Intro to Polymorphism

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Definition

polymorphism: the ability to manipulate objects of distinct classes using only knowledge of their common properties without regard for their exact class (Kafura)

Note that polymorphism involves both algorithms and types of data (classes).

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Base Class: Number

First we have a base class that encapsulates a single integer value:

```
class Number {
protected:
   int Count;
public:
   Number(int InitCount = 0);
   void Reset();
   int Value() const;
};

Number::Number(int InitCount) {
   Count = InitCount;
}

void Number::Reset() {
   Count = 0;
}

int Number::Value() const {
   return Count;
}
```


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Derived Class: Counter

Then a derived class that extends `Number` to provide a simple capped counter object:

```
class Counter : public Number {
protected:
   int Start;    // starting value for counter
   int Limit;    // upper limit for counter
public:
   Counter(int L = 0, int C = 0);
   void Reset();
   bool Next();
};
```

```
Counter::Counter(int L, int C) {
   Start = Count = C;
   Limit = (L >= C ? L : C);
}

void Counter::Reset() {
   Count = Start;
}
```

```
bool Counter::Next() {
   if (Count < Limit) {
      Count++;
      return true;
   }
   return false;
}
```

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Derived Class: Cycler

And a derived class that extends `Counter` to provide a circular counter:

```
class Cycler : public Counter {
public:
   Cycler(int L = 10, int C = 0);
   void Reset();
   bool Next();
};
```

```
Cycler::Cycler(int L, int C) {

   Limit = (L > 1 ? L : 10);
   Start = Count = C % Limit;
}

void Cycler::Reset() {
   Count = Start;
}

bool Cycler::Next() {
   Count = (Count + 1) % Limit;
   return true;
}
```


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Testing Counter

Consider the following function for testing the operation of a `Counter` object:

```
void Run(Counter C, ostream& Out) {

   do {
      Out << "C:" << setw(5) << C.Value() << endl;
   } while ( C.Next() );
}
```

If we declare a `Counter` object and call the function, the results are predictable:

```
Counter C(10, 0);
Run(C, cout);
```

```
C:    0
C:    1
C:    2
C:    3
C:    4
C:    5
C:    6
C:    7
C:    8
C:    9
C:   10
```


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Testing Cycler

If we pass a `Cycler` object to the same function…

```
Cycler D(10, 0);
Run(D, cout);
```

… the results may be surprising:

```
C:     0
C:     1
C:     2
C:     3
C:     4
C:     5
C:     6
C:     7
C:     8
C:     9
C:    10
```

The `Cycler` object is behaving like a `Counter` object!

Is this a result of slicing??

Is this objectionable? After all, we could write a second test function that expects a `Cycler` object (and that would produce `Cycler`-like behavior).

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Polymorphism Revisited

Actually the results are not really acceptable. There are times when we definitely want to be able to write a single function, and pass it objects of related but different types, and have the resulting behavior reflect the type of the actual parameter.

For example, suppose that we derived a new type, say `OTHourlyEmployee`, from `HourlyEmployee` (from the last chapter of notes), where an employee of the new type will receive an increased pay rate for any hours beyond some floor. This might be reflected by having each type now incorporate a function to compute and return the correct pay amount…

```
double HourlyEmployee::Pay() { return (Hours * Rate); }
```

```
double OTHourlyEmployee::Pay() {
   if (Hours <= 40)
      return (Hours * Rate);
   return (40 * Rate + (Hours - 40)*1.5*Rate);
}
```


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Polymorphism Demanded

We may well want to use a single linked list (or other container object) to organize all the `HourlyEmployee` and `OTHourlyEmployee` objects, rather than keep them in different data structures.

We can easily accomplish that by having the list nodes store pointers to objects, rather than the objects themselves.

It would also be natural to write a function to print paychecks from the data in the list, perhaps something like:

```
void PrintChecks(LinkList E) {
   HourlyEmployee thisEmp;
   E.gotoHead();
   while ( E.moreList() ) {
      thisEmp = E.getCurrentData();
      PrintACheckFor(thisEmp);
      E.Advance();
   }
}
```

`PrintACheck()` will call the member function `Pay()` and that had better be the right one, whether `thisEmp` is an `HourlyEmployee` or an `OTHourlyEmployee`!

But how can we make this happen automatically?

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C++ Support for Polymorphism

In C++, polymorphic behavior can be attained by combining:

- an inheritance hierarchy
- object accesses via pointers
- use of virtual member functions in base classes

```
class Number {
protected:
   int Count;
public:
   Number(int InitCount = 0);
   void Reset();
   int Value() const;
   virtual bool Next();
};
```

Now, passing a `Cycler` object will produce an infinite loop.

```
void Run(Number* C, ostream& Out) {

   do {
      Out << "C:" << setw(5) << C->Value() << endl;
   } while ( C->Next() );
}
```


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Virtual Functions and Binding

A member function is declared to be virtual by using the keyword `virtual`.

