Languages and Compilers (SProg og Oversættere)

Abstract Data Types and Object Oriented Features

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The Concept of Abstraction

- The concept of abstraction is fundamental in programming (and computer science)
- Nearly all programming languages support process abstraction with subprograms
- Nearly all programming languages designed since 1980 have supported data abstraction:
  - Abstract data type
  - Objects
  - Module

What have we seen so far?

- Structured data
  - Arrays
  - Records or structs
  - Lists
- Visibility of variables and subprograms
  - Scope rules
- Why is this not enough?

Information Hiding

- Consider the C code:

```
typedef struct RationalType {
   int numerator;
   int denominator;
} Rational

Rational mk_rat (int n,int d) { …}
Rational add_rat (Rational x, Rational y) {
… }
```

- Can use **`mk_rat`**, **`add_rat`** without knowing the details of **`RationalType`**

Need for Abstract Types

- Problem: abstraction not enforced
  - User can create Rationals without using **`mk_rat`**
  - User can access and alter numerator and denominator directly without using provided functions
- With abstraction we also need information hiding

Abstract Types - Example

- Suppose we need sets of integers
- Decision: implement as lists of int
- Problem: lists have order and repetition, sets don’t
- Solution: use only lists of int ordered from smallest to largest with no repetition (data invariant)

Abstract Type – SML code Example

```
type intset = int list
val empty_set = []:intset
fun insert {elt, set = [] } = [elt]
      |  insert {elt, set = x :: xs} =
         if elt < x then elt :: x :: xs
         else if elt = x then x :: xs
         else x :: (insert {elt = elt, set = xs})

fun union ([],ys) = ys
    | union (x::xs,ys) =
       union(xs,insert{elt=x,set = ys})

fun intersect ([],ys) = []
   | intersect (xs,[]) = []
   | intersect (x::xs,y::ys) =
        if x <y then intersect(xs, y::ys)
        else if y < x then intersect(x::xs,ys)
        else x :: (intersect(xs,ys))
```

```
fun elt_of {elt, set = []} = false
   | elt_of {elt, set = x::xs} =
      (elt = x) orelse
      (elt > x andalso
       elt_of{elt = elt, set = xs})
```

Abstract Type – Example

- Notice that all these definitions maintain the data invariant for the representation of sets, and depend on it
- Are we happy now?
- NO!
- As is, user can create any pair of lists of int and apply union to them; the result is meaningless

Solution: abstract datatypes

```
abstype intset = Set of int list with
val empty_set = Set []
local
fun ins {elt, set = [] } = [elt]
   |  ins {elt, set = x :: xs} =
        if elt < x then elt :: x :: xs
        else if elt = x then x :: xs
        else x :: (ins {elt = elt, set =
         xs})
fun un ([],ys) = ys
   | un (x::xs,ys) =
      un (xs,ins{elt=x,set = ys})
in
      fun insert {elt, set = Set s}=
            Set(ins{elt = elt, set  = s})
      fun union (Set xs, Set ys) =
          Set(un (xs, ys))
end
```

```
local
fun inter ([],ys) = []
   | inter (xs,[]) = []
   | inter (x::xs,y::ys) =
        if x <y then inter(xs, y::ys)
        else if y < x then inter(x::xs,ys)
        else x :: (inter(xs,ys))

in
       fun intersect(Set xs, Set ys) =
           Set(inter(xs,ys))
end
fun elt_of {elt, set = Set []} = false
   | elt_of {elt, set = Set (x::xs)} =
      (elt = x) orelse
      (elt > x andalso
       elt_of{elt = elt, set = Set xs})
fun set_to_list (Set xs) = xs
end (* abstype *)
```

Abstract Type – Example

- Creates a new type (not equal to **int list**)
- Functional implementation of integer sets – **insert** creates new intset
- Exports
  - type **intset,**
  - Constant **empty_set**
  - Operations: **insert, union, elt_of,** and **set_to_list**; act as primitive
  - Cannot use pattern matching or list functions; won't type check

Abstract Type – Example

- Implementation: just use **int list**, except for type checking
- Data constructor **Set** only visible inside the asbtype declaration; type intset visible outside
- Function **set_to_list** used only at compile time
- Data abstraction allows us to prove data invariant holds for all objects of type intset

Abstract Types

- A type is abstract if the user can only see:
  - the type
  - constants of that type (by name)
  - operations for interacting with objects of that type that have been explicitly exported
- Primitive types are built in abstract types

  e.g. **int** type in Java
  - The representation is hidden
  - Operations are all built-in
  - User programs can define objects of **int** type
- User-defined abstract data types must have the same characteristics as built-in abstract data types

User Defined Abstract Types

- Syntactic construct to provide encapsulation of abstract type implementation
- Inside, implementation visible to constants and subprograms
- Outside, only type name, constants and operations, not implementation, visible
- No runtime overhead as all the above can be checked statically

Advantage of Data Abstraction

- Advantage of Inside condition:
  - Program organization, modifiability (everything associated with a data structure is together)
  - Separate compilation may be possible
- Advantage of Outside condition:
  - Reliability--by hiding the data representations, user code cannot directly access objects of the type. User code cannot depend on the representation, allowing the representation to be changed without affecting user code.

Limitation of Abstract data types

Queue

```
abstype q
with
  mk_Queue : unit -> q
  is_empty : q -> bool
  insert   : q * elem -> q
  remove   : q -> elem
is  …
in
  program
end
```

Priority Queue

```
abstype pq
with
  mk_Queue : unit -> pq
  is_empty : pq -> bool
  insert   : pq * elem -> pq
  remove   : pq -> elem
is …
in
  program
end
```

But cannot intermix pq's and q's

Abstract Data Types

- Guarantee invariants of data structure
  - only functions of the data type have access to the internal representation of data
- Limited “reuse”
  - Cannot apply queue code to pqueue, except by explicit parameterization, even though signatures identical
  - Cannot form list of points, colored points
- Data abstraction is important – how can we make it extensible?

