Lecture 17

COMPILER DESIGN

Announcements

- **HW4**: due soon

- **HW5**: OAT v. 2.0
  - Records, function pointers, type checking, array-bounds checks, etc.

Method Dispatch (Single Inheritance)

- Idea: every method has its own small integer index
- Index is used to look up the method in the dispatch vector

Index

```
interface A {
  void foo();
}
```

0

```
interface B extends A {
  void bar(int x);
  void baz();
}
```

1
2

Inheritance / Subtyping

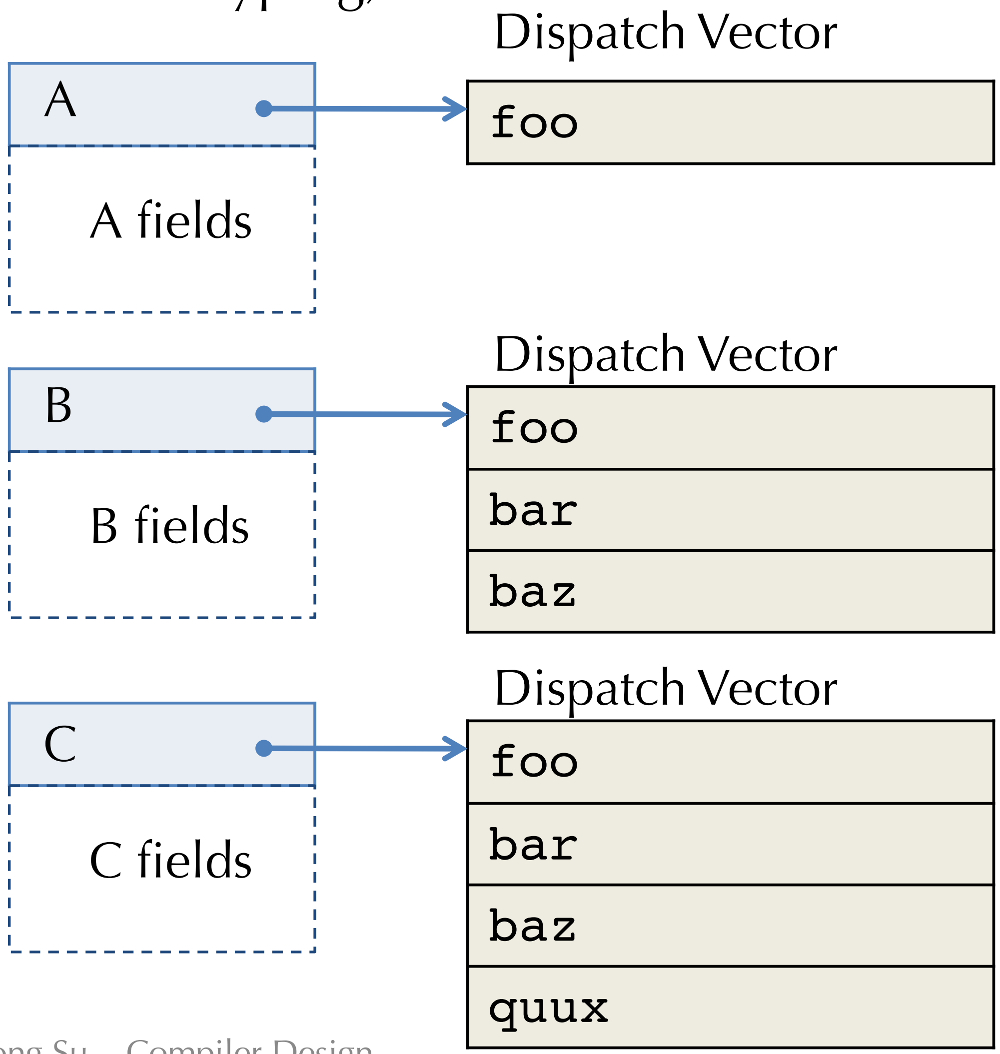
C <: B <: A

```
class C implements B {
  void foo() {…}
  void bar(int x) {…}
  void baz() {…}
  void quux() {…}
}
```

0
1
2
3

Dispatch Vector Layouts

- Each interface and class gives rise to a dispatch vector layout
- Note that inherited methods have identical dispatch indices in the subclass (Width subtyping)



Dispatch Vector

A

A fields

`foo`

Dispatch Vector

B

B fields

`foo`

`bar`

`baz`

Dispatch Vector

C

C fields

`foo`

`bar`

`baz`

`quux`

MULTIPLE INHERITANCE

Multiple Inheritance

- C++: a class may declare more than one superclass

- Semantic problem: *ambiguity*

```
class A { int m(); }
class B { int m(); }
class C extends A,B {…}      // which m?
```

- Same problem can happen with fields

- In C++, fields/methods can be duplicated when such ambiguities arise
  - Explicit sharing can also be declared

Multiple Inheritance

- Java: a class may implement more than one interface

- No semantic ambiguity when two interfaces declare the same method
  - The class will implement a single method

```
interface A { int m(); }
interface B { int m(); }
class C implements A,B {int m() {…}}     // only one m
```

Dispatch Vector Layout Strategy Breaks

```
interface Shape {                      D.V.Index
  void setCorner(int w, Point p);            0
}

interface Color {
  float get(int rgb);                        0
  void set(int rgb, float value);            1
}

class Blob implements Shape, Color {
  void setCorner(int w, Point p) {…}         0?
  float get(int rgb) {…}                     0?
  void set(int rgb, float value) {…}         1?
}
```

General Approaches

Problem: Cannot directly identify methods by position anymore

- Option 1: Allow multiple D.V. tables (C++)
  - Choose which D.V. to use based on static type
  - Casting from/to a class may require runtime operations

- Option 2: Use a level of indirection
  - Map method identifiers to code pointers (e.g. index by method name)
  - Use a hash table
  - May need to search up the class hierarchy

- Option 3: Give up separate compilation
  - Use “sparse” dispatch vectors, or binary decision trees
  - Must know the entire class hierarchy

