CSc 453

Compilers and Systems Software

10 : Semantic Analysis II

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Introduction

Overview

- Several independent tasks have to be performed during semantic analysis:

Declaration Analysis

- Go through and check the legality of the declarations (types, variables, procedures, etc) in the program. Check for:
  1. multiple declarations: `VAR x,y,x : int`.
  2. undeclared types : `VAR x : intger`.
  3. illegal symbol kinds: `VAR X : integer; VAR Y : X`.
- Construct **symbol tables** and **environments** to be used during name and expression analysis.

Overview...

Name Analysis

- Match up each use of an identifier with the correct declaration. Report any undeclared identifiers.

Expression Analysis

- Assign types to every sub-expression.
- Report type mismatches: `X:="Hi" * "there"`.

Prepare for Code Generation

- Insert explicit type conversions: `X:=5+6.7` ⇒ `X:=float(5)+6.7`.
- Compute labels for conditional- and loop-statements.

Name Analysis

Name Analysis

- Algol-like languages allow the same name to be declared in different scopes. During name analysis the use of a name is matched up with the corresponding declaration.

```
VAR I, K : INTEGER;
PROCEDURE P (K : INTEGER);
   PROCEDURE Q (L : INTEGER);
   BEGIN I := L + K; (* I_global := L_Q + K_P *) END Q;
   VAR J : INTEGER;
BEGIN I := J + K; (* I_global := J_P + K_P *) END P;
```

Declaration Analysis

Symbol Tables

- All compilers use a **symbol table**. In it we record all information regarding every declared item (variable, procedure, constant, etc).
- The symbol table is built during declaration analysis.
- The symbol table is used during name analysis and type checking to look up identifiers.
- Some compilers build one (huge) symbol table for the entire input program. Others build one separate symbol table for each **scope**.
- The type of information which is stored in a symbol table node depends on the declaration:

Symbol Tables. . .

All Symbols	Name, Position, Level, Enclosing Block, . . .
Variables	Type, Size, . . .
Constants	Type, Size, Value, . . .
Types	Size, . . .
	Records: Fields
	Arrays: Index-Type, Index-Range, Element-Type
Procedures	Formal Parameters, Size of Local Data, . . .

```
TYPE T = RECORD a, b :  CHAR END;
VAR X : T;
PROCEDURE Q (a:  T); BEGIN ...  END Q;
```

Example — Building the Symbol Table

Building the Symbol Table

- This time we want to build a symbol table from a sequence of declarations. At the same time we want to check for multiply declared identifiers.
- In this example, the symbol table is simply a set of identifiers. Normally, we'd also want the symbol table to include other kinds of information: type, size, and offset for variables, formal parameters for procedures, etc.
- Operations on `SyTabs`: Union ($\cup$) and member ($\in$).

Threaded Attributes

- We use a threaded attribute `Ids` of type `SyTab={String}` (set of strings).
- A threaded attribute `Attr` is really a combination of two attributes, a synthesized attribute `AttrOut` and an inherited attribute `AttrIn`.
- Threaded attributes are used to collect information from a subtree. The evaluator uses the inherited attribute to collect information on the way down the tree, and the synthesized attribute to move that information back up the tree.
- In our example, `IdsIn` is inherited and holds the current set of identifiers. `IdsOut` is synthesized and returns the complete symbol table.

Building the Symbol Table...

- At any node `n`, `n.IdsOut-n.IdsIn` is the set of variables declared in the subtree rooted at `n`.

Abstract Syntax:

Program ::= $\Leftarrow$`Id`:**String** DeclSeq:Decl StatSeq:Stat

Decl ::= VarDecl | ProcDecl | NoDecl

VarDecl ::= $\Leftarrow$`Id`:**String** $\Leftarrow$`TypeName`:**String** Next:Decl
$\Updownarrow$`Ids`:**SyTab**

ProcDecl ::= $\Leftarrow$`Id`:**String** Locals:Decl StatSeq:Stat Next:Decl
$\Updownarrow$`Ids`:**SyTab**

