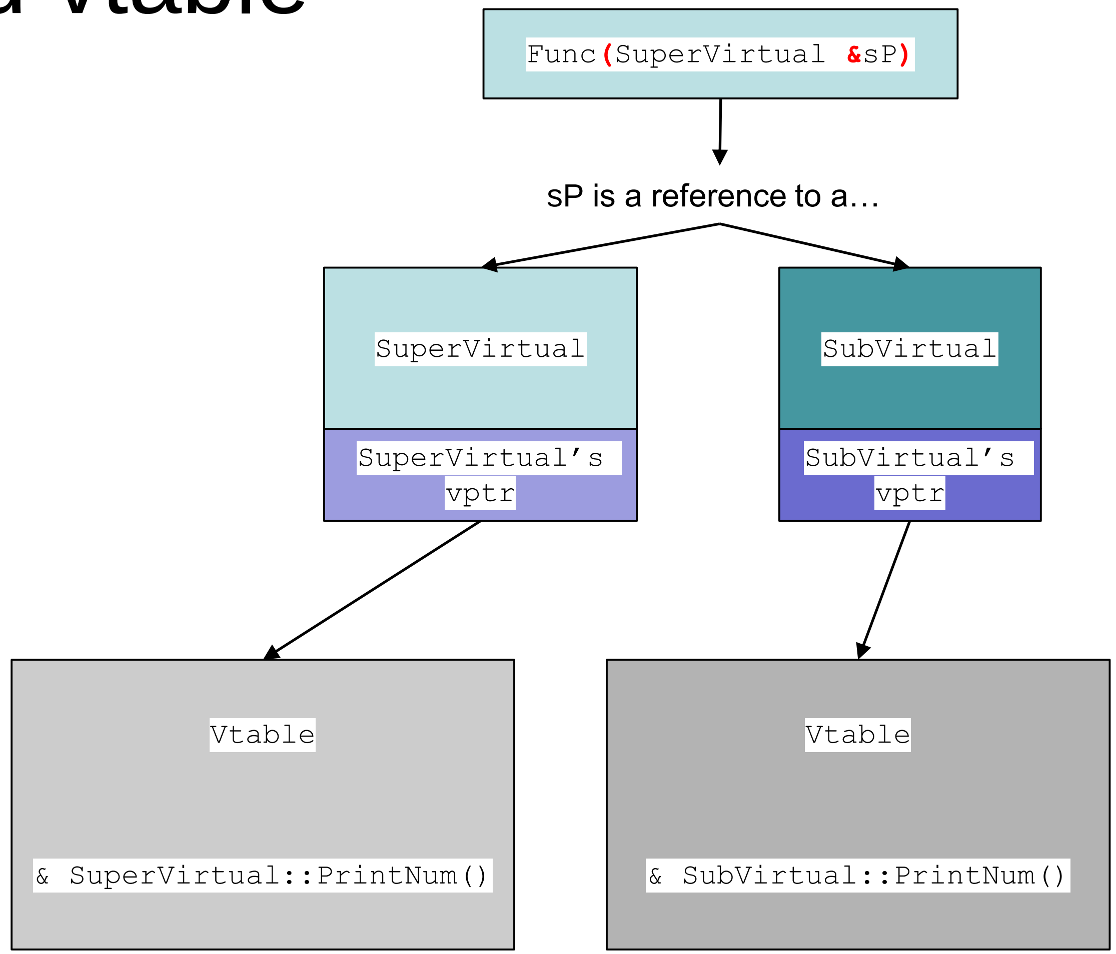
- What is going on here?
- Leaving out the virtual keyword on a method that is overridden results in the compiler deciding *at compile time* which version (subclass or superclass) of the method to call.
- This is called early or static *binding*.
- At compile time, a function that takes a superclass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



BOSTON UNIVERSITY

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 implemenations of Func()
- Make sure the “Watches” debugging window is open.

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.

BOSTON UNIVERSITY

Why all this complexity?