The answer is: Objects

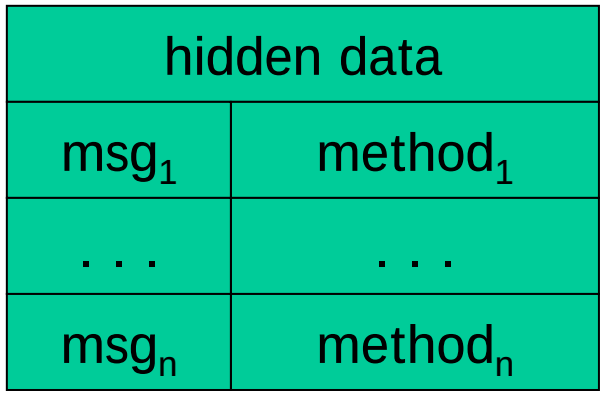
- An object consists of
  - hidden data

    instance variables, also called member data

    hidden functions also possible
  - public operations

    methods or member functions

    can also have public variables in some languages



- Object-oriented program:
  - Send messages to objects

What's interesting about this?

- Universal encapsulation construct
  - Data structure
  - File system
  - Database
  - Window
  - Integer
- Metaphor usefully ambiguous
  - sequential or concurrent computation
  - distributed, sync. or async. communication

Object-oriented programming

- Programming methodology
  - organize concepts into objects and classes
  - build extensible systems
- Language concepts
  - encapsulate data and functions into objects
  - subtyping allows extensions of data types
  - inheritance allows reuse of implementation
  - dynamic lookup

Dynamic Lookup – dynamic dispatch

- In object-oriented programming,

  object → message (arguments)

  object.method(arguments)

  code depends on object and message

  – Add two numbers x → add (y)

    different add if x is integer or complex

- In conventional programming,

  operation (operands)

  meaning of operation is always the same

  – Conventional programming add (x, y)

    function add has fixed meaning

Dynamic dispatch

- If methods are overridden, and if the PL allows a variable of a particular class to refer to an object of a subclass, then method calls entail **dynamic dispatch**.
- Consider the Java method call "$O.M(E_1, \ldots, E_n)$":
  - The compiler infers the type of *O*, say class *C*.
  - The compiler checks that class *C* is equipped with a method named *M*, of the appropriate type.
  - Nevertheless, it might turn out (at run-time) that the target object is actually of class *S*, a subclass of *C*.
  - If method *M* is overridden by any subclass of *C*, a run-time tag test is needed to determine the actual class of the target object, and hence which of the methods named *M* is to be called.

Dynamic Dispatch Example

```
class point {
    int c;
    int getColor() { return(c); }
    int distance() { return(0); }
}
class cartesianPoint extends point{
    int x, y;
    int distance() { return(x*x + y*y); }
}
class polarPoint extends point {
    int r, t;
    int distance() { return(r*r); }
    int angle() { return(t); }
}
```

Dynamic Dispatch Example

```
if (x == 0) {
    p = new point();
} else if (x < 0) {
    p = new cartesianPoint();
} else if (x > 0) {
    p = new polarPoint();
}
y = p.distance();
```

Which distance method is invoked?

- Invoked Method Depends on Type of Receiver!
  - if p is a point
    - return(0)
  - if p is a cartesianPoint
    - return(x*x + y*y)
  - if p is a polarPoint
    - return(r*r)

Overloading vs. Dynamic Dispatch

- Dynamic Dispatch
  - Add two numbers x → add (y)

    different add if x is integer, complex, ie. depends on the type of x

- Overloading
  - add (x, y) function add has fixed meaning
  - int-add if x and y are ints
  - real-add if x and y are reals

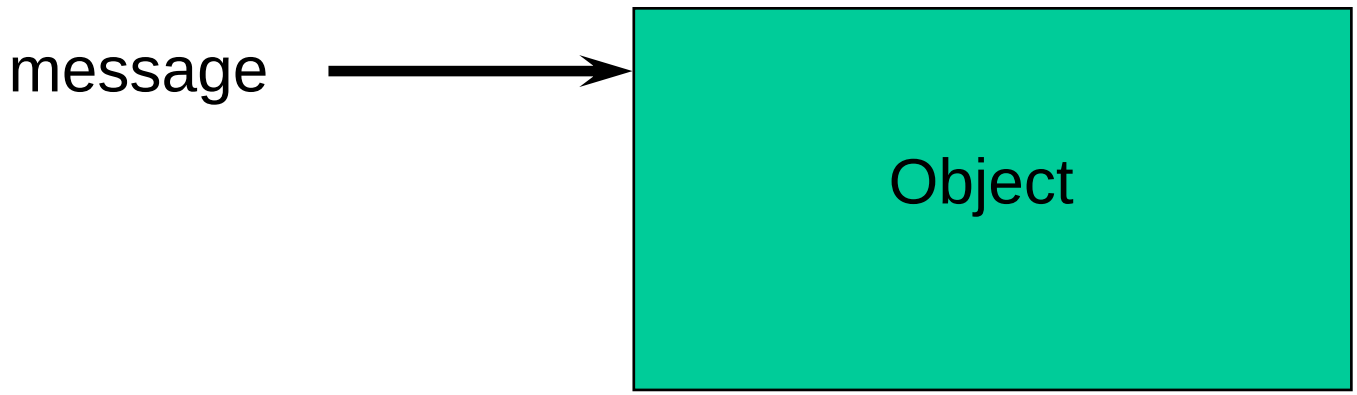
Important distinction:

Overloading is resolved at compile time,

Dynamic lookup at run time.

Encapsulation

- Builder of a concept has detailed view
- User of a concept has “abstract” view
- Encapsulation is the mechanism for separating these two views



Comparison

- Traditional approach to encapsulation is through abstract data types
- Advantage
  - Separate interface from implementation
- Disadvantage
  - Not extensible in the way that OOP is

Subtyping and Inheritance

- Interface
  - The external view of an object
- Subtyping
  - Relation between interfaces
- Implementation
  - The internal representation of an object
- Inheritance
  - Relation between implementations

Object Interfaces

- Interface
  - The messages understood by an object
- Example: point
  - x-coord : returns x-coordinate of a point
  - y-coord : returns y-coordinate of a point
  - move : method for changing location
- The interface of an object is its *type*.

Subtyping

- If interface A contains all of interface B, then A objects can also be used B objects.