NoDecl ::= $\Updownarrow$`Ids`:**SyTab**

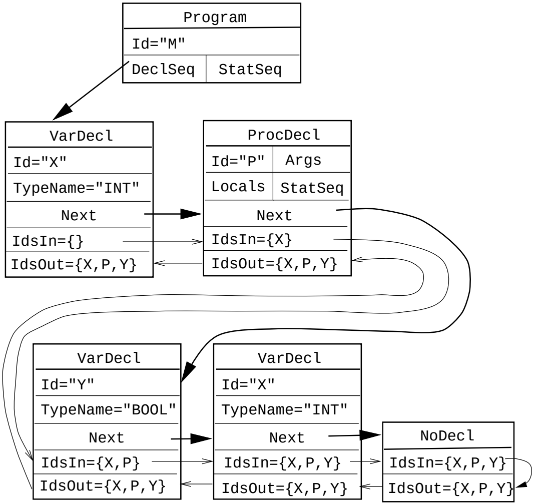
```
Program ::= ⇐Id:String DeclSeq:Decl StatSeq:Stat
    { DeclSeq.IdsIn:={} }

VarDecl ::= ⇐Id:String ⇐TypeName:String
                Next:Decl ⇕Ids:SyTab
    {
        CHECK Id ∈ IdsIn ⇒ ERROR("Multiple Declaration")
        Next.IdsIn := IdsIn ∪ Id
        IdsOut := Next.IdsOut
    }

Decl ::= ⇕Ids:SyTab
    { IdsOut := IdsIn }
```

```
PROCEDURE Program (n:  Node);
   n.DeclSeq.IdsIn:={}; Decl(n.DeclSeq);

PROCEDURE Decl (n:  Node);
   IF n.Kind ∈ {VarDecl,ProcDecl} THEN
      IF n.Id ∈ n.IdsIn THEN
         PRINT n.Pos ":Multiple "declaration:  " n.Id;
      ENDIF;
      n.Next.IdsIn := n.IdsIn ∪ {n.Id};
      Decl(n.Next);
      n.IdsOut := n.Next.IdsOut
   ELSIF n.Kind = NoDecl THEN
      n.IdsOut := n.IdsIn
   ENDIF
```


Program
Id="M"
DeclSeq
StatSeq
VarDecl
Id="X"
TypeName="INT"
Next
IdsIn={}
IdsOut={X,P,Y}
ProcDecl
Id="P"
Args
Locals
StatSeq
Next
IdsIn={X}
IdsOut={X,P,Y}
VarDecl
Id="Y"
TypeName="BOOL"
Next
IdsIn={X,P}
IdsOut={X,P,Y}
VarDecl
Id="X"
TypeName="INT"
Next
IdsIn={X,P,Y}
IdsOut={X,P,Y}
NoDecl
IdsIn={X,P,Y}
IdsOut={X,P,Y}

Putting it all together

Putting it all together...

- Obviously, We don't write one tree-walk evaluator for each attribute. Rather, we walk over the tree once (or maybe twice or three times, depending on the language) and evaluate as many attributes as possible.
- In this example we'll just use several attribute evaluation rules in order to
    1. Check for multiple declarations and build a symbol table containing all the identifiers.
    2. Assign an offset to each variable and compute the total size of the variables declared.
    3. Assign a unique number to each declared identifier and count the number of identifiers.

Putting it all together...

Abstract Syntax:

Program ::= $\Leftarrow$`Id`:**String** DeclSeq:Decl StatSeq:Stat

Decl ::= VarDecl | ProcDecl | NoDecl

VarDecl ::= $\Leftarrow$`Id`:**String** $\Leftarrow$`TypeName`:**String** Next:Decl
$\Updownarrow$`Ids`:**SyTab** $\Updownarrow$`Count`:**INTEGER** $\Updownarrow$`Size`:**INTEGER**

ProcDecl ::= $\Leftarrow$`Id`:**String** Args:Decl Locals:Decl StatSeq:Stat
Next:Decl $\Updownarrow$`Ids`:**SyTab** $\Updownarrow$`Count`:**INTEGER** $\Updownarrow$`Size`:**INTEGER**

