Implementing OOPLs

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Features of 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.

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

Unified access is desirable

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

  Inheritance

  Multiple inheritance

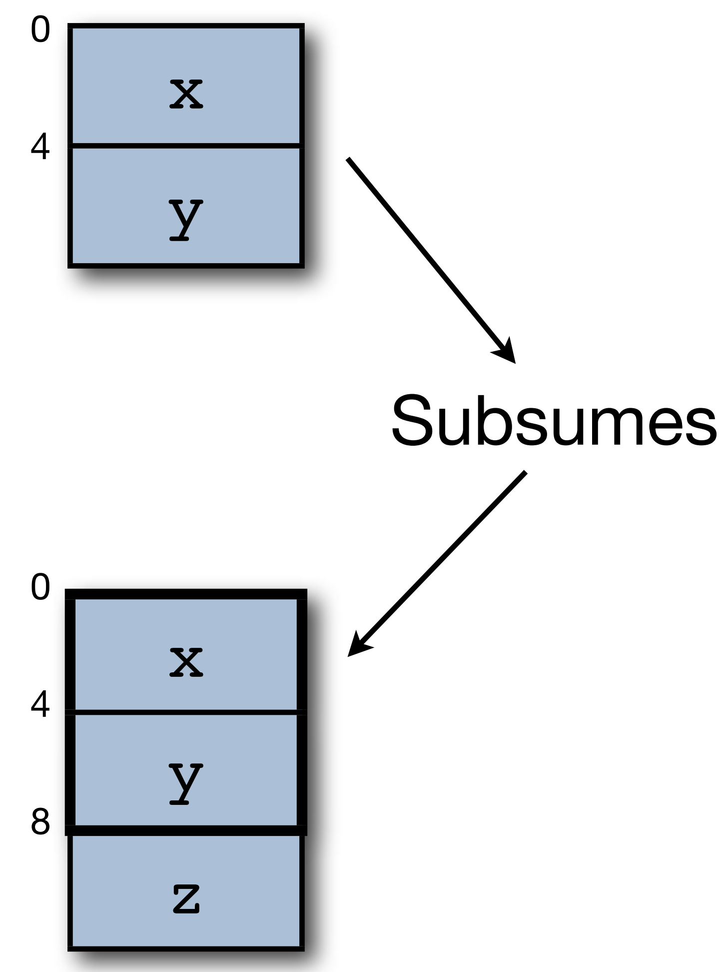
  Separate compilation

  Dynamic class loading

Prefixing for unified access

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

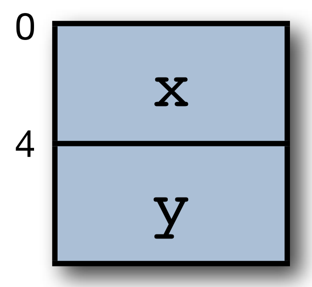
class Point3D $\triangleleft$ Point 2D {
  int z;
}



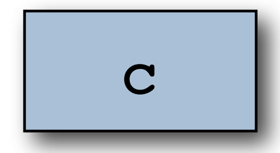

```
Point2D p = Point3D()
p.y # can be translated to ~ *(p+1)
```

Prefixing with multiple inheritance

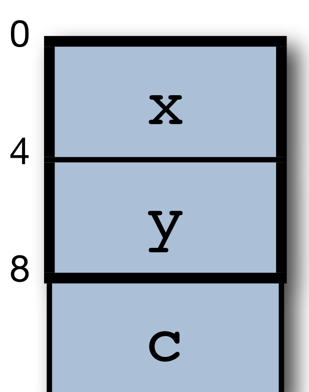
```
class Point2D {
  int x;
  int y;
}
```



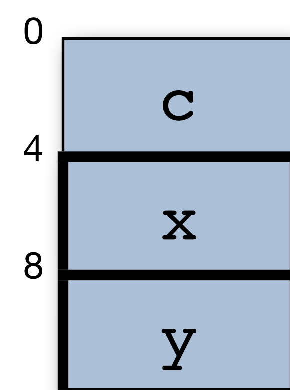

```
class Coloured {
  colour c;
}
```



class ColouredPoint ◁ Point2D, Coloured {}

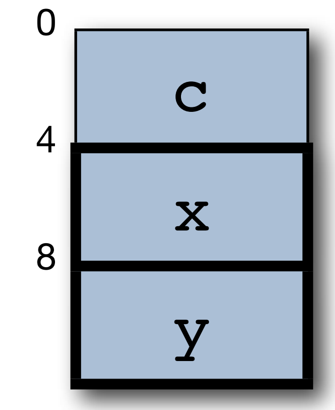


which one?