Point
- x-coord
- y-coord
- move

Colored_point
- x-coord
- y-coord
- color
- move
- change_color

- Colored_point interface contains Point
  - Colored_point is a *subtype* of Point

Inheritance

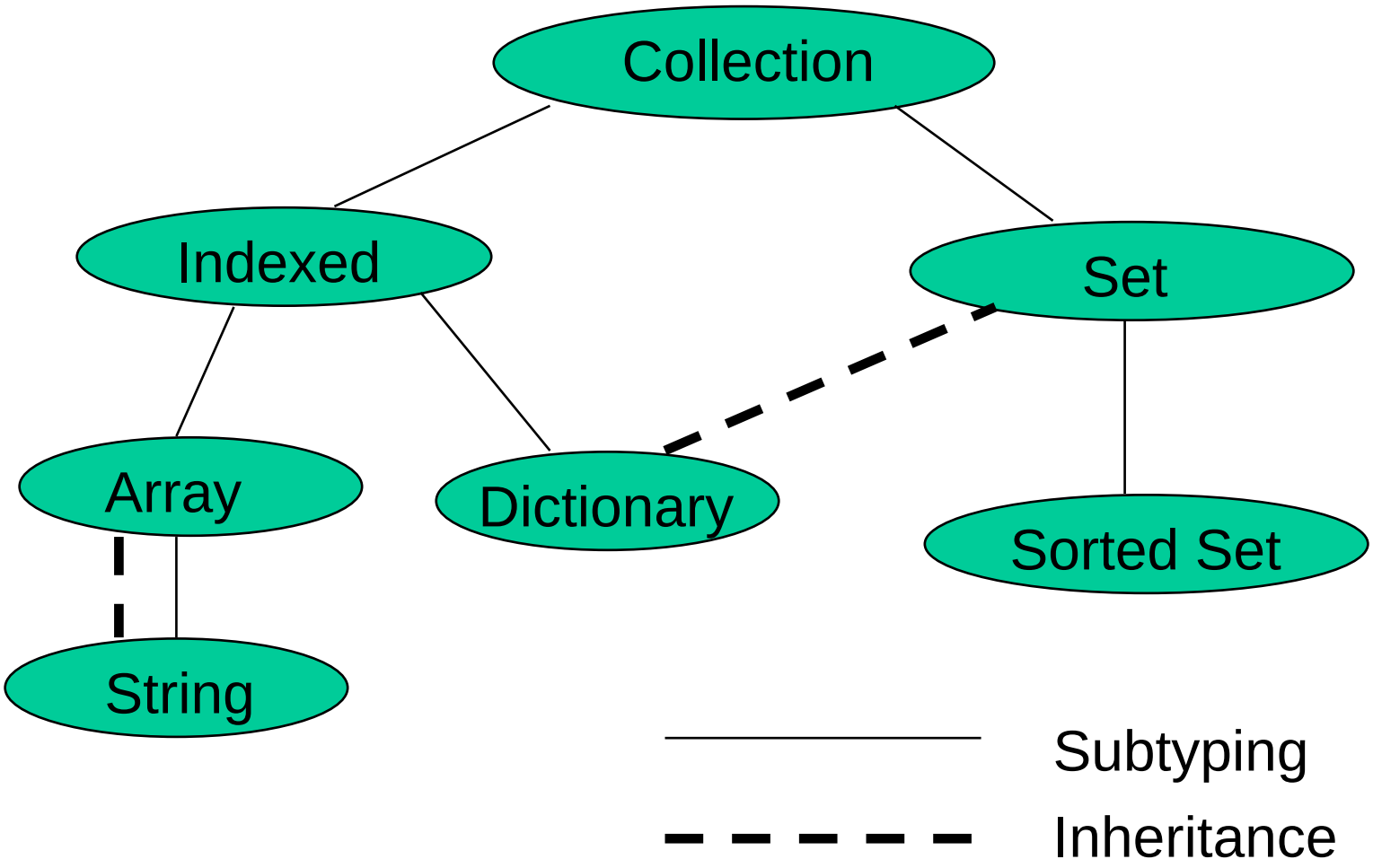
- Implementation mechanism
- New objects may be defined by reusing implementations of other objects

Example

```
class Point
    private
        float x, y
    public
        point move (float dx, float dy);
class Colored_point
    private
        float x, y; color c
    public
        point move(float dx, float dy);
       point change_color(color newc);
```

- Subtyping
  - Colored points can be used in place of points
  - Property used by client program
- Inheritance
  - Colored points can be implemented by resuing point implementation
  - Propetry used by implementor of classes

