C++ Inheritance Continued and Casting

CSE 333

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Administrivia

- Congrats on finishing the midterm!
- Everyone should have grades for HW1 now
  - If you got a zero and you turned it in, it's likely a tagging issue. File a regrade request!
- Exercise 12 was due this morning
- Exercise 13 isn't due until **Monday (July 29th)**
  - Take a break or work on HW3
- HW3 due **next Thursday (August 1st)**

Lecture Outline

- **C++ Inheritance**
  - **Dynamic Dispatch & VTables**
  - Static Dispatch
  - Abstract Classes
  - Constructors and Destructors
  - Assignment
- Casting

Reference: *C++ Primer*, Chapter 15

Most-Derived

Asset.h

```
class Asset {
 public:
  // GetCost will use dynamic
  // dispatch
  virtual void GetCost();
};
```

Asset.cc

```
void Foo(Asset* asset_ptr) {

  // Whose GetCost() is
  // called?
  asset_ptr->GetCost();
}
```

Stock.h

```
class Stock : public Asset {
 public:
  // Stock::GetCost overrides
  // Asset::GetCost
  virtual void GetCost();
};

class DividendStock : public Stock {
  // DividendStock inherits
  // Stock::GetCost()
};
```

Stock.cc

```
int main(int argc, char** argv) {
  DividendStock d;
  // Calls Stock::GetCost()
  Foo(&d);
}
```

How Can This Possibly Work?

- The compiler produces `Asset.o` from *just* `Asset.cc`
  - It doesn't know that `Stock` exists during this process
  - So then how does the emitted code for **`Bar`** in `Asset.o` know to call `Stock::`**`GetCost`**`()` instead of `Asset::`**`GetCost`**`()`?

Function pointers!

Dynamic Dispatch in C - Simple Version

Asset.h

```
typedef struct {
  void (*CostImpl)();
} Asset;
void Asset_GetCost();
Asset mkAsset();
```

Asset.c

```
Asset mkAsset(){
  Asset asset;
  asset.CostImpl =
    Asset_GetCost();
  return asset;
}
void Bar(Asset* asset_ptr)
{
  asset_ptr->CostImpl();
}
```

Stock.h

```
typedef struct {
  void (*CostImpl)();
} Stock;
void Stock_GetCost();
Stock mkStock(); // Don't need for now
typedef struct {
  void (*CostImpl)();
} DividendStock;
DividendStock mkDividendStock();
```

Stock.c

```
DividendStock mkDividendStock() {
  DividendStock dstock;
  dstock.CostImpl = Stock_GetCost();
  return dstock;
}
void Foo() {
  DividendStock d = mkDividendStock();
  Bar(&d);
}
```

vtables

- Conceptually, this is how it works at runtime
  - At compile time there is more type-checking
- In practice, C++ adds another layer of indirection
  - Instead of storing all function pointers on every object, one global table of function pointers per class
  - Each object stores a pointer to that table
  - Called the class's "vtable" ("v" for "virtual")
  - Better when there are lots of virtual functions

