ĐẠI HỌC BÁCH KHOA HÀ NỘI
VIỆN CÔNG NGHỆ THÔNG TIN VÀ TRUYỀN THÔNG

Unit 10
Semantic Analysis

Summary

- **Semantics of programming languages**
- **Symbol tables**
  - Scope Rules and Symbol Tables
  - Translation Schemes for building Symbol Tables
- **Type checking**
  - Type system
  - Specifying a Type Checker
  - Type Conversion

Semantic analysis

- Extract types and other information from the program
- Check language rules that go beyond the grammar
- Assign storage locations
- Construct symbol tables – For each identifier in the program, record its attributes (kind, type, etc.)

Semantic analysis

- Find errors after parsing
  - The type of the right-side expression of an assignment statement should match the type of the left-side, and the left-side needs to be a properly declared and assignable identifier (i.e. not some sort of constant).
  - The parameters of a function should match the arguments of a function call in both number and type.
  - The language may require that identifiers are unique, disallowing a global variable and function of the same name.
  - The operands to multiplication operation will need to be of numeric type, perhaps even the exact same type depending on the strictness of the language
- Parse trees are used in semantic analysis

Type checking

- A **compiler** must check that the program follows the *Type Rules* of the language.
- Information about *Data Types* is maintained and computed by the **compiler**.
- The *Type Checker* is a module of a **compiler** devoted to type checking tasks.

Examples of Tasks

- The operator modulus (%) is defined only if the operands are integers;
- Indexing is allowed only on an array and the index must be an integer;
- A function must have a precise number of arguments and the parameters must have a correct type;

Type checking

- Type Checking may be either *static* or *dynamic*.
- The one done at compile time is static.
- In languages like Pascal and C type checking is primarily static and is used to check the correctness of a program before its execution.
- Static type checking is also useful to determine the amount of memory needed to store variables.
- The design of a Type Checker depends on the syntactic structure of language constructs, the *Type Expressions* of the language, and the rules for assigning types to constructs.

Type Expressions

- A **Type Expression** denotes the type of a language construct.
- A type expression is either a *Basic Type* or is built applying *Type Constructors* to other types.
- A *Basic Type* is a type expression (int, real, boolean, char). The basic type void represents the empty set and allows statements to be checked;
- Type expressions can be associated with a name: *Type Names* are type expressions;
- A *Type Constructor* applied to type expressions is a type expression.

Type expresions (con'd)

- *Array*. If T is a type expression, then *array*(I,T) is a type expression denoting an array with elements of type T and index range in I (e.g.,array[1..10] of int == array(1..10,int))
- Cartesian Product If $T_1$and T_2 are type expressions, then their Cartesian Product T1× T2 is a type expression;
- Record. Similar to Product but with names for different fields (used to access the components of a record).

  Example of a C record type

```
struct
{
double r;
int i;
}
```

Type expressions (con'd)

- *Pointer*. If T is a type expression, then pointer(T) is the type expression "pointer to an object of type T"
- *Function*. If D is the domain and R the range of the function then wedenote its type by the type expression: D : R.
- Example

  The Pascal function:

  function f(a, b: char): integer

  has type: $char \times char : int$.

Type System

- **Type System:** Collection of rules for assigning type expressions to the various part of a program.
- Type Systems are specified using syntax directed definitions.
- A *type checker* implements a type system.
- A language is *strongly typed* if its **compiler** can guarantee that the program it accepts will execute without type errors.

Specification of a Type Checker

- We specify a type checker for a simple language where identifiers have an associated type.
- Attribute Grammar for Declarations and Expressions:

$P \rightarrow D;E$

$D \rightarrow D;D \mid id : T$

$T \rightarrow char \mid int \mid array[num]\ of\ T \mid \uparrow T$

$E \rightarrow literal \mid num \mid id \mid E\ mod\ E \mid E[E] \mid E\uparrow$

Syntax-Directed Translation

- Technique used to build semantic information for large structures, based on its syntax.
- In a compiler, Syntax-Directed Translation is used for
  - Constructing Abstract Syntax Tree
  - Type checking
  - Intermediate code generation
- The semantics (i.e., meaning) of the various constructs in the language is viewed as attributes of the corresponding grammar symbols.
- Attributes are associated with Terminal as well as Nonterminal symbols

Attributes

- **Synthesized attribute**: An **attribute** that gets its values from the attributes attached to the children of its nonterminal.
  - Value flows from child to parent in the parse tree.
  - Example: val in Expression grammar
- **Inherited attribute**: An **attribute** that gets its values from the attributes attached to the parent (or siblings) of its nonterminal.
  - Value flows into a node in the parse tree from parents and/or siblings.
  - Example: type of VarList in declaration grammar

Syntax Directed Definition

- **Syntax Directed Definitions** are a generalization of context-free grammars in which:
  1. Grammar symbols have an associated set of **Attributes**;
  2. Productions are associated with **Semantic Rules** for computing the values of attributes.
- Such formalism generates **Annotated Parse-Trees** where each node of the tree is a record with a field for each attribute (e.g., X.a indicates the attribute a of the grammar symbol X).