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

- Called by reference – late binding to PrintNum()

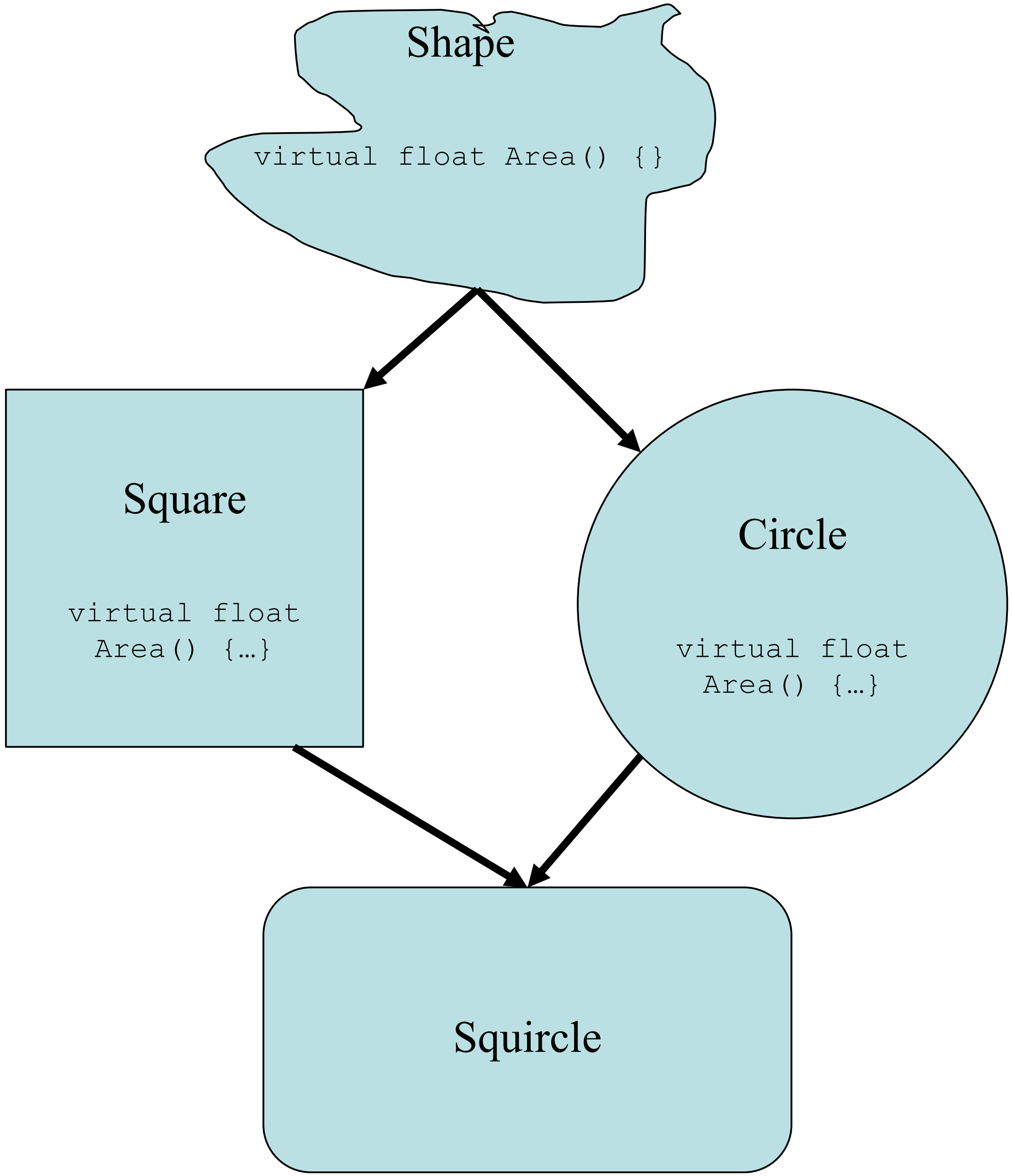
```
void FuncLate(SuperVirtual sP)
{
    sP.PrintNum() ;
}
```

- Called by **value** – early binding to PrintNum even though it's virtual!

- 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.

