Polymorphism

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Today's Plan

Inheritance Recap
Polymorphism

Announcements

Q: Why use dynamic memory allocation?

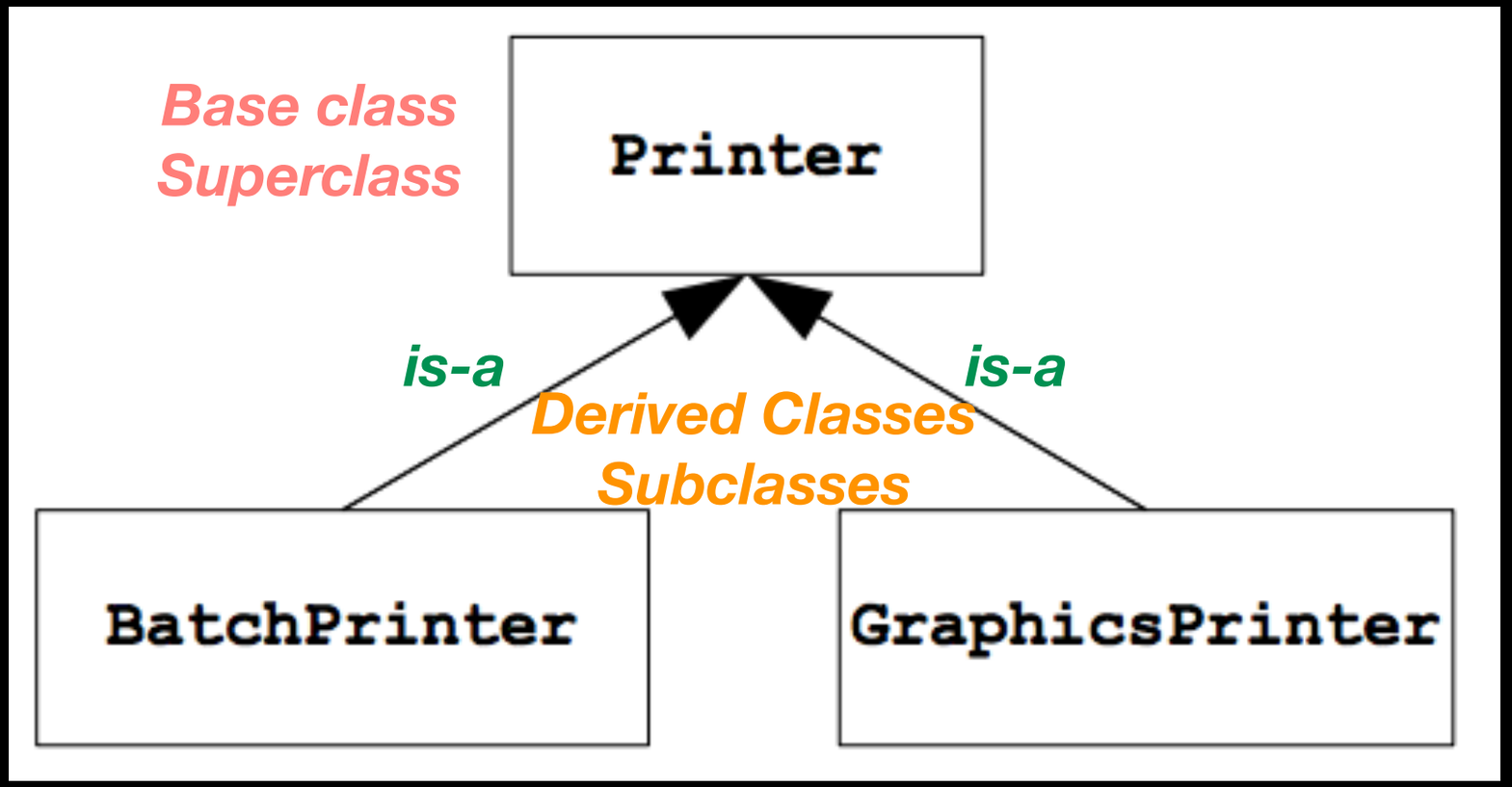
Inheritance Recap

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)
BatchPrinter batch;
initizlizePrinter(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

