

CSE 333

Lecture 15 - inheritance

Hal Perkins

Department of Computer Science & Engineering

University of Washington



Administrivia

HW3 due Thursday - how's it look?

No new exercise due Monday. Next exercise is about subclasses and is out now, but not due until Wednesday morning.

- (We might not get to absolutely everything involved today, but we should get to most of it, and all topics are included in these slides and the *C++ Primer*)

HW3 tip

HW3 writes some pretty big index files

- Hundreds of thousands of write operations
- No problem for today's fast machines and disks!!

Except...

- If you're running on attu or a CSE lab linux workstation, every write to your personal directories goes to a network file server(!)
 - ▶ ∴ Lots of slow network packets vs full-speed disks — can take much longer to write an index to a server vs. a few sec. locally (!!)
 - ▶ Suggestion: write index files to /tmp/... . That's a local scratch disk and is very fast. But please clean up when you're done.

Today

C++ inheritance

- Review of basic idea (pretty much the same as 143)
- What's different in C++ (compared to Java)
 - ▶ *Static vs dynamic dispatch - virtual functions and vtables*
 - ▶ *Pure virtual functions, abstract classes, why no Java "interfaces"*
 - ▶ *Assignment slicing, using class hierarchies with STL*
- Casts in C++
- Reference: C++ Primer, ch. 15
 - Credits: Thanks to Marty Stepp for stock portfolio example

Let's build a stock portfolio

A portfolio represents a person's financial investments

- each asset has a cost (how much was paid for it) and a market value (how much it is worth)
 - ▶ the difference is the profit (or loss)
- different assets compute market value in different ways
 - ▶ **stock**: has a symbol ("GOOG"), a number of shares, share price paid, and current share price
 - ▶ **dividend stock**: is a stock that also has dividend payments
 - ▶ **cash**: money; never incurs profit or loss. (hah!)

One possible design

| Stock |
|---|
| symbol_ total_shares_ total_cost_ current_price_ |
| GetMarketValue() GetProfit() GetCost() |

| DividendStock |
|---|
| symbol_ total_shares_ total_cost_ current_price_ dividends_ |
| GetMarketValue() GetProfit() GetCost() |

| Cash |
|-------------------|
| amount_ |
| GetMarketValue() |

One class per asset type

- Problem: redundancy
- Problem: cannot treat multiple investments the same way
 - ▶ e.g., cannot put them in a single array or Vector