Note: many variations on these themes

- Different Java compilers pick different approaches to options 2 & 3

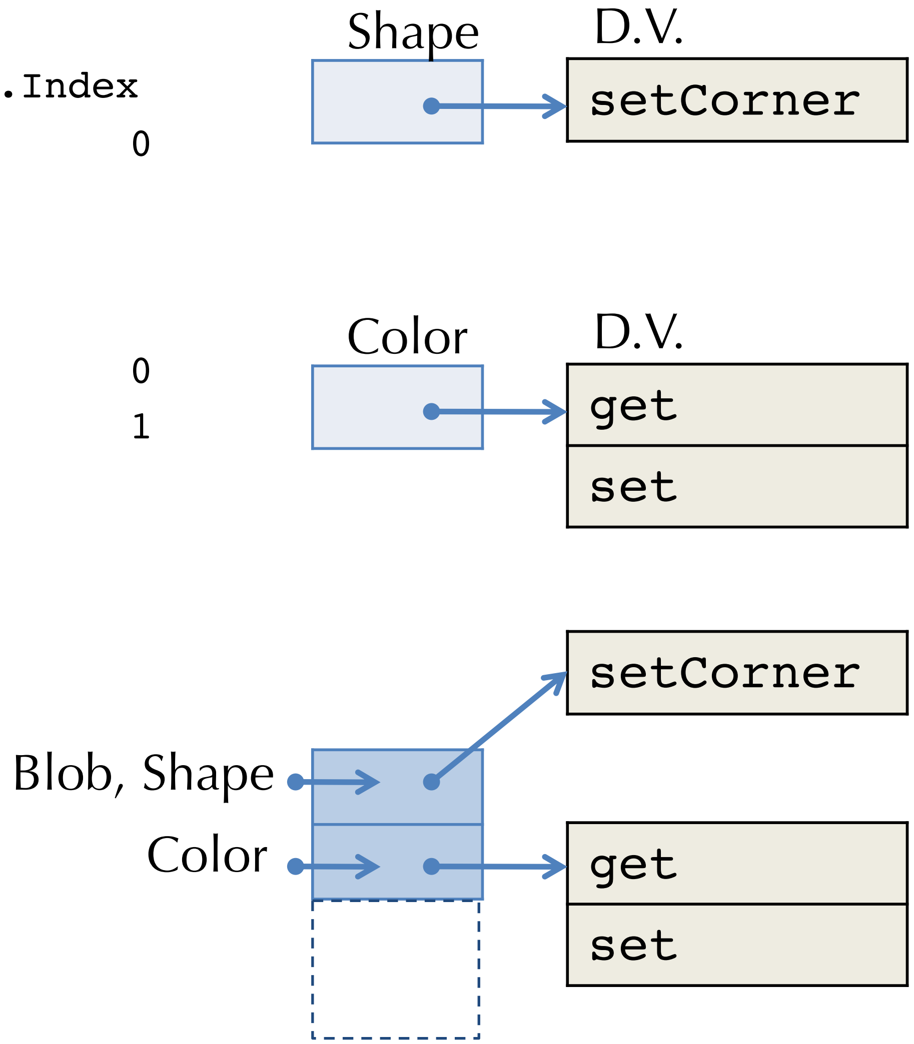
Option 1: Multiple Dispatch Vectors

- Duplicate the D.V. pointers in the object representation
- Static type of the object determines which D.V. is used

```
interface Shape {                          D.V.Index
  void setCorner(int w, Point p);                  0
}

interface Color {
  float get(int rgb);                              0
  void set(int rgb, float value);                  1
}

class Blob implements Shape, Color {
  void setCorner(int w, Point p) {…}
  float get(int rgb) {…}
  void set(int rgb, float value) {…}
}
```



Multiple Dispatch Vectors

- An object may have multiple "entry points"
  - Each entry point corresponds to a dispatch vector
  - Which one to use depends on the object's static type

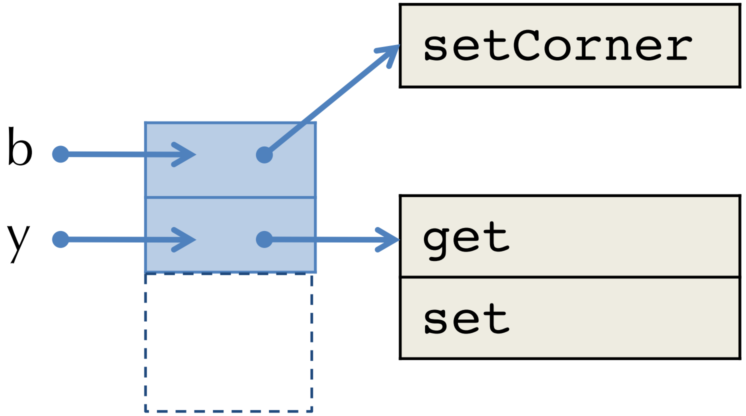
```
Blob b = new Blob();
Color y = b;      // implicit cast!
```

- Compile

```
Color y = b;
```

↓

```
Movq ⟦b⟧ + 8 , y
```



Multiple D.V. Summary

- **Pros**
  - Efficient dispatch, similar cost as for single inheritance

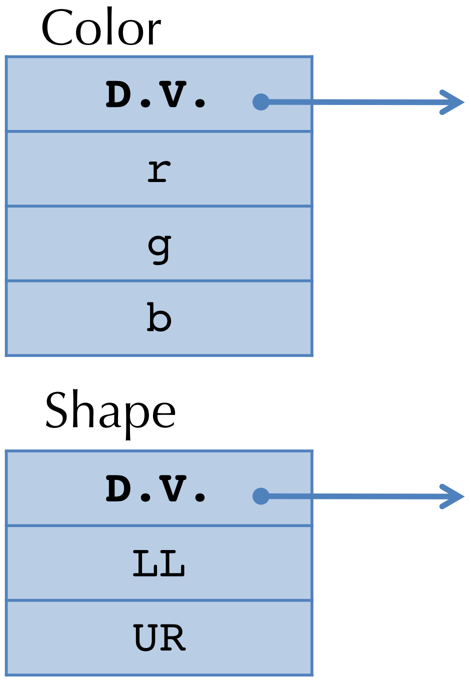
- **Cons**
  - Cast has a runtime cost
  - More complicated programming model, hard to understand/debug

- What about multiple inheritance and fields?

Multiple Inheritance: Fields

- Multiple supertypes (Java): methods conflict (as we saw)
- Multiple inheritance (C++): fields can also conflict
  - Fields can no longer be constant offsets from the start of the object

```
class Color {
   float r, g, b; /* offsets: 4,8,12 */
}
class Shape {
   Point LL, UR; /* offsets: 4, 8 */
}
class ColoredShape extends
 Color, Shape {
   int z;
}
```



ColoredShape ??

vtable for C++ Multiple Inheritance

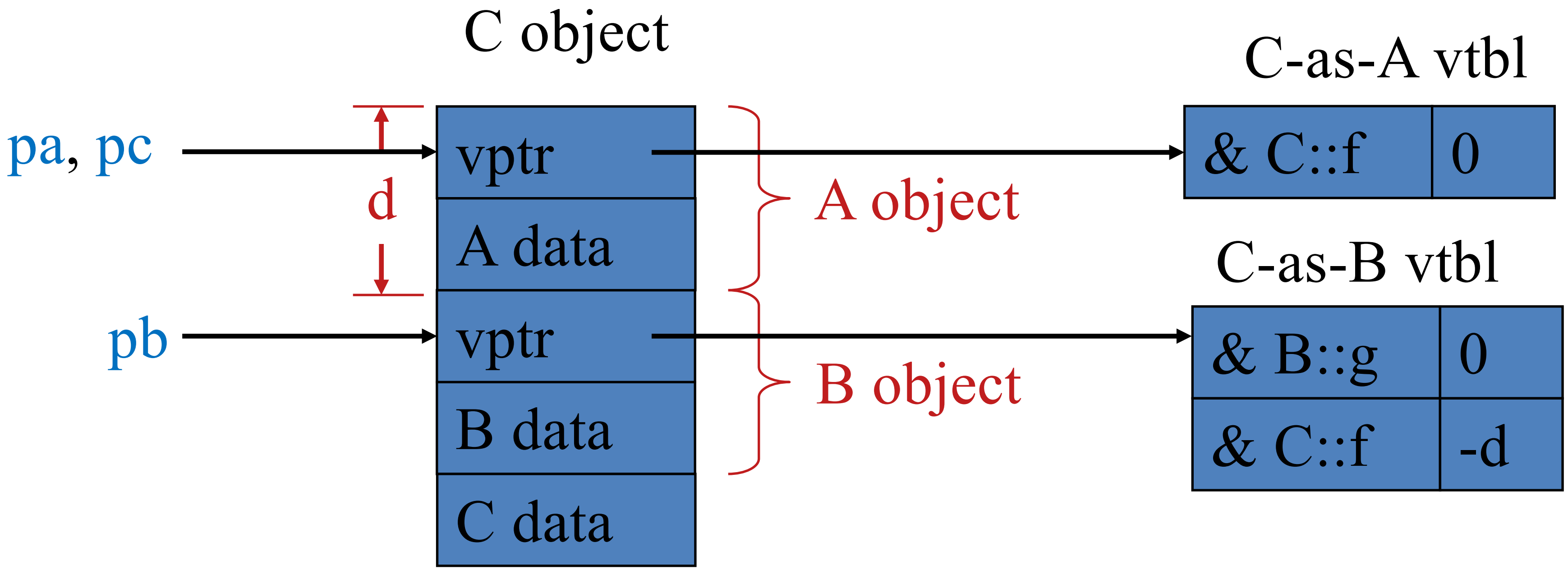
```
class A {
    public:
        int x;
        virtual void f();
};
class B {
   public:
        int y;
        virtual void g();
        virtual void f();
};
```

```
class C: public A, public B {
    public:
        int z;
        virtual void f();
};
```

```
C *pc = new C;
B *pb = pc;
A *pa = pc;
```

