Implementing OOPLs

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Features in OOPLs

- Polymorphism and subtyping
- Dynamic binding—virtual calls need run-time support
- Run-time type testing
- Inheritance

Only consider class-based OOPLs. Prototype-based roughly the same.

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  ***Want**: fast tests and cheap metadata*
- Inheritance
  Complicates lookup and analysis

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Outline

- **Field access**
- Method calls
- Calls through interface types
- Options for untyped languages
- Call-site optimisation techniques

Simplified World View

- Accessing C struct

  x.f # address of x + compile-time calculated offset of f in x’s type

- Accessing instance variable

  x.f # location (existence) of f depends on run-time type of x’s value

```
0  struct Point {
4    int x;
8    int y;
     Colour* colour;
   };
```

Unified access is desirable

- Simple—can use same method of access everywhere
- Not as simple as records

  Inheritance

  Multiple inheritance

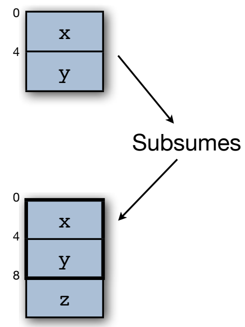
  Separate compilation

  Dynamic class loading

Prefixing for unified access

```
class Point2D {
  int x;
  int y;
}

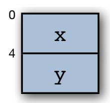
class Point3D ⊲ Point 2D {
  int z;
}
```



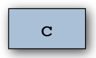

```
Point2D p = Point3D()
p.y # can be translated to ~ *(p+1)
```


Prefixing with multiple inheritance

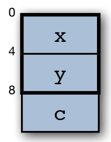
```
class Point2D {
  int x;
  int y;
}
```



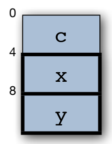

```
class Coloured {
  colour c;
}
```




```
class ColouredPoint ⊲ Point2D, Coloured {}
```

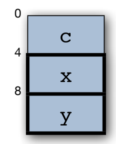


which one?

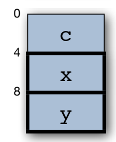


Prefixing with multiple inheritance (cont'd)

```
Coloured p = ColouredPoint()
p.c # works fine, *(p+0) still denotes a colour c
```




```
Point2D p = ColouredPoint()
p.x # breaks! *(p+0) is a colour, not an integer
```

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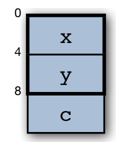


C++: pointer shifting

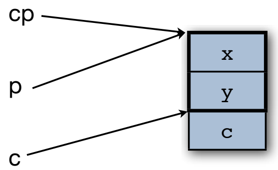
- Modify pointer address whenever type of variable changes

  Pick any of the possible embeddings
- Keeps field access a constant-time operation (*good*)
- Implicit casts gets a run-time cost (*bad*)
- Tricky if type information gets lost (e.g., void* pointers) (*bad*)

ColouredPoint cp = ColouredPoint()

Point2D p = cp

Coloured c = cp



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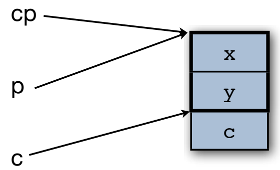

Limitations

- Does not work in an untyped setting
- Subtyping the only way to extend a class layout
  - Does not work with ”open classes”
  - Does not work if class layout can be modified dynamically

- For untyped/dynamic/… languages
  - Store fields in a hash table, loads and stores are hash table accesses

  (talk more about this later)

Not the Whole Story

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- Check access control at run-time (e.g. due to separate compilation)
    - Store a table of flags for variables in a class
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- When does offset calculation happen?
    - Load time—might trigger propagating inclusion
    - Run-time—too expensive?
- Opportunity for optimisation, if classes are invariant
    - Direct second access after slow first-time check
    - JIT:ed code can omit checks and use calculated offsets

Object Layout

- Languages with GC, RTTI, etc. will use additional overhead per object, e.g.,
    - Forward pointer space for copying GC, mark bits, etc.
    - Pointer to object's class
    - Sometimes, object can be broken up in slices (e.g., for fragmentation-sensitive applications)
    - Monitor for storing a lock
- Push as much shared information into the class
- Java and C++ are about equally efficient wrt. object layout (except for POD)
- Dynamic languages generally more space demanding

Example: JRuby

- JRuby is considered an efficient implementation of Ruby on the JVM
- Ruby is a dynamic language, fields are ultimately stored in Java hash maps
- Empty JRuby object uses ~72 bytes

  plus 40 bytes per variable for a 32 bit VM

  plus 64 bytes per variable for a 64 bit VM
- Compare with an empty Java object that should use <12 bytes

Outline

- Field access
- **Method calls**
- Calls through interface types
- Options for untyped languages
- Call-site optimisation techniques

Simplified World View (cont'd)

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  foo(y) # location of foo can be determined at compile-time (link-time)

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- Calling methods:

  x.foo(y) # which foo depends on run-time type of x's value

  Inheritance may require class tree search every call (expensive!)