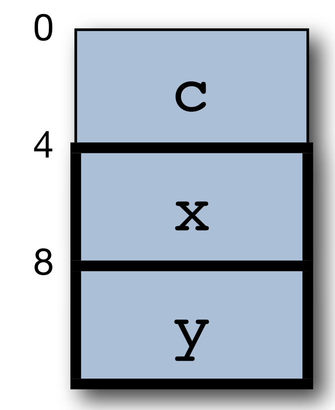


Prefixing with multiple inheritance (cont'd)

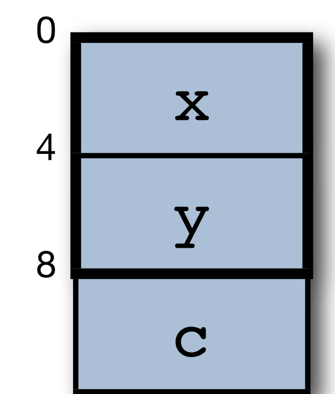
Coloured p = ColouredPoint()
p.c # works fine, *(p+0) still denotes a colour c



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



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



C++: pointer shifting

- Modify pointer address whenever type of variable changes

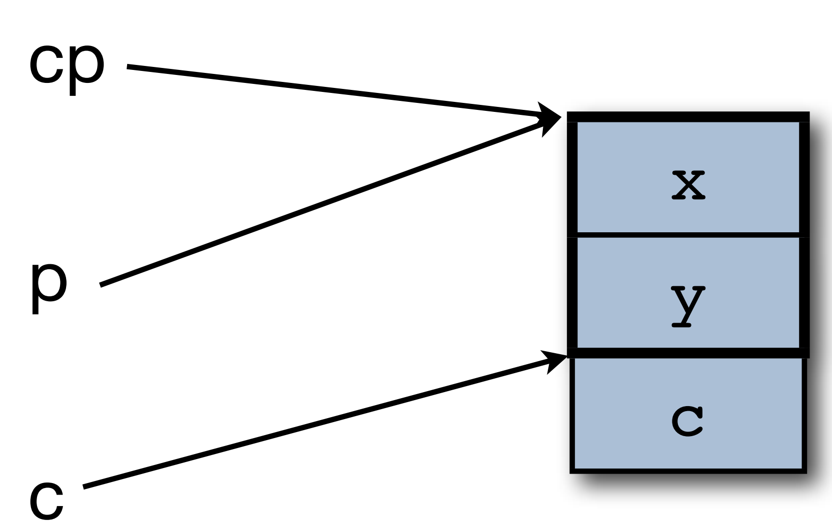
  Pick any of the possible embeddings

- Keeps field access a constant-time operation (*good*)
- Explicit and 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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Needs RTTI!

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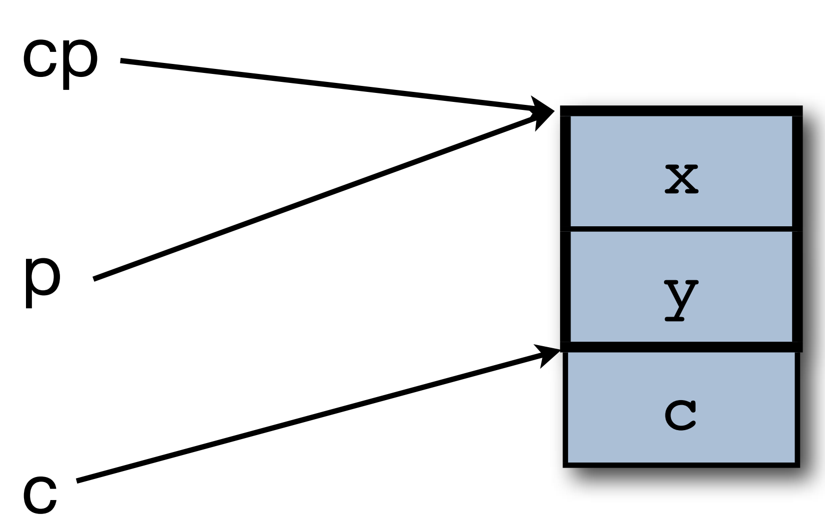


Limitations

- 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

- Check access control at run-time (e.g. due to separate compilation)

  Store a table of flags for variables in a class

  Perform expensive access control check

- When does offset calculation happen?

  Load time—might trigger propagating inclusion

  Run-time—perform expensive offset calculation

- 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)

- Calling functions and procedures:

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

  Allows inlining to reduce call-time overhead, etc.

