Dynamic Binding Implementation

Object-Oriented Programming

236703

Spring 2015

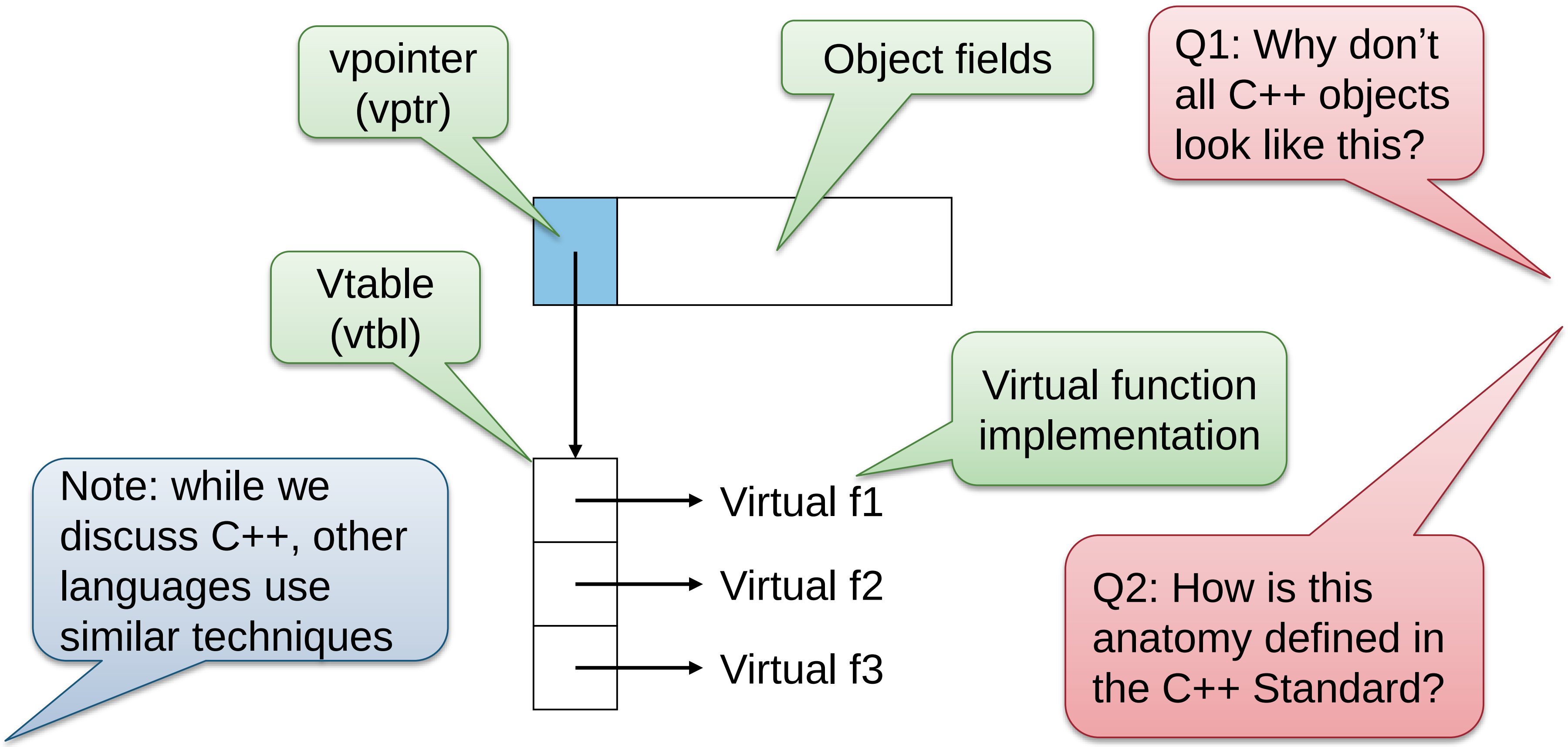
Dynamic Binding

- Reminder: dynamic binding is required when the *dynamic type* can be different from the *static type*
  - I.e., *polymorphism* is involved
- We focus on statically-typed languages
  - Given: static type *protocol*
  - Required: dynamic type *behavior*
  - Can we check the receiver’s type, go to the class object, and invoke the right method?
    - Maybe. But we can do much better.
- We will also discuss dynamically-typed languages a bit

