CSc 453 — Compilers and Systems Software

11 : Semantic Analysis III

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Basic and Structured Types

2 Basic Types

- Which basic types does the language have? In Pascal `boolean`, `real`, `integer`, `char` are basic types.
- Integers: may come in different sizes and signed/unsigned.
- Reals: may come in different sizes. Some languages allow programmer control over precision.
- Some languages have fix-point numbers, complex numbers, rational numbers,. . . .
- Does the language automatically convert from one type to another? Can I add a complex number and an integer?

3 Basic Types. . .

Enumeration types

```
TYPE E1 = (white,blue,yellow,green,red);
TYPE E2 = (apple=4,pear=9,kumquat=99);
```

- Pascal, Ada, Modula-2, C have some variant of enumeration types.

Subrange types

```
TYPE S1 = [0..10];
TYPE S2 = ['a'..'z'];
TYPE S3 = [blue..green];
```

- Subranges can be used to force additional runtime checks. Some languages use them as array index types.

4 Structured Types: Arrays

- Are they static or dynamic? I.e. do I create them at compile-time (C) or run-time (Java)?
- Do I check for out-of-bounds errors (Java) or not (C)?
- Are they 0-based (C) or 1-based (Icon)?
- Can the user define both the lower and upper bounds (Pascal)?
- Must the index type be integer (C,Java) or any enumerable type (Pascal)?

5 Structured Types: Arrays...

```
TYPE A1 = ARRAY 100 OF CHAR;
TYPE A2 = ARRAY [5..99] OF INTEGER;
TYPE A3 = ARRAY CHAR OF INTEGER;
TYPE A4 = ARRAY OF INTEGER;
VAR a3 :  A3;
VAR a4 :  A4;
BEGIN
   a3['X'] := 55;
   a4 := NEW ARRAY 99 OF INTEGER;
END
```

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- Most languages lay out arrays in row-major order. FORTRAN uses column-major.

A[1,1]	A[1,2]
A[2,1]	A[2,2]
A[3,1]	A[3,2]
A[4,1]	A[4,2]

Matrix

0	A[1,1]
1	A[1,2]
2	A[2,1]
3	A[2,2]
4	A[3,1]
5	A[3,2]
6	A[4,1]
7	A[4,2]

Row Major

0	A[1,1]
1	A[2,1]
2	A[3,1]
3	A[4,1]
4	A[1,2]
5	A[2,2]
6	A[3,2]
7	A[4,2]

Column Major

7 Array Indexing – 1 Dimensions

- How do we compute the address (L-value) of the n:th element of a 1-dimensional array?
- $\mathtt{A_{elsz}}$ is A's element-size, $\mathtt{A_{addr}}$ is its base address.

VAR `A` **:** **ARRAY** `[l .. h]` **OF** `T;`

$$\begin{aligned}
\mathtt{L\text{-}VAL}(A[i]) &\equiv \mathtt{A_{addr}} + (i - l) * \mathtt{A_{elsz}} \\
&\equiv \mathtt{A_{addr}} + (l * \mathtt{A_{elsz}}) + i * \mathtt{A_{elsz}} \\
C &\equiv \mathtt{A_{addr}} + (l * \mathtt{A_{elsz}}) \\
\mathtt{L\text{-}VAL}(A[i]) &\equiv C + i * \mathtt{A_{elsz}}
\end{aligned}$$

- Note that C can be computed at compile-time.

8 Array Indexing – 2 Dimensions

VAR `A` **:ARRAY** $[l_1 .. h_1][l_2 .. h_2]$ **OF** `T`;

$$
\begin{aligned}
w_1 &\equiv h_1 - l_1 + 1 \\
w_2 &\equiv h_2 - l_2 + 1 \\
\texttt{L-VAL}(A[i_1, i_2]) &\equiv \texttt{A}_{\texttt{addr}} + ((i_1 - l_1) * w_2 + i_2 + l_2) * \texttt{A}_{\texttt{elsz}} \\
&\equiv \texttt{A}_{\texttt{addr}} + (i_1 * w_2 + i_2) * \texttt{A}_{\texttt{elsz}} - \\
&\quad (l_1 * w_2 - l_2) * \texttt{A}_{\texttt{elsz}} \\
C &\equiv \texttt{A}_{\texttt{addr}} - (l_1 * w_2 - l_2) * \texttt{A}_{\texttt{elsz}} \\
\texttt{L-VAL}(A[i_1, i_2]) &\equiv (i_1 * w_2 + i_2) * \texttt{A}_{\texttt{elsz}} + C
\end{aligned}
$$

- C can be computed at compile-time.