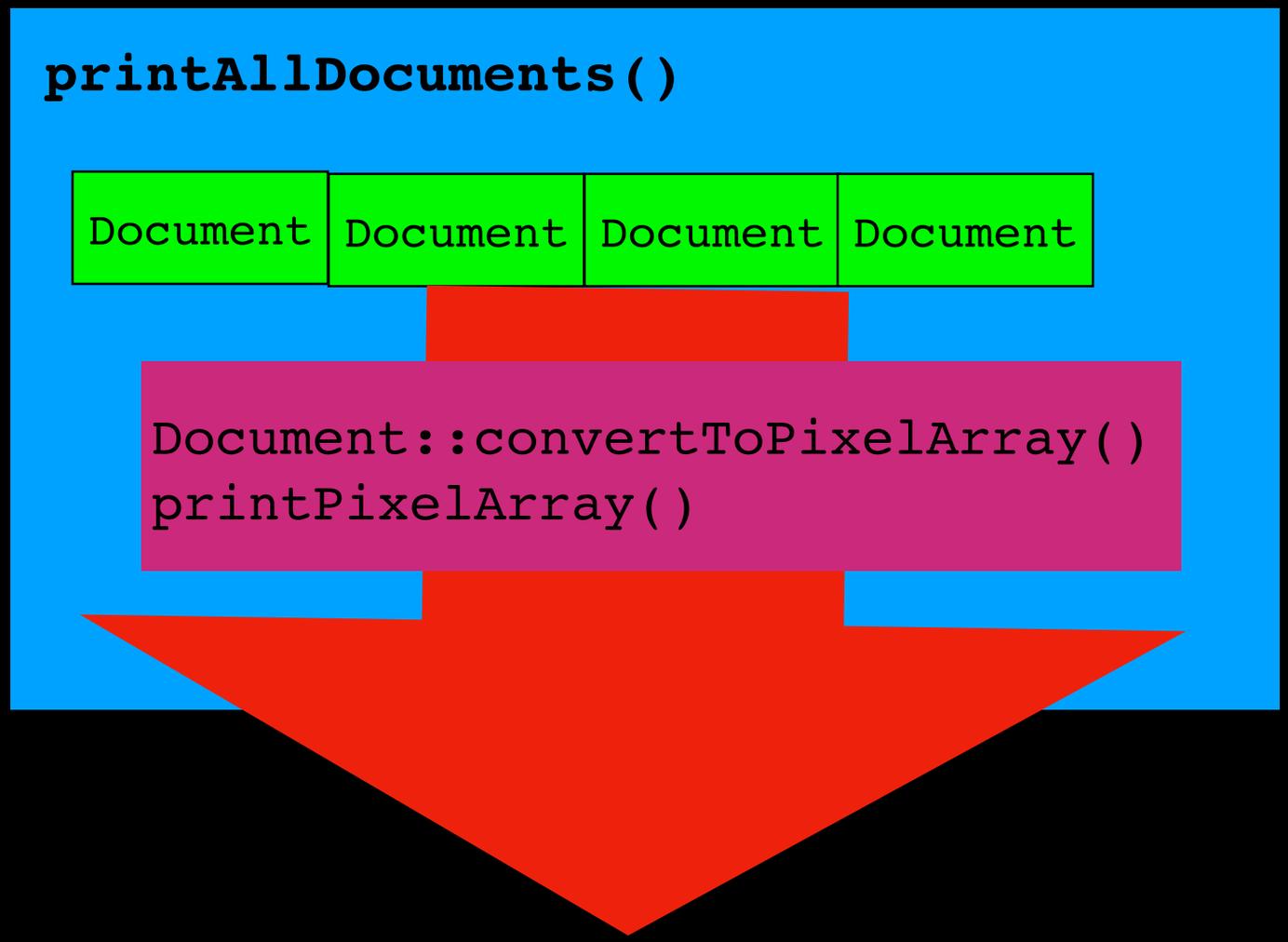
We would like to print all kinds of documents not just text
`documents` **should be able to store different types of documents**

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!