see initial_design/

Inheritance

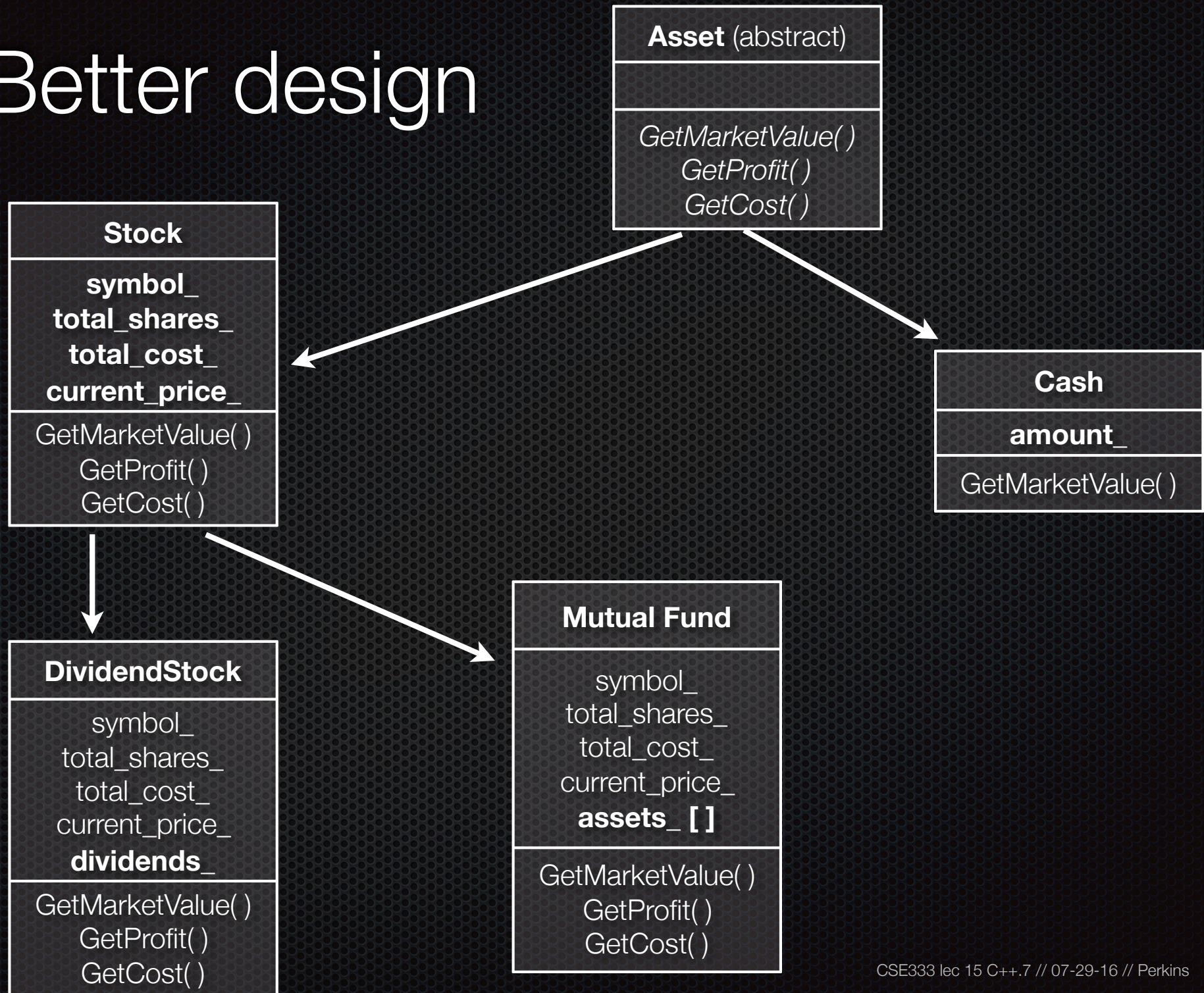
A parent-child “is-a” relationship between classes

- a child (**derived** class) extends a parent (**base** class)

Benefits:

- code reuse: subclasses inherit code from superclasses
- polymorphism
 - ▶ ability to redefine existing behavior but preserve the interface
 - ▶ children can override behavior of parent
 - ▶ others can make calls on objects without knowing which part of the inheritance tree it is in
- extensibility: children can add behavior

Better design



Like Java: Access specifiers

public: visible to all other classes

protected: visible to current class and its subclasses

private: visible only to the current class

declare members as **protected** if:

- you don't want random clients accessing them, but...
 - ▶ you want to be subclassed and let subclasses access them

Like Java: Public inheritance

```
#include "BaseClass.h"

class Name : public BaseClass {
    ...
};
```

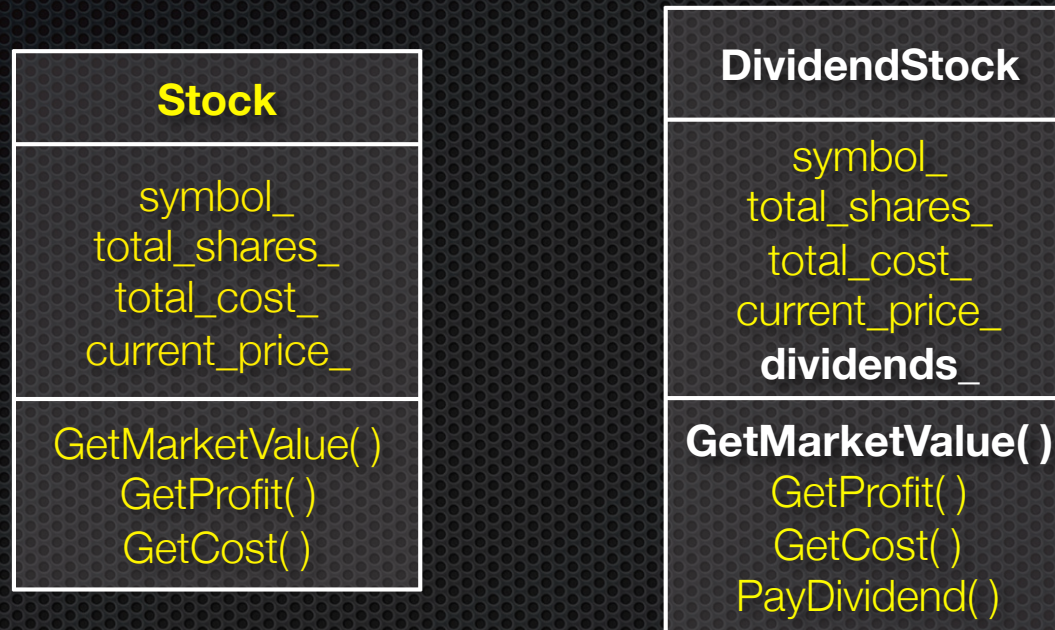
- “public” inheritance
 - ▶ anything that is [*public, protected*] in the base is [*public, protected*] in the derived class - this is interface (specification) + implementation inheritance
- derived class inherits **almost** all behavior from the base class
 - ▶ not constructors and destructors
 - ▶ not the assignment operator or copy constructor
- (Yes there is “private” inheritance — don’t ask and don’t use)