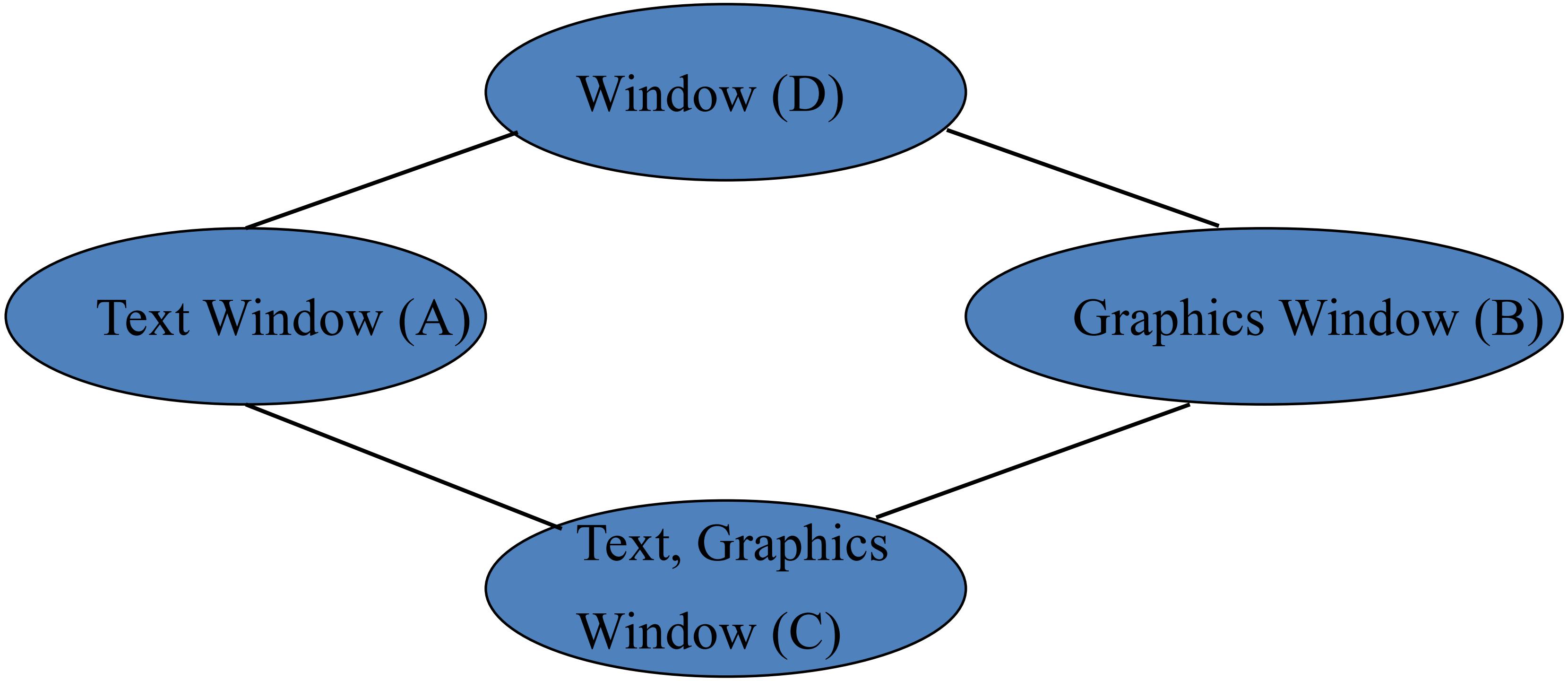
Three pointers to the same object, but different static types

Objects & Classes



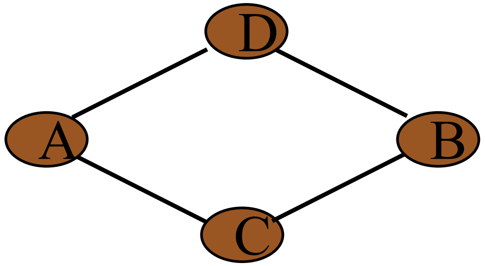
- Call to **pc->g** can proceed through **C-as-B vtbl**
- Offset **d** in vtbl is used in call to **pb->f**, why?
  - Since **C::f** may refer to **A** data that is above the pointer **pb**

Multiple Inheritance "Diamond"



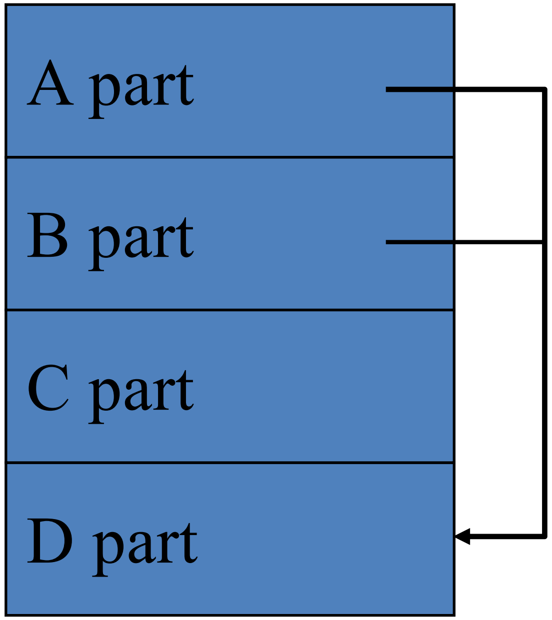
- Is interface or implementation inherited twice?
- What if definitions conflict?