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

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

This function has no implementation**

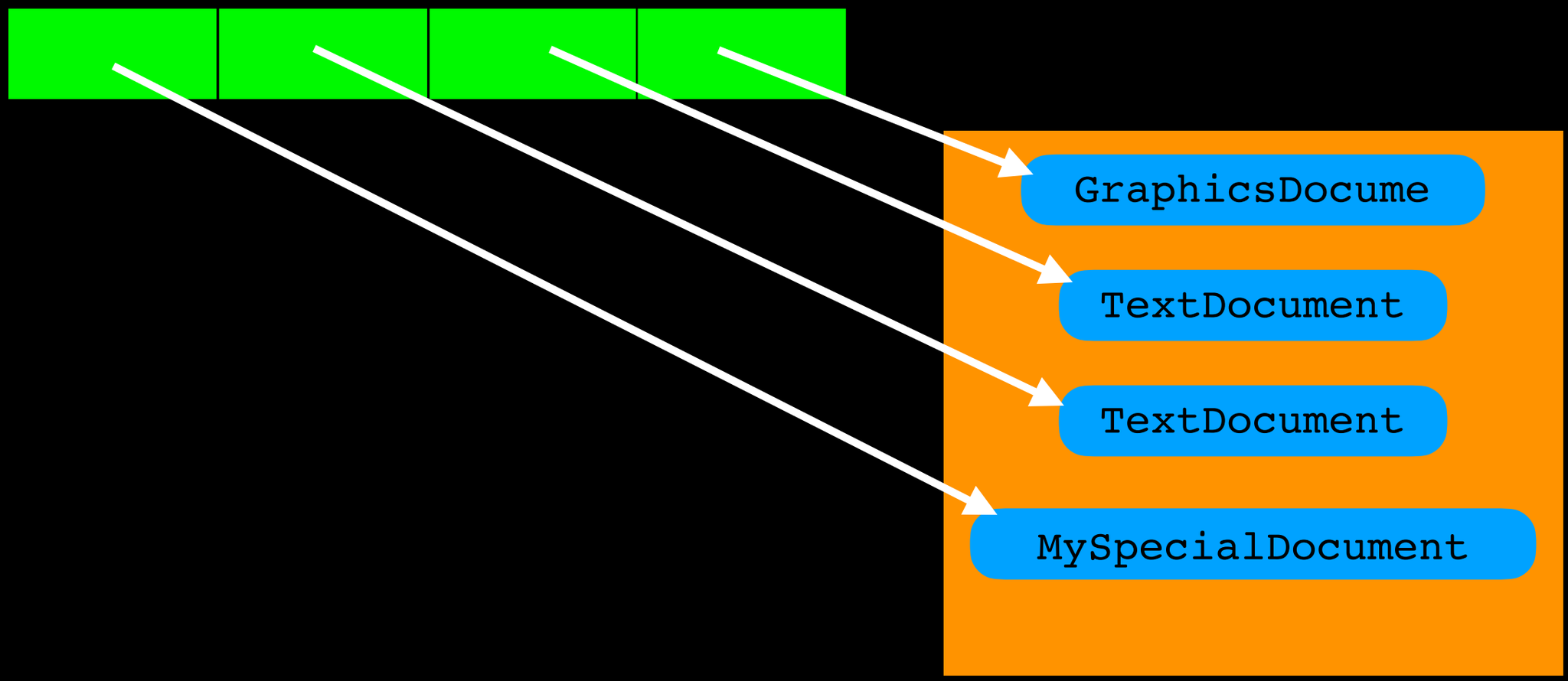
I'll explain this next

**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();
```

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

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

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!
```