- Calling closures:

  foo(y) # push y onto stack, jump to address of foo (~ish)

- 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

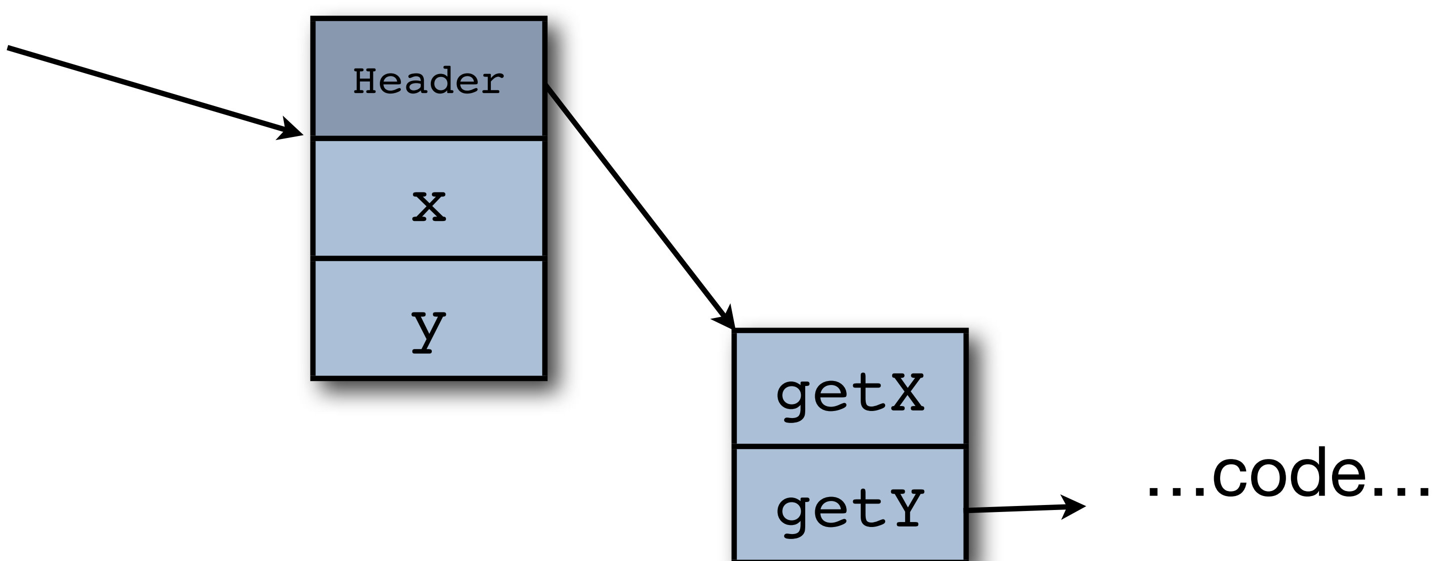
- Optimisation: share method entries for objects of same class in *vtables*

  Much smaller object for the cost of one extra indirection

Vtables for efficient dispatch

- Virtual tables
- Complication due to multiple inheritance

p.getY()