Diamond Inheritance in C++



- Standard base classes
  - D members appear twice in C
- Virtual base classes

  class A : public virtual D { … }
  - Avoid duplication of base class members
  - Require additional pointers so that D part of A, B parts of object can be shared



Multiple inheritance is complicated in C++ due to its desire for efficient lookup

Dispatch Vector Layout Strategy Breaks

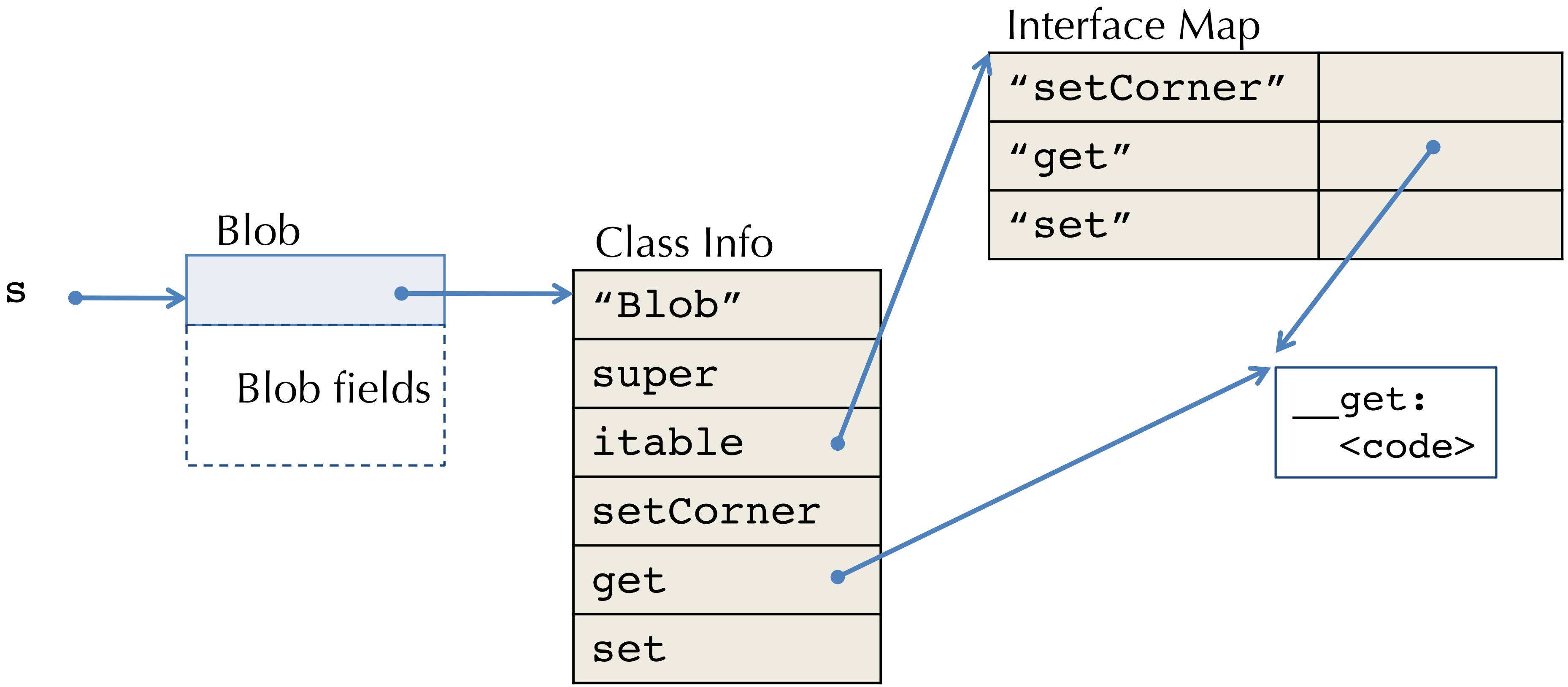
```
interface Shape {                      D.V.Index
  void setCorner(int w, Point p);            0
}

interface Color {
  float get(int rgb);                        0
  void set(int rgb, float value);            1
}

class Blob implements Shape, Color {
  void setCorner(int w, Point p) {…}         0?
  float get(int rgb) {…}                     0?
  void set(int rgb, float value) {…}         1?
}
```

Option 2: Search + Inline Cache

- For each class/interface, keep a table: method names → method code
  - Recursively walk up the hierarchy looking for the method name
- Note
  - Identifiers in quotes are not strings
  - In practice, they are some kind of unique identifiers



Why is search necessary?

```
interface Incrementable {
    public void inc();
}
class IntCounter implements Incrementable {
    public void add(int);
    public void inc();
    public int value();
}
class FloatCounter implements Incrementable {
    public void inc();
    public void add(float);
    public float value();
}
```

```
void add2(Incrementable x) { x.inc(); x.inc(); }
```

Inline Cache Code

- Optimization
  - At call site, store class and code pointer in a cache
  - On method call, check whether class matches cached value
- Compiling: `Shape s = new Blob();  s.get();`

  Call site 434

- Compiler knows that s is a Shape
  - Suppose `%rax` holds object pointer

Table in data seg.

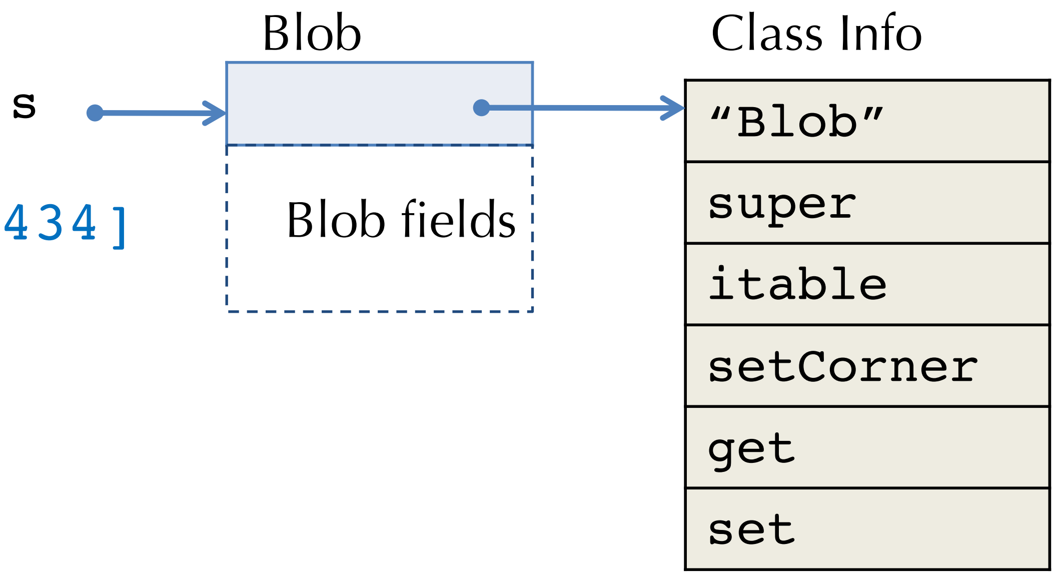
```
cacheClass434:
  "Blob"
cacheCode434:
  <ptr>
```

- Cached interface dispatch

// set up parameters

```
  movq [%rax], tmp
  cmpq tmp, [cacheClass434]
  Jnz __miss434
  callq [cacheCode434]
__miss434:
```

// do the slow search



Option 2 variant 2: Hash Table

- Idea: don't try to give all methods unique indices
  - Resolve conflicts by checking that the entry is correct at dispatch
- Use hashing to generate indices
  - Range of the hash values should be relatively small
  - Hash indices can be pre computed, but passed as an extra parameter