Terminology

| C++, etc. | Java, etc. |
|----------------------|-------------------|
| <i>base class</i> | <i>superclass</i> |
| <i>derived class</i> | <i>subclass</i> |

Means the same. You'll hear both.

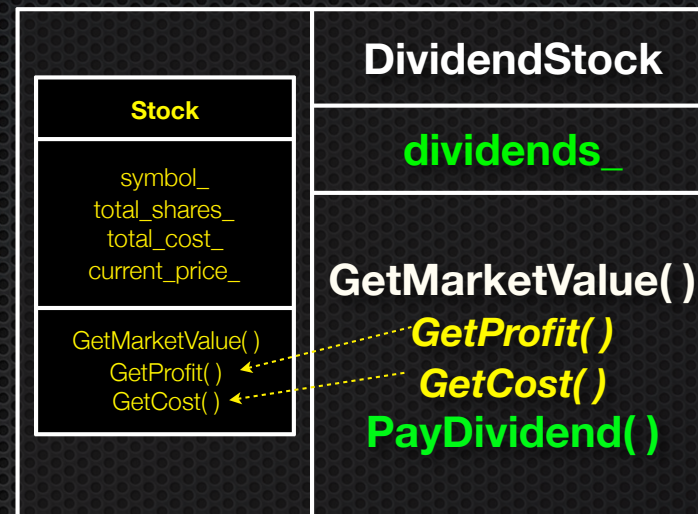
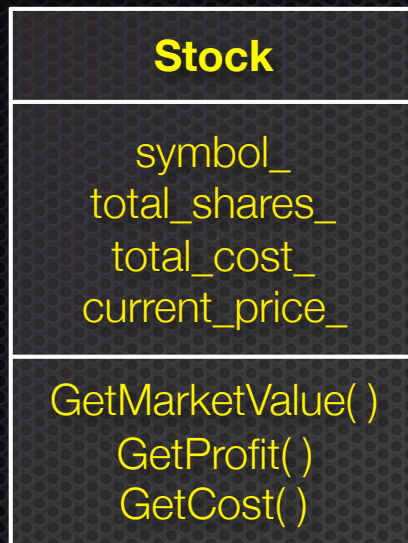
Revisiting the portfolio example



Without inheritance (separate class per type)

- lots of redundancy
- no type relationship between the classes

Revisiting the portfolio example



A derived class:

- **inherits** the behavior and state of the base class
- **overrides** some of the base class's member functions
- **extends** the base class with new member functions, variables

(implement better_design/)

Like Java: Dynamic dispatch

Usually, when a derived function is available to an object, we want that derived function to be invoked by it

- as we will see, this requires a runtime decision of what code to invoke

When a member function is invoked on an object...

- the code that is invoked is decided at run time, and is the **most-derived function** accessible to the object's visible type

How to use dynamic dispatch

If you want a member function to use dynamic dispatch, prefix its declaration with the “virtual” keyword

- derived (child) functions don't need to repeat the virtual keyword, but it traditionally has been good style to do so
 - ▶ “override” added in C++ 11 - always use if it's available
 - “virtual” + “override”? Be consistent; follow local conventions
- This is how method calls work in Java (all normal methods are virtual; no “virtual” keyword needed)

(see even_better_design/)