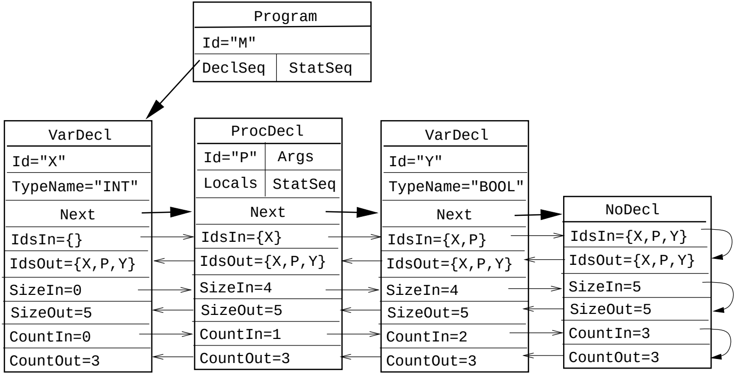
NoDecl ::= $\Updownarrow$`Ids`:**SyTab** $\Updownarrow$`Count`:**INTEGER** $\Updownarrow$`Size`:**INTEGER**

```
PROCEDURE Program (n:  Node);
   n.DeclSeq.IdsIn := {};
   n.DeclSeq.CountIn:=0;
   n.DeclSeq.SizeIn:=0;
   Decl(n.DeclSeq);

PROCEDURE Decl (n:  Node);
   IF n.Kind = VarDecl THEN VarDecl(n);
   ELSIF n.Kind = ProcDecl THEN ProcDecl(n);
   ELSIF n.Kind = NoDecl THEN
      n.CountOut := n.CountIn;
      n.SizeOut := n.SizeIn;
      n.IdsOut := n.IdsIn
   ENDIF
```

```
PROCEDURE VarDecl (n:  Node);
   n.Next.SizeIn := n.SizeIn + size(n.TypeName);
   n.Next.CountIn := n.CountIn + 1;
   IF n.Id ∈ n.IdsIn THEN
      PRINT n.Pos ":Multiple declaration:  " n.Id;
   ENDIF;
   n.Next.IdsIn := n.IdsIn ∪ {n.Id};
   Decl(n.Next);
   n.CountOut := n.Next.CountOut;
   n.SizeOut := n.Next.SizeOut;
   n.IdsOut := n.Next.IdsOut
PROCEDURE ProcDecl (n:  Node);
   n.Next.SizeIn := n.SizeIn;
   (* Rest is same as for VarDecl *)
```

Putting it all together. . .



Building the Symbol Table

Symbol Tables

- For all symbols we'll store **Kind** (`VAR` or `PROC`), **Name**, and **Number** (every identifier has a unique number). For variables we'll also store **Size**, **Type**, and **Offset** (address).
- We'll assume that $\Updownarrow$`Count`:**INTEGER** and $\Updownarrow$`Size`:**INTEGER** are available.

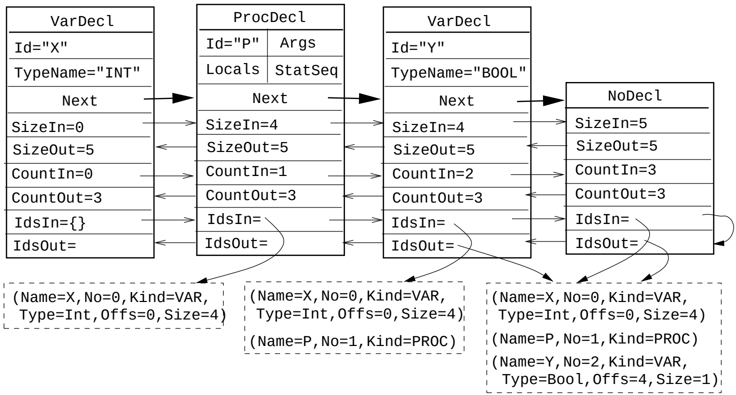
```
VAR X : INTEGER;
PROCEDURE P (); BEGIN ...END P;
VAR Y : BOOLEAN;
```

$\Downarrow$ Build Symbol Table $\Downarrow$

```
{ (Name="X",No=0,Kind=VAR,Size=4,Type=Int,Offset=0),
  (Name="P",No=1,Kind=PROC),
  (Name="Y",No=2,Kind=VAR,Size=1,Type=Bool,Offset=4)}
```

```
PROCEDURE Decl (n:  Node);
  IF n.Kind = VarDecl THEN
    Sy := (Name=n.Id, No=n.CountIn,Offset=n.SizeIn,
           Kind=VAR,Size=size(n.TypeName),Type=n.TypeName);
    n.Next.IdsIn := n.IdsIn ∪ {Sy};
    Decl(n.Next);
    n.IdsOut:=n.Next.IdsOut
  ELSIF n.Kind = ProcDecl THEN
    Sy := (Name=n.Id, Kind=PROC,No=n.CountIn);
    n.Next.IdsIn := n.IdsIn ∪ {Sy};
    Decl(n.Next); n.IdsOut:=...
  ELSIF n.Kind = NoDecl THEN
    n.IdsOut := n.IdsIn
  ENDIF
```

Symbol Tables. . .