Disclaimer

- Languages usually define <u>semantics</u> and not <u>implementation</u>
    - E.g., C++ requires dynamic binding of virtual functions, but does not care how that binding is achieved
        - No ABI (Application Binary Interface) – good luck linking GCC and VS object files
- The following 3 lectures present common, not mandatory, <u>implementations</u>
    - Enough for the final exam, not for professional programming

Anatomy of C++ Polymorphic* Object

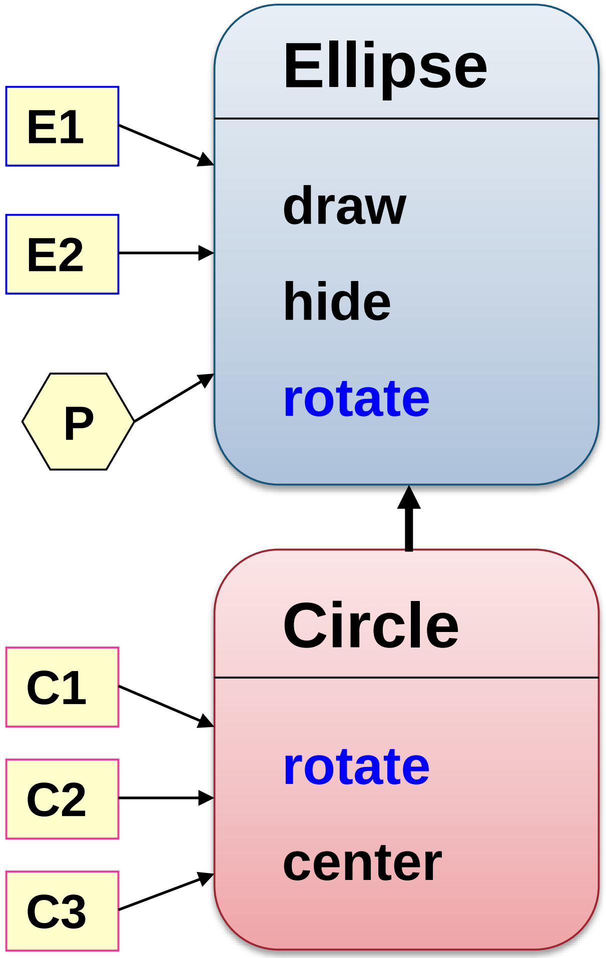

vpointer (vptr)
Object fields
Q1: Why don't all C++ objects look like this?
Vtable (vtbl)
Virtual function implementation
Note: while we discuss C++, other languages use similar techniques
Virtual f1
Virtual f2
Virtual f3
Q2: How is this anatomy defined in the C++ Standard?