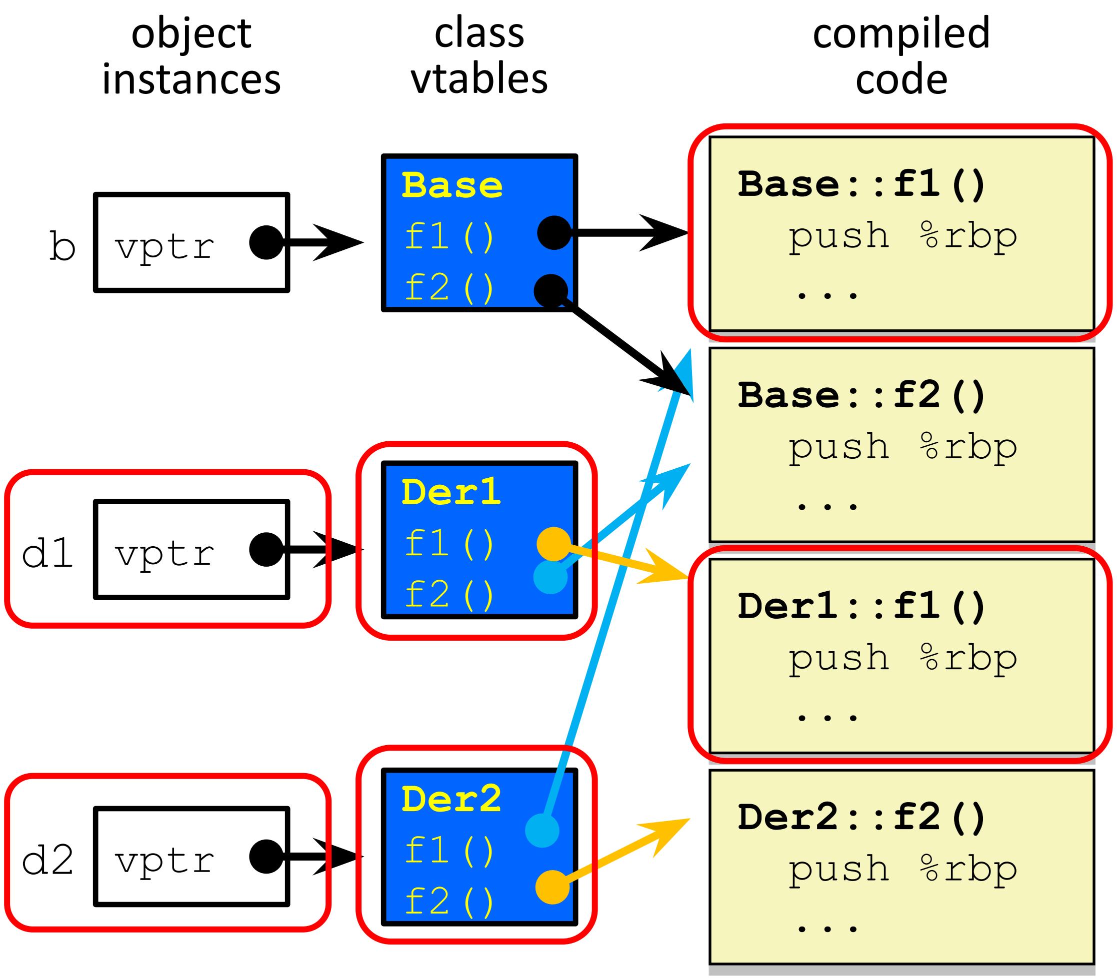
vtables and the vptr

- If a class contains *any* virtual methods, the compiler emits:
  - A (single) virtual function table (vtable) for *the class*
    - Contains a function pointer for each virtual method in the class
    - The pointers in the vtable point to the most-derived function for that class
  - A virtual table pointer (vptr) for *each object instance*
    - A pointer to a virtual table as a "hidden" member variable
    - When the object's constructor is invoked, the vptr is initialized to point to the vtable for the newly constructed object's class
    - Thus, the vptr "remembers" what class the object is

```cpp
class Base {
 public:
  virtual void f1();
  virtual void f2();
};

class Der1 : public Base {
 public:
  virtual void f1();
};

class Der2 : public Base {
 public:
  virtual void f2();
};
```

```cpp
Base b;
Der1 d1;
Der2 d2;

Base* b0ptr = &b;
Base* b1ptr = &d1;
Base* b2ptr = &d2;

b0ptr->f1();  // Base::f1()
b0ptr->f2();  // Base::f2()

b1ptr->f1();  // Der1::f1()
b1ptr->f2();  // Base::f2()

d2.f1();      // Base::f1()
b2ptr->f1();  // Base::f1()
b2ptr->f2();  // Der2::f2()
```

vtable/vptr Example




```
Base b;
Der1 d1;
Der2 d2;

Base* b0ptr = &d1;

b0ptr->f1();
// b0ptr -->
// d1.vptr -->
// Der1.vtable.f1 -->
// Der1::f1()

Base* b2ptr = &d2;

b2ptr->f1();
// b2ptr -->
// d2.vptr -->
// Der2.vtable.f1 -->
// Base::f1()
```

Lecture Outline

- **C++ Inheritance**
  - Vtables
  - **Static Dispatch**
  - **Abstract Classes**
  - Constructors and Destructors
  - Assignment
- Casting

Reference: *C++ Primer*, Chapter 15

What happens if we omit "virtual"?