Implementing Symbol Tables

Implementing Symbol Tables

Symbol tables are sets of tuples. Any set data structure will do fine. Hash tables, binary search trees, or linked lists will be OK, depending on the size of the table.

```
TYPE KindT = (Var,Proc,Type,Const);
     DataT = RECORD
        Name: String; Number: INTEGER; Pos: Position;
        CASE Kind : KindT OF
             Var : Type:String; ··· |
             Const : Value:INTEGER;···|
        END;
        Next : SyTab;
     END;
     SyTab = POINTER TO DataT;
```

Building Symbol Tables for Nested Scope

SyTabs for Nested Scope

- This time we are going to build one symbol table for each nested scope.
- Note that the formal parameters and local variables of a procedure belong to the same scope.
- The next slide shows the abstract syntax for a language with variable and procedure declarations. The following slides show an example program, the attribute grammar, and the tree-walker.

SyTabs for Nested Scope...

Program ::= $\Leftarrow$`Id`:**String** DeclSeq:Decl StatSeq:Stat

Decl ::= VarDecl | ProcDecl | NoDecl

VarDecl ::= $\Leftarrow$`Id`:**String** $\Leftarrow$`TypeName`:**String** Next:Decl
$\Updownarrow$`Ids`:**SyTab**

Formal ::= $\Leftarrow$`Id`:**String** $\Leftarrow$`TypeName`:**String** Next:Decl
$\Updownarrow$`Ids`:**SyTab**

ProcDecl ::= $\Leftarrow$`Id`:**String** Args:Decl Locals:Decl Formals:Decl
StatSeq:Stat Next:Decl $\Updownarrow$`Ids`:**SyTab**

NoDecl ::= $\Updownarrow$`Ids`:**SyTab**

SyTabs for Nested Scope. . .

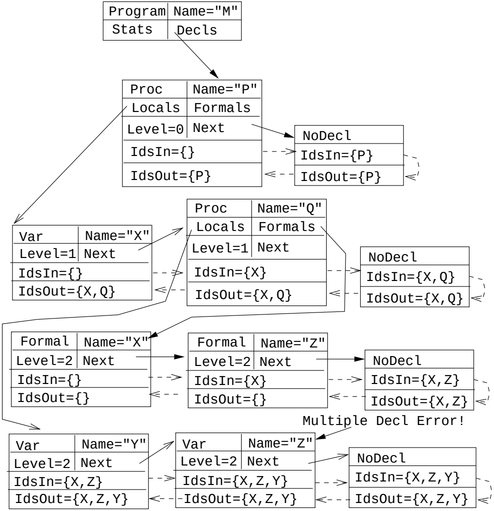
```
PROGRAM M;
    PROCEDURE P ();
        VAR X : INTEGER;
        PROCEDURE Q (
            X : CHAR;
            Z : INTEGER);
            VAR Y : INTEGER;
            VAR Z : CHAR;
        BEGIN END Q;
    BEGIN END P;
BEGIN END M;
```

```
Formal, VarDecl ::= ⇐Id:String ⇐TypeName:String
                    Next:Decl ⇕Ids:SyTab
   {  Next.IdsIn := IdsIn ∪ {(Name=Id,Kind=VAR,···)};
      IdsOut:=Next.IdsOut }

ProcDecl ::= ⇐Id:String Locals:Decl
         Formals:Decl StatSeq:Stat Next:Decl ⇕Ids:SyTab
   {  Formals.IdsIn := {};
      Locals.IdsIn := Formals.IdsOut;
      Next.IdsIn := IdsIn ∪
         {(Name=Id,Kind=PROC,Vars=Locals.IdsOut,···)};
      IdsOut:=Next.IdsOut }

NoDecl ::= ⇕Ids:SyTab { IdsOut := IdsIn }
```