* In C++ terminology, a class is *polymorphic* if it has a virtual function

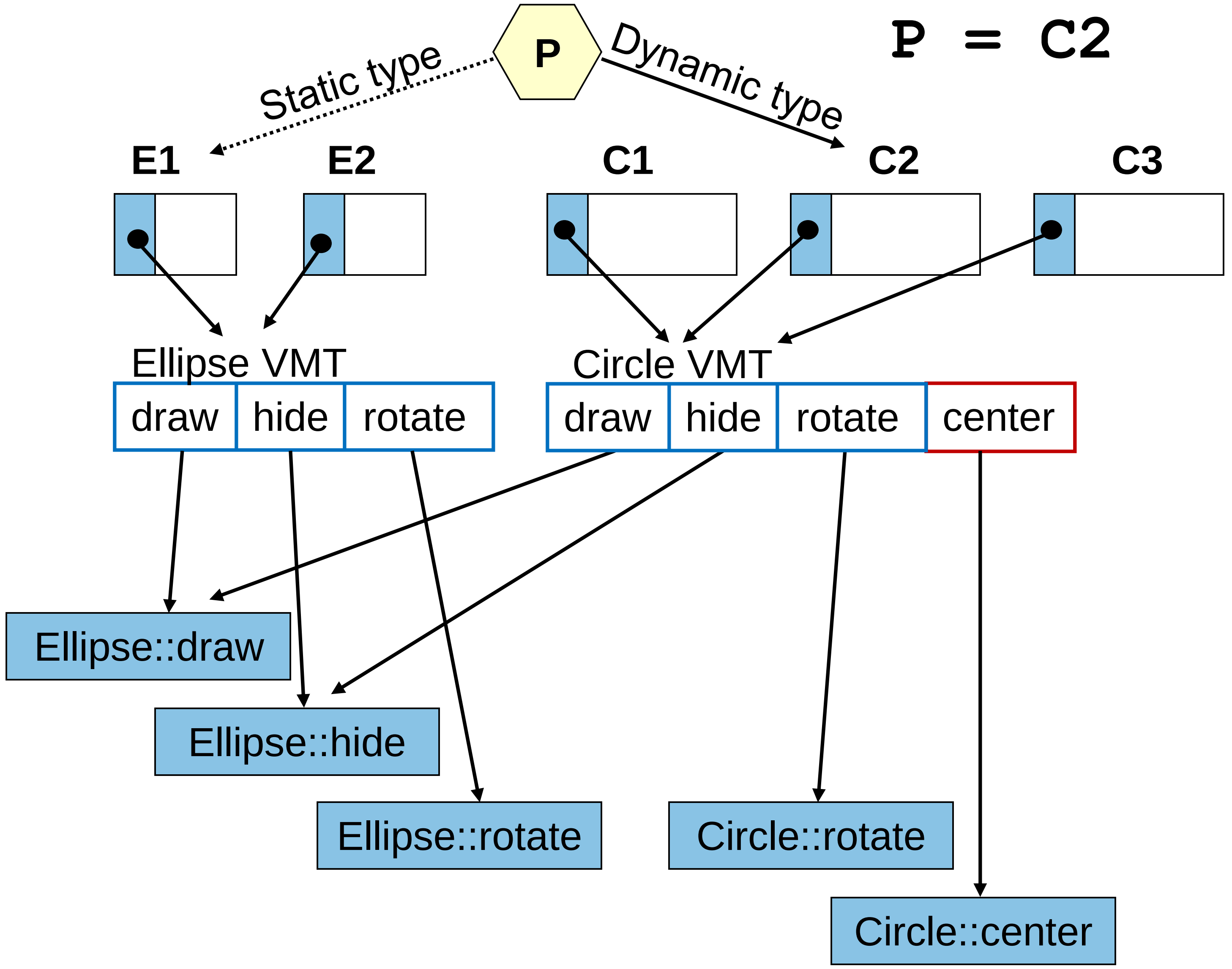
C++ Virtual Functions Implementation

```
class Ellipse {
// ...
public:
  virtual void draw() const;
  virtual void hide() const;
  virtual void rotate(int);
} E1, E2, *P;
```

```
class Circle : public Ellipse {
//...
public:
  void rotate(int) override;
  virtual Point center();
} C1, C2, C3;
```

