HARVARD
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School of Engineering
and Applied Sciences

CS153: Compilers
Lecture 18:
Compiling Objects ctd.

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

Contains content from lecture notes by Steve Zdancewic and Greg Morrisett

Announcements

- HW5: Oat v.2
  - Due Tuesday Nov 19
  - Files will be released on Canvas Saturday 12am
  - **If you have submitted HW4 and want HW5 files now, email cs153-staff@seas.harvard.edu**
    - We will email you a link to the files
- Guest lecturer Tuesday Nov 5: Eliza Kozyri
  - Steve away

Today

- Object Oriented programming ctd.
  - Dynamic dispatch
  - Code generation for methods and method calls
  - Fields
  - Creating objects
  - Extensions
  - Type system

Need for Dynamic Dispatch

- Methods look like functions. Can they be treated the same?
- Consider the following Java code: Same interface implemented by multiple classes

```
interface IntSet {
    public IntSet insert(int i);
    public boolean has(int i);
    public int size();
}
```

```
class IntSet1 implements IntSet {
  private List<Integer> rep;
  public IntSet1() {
    rep = new LinkedList<Integer>();}

  public IntSet1 insert(int i) {
     rep.add(new Integer(i));
    return this;}

  public boolean has(int i) {
    return rep.contains(new Integer(i));}

  public int size() {return rep.size();}
}
```

```
class IntSet2 implements IntSet {
  private Tree rep;
  private int size;
  public IntSet2() {
    rep = new Leaf(); size = 0;}

  public IntSet2 insert(int i) {
     Tree nrep = rep.insert(i);
    if (nrep != rep) {
      rep = nrep; size += 1;
    }
     return this;}

  public boolean has(int i) {
     return rep.find(i);}

  public int size() {return size;}
}
```

Need for Dynamic Dispatch

```
interface IntSet {
    public IntSet insert(int i);
    public boolean has(int i);
    public int size();
}
```

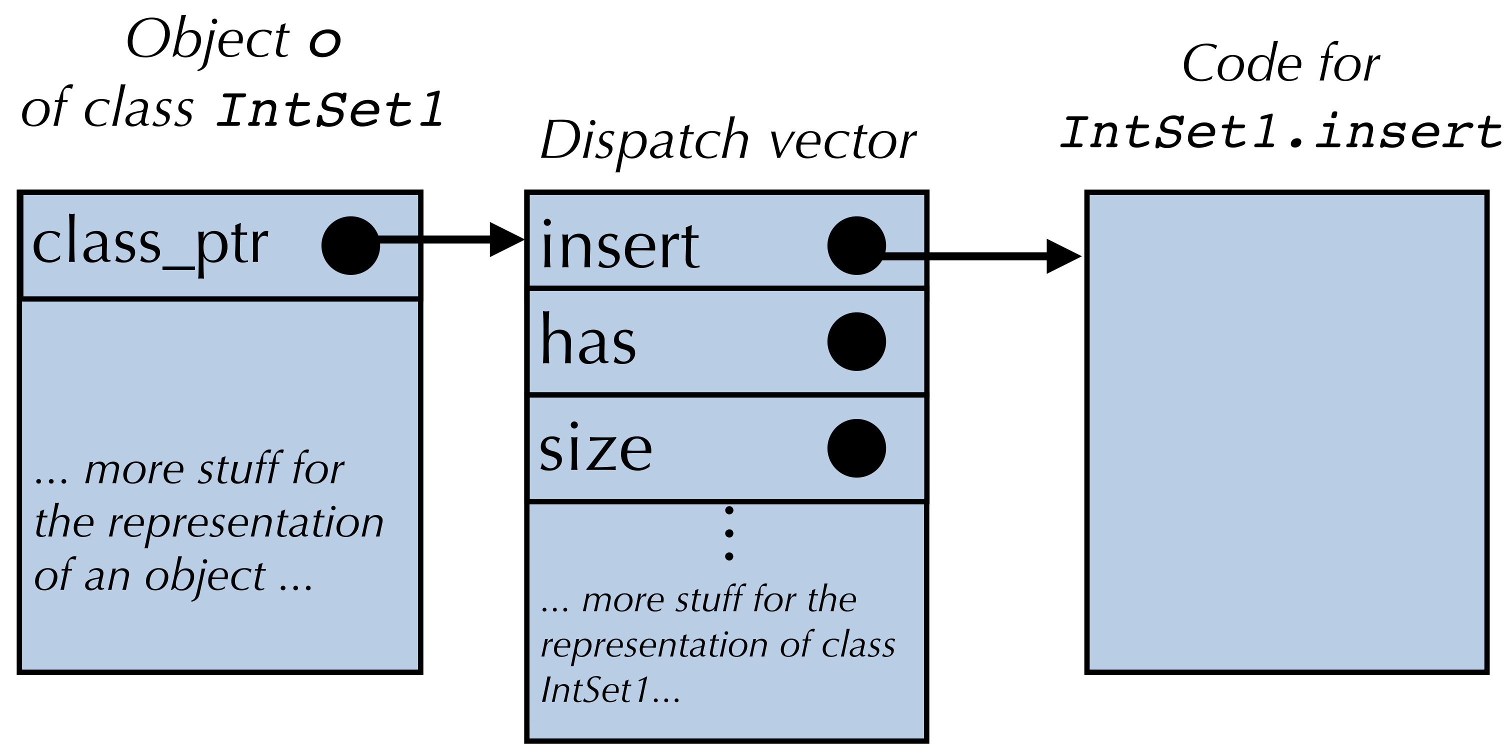
- Suppose a client uses the IntSet interface

```
IntSet set = foo();
int x = set.size();
```

