Polymorphism

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Today's Plan

What have we done so far

Inheritance Recap

Polymorphism

What have we done so far

- OOP
    - Inheritance
- Algorithm Analysis
- ADT & Templates
    - ArrayBag
    - Pointers and dynamic memory allocation
    - LinkedBag
    - LinkedList
    - DoublyLinkedList
    - Exception handling
- OOP
    - Polymorphism (TODAY)

Midterm Exam

Next class

Tuesday 3/12

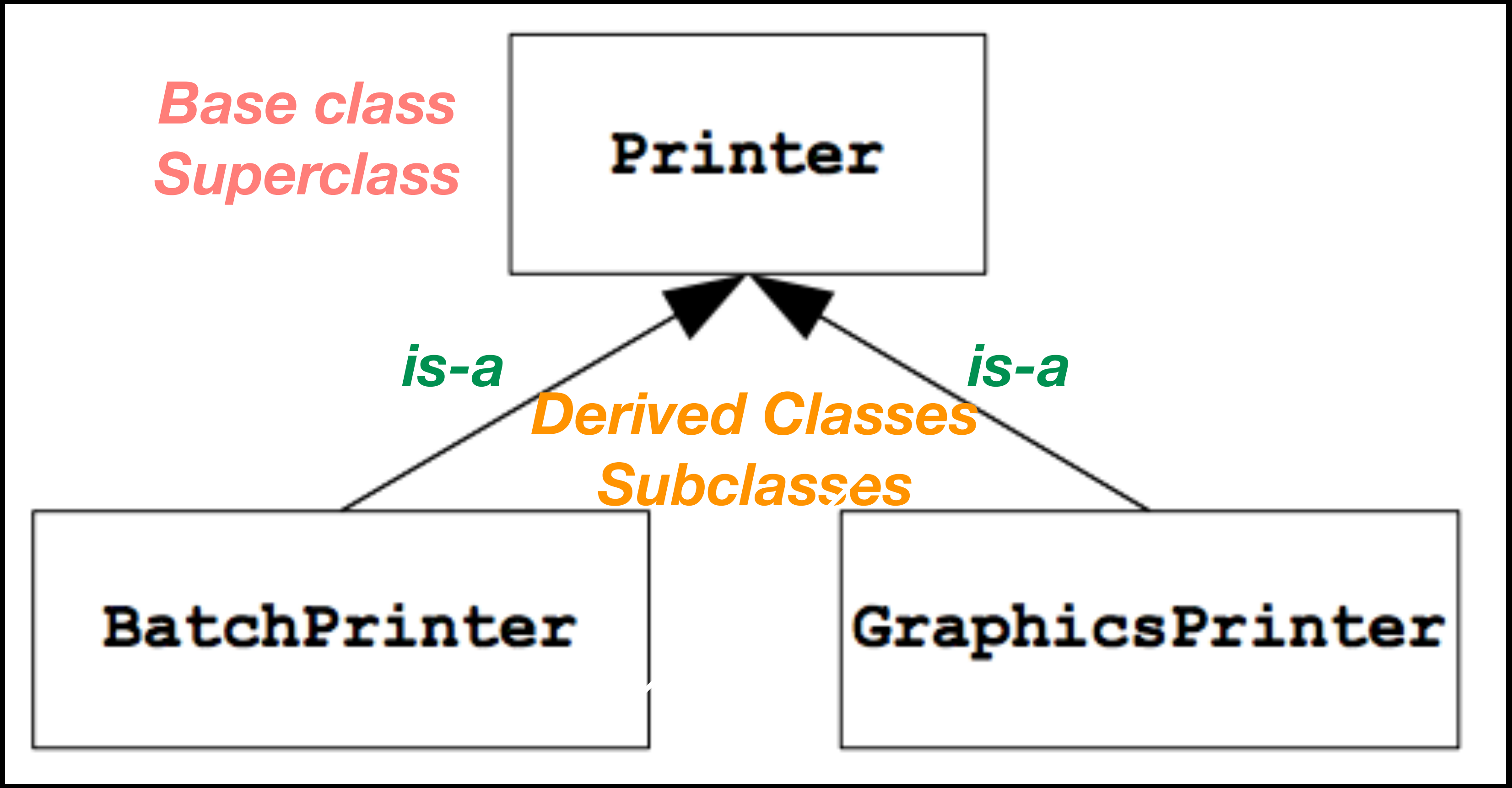
Inheritance Recap

Basic Inheritance

```
class Printer
{
public:
    //Constructor, destructor

    void setPaperSize(const int size);
    void setOrientation(const string& orientation);
    void changeCartridge();
    void printDocument(const string& document);
private:
    // stuff here
};  //end Printer

class BatchPrinter: public Printer // inherit from printer
{
public:
    //Constructor, destructor
    void addDocument(const string& document);
    void printAllDocuments();
private:
    vector<string> documents; //Document queue
};  //end BatchPrinter
```

```
class GraphicsPrinter: public Printer // inherit from printer
{
public:
    //Constructor, destructor
    void changeCartridge();
    void printDocument(const Picture& picture);

private:
    //stuff here
}; //end GraphicsPrinter
```

Basic Inheritance




```
void initializePrinter(Printer& p)
{
 //some initialization function
}
```

```
BatchPrinter batch;
initializePrinter(batch); //legal because batch is-a printer
```

Think of argument types as specifying minimum requirements

Problem

```
class BatchPrinter: public Printer // inherit from printer
{
public:
    //Constructor, destructor
    void addDocument(const string& document);
    void printAllDocuments();
private:
    vector<string> documents; //Document queue
}; //end BatchPrinter
```