Dynamic dispatch

When a member function is invoked on an object

- the code that is invoked is decided at run time, and is the **most-derived function** accessible to the object's visible type

```
double DividendStock::GetMarketValue() const {  
    return get_shares() * get_share_price() + _dividends;  
}  
  
double DividendStock::GetProfit() const {  
    return DividendStock::GetMarketValue() - GetCost();  
}  
DividendStock.cc
```

```
double Stock::GetMarketValue() const {  
    return get_shares() * get_share_price();  
}  
  
double Stock::GetProfit() const {  
    return GetMarketValue() - GetCost();  
}  
Stock.cc
```

Dynamic dispatch

```
DividendStock dividend();

DividendStock *ds = &dividend;
Stock *s = &dividend;

// invokes Stock::GetProfit(), since that function is
// inherited (i.e, not overridden). Stock::GetProfit()
// invokes Dividend::GetMarketValue(), since that is
// the most-derived accessible function.
ds->GetProfit();

// invokes DividendStock::GetMarketValue()
ds->GetMarketValue();

// invokes DividendStock::GetMarketValue()
s->GetMarketValue();
```

Dynamic dispatch

Here's what "most derived" means:

```
class A {  
    public:  
    // Foo will use dynamic dispatch  
    virtual void Foo();  
};  
  
class B : public A {  
    public:  
    // B::Foo overrides A::Foo  
    virtual void Foo();  
};  
  
class C : public B {  
    public:  
    // C inherits B::Foo()  
};
```

```
void function() {  
    A *a_ptr;  
    C c;  
  
    // Why is this OK?  
    a_ptr = &c;  
  
    // Whose Foo() is called?  
    a_ptr->Foo();  
}
```

Dynamic dispatch

```
class A {
public:
    virtual void Foo();
};

class B : public A {
public:
    virtual void Foo();
};

class C : public B {
};

class D : public C {
public:
    virtual void Foo();
};

class E : public C {
};
```

A more extreme version

```
void function() {
    A *a_ptr;
    C c;
    E e;

    // Whose Foo() is called?
    a_ptr = &c;
    a_ptr->Foo();

    // Whose Foo() is called?
    a_ptr = &e;
    a_ptr->Foo();
}
```

But how can this possibly work??

The compiler produces Stock.o from Stock.cc

- while doing this, it can't know that DividendStock exists
 - ▶ so, how does the code emitted for Stock::GetProfit() know to invoke Stock::GetMarketValue() some of the time, and DividendStock::GetMarketValue() other times????!

```
virtual double Stock::GetMarketValue() const;  
virtual double Stock::GetProfit() const; Stock.h
```

```
double Stock::GetMarketValue() const {  
    return get_shares() * get_share_price();  
}  
  
double Stock::GetProfit() const {  
    return GetMarketValue() - GetCost();  
}
```

Stock.cc

vtables and the vptr

If a member function is virtual, the compiler emits:

- a “vtable”, or virtual function table, **for the class**
 - ▶ it contains a function pointer for each virtual function in the class
 - ▶ the pointer points to the most-derived function for that class
- a “vptr”, or virtual table pointer, **for each object instance**
 - ▶ the vptr is a pointer to a virtual table, and it is essentially a hidden member variable inserted by the compiler
 - ▶ when the object’s constructor is invoked, the vptr is initialized to point to the virtual table for the object’s class
 - ▶ thus, the vptr “remembers” what class the object is

vtable/vptr example

```
class Base {
public:
    virtual void fn1() {};
    virtual void fn2() {};
};

class Dr1: public Base {
public:
    virtual void fn1() {};
};

class Dr2: public Base {
public:
    virtual void fn2() {};
};
```

```
// what needs to work
```

```
Base b;
Dr1 d1;
Dr2 d2;
```

```
Base *bptr = &b;
Base *d1ptr = &d1;
Base *d2ptr = &d2;
```

```
bptr->fn1(); // Base::fn1()
bptr->fn2(); // Base::fn2()
```

```
d1ptr->fn1(); // Dr1::fn1()
d1ptr->fn2(); // Base::fn2()
```

```
d2.fn1(); // Base::fn1()
d2ptr->fn1(); // Base::fn1()
d2ptr->fn2(); // Dr2::fn2()
```