  Subtype polymorphism and late binding/class loading makes efficiency difficult to achieve

Method call in untyped OOPLs

- Seach inheritance hierarchy from x's class for foo/1

  Very slow lookup time! (function of #classes and #methods)

- Use a hash table in each object x.foo(y) ~> push x,y + jmp x.get(foo/1)

  Still much slower than a procedure call!

- Make an entry for each method in the object just like a field

  Fast, constant-time dispatch (load + jump)

  Very large objects

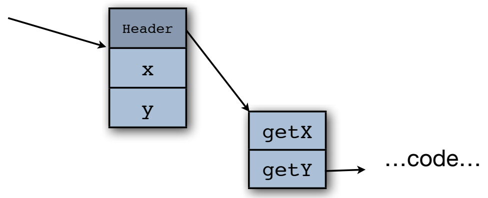
- Optimisation: share method entries for objects of same class in *vtables*

  Much smaller object for the cost of one extra indirection

Vtables for efficient dispatch

- Virtual tables
- Complication due to multiple inheritance

p.getY()

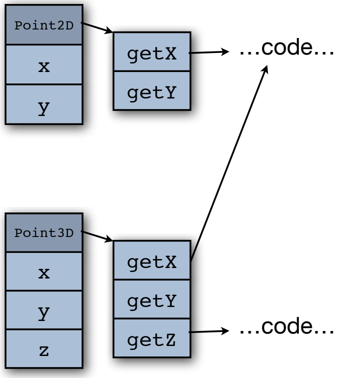



```
void* header = p-1;
void* vtable = *header;
int (*getY)() = vtable+1;
int temp = getY(p); // this
```

Vtable prefixing with single inheritance

class Point2D {
  int x, y;
  int getX() …
  int getY() …
}

class Point3D ◁ Point2D {
  int z;
  int getZ() …
}



Vtable prefixing with multiple inheritance

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class Coloured {
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class ColouredPoint ◁
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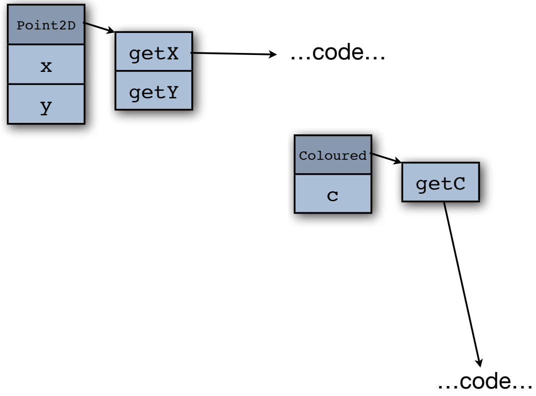

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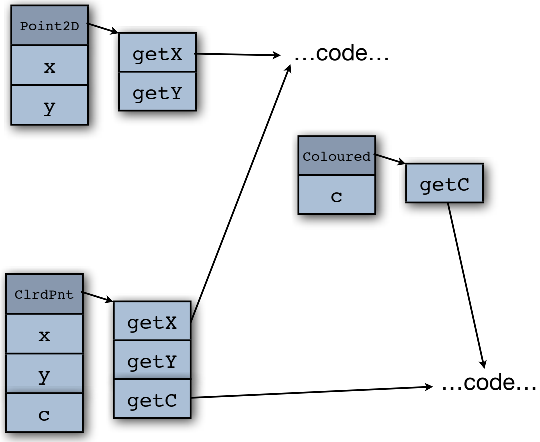

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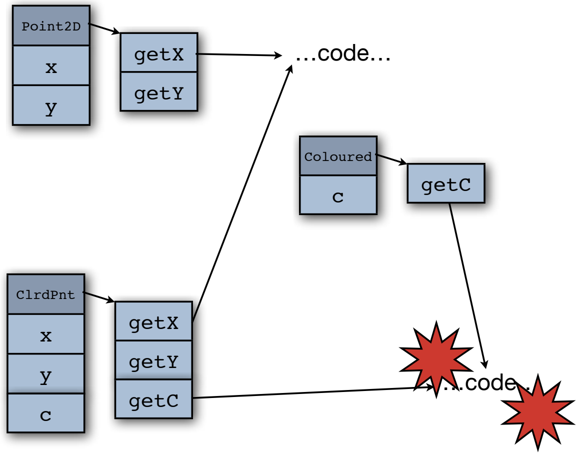

