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`).

Typechecking Rules

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

<table>
<thead>
<tr>
<th>Assignment</th>
<th>Compile-time</th>
<th>Run-Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t := r$;</td>
<td>Legal</td>
<td>Legal</td>
</tr>
<tr>
<td>$t := u$;</td>
<td>Legal</td>
<td>Legal</td>
</tr>
<tr>
<td>$u := t$;</td>
<td>Legal</td>
<td>Check</td>
</tr>
<tr>
<td>$s := u$;</td>
<td>Illegal</td>
<td></td>
</tr>
</tbody>
</table>

VAR $S : Shape$; $Q : Square$; $C : Circle$;
BEGIN
  $Q := \text{NEW} (\text{Square})$;
  $C := \text{NEW} (\text{Circle})$;

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

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

$L_1$: $S := \text{NEW} (\text{Shape})$;
$L_2$: $C := S$; (* Run-time Error *)
END;
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 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;
```

Implementing 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;
END;
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 — An $O(1)$ Algorithm

The time for a type test is proportional to the depth of the inheritance hierarchy. Two 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”.

The second is more efficient, but requires the entire type hierarchy to be known. This is a problem in separately compiled languages.

SRC Modula-3 uses Dietz’ method and builds type hierarchies of separately compiled modules at link-time.

These algorithms only work for single inheritance.
Run-time Checks – Alg. II (b)

In the Compiler (or Linker):
1. Build the inheritance tree.
2. Perform a preorder traversal and assign preorder numbers to each node.
3. Similarly, assign postorder numbers to each node.
4. Store T's pre- and postorder numbers in T's template.

In the Runtime System:

PROCEDURE ISTYPE (S, T : TemplatePtr) : BOOLEAN;
BEGIN
RETURN (T.pre ≤ S.pre) AND (T.post ≥ S.post);
END ISTYPE;

Run-time Checks – Alg. II (c)

TYPE
T = CLASS [⋯];
S = T CLASS [⋯];
U = T CLASS [⋯];
V = U CLASS [⋯];
X = S CLASS [⋯];
Y = U CLASS [⋯];
Z = U CLASS [⋯];

\[ \sqrt{\text{ISTYPE}(Y,U)} \quad U.pre \leq Y.pre \quad U.post \geq Y.post \]
\[ \text{ISTYPE}(Z,S) \quad S.pre \leq Z.pre \quad S.post \nless Z.post \]
\[ \sqrt{\text{ISTYPE}(Z,T)} \quad T.pre \leq Z.pre \quad T.post \geq Z.post \]

Run-time Checks – Alg. II (d)

Consider U:
1. U’s pre-number is ≤ all it’s children’s pre numbers.
2. U’s post-number is ≥ all it’s children’s post numbers.


Inlining Methods
**Inlining Methods**

Consider a method invocation \( m.P() \). The actual procedure called will depend on the run-time type of \( m \).

If more than one method can be invoked at a particular call site, we have to inline all possible methods. The appropriate code is selected code by branching on the type of \( m \).

To improve on method inlining we would like to find out when a call \( m.P() \) can call exactly one method.

---

**Inlining Methods — Example**

```plaintext
TYPE T = CLASS [f : T][
  METHOD M (); BEGIN END M;
];
TYPE S = CLASS EXTENDS T [
  METHOD N (); BEGIN END N;
  METHOD M (); BEGIN END M;
];
VAR x : T; y : S;
BEGIN
  x.M();
  y.M();
END;
```

---

**Type Hierarchy Analysis**

- For each type \( T \) and method \( M \) in \( T \), find the set \( S_{T,M} \) of method overrides of \( M \) in the inheritance hierarchy tree rooted in \( T \).
- If \( x \) is of type \( T \), \( S_{T,M} \) contains the methods that can be called by \( x.M() \).
- We can improve on type hierarchy analysis by using a variant of the Reaching Definitions data flow analysis.
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;
    }
}