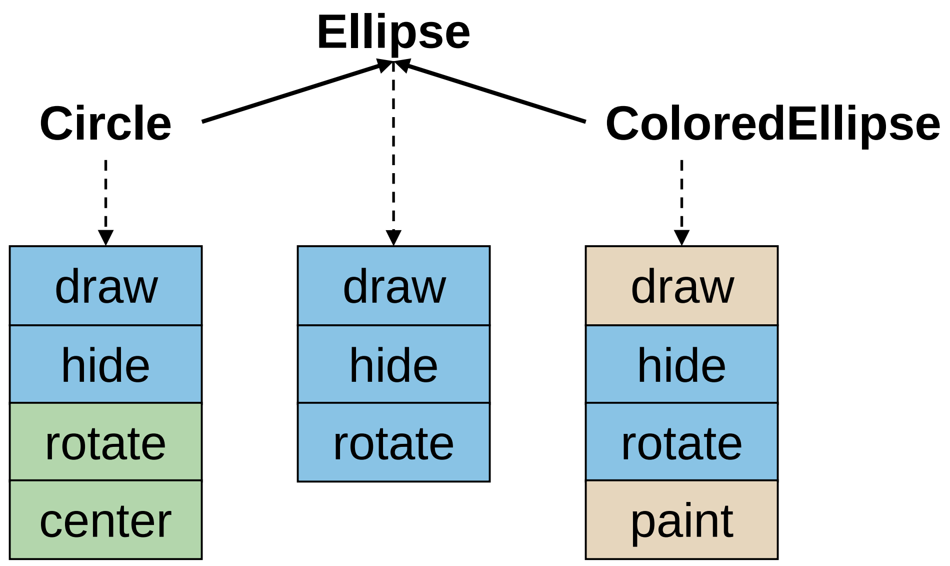


The Virtual Methods Table

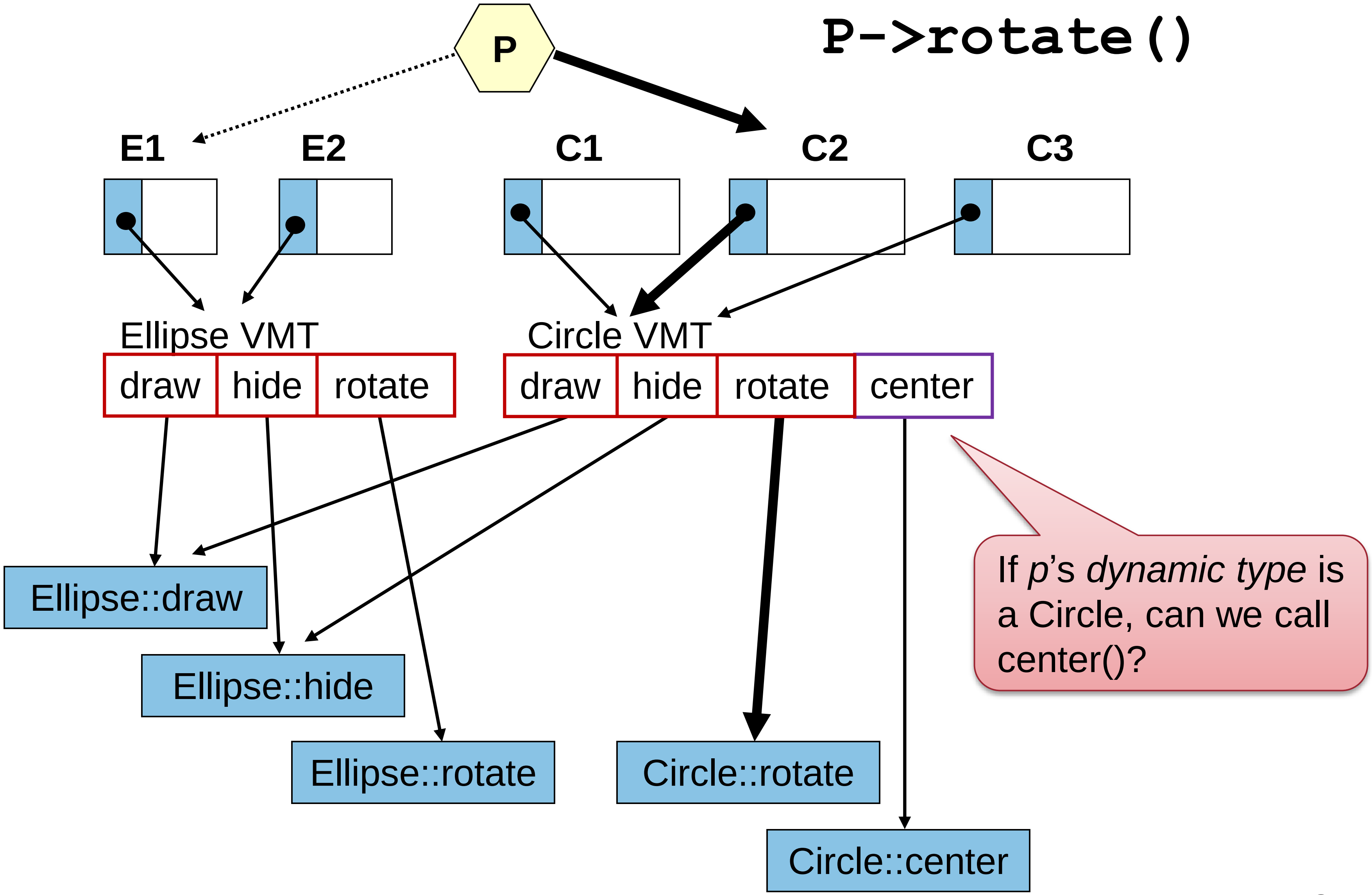


Virtual Method Table & Inheritance

- Given a Circle that inherits from Ellipse:
  - Virtual methods first declared in Circle are *appended* to Ellipse's VMT
  - Overridden virtual methods *replace* content of existing entries
- Each class usually has its own VMT, even if the VMT is identical to another

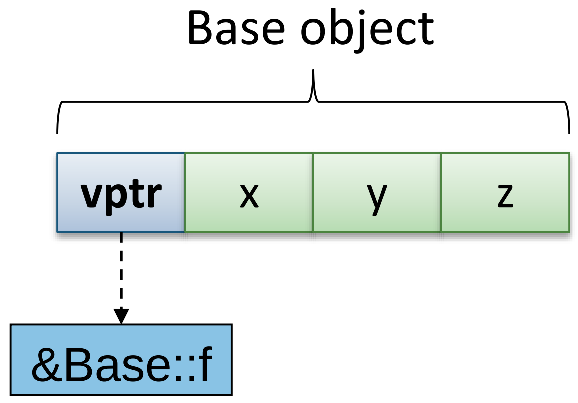


Virtual Function at Work



Borland Style VPTR