- By default, without virtual, methods are dispatched *statically*
  - At compile time, the compiler writes in a `call` to the address of the class' method in the generated code `.text` segment
    - Based on the compile-time visible type of the called code (callee)
  - This is *different* than Java

```
class Derived : public Base {
...
  void foo();
...
};

int main(int argc, char** argv) {
  Derived d;
  Derived* dp = &d;
  Base* bp = &d;
  dp->foo();
  bp->foo();
  return 0;
}
```

```
Derived::foo()
...
```

```
Base::foo()
...
```

Static Dispatch Example

- Removed `virtual` on methods:

Stock.h

```
double Stock::GetMarketValue() const;
double Stock::GetProfit() const;
```

```
DividendStock dividend();
DividendStock* ds = &dividend;
Stock* s = &dividend;
// Calls DividendStock::GetMarketValue()
ds->GetMarketValue();

// Calls Stock::GetMarketValue()
s->GetMarketValue();

// Calls Stock::GetProfit(), since that method is inherited.
// Stock::GetProfit() calls Stock::GetMarketValue().
ds->GetProfit();

// Calls Stock::GetProfit().
// Stock::GetProfit() calls Stock::GetMarketValue().
s->GetProfit();
```

`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) `f`
- `f()` will be called using dynamic dispatch even if overridden in a derived class without the `virtual` keyword
  - Good style to help the reader *and avoid bugs* by using `override`
    - Style guide controversy, if you use `override` should you use `virtual` in derived classes? Recent style guides say just use `override`, but you'll sometimes see both, particularly in older code

Why Not Always Use `virtual`?

- Two (fairly uncommon) reasons:
  - Efficiency:
    - Non-virtual function calls are a tiny bit faster (no indirect lookup)
    - A class with no virtual functions has objects without 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 methods are virtual, except `static` class methods, which aren't associated with objects
- In C++, you can pick what you want
  - Omitting virtual can cause obscure bugs

Why Not Always Use `virtual`?

- Two (fairly uncommon) reasons:
  - Efficiency:
    - Non-virtual function calls are a tiny bit faster (no indirect lookup)
    - A clas[…] `vptr` field
  - Contro[…]
    - If `f` ([…]aranteed to call `X::`[…]
      - Par[…]

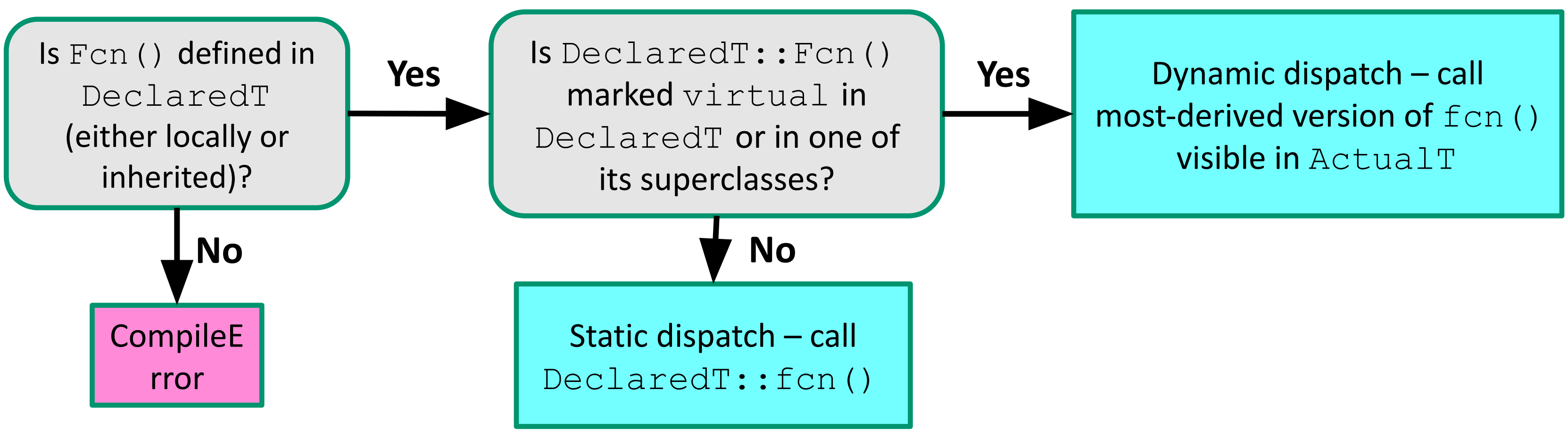
In practice (for this class), always use virtual!

