Implementing Object-Oriented Languages

Key features:

- inheritance (possibly multiple)
- subtyping & subtype polymorphism
- message passing, dynamic binding, run-time type testing

Subtype polymorphism is the key problem

- support uniform representation of data (analogous to boxing for polymorphic data)
  - store the class of each object at a fixed offset
- organize layout of data to make instance variable access and method lookup & invocation fast
  - code compiled expecting an instance of a superclass still works if run on an instance of a subclass
  - multiple inheritance complicates this
- perform static analysis to bound polymorphism
- perform transformations to reduce polymorphism

Implementing instance variable access

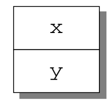
Key problem: subtype polymorphism

Solution: **prefixing**

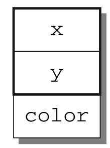
- layout of subclass has layout of superclass as a prefix
- code that accesses a superclass will access the superclass part of any subclass properly, transparently

\+ access is just a load or store at a constant offset

```
class Point {
  int x;
  int y;
}
```




```
class ColorPoint
    extends Point {
  Color color;
}
```



// OK: subclass polymorphism

```
Point p = new ColorPoint(3,4,Blue);
```

// OK: `x` and `y` have same offsets in all `Point` subclasses

```
int manhattan_distance = p.x + p.y;
```


Implementing dynamic dispatching (virtual functions)

How to find the right method to invoke for a dynamically dispatched message `rcvr.Message(arg1, ...)`?

Option 1: search inheritance hierarchy, starting from run-time class of `rcvr`

– very slow, penalizes deep inheritance hierarchies

Option 2: use a hash table

- can act like a cache on the front of Option 1

– still significantly slower than a direct procedure call
  - but used in early Smalltalk systems!

Option 3: store method addresses in the receiver objects, as if they were instance variables

- each message/generic function declares an instance variable
- each inheriting object stores an address in that instance variable
- invocation = load + indirect jump!

\+ good, constant-time invocation, independent of inheritance structure, overriding, ...

– much bigger objects

Virtual function tables

Observation: in Option 3, all instances of a given class will have identical method addresses

Option 4: factor out class-invariant parts into shared object

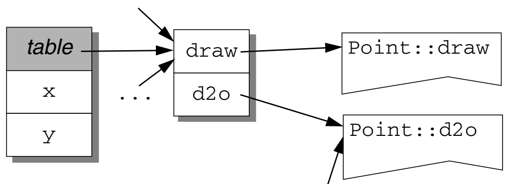
- instance variables whose values are common across all instances of a class (e.g. method addresses) are moved out to a separate object
  - historically called a **virtual function table** (vtbl)
- each instance contains a single pointer to the vtbl
  - combine with (or replace) class pointer
- layout of subclass's vtbl has layout of superclass's vtbl as a prefix

\+ dynamic dispatching is fast & constant-time
  - – but an extra load

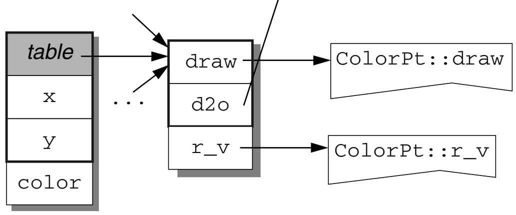
\+ no space cost in object
  - aside from vtbl/class pointer

Example of virtual function tables

```
class Point {
  int x;
  int y;
  void draw();
  int distance2origin();
}
```



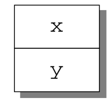

```
class ColorPoint extends Point {
  Color color;
  void draw();
  void reverse_video();
}
```



Multiple inheritance

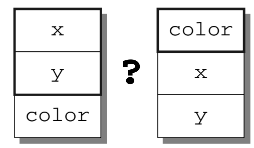
Problem: prefixing doesn't work with multiple inheritance

```
class Point {
  int x;
  int y;
}
```




```
class ColoredThing {
  Color color;
}
```


```
class ColorPoint
  extends Point,
          ColoredThing {
}
```




```
ColorPoint cp = new ColorPoint(3, 4, Blue);
Point p = cp; // OK
ColoredThing t = cp; // OK
ColorPoint cp2 =
  new ColorPoint(p.x, p.y, t.color); // breaks
```


