CSc 553

Principles of Compilation

15 : 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**.

Example

Object-Oriented Example

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

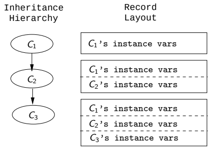
Example in Oberon-2

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

Record Layout

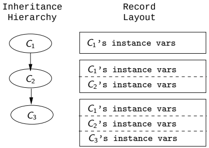
Record Layout

- 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.



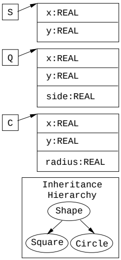
Record Layout...

```
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...

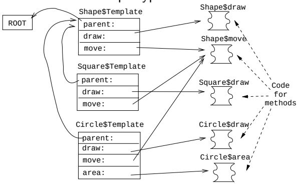
- An OO language compiler would translate the declarations in the previous slide into something similar to this:

```
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;
```

Templates

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' 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...

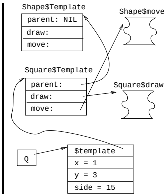
Each method is a procedure with an extra argument (**SELF**), a pointer to the object through which the method was invoked.

```
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 Lookup

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;
```

$\Downarrow$

```
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.

Summary

Readings and References

- Read Scott: 467–489, 497–504

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;
  }
}
```