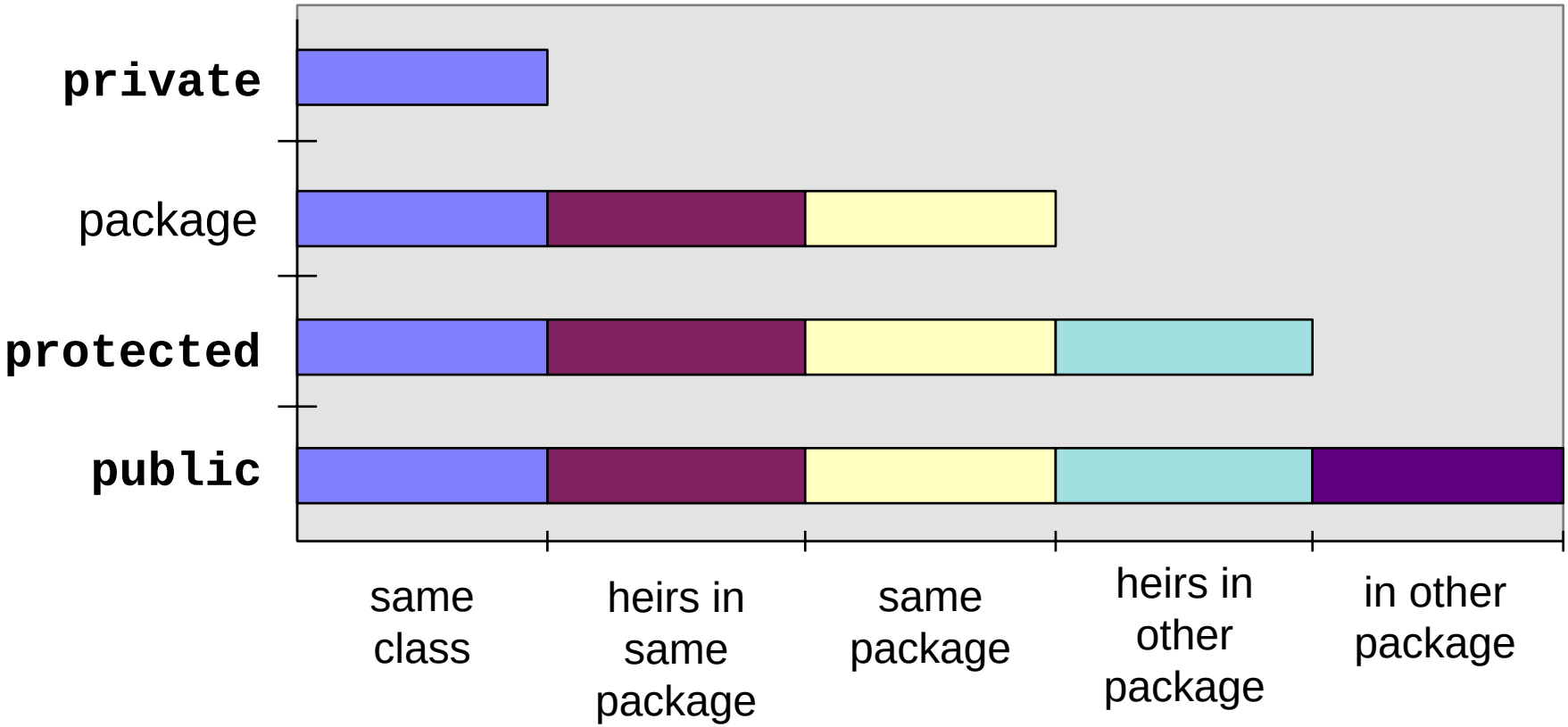
Subtyping differs from inheritance



Access Control

- In many OOPLs it is possible to declare attributes (and methods) **private** or **public** or **protected** etc.
- This has no effect on the running program, but simply means that the compiler will reject programs which violate the access-rules specified
- The control is done as part of static semantic analysis

Access Privileges in Java



Varieties of OO languages

- class-based languages
  - behavior of object determined by its class
- object-based
  - objects defined directly
- multi-methods
  - operation depends on all operands

History

- Simula 1960’s
  - Object concept used in simulation
- Smalltalk 1970’s
  - Object-oriented design, systems
- C++ 1980’s
  - Adapted Simula ideas to C
- Java 1990’s
  - Distributed programming, internet
- C# 2000’s
  - Combine the efficiency of C/C++ with the safety of Java

Runtime Organization for OO Languages

What is this about?

How to represent/implement object oriented constructs such as **object**, **classes, methods**, **instance variables** and **method invocation**

Some definitions for these concepts:

- An **object** is a group of instance variables to which a group of instance methods are attached.
- An **instance variable** is a named component of a particular object.
- An **instance method** is a named operation is attached to a particular object and is able to access that objects instance variables
- An **object class** (or just **class)** is a family of objects with similar instance variables and identical methods.

Runtime Organization for OO Languages

Objects are a lot like records and instance variables are a lot like fields.
=> The representation of objects is similar to that of a record.

Methods are a lot like procedures.
=> Implementation of methods is similar to routines.

But… there are differences:

Objects have methods as well as instance variables, records only have fields.

The methods have to somehow know what object they are associated with (so that methods can access the object's instance variables)

Example: Representation of a simple Java object

Example: a simple Java object (no inheritance)

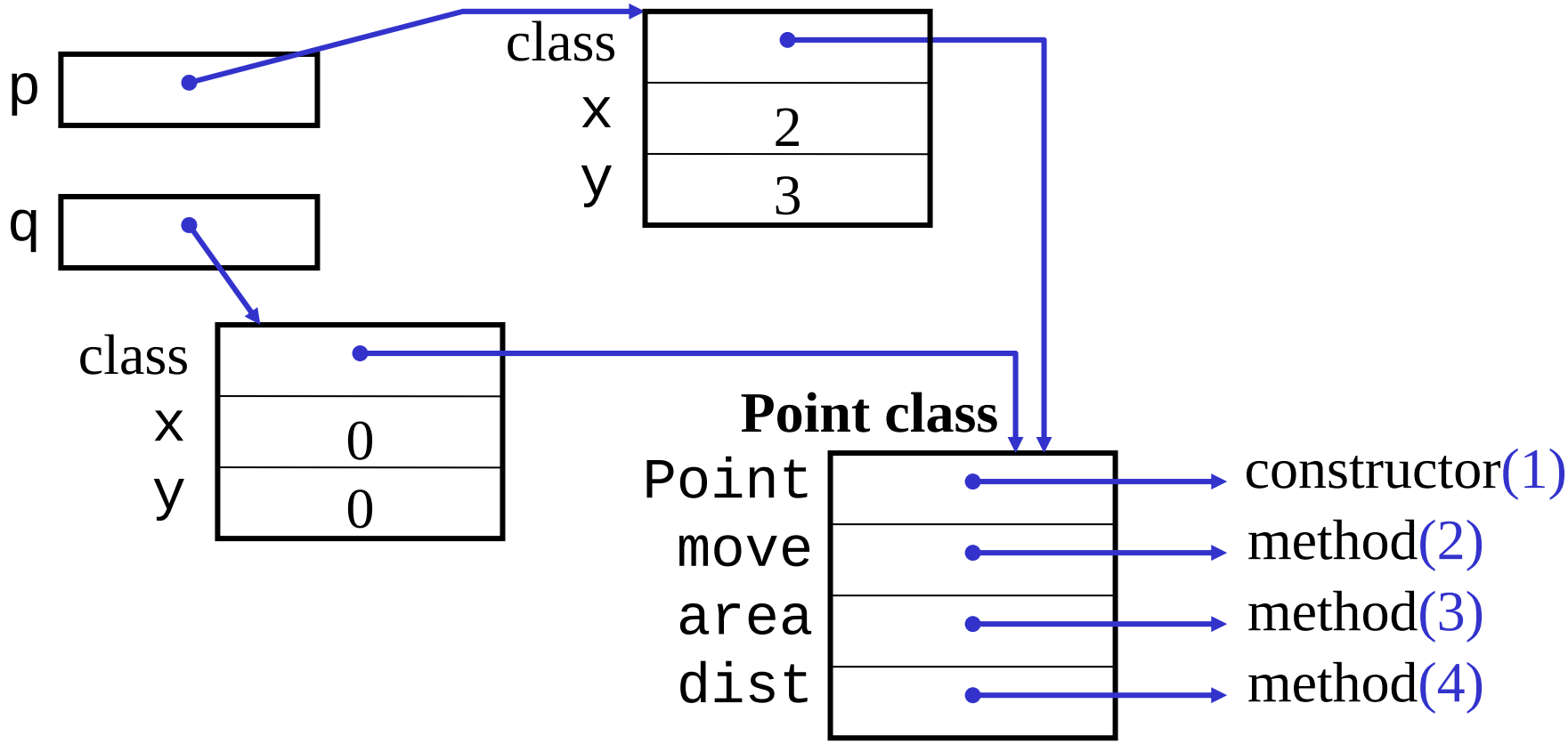
```
class Point {
  int x,y;
(1)public Point(int x, int y) {
     this.x=x; this.y=y;
  }

(2)public void move(int dx, int dy) {
     x=x+dx; y=y+dy;
  }

(3)public float area() { ...}
(4)public float dist(Point other) { ... }
}
```