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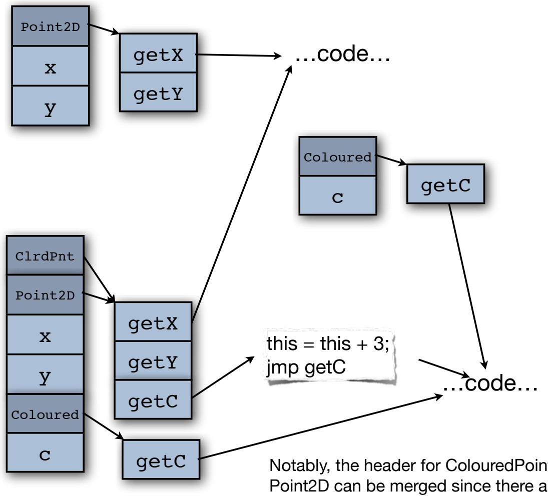

Notably, the header for ColouredPoint and Point2D can be merged since there are no members in the class.

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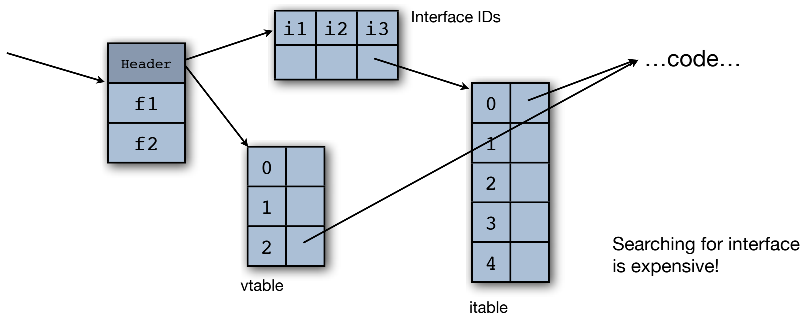
- **Calls through interface types**
- Options for untyped languages
- Call-site optimisation techniques

Invocation through interface types

- Observation: Impossible to achieve uniform access through interface types
- **Technique 1:** translate interface offsets to implementing class offsets

  Each class has a dispatch ”itable” for each interface it implements

  On call: search for correct itable by some interface id and use it for dispatch



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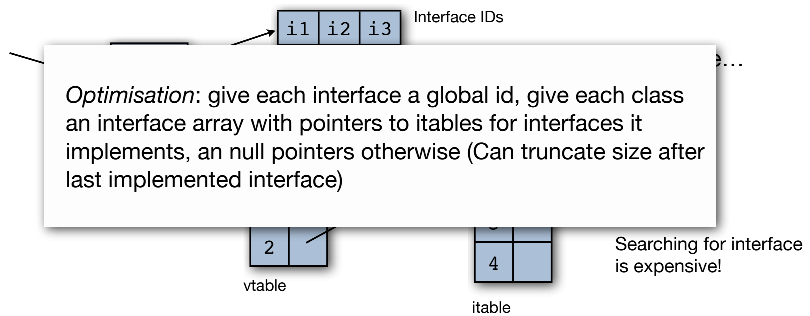
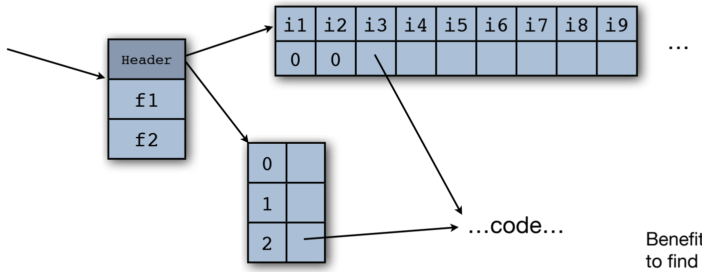


Optimisation: give each interface a global id, give each class an interface array with pointers to itables for interfaces it implements, an null pointers otherwise (Can truncate size after last implemented interface)

Invocation through interface types (cont’d)

- **Technique 2:** ”Selector-indexed tables”

  Give each interface method a numerical id (e.g., at load-time)
  Give each class an itable for *all* methods in *all* interfaces
  Dispatch becomes additional indirection—lookup in the selector index table
  Fast but very costly wrt. space



Benefit: constant-time to find correct itable

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Optimisation: Use graph colouring to re-use same numerical index for methods that may never be called on the same classes.

Can greatly reduce size of all itables.

…code…

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Observation: We can get more space-efficient by using a small selector table. But hashing might produce duplicates—same index for different methods.

Solution: store pointer to code that switches on receiver class type to find the correct implementation.