Can't store different types of documents in printer queue

We would like to print all kinds of documents not just text

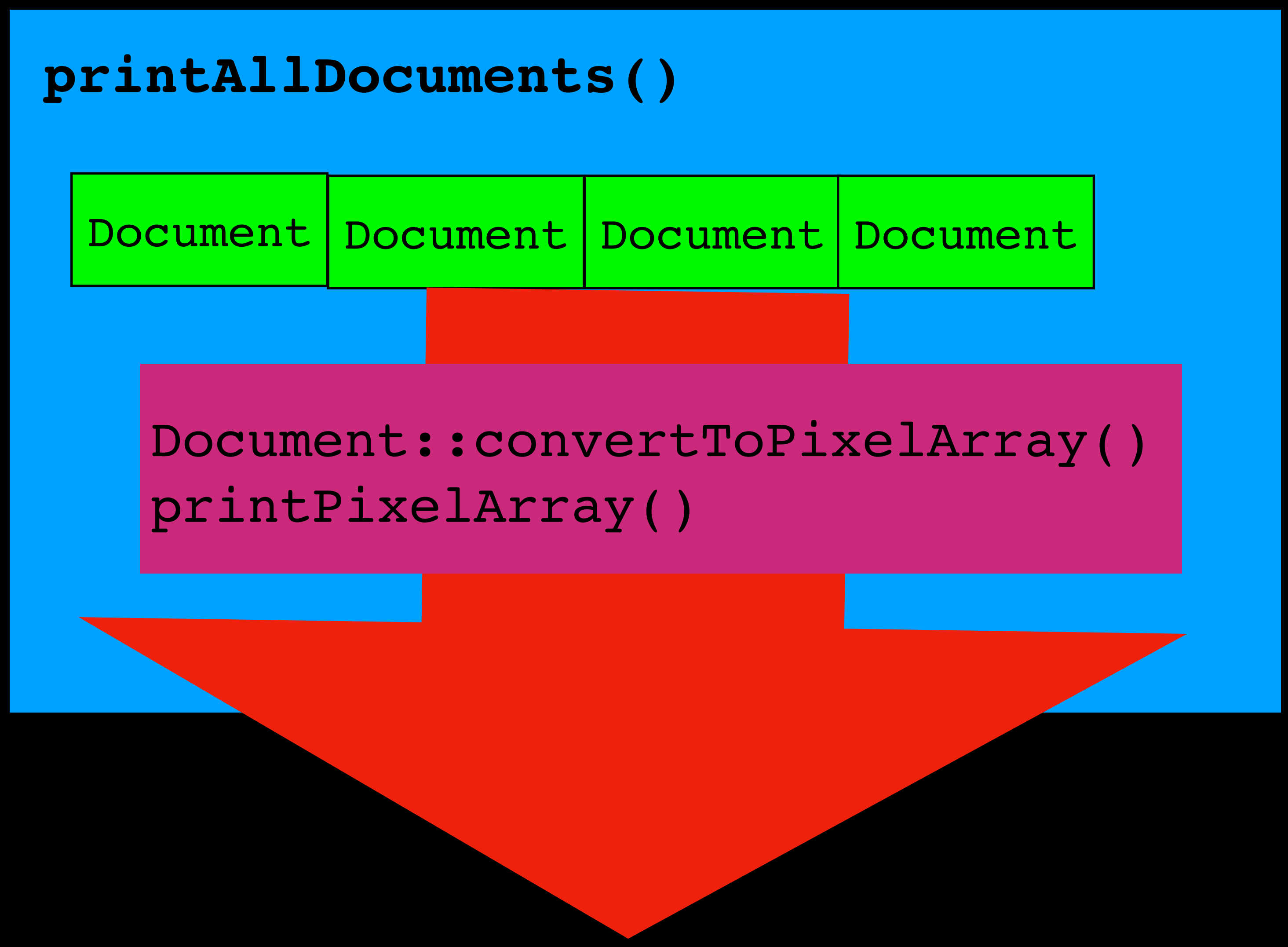
`documents` **should be able to store different types of documents**

Generalized Document

Whatever the type of document, a printer ultimately prints a grid of pixels

Generalized `Document` should know how to convert itself into a printable format

We want `Document` to be an *interface* => not concerned with implementation details


printAllDocuments()
Document
Document
Document
Document
Document::convertToPixelArray()
printPixelArray()

Polymorphism

```
class BatchPrinter: public Printer // inherit from printer
{
public:
    //Constructor, destructor
    void addDocument(const Document* document);
    void printAllDocuments();
private:
    vector<Document*> documents; //Document queue
}; //end BatchPrinter
```

Abstract Class!

This function has no implementation**

```
class Document
{
public:
    //Constructor, destructor
    virtual void convertToPixelArray() const = 0;
    virtual int getPriority() const = 0;

private:
    //stuff here
}; //end Document
```