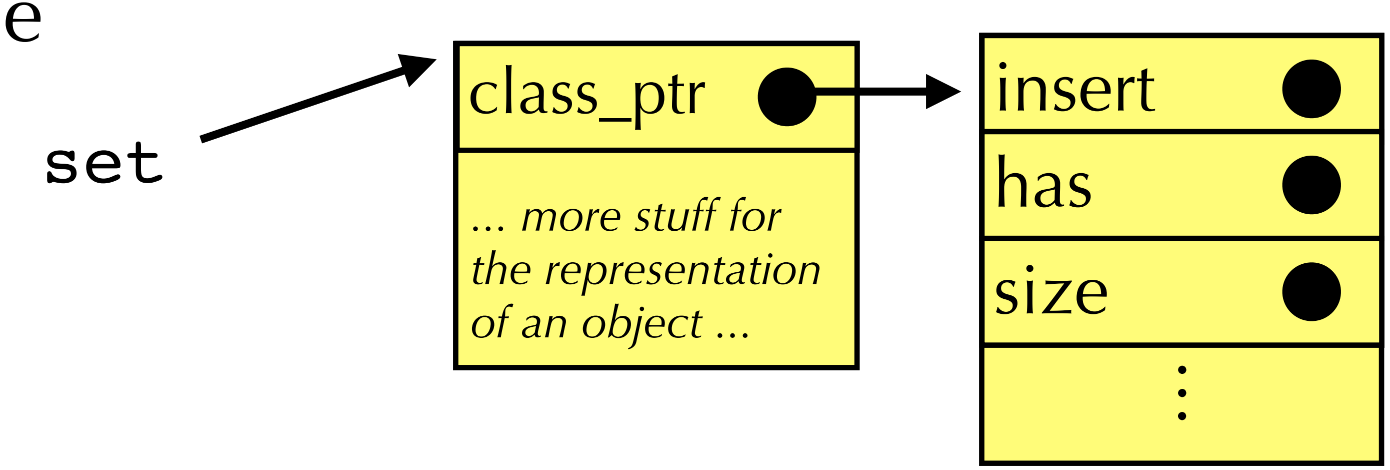
- Which code to call?
  - `IntSet1.size`? `IntSet2.size`?
- Client code doesn't know which code! Could be either at runtime.
  - Objects must "know" which code to call
  - Invocation of method must indirect through object

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




```
IntSet set = foo();
int x = set.size();
```



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**!

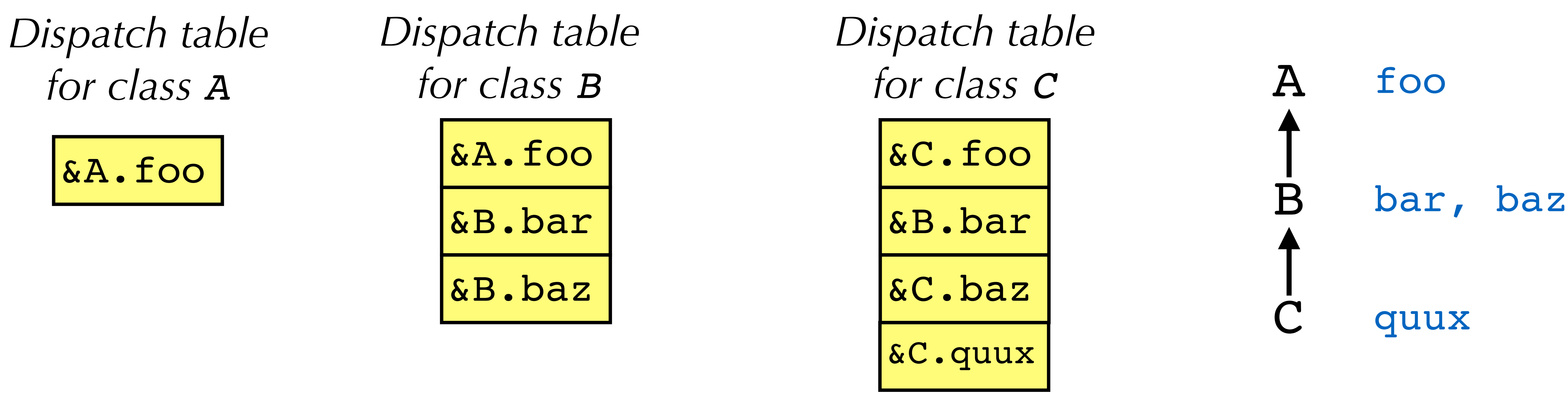
```
class A {
① void foo() { ... }
}
class B extends A {
② void bar() { ... }
③ void baz() { ... }
}
```

```
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
  - Compiled just like top-level procedures, but...
  - 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)
```