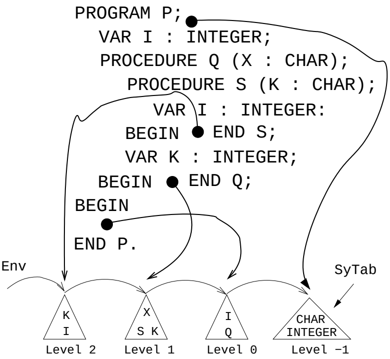
```
PROCEDURE Decl (n:  Node);
   IF n.Kind = VarDecl THEN
      Sy := (Name=n.Id,Kind=VAR,···);
      n.Next.IdsIn := n.IdsIn ∪ {Sy};
      Decl(n.Next); n.IdsOut:=n.Next.IdsOut
   ELSIF n.Kind = ProcDecl THEN
      n.Formals.IdsIn := {}; ⇐ NEW!
      Decl(n.Formals); ⇐ NEW!
      n.Locals.IdsIn := n.Formals.IdsOut; ⇐ NEW!
      Decl(n.Locals); ⇐ NEW!
      Sy := (Name=n.Id,Kind=PROC,···);
      n.Next.IdsIn := n.IdsIn ∪ {Sy};
      Decl(n.Next); n.IdsOut:=n.Next.IdsOut
   ELSIF n.Kind = NoDecl THEN n.IdsOut := n.IdsIn ENDIF
```


Program
Name="M"
Stats
Decls
Proc
Name="P"
Locals
Formals
Level=0
Next
IdsIn={}
IdsOut={P}
NoDecl
IdsIn={P}
IdsOut={P}
Var
Name="X"
Level=1
Next
IdsIn={}
IdsOut={X,Q}
Proc
Name="Q"
Locals
Formals
Level=1
Next
IdsIn={X}
IdsOut={X,Q}
NoDecl
IdsIn={X,Q}
IdsOut={X,Q}
Formal
Name="X"
Level=2
Next
IdsIn={}
IdsOut={}
Formal
Name="Z"
Level=2
Next
IdsIn={X}
IdsOut={}
NoDecl
IdsIn={X,Z}
IdsOut={X,Z}
Multiple Decl Error!
Var
Name="Y"
Level=2
Next
IdsIn={X,Z}
IdsOut={X,Z,Y}
Var
Name="Z"
Level=2
Next
IdsIn={X,Z,Y}
IdsOut={X,Z,Y}
NoDecl
IdsIn={X,Z,Y}
IdsOut={X,Z,Y}

Environments

Building Environments

- Environments are used to represent scope information. They are linked lists of symbol tables where each symbol table represents the identifiers declared in a given scope.



Building Environments...

- First a symbol table is built for each scope. Then environments are constructed and sent down to statements to be used during name analysis.
- `EnvT = LIST OF SyTab` = `LIST OF SET OF Symbol`.

Abstract Syntax:

VarDecl ::= $\Leftarrow$`Id`:**String** $\Leftarrow$`TypeName`:**String** Next:Decl
$\Updownarrow$`Ids`:**SyTab** $\Downarrow$`Env`:**EnvT**

Formal ::= $\Leftarrow$`Id`:**String** $\Leftarrow$`TypeName`:**String** Next:Decl
$\Updownarrow$`Ids`:**SyTab** $\Downarrow$`Env`:**EnvT**

ProcDecl ::= $\Leftarrow$`Id`:**String** Locals:Decl Formals:Decl StatSeq:Stat
Next:Decl $\Downarrow$`Env`:**EnvT** $\Updownarrow$`Ids`:**SyTab**

Assign ::= Des:Des Expr:Expr $\Downarrow$`Env`:**EnvT**

```
Program ::= ⇐Id:String DeclSeq:Decl StatSeq:Stat
   {
      DeclSeq.Env := {INT,REAL,CHAR,TRUNC,FLOAT};
      DeclSeq.IdsIn:={};
      StatSeq.Env := cons(DeclSeq.IdsOut,DeclSeq.Env);
   }

Formal, VarDecl ::= ⇐Id:String ⇐TypeName:String
                    Next:Decl ⇕Ids:SyTab ⇓Env:EnvT
   {
      CHECK NOT member(Env,TypeName)
                ⇒ ERROR("Ident not declared")
      Next.Env := Env;
   }
```

```
ProcDecl ::= ⇐Id:String Locals:Decl Formals:Decl
                 StatSeq:Stat Next:Decl ⇓Env:EnvT
                 ⇕Ids:SyTab
    {
        Formals.IdsIn := {};
        Formals.Env := Locals.Env:= Env;
        Locals.IdsIn := Formals.IdsOut;
        StatSeq.Env := cons(Locals.IdsOut, Env);
        Next.Env := Env;
    }

Assign ::= ⇓Env:EnvT
    { Des.Env := Expr.Env := Env; }
```

Building Environments. . .

```
PROCEDURE Program (n:  Node);
  StdEnv := {INT,REAL,CHAR,TRUNC,FLOAT};
  n.DeclSeq.Env := StdEnv;
  n.DeclSeq.IdsIn:={}; Decl(n.DeclSeq);
  n.StatSeq.Env := cons(n.DeclSeq.IdsOut,StdEnv);
  Stat(n.StatSeq);

PROCEDURE Decl (n:  Node);
  IF n.Kind=VarDecl THEN VarDecl(n);
  ELSIF n.Kind=ProcDecl THEN ProcDecl(n);
  ELSIF n.Kind=NoDecl THEN (* Same *)
  ENDIF
```

Building Environments...