Normally functions are declared virtual in a base class and then overridden in each derived class for which the function should have a specialized implementation.

This modifies the rules whereby a function call is bound to a specific function implementation.

In normal circumstances (I.e., what we've done before) the compiler determines how to bind each function call to a specific implementation by searching within the current scope for a function whose signature matches the call, and then expanding that search to enclosing scopes if necessary.

With an inheritance hierarchy, that expansion involves moving back up through the inheritance tree until a matching function implementation is found.

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Early Binding

When the binding of call to implementation takes place at compile-time we say we have early binding (aka static binding).

```
Counter C(100, 0);

C.Next();

cout << C.Value() << endl;
```

This call binds to the local implementation of `Next()` given in the class `Counter`.

This call binds to the implementation of `Value()` inherited from the class `Number`.

Early binding is always used if the invocation is direct (via the name of an object using the dot operator), whether virtual functions are used or not.

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Invocation via a Pointer w/o Virtuality

When a function call is made using a pointer, and no virtual functions are involved, the binding of the call to an implementation is based upon the type of the pointer (not the actual type of its target).

```
Cycler  CC(10, 5);
CC.Next();


Cycler* pC = &CC;
CC.Next();
pC->Reset();


Number* pN = &CC;
CC.Next();
pN->Reset();
```

This call binds to the local implementation of `Reset()` given in the class `Cycler` and sets the counter value to 5.

This call binds to the implementation of `Reset()` inherited from the class `Number` and sets the counter value to 0.

Note: this assumes the original declaration and implementation of the class `Number` from slide 3.

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Enabling Polymorphism with Virtual Functions

However, when a function call is made using a pointer, and virtual functions are involved, the binding of the call to an implementation is based upon the type of the target object (not the declared type of the pointer).

Modify the declaration of `Number` to make `Reset()` and `Next()` virtual functions:

```
class Number {
protected:
   int Count;
public:
   Number(int InitCount = 0);
   virtual void Reset();
   int Value() const;
   virtual bool Next(); // does nothing
};
```

Note this doesn't change the implementation of the function `Reset()`.

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Invocation via a Pointer with Virtuality

Now, if we access objects in this inheritance hierarchy via pointers, we get polymorphic behavior. That is, the results are consistent with the type of the target, rather than the type of the pointer:

```
Cycler  CC(10, 5);
CC.Next();


Cycler* pC = &CC;
CC.Next();
pC->Reset();


Number* pN = &CC;
CC.Next();
pN->Reset();
```

Now both calls to `Reset()` bind to the local implementation of `Reset()` given in the class `Cycler`. even though the access is through a base type pointer.

If you don't think that's cool...

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Late Binding

When the binding of call to implementation takes place at runtime we say we have late binding (aka dynamic binding).

```
Counter C(10, 0);
Cycler  CC(10, 5);

Number* pN;

char ch;
cout << "Enter choice: ";
cin >> ch;
if (ch == 'y')
   pN = &C;
else
   pN = &CC;

pN->Next();
pN->Reset();
```

There's no way to know the type of the target of `pN` until runtime.

However, the calls to `Next()` and `Reset()` will be bound to the correct implementations regardless.

But HOW is this done? See Stroustrup 2.5.5 and 12.2.6.

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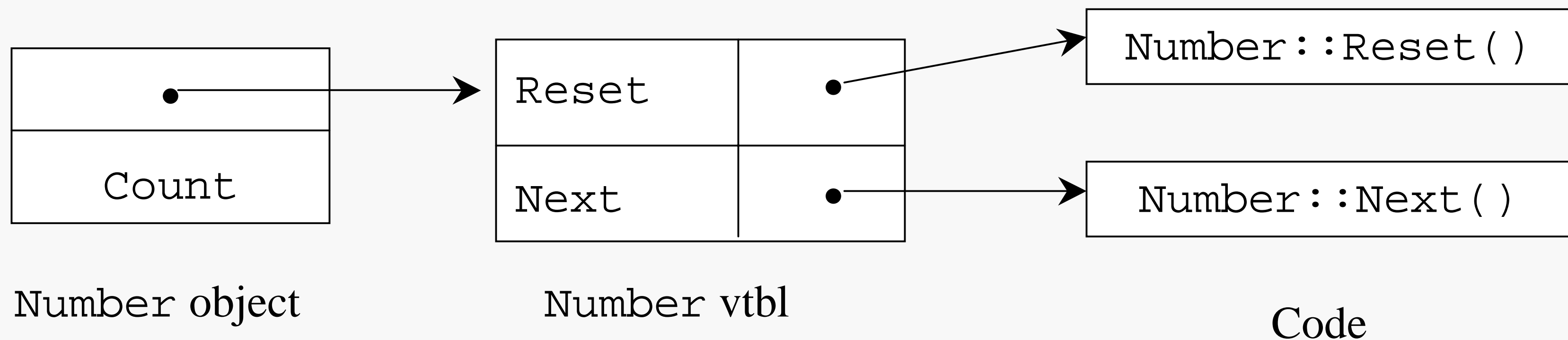
Virtual Function Tables

When the binding of call to implementation takes place at runtime, the address of the called function must be managed dynamically.