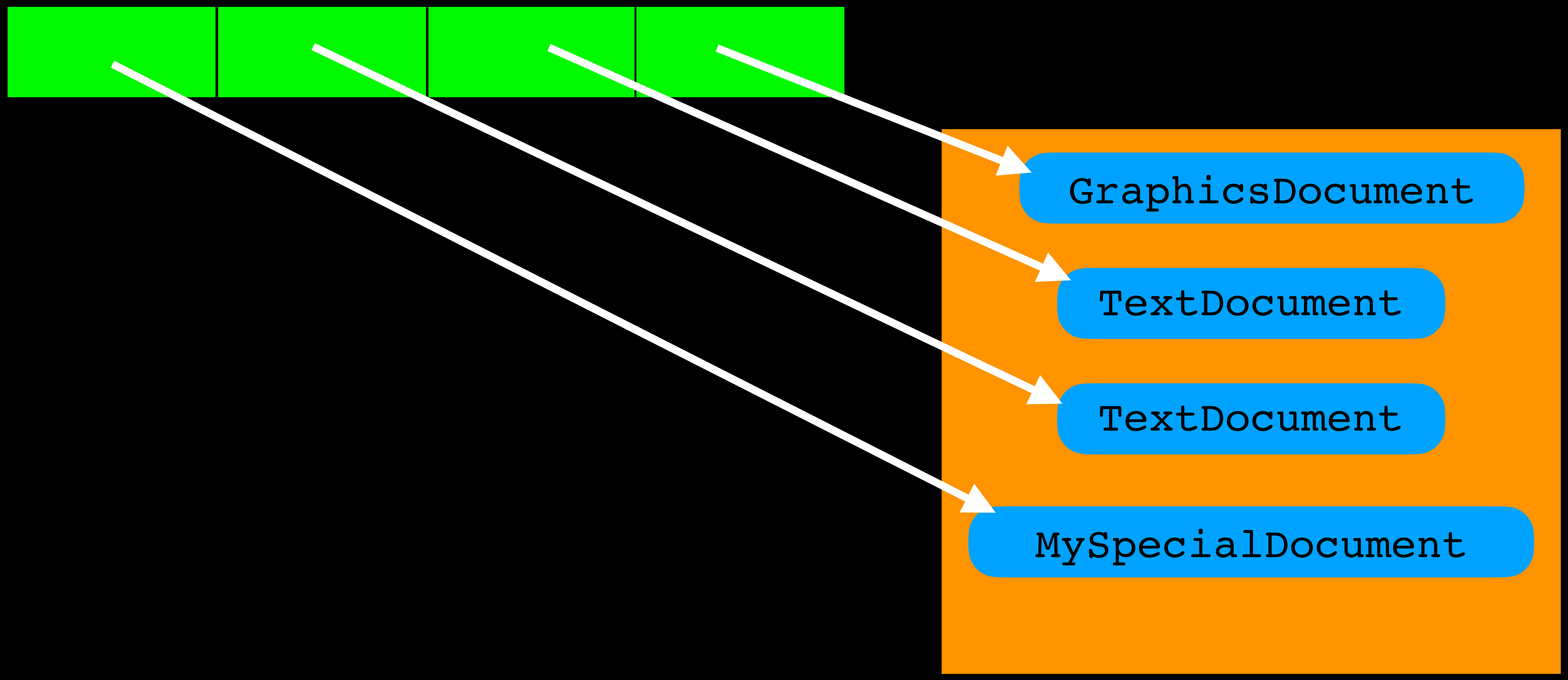
I'll explain this next

**odd syntax due to historical/political reasons, explained in quote later

```
class TextDocument: public Document// inherit from Document
{
public:
    //Constructor, destructor
    virtual void convertToPixelArray() const override;
    virtual int getPriority() const override;

    void setFont(const string& font); //text-specific formatting
    void setSize(int size);

private:
    //stuff here
}; //end TextDocument
```

Have implementation

```
class TextDocument: public Document

class GraphicsDocument: public Document

class PortableFormatDocument: public Document

class SpreadsheetDocument: public Document
```



But how does compiler know whose `convertToPixelArray()` to call?

`TextDocument::convertToPixelArray?`

`GraphicsDocument::convertToPixelArray?`

Where are we going?

I want to store all kinds of documents in my `BatchPrinter` queue

I want to access the correct `convertToPixelArray()` method specific to each different document type

```
main()
```

```
BatchPrinter myBatchPrinter;

Document* myTextDocument = new TextDocument;
Document* myGraphicsDocument = new GraphicsDocument;

//do stuff

myBatchPrinter.addDocument(myTextDocument)
myBatchPrinter.addDocument(myGraphicsDocument)

myBatchPrinter.printAllDocuments();

    myTextDocument->convertToPixelArray();
    myGraphicsDocument->convertToPixelArray();
```

`TextDocument` ***is-a*** `Document`
`GraphicsDocument` ***is-a*** `Document`
We can point to objects of derived class using pointers to base class

We store in printer queue pointers to `Document` **but really can access any derived class document**

`convertToPixelArray` **is marked** `virtual` **so the appropriate function call is determined at runtime**

Late Binding via Virtual Functions

Avoid statically binding function calls at compile time

Must declare functions as `virtual` for **late binding**

Polymorphism

We just saw an example of *polymorphism* (literally many forms)

With `virtual` functions the outcome of an operation is determined at execution time

With basic inheritance we were just saving ourselves the trouble of re-writing code

Abstract Class

Pure virtual function (=0) has no implementation

Abstract class

- Has at least one pure virtual function
- Cannot be instantiated because does not have implementation for some/all its member functions

```
Document myDocument; //Error!
Document* myDocument = new Document;//Error!
```

“The curious `=0` syntax was chosen over the obvious alternative of introducing a new keyword `pure` or `abstract` because at the time I saw no chance of getting a new keyword accepted. Had I suggested `pure`, Release 2.0 would have shipped without abstract classes, I chose abstract classes. Rather than risking delay and incurring the certain fights over `pure`, I used the traditional C and C++ convention of using 0 to represent ‘not there’ ”

Bjarne Stroustrup

Recap Basic Inheritance

```
Base

someMethod();
. . .
```

```
Derived: public Base

someMethod() override;
. . .
```

main()

```
Base base_object;
Derived derived_object;

// stuff here

base_object.someMethod();    //calls Base function
derived_object.someMethod(); // calls Derived function - Overriding!!!
```

Recap Polymorphism

main()

```
Base* base_ptr = new Base;
Base* derived_ptr = new Derived;

// stuff here

base_ptr->someMethod();  //calls Base function
derived_ptr->someMethod();  // ???
```

```
Base

someMethod();
. . .
```

```
Derived

someMethod() override;
. . .
```

Recap Polymorphism

```
Base

virtual someMethod();
. . .
```

```
Derived

someMethod() override;
. . .
```

main()

```
Base* base_ptr = new Base;
Base* derived_ptr = new Derived;

// stuff here

base_ptr->someMethod(); //calls Base function
derived_ptr->someMethod(); // call Derived function - LATE BINDING!!!!
```