9 Array Indexing – n Dimensions

VAR `A` : **ARRAY** $[l_1 .. h_1]$ ... $[l_n .. h_n]$ **OF** `T`;

$$
w_k \equiv h_k - l_k + 1
$$

$$
\begin{aligned}
&C \equiv \\
&\quad \texttt{A}_{\texttt{addr}} - ((\cdots (l_1 * w_2 + l_2) * w_3 + l_3) \cdots) * w_n + l_n) * \texttt{A}_{\texttt{elsz}}
\end{aligned}
$$

$$
\begin{aligned}
&\texttt{L-VAL}(A[i_1, i_2, ..., i_n]) \equiv \\
&\quad ((\cdots (i_1 * w_2 + i_2) * w_3 + i_3) \cdots) * w_n + i_n) * \texttt{A}_{\texttt{elsz}} + C
\end{aligned}
$$

10 Record Types

- Pascal, C, Modula-2, Ada and other languages have variant records (C's union type):

```
TYPE R1 = RECORD tag :  (red,blue,green);
             CASE tag OF
                red :  r :  REAL; |
                blue :  i :  INTEGER; |
                ELSE c :  CHAR;
             END;
          END;
```

  Depending on the `tag` value `R1` has a real, integer, or char field.

- The size of a variant part is the max of the sizes of its constituent fields.

11 Record Types...

- Oberon has extensible record types:

```
TYPE R3 = RECORD
             a :  INTEGER;
          END;
TYPE R4 = (R3) RECORD
             b :  REAL;
          END;
```

  R4 has both the a and the b field.

- Extensible records are similar to classes in other languages.

12 Pointer Types

- In order to build recursive structures, most languages allow some way of declaring recursive types. These are necessary in order to construct linked structures such as lists and trees:

```
TYPE P = POINTER TO R;
TYPE R = RECORD
            data :  INTEGER;
            next :  P;
         END;
```

- Note that P is declared before its use. Languages such as Pascal and C don't allow forward declarations, but make an exception for pointers.

13 Procedure Types

- C, Modula-2, and other languages support procedure types. You can treat the address of a procedure like any other object:

```
TYPE P = PROCEDURE(x:INTEGER; VAR Y:CHAR):REAL;
VAR z :  P; VAR c :  CHAR; VAR r :  REAL;
PROCEDURE M (x:INTEGER; VAR Y:CHAR):REAL; BEGIN···END;
BEGIN
   z := M; /* z holds the address of M. */
   r := z(44,c);
END.
```

- Languages differen in whether they allow procedures whose address is taken to be nested or not. (Why?)

14 Class Types

- Java's classes are just record types. Some languages (Object Pascal, Oberon, MODULA-3) define classes just like records:

```
TYPE C1 = CLASS
             x :  INTEGER;
             void M() { ··· };
             void N() { ··· };
          END;
TYPE C2 = CLASS EXTENDS C1
             r :  REAL; // Add another field.
             void M() { ··· }; // Overrides C1.M
             void Q() { ··· }; // Add another method.
          END;
```

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Type Constructors

16 Type Expressions (TE)

- To reason about types we build up an algebra of TEs:

$$
\begin{aligned}
TE &= \texttt{int}, \texttt{string}, \texttt{real}, \cdots, \texttt{type\_error}, \texttt{void} \\
&= \texttt{subrange}(\texttt{from}, \texttt{to}) \\
&= \texttt{array}(\texttt{idx}, \texttt{eltype}) \\
&= \texttt{record}((f_1 \times t_1) \times \cdots \times (f_n \times t_n)) \\
&= \texttt{pointer}(\texttt{type}) \\
&= d_1 \times \cdots \times d_n \rightarrow r
\end{aligned}
$$

- The f_i:s are field names and t_i:s are field types (TEs).
- $d_1 \times \cdots \times d_n$ is the domain and r is the range of a function type. d_i and r are TEs.

