HARVARD
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CS153: Compilers
Lecture 11: Compiling Objects

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https://www.seas.harvard.edu/courses/cs153

Announcements

- Project 3 due today
- Project 4 out
  - Due Thursday Oct 25 (16 days)
- Project 5 released on Thursday

Today

- Object Oriented programming
    - What is it
    - Dynamic dispatch
    - Code generation for methods and method calls
    - Fields
    - Creating objects
    - Extensions
    - Type system

What Is Object-Oriented Programming?

- Programming based on concept of **objects**, which are **data plus code**
- OOP can be an effective approach to writing large systems
  - Objects naturally model entities
  - OO languages typically support
    - **information hiding** (aka **encapsulation**) to support modularity
    - **inheritance** to support code reuse
- Several families of OO languages:
  - Prototype-based (e.g. Javascript, Lua)
  - Class-based (e.g. C++, Java, C#)
- We focus on the compilation of class-based OO languages

Brief Incomplete History of OO

- (Early 60's) Key concepts emerge in various languages/programs: sketchpad (Sutherland), SIMSCRIPT (Hoare), and probably many others.
- (1967) Simula 67 (Dahl, Nygaard) crystalizes many ideas (class, object, subclass, dispatch) into a coherent OO language
- (1972) Smalltalk (Kay) introduces the concept of object-oriented programming (you should try Squeak!)
- (1978) Modula-2 (Wirth)
- (1985) Eiffel (Meyer)
- (1990's) OO programming becomes mainstream: C++, Java, C#, ...

Classes

- What's the difference between a class and an object?
- A class is a blueprint for objects
- Class typically contains
  - Declared fields / instance variables
    - Values may differ from object to object
    - Usually mutable
  - Methods
    - Shared by all objects of a class
    - Inherited from superclasses
    - Usually immutable
- Methods can be overridden, fields (typically) can not

Example Java Code

```
class Vehicle extends Object {
    int position = 0;
    void move(int x) { this.position += x; }
}

class Car extends Vehicle {
    int passengers = 0;
    void await(Vehicle v) {
        if (v.position < this.position) {
            v.move(this.position - v.position);
        } else { this.move(10); }
    }
}

class Truck extends Vehicle {
    void move(int x) { if (x < 55) this.position += x;}
}
```

- Every `Vehicle` is an `Object`
- Every `Car` is a `Vehicle`, every `Truck` is a `Vehicle`
- Every `Vehicle` (and thus every `Car` and `Truck`) have a `position` field and a `move` method
- Every `Car` also has a `passengers` field and an `await` method

Example Java Code

```
class Vehicle extends Object {
    int position = 0;
    void move(int x) { this.position += x; }
}

class Car extends Vehicle {
    int passengers = 0;
    void await(Vehicle v) {
        if (v.position < this.position) {
            v.move(this.position - v.position);
        } else { this.move(10); }
    }
}

class Truck extends Vehicle {
    void move(int x) { if (x < 55) this.position += x;}
}
```

- A `Car` can be used anywhere a `Vehicle` is expected (because a `Car` is a `Vehicle`!)
- Class `Truck` **overrides** the `move` method of `Vehicle`
  - Invoking method `o.move(i)` will invoke `Truck`'s `move` method if `o`'s class at run time is `Truck`

Code Generation for Objects

- Methods
  - How do we generate method body code?
  - How do we invoke methods (dispatching)
  - Challenge: handling inheritance
- Fields
  - Memory layout
  - Alignment
  - Challenge: handling inheritance

Need for Dynamic Dispatch

- Methods look like functions. Can they be treated the same?
- Consider the following Java code

```
interface Point { int getx(); float norm(); }

class ColoredPoint implements Point {
    ...
    float norm() { return sqrt(x*x+y*y); }
}

class 3DPoint implements Point {
    ...
    float norm() { return sqrt(x*x+y*y+z*z); }
}
Point p = foo();
p.norm();
```

Need for Dynamic Dispatch

- Methods look like functions. Can they be treated the same?
- Consider the following Java code

```
interface Point { int getx(); float norm(); }

class ColoredPoint implements Point {
    ...
    float norm() { return sqrt(x*x+y*y); }
}

class 3DPoint implements Point {
    ...
    float norm() { return sqrt(x*x+y*y+z*z); }
}
Point p = foo();
p.norm();
```