Example: Representation of a simple Java object

Example: a simple Java object (no inheritance)

```
Point p = new Point(2,3);
Point q = new Point(0,0);
```

new allocates an object in the heap



Inheritance

Example 2: Points and other “shapes”

```
abstract class Shape {
  int x,y; // “origin” of the shape
(S1) public Shape(int x, int y) {
     this.x=x; this.y=y;
  }

(S2) public void move(int dx, int dy) {
     x=x+dx; y=y+dy;
  }

  public abstract float area();
(S3) public float dist(Shape other) { ... }
}
```

Inheritance

Example 2: Points and other “shapes”

```
class Point extends Shape {

(P1) public Point(int x, int y) {
        super(x,y);
     }

(P2) public float area() { return 0.0; }
}
```

Inheritance

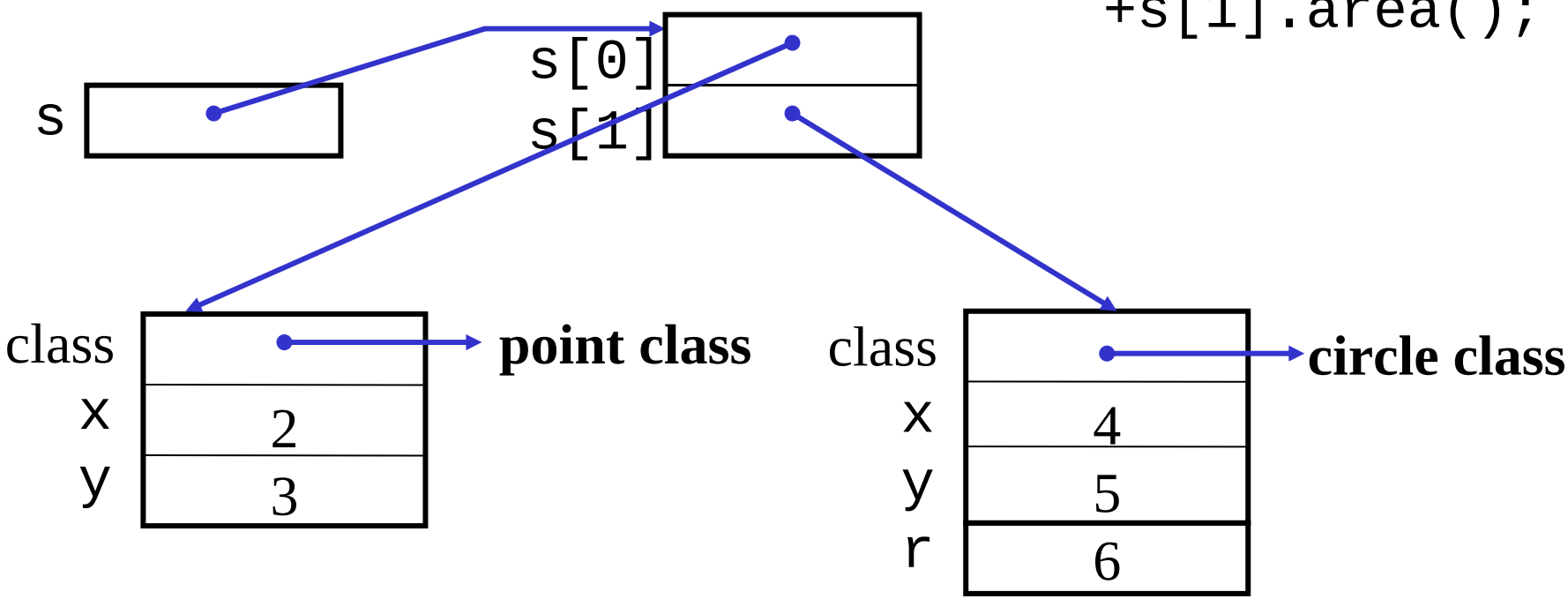
Example 2: Points and other “shapes”

```
class Circle extends Shape {
  int r;
(C1) public Circle(int x,int y,int r) {
       super(x,y); this.r = r;
  }

(C2) public int radius() { return r; }

(C3) public float area() {
       return 3.14 * r * r;
  }
}
```