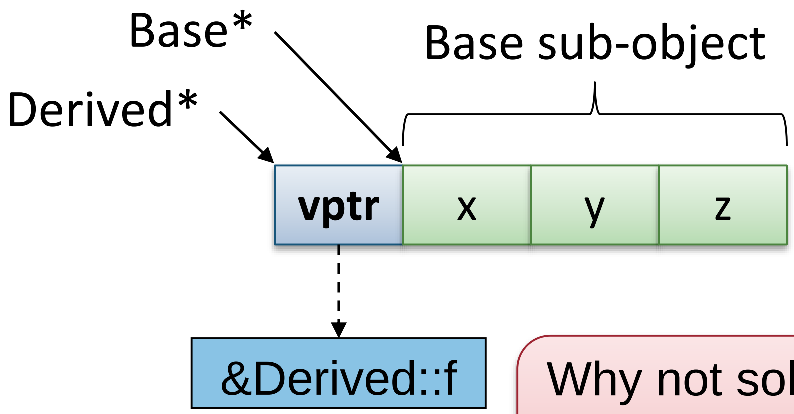
```
struct Base {
  int x, y, z;
  virtual void f();
};
```



- Virtual pointer is always located at the beginning of the object
  - Given, of course, the class is polymorphic
- Easy access to vptr – always at the same offset (0)
  - Dynamic binding = exactly 2 pointer dereferences

Borland Style & Inheritance

```
struct Base {
  int x, y, z;
};
struct Derived : Base {
  virtual void f();
};
Derived* d = new Derived;
Base* b = d;                b->x = 1;
d = static_cast<D*>(b); d->x = 2;
```