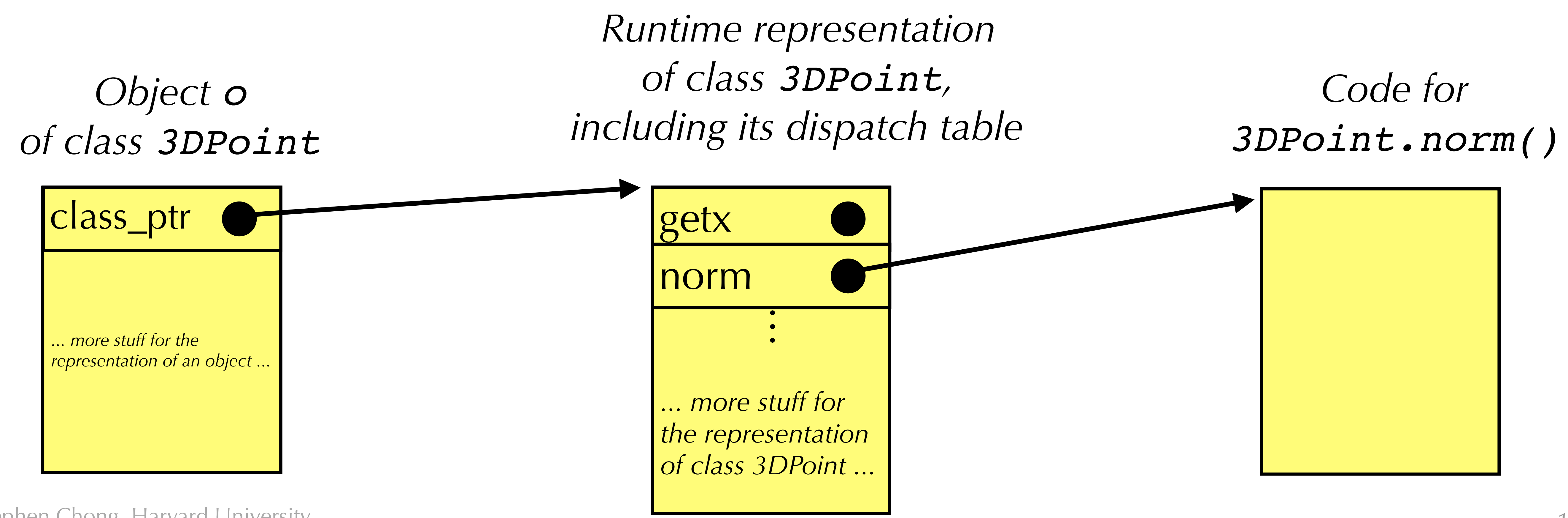
If `p` is object of class `ColoredPoint`, should execute `ColoredPoint.norm()`

If `p` is object of class `3DPoint`, should execute `3DPoint.norm()`

At run time could be either case!

Dynamic Dispatch Solution

- So we need some way at run time to figure out which code to invoke
- Solution: **dispatch table** (aka **virtual method table**, **vtable)**
  - Each class has table (array) of function pointers
  - Each method of class is at a known index of table



What Offset Into the VTable?

- Want to make sure that every object of class **`B`** has same layout of dispatch table
  - Even if object is actually a subclass of **`B`**!

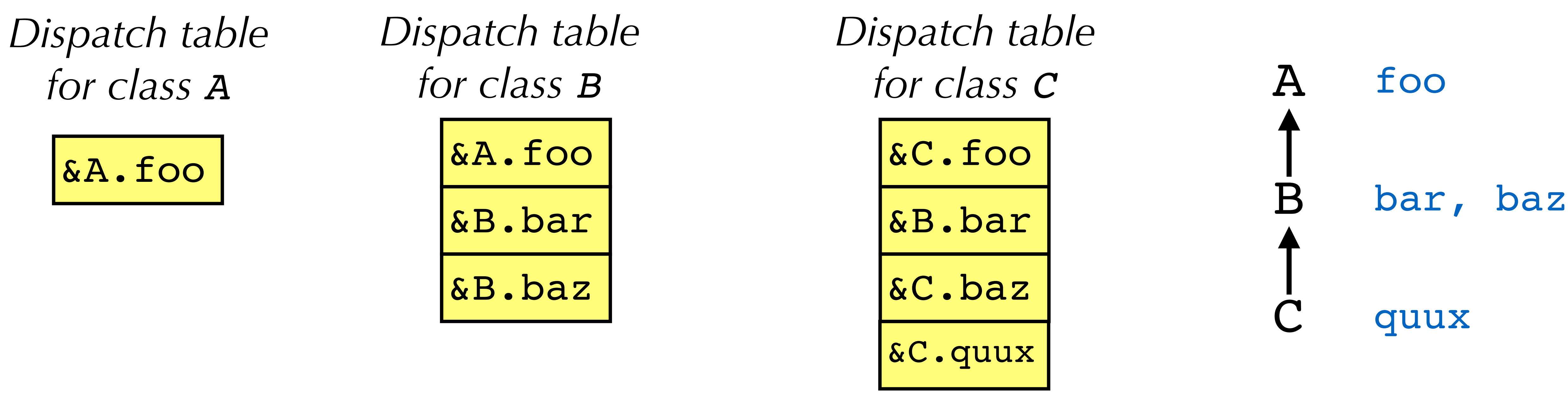
```
  class A {
1   void foo() { ... }
  }
  class B extends A {
2   void bar() { ... }
3   void baz() { ... }
  }
```

```
class C extends B {
  void foo() { ... }

  void baz() { ... }
4 void quux() { ... }
}
```