Inheritance

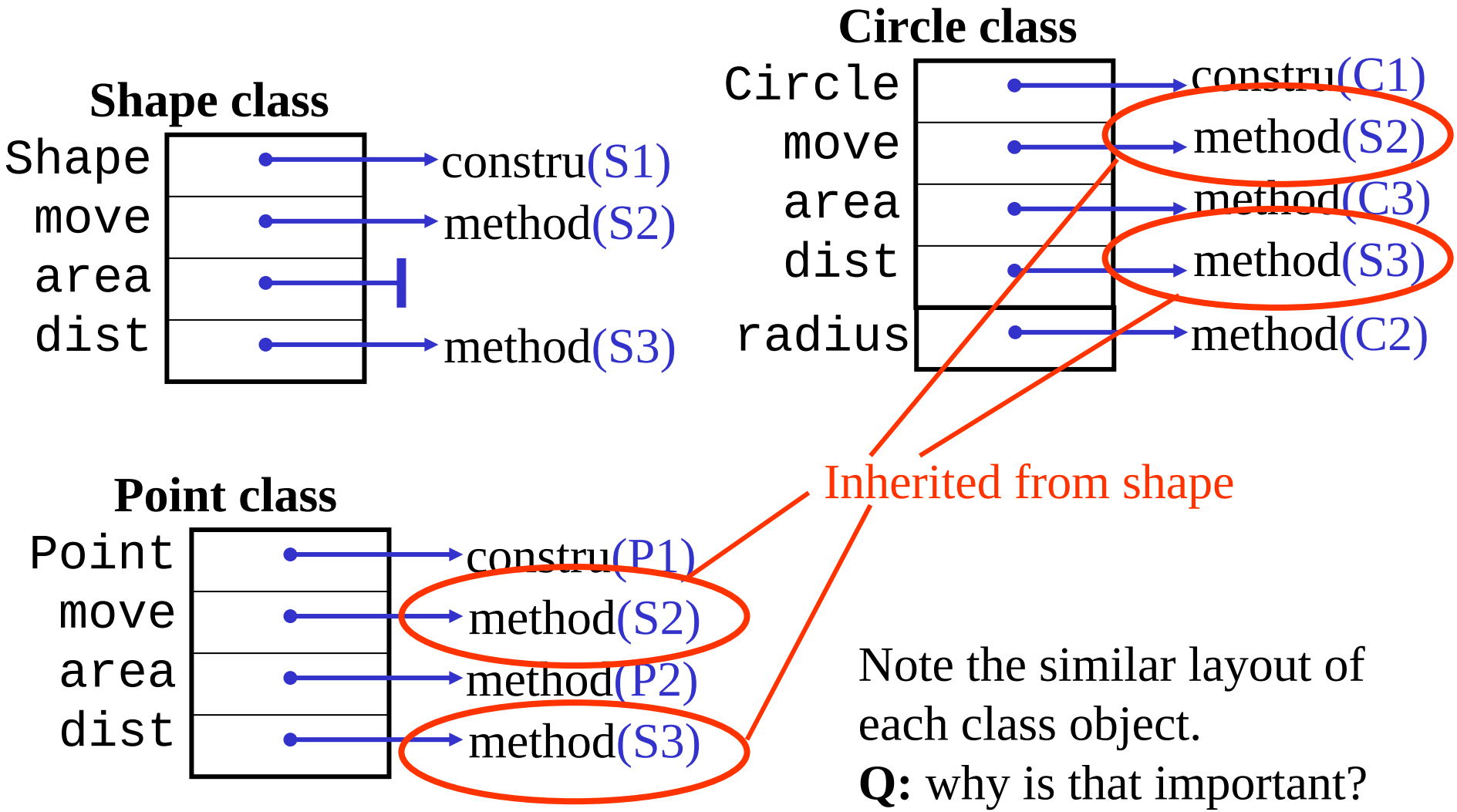
```
Shape[] s = new Shape[2];
s[0] = new Point(2,3);
s[1] = new Circle(4,5,6);
```

```
s[0].x = ...;
s[1].y = ...;
float areas =
    s[0].area()
   +s[1].area();
```



Note the similar layout between point and circle objects!

Inheritance

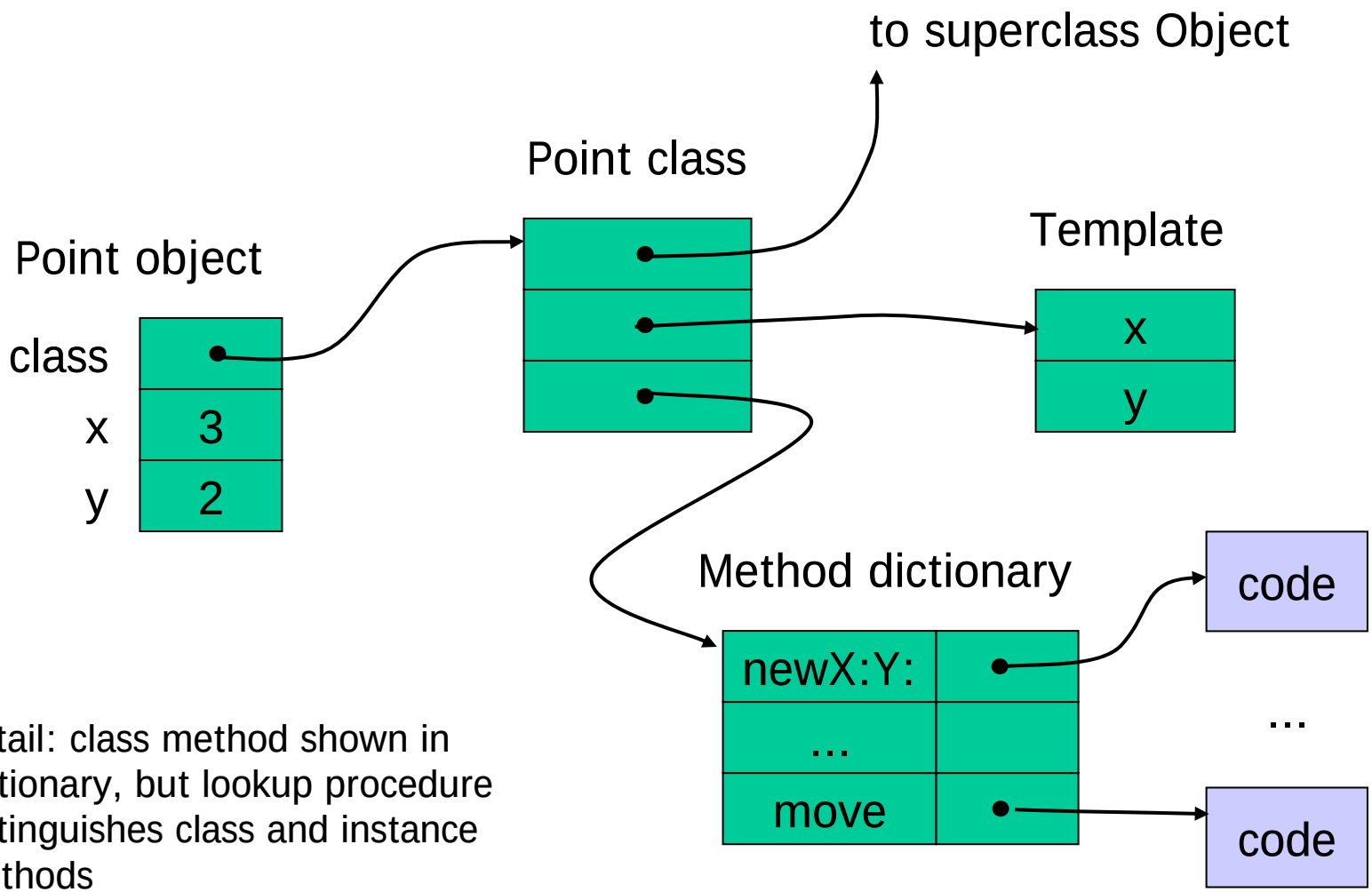


Note the similar layout of each class object.

Q: why is that important?