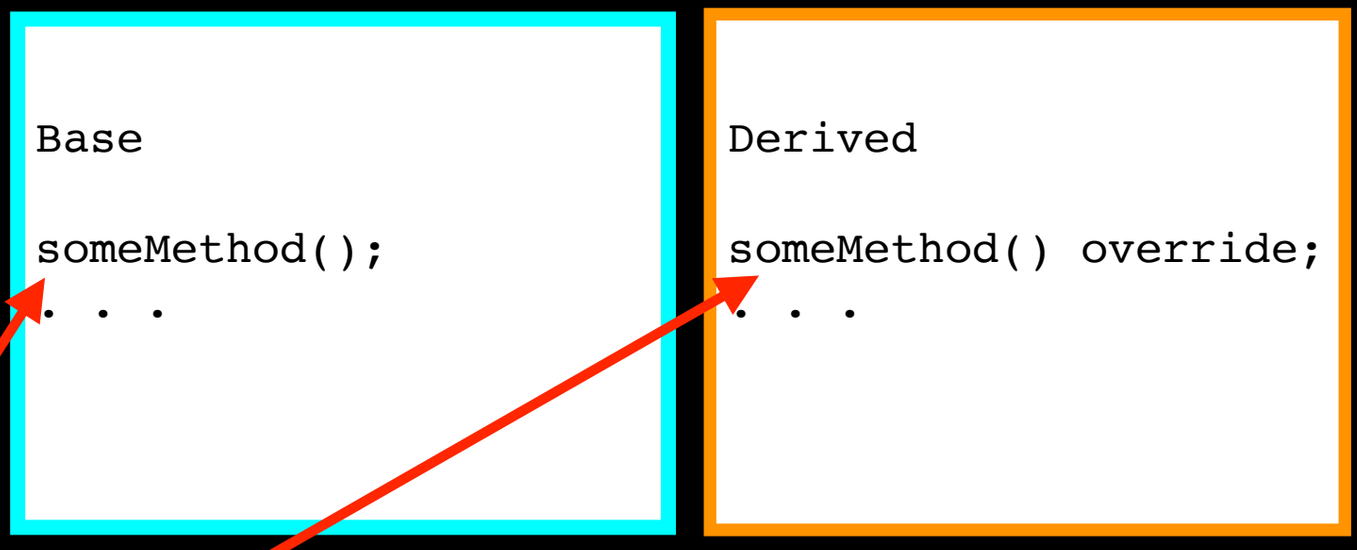
"The curious =0 syntax was chosen over the obvious alternative of introducing a new keyword `pure` or `abstract` because at the time I saw no chance of getting a new keyword accepted. Had I suggested `pure`, Release 2.0 would have shipped without abstract classes, I chose abstract classes. Rather than 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

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;
. . .
```

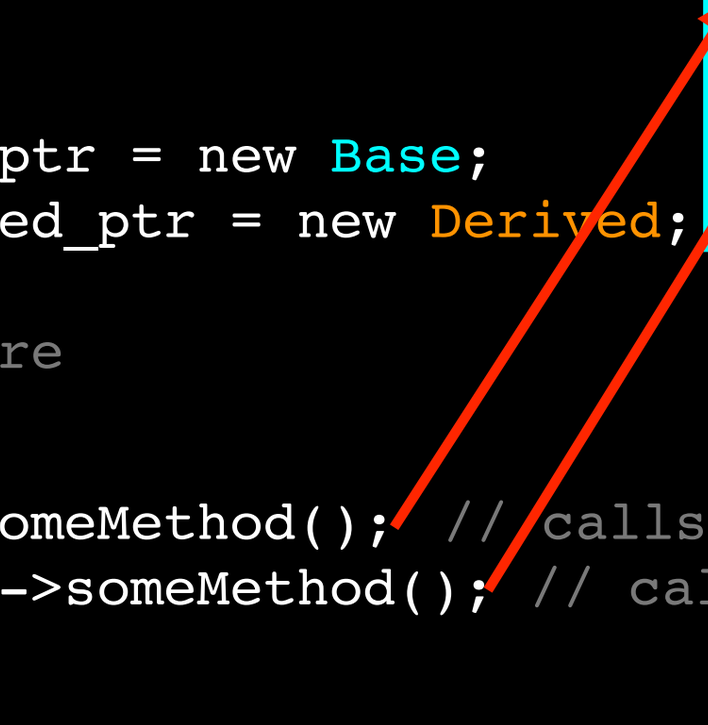
Recap Polymorphism

main()

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

// stuff here


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

```
Base

someMethod();
. . .
```

```
Derived

someMethod() override;
. . .
```



Recap Polymorphism

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!!!!
```

```
Base

virtual someMethod();
. . .
```

```
Derived

someMethod() override;
. . .
```

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()
{
    applyBreaks();
} //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();    // applyBreaks()

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();       // applyBreaks()
```

Warning

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

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