Forms of a syntax directed definition

- A grammar production Y --> $X_1 \ldots X_n$ may have zero or more associated semantic rules. Each semantic rules has the form, $b = f(c_1,\ldots,c_k)$ are attributes of the grammar symbol in the production such that:
  1. b is a synthesized attribute and $c_1,\ldots,c_k$ are the attributes of the grammar symbols on the rhs or
  2. b is an inherited attribute of one of the RHS grammar symbols and $c_1,\ldots,c_k$ are any other attributes in the production.
- If the function f does not have side effects, syntax directed definitions is also called as attribute grammars.

Example

Production	Semantic rules
$L \rightarrow E$ return	Print (E.val)
$E \rightarrow E_1+T$	E.val = E1.val + T.val
$E \rightarrow T$	E.val = T.val
$T \rightarrow T_1 * F$	T.val = T1.val * F.val
$T \rightarrow F$	T.val = F.val
$F \rightarrow (E)$	F.val = E.val
$F \rightarrow$ num	F.val = num.Lexval

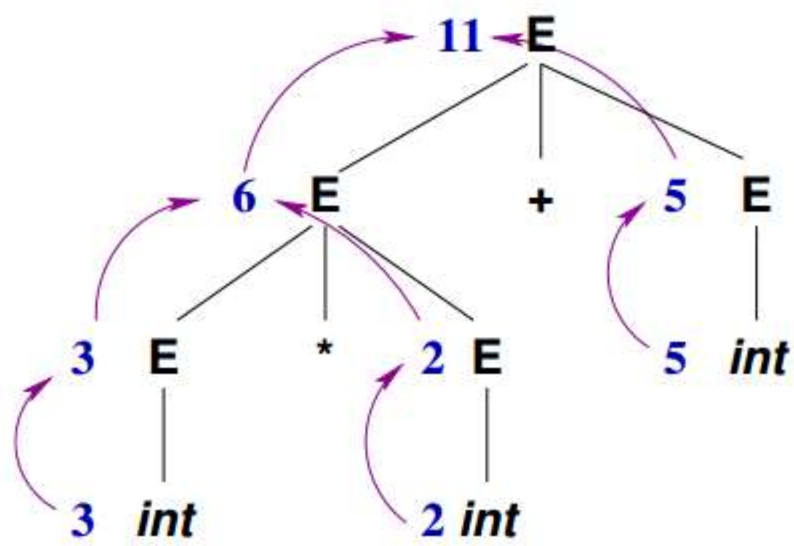
*Consider the Grammar for arithmetic expressions above. The **Syntax Directed Definition** associates to each non terminal a synthesized an attribute called **val**.*

Synthesized Attribute Example

$$
\begin{array}{|lll|}
\hline
E & \longrightarrow & E * E \\
E & \longrightarrow & E + E \\
E & \longrightarrow & \texttt{int} \\
\hline
\end{array}
$$

$$
\begin{array}{llll}
E & \longrightarrow & E_1 * E_2 & \{E.val := E_1.val * E_2.val\} \\
E & \longrightarrow & E_1 + E_2 & \{E.val := E_1.val + E_2.val\} \\
E & \longrightarrow & \texttt{int} & \{E.val := \texttt{int}.val\}
\end{array}
$$