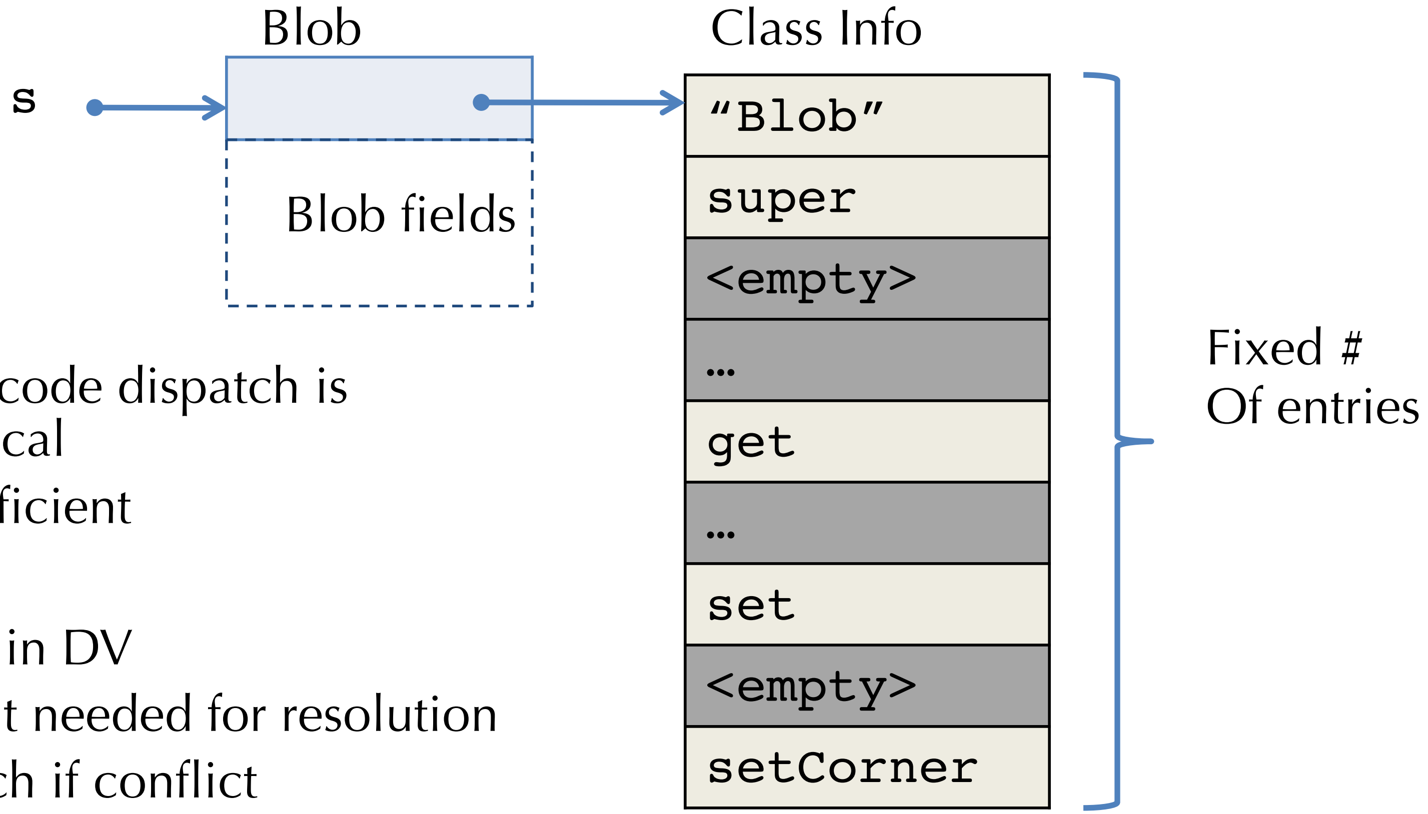
```
interface Shape {                    D.V.Index
  void setCorner(int w, Point p);    hash("setCorner") = 11
}

interface Color {
  float get(int rgb);                hash("get") = 4
  void set(int rgb, float value);    hash("set") = 7
}

class Blob implements Shape, Color {
  void setCorner(int w, Point p) {…}       11
  float get(int rgb) {…}                   4
  void set(int rgb, float value) {…}       7
}
```

Dispatch with Hash Tables

- What if there is a conflict?
  - Entries containing several methods point to code that resolves conflict (e.g. by searching through a table based on class name)



- Advantage
  - Simple, basic code dispatch is (almost) identical
  - Reasonably efficient
- Disadvantage
  - Wasted space in DV
  - Extra argument needed for resolution
  - Slower dispatch if conflict

Option 3 variant 1: Sparse D.V. Tables

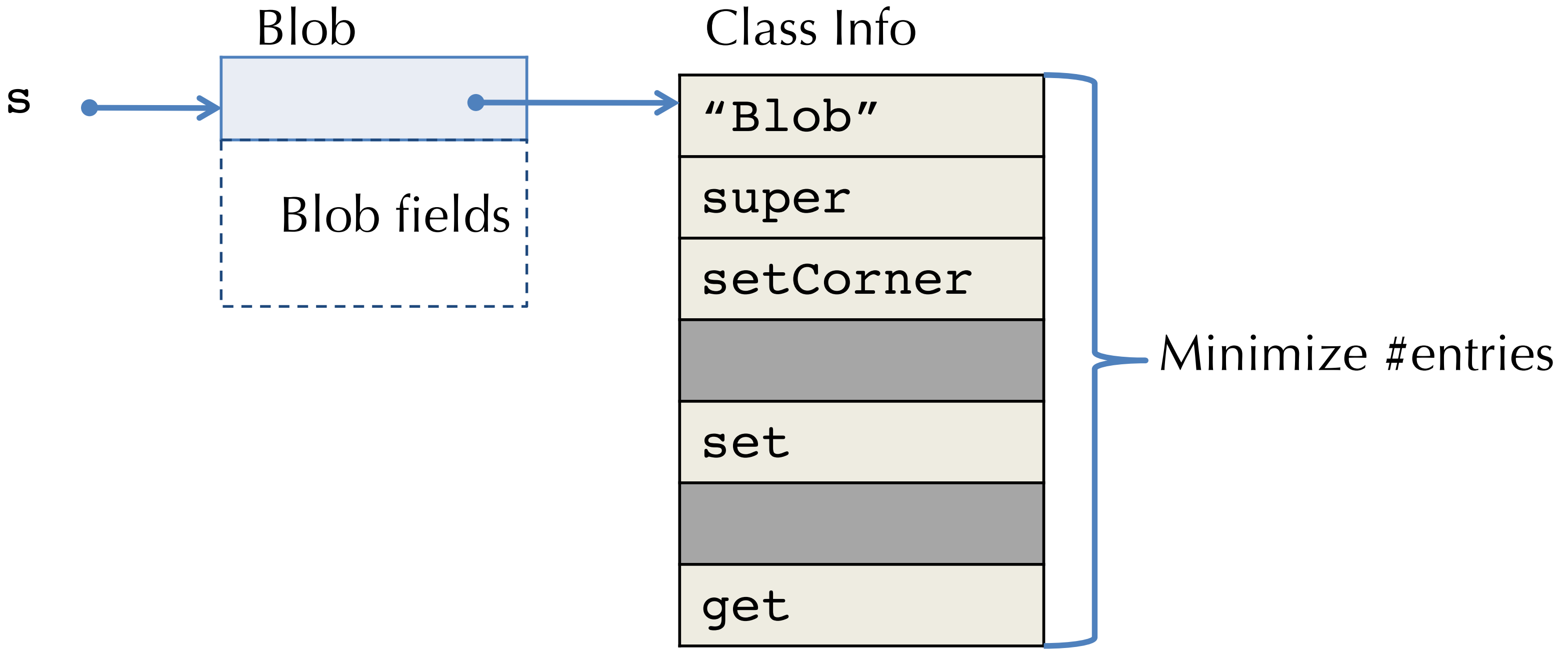
- Give up on separate compilation …
- Now we have access to the whole class hierarchy

