CSc 453

Compilers and Systems Software

23 : OO Languages

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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

```
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

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 *)
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 (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;
```

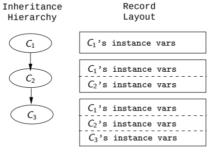
Example in Oberon-2

```
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;
```

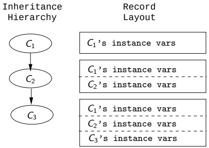
Record Layout

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.



- 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.

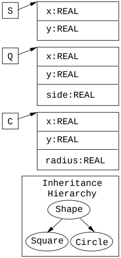



```
TYPE Shape =
  CLASS x,y:  REAL; END;

TYPE Square = Shape
  CLASS side:REAL; END;

TYPE Circle = Shape
  CLASS radius:REAL; END;

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



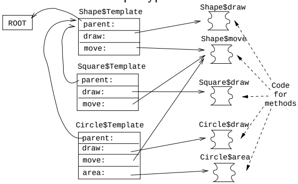
- An OO language compiler would translate the declarations in the previous slide into something similar to this:

```
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's methods and supertype.



- 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); ];
```

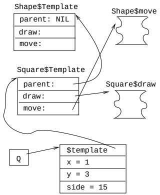
Each method is a procedures with an extra argument (**SELF**), a pointer to the object through which the method was invoked.

```
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 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.




```
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;
```

Runtime Type Checking

Inclusion Polymorphism

Consider the last two lines of the example in the following slide:

- In L_1, `S` points to a `Shape` object, but it could just as well have pointed to an object of any one of `Shape`'s subtypes, `Square` and `Circle`.
- If, for example, `S` had been a `Circle`, the assignment `C := S` would have been perfectly OK. In L_2, however, `S` is a `Shape` and the assignment `C := S` is illegal (a `Shape` **isn't** a `Circle`).

```
VAR S : Shape; Q : Square; C : Circle;
BEGIN
   Q := NEW (Square);
   C := NEW (Circle);

   S := Q; (* OK *)
   S := C; (* OK *)

   Q := C; (* Compile-time Error *)

   L1:  S := NEW (Shape);
   L2:  C := S; (* Run-time Error *)
END;
```

Typechecking Rules

```
TYPE   T =   CLASS ··· END;
       U = T CLASS ··· END;
       S = T CLASS ··· END;
VAR    t,r :  T; u :  U; s :  S;
```

- A variable of type T may refer to an object of T or one of T's subtypes.

Assignment	Compile-time	Run-Time
t := r;	Legal	Legal
t := u;	Legal	Legal
u := t;	Legal	Check
s := u;	Illegal	

Run-time Type Checking

Modula-3 Type-test Primitives:

`ISTYPE(object, T)` Is object's type a subtype of `T`?

`NARROW(object, T)` If object's type is *not* a subtype of `T`, then issue a run-time type error. Otherwise return object, typecast to `T`.

`TYPECASE Expr OF` Perform different actions depending on the runtime type of `Expr`.

- The assignment `s := t` is compiled into `s := NARROW(t, TYPE(s))`.

Run-time Type Checking...

- The Modula-3 runtime-system has three functions that are used to implement typetests, casts, and the `TYPECASE` statement
- **NARROW** takes a template and an object as parameter. It checks that the type of the object is a subtype of the type of the template. If it is not, a run-time error message is generated. Otherwise, **NARROW** returns the object itself.

1. `ISTYPE(S,T : Template) : BOOLEAN;`
2. `NARROW(Object, Template) : Object;`
3. `TYPECODE(Object) : CARDINAL;`

Algorithm

Run-time Checks

- Casts are turned into calls to **NARROW**, when necessary:

```
VAR S : Shape; VAR C : Circle;
BEGIN
   S := NEW (Shape); C := S;
END;
          ⇓
VAR S : Shape; VAR C : Circle;
BEGIN
   S := malloc (SIZE(Shape));
   C := NARROW(S, Circle$Template);
END;
```

Imlementing **ISTYPE**

- We follow the object's template pointer, and immediately (through the templates' parent pointers) gain access to it's place in the inheritance hierarchy.

```
PROCEDURE ISTYPE (S, T : TemplatePtr) :  BOOLEAN;
BEGIN
   LOOP
      IF S = T THEN RETURN TRUE; ENDIF;
      S := S^.parent;
      IF S = ROOT THEN RETURN FALSE; ENDIF;
   ENDLOOP
END ISTYPE;
```

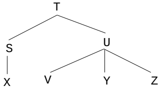
Implementing **NARROW**

- **NARROW** uses **ISTYPE** to check if S is a subtype of T. Of so, S is returned. If not, an exception is thrown.

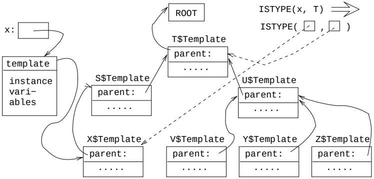
```
PROCEDURE NARROW(T:TemplatePtr; S:Object):Object;
BEGIN
   IF ISTYPE(S^.$template, T) THEN
      RETURN S (* OK *)
   ELSE WRITE "Type error"; HALT;
   ENDIF;
END NARROW;
```

Run-time Checks — Example

```
TYPE T =   CLASS [···];
     S = T CLASS [···];
     U = T CLASS [···];
     V = U CLASS [···];
     X = S CLASS [···];
     Y = U CLASS [···];
     Z = U CLASS [···];
VAR x :  X;
```



Run-time Checks — Example...



Compile-Time Organization

Organizing the Symbol Table

- In $C.M$'s method body we can refer to
  1. M's locals and formals, and M's **SELF**.
  2. C's methods and instance variables.
  3. Methods and instance variables of C's superclasses.

```
TYPE T = CLASS [
   v :  INTEGER; c :  CHAR;
   METHOD P(x:INTEGER); BEGIN ···v···c··· END;
   METHOD Q(x:CHAR); BEGIN ···v···c··· END;
];
TYPE U = T CLASS [
   c :  REAL; k :  INTEGER;
   METHOD P(x:INTEGER); BEGIN ···v···c···k··· END;
   METHOD Q(r:REAL); BEGIN ···v···c···k··· END;
];
```

Homework

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;
   ];
```

```
   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 the Tiger book:
  Object-oriented Languages pp. 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;
  }
}
```