Recap Abstract Class

This function has no implementation**

```
class Document:
{
public:
    //Constructor, destructor
    virtual void convertToPixelArray() const = 0;
    virtual int getPriority() const = 0;

private:
    //stuff here
}; //end Document
```

Polymorphism without abstraction

Superclass need not be abstract

Virtual functions in superclass need not be pure virtual

Polymorphism without Abstract Classes

```
class Skater
{
public:
    //constructor, destructor
    virtual void slowDown();
    //virtual, not pure

private:
    //stuff here
}; //end Skater
```

```
class InexperiencedSkater:
         public Skater
{
public:
    //constructor, destructor
    virtual void slowDown() override;
private:
    //stuff here
}; //end InexperiencedSkater
```

```
void Skater::slowDown()
{
    applyBrakes();
} //end slowDown
```

```
void InexperiencedSkater
                     ::slowDown()
{
    fallDown();
} //end slowDown
```

implementation does not have **virtual** or **override** keyword

Polymorphism without Abstract Classes

main()

```
Skater* firstSkater = new Skater;
firstSkater->slowDown();    // applyBrakes()

Skater* secondSkater = new InexperiencedSkater;
secondSkater->slowDown();      // fallDown() - LATE BINDING!
```

Polymorphism without Abstract Classes

Need not override non-pure virtual functions

```
class StuntSkater: public Skater
{
public:
    //constructor, destructor - note no mention of slowDown
    void frontFlip();
    void backFlip();
private:
    //stuff here
};  //end StuntSkater


// stuff here


Skater* stunt_skater = new StuntSkater;
stunt_skater->slowDown();       // applyBrakes()
```

Warning

```
class NotVirtual
{
public:
    void notAVirtualFunction();
}; //end NotVirtual

class NotVirtualDerived: public NotVirtual
{
public:
    void notAVirtualFunction() override;
}; //end NotVirtualDerived



NotVirtual* nv = new NotVirtualDerived;
nv->notAVirtualFunction(); // OUCH!!! calls NotVirtual's member
                           // instead of NotVirtualDerived's member
```

When using pointers to base class, to let derived classes override functions in base class must make the base class's function virtual

More design considerations

Back to `Document` class

Assume we realize all types of documents have `width` and `height` data members

Makes sense to move them into base class

Don't want client to have direct access to data members

```
class Document:
{
public:
    //Constructor, destructor
    virtual void convertToPixelArray() const = 0;
    virtual int getPriority() const = 0;

private:
    int width, height; //Problem!!!
    //stuff here
}; //end Document
```

protected Access in Base Class

```
class Document:
{
public:
    //Constructor, destructor
    virtual void convertToPixelArray() const = 0;
    virtual int getPriority() const = 0;

protected:
    int width, height;
    //stuff here

private:
    //stuff here
}; //end Document
```

Access Specifiers Base Class members

`public`

accessible by everyone

`private`

accessible within class and by friends

`protected`

accessible within class, by friends and by derived classes

Access Specifiers for Inheritance

```
class Derived: public Base
{
public:
    //Stuff here


private:
    //Stuff here



}; //end Derived
```

Inheritance accessibility

Access in Base Class	Inheritance Method	Access in Derived Class
public	public *is-a*	public
protected		protected
private		**no access**
public	protected *is-implemented-and-inherited-as*	protected
protected		protected
private		**no access**
public	private *is-implemented-as*	private
protected		private
private		**no access**

We will not discuss the details of protected and private inheritance in this course

`override` specifier

Explicitly tell compiler you mean to override a function

Compiler will check!

Also self-documenting

```
class BaseClass
{
    virtual void f(int);
};

class DerivedClass: public BaseClass
{
    virtual void f(float) override; //Compile-time error
};
```