- List methods in order
- Ensures that a dispatch table for class **`C`** also looks like a dispatch table for class **`B`**, and for class **`A`**

Dispatch Tables



- Dispatch table for class `C` looks like a dispatch table for class `B`
  - i.e., address for method `foo` is at index 0 (offset 0 bytes)
    address for method `bar` is at index 1 (offset 4 bytes)
    address for method `baz` is at index 2 (offset 8 bytes)
- And it looks like a dispatch table for class `A`
  - i.e., address for method `foo` is at index 0

Generating Code for Methods

- For method declarations
  - Methods have implicit argument, the **receiver object** (i.e., `this`, `self`)
  - In essence, method `bar` declared in class `B`

```
class B {
  void bar(int x) { ... }
}
```

  is translated like a function

```
void bar(B this, int x)
```

- For method call `o.bar(54)`
  - Essentially:

```
void (*f)(obj *,int);
f = o->class_ptr->vtable[offset for bar]
f(o, 54);
```

  - i.e., use vtable to get pointer to appropriate function, invoke it with receiver and arguments

Fields

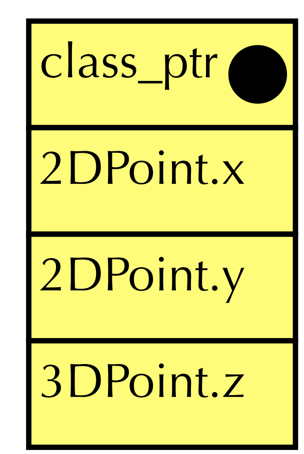
- Same basic idea for fields as for methods!

```
class 2DPoint implements Point {
  1 int x;
  2 int y;
      ...
}

class 3DPoint implements Point {
  3 int z;
      ...
}
```

- Representation of object of class 3DPoint has space to store fields of 3DPoint and superclasses

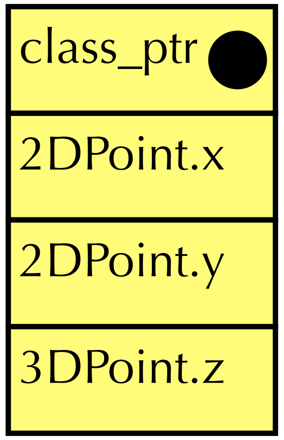
Object **o**
of class ***3DPoint***



Generating Code for Field Accesses

- To access field **`x.f`**
  - **`x`** will be represented as pointer to object
  - Need to know (static) type of **`x`**
  - **`x.f`** refers to memory location at appropriate offset from base of object x
- E.g., reading **`o.y`** would translate to dereferencing address **`o+(`*`offset for y`*`)`**

Object `o`
of class `3DPoint`



Creating Objects

- `new C` creates a new object of class `C`
  - Creates record big enough to hold a `C` object
  - Initializes instance variables
  - Evaluates to pointer to newly created object

Extensions...

- Multiple inheritance
  - Typically use multiple vtables (one for each base class) and switch between them based on the static type
  - Other approaches possible
- Separate compilation
  - Don't know how many fields/method in superclass! (Superclass could be recompiled after subclass)
  - Resolve offsets at link or load time

Extensions...

- Prototype based OO languages
  - Similar approach, but vtable belongs with object (no classes!)
  - Objects are created by cloning other objects
  - Many objects will have the same vtable: can share them, with copy-on-write
- Runtime type check: `o instanceof C`
  - Each object contains pointer to its class, so can figure out at runtime if a `o`'s class is a subclass of `C`
  - But how to efficiently store inheritance information in runtime representation of classes?

OO Type Systems

- Visibility
  - To support encapsulation, some OO languages provide visibility restrictions on fields and methods
  - Java has `private`, `protected`, `public` (and some more)
    - private members accessible only to implementation of class
    - public members accessible by any code
    - protected members accessible only to implementation of class and subclasses
- Subclassing vs inheritance
  - Somewhat conflated in Java
  - Inheritance: reuse code from another class;
    Subclassing: every object of `subclass` is a superclass `object`
  - C++ has visibility restrictions on inheritance

OO Type Systems

- Subclassing vs subtyping
  - Not the same!
  - No contravariance in argument type in Java methods
  - Overriding vs overloading
    - Given `C.m(T1, T2, ..., Tn)` and `D.m(S1, S2, ..., Sm)` where `C` is subclass of `D`, `C.m` overrides `D.m` only if $T_1, T_2, \ldots, T_n = S_1, S_2, \ldots, S_m$
    - Otherwise, `D.m` just overloads the method name `m`...
- Null values
  - In Java type C for class C is analogous to C option in ML
    - Since any object value can be `null`
- ...