# CSc 520

# Principles of Programming Languages

## *45: OO Languages — Introduction*

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# Object-Oriented Languages

- Object-oriented languages extend imperative languages with:
  1. A classification scheme that allows us to specify is-a as well as has-a relationships. Has-a is supported by Pascal, where we can declare that one data item **has** another item (a record variable *has-a* record field). Object-Pascal, Oberon, etc, extends this capability with **inheritance** which allows us to state that one data item **is** (an extension of) another item.
  2. Late binding, which allows us to select between different implementations of the same abstract data type at run-time.



# Object-Oriented Languages...

- 3. Polymorphism, which is the ability of a variable to store values of different types. OO languages support a special kind of polymorphism, called inclusion polymorphism, that restricts the values that can be stored in a variable of type $T$ to values of type $T$ or subtypes of $T$.
  4. Data encapsulation. Data (instance variables) and operations (methods) are defined together.
  5. Templates and objects. A template (**class** or **prototype**) describes how to create new objects (instances of abstract data types).



# Compiling OO Languages

- Runtime type checking (a variable of type **ref** $T$ may only reference objects of type $T$ or $T$'s subtypes).
- Because of the polymorphic nature of OO languages, we can't always know (at compile-time) the type of the object that a given variable will refer to at run-time. When we invoke a method we can't actually know which piece of code we should execute. Finding the right piece of code is called **method lookup**. It can be done by name (Objective-C) or number (C++).
- Most OO languages rely on dynamic allocation. Garbage collection is a necessary part of the runtime system of a compiler for an OO language (C++ non-withstanding). This requires **runtime type description**.

# Object-Oriented Example

```
PE Shape = CLASS
     x, y :  REAL;
     METHOD draw(); BEGIN ···; END;
     METHOD move(X,Y:REAL); BEGIN x := x+X; END;
 END;
PE Square = Shape CLASS
     side :  REAL;
     METHOD draw(); BEGIN ···; END;
 END;
PE Circle = Shape CLASS
     radius :  REAL;
     METHOD draw(); BEGIN ···; END;
     METHOD area():REAL; BEGIN ··· END;
 END;
```



# Example in Java

```
// Example in Java

class Shape {
   double x, y;
   void draw(); { ··· }
   void move(double X, double Y); {x = x+X; }}
class Square extends Shape {
   double side;
   void draw(); { ···}}
class Circle extends Shape {
   double radius;
   void draw(); { ··· }
   double area(); { ··· }}
```



# Example in Modula-3 (A)

```
(* Example in Modula-3 *)
TYPE  Shape = OBJECT
         x, y :  REAL
         METHODS
         draw() := DefaultDraw; move(X, Y : REAL) := Move;
      END;
      Square = Shape OBJECT
         side :  REAL
         METHODS
         draw() := SquareDraw
      END;
      Circle = Shape OBJECT
         radius :  REAL
         METHODS
         draw() := CirlceDraw; area() := ComputeArea
      END;
```



# Example in Modula-3 (B)

```
(* Example in Modula-3 (continued) *)
PROCEDURE Move (Self :  Shape; X, Y : REAL) =
BEGIN ··· END Move;
PROCEDURE DefaultDraw (Self :  Shape) =
BEGIN ··· END DefaultDraw;
PROCEDURE SquareDraw (Self :  Square) =
BEGIN ··· END SquareDraw;
PROCEDURE CircleDraw (Self :  Circle) =
BEGIN ··· END CircleDraw;
PROCEDURE ComputeArea (Self :  Circle) :  REAL =
BEGIN ··· END ComputeArea;
```

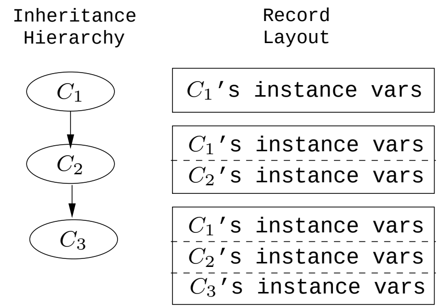
# Example in Oberon-2

```
      Shape = RECORD x, y :  REAL END;
      Square = RECORD (Shape) side :  REAL END;
      Circle = RECORD (Shape) radius :  REAL END
CEDURE (Self :  Shape) Move (X, Y : REAL) =
N ··· END Move;
CEDURE (Self :  Shape) DefaultDraw () =
N ··· END DefaultDraw;
CEDURE (Self :  Square) SquareDraw () =
N ··· END SquareDraw;
CEDURE (Self :  Circle) CircleDraw () =
N ··· END CircleDraw;
CEDURE (Self :  Circle) ComputeArea () :  REAL =
N ··· END ComputeArea;
```