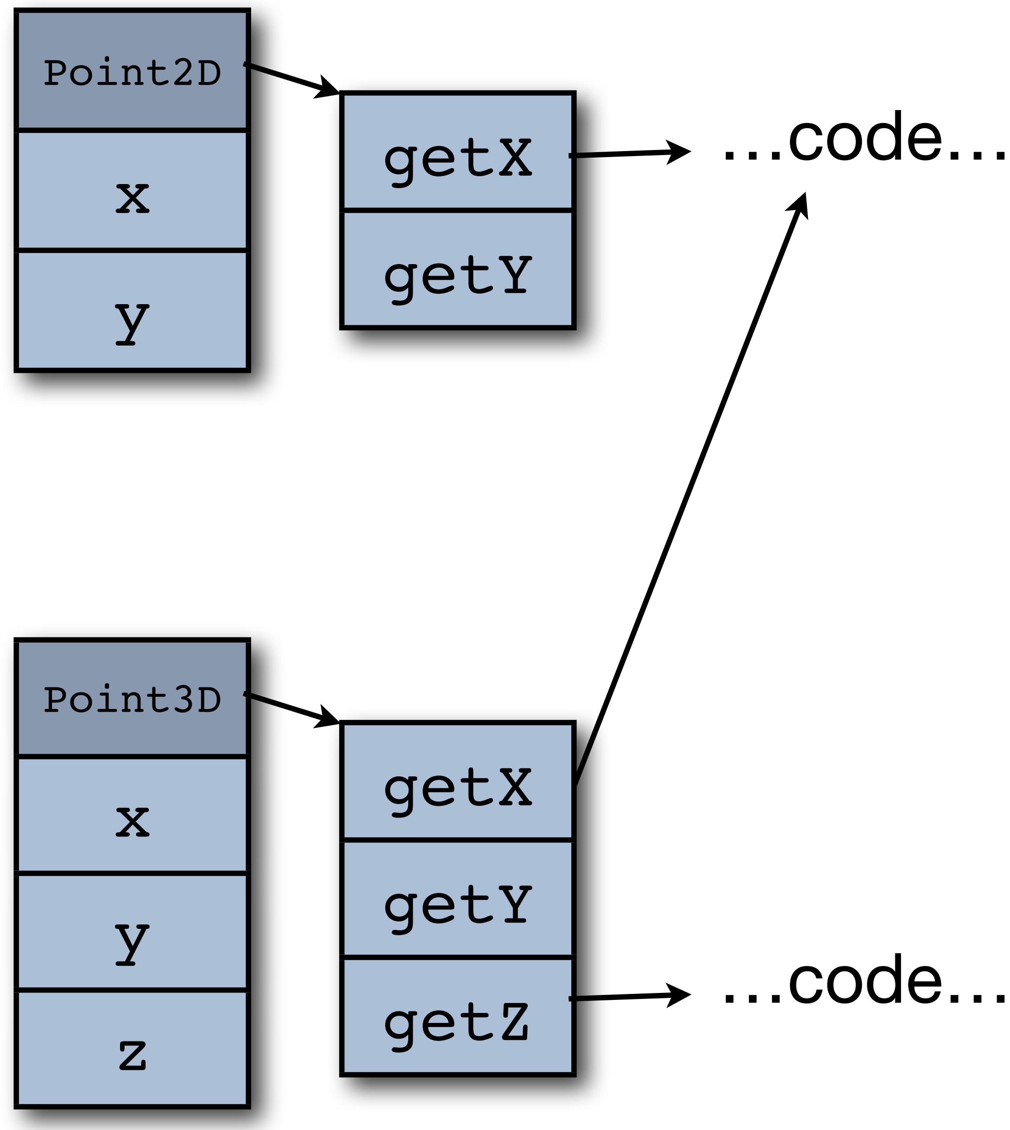


void* header = p-1;
void* vtable = *header;
int (*getY)() = vtable+1;
int temp = getY(p); // this