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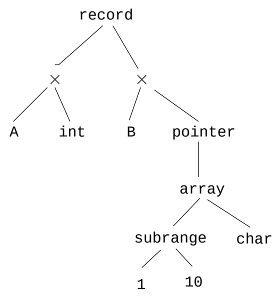
TYPE `T` = **RECORD**
`A` : **INTEGER**;
`B` : **POINTER TO ARRAY** `[1..10]` **OF CHAR**;
END

```
record(
   A × int,
   B × pointer(
      array(subrange(1,10),char))))
```

Type Expression



Type Graph

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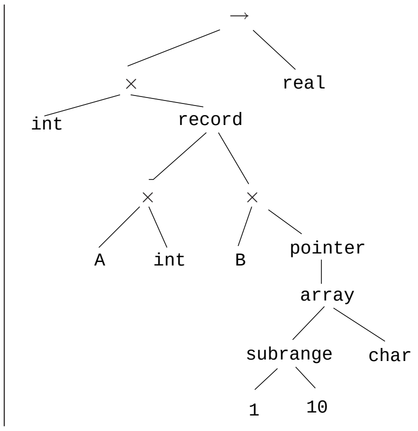
```
TYPE P = PROCEDURE (A:INTEGER; B:T) : REAL;
```

int × T → real



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Typechecking

20 Static/Dynamic Typechecking

- Semantic checking can be done both at compile-time (static checking) and run-time (dynamic checking).
- Some translators also do some checking at link-time and load-time. Java, for example, verifies the correctness of class-files at class load time.
- A language has a Sound Type System if no dynamic typechecking necessary.
- In a Strongly Typed Language there are no type errors at run time.

21 Static/Dynamic Typechecking. . .

```
VAR V : REAL;
VAR S = [1 .. 10];
BEGIN
   V := V + 3.14; // Static check
   S := READ; // Dynamic check
END
```

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Type Equivalence

23 Equivalence Types

- Equivalence types are used to create type aliases:

```
TYPE Flag = (red,white,blue);
TYPE Q = Flag;
VAR x :  Flag;
VAR y :  Q;
BEGIN
x := y; /* Legal?  */ END;
```

- But, when are two types equivalent? I.e. when can we compare two variables of "different" types?
- Some languages use structural type equivalence, others name equivalence, others a mixture of the two.

24 Structural Equivalence

PROCEDURE Equiv(s, t) : **BOOLEAN**
    IF basic(s) & basic(t) & $s = t$ **THEN**
        RETURN TRUE
    ELSIF $s =$ array(i_1, t_1) & $t =$ array(i_2, t_2) **THEN**
        RETURN Equiv(i_1, i_2) & Equiv(t_1, t_2)
    ELSIF $s = l_1 \times r_1$ & $t = l_2 \times r_2$ **THEN**
        RETURN Equiv(l_1, l_2) & Equiv(r_1, r_2)
    ELSIF $s =$ pointer(p_1) & $t =$ pointer(p_2) **THEN**
        RETURN Equiv(p_1, p_2)
    ELSIF $s = d_1 \rightarrow r_1$ & $t = d_2 \rightarrow r_2$ **THEN**
        RETURN Equiv(d_1, d_2) & Equiv(r_1, r_2)
    ELSE RETURN FALSE
END

25 Structural Equivalence...

```
class Square {void move(){···}; void draw(){···};}
class Cowboy {void move(){···}; void draw(){···};}
void main(){Square s=new Square(); Cowboy c=s;} // Legal?
```

- Structural type equivalence will sometimes get us in trouble.
- Structural type equivalence make sense in distributed systems — what type does an object have after I have packed it into a bit-string and sent it over the net to another process?
- In MODULA-3 (which uses structural type equivalence) you can tag a type with a unique string to make sure it's not equivalent to other types by chance.

26 Modula-2 Type Equivalence

PROCEDURE Equiv(s, t) : **BOOLEAN**
    IF $s = t$ **THEN**
        RETURN TRUE
    ELSIF $s =$ subrange(t_1, l_1, h_1) &

$t =$ `subrange`(t_2, l_2, h_2) **THEN**
RETURN `Equiv`(t_1, t_2)
ELSIF $s = l_1 \times r_1$ & $t = l_2 \times r_2$ **THEN**
RETURN `Equiv`(l_1, l_2) & `Equiv`(r_1, r_2)
ELSIF $s = d_1 \rightarrow r_1$ & $t = d_2 \rightarrow r_2$ **THEN**
RETURN `Equiv`(d_1, d_2) & `Equiv`(r_1, r_2)
ELSE
RETURN FALSE
END