Some solutions

Option 1: stick with single inheritance [e.g. Smalltalk]
- some examples really benefit from MI

Option 2: distinguish classes from interfaces [e.g. Java, C#]
- only single inheritance below classes
  ⇒ if `rcvr` statically of class type, then can exploit prefixing for its instance variable accesses and message sends
- disallow instance variables in interfaces
  ⇒ no problems accessing them!
- only messages to receivers of interface type are unresolved
  ⇒ much smaller problem; can use e.g. hashing

Option 3: compute offset of a field in `rcvr` by sending `rcvr` a message [Cecil/Vortex]
- reduced problem to dynamic dispatching
- apply CHA etc. to optimize (all) dispatches
  ⇒ for fields whose offsets never change, static binding + inlining reduces dispatches to constant

Another solution

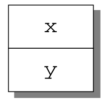
Option 4: embedding + pointer shifting [C++]
- concatenate superclass layouts, extend with subclass data
- when upcasting to a superclass, shift pointer to point to where superclass is embedded
  - downcasting does the reverse
- virtual function calls may need to shift rcvr pointers
  - "trampolines" may get inserted

\+ gets back to constant-time access in most cases

– very complicated, lots of little details
– some things (e.g. casting) may now have run-time cost
– does poorly if using "virtual base classes", i.e., diamond-shaped inheritance hierarchies
– some sensible programs now disallowed
  - e.g. casting through void*, downcasting from virtual base class
– interior pointers may complicate GC, equality testing, debugging, etc.

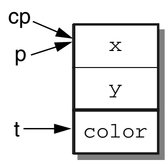
Example

```
class Point {
  int x;
  int y;
}
```




```
class ColoredThing {
  Color color;
}
```

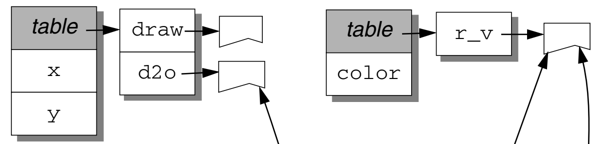

```
class ColorPoint
  extends Point,
          ColoredThing {
}
```



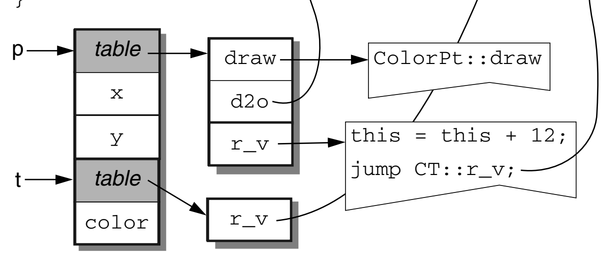

```
ColorPoint cp = new ColorPoint(3, 4, Blue);
Point p = cp; // OK
ColoredThing t = cp; // OK: adds 8 to cp
// now this works:
ColorPoint cp2 =
  new ColorPoint(p.x, p.y, t.color);
// this works, too:
ColorPoint cp3 =
  (ColorPoint) t; // subtracts 8 from t
```


Example of virtual function tables

```
class Point {             class ColoredThing {
  int x;                    Color color;
  int y;                    void reverse_video();
  void draw();            }
  int d2o();
}
```




```
class ColorPoint extends Point, ColoredThing {
  void draw();
}
```



Limitations of table-based techniques

Table-based techniques only work well when:

- have static type information to use to map message/ instance variable names to offsets in tables/objects
  - not true in dynamically typed languages
- cannot extend classes with new operations except via subclassing
  - not true in languages with open classes (e.g. MultiJava [Clifton *et al.* 00]) or multiple dispatching (e.g. CLOS, Dylan, Cecil)
- cannot modify classes dynamically
  - not true in fully reflective languages (e.g. Smalltalk, Self, CLOS)
- memory loads and indirect jumps are inexpensive
  - may not be true with heavily pipelined hardware

Dynamic table-based implementations

Standard implementation: global hash table in runtime system
- indexed by class × msg
- filled dynamically as program runs
- can be flushed after reflective operations
- \+ reasonable space cost
- \+ incremental
- – fair average-case dispatch time, poor worst-case time