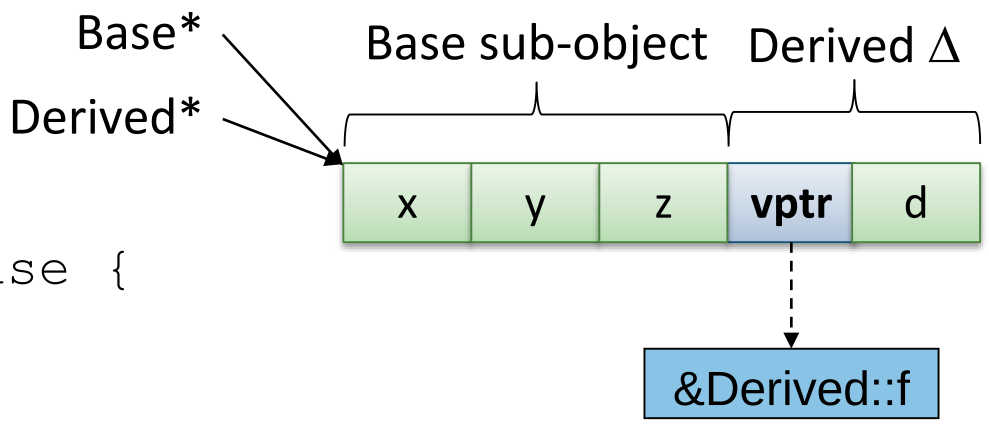


Why not solve this by having *all* objects have a vptr?

- If Base isn't polymorphic and Derived is, *this adjustment* is required upon cast
  - sizeof(vptr) must be added or subtracted
  - nullptr check must be done as well (why?)

Gnu Style VPTR

```
struct Base {
  int x, y, z;
};
struct Derived : Base {
  int d;
  virtual void f();
};
```



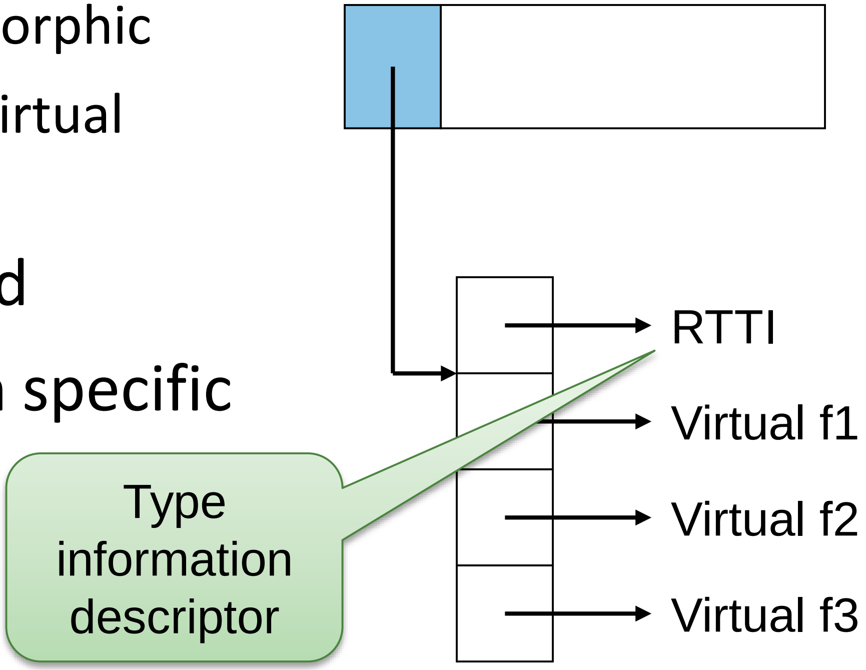
- VPTR is located at the beginning of the first sub-object that has virtual functions
  - Must add sizeof(Base) to reach vptr – on every virtual function call!
    - Note: the offset is calculated at compile time; the addition is done at run time
- But now, casting is free
  - Well, not dynamic_cast, which must do type checking…

Borland vs. Gnu

- Optimization decision: what should work faster?
  - Borland – virtual functions invocation
  - Gnu – casting
- Can’t mix binaries using different styles
  - But that’s the case with every aspect of virtual functions, RTTI, multiple inheritance etc. – C++ has no standard ABI ☹
  - A compiler can use both styles as long as each class is treated consistently
- In practice, most compilers use Borland style (yes, even GCC – the Gnu Compiler Collection…)

Run-time Type Information (RTTI)

- Conceptually and practically related to virtual functions and virtual tables:
  - No RTTI if class not polymorphic
  - RTTI usually reached via virtual table
- Use: dynamic_cast, typeid
- Content: implementation specific



Binding within Constructors (and Destructors)

- Given an object of class B, which inherits class A; how is it initialized?
- In C++ and Java, the constructor of A is invoked before the constructor of B
  - Why?
    - So B’s constructor never sees uninitialized attributes
- What happens if A’s constructor invokes a virtual function?
  - And that virtual function is overridden by B?