- In Java, all methods are virtual, except `static` class methods, which aren't associated with objects
- In C++, you can pick what you want
  - Omitting virtual can cause obscure bugs

Mixed Dispatch

- Which function is called is a mix of both compile time and runtime decisions as well as *how* you call the function
  - If called on an object (*e.g.* `obj.Fcn()`), usually optimized into a hard-coded function call at compile time
  - If called via a pointer or reference:

```
DeclaredT *ptr = new ActualT;
ptr->Fcn();  // which version is called?
```



Mixed Dispatch Example

mixed.cc

```
class A {
 public:
  void m1() { cout << "a1"; }
  virtual void m2() { cout << "a2"; }
};

class B : public A {
 public:
  void m1() { cout << "b1"; }
  void m2() { cout << "b2"; }
};
```

```
void main(int argc,
          char** argv) {
  A a;
  B b;

  A* a_ptr_a = &a;
  A* a_ptr_b = &b;
  ~~B* b_ptr_a = &a;~~
  B* b_ptr_b = &b;

  a_ptr_a->m1();   // a1
  a_ptr_a->m2();   // a2

  a_ptr_b->m1();   // a1
  a_ptr_b->m2();   // b2

  b_ptr_b->m1();   // b1
  b_ptr_b->m2();   // b2
}
```

Mixed Dispatch Example

mixed.cc

```
class A {
 public:
  // m1 will use static dispatch
            void m1() { cout << "a1"; }
  // m2 will use dynamic dispatch
  virtual void m2() { cout << "a2"; }
};

class B : public A {
 public:
  void m1() { cout << "b1, "; }
  // m2 is still virtual by default
  void m2() { cout << "b2"; }
};
```

```
void main(int argc,
          char** argv) {
  A a;
  B b;

  A* a_ptr_a = &a;
  A* a_ptr_b = &b;
  B* b_ptr_a = &a;
  B* b_ptr_b = &b;

  a_ptr_a->m1();  // a1
  a_ptr_a->m2();  // a2

  a_ptr_b->m1();  // a1
  a_ptr_b->m2();  // b2

  b_ptr_b->m1();  // b1
  b_ptr_b->m2();  // b2
}
```

Lecture Outline

- **C++ Inheritance**
  - Vtables
  - Static Dispatch
  - Abstract Classes
  - **Constructors and Destructors**
  - **Assignment**
- Casting

Reference: *C++ Primer*, Chapter 15

Derived-Class Objects

- A derived object contains "subobjects" corresponding to the data members inherited from each base class
  - No guarantees about how these are laid out in memory (not even contiguousness between subobjects)

- Conceptual structure of `DividendStock` object:

members inherited from `Stock`	`symbol_` `total_shares_` `total_cost_` `current_price_`
members defined by `DividendStock`	`dividends_`

Constructors and Inheritance

- A derived class **does not inherit** the base class' constructor
  - The derived class must have its own constructor
  - A synthesized default constructor for the derived class first invokes the default constructor of the base class and then initializes the derived class' member variables
    - Compiler error if the base class has no default constructor
  - The base class constructor is invoked *before* the constructor of the derived class
    - You can use the initialization list of the derived class to specify which base class constructor to use

Constructor Examples

badctor.cc

```
class Base {  // no default ctor
 public:
  Base(int y) : y(y) { }
  int y;
};

// Compiler error when you try to
// instantiate a Der1, as the
// synthesized default ctor needs
// to invoke Base's default ctor.
class Der1 : public Base {
 public:
  int z;
};

class Der2 : public Base {
 public:
  Der2(int y, int z)
    : Base(y), z(z) { }
  int z;
};
```

goodctor.cc

```
// has default ctor
class Base {
 public:
  int y;
};

// works now
class Der1 : public Base {
 public:
  int z;
};

// still works
class Der2 : public Base {
 public:
  Der2(int z) : z(z) { }
  int z;
};
```

Destructors and Inheritance

- Destructor of a derived class:
  - *First* runs body of the dtor
  - *Then* invokes of the dtor of the base class
- Static dispatch of destructors is almost always a mistake!
  - Good habit to always define a dtor as virtual
    - Empty body if there's no work to do

baddtor.cc

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

class Der1 : public Base {
 public:
  Der1() { y = new int; }
  ~Der1() { delete y; }
  int* y;
};

void foo() {
  Base* b0ptr = new Base;
  Base* b1ptr = new Der1;

  delete b0ptr;  // OK
  delete b1ptr;  // leaks Der1::y
}
```

Assignment and Inheritance

- C++ allows you to assign the value of a derived class to an instance of a base class
  - Known as object slicing
    - It's legal since `b=d` passes type checking rules
    - But b doesn't have space for any extra fields in d

slicing.cc

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

class Der1 : public Base {
 public:
  Der1(int y) : Base(16), y_(y) { }
  int y_;
};

void foo() {
  Base b(1);
  Der1 d(2);

  d = b;  // compiler error
  b = d;  // what happens to y_?
}
```

STL and Inheritance

- Recall: STL containers store **copies of values**
  - What happens when we want to store mixes of object types in a single container? (*e.g.* `Stock` and `DividendStock`)
  - You get sliced ☹️

```
#include <list>
#include "Stock.h"
#include "DividendStock.h"

int main(int argc, char** argv) {
  Stock s;
  DividendStock ds;
  list<Stock> li;

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

  return 0;
}
```

STL and Inheritance

- Instead, store **pointers to heap-allocated objects** in STL containers
  - No slicing! ☺️
  - `sort()` does the wrong thing ☹️
  - You have to remember to `delete` your objects before destroying the container ☹️
    - Smart pointers next lecture will help with this!