The presence of a virtual function in a class causes the generation of a virtual function table (vtbl) for the class, and an association to that table in each object of that type:



This increases the size of each object, but only by the size of one pointer.

Key fact: if a function is virtual in a base class, it's also virtual in the derived class, whether it's declared virtual there or not.

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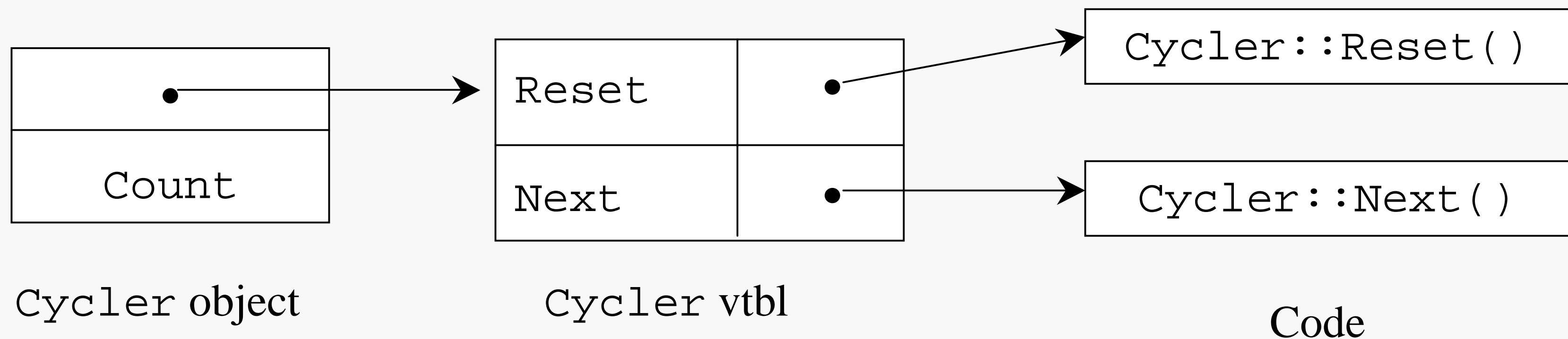
Derived Class View

So for a `Cycler` object we'd have:



In this simple case, the derived object has its own implementations to replace each of the virtual functions inherited from the base class.

That's often NOT the case. Then, one or more of the derived class vtbl pointers will target the base class implementation….

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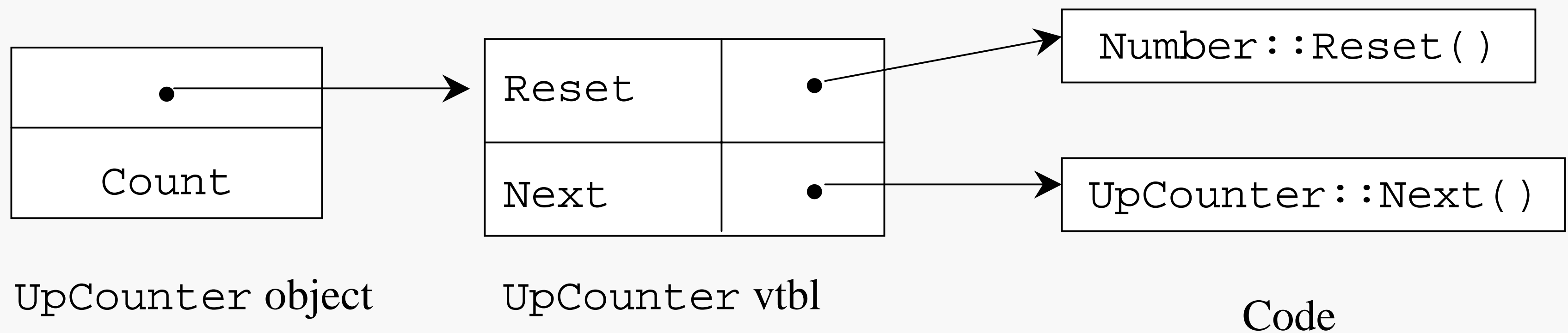
Another Derived Class View

Consider another derived class:

```
class UpCounter : public Number {
public:
   Counter(int C = 0);
   void Next() {Count++;}
};
```

So for an `UpCounter` object we'd have:



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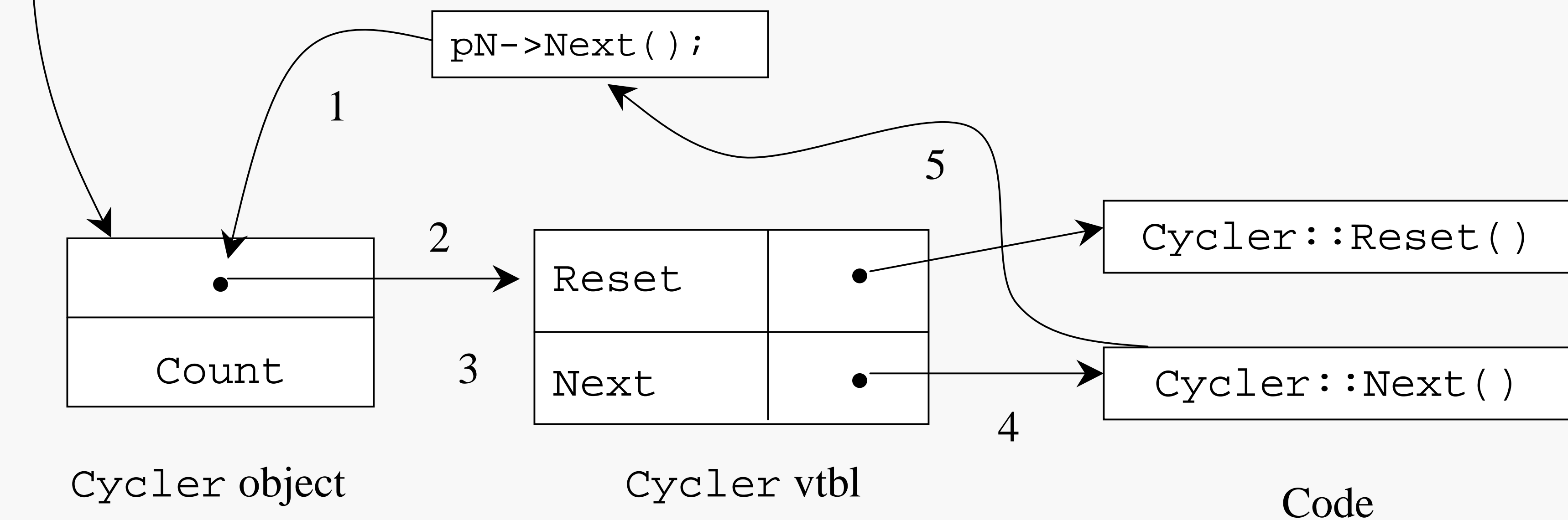
So, at Runtime:

Resuming the example from slide 16, say the user enters 'y'.

`pN` stores the address of a `Cycler` object.

The compiler generates code to follow the vtbl pointer in the target of `pN` (at runtime) to retrieve the address of the appropriate function.



Detail: the vtbl pointer must be at a fixed offset within the target object.

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Abstract Classes

The root class `Number` does not seem to have any compelling application in its own right. The class serves a useful purpose within the logical specification of an inheritance hierarchy, but instances of it (arguably) do not.

An abstract class is simply a class that exists for high-level organizational purposes, but that cannot ever be instantiated.

In C++, a class is abstract if one or more of its member functions are pure virtual.

A pure virtual member function has no implementation, only a declaration (prototype) in the abstract class declaration.

Pure virtual member functions remain pure virtual in derived classes that do not provide an implementation that overrides the base class prototype.

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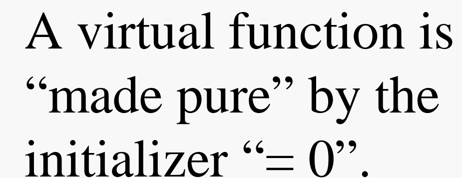
Pure Virtual Function Example

The class `Number` can be revised into an abstract class by specifying one or more pure virtual member functions.

Question: which member functions should be pure virtual?

One answer: those that do not have sensible implementations at the root level of the hierarchy. For example, Next() is different for most, if not all, of the derived classes developed above, so there's not much point in providing a base implementation.

```
class Number {
protected:
   int Count;
public:
   Number(int InitCount = 0);
   virtual void Reset() = 0;
   int Value() const {return Count;}
   virtual bool Next() = 0;
};
```



A virtual function is "made pure" by the initializer "= 0".

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Using the Abstract Class

Assuming the revised declaration just given, the class `Number` can be derived from, but an attempt to declare an object of type `Number` will generate a compile-time error.

Since the classes `Cycler` and `Counter` presented earlier provide overridings for the pure virtual members of Number, their declarations do not need to be changed.

The class `UpCounter`, however, will itself be an abstract class unless it is revised. Why?

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