Vtable prefixing with single inheritance

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

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

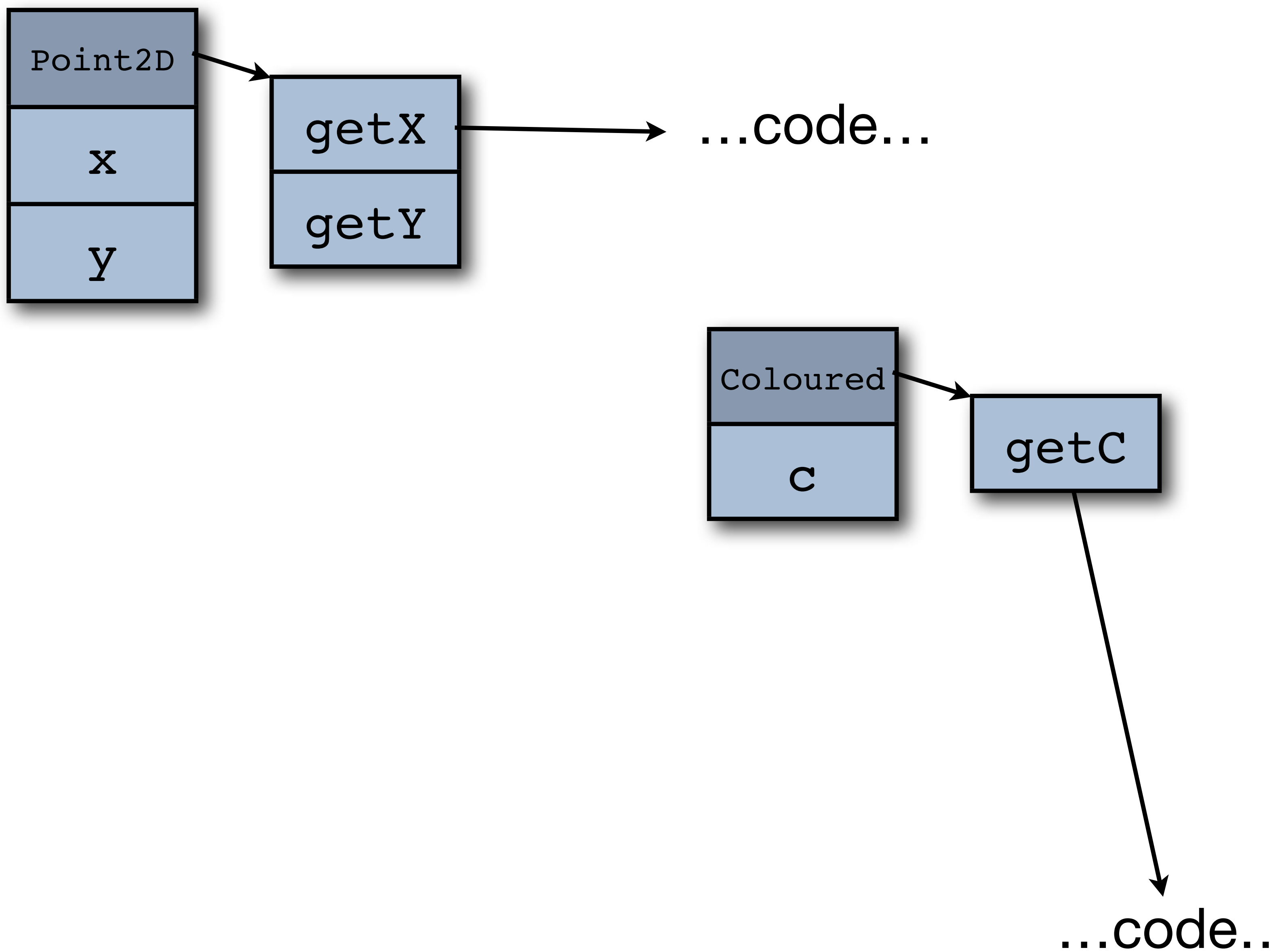


Vtable prefixing with multiple inheritance

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

class Coloured {
  colour c;
  colour getC() …
}

class ColouredPoint ⊲
   Point2D, Coloured { }
```



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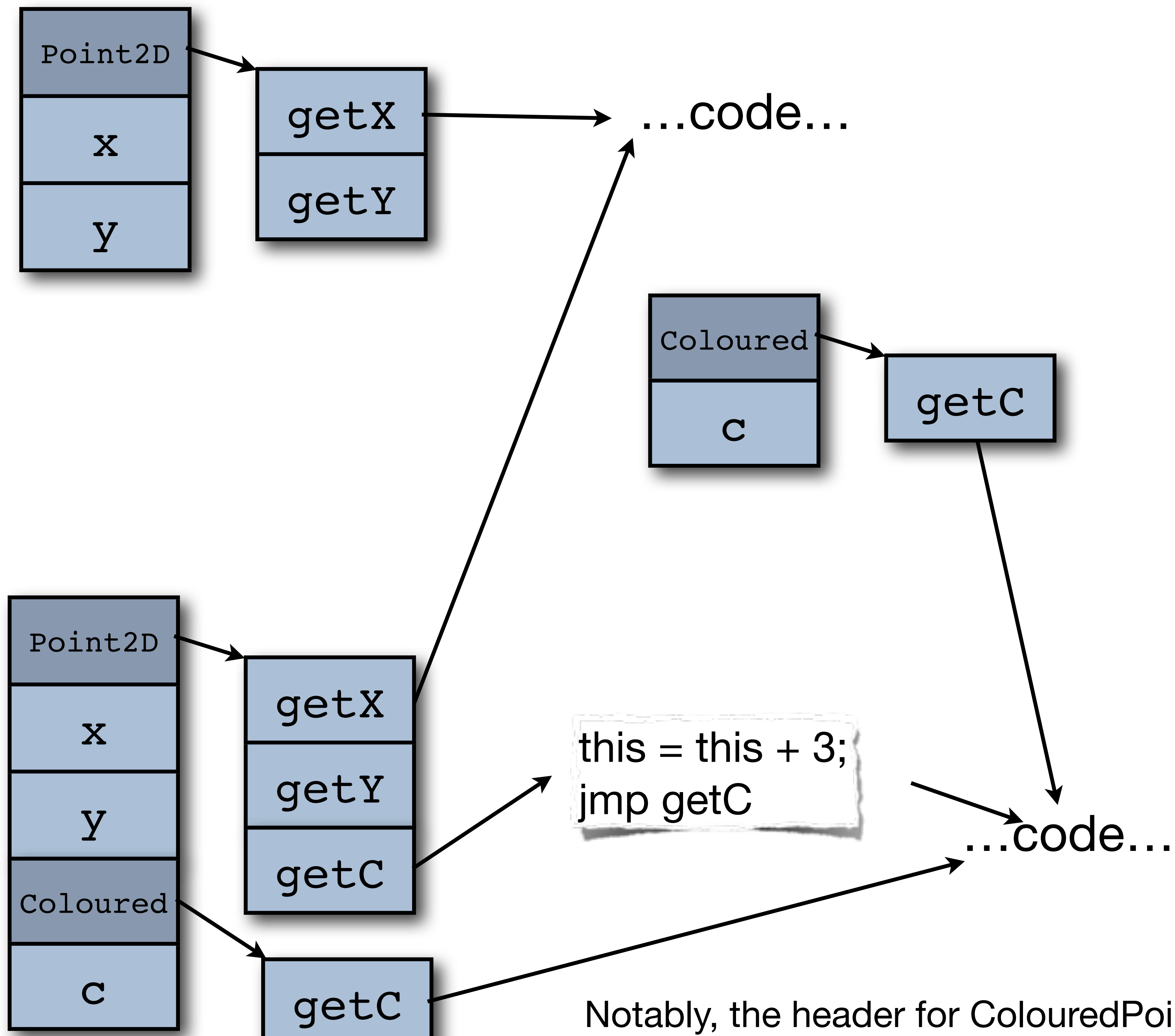

Notably, the header for ColouredPoint and Point2D can be merged since there are no fields in the class.

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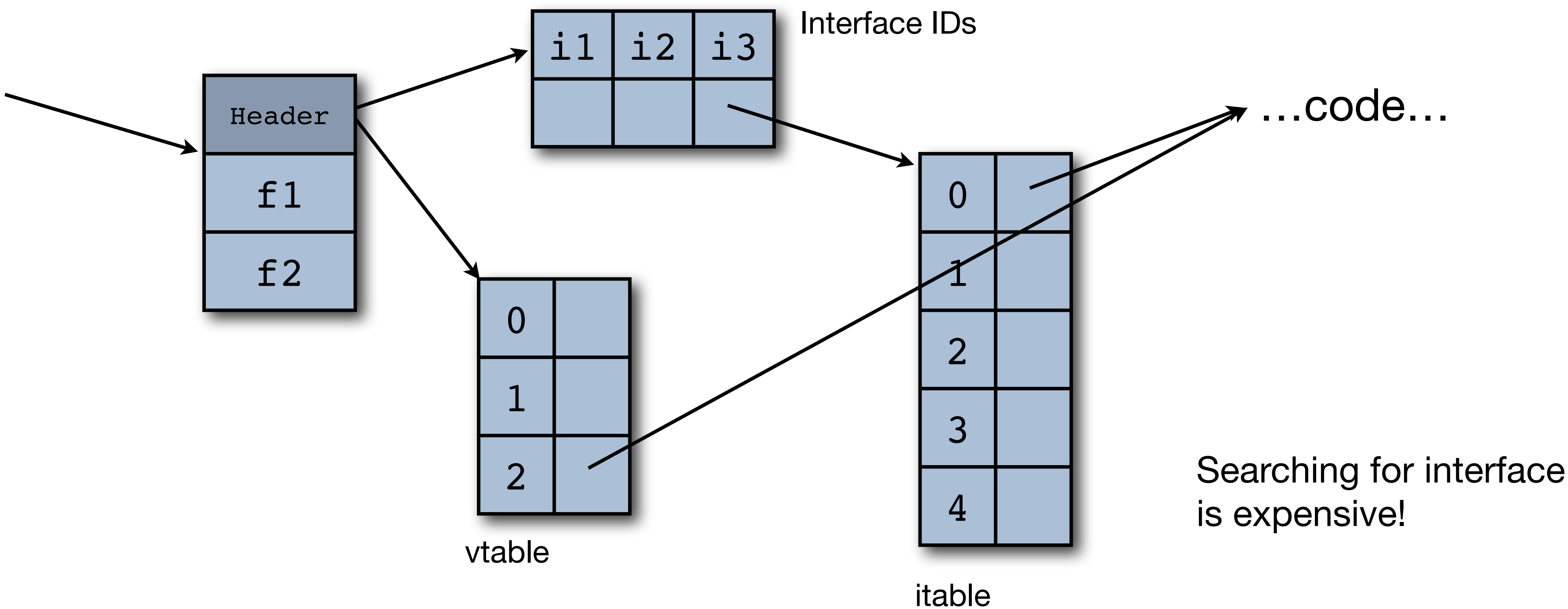
Invocation through interface types

- 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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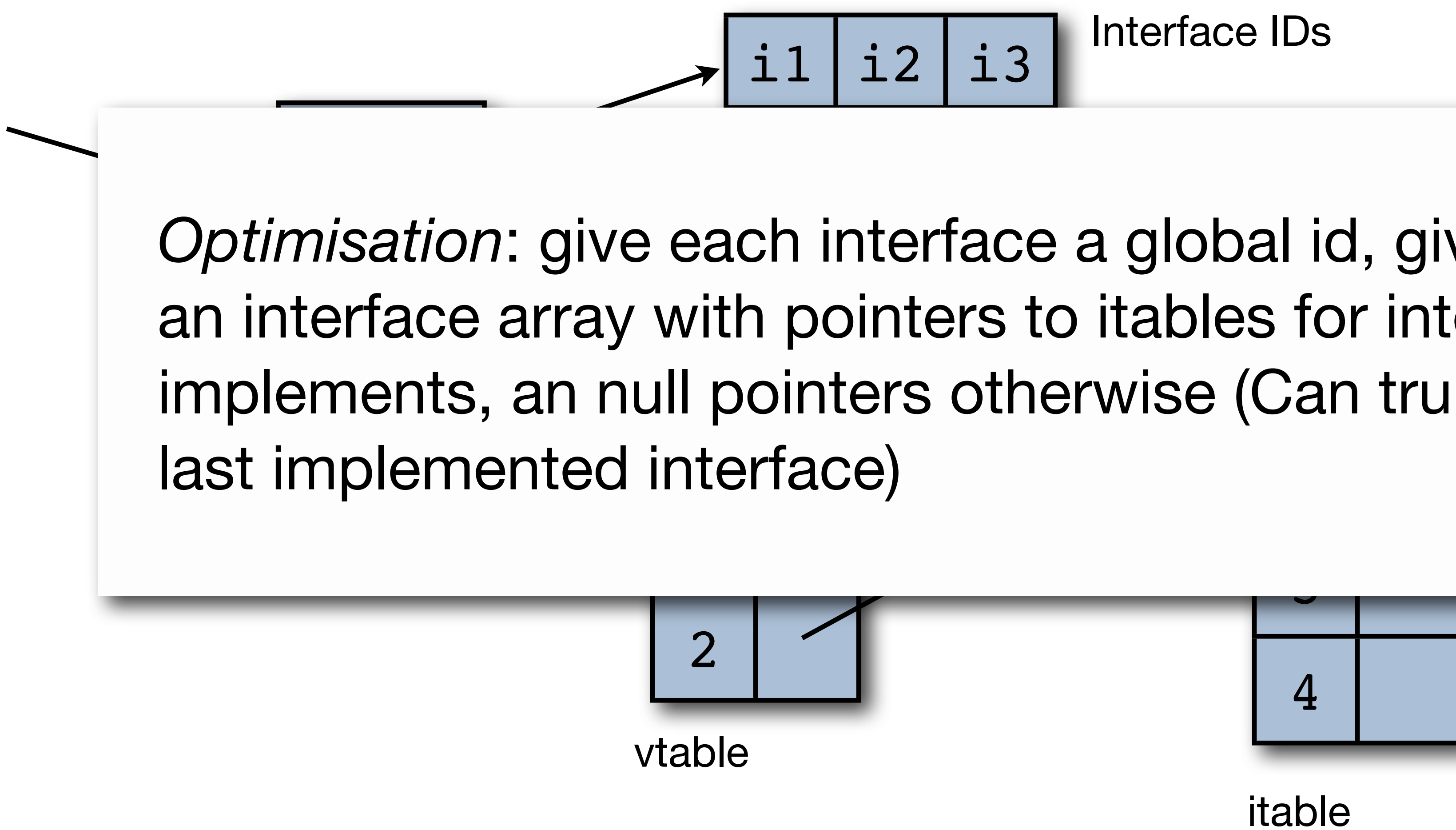


Optimisation: give each interface a global id, give each class an interface array with pointers to itables for interfaces it implements, an null pointers otherwise (Can truncate size after last implemented interface)