```
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
```

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

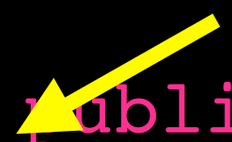
`private`

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

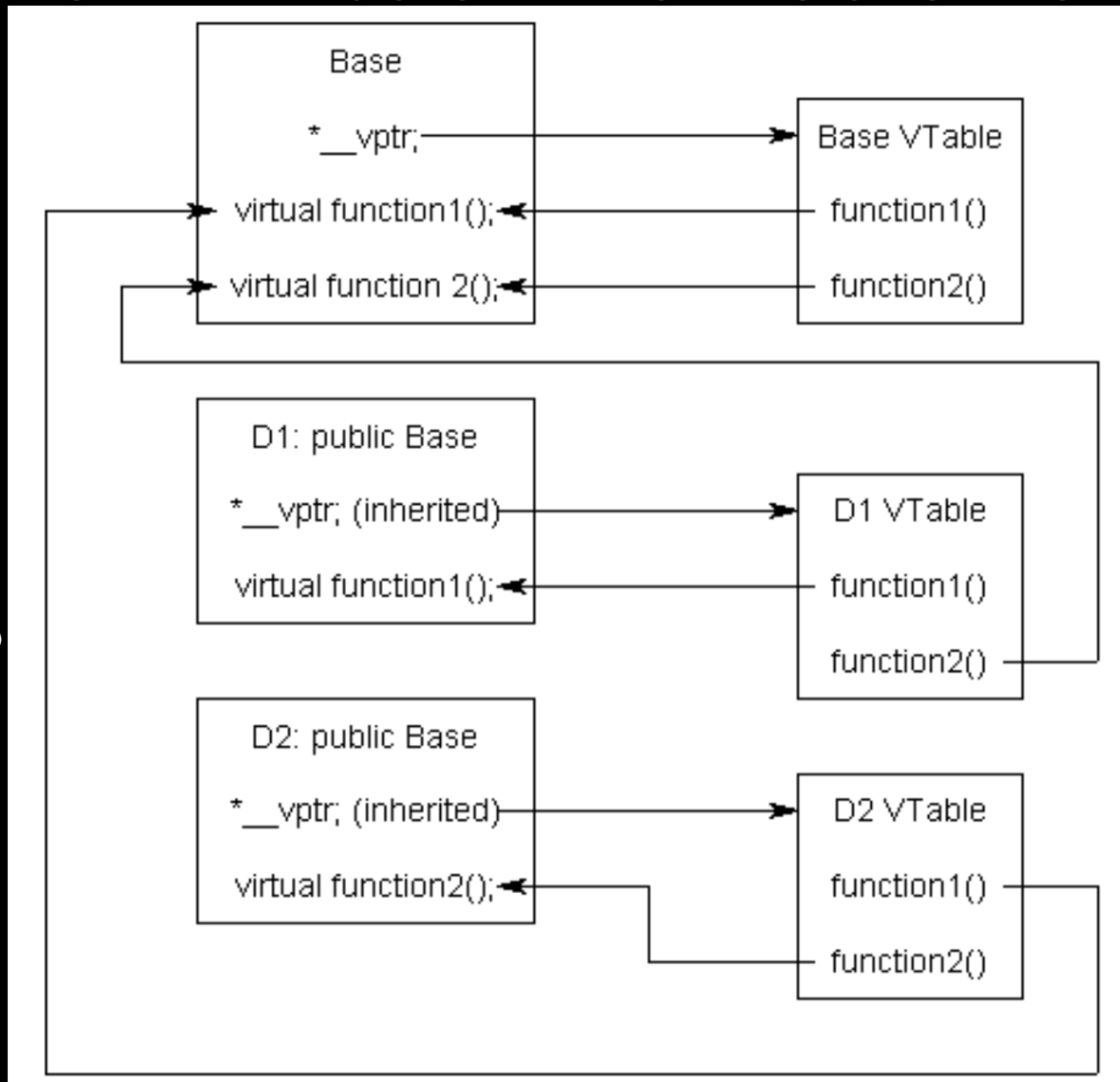
- C++ maintains ***virtual function tables*** that store pointers to each virtual function

- 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

Recap

Polymorphism -> virtual functions

Pure vs non-pure virtual functions

Polymorphism with or without abstract classes

`override` and `final`

Overhead

Review Questions

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
```

```
main()

DerivedClass myDerivedClas;
```

Standard output:
Base

```
class DerivedClass: public BaseClass
{
public:

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

};  //end DerivedClass
```

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

```
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
```

```
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

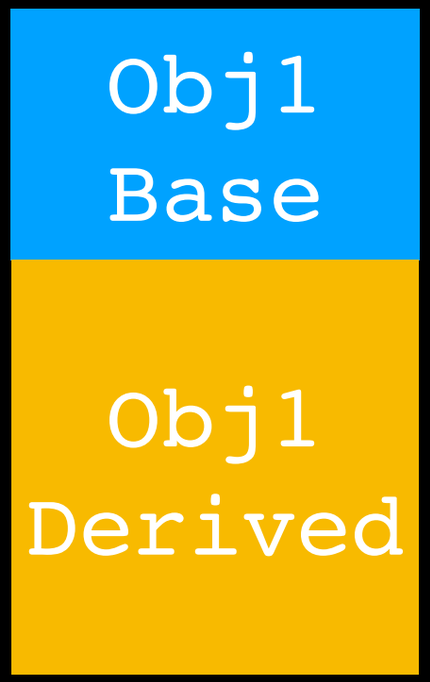
```
//generic “copy other” private member function
void Derived::copyOther(const Derived& other)
{
    theString = new char[strlen(other.theString)+1];
    strcpy(theString, other.theString);
}