- So, ensure no 2 methods in same class are allocated the same D.V. offset
  - Allow holes in the D.V. just like the hash table solution
  - Unlike hash table, there is never a conflict

- Compiler needs to construct the method indices
  - Graph coloring can be used to construct D.V. layouts reasonably efficiently (to minimize size)
  - Finding an optimal solution is NP complete

Example Object Layout

- Advantage: Identical dispatch & performance to single-inheritance case
- Disadvantage: Must know entire class hierarchy

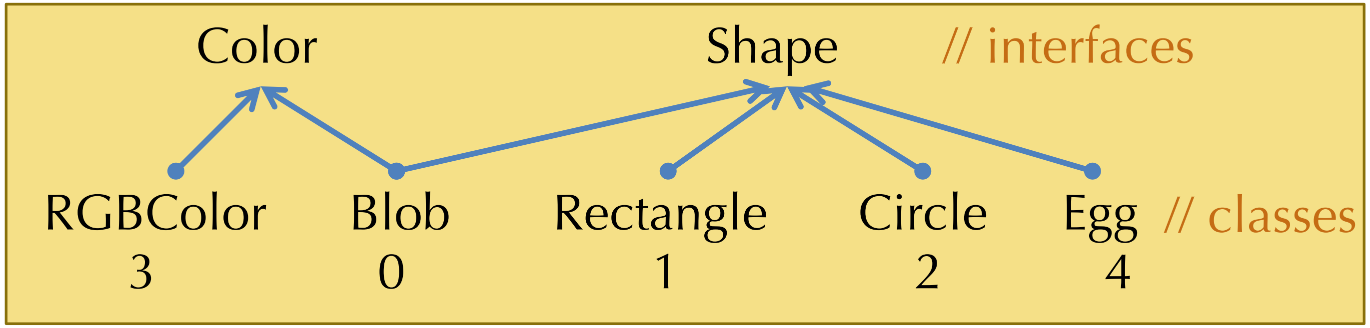


Option 3 variant 2: Binary Search Trees

- Idea: Use conditional branches not indirect jumps
- Each object has a class index (unique per class) as first word
  - Instead of D.V. pointer (no need for one!)
- Method invocation uses range tests to select among *n* possible classes in *lg n* time
  - Direct branches to code at the leaves

```
Shape x;
x.SetCorner(…);
```

```
  Mov eax, ⟦x⟧
  Mov ebx, [eax]
  Cmp ebx, 1
  Jle  __L1
  Cmp ebx, 2
  Je __CircleSetCorner
  Jmp __EggSetCorner
__L1:
  Cmp ebx, 0
  Je __BlobSetCorner
  Jmp __RectangleSetCorner
```



Color

Shape

// interfaces

RGBColor 3

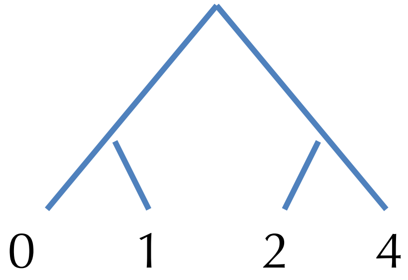
Blob 0

Rectangle 1

Circle 2

Egg 4

// classes



0 1 2 4

Decision tree

Search Tree Tradeoffs

- Binary decision trees work well if the distribution of classes that may appear at a call site is skewed
  - Branch prediction hardware eliminates branch stall of ~10 cycles (on X86)

- Profiling helps find the common paths for each call site individually
  - Put the common case at the top of the decision tree (so less search)
  - 90%/10% rule of thumb: 90% invocations at a call site go to the same class

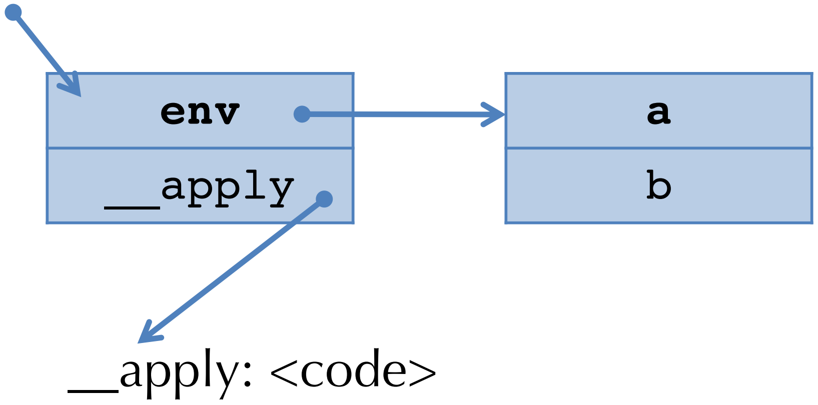
- Drawbacks
  - Like sparse D.V.'s you need the whole class hierarchy to know how many leaves you need in the search tree
  - Indirect jumps can have better performance if there are >2 classes (at most one mispredict)

Observe: Closure ≈ Single-method Object

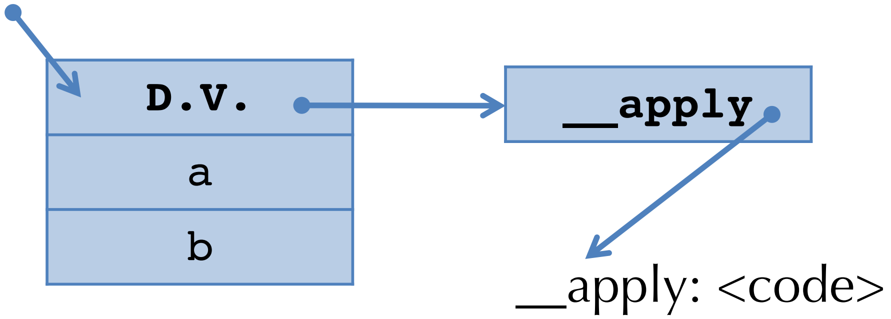
- Free variables ≈ Fields
- Environment pointer ≈ “this” parameter
- Closure for function: ≈ Instance of this class:

```
fun (x,y) ->
   x + y + a + b
```

```
class C {
   int a, b;
   int apply(x,y) {
      x + y + a + b
   }
}
```



env
__apply
a
b
__apply: <code>



D.V.
a
b
__apply
__apply: <code>

CLASSES & OBJECTS IN LLVM

Representing Classes in the LLVM

- During typechecking, create a *class hierarchy*
  - Maps each class to its interface
    - Superclass
    - Constructor type
    - Fields
    - Method types (plus whether they inherit & which class they inherit from)

- Compile the class hierarchy to produce
  - An LLVM IR struct type for each object instance
  - An LLVM IR struct type for each vtable (a.k.a. class table)
  - Global definitions that implement the class tables