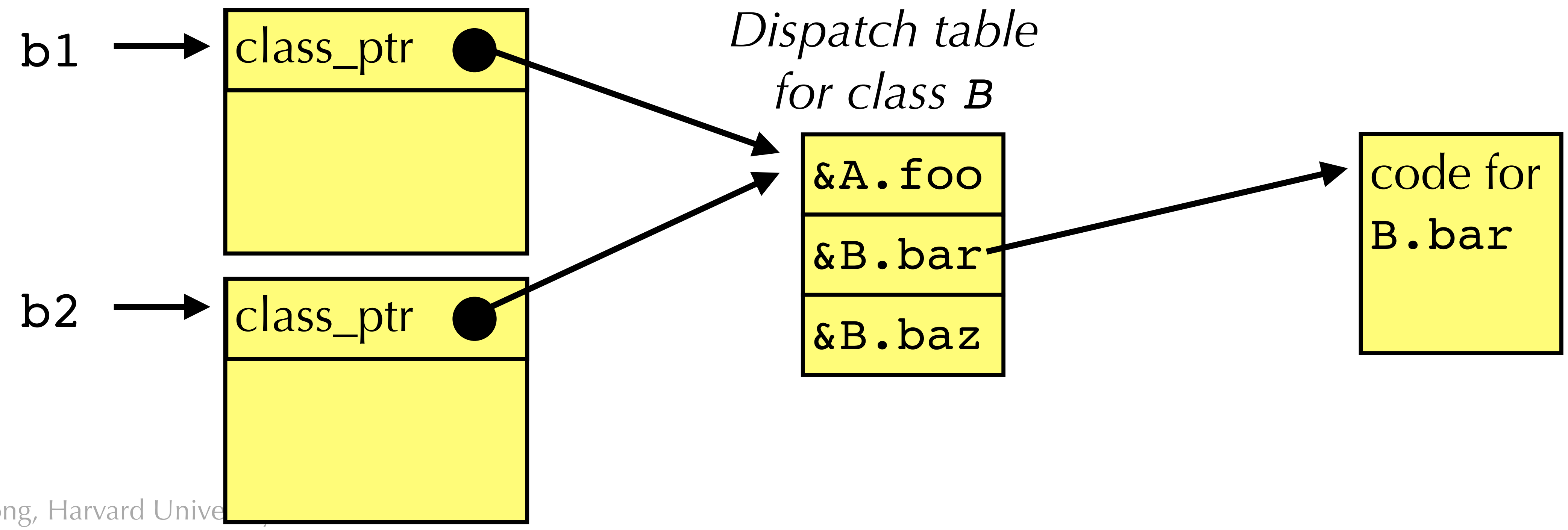
- For method call `o.bar(54)`
  - Essentially:

```
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

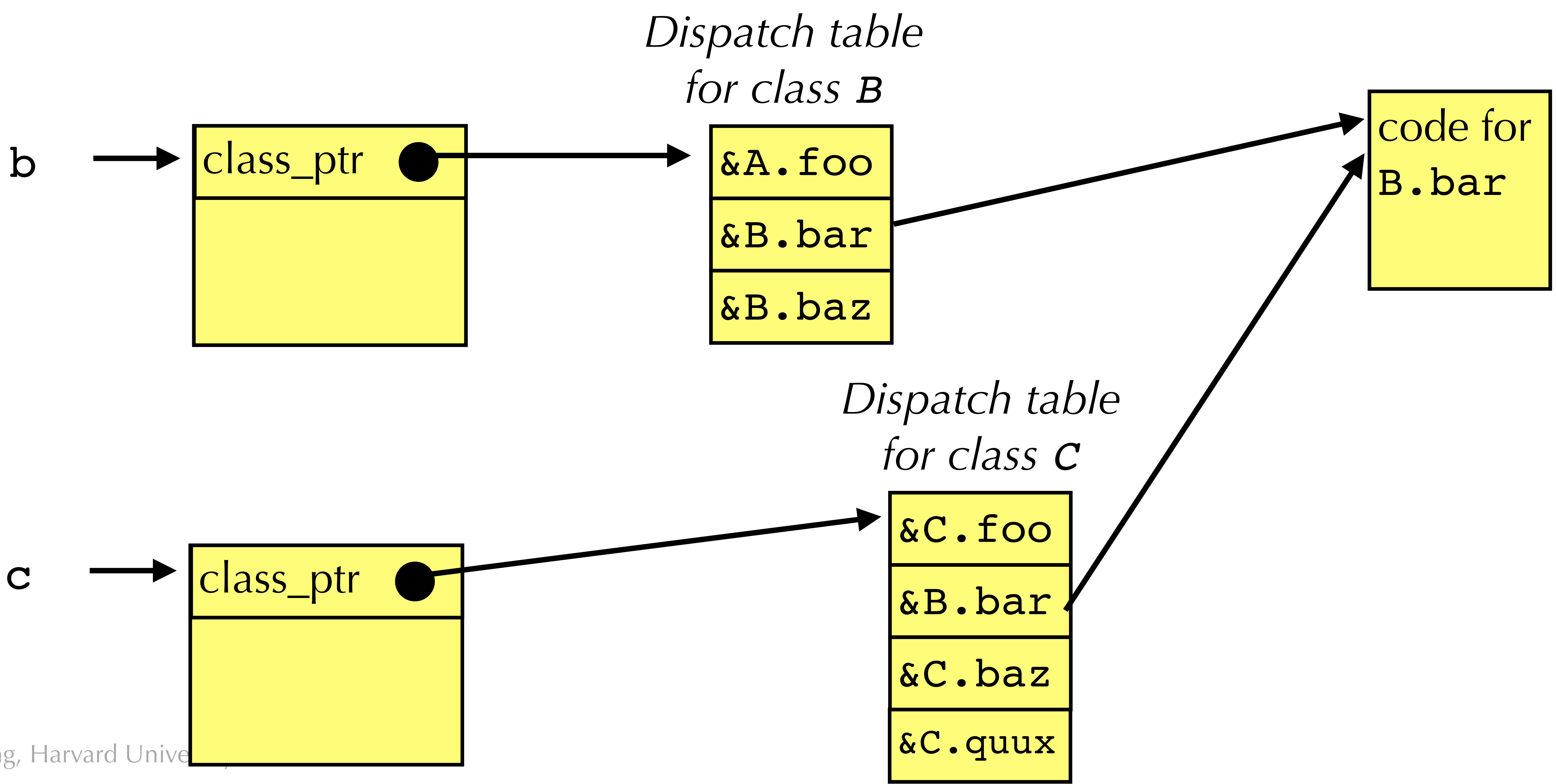
Sharing Dispatch Tables

- All instances of a class may share same dispatch vector
  - Assuming that methods are immutable
- When object is constructed, object needs to point to the appropriate dispatch table



Inheritance: Sharing Code

- Inheritace: Method code “copied down” from the superclass
  - If not overridden in the subclass



Fields

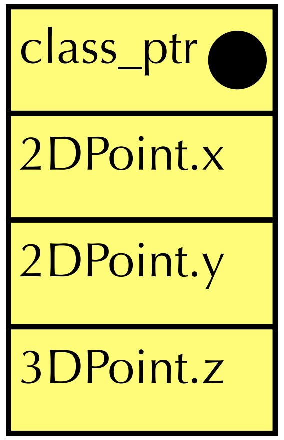
- Same basic idea for fields as for methods!

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

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

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

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

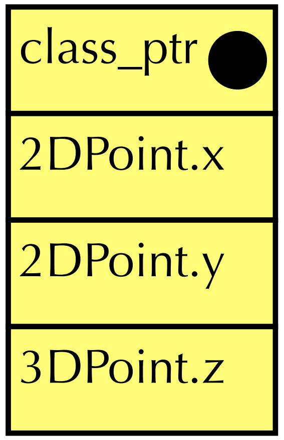


- Representation of object of class 3DPoint has space to store fields of 3DPoint and superclasses

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 pointer to dispatch table
  - Initializes instance variables
  - Evaluates to pointer to newly created object

Representation in LLVM

- During typechecking, create a class hierarchy
  - (We will discuss typechecking more later)
  - Map each class to its interface
    - Superclass
    - Constructor type
    - Fields
    - Method types (plus whether they inherit and from where)
- Compile the class hierarchy to produce
  - An LLVM IR struct type for each object instance
  - An LLVM IR struct type for each dispatch table
  - Global definitions that implement the class tables

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(`T_1`, `T_2`, ..., `T_n`)` and `D.m(`S_1`, `S_2`, ..., `S_m`)` 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`
- ...