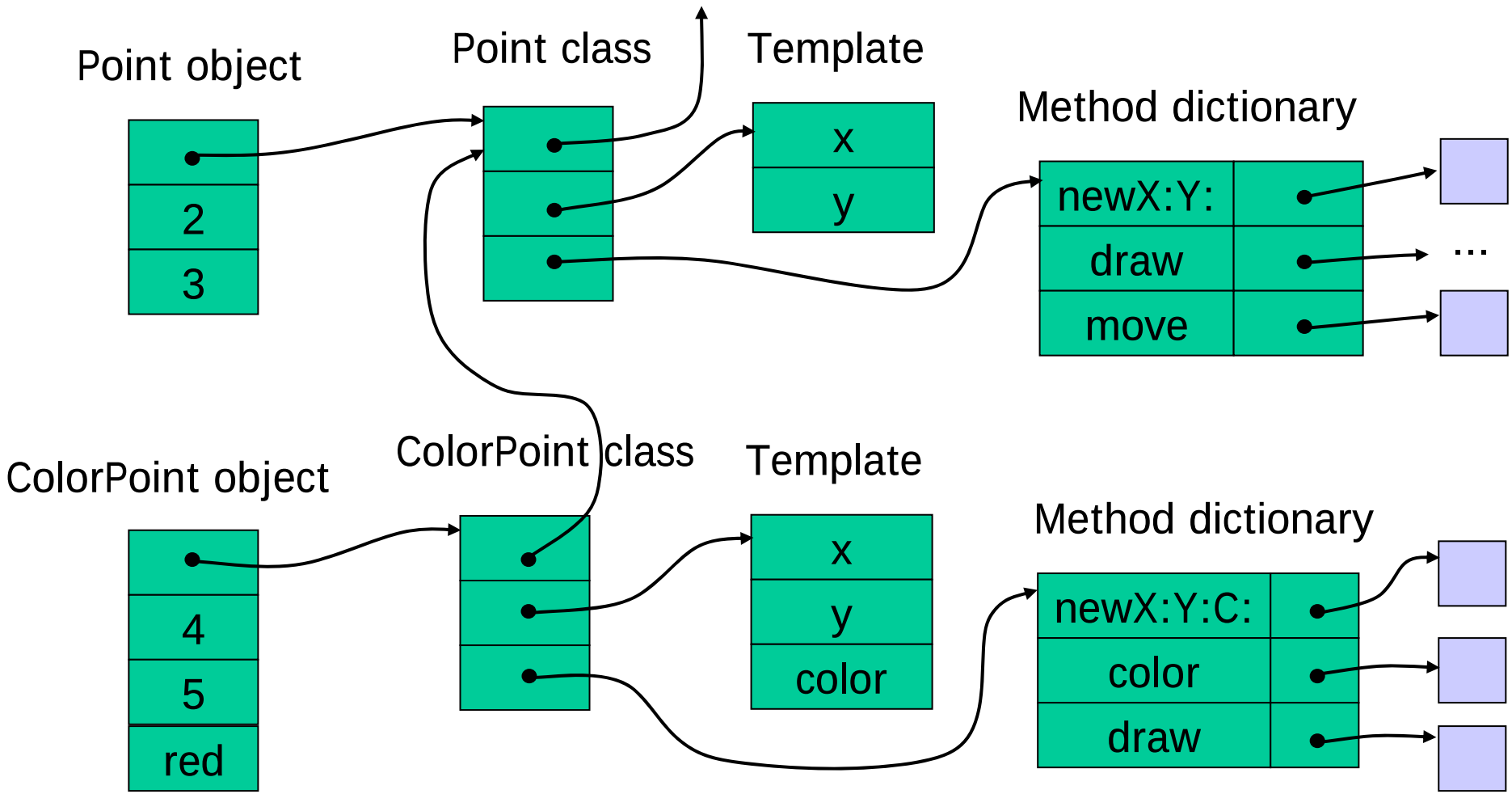
Q: why don't we need a pointer to the super class in a class object?

Alternative Run-time representation of point



Detail: class method shown in dictionary, but lookup procedure distinguishes class and instance methods

Alternative Run-time representation



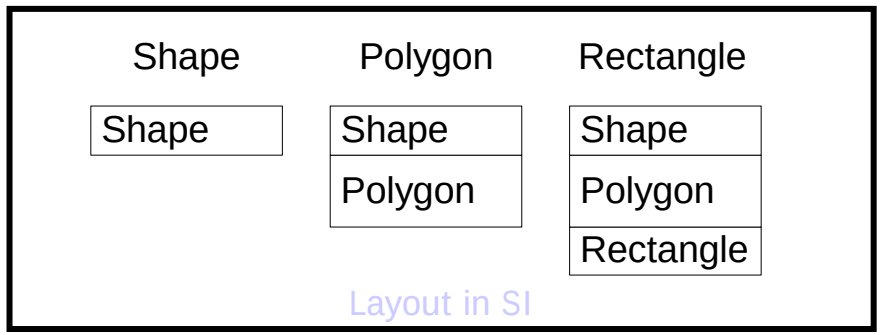
This is a schematic diagram meant to illustrate the main idea. Actual implementations may differ

Multiple Inheritance

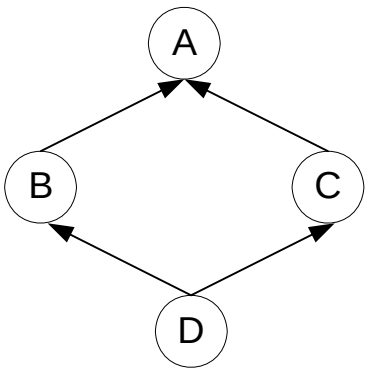
- In the case of simple inheritance, each class may have one direct predecessor; multiple inheritance allows a class to have several direct predecessors.
- In this case the simple ways of accessing attributes and binding method-calls (shown previously) don’t work.
- The problem: if class C inherits class A and class B the objects of class C cannot begin with attributes inherited from A and at the same time begin with attributes inherited from B.
- In addition to these implementation problems multiple inheritance also introduces problems at the language (conceptual) level.