vtable/vptr example

```
// what happens
```

```
Base b;
```

```
Dr1 d1;
```

```
Dr2 d2;
```

```
Base *d2ptr = &d2;
```

```
d2.fn1();
```

```
// d2.vptr -->
```

```
// Dr2.vtable.fn1 -->
```

```
// Base::fn1()
```

```
d2ptr->fn2();
```

```
// d2ptr -->
```

```
// d2.vptr -->
```

```
// Dr2.vtable.fn2 ->
```

```
// Dr2::fn2()
```

compiled code

Base :: fn1()

```
mov  (%eax),%eax
add  $0x18,%eax
...
```

Base :: fn2()

```
add  $0x1c,%eax
sub  $0x4,%esp
...
```

Dr1 :: fn1()

```
add  $0x1c,%eax
mov  (%eax),%eax
...
```

Dr2 :: fn2()

```
sub  $0x4,%esp
mov  (%eax),%eax
...
```

class
vtables

Base

● fn1()
● fn2()

Dr1

● fn1()
● fn2()

Dr2

● fn1()
● fn2()

object
instances

b

● vptr

d1

● vptr

d2

● vptr

actual code

```
class Base {
public:
    virtual void fn1 () {};
    virtual void fn2 () {};
};

class Dr1: public Base {
public:
    virtual void fn1 () {};
};

main() {
    Dr1    d1;
    d1.fn1();
    Base *ptr = &d1;
    ptr->fn1();
}
```

vtable.cc

Let's compile this and use objdump to see what g++ emits!

- g++ -g vtable.cc
- objdump -CDSRTx a.out | less

Static dispatch - What if we omit “virtual”?

When a member function is invoked on an object...

- the code that is invoked is decided at compile time, based on the compile-time visible type of the callee

```
double DividendStock::GetMarketValue() const {  
    return get_shares() * get_share_price() + _dividends;  
}  
  
double DividendStock::GetProfit() const {  
    return GetMarketValue() - GetCost();  
}
```

DividendStock.cc

```
double Stock::GetMarketValue() const {  
    return get_shares() * get_share_price();  
}  
  
double Stock::GetProfit() const {  
    return GetMarketValue() - GetCost();  
}
```

Stock.cc

Static dispatch

```
DividendStock dividend();

DividendStock *ds = &dividend;
Stock *s = &dividend;

// invokes Stock::GetProfit(), since that function is
// inherited (i.e, not overridden). Stock::GetProfit()
// invokes Stock::GetMarketValue(), since C++ uses
// static dispatch by default.
ds->GetProfit();

// invokes DividendStock::GetMarketValue()
ds->GetMarketValue();

// invokes Stock::GetMarketValue()
s->GetMarketValue();
```

Why not always use “virtual”?

Two (fairly uncommon) reasons:

- Efficiency:
 - ▶ non-virtual function calls are a tiny bit faster (no indirect lookup)
 - ▶ if the class has no virtual functions, objects will not have a vptr field
- Control: If $f()$ calls $g()$ in class X and g is not virtual, we're guaranteed to call $X::g()$ and not $g()$ in some subclass
 - ▶ Particularly useful for framework design

In Java, all functions (methods) are virtual (exception: static class methods, but these aren't associated with objects — no “this” ptr)

In C++ and C# you can pick what you want

- ▶ But omitting “virtual” often causes obscure bugs

Virtual is “sticky”

If `x::f()` is declared virtual, then a vtable will be created for class `x` and for all of its subclasses. The vtables will include function pointers for (the correct version of) `f`.

`f()` will be called using dynamic dispatch even if overridden but not explicitly specified as `virtual` in a subclass

- But it's good style to help the reader by using `override` (and, particularly in older code, `virtual`) in subclasses

Pure virtual fcn, abstract classes

Sometimes we want to include a function in a class but only implement it in subclasses. In Java we would use an abstract method. In C++ we use a “pure virtual” function.

- Example: `virtual string noise() = 0;` // see zoo.cc

A class that contains a pure virtual method is abstract

- ▶ Can't create instances of an abstract class (like Java)
- ▶ Extend abstract classes and override methods to use them (like Java)

A class containing *only* pure virtual methods is the same as a Java interface (∴ no separate “interface” thingys in C++)

- ▶ Pure type specification without implementations

Inheritance and constructors

A derived class **does not inherit** the base class's constructor

- the derived class ***must*** have its own constructor
 - ▶ if you don't provide one, C++ synthesizes a default constructor for you
 - it initializes derived class's non-POD member variables to zero-equivalents and invokes the default constructor of the base class
 - if the base class has no default constructor, a compiler error
- a constructor of the base class is invoked before the constructor of the derived class
 - ▶ you can specify which base class constructor in the initialization list of the derived class, or C++ will invoke default constructor of base class