Binding within Constructors – C++

- The binding of function calls within constructors ~~is static~~ – must be *as if* it is static. Why?
  - B’s memory has not been initialized yet

```
struct A {
  int x;
  virtual void f() { cout << “x=“ << x; }
  A() : x(1) { f(); }
};

struct B : A {
public:
  int y;
  void f() override { cout << “y=” << y; }
  B() : y(2) {}
};
```

  - The output of **new** `B` should be ”x=1”

Statically Binding Vfuncs in C’tors

- If binding must be *as if* it is static, why not just use static binding?
  - `A() {f();}` → `A() {A::f();}` will work!
- Now, say we have some global function:

```
void g(A* a) { a->f(); }
```

- What should the compiler do if A’s constructor is modified as follows?

```
A() { g(this); }
```

- Static binding can’t handle indirect invocations!

Bounding Dynamic Binding

- Instead of statically binding within constructors, dynamic binding can be used but limited
- The compiler generates code as follows when creating a new B:
  1. Call A’s constructor
  2. Have vptr point on A’s vtable
  3. Execute A’s constructor
  4. Have vptr point on B’s vtable
  5. Execute B’s constructor
- Now, the B::A is really an A during construction
  - Including indirect calls and RTTI
- This is why abstract classes must have vtables!
  - Once constructed, vtable of derived class is used

Pitfall of Bounded Dynamic Binding

```
struct A {
  virtual void f() = 0;
  A() { f(); }
};

struct B : A {
  void f() override { cout << “B’s f”; }
};
```

- What happens in **new** B?
- Some compilers do not allow calling a pure virtual function directly from constructors
  - But indirect invocations can’t always be detected
- Invoking a pure virtual function is Undefined Behavior
  - In practice, will probably yield an error message and abort

Binding within Constructors – Java

- Function binding within constructors is fully dynamic
  - An initialization phase precedes the constructor invocation, setting fields to default values

```
class A {
  private int x = 1;
  public void f() { System.out.print(“x=“+x); }
  public A() { f(); }
}

class B extends A {
  private int y = 2;
  public void f() { System.out.print(“y=”+y); }
  public B() {}
}
```

Why can’t C++ have a similar initialization phase?

- The output of **new** `B()` is: ”y=0”