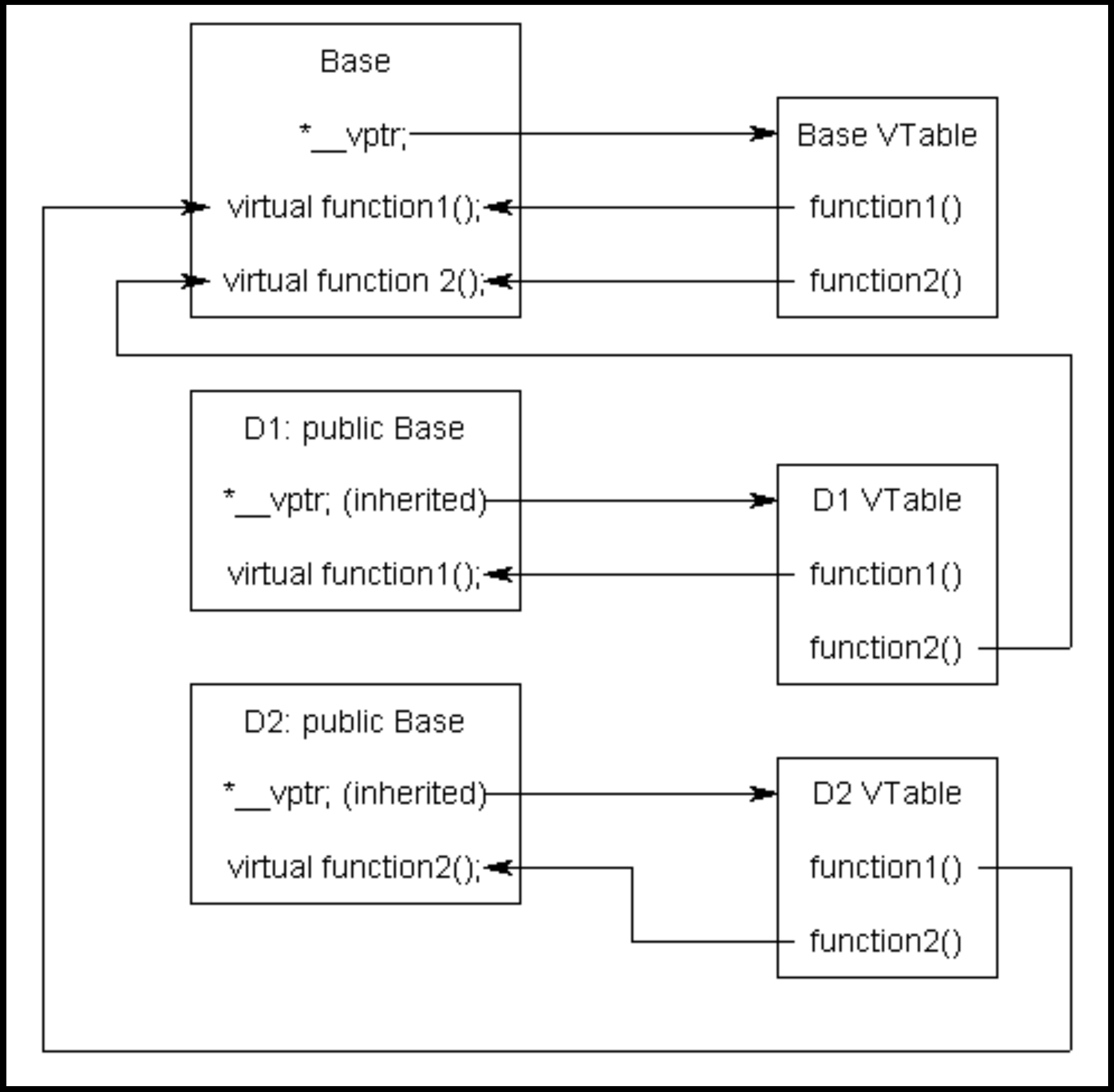
`final` specifier

- Prevents inheritance
- Prevents deriving classes from overriding methods

```
class A
{
    virtual void f();
};

class B : public A
{
    void f() final override; //cannot override f()
};

class C: public B final  //cannot inherit from C
{
    void f() override; //Error, f is final!
}


class D: public C{}   //Error C is final!
```

Runtime Costs of Virtual Functions

Function call overhead
- C++ maintains ***virtual function tables*** that store pointers to each virtual function
- Determine which function to call at execution time by looking-up **v-table** of object being pointed to



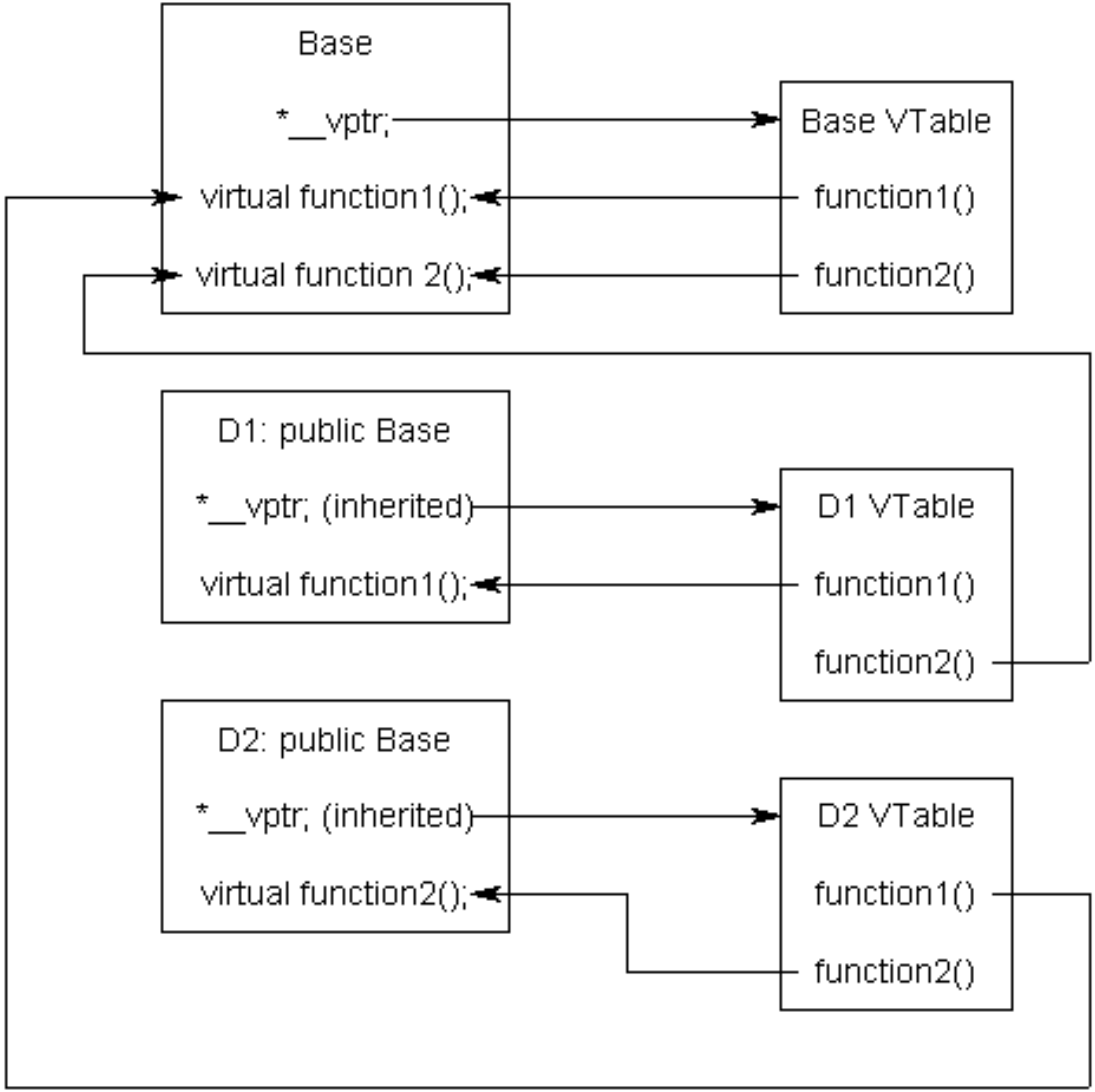
Clever! But still

Slower

Extra space for v-tables

Overhead ->mark individual functions virtual to take advantage of polymorphism only when appropriate