Examples

```
// Base has no default constructor
class Base {
public:
    Base(int x) : y(x) { }
    int y;
};

// Compiler error when you try
// to instantiate a D1, as D1's
// synthesized default constructor
// needs to invoke Base's default
// constructor.
class D1 : public Base {
public:
    int z;
};

// Works.
class D2 : public Base {
public:
    D2(int z) : Base(z+1) {
        this->z = z;
    }
    int z;
};
```

badcons.cc

```
// Base has a default constructor.
class Base {
public:
    int y;
};

// Works.
class D1 : public Base {
public:
    int z;
};

// Works.
class D2 : public Base {
public:
    D2(int z) {
        this->z = z;
    }
    int z;
};
```

goodcons.cc

Destructors

baddestruct.cc

When the destructor of a derived class is invoked...

- the destructor of the base class is invoked after the destructor of the derived class finishes

Note that static dispatch of destructors is almost always a mistake!

- good habit to always define a destructor as virtual
 - ▶ empty if you have no work to do

```
class Base {
public:
    Base() { x = new int; }
    ~Base() { delete x; }
    int *x;
};

class D1 : public Base {
public:
    D1() { y = new int; }
    ~D1() { delete y; }
    int *y;
};

Base *b = new Base;
Base *dptr = (Base *) new D1;

delete b; // ok
delete dptr; // leaks D1::y
```

Slicing -- C++'s revenge

C++ allows you to...

- assign to...
 - ▶ an instance of a base class...
 - ▶ ...the value of a derived class

slicing.cc

```
class Base {
public:
    Base(int x) : x_(x) { }
    int x_;
};

class Dr : public Base {
public:
    Dr(int y) : Base(16), y_(y) { }
    int y_;
};

main() {
    Base b(1);
    Dr d(2);
    b = d;    // what happens to y_?
    // d = b; // compiler error
}
```

Given this, STL containers?? :(

STL stores **copies of values** in containers, not pointers to object instances

- so, what if you have a class hierarchy, and want to store mixes of object types in a single container?
 - ▶ e.g., Stock and DividendStock in the same list
- you get sliced! :(

```
class Stock {
    ...
};

class DivStock : public Stock {
    ...
};

main() {
    Stock      s;
    DivStock   ds;
    list<Stock> li;

    li.push_back(s);    // OK
    li.push_back(ds);  // OUCH!
}
```

STL + inheritance: use pointers?

Store pointers to heap-allocated objects in STL containers

- no slicing :)
- ▶ you have to remember to delete your objects before destroying the container :(
- ▶ sort() does the wrong thing :(:(

Use smart pointers!

```
#include <list>
using namespace std;

class Integer {
public:
    Integer(int x) : x_(x) { }
private:
    int x_;
};

main() {
    list<Integer *> li;
    Integer *i1 = new Integer(2);
    Integer *i2 = new Integer(3);

    li.push_back(i1);
    li.push_back(i2);
    li.sort(); // waaaaah!!
}
```

Explicit casting in C

C's explicit typecasting syntax is simple

```
lhs = (new_type) rhs;
```

- C's explicit casting is used to...
 - ▶ convert between pointers of arbitrary type
 - ▶ forcibly convert a primitive type to another
 - e.g., an integer to a float, so that you can do integer division

```
int x = 5;  
int y = 2;  
printf("%d\n", x / y);           // prints 2  
printf("%f\n", ((float) x) / y); // prints 2.5
```

C++

You can use C-style casting in C++, but C++ provides an alternative style that is more informative

- `static_cast<to_type>(expression)`
- `dynamic_cast<to_type>(expression)`
- `const_cast<to_type>(expression)`
- `reinterpret_cast<to_type>(expression)`

Always use these in C++ code - helps document intent

static_cast

C++'s `static_cast` can convert:

- pointers to classes **of related type**
 - ▶ get a compiler error if you attempt to `static_cast` between pointers to non-related classes
 - ▶ dangerous to cast a pointer to a base class into a pointer to a derived class
- non-pointer conversion
 - ▶ float to int, etc.