Pitfall of Full Dynamic Binding

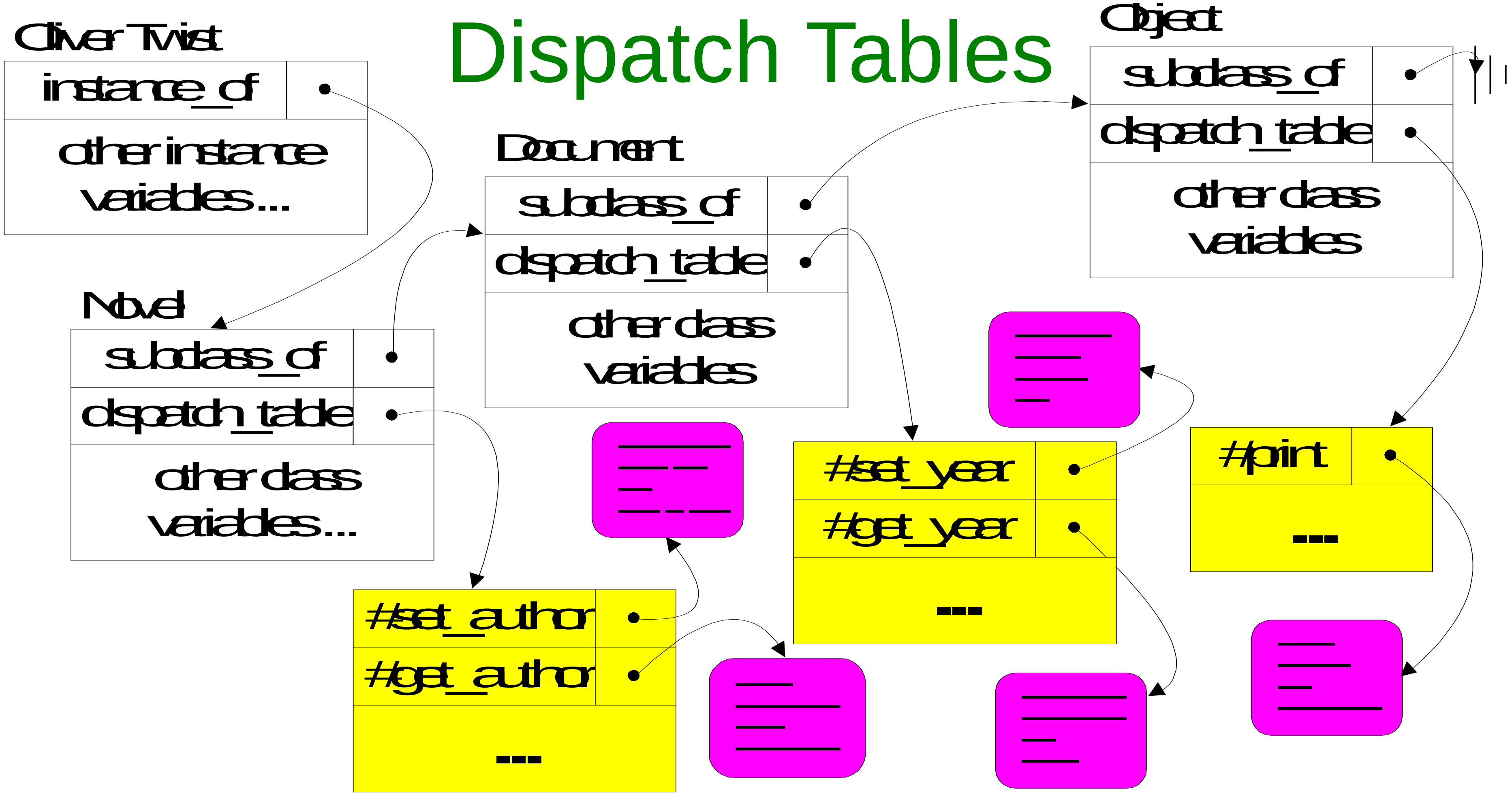
```
class A {
  public A() { System.out.print( toString() ); }
}

class B extends A {
  private String s = “Class B”
  public String toString() { return s.toLowerCase(); }
}
```

- What happens in **new** `B();` ?
  - `s` is initialized to **`null`** when A’s constructor is invoked
  - B’s `toString()` is invoked from A’s constructor
  - The result: `NullPointerException`

Dynamic Binding & Dynamic Typing

- Dynamic Typing: no constraints on the values stored in a variable
  - Usually implies reference semantics
- Run-time type information: dynamic type is associated with the value
  - There is no notion of static type to be associated with a variable
- No type safety: run-time error if an object doesn't recognize a message

Dispatch Tables



- Used in dynamic type systems
- Support:
  - Runtime introduction of new types
  - Runtime changes to type hierarchy
  - “Method not found” error messages

- Space Efficiency: optimal!
- Time Efficiency: lousy; mitigated by a cache of triples:
  - Class where search started
  - Selector searched
  - Address of method found

Virtual Table vs. Dispatch Table

- Statically typed languages use virtual tables, while dynamically typed languages use dispatch tables (AKA method dictionaries)
- Virtual tables are much faster – direct access instead of lookup
    - Access is determined on compile type based on static type, hence N/A for dynamic languages
    - Still, even statically typed languages must sometimes do a lookup
        - E.g., Java interfaces – more on that in 2 weeks