Fully polymorphic inheritance would be overkill in most cases


Base
*__vptr;
virtual function1();
virtual function 2();
Base VTable
function1()
function2()
D1: public Base
*__vptr; (inherited)
virtual function1();
D1 VTable
function1()
function2()
D2: public Base
*__vptr; (inherited)
virtual function2();
D2 VTable
function1()
function2()

Recap

Polymorphism -> virtual functions

Pure vs non-pure virtual functions

Polymorphism with or without abstract classes

`override` and `final`

Overhead

Polymorphism Recap

Base-class pointer to Derived class

Determine behavior at runtime (**late binding)**

HOW? `virtual`

WHY? store different type of (Derived) objects in same container and retain access to each object's distinct behavior

Details

There is a lot of detail one needs to pay attention to when using Polymorphism

The following slides are for those of you who wish to dig a little deeper into the topic but will not be on exams

These are marked with 

Need to pay **extra** attention to **destructors**!!!

With Polymorphism destructor **MUST** always be virtual!!!

```
class BaseClass()
{
public:
    BaseClass();
    ~BaseClass();

}; //end BaseClass
```

```
class DerivedClass:
            public BaseClass
{
public:
    DerivedClass();
    ~DerivedClass();

private:
    char* myString;
}; //end DerivedClass
```

```
DerivedClass::DerivedClass()
{
    //allocate some memory
    myString = new char[128];
}

DerivedClass::~DerivedClass()
{
    //deallocate memory
    delete[] myString;
}
```

```
main()

BaseClass* myClass = new DerivedClass;
delete myClass; //PROBLEM!!!
```

BaseClass destructor is invoked.
Need to allow late binding for destructor!!!

Fix

```
class BaseClass()
{
public:
    BaseClass();
    virtual ~BaseClass();

}; //end BaseClass

class DerivedClass:
            public BaseClass
{
public:
    DerivedClass();
    ~DerivedClass();

private:
    char* myString;
}; //end DerivedClass
```

```
DerivedClass::DerivedClass()
{
    //allocate some memory
    myString = new char[128];
}

DerivedClass::~DerivedClass()
{
    //deallocate memory
    delete[] myString;
}
```

main()

```
BaseClass* myClass = new DerivedClass;
delete myClass; // both destructors
                //invoked
```

Problem fixed! BOTH destructors invoked

Virtual Functions in Constructors and Destructors

Recall

- `BaseClass` constructor invoked before `DerivedClass`'
- `DerivedClass` destructor invoked before `BaseClass`'

If virtual function in constructor/destructor is called polymorphically could try to access uninitialized/deallocated data

C++ prevents this by calling virtual functions in constructors/destructors **non-polymorphically**

```
class BaseClass()
{
public:
    BaseClass()
    {
        someVirtualFunction();
    }
    virtual void someVirtualFunction()
    {
        cout << “Base” << endl;
    }

}; //end BaseClass
```

```
class DerivedClass: public BaseClass
{
public:

    virtual void someVirtualFunction()
    {
        cout << “Derived” << endl;
    }

}; //end DerivedClass
```

```
main()

DerivedClass myDerivedClas;
```

Standard output:
Base

Invoking Virtual Members Non-Virtually

Sometimes may need to call the `BaseClass` version of a virtual function from a `DerivedClass`

```
void DerivedClass::someFunction()
{
    BaseClass::someVirtualFunction(); // no polymorphism
    //do more stuff
}
```

Copy Constructors and Assignment Operators with Inheritance

Can become complicated beasts with inheritance!!!

Must **always call explicitly** BaseClass within DerivedClass

```cpp
class Base()
{
public:
    Base();
    Base(const Base& other);
    Base& operator=(const Base& other);
    virtual ~Base();
    //other public and protected members here that will be inherited

}; //end BaseClass
```

```cpp
class Derived: public Base
{
public:
    Derived();
    Derived(const Derived& other);
    Derived& operator=(const Derived& other);
    virtual ~Derived();
private:
    char* theString;  //a C string
    //generic helper functions
    void copyOther(const Derived& other);
    void clear();
}; //end DerivedClass
```