# Record Layout

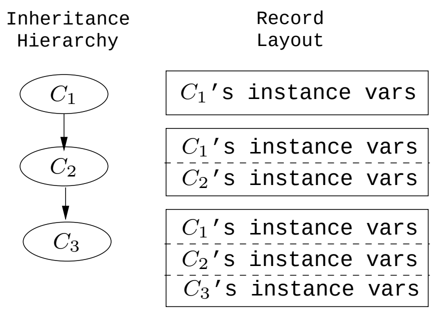
- Single inheritance is implemented by *concatenation*, i.e. the instance variables of class $C$ are
  1. the variables of $C$'s supertype, *followed by*
  2. the variables that $C$ declares itself.






# Record Layout

- The offsets of the variables that $C$ inherits from its supertype will be the same as in the supertype itself.
- In this example, $C_3$ inherits from $C_2$ which inherits from $C_1$.
- $C_3$ will have the fields from $C_1$ followed by the fields from $C_2$ followed by $C_3$'s own fields. The order is significant.





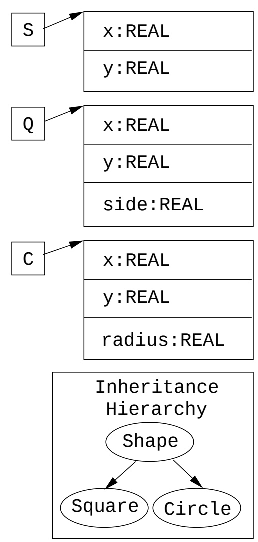

# Record Layout. . .

```
TYPE Shape =
  CLASS x,y:  REAL; END;

TYPE Square = Shape
  CLASS side:REAL; END;

TYPE Circle = Shape
  CLASS radius:REAL; END;

VAR S:Shape;
VAR Q:Square;
VAR C:Circle;
```



# Record Layout…

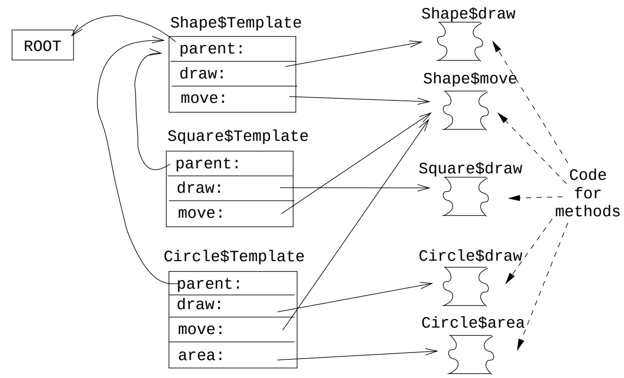
- An OO language compiler would translate the declarations in the previous slide into something similar to this:

```
TYPE Shape=POINTER TO RECORD
   x, y:  REAL;
END;
TYPE Square=POINTER TO RECORD
   x, y:  REAL;
   side:REAL;
END;
TYPE Circle=POINTER TO RECORD
   x, y:  REAL;
   radius:REAL;
END;
VAR S:Shape; Q:Square; C:Circle;
```



# Class Templates

To support late binding, runtime typechecking, etc, each class is represented by a *template* at runtime. Each template has pointers to the class's methods and supertype.






# Class Templates…

- Square's x,y fields are inherited from Shape. Their offsets are the same as in Shape.

```
TYPE $TemplateT=POINTER TO RECORD
       parent : $TemplateT;
       move : ADDRESS;
       draw : ADDRESS;
    END;
TYPE Square=POINTER TO RECORD
       $template : $TemplateT;
       x, y : REAL;
       side : REAL;
    END;
CONST Square$Template:$TemplateT =
  [ parent= ADDR(Shape$Template);
    move  = ADDR(Shape$move);
    draw  = ADDR(Square$draw); ];
```