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

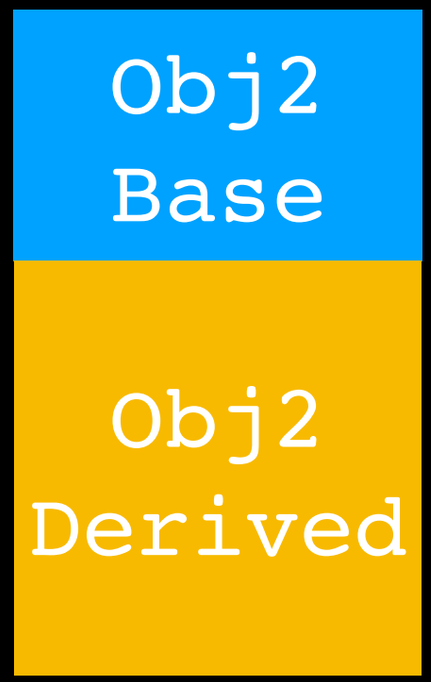
Derived Incorrect Implementation

```
//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

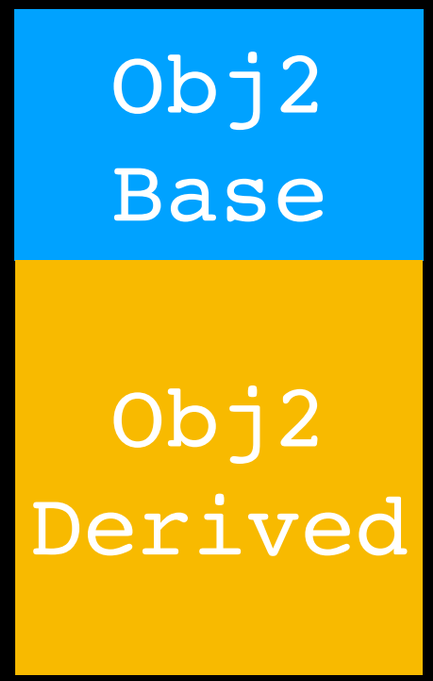
```
//copy constructor
Derived::Derived(const Derived& other)
{
    copyOther(other);                          //WRONG!!!
}

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





After invoking copy constructor or assignment operator

PROBLEM!!!



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);
```

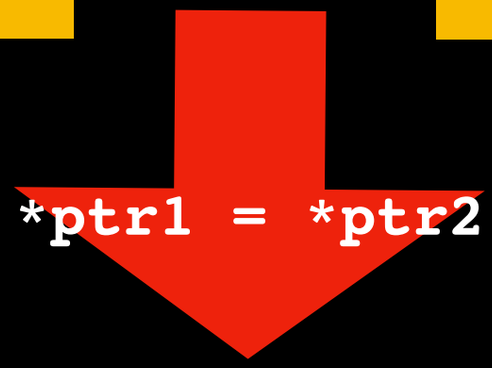
Invoking the `operator=` of the `Base` loosing all data of `Derived` portion

*ptr1
Base

*ptr1
Derived

*ptr2
Base

*ptr2
Derived



PROBLEM!!!

*ptr2
Base

Nothing
copied
here

*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

Review Questions

What is an Abstract Class?

Review Questions

Why Polymorphism?

When would you use it? What problems does it solve?

Review Questions

What does = 0 mean?

Review Questions

What is Encapsulation?

Review Questions

What does it mean to override?

Review Questions

What is OOP?

Review Questions

What is an ADT?

Review Questions

Why dynamic memory allocation?

When would you use it? What problems does it solve?

Review Questions

What does final mean?

Review Questions

How is basic inheritance different from polymorphism?

Review Questions

Why Inheritance?

When would you use it? What problems does it solve?

Review Questions

What is the overhead in Polymorphism?

Review Questions

What is Information hiding?