Derived Implementation

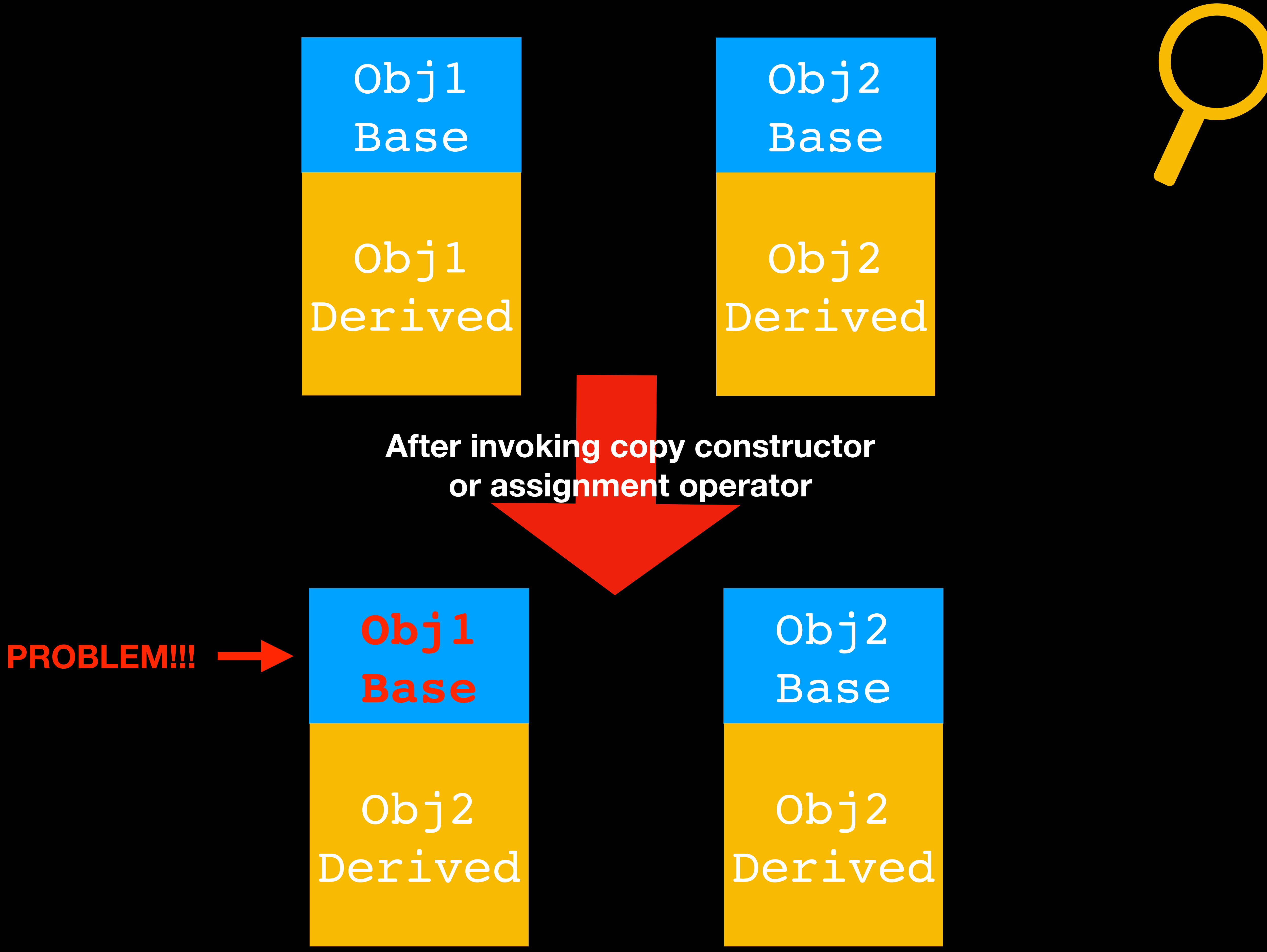
```
//generic "copy other" private member function
void Derived::copyOther(const Derived& other)
{
   theString = new char[strlen(other.theString)+1];
   strcpy(theString, other.theString);
}

// clear out private member function
void Derived::clear()
{
   delete[] theString; //deallocate memory
   theString = NULL;    //avoid dangling pointer
}
```

Derived Incorrect Implementation

```
//copy constructor
Derived::Derived(const Derived& other)
{
    copyOther(other);
}

//assignment operator
Derived& Derived::operator=(const Derived& other)
{
    if(this != other)
    {
        clear();
        copyOther(other);
    }
    return *this;
}
```

Derived Incorrect Implementation

```
//copy constructor
Derived::Derived(const Derived& other)
{
    copyOther(other);                         //WRONG!!!
}

//assignment operator
Derived& Derived::operator=(const Derived& other)
{
    if(this != other)
    {
        clear();
        copyOther(other);                 //WRONG!!!
    }
    return *this;
}
```


Obj1
Base
Obj1
Derived
Obj2
Base
Obj2
Derived
After invoking copy constructor
or assignment operator
PROBLEM!!!
Obj1
Base
Obj2
Derived
Obj2
Base
Obj2
Derived

Derived Correct Implementation

```
//copy constructor
Derived::Derived(const Derived& other): Base(other) //CORRECT!!!
{
    copyOther(other);
}

//assignment operator
Derived& Derived::operator=(const Derived& other)
{
    if(this != other)
    {
        clear();
        Base::operator= (other);//CORRECT!!!Invoke Base operator=
                                //explicitly
        copyOther(other);
    }
    return *this;
}
```