Example OO Code (Java)

```
class A {
  A (int x)                    // constructor
  { super(); int x = x; }

  void print() { return; }     // method1
  int blah(A a) { return 0; }  // method2
}

class B extends A {
  B (int x, int y, int z){
    super(x);
    int y = y;
    int z = z;
  }

  void print() { return; }   // overrides A
}

class C extends B {
  C (int x, int y, int z, int w){
    super(x,y,z);
    int w = w;
  }
  void foo(int a, int b) {return;}
  void print() {return;}    // overrides B
}
```

Example OO Hierarchy in LLVM

Object instance types

Class table types

```
%Object = type { %_class_Object* }
%_class_Object = type {  }

%A = type { %_class_A*, i64 }
%_class_A = type { %_class_Object*, void (%A*)*, i64 (%A*, %A*)* }

%B = type { %_class_B*, i64, i64, i64 }
%_class_B = type { %_class_A*, void (%B*)*, i64 (%A*, %A*)* }

%C = type { %_class_C*, i64, i64, i64, i64 }
%_class_C = type { %_class_B*, void (%C*)*, i64 (%A*, %A*)*, void (%C*, i64, i64)* }
```

```
@_vtbl_Object = global %_class_Object {  }

@_vtbl_A = global %_class_A { %_class_Object* @_vtbl_Object,
                    void (%A*)* @print_A,
                    i64 (%A*, %A*)* @blah_A }

@_vtbl_B = global %_class_B { %_class_A* @_vtbl_A,
                    void (%B*)* @print_B,
                    i64 (%A*, %A*)* @blah_A }

@_vtbl_C = global %_class_C { %_class_B* @_vtbl_B,
                    void (%C*)* @print_C,
                    i64 (%A*, %A*)* @blah_A,
                    void (%C*, i64, i64)* @foo_C }
```

Class tables
(structs containing
function pointers)

Method Arguments

- Methods bodies are compiled just like top-level procedures …
- … except that they have an implicit extra argument: `this` or `self`
    - Historically (Smalltalk), these were called the "receiver object"
    - Method calls were thought of a sending "messages" to "receivers"

A method in a class

```
class IntSet1 implements IntSet {
   …
  IntSet1 insert(int i) { <body> }
}
```

… is compiled like this (top-level) procedure

```
IntSet1 insert(IntSet1 this, int i) { <body> }
```

- Note
    - The type of "`this`" is the class containing the method
    - References to fields inside <body> are compiled like `this.field`

LLVM Method Invocation Compilation

Consider method invocation ⟦H;G;L ⊢ `e.m(e`$_1$`,…,e`$_n$`):t`⟧

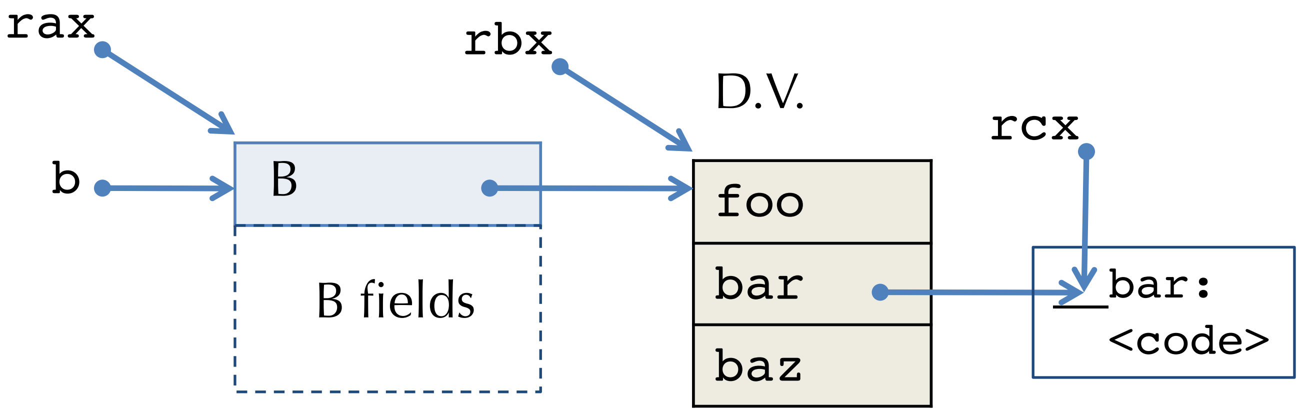
1. Compile ⟦H;G;L ⊢ `e : C`⟧
   - To get a (pointer to) an object value of class type C
   - Call this value obj_ptr
2. Use Getelementptr to extract the vtable pointer from obj_ptr
3. Load the vtable pointer
4. Use Getelementptr to extract the function pointer's address from vtable
   - Use the information about C in H
5. Load the function pointer
6. Call through the function pointer, passing 'obj_ptr' for this

`call (cmp_typ t) m(obj_ptr,` ⟦`e`$_1$⟧, …, ⟦`e`$_n$⟧)

In general, function calls may require bitcast to account for subtyping: arguments may be a subtype of the expected "formal" type

X86 Code For Dynamic Dispatch

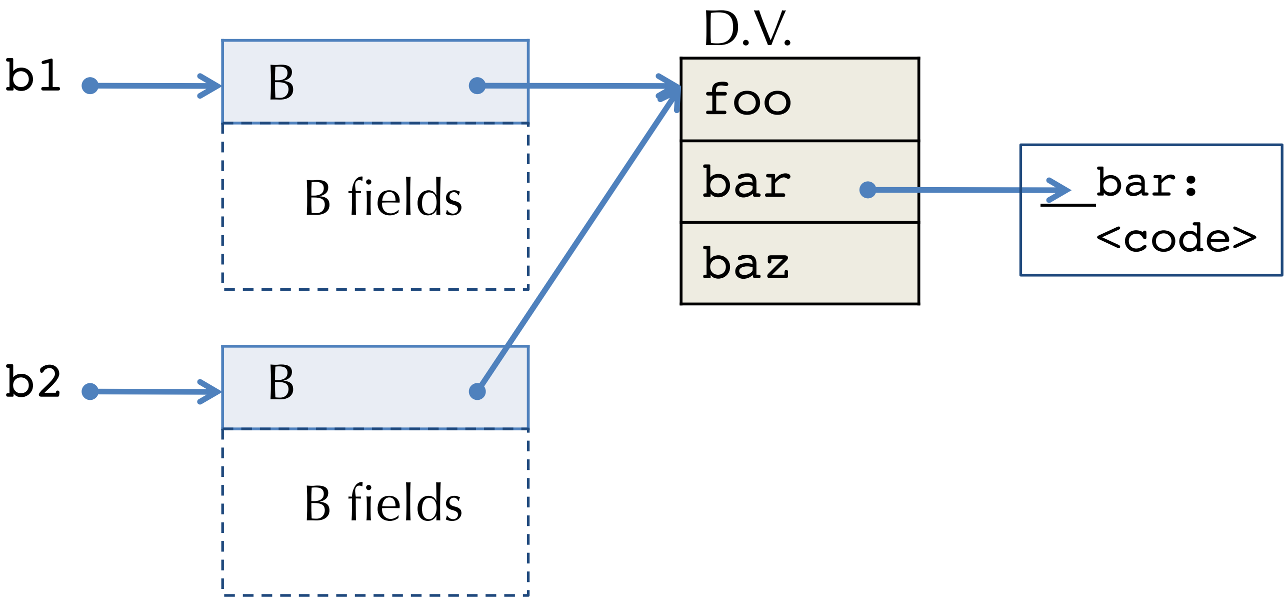
- Suppose `b : B`
- What code for `b.bar(3)`?
  - `bar` has index 1
  - Offset = 8 * 1



```
movq ⟦b⟧, %rax
movq [%rax], %rbx
movq [rbx+8], %rcx     // D.V. + offset
movq %rax, %rdi        // "this" pointer
movq 3, %rsi           // Method argument
call %ecx              // Indirect call
```