Searching for interface is expensive!

Invocation through interface types (cont'd)

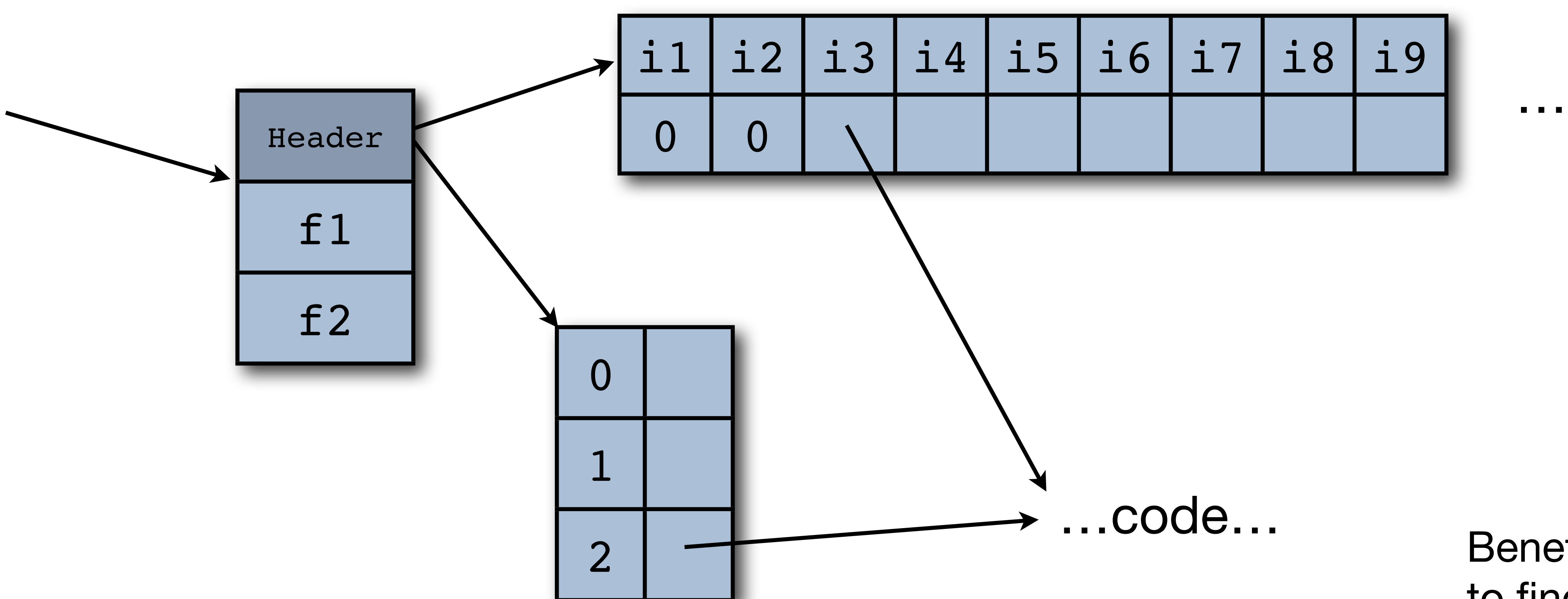
- **Technique 2:** ”Selector-indexed tables”

  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

Invocation through interface types (cont'd)

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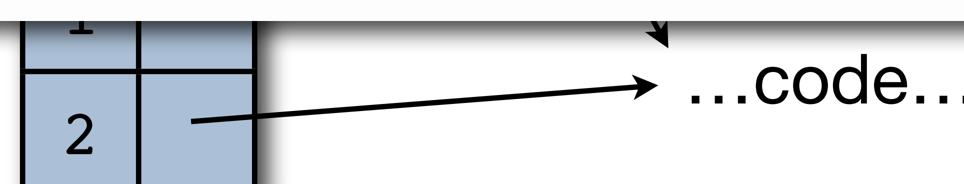
Optimisation: Use graph colouring to re-use same numerical index for methods that may never be called on the same classes.

Can greatly reduce size of all itables.



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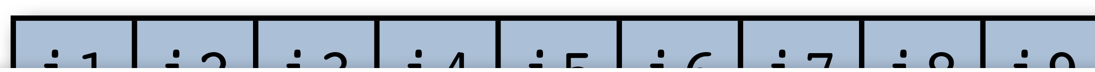

Observation: We can get more space-efficient by using a small selector table. But hashing might produce duplicates—same index for different methods.

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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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

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

Global dynamic table

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- Space costs are reasonable
- Overhead is reasonable and table is constructed incrementally

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

Outline

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- **Call-site optimisation techniques**

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. $\nexists B <: A$ 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(…) → next call

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

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

Inline Caching [Deutsch and Shiffman 1984]

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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- Efficient implementation through self-modifying code

x.m(…)

c = x.class
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jump am

next call

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jump am }

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;
default: … # lookup + install
}
```