`static_cast` is checked at compile time

```
class Foo {
public:
    int x_;
};

class Bar {
public:
    float x_;
};

class Wow : public Bar {
public:
    char x_;
};

int main(int argc, char **argv) {
    Foo a, *aptr;
    Bar b, *bptr;
    Wow c, *cptr;

    // compiler error
    aptr = static_cast<Foo *>(&b);

    // OK
    bptr = static_cast<Bar *>(&c);

    // compiles, but dangerous
    cptr = static_cast<Wow *>(&b);
    return 0;
}
```


dynamic_cast

C++'s `dynamic_cast` can convert:

- pointers to classes of related type
- references to classes of related type

`dynamic_cast` is checked at both compile time and run time

- casts between unrelated classes fail at compile time
- casts from base to derived fail at run-time if the pointed-to object is not a full derived object
 - ▶ result is `nullptr` if cast fails

dynamiccast.cc

```
class Base {
public:
    virtual int foo() { return 1; }
    float x_;
};

class Deriv : public Base {
public:
    char x_;
};

int main(int argc, char **argv) {
    Base b, *bptr = &b;
    Deriv d, *dptr = &d;

    // OK (run-time check passes).
    bptr = dynamic_cast<Base *>(&d);
    assert(bptr != NULL);

    // OK (run-time check passes).
    dptr = dynamic_cast<Deriv *>(bptr);
    assert(dptr != NULL);

    // Run-time check fails, so the
    // cast returns NULL.
    bptr = &b;
    dptr = dynamic_cast<Deriv *>(bptr);
    assert(dptr != NULL);

    return 0;
}
```

const_cast

Is used to strip or add const-ness

- dangerous!

```
void foo(int *x) {                                     constcast.cc
    *x++;
}

void bar(const int *x) {
    foo(x); // compiler error
    foo(const_cast<int *>(x)); // succeeds
}

main() {
    int x = 7;
    bar(&x);
}
```

reinterpret_cast

casts between incompatible types

- storing a pointer in an int, or vice-versa
 - ▶ works as long as the integral type is “wide” enough
- converting between incompatible pointers
 - ▶ dangerous!
 - But used (carefully) in HW3!!

Implicit conversion

The compiler tries to infer some kinds of conversions

- when you don't specify an explicit cast, and types are not equal, the compiler looks for an acceptable implicit conversion

```
void bar(std::string x);

void foo() {
    int x = 5.7;    // implicit conversion float -> int
    bar("hi");     // implicit conversion, (const char *) -> string
    char c = x;    // implicit conversion, int -> char
}
```

Sneaky implicit conversions

How did the `(const char *) --> string` conversion work??

- if a class has a constructor with a single parameter, the compiler will exploit it to perform implicit conversions
- at most one user-defined implicit conversion will happen
 - ▶ can do `int --> Foo`
 - ▶ can't do `int --> Foo --> Baz`

```
implicit.cc
class Foo {
public:
    Foo(int x) : x_(x) { }
    int x_;
};

int Bar(Foo f) {
    return f.x_;
}

int main(int argc, char **argv) {
    // The compiler uses Foo's
    // (int x) constructor to make
    // an implicit conversion from
    // the int 5 to a Foo.

    // equiv to return Bar(Foo(5));
    // !!!
    return Bar(5);
}
```

Avoiding sneaky implicits

Declare one-argument constructors as “explicit” if you want to disable them from being used as an implicit conversion path

- usually a good idea

explicit.cc

```
class Foo {
public:
    explicit Foo(int x) : x_(x) { }
    int x_;
};

int Bar(Foo f) {
    return f.x_;
}

int main(int argc, char **argv) {

    // compiler error
    return Bar(5);
}
```

Exercise 1

Design a class hierarchy to represent shapes:

- examples of shapes: Circle, Triangle, Square

Implement methods that:

- construct shapes
- move a shape (i.e., add (x, y) to the shape position)
- returns the centroid of the shape
- returns the area of the shape
- `Print()`, which prints out the details of a shape

Exercise 2

Implement a program that:

- uses your exercise 1
 - ▶ constructs a vector of shapes
 - ▶ sorts the vector according to the area of the shape
 - ▶ prints out each member of the vector
- notes:
 - ▶ to avoid slicing, you'll have to store pointers in the vector
 - ▶ to be able to sort, you'll have to implement a wrapper for the pointers, and you'll have to override the "<" operator

See you on Wednesday!