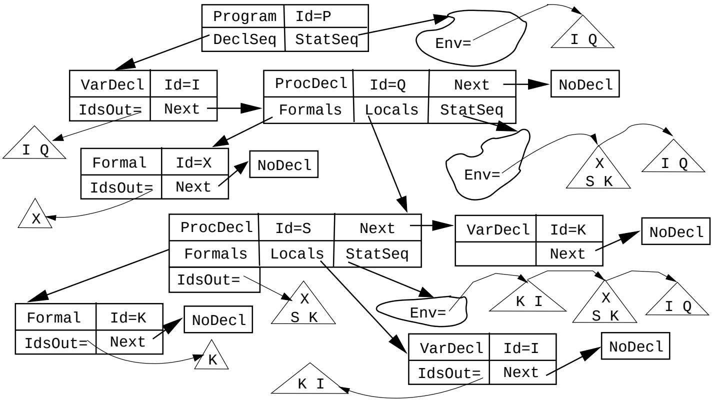
```
PROCEDURE Assign (n:  Node);
   Des.Env := Expr.Env := n.Env; ···

PROCEDURE VarDecl (n:  Node);
   IF NOT member(n.Env,n.TypeName) THEN
      PRINT n.Pos ":Identifier not declared " n.TypeName;
   ENDIF;
   n.Next.Env := Env;
   (* More here...*)
```

Building Environments...

```
PROCEDURE ProcDecl (n:  Node);
   n.Formals.IdsIn := {};
   n.Formals.Env := n.Locals.Env:=n.Env;
   Decl(n.Formals);
   n.Locals.IdsIn := n.Formals.IdsOut;
   Decl(n.Locals);
   n.StatSeq.Env := cons(n.Locals.IdsOut, n.Env);
   Stat(n.StatSeq);
   n.Next.Env := Env;
   (* More here...*)
```

Building Environments. . .



Environment ADTs

Implementing Environments

Symbol Table ADT

```
Create() :  SyTabT;
Insert(S:SyTabT; N:Name) :  SymbolRef;
Lookup(S:SyTabT; N:Name) :  SymbolRef;
```

- Each symbol `R` has a set of attributes (Type, Size,...) that can be set/retrieved using operations `Set<Attr>/Get<Attr>(S,R,A)`.

Implementing Environments...

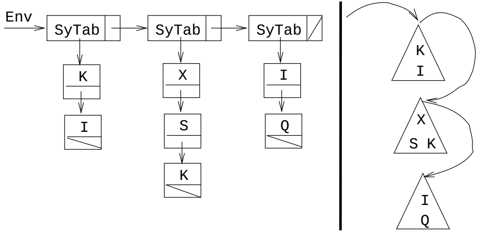
Environment ADT

```
Create() :  EnvT;
Cons(S:SyTabT; E:EnvT) : Env;
Identify(E:EnvT; N:Name) :  SymbolRef;
Member(E:EnvT; N:Name) :  BOOLEAN;
```

- `Cons(S,E)` creates a new environment consisting of the symbol table `S` followed by the symbol tables of `E`.
- `Identify(E, N)` searches the symbol tables of `E` sequentially until a definition of the name `N` is found.

Implementing Environments. . .

- Symbol tables are sets of tuples (collections of data), environments are lists of symbol tables.



Implementing Environments...

```
TYPE KindT = (Var,Proc,Type,Const);
     SyTabT =POINTER TO RECORD
        CASE Kind :  KindT OF ··· END;
        Name :  String; Next :  SyTabT;
     END;
     EnvT =  POINTER TO RECORD
        SyTab :  SyTabT; Next :  EnvT;
     END;
```

Summary

Readings and References

- Read Louden:

  Symbol Tables 295–313

  Note that Louden uses different algorithms for symbol-tables and environments than I do in this lecture.