Slicing

Copy ONLY `BaseClass` portion of object

Opposite of previous case

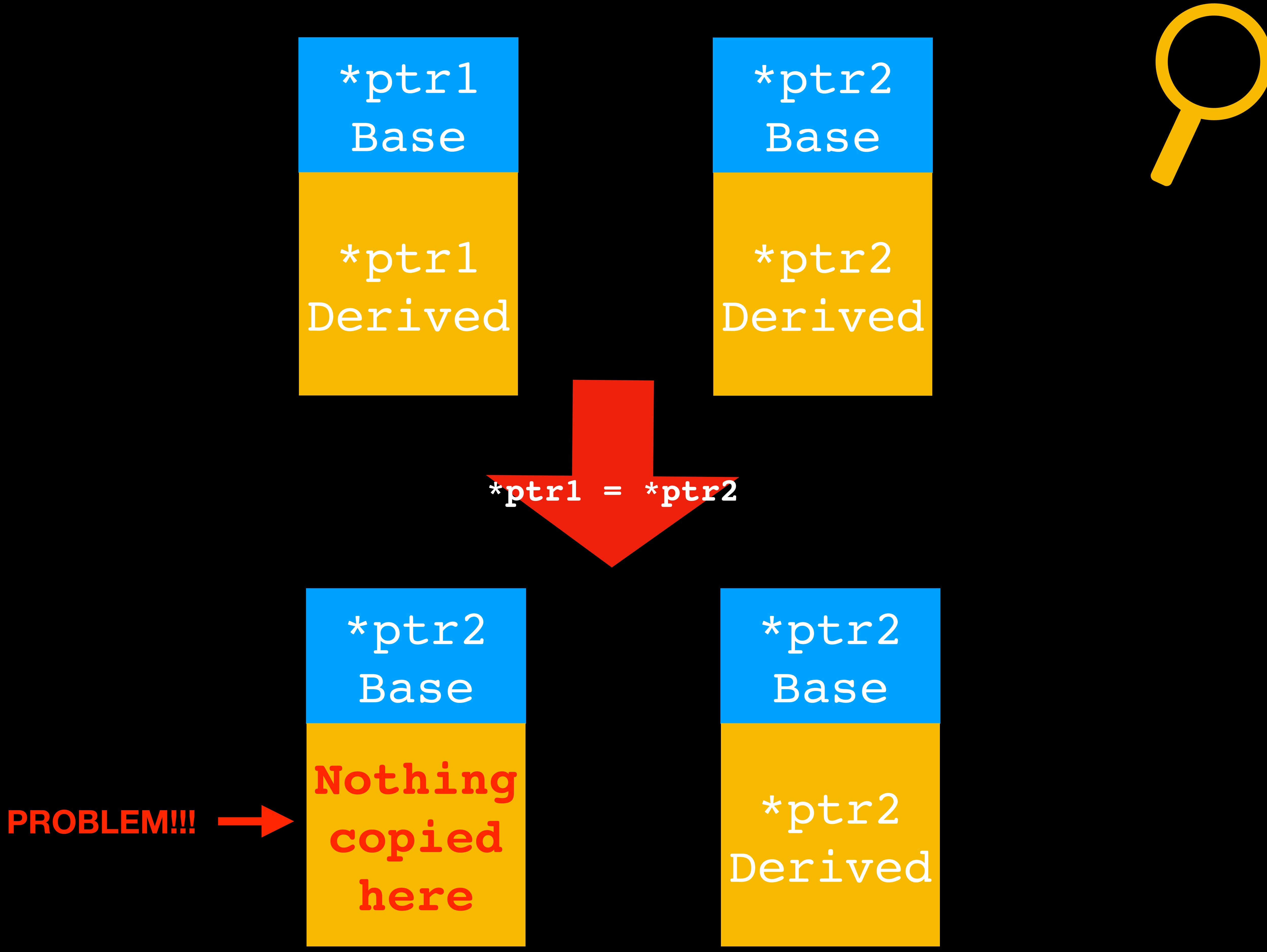
```
Base* ptr1;
Base* ptr2 = new Derived; // pointer of type Base that points to type Derived

//do stuff

*ptr1 = *ptr2; //copy value pointed to by ptr2 into variable pointed to by
                  //ptr1
```

Note potential problem!!!

The above expands into

```
ptr1->operator= (*ptr2);
```

Invoking the `operator=` of the `Base` loosing all data of `Derived` portion



*ptr1
Base
*ptr1
Derived
*ptr2
Base
*ptr2
Derived
*ptr1 = *ptr2
*ptr2
Base
Nothing
copied
here
PROBLEM!!!
*ptr2
Base
*ptr2
Derived

Slicing via Copy Constructor

```
void doSomething(Base baseObject)
{
   //do something
}

Derived myDerived;
doSomething(myDerived);
```

PROBLEM!!! Parameter `baseObject` will be initialized using `Base` copy constructor

Slicing
Ever more insidiously!!!

```
vector<Base> myBaseVector;
Base* myBasePtr = someFunction(); //pointer to Base
//ATTENTION myBasePtr could point to Derived object
myBaseVector.push_back(*myBasePtr);
```

If `someFunction` returns a pointer to an object of type `Derived` calling `push_back` on object of type `Derived` will likely **slice** the object storing only its `Base` data

Possible solution: store pointers in myBaseVector instead of objects

Casting

Forcing one datatype to be converted into another

Up-casting (`Derived` to `Base`) automatically available through inheritance

```
Base* basePtr;
Derived* derivedPtr;
//do stuff
basePtr = derivedPtr; //automatic conversion Derived is-a Base
```

Down-casting (`Base` to `Derived`)

```
Base* basePtr = new Derived; // pointer of type Base points to Derived
//do stuff
Derived* derivedPtr = (Derived*) basePtr;
```

Casting

Classic C++ cast too powerful => no checks.
Could write something totally nonsensical

```
Base* basePtr;
vector<double>* myVectorPtr = (vector<double>*) basePtr;
//PROBLEM!! Makes no sense, BUT no compiler error


const Base* basePtr = new Derived;
// do stuff
Derived* derivedPtr = (Derived*) basePtr;
//PROBLEM!!! Lost constness of Base object
//derivedPtr  is now free to modify it
```

static_cast

`static_cast` checks at compile time that cast "makes sense”

Allows:

- Converting between primitive types (e.g. `int` to `float`)
- Converting pointers or references of `Derived` type to pointers or references of `Base` type (e.g. `Derived`* to `Base`*) where target is at least as `const` as the source
- Converting pointers or references of `Base` type to pointers or references of `Derived` type (e.g. `Base`* to `Derived`*) where target is at least as `const` as the source

```
Base* basePtr = new Derived;
// do stuff
Derived* derivedPtr = static_cast<Derived*>(basePtr);
```

dynamic_cast

If Base* did not point to Derived object, static_cast would succeed

=> runtime problems

e.g. access Derived data members not present in Base

```
Base* basePtr = new Base;
Derived* derivedPtr1 = (Derived*)basePtr; //BAD!!!
Derived* derivedPtr2 = static_cast<Derived*>(basePtr); //BAD!!!
Derived* derivedPtr3 = dynamic_cast<Derived*>(basePtr); //GOOD!!!
```

Will return a NULL pointer

Conclusion

Polymorphism is easy, Just put `virtual` everywhere and the compiler will take care of the rest!

Conclusion

Polymorphism is easy, Just put `virtual` everywhere and the compiler will take care of the rest!

Real Conclusion

Overhead! Use it only when useful/necessary

Carefully craft constructors

Always make destructor virtual

Beware of Slicing (in all its forms)

Beware of casting and use level most appropriate and safe for your situation