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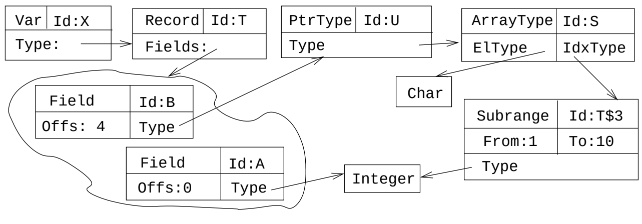
Typechecking Designators

28 Semantic analysis of Structured Types

- Declarations of structured types (arrays, records, pointers) become a **type graph** of type dependencies in the symbol table:

TYPE `S =` **ARRAY** `[1..10]` **OF CHAR**;
`U =` **POINTER TO** `S`;
`T =` **RECORD** `A:`**INTEGER**`1 B:U;` **END**



29 Typechecking Designators

- A designator is any part of an expression that references a memory location.
  1. Simplest case: `X`.
  2. Structured types complicate things: `X^^.V[5][7]^.P`.
- Designators are typechecked using the symbol table type graph.
- An attribute $\Updownarrow$`Type:`**TypeT**`.TypeIn` stores the type of partially processed designator.
- A synthesized attribute `TypeOut` returns the type of the complete designator.

30 Typechecking Designators. . .

TYPE `S =` **ARRAY** `[1..10]` **OF CHAR**;
TYPE `U =` **POINTER TO** `S`;
TYPE `T =` **RECORD** `A:`**INTEGER** `B:U;` **END**

```
PROCEDURE P (VAR X : T); ···
VAR X : T; C : CHAR;
BEGIN
   P(X.B^[5]);    (* L-Value *)
   X.B^[5] := "x";(* L-Value *)
   C := X.B^[5];  (* R-Value *)
END
```

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```
PROCEDURE Des (n :  Node);
  IF n.Kind = VarRef THEN
    Symbol := Lookup(n.Id,n.Env);
    n.Next.TypeIn := GetType(Symbol);
    Des(n.Next); n.Type:=n.Next.TypeOut;
  ELSIF n.Kind = FieldRef THEN
    IF TypeKind(n.TypeIn) ≠ Record THEN
      PRINT "Record Type Expected"
    ENDIF;
    Symbol := FindField(n.Id,n.TypeIn);
    n.Next.TypeOut := FieldType(Symbol);
    Des(n.Next);
    n.TypeOut:=n.Next.TypeOut;
            .........
```

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```
  ELSIF n.Kind = ArrayRef THEN
    IF TypeKind(n.TypeIn) ≠ Array THEN
      PRINT "Array Type Expected"
    ENDIF;
    Expr(n.Expr);
    IdxType := ArrayIndexType(n.TypeIn);
    IF n.Expr.Type ≠ IdxType THEN
      PRINT "Wrong Index Type"
    ENDIF;
    n.Next.TypeIn:=ArrayType(n.TypeIn);
    Des(n.Next);
    n.TypeOut:=n.Next.TypeOut;
            .........
```

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```
   ELSIF n.Kind = PointerRef THEN
      IF TypeKind(n.TypeIn) ≠ Pointer THEN
         PRINT "Pointer Type Expected"
      ENDIF;
      n.Next.TypeIn := PtrType(n.TypeIn);
      Des(n.Next);
      n.TypeOut:=n.Next.TypeOut;
```