- or read the Dragon book:

  Symbol Tables 429–438
  Nested Procedures 415–416
  Environments 438–440

Summary

- During declaration analysis we build symbol tables that will be used during name analysis.
- A symbol table is a collection of information about the identifiers declared in a program. The kind of information that is stored for a particular identifier depends on its **kind** (variable, procedure, etc).
- For every identifier we store its name, kind, and position (line and column number in the source code where the identifier is declared).

Summary...

- A threaded attribute $\Updownarrow$`A`:**T** actually consists of two attributes: an inherited attribute $\Downarrow$`AIn`:**T** and a synthesized attribute $\Uparrow$`AOut`:**T**. As we perform an inorder traversal of a subtree, `AIn` collects information from the tree, and `AOut` brings it back up the tree.
- Threaded attributes are used to gather information from a subtree. Since gathering information is exactly what we do when we build a symbol table, we use a threaded attribute $\Updownarrow$`Ids`:**SyTabT** to construct the symbol table.
- This symbol table can then be passed down the tree (using an inherited attribute $\Downarrow$`Env`:**SyTabT**) during name analysis.

- An inherited attribute is given a value **before** a recursive call is made:

```
n.LOP.Env := n.Env; Expr(n.LOP);
```

- An syntesized attribute is given a value **before** a recursive call returns:

```
PROCEDURE Expr (n:  Node);
   IF n.Kind = IntConst THEN n.Type := "INT";
```

- For a threaded attribute pair, the inherited part is given a value **before** the recursive call is made and the syntesized parts is given a value **after** the call returns:

```
n.Next.IdsIn := n.IdsIn ∪ {Sy};
Decl(n.Next);
n.IdsOut := n.Next.IdsOut
```

Summary...

- Tree-walkers use *environments* to perform *name analysis*. An environment is a list of symbol tables, where each table consists of the symbols collected in a particular scope.
- Environments are organized so that if they are searched sequentially from the start, we'll always find the correct (most closely nested) identifier first.
- Environments are passed **down** the tree (using inherited attributes) in order to inform lower level nodes about the **context** in which they occur.

Confused Student Email

Why do we have to store all information in the AST? Why can't we just use one global symbol-table to keep all data about all symbols? Passing these environments around seems really inefficient and confusing. It is true that some compilers build one huge symbol table for the entire program and keep that outside the tree. This method works well for simple languages like C, which does not support nested procedures, classes, etc.

For other languages, it's better to build one symbol table for each scope, and pass them around the tree using attributes. Then we'll have complete control of the information that is available at each point in the program; we'll know exactly what information is passed into each node, and what attributes are computed at each node.

Homework

Exam Question

Show the environment in effect at each point i in this program. Identifiers must be declared before use. Recursion is allowed.

```
PROGRAM M;
   2
   TYPE T = ARRAY 5 OF CHAR; VAR X : INTEGER;
   PROCEDURE P ();
      VAR Z : T;
      PROCEDURE Q ();
         VAR R : CHAR; PROCEDURE Z (X:CHAR); BEGIN 3 END Z
         VAR Y : CHAR; PROCEDURE V (); BEGIN 4 END V;
      BEGIN 5 END Q;
      VAR Y : INTEGER;
   BEGIN 6 END P;
   VAR Y : INTEGER;
BEGIN 1 END M.
```

Homework I

- Show the environment in effect at each point i in the program below.

```
PROGRAM M;
   VAR X : INTEGER;
   PROCEDURE P (X : CHAR);
      VAR Z : INTEGER;
      PROCEDURE Q (X : INTEGER);
         VAR R : CHAR;
         PROCEDURE Z (); BEGIN 1 END Z;
         VAR Y : CHAR;
      BEGIN 2 END Q;
      VAR Y : INTEGER;
   BEGIN 3 END P;
   VAR Y : INTEGER;
BEGIN 4 END M.
```

Homework II

- Show the symbol tables resulting from the declarations below. Include as much information about each symbol as possible. Give each identifier a unique number (set `INTEGER=1` and `CHAR=2`), and use these numbers to represent types.

Problem (A):

```
PROCEDURE P (X:INTEGER; Y:CHAR);
VAR Z:INTEGER;
BEGIN END P;
```

Homework II. . .