Sharing Dispatch Vectors

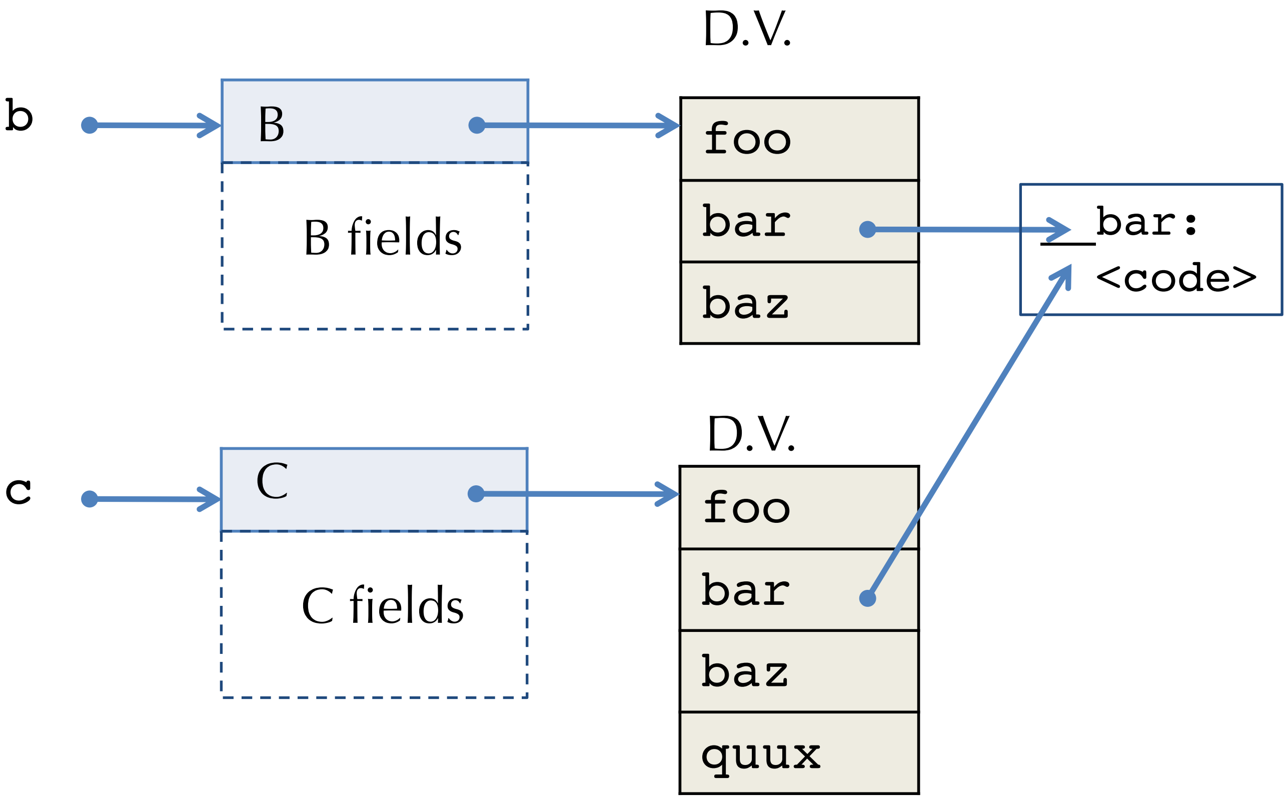
- All instances of a class may share the same dispatch vector
  - Assuming that methods are immutable
- Code pointers stored in the dispatch vector are available at link time – dispatch vectors can be built once at link time



- One job of object constructor is to fill in the object's pointer to the appropriate dispatch vector
- Note
  - The address of the D.V. *is* the runtime representation of the object's type

Inheritance: Sharing Code

- Inheritance: Method code "copied down" from the superclass
  - If not overridden in the subclass
- Works with separate compilation – superclass code not needed



Compiling Static Methods

- Java supports *static* methods
  - Methods that belong to a class, not the instances of the class.
  - They have no "this" parameter (no receiver object)

- Compiled exactly like normal top-level procedures
  - No slots needed in the dispatch vectors
  - No implicit "this" parameter

- They're not really methods
  - They can only access static fields of the class

Compiling Constructors

- Java and C++ classes can declare constructors that create new objects
  - Initialization code may have parameters supplied to the constructor
  - e.g. `new Color(r,g,b);`

- Modula-3: object constructors take no parameters
  - e.g. `new Color;`
  - Initialization would typically be done in a separate method

- Constructors are compiled just like static methods, except
  - The "this" variable is initialized to a newly allocated block of memory big enough to hold D.V. pointer + fields according to object layout
  - Constructor code initializes the fields
    - What methods (if any) are allowed?
  - The D.V. pointer is initialized
    - When? Before/After running the initialization code?

Compiling Checked Casts

- How do we compile downcast in general?
  Consider this generalization of Oat's checked cast

```
        if? (t x = exp) { … } else { … }
```

- Reason by cases
  - t must be either null, ref or ref? (can't be just int or bool)
- If t is null
  - The static type of exp must be ref? for some ref.
  - If exp == null then take the true branch, otherwise take the false branch
- If t is string or t[]
  - The static type of exp must be the corresponding string? Or t[]?
  - If exp == null take the false branch, otherwise take the true branch
- If t is C
  - The static type of exp must be D or D? (where C <: D)
  - If exp == null take the false branch, otherwise
  - emit code to walk up the class hierarchy starting at T to look for C (T is `exp`'s dynamic type)
  - If found, then take true branch else take false branch
- If t is C?
  - The static type of exp must be D? (where C <: D)
  - If exp == null take the true branch, otherwise
  - Emit code to walk up the class hierarchy starting at T to look for C (T is `exp`'s dynamic type)
  - If found, then take true branch else take false branch

“Walking up the Class Hierarchy”

- A non-null object pointer refers to an LLVM struct with a type like

```
%B = type { %_class_B*, i64, i64, i64 }
```

- The first entry of the struct is a pointer to the vtable for Class B
  - This pointer *is* the dynamic type of the object
  - It will have the value @vtbl_B
- The first entry of the class table for B is a pointer to its superclass

```
@_vtbl_B = global %_class_B { %_class_A* @_vtbl_A,
                              void (%B*)* @print_B,
                              i64 (%A*, %A*)* @blah_A }
```

- Therefore, to find out whether an unknown type X is a subtype of C
  - Assume C is not Object (ruled out by “silliness” checks for downcast)

LOOP

- If X == @_vtbl_Object then NO, X is not a subtype of C
- If X == @_vtbl_C then YES, X is a subtype of C
- If X = @_vtbl_D, so set X to @_vtbl_E where E is D’s parent and goto LOOP