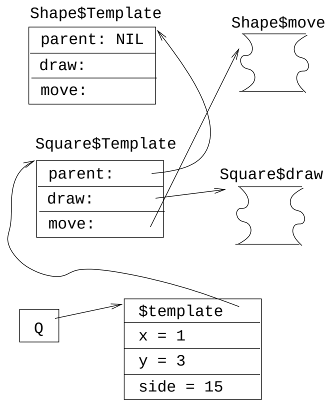
# Class Templates…

Each method is a procedures with an extra argument (**SELF**), a pointer to the object through which the method was invoked.

```
TYPE     Shape = CLASS
         x, y :  REAL;
         METHOD draw (); BEGIN ···;
         METHOD move (X, Y : REAL);
         BEGIN x := x+X; ··· END;
      END;
                ⇓
PROCEDURE Shape$move (SELF : Shape; X,Y:REAL);
BEGIN
   SELF^.x := SELF^.x + X;
   SELF^.y := SELF^.y + X;
END;
```

# Method Invocation

- Sending the message `draw` to `Q`:
  1. Get `Q`'s template, $T$.
  2. Get `draw`'s address at offset 4 in $T$.
  3. Jump to `draw`'s address, with `Q` as the first argument.






# Method Invocation. . .

```
VAR Q : Square;
BEGIN
    Q := NEW (Square);
    Q.x := 1; Q.y := 3; Q.side := 15;
    Q.draw(); Q.move(20, 30);
END;
```

⇓

```
BEGIN
    Q := malloc(SIZE(Square));
    Q^.$template := Square$Template;
    Q^.x := 1; Q^.y := 3; Q^.side := 15;
    Q^.$template^.draw(Q);
    Q^.$template^.move(Q, 20, 30);
END;
```



# Exam Problem

- In the following object-oriented program
  - "`TYPE U = T CLASS`" means that `U` inherits from `T`.
  - `NEW T` means that a new object of type `T` is created.
  - All methods are *virtual*, i.e. a method in a subclass overrides a method with the same name in a superclass.

```
PROGRAM X;
  TYPE T = CLASS [
          v : INTEGER;c : CHAR;
          METHOD P (x:INTEGER); BEGIN ··· END P;
          METHOD Q (x:CHAR); BEGIN ··· END Q;
  ];
```



# Exam Problem I. . .

```
  TYPE U = T CLASS [
          x : REAL; k : INTEGER;
          METHOD R(x:INTEGER); BEGIN ··· END R;
          METHOD Q(r:REAL); BEGIN ··· END Q;
  ];
VAR t : T; u : U;
BEGIN
  t := NEW T; u := NEW U; ◇
END
```

1. Draw a figure that describes the state of the program at point ◇. It should have one element for each item stored in memory (i.e. global/heap variables, templates, method object code, etc.) and should explicitly describe what each pointer points to.

# Readings and References

- Read Scott: 529–551,554–561,564–573
- Appel's Tiger book: 283–298.
- For information on constructing layouts for multiple inheritance, see
  - William Pugh and Grant Weddell: "Two-directional record layout for multiple inheritance."
- The time for a type test is proportional to the depth of the inheritance hierarchy. Many algorithms do type tests in constant time:
  1. Norman Cohen, "Type-Extension Type Tests can be Performed in Constant Time."
  2. Paul F.Dietz, "Maintaining Order in a Linked List".



# Summary

- For single inheritance languages, an instance of a class $C$ consists of (in order):
  1. A pointer to $C$'s template.
  2. The instance variables of $C$'s ancestors.
  3. $C$'s instance variables.
- For single inheritance languages, subtype checks can be done in $\mathcal{O}(1)$ time.
- Method invocation is transformed to an indirect call through the template.
- If we can determine the exact type of an object variable at compile time, then method invocations through that variable can be turned into "normal" procedure calls.



# Summary. . .

- A template for class $C$ consists of (in order):
  1. A pointer to the template of $C$'s parent.
  2. The method addresses of $C$'s ancestors.
  3. Addresses of $C$'s methods.
  4. Other information needed by the runtime system, such as
     - The size of a $C$ instance.
     - $C$'s pre- and postorder numbers, if the $\mathcal{O}(1)$ subtype test algorithm is used.
     - $C$'s type code.
     - A type description of $C$'s instance variables. Needed by the garbage collector.



# Confused Student Email

*What happens when both a class and its subclass have an instance variable with the same name?*

- The subclass gets both variables. You can get at both of them, directly or by casting. Here's an example in Java:

```
class C1 {int a;}
class C2 extends C1 {double a;}
class C {
  static public void main(String[] arg) {
   C1 x = new C1(); C2 y = new C2();
   x.a = 5; y.a = 5.5;
   ((C1)y).a = 5;
  }
}
```