Problem (B):

```
TYPE T = RECORD A, B : CHAR END;
VAR X : T;
```

Problem (C):

```
TYPE T2 = POINTER TO CHAR;
TYPE T2 = ARRAY 100 OF T1;
TYPE T3 = ARRAY 20 OF T2;
```

Homework III

Build an abstract syntax tree for the program below. Show — in detail — how the symbol tables and environments are built.

```
PROGRAM M;
   VAR X : INTEGER;
   VAR Y : INTEGER;
   PROCEDURE P (X : CHAR);
      VAR Z : INTEGER;
      PROCEDURE Q (X : INTEGER);
         VAR R : CHAR;
         VAR V : CHAR;
      BEGIN END Q;
      VAR Y : INTEGER;
   BEGIN END P;
BEGIN END M.
```

Homework IV

1. Build an abstract syntax tree for the program below. Show — in detail — how the statements are type checked. Which error messages should be generated?

```
PROGRAM M;
   VAR X : INTEGER;
   VAR Y : INTEGER;
   PROCEDURE P (Z : INTEGER; VAR X : CHAR);
      VAR Z : INTEGER;
   BEGIN
      X := "D";
      Y := Z + X;
   END P;
BEGIN
   P(X, "C");
END M.
```

Homework V

- Assume a small Modula-2 like language:

Concrete Syntax:

Block ::= **BEGIN** StatSeq **END**

AssignStat ::= ident **':='** Expr

ForStat ::= **FOR** ident **':='** expr **TO** expr [ByPart] **DO** StatSeq **END**

ByPart ::= **BY** ConstExpr

Stat ::= AssignStat | IfStat | ForStat

StatSeq ::= Stat **';'** StatSeq | ϵ

Expr ::= Expr **+** Expr | ident | IntConst

Homework V. . .

1. Give an abstract syntax corresponding to the concrete syntax above.
2. Write a attribute grammar/tree-walk evaluator which checks that the ByPart, if present, is a constant expression.

Homework VI

- Assume a small Modula-2 like language like in the previous exercise, but with **IF**-statements:

Concrete Syntax Extension:

IfStat ::= **IF** Expr **THEN** StatSeq **ELSE** StatSeq **END**

IfStat ::= **IF** Expr **THEN** StatSeq **END**

ForStat ::= **FOR** ident **':='** expr **TO** expr [ByPart] **DO** StatSeq **END**

ByPart ::= **BY** ConstExpr

Homework VI. . .

1. Give an abstract syntax corresponding to the concrete syntax.
2. Write a attribute-grammar/tree-walk evaluator which checks that the iteration variable of a **FOR**-loop is not changed within the body of the loop. Remember that loops can be nested!

Homework VII

- Assume that enumerated types are declared in this fashion:

  ```
  TYPE T = ENUM[Marge=1, Bart=2,
                Maggie=5, Lisa=10];
  ```

  I.e., unlike Pascal, we're allowed to number the identifiers however we like.
- Give a suitable abstract syntax and a tree-walk evaluator that checks that all identifiers **and** values are unique (within the declaration).

Homework VII. . .

- In other words, the static semantics should flag these declarations as erroneous:

```
TYPE T1 = ENUM[Ren=3, Stimpy=4, Ren=2];
```

"ERROR: Multiple enumeration id: `Ren`"

```
TYPE T2 = ENUM[CB=10, Linus=4, Lucy=10];
```

"ERROR: Repeated enumeration value: 10"

Homework VIII

- Assume that enumerated types are declared in the "normal" Pascal fashion:

```
TYPE T = ENUM[Marge, Homer, Bart,
              Maggie, Lisa];
```

- Assume furthermore that the individual identifiers are given numbers $0, 1, 2, \cdots$.
- Give a suitable abstract syntax and a tree-walk evaluator that computes the minimum number of bits required to store variables of the type.

Homework VIII...

Examples:

```
TYPE T = ENUM[a]           ⇒ 1 bit
TYPE T = ENUM[a,b]         ⇒ 1 bit
TYPE T = ENUM[a,b,c]       ⇒ 2 bits
TYPE T = ENUM[a,b,c,d]     ⇒ 2 bits
TYPE T = ENUM[a,b,c,d,e]   ⇒ 3 bits
TYPE T = ENUM[a,b,c,d,e,f] ⇒ 3 bits
```

Homework IX

1. Write a concrete and an abstract grammar for Pascal-like variable declarations.
2. Write a tree-walk evaluator that checks for multiple declarations of the same identifier.

Example 1 (Correct):

```
VAR x : CHAR; y,z,a,b : INTEGER; n,s : BOOLEAN;
```

Example 2 (Wrong):

```
VAR x, y, z, x, a : CHAR;
```

Example 3 (Wrong):

```
VAR x : CHAR; y,z,a,x : INTEGER; n,x : BOOLEAN;
```