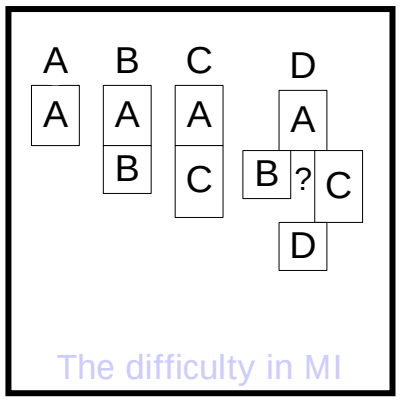
Object Layout

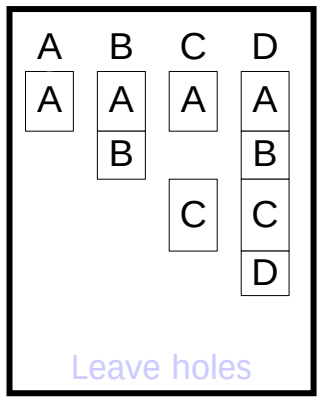
- The memory layout of the **object's fields**
- How to access a field if the dynamic type is unknown?
  - Layout of a type must be "compatible" with that of its supertypes
  - Easy for Single Inheritance hierarchies
    - The new fields are added at the end of the layout

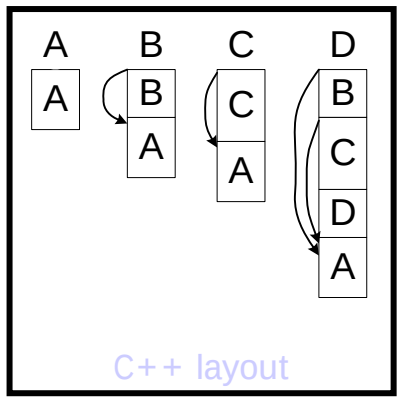


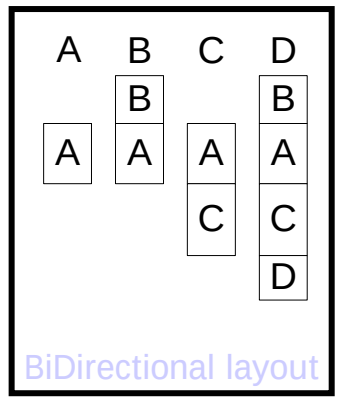
- Hard for MI hierarchies











Dynamic (late) Binding

- Consider the method call:
  - x.f(a,b) where is f defined? in the class (type)of x? Or in a predecessor?
- In single inheritance languages
  1. Determine the target object from x.
  2. Follow the pointer from the target object's tag field to the corresponding class object.
  3. Select the method named f in the class object.
  4. Call that method, passing the target object's address along with the ordinary arguments.
- If multiple inheritance is supported then the entire predecessor graph must be searched:
  - This costs a large overhead in dynamic typed languages like Smalltalk (normally these languages don't support multiple inheritance)
  - In static typed languages like Java, Eiffel, C++ the compiler is able to analyse the class-hierarchy (or more precise: the graph) for x and create a display-array containing addresses for all methods of an object (including inherited methods)
  - According to Meyer the overhead of this compared to static binding is at most 30%, and overhead decreases with complexity of the method
- If multi-methods are supported a forest like data structure has to be searched

Implementation of Object Oriented Languages

- Implementation of Object Oriented Languages differs only slightly from implementations of block structured imperative languages
- Some additional work to do for the contextual analysis
  - Access control, e.g. private, public, procted directives
  - Subtyping can be tricky to implement correctly
- The main difference is that methods usually have to be looked up dynamically, thus adding a bit of run-time overhead
  - For efficiency reasons some language introduce modifiers like:
    - **final** (Java) or **virtual/override** (C#)
  - multiple inheritance poses a bigger problem
  - Multi methods poses an even bigger problem

Encapsulation Constructs

- Original motivation:
  - Large programs have two special needs:
  1. Some means of organization, other than simply division into subprograms
  2. Some means of partial compilation (compilation units that are smaller than the whole program)
- Obvious solution: a grouping of subprograms that are logically related into a unit that can be separately compiled (compilation units)
  - These are called encapsulations

Modules

- Language construct for grouping related types, data structures, and operations
- Typically allows at least some encapsulation
  - Can be used to provide abstract types
- Provides scope for variable and subprogram names
- Typically includes interface stating which modules it depends upon and what types and operations it exports
- Compilation unit for separate compilation

Encapsulation Constructs

- Nested subprograms in Ada and Fortran 95
- Encapsulation in C
  - Files containing one or more subprograms can be independently compiled
  - The interface is placed in a header file
  - Problem: the linker does not check types between a header and associated implementation
- Encapsulation in C++
  - Similar to C
  - Addition of friend functions that have access to private members of the friend class

Encapsulation Constructs

- Ada Package
  - Can include any number of data and subprogram delcarations
  - Two parts: specification and body
  - Can be compiled separately
- C# Assembly
  - Collection of files that appears to be a single dynamic link library or executable
  - Larger construct than class; used by all .NET programming languages

Naming Encapsulations

- Large programs define many global names; need a way to divide into logical groupings
- A naming encapsulation is used to create a new scope for names
- C++ Namespaces
  - Can place each library in its own namespace and qualify names used outside with the namespace
  - C# also includes namespaces

Naming Encapsulations

- Java Packages
  - Packages can contain more than one class definition; classes in a package are partial friends
  - Clients of a package can use fully qualified name or use the `import` declaration
- Ada Packages
  - Packages are defined in hierarchies which correspond to file hierarchies
  - Visibility from a program unit is gained with the `with` clause
- SML Modules
  - called **structure**; interface called **signature**
  - Interface specifies what is exported
  - Interface and structure may have different names
  - If structure has no signature, everything exported
  - Modules may be parameterized (**functors)**
  - Module system quite expressive

Issues

- The target language usually has one spaces
  - Generate unique names for modules
  - Some assemblers support local names per file
  - Use special characters which are invalid in the programming language to guarantee uniqueness

- Generate code for initialization
  - Modules may use items from other modules
  - Init before used
  - Init only once
  - Circular dependencies

Avoiding Multiple Initializations

- If module A uses module B and C and B uses C
  - How to initialize C once
- Similar problem occurs when using C include files
- Two solutions
  - Compute a total order and init before use
  - Use special compile-time flag

Detecting Circular Dependencies

- Check the graph of used specifications is acyclic
- But what about implementation
- A's specification can use B's implementation
- B's specification can use A's implementation
- Detect at runtime (link time)

Summary

- Abstract Data Types
  - Encapsulation
  - Invariants may be preserved
- Objects
  - Reuse
  - Subtyping
  - Inheritance
  - Dynamic dispatch
- Modules
  - Grouping (related) entities
  - Namespace management
  - Separate compilation

“I invented the term *Object-Oriented* and I can tell you I did not have C++ in mind.”

Alan Kay