Refinement: hash table per message name
- each call site knows statically which table to consult
- \+ faster dispatching

Inline caching

Give each dynamically-dispatched call site its own small method lookup cache

+ call site knows its message name
+ cache is isolated from other call sites

Trick: use machine call instruction itself as a one-element cache

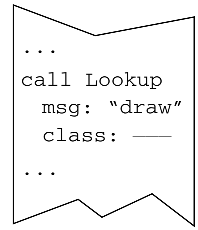
- initially: call runtime system's `Lookup` routine
- `Lookup` routine patches call instruction to branch to invoked method
  - record receiver class
- next time through, jump directly to expected target method
  - method checks whether current receiver class is same as last receiver class
  - if so, then cache hit (90-95% frequency, for Smalltalk)
  - if not, then call `Lookup` and rebind cache

+ fast dispatch sequence if cache hit (≈4 instructions plus call)
+ hardware call prefetching works well
– exploits self-modifying code
– low performance if not a cache hit

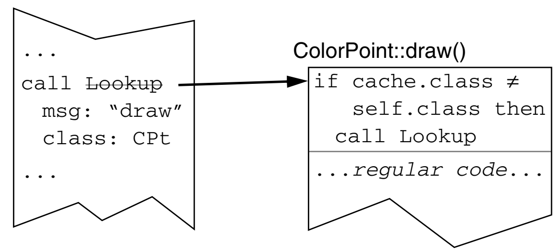
[Deutsch & Schiffman 84]

Example of inline caching

Initially:



After caching target method:



Polymorphic inline caching (PIC)

Idea: support a multi-element cache by generating a call-site-specific dispatcher stub

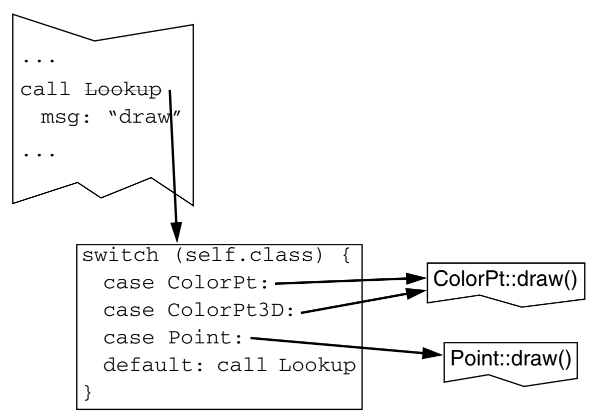
+ fast dispatching even if several classes are common
– still slow performance if many classes equally common
– some space cost

Foreshadowing:
dispatching stubs record dynamic profile data of which receiver classes occur at which call sites

[Hölzle *et al.* 91]

Example of polymorphic inline caching

After a few receiver classes:



Implementing the dispatcher stub switch

In original PIC design, switch implemented with a linear chain of class identity tests

Alternatively, can implement with a binary search, exploiting ordering of integer class IDs or addresses

+ avoid worst-case behavior of long linear searches
+ a single test can direct many classes to same target method
– requires global knowledge to construct dispatchers

In traditional compilers, switch implemented with a jump table, akin to C++ dispatch tables

Can blend table-based lookups, linear search, and binary search [Chambers & Chen 99]

- exploit available static analysis of possible receiver classes, profile information of likely receiver classes
- construct dispatcher best balancing expected dispatching speed against dispatch space cost

Handling multiple dispatching

Languages with multimethods (e.g. CLOS, Dylan, Cecil) allow methods to dispatch on the run-time classes of any of the arguments

- call sites do not know statically which arguments may be dispatched upon

Implementation schemes:

- hash table indexed by *N* keys [Kiczales & Rodriguez 89]
- *N*-deep tree of hash tables, each indexed by 1 key [Dussud 89]
    - can stop dispatching at any subtree if all remaining arguments undispatched
- *N*-deep DAG of 1-key dispatches [Chen & Turau 94, Chambers & Chen 99]
- compressed *N*+1-dimensional dispatch table [Amiel *et al.* 94, Pang *et al.* 99]

Probably more efficient to support multimethods directly than if simulated with double-dispatching [Ingalls 86] or visitor pattern [Gamma *et al.* 95]