Lecture Outline

- C++ Inheritance
  - Vtables
  - Static Dispatch
  - Abstract Classes
  - Constructors and Destructors
  - Assignment
- **Casting**

- Reference: *C++ Primer*, Chapter 12.1

Explicit Casting in C

- Simple syntax: `lhs = (new_type) rhs;`
- Used to:
  - Convert between pointers of arbitrary type
    - Don’t change the data, but treat differently
  - Forcibly convert a primitive type to another
    - Actually changes the representation

- You *can* still use C-style casting in C++, but that uses one notation for different purposes

Casting in C++

- C++ provides an alternative casting 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
  - Intent is clearer
  - Easier to find in code via searching

staticcast.cc

static_cast

- `static_cast` can convert:
  - Pointers to classes **of related type**
    - Compiler error if classes are not related
    - Dangerous to cast *down* a class hierarchy
  - Non-pointer conversion
    - e.g. `float` to `int`
- `static_cast` is checked at compile time

```
class A {
 public:
  int x;
};

class B {
 public:
  float x;
};

class C : public B {
 public:
  char x;
};
```

```
void foo() {
  B b; C c;

  // compiler error
  A* aptr = static_cast<A*>(&b);
  // OK
  B* bptr = static_cast<B*>(&c);
  // compiles, but dangerous
  C* cptr = static_cast<C*>(&b);
}
```

Use static_cast to cast pointers **up** the class hierarchy, or for numeric casts dynamiccast.cc

dynamic_cast

- 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 the derived type

```
class Base {
 public:
  virtual void foo() { }
  float x;
};

class Der1 : public Base {
 public:
```

Use static_cast to cast pointers **down** the class hierarchy, or for casting references

```
void bar() {
  Base b; Der1

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

  // OK (run-time check passes)
  Der1* dptr = dynamic_cast<Der1*>(bptr);
  assert(dptr != nullptr);

  // Run-time check fails, returns nullptr
  bptr = &b;
  dptr = dynamic_cast<Der1*>(bptr);
  assert(dptr != nullptr);
}
```

const_cast

- `const_cast` adds or strips const-ness
  - Dangerous (!)

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

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

int main(int argc, char** argv) {
  int x = 7;
  bar(&x);
  return 0;
}
```

`reinterpret_cast`

- `reinterpret_cast` casts between *incompatible* types
  - Low-level reinterpretation of the bit pattern
  - *e.g.* storing a pointer in an `int64_t`, or vice-versa
    - Works as long as the integral type is "wide" enough
  - Converting between incompatible pointers
    - Dangerous (!)
    - This is used (carefully) in hw3

Implicit Conversion

- The compiler tries to infer some kinds of conversions
  - When types are not equal and you don't specify an explicit cast, the compiler looks for an acceptable implicit conversion

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

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

Sneaky Implicit Conversions

- `(const char*)` to `string` conversion?
  - If a class has a constructor with a single parameter, the compiler will use it it to perform implicit conversions
  - At most, one user-defined implicit conversion will happen
    - Can do `int` → `Foo`, but not `int` → `Foo` → `Baz`

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

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

int main(int argc, char** argv) {
  return Bar(5);  // equivalent to return Bar(Foo(5));
}
```

But `char` → `int` → `Foo` is fine!

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

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

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

int main(int argc, char** argv) {
  return Bar(5);  // compiler error
}
```

Administrivia

- Check your HW1 grades
  - If you got a zero and you turned it in, it's likely a tagging issue. File a regrade request!
- Exercise 13 isn't due until **Monday (July 29th)**
  - Take a break or work on HW3
- HW3 due **next Thursday (August 1st)**

Extra Exercise #1

- Design a class hierarchy to represent shapes
  - *e.g.* 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

Extra Exercise #2

- Implement a program that uses Extra Exercise #1 (shapes class hierarchy):
  - Constructs a vector of shapes
  - Sorts the vector according to the area of the shape
  - Prints out each member of the vector

- Notes:
  - Avoid slicing!
  - Make sure the sorting works properly!