```
ELSIF n.Kind = NoDes THEN
   n.TypeOut := n.TypeIn;
END;
```

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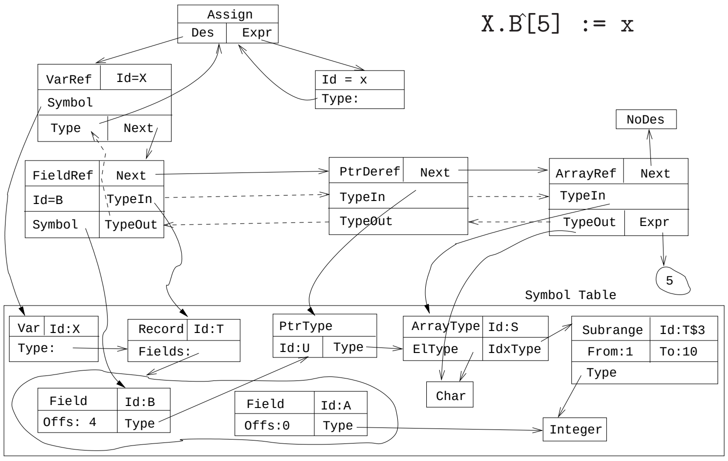

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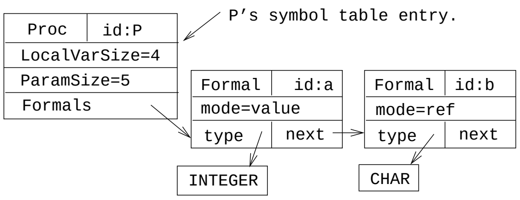
Typechecking Procedure Calls

36 Typechecking Procedure Calls

- To typecheck procedure calls we first have to build an appropriate symbol table structure.
- This is simply a linked list of the procedure's formal parameters. For each parameter we give its **name**, **type** and **mode** (value or reference (`VAR` in Pascal)).

PROCEDURE `P (a`:**INTEGER**; **VAR** `b`:**CHAR**);
VAR `c`:**INTEGER**; **BEGIN** $\cdots$ **END** `P`;



37 Procedure Calls...

- Checking a procedure call becomes very simple: just traverse the list of actual parameters and the list of formal parameters in parallel, checking one type at a time.
- Obviously, we have to check that the lists are of the same length.

- We give each `Actual`-node an inherited attribute $\Downarrow$`Formal`:**FormalT** that points to the current formal parameter in the symbol table.

Example Procedure Call:

```
VAR x :  INTEGER;
VAR y :  INTEGER;
BEGIN P(5+x, y) END
```

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1. Look up the name of the procedure in the current environment.
2. Get a pointer to the first formal node in the symbol table. Start checking the actuals.

```
PROCEDURE Statement (n:Node);
   IF n.Kind = ProcCall THEN
      IF Member(n.Name, n.Env) THEN
         Symbol := Lookup(n.Name, n.Env);
         n.Actuals.Formal := GetFormals(Symbol);
         n.Actuals.Env := n.Env;
         CheckCall(n.Actuals);
      ELSE
         PRINT "Procedure not declared" ENDIF;
```

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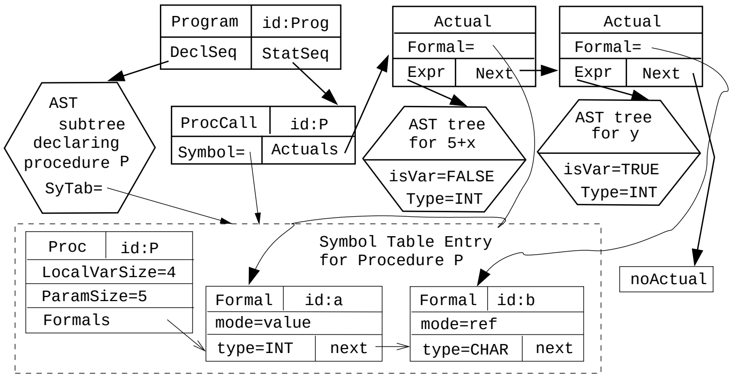
- The attribute $\Uparrow E$.`IsVar`:**BOOL** is `TRUE` if expression E is an `L-Value`.

```
PROCEDURE CheckCall(n:Node);
   IF n.Kind = Actual THEN
      n.Expr.Env := n.Env; Expr(n.Expr);
      IF n.Expr.Type ≠ n.Formal.type THEN
         PRINT "Wrong Parameter Type"
      ENDIF;
      IF n.Formal.mode = ref AND n.Expr.IsVar = FALSE THEN
         PRINT "Variable expected"
      ENDIF;
      n.Next.Formal := GetNextFormal(n.Formal);
      n.Next.Env := n.Env;
      CheckCall(n.Next);
```

40 Procedure Calls...



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Homework

42 Homework I

- Build an AST for the program below. Show – in detail – how the assignment statements are checked for type correctness.

```
PROGRAM M;
   TYPE A = RECORD
         X : ARRAY [1..10] OF INTEGER;
      END;
      B = POINTER TO A;
      C = ARRAY [1..2] OF B;
   VAR V : C;
BEGIN
   V[1]^.X[4] := "C";
   V[2].X[4] := 5;
END.
```

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Summary

44 Readings and References

- Read Louden: pp. 313–331.
- Or, read the Dragon book: 343–360.