Polymorphic inline caching [Hölzle and Ungar, 1991]

- Handles polymorphic and megamorphic call sites

Ext

All

If s

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

> *Extensions: change case ordering based on hit frequency.*
>
> *But will it earn back the incurred run-time overhead?*

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Extensions: change case ordering based on hit frequency.

But will it earn back the incurred run-time overhead?

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}

default: … # lookup + install
}

Improvement: use binary search instead of linear switch.

Requires global knowledge (to map classes to integer ids)

Little additional overhead

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, methodName, arg1);
    }
    return cacheAndCall(caller, selfType, self, arg1);
}
```

(Simplified to fit on screen)

(Notably not polymorphic)

References

1. Craig Chambers, *Efficient Implementation of Object-Oriented Programming Languages*, Tutorial, OOPSLA 2000
2. Bowen Alpern, Anthony Cocchi, Stephen J. Fink, David Grove, and Derek Lieber, *Efficient Implementation of Java Interfaces: Invokeinterface Considered Harmless,* OOPSLA 2001
3. Urs Hölzle and Ole Agesen, *Dynamic vs. Static Optimization Techniques for Object-Oriented Languages*, in Theory and Practice of Object Systems 1(3), 1995
4. Urs Hölzle, Craig Chambers and David Ungar, *Optimizing Dynamically-Typed Object-Oriented Languages With Polymorphic Inline Caches*, ECOOP 1991
5. L. Peter Deutsch and Allan M. Schiffman, *Efficient implementation of the smalltalk-80 system,* POPL 1984
6. Stefan Matthias Aust et al., *JRuby 1.4.0. source code*, retrieved Feb 2010