- 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:

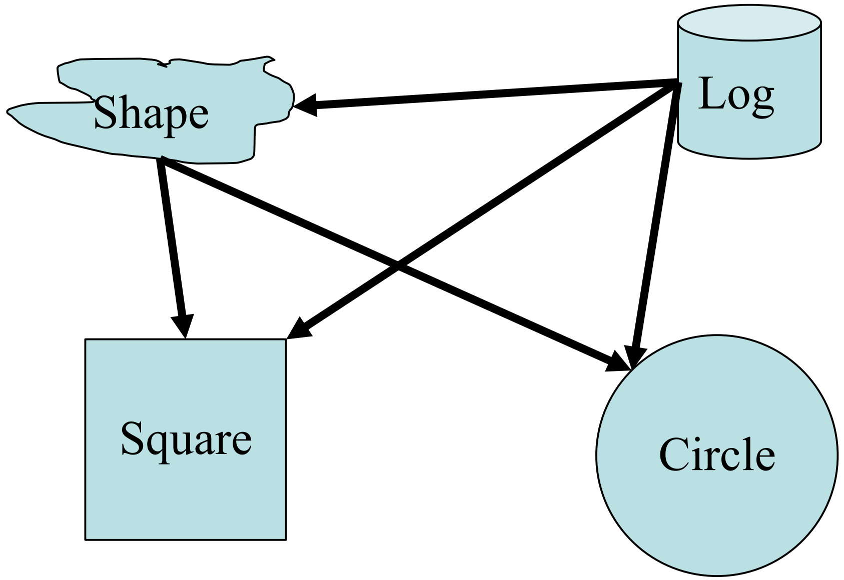
    class Squircle : public Square, public Circle
- The Shape class implements an empty Area() method. The Square and Circle classes override it. Squircle does not.
- Under late binding, which version of Area is accessed from Squircle? Square.Area() or Circle.Area()?



BOSTON UNIVERSITY

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.

BOSTON UNIVERSITY

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?

```
(…error…)
include/square.h:10:7: note:   because the following virtual
functions are pure within 'Square':
 class Square : public Rectangle, Log
       ^
include/square.h:7:18: note:  virtual void Log::LogInfo()
     virtual void LogInfo()=0 ;
```

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

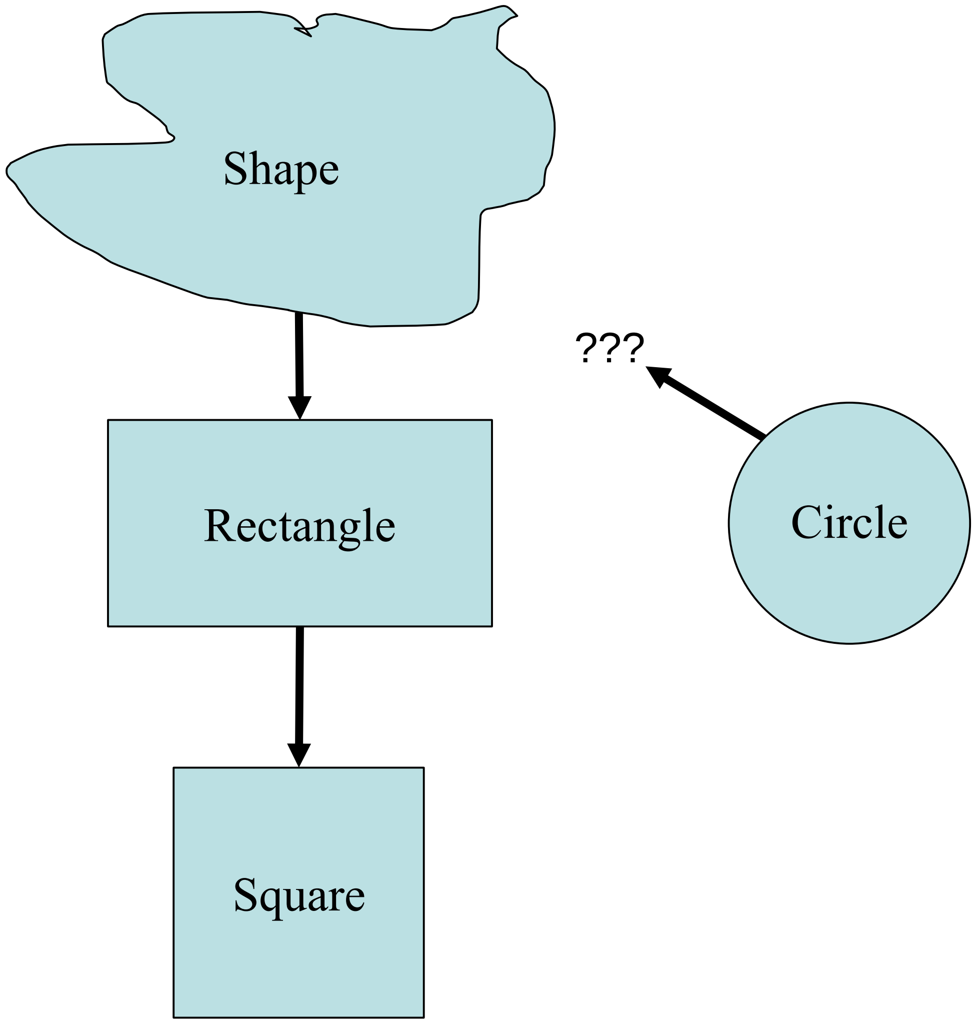
```
#ifndef SQUARE_H
#define SQUARE_H

#include "rectangle.h"

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

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

    private:
};

#endif // SQUARE_H
```