Class type can be a *hidden parameter* [Alpern et. al., OOPSLA 2001]

constant-time to find correct itable

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- **Options for untyped languages**
- Call-site optimisation techniques

Alternatives for untyped code

- No type information to base field, vtable (or itable) offsets from
- Storing closures in hash tables is not space efficient for *methods* (but for fields)
- Naïve implementation:

  Search receiver's class' hierarchy for method signature, and call

  Slow, terrible worst-case times
- Possible to use static table internally, esp. with JIT compilation

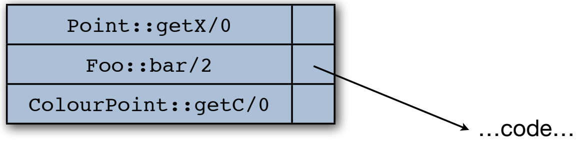
  For example, each class trivially knows it super class statically

Global dynamic table

- Global cache in the form of a hash table indexed by class + signature

  Translate invocations into lookups in hash table

  Cache miss: perform expensive search through class hierarchy, then update cache
- Flush (part of) the cache as a result of reflective operations that change classes
- Space costs are reasonable
- Overhead is reasonable and table is constructed incrementally



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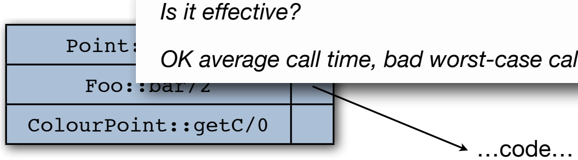
Is it effective?

OK average call time, bad worst-case call time

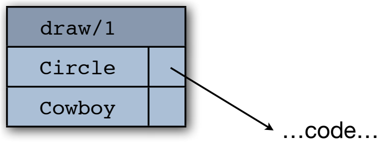


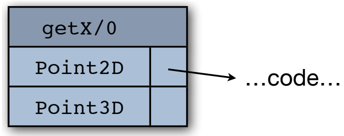
One dispatch table per message names

- Create a separate table per unique signature mapping classes to methods
- Each call site can statically know what table to consult
- Performance is better than the single global table

  Especially if methods names are relatively unique

  (Smalltalk names fare quite well here)
- Per-signature dispatch tables can be constructed incrementally





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Inlining

- Difficult to do in flexible programs

  Analysis of e.g., possible run-time binding is limited by dynamic loading

- Java

  Can possibly inline **final** and **static** methods

  JITing allows more aggressive inlining

  class A {
  int foo(*int* x, *int* y) { **return** x+y; } // can be inlined by HotSpot if ∄B <: A
  }

- Dynamic class loading requires remembering JITed methods and storing their prerequisites (e.g. ∄B <: A above)

  Check prerequisites and possibly ”retire” (unoptimise) compiled code on class loading

Call-site optimising through caching

- Useful esp. for untyped code and interface calls
- Techniques addressed here:

  Inline Caching [Deutsch and Shiffman, 1984]

  Polymorphic Inline Caching [Hölzle et al., 1991]

Inline Caching [Deutsch and Shiffman 1984]

- Each call site has a single-element lookup cache

  Remember what actual method was called for class of last receiver

  Next call, if same receiver we can get method immediately from cache

  Cache miss: slow-path through lookup, update caches

- Efficient implementation through self-modifying code

x.m(…)

```
c = x.class
am = c.search(m/1)
jump am
```

→

next call

```
switch (x.class) {
case c: jump am; break
default:
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am = c.search(m/1)
jump am }
```

Inline Caching [Deutsch and Shiffman 1984]

• Each

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Ne

Ca

Is it effective?

Smalltalk: 90-95% cache hit frequency and ≈ 4 instructions for fast path. Slow path real slow though.

Polymorphic and megamorphic call sites terrible performance!

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Polymorphic inline caching [Hölzle and Ungar, 1991]

• Handles polymorphic and megamorphic call sites

Extension is simple: use a multi-element cache

Allows relatively fast dispatch for polymorphic call sites

If several classes are equally common, performance degrades

Can get large space overhead (esp. for megamorphic call sites)

call when x is a Bar

```
switch (x.class) {
case Foo: jump m1 break;
default: … # lookup + install
}
```

→

```
switch (x.class) {
case Foo: jump m1 break;
case Bar: jump m2 break;
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Improvement: use binary search instead of linear switch.

Requires global knowledge (to map classes to integer ids)

Little additional overhead

```
sw
ca
de
}
```

```
default: … # lookup + install
}
```

JRuby use of IC [Bini et al.]

```
public IRubyObject call(IRubyObject caller, IRubyObject self, IRubyObject arg1) {
    RubyClass selfType = pollAndGetClass(self);
    if (CacheEntry.typeOk(localCache, selfType)) {
        return localCache.method.call(self, selfType, arg1);
    }
    return cacheAndCall(caller, selfType, self, arg1);
}
```

(Simplified to fit on screen)

(Notably not polymorphic)

References

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