BOSTON UNIVERSITY

- 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.

```cpp
#ifndef SHAPE_H
#define SHAPE_H


class Shape
{
    public:
        Shape() {}
        virtual ~Shape() {}

        virtual float Area()=0 ;
    protected:

    private:
};

#endif // SHAPE_H
```

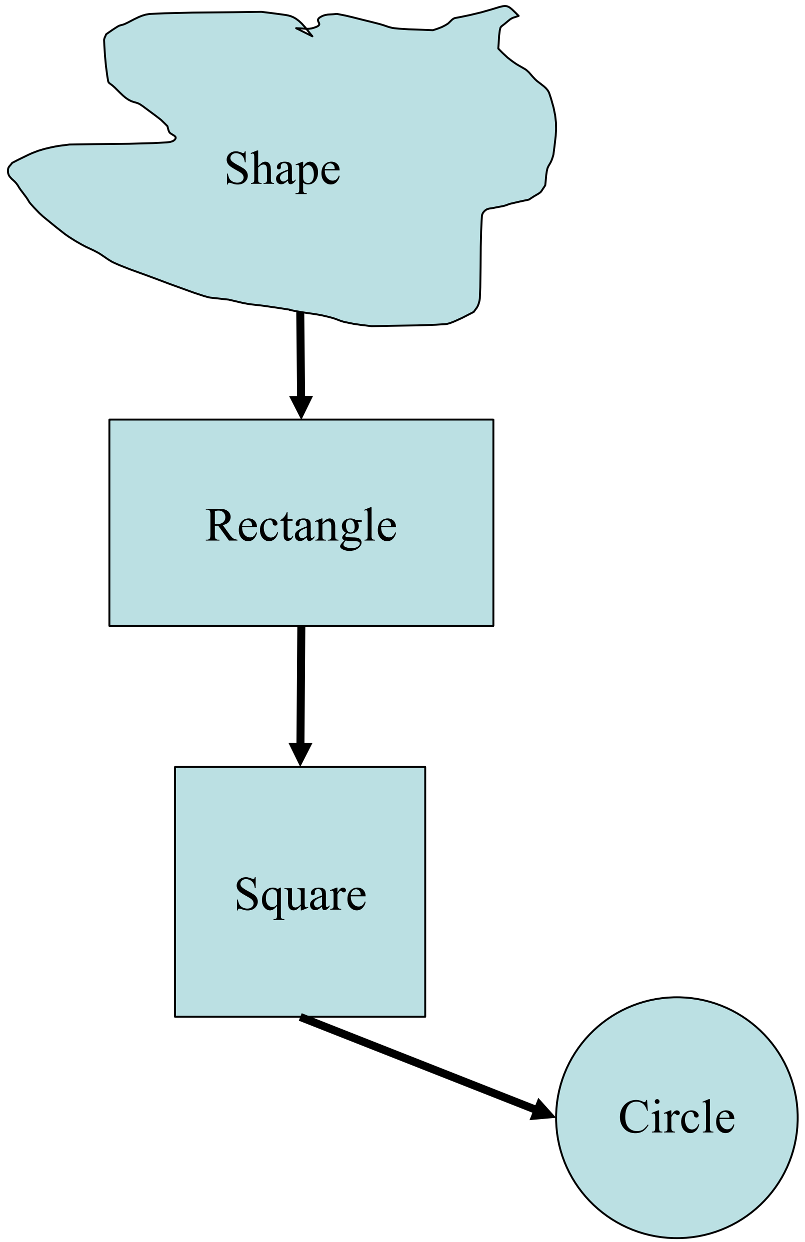
Give it a try

- 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

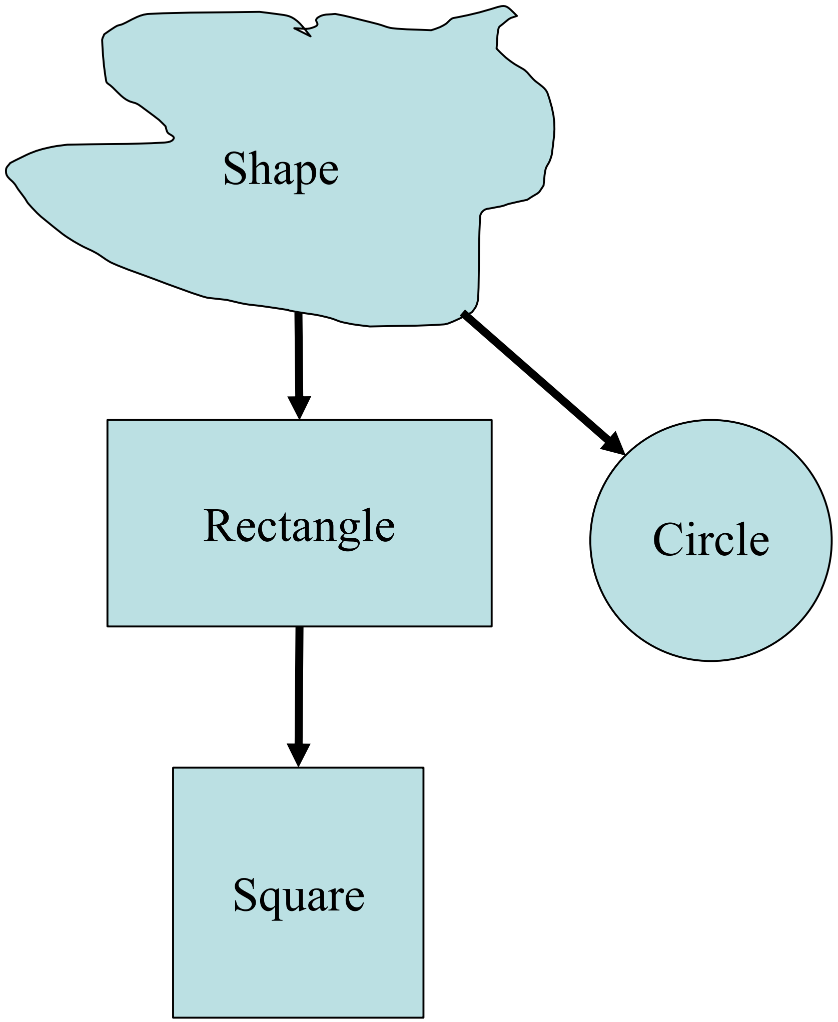
- A Circle has one dimension (radius), like a Square.
  - Would only need to override the Area() method
- But…
  - Would be storing the radius in the members m_width and m_length. This is not a very obvious to someone else who reads your code.
- Maybe:
  - Change m_width and m_length names to m_dim_1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



BOSTON UNIVERSITY

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 m_radius to store the radius.
- Implement the 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 π
  - 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.

```
#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
```

BOSTON UNIVERSITY

- circle.cpp
- Questions?

```
#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 ;
}
```

BOSTON UNIVERSITY

Quiz time!

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

```
void PrintArea(Shape shape)
```

```
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;
}
```

BOSTON UNIVERSITY

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:

```
string str = "ABC" ;
str = str + "DEF" ;
//  str is now "ABCDEF"
```

- It's possible to override +,-,=,<,>, brackets, parentheses, etc.

- Syntax:

```
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()

BOSTON UNIVERSITY

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!

BOSTON UNIVERSITY