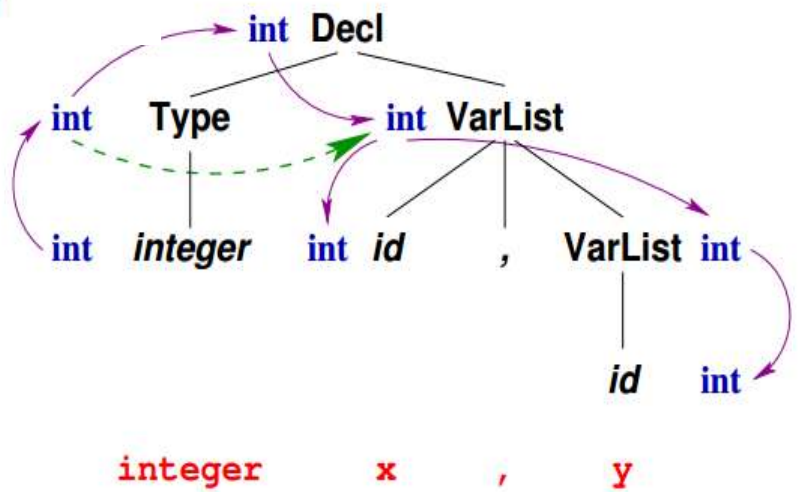
Information Flow for 3*2+5



Inherited Attribute Example

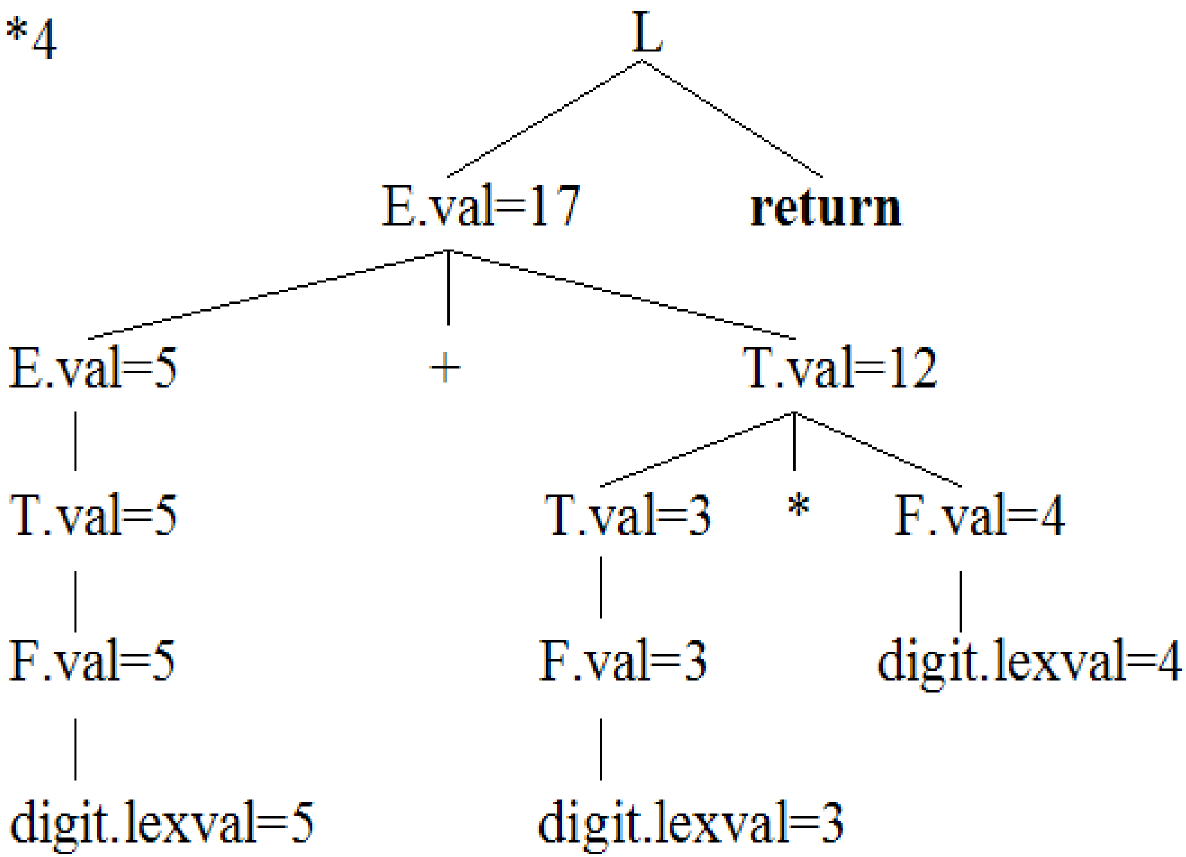
$$\begin{array}{rcl}
\textit{Decl} & \longrightarrow & \textit{Type VarList} \\
\textit{Type} & \longrightarrow & \texttt{integer} \\
\textit{Type} & \longrightarrow & \texttt{float} \\
\textit{VarList} & \longrightarrow & \texttt{id}\ \texttt{,}\ \textit{VarList} \\
\textit{VarList} & \longrightarrow & \texttt{id}
\end{array}$$

$$\begin{array}{rcll}
\textit{Decl} & \longrightarrow & \textit{Type VarList} & \{\textit{VarList.type} := \textit{Type.type}\} \\
\textit{Type} & \longrightarrow & \texttt{integer} & \{\textit{Type.type} := \textit{int}\} \\
\textit{Type} & \longrightarrow & \texttt{float} & \{\textit{Type.type} := \textit{float}\} \\
\textit{VarList} & \longrightarrow & \texttt{id}\ \texttt{,}\ \textit{VarList}_1 & \{\textit{VarList}_1\textit{.type} := \textit{VarList.type}; \\
 & & & \quad \texttt{id}\textit{.type} := \textit{VarList.type}\} \\
\textit{VarList} & \longrightarrow & \texttt{id} & \{\texttt{id}\textit{.type} := \textit{VarList.type}\}
\end{array}$$



Example of annotated parse tree

Input: 5+3*4



Type checker of identifiers

PRODUCTIONS	SEMANTIC RULES
$D \to \mathsf{id} : T$	$addtype(\mathsf{id}.entry, T.type)$
$T \to \mathsf{char}$	$T.type := char$
$T \to \mathsf{int}$	$T.type := int$
$T \to \uparrow T_1$	$T.type := pointer(T_1.type)$
$T \to \mathsf{array}[\mathsf{num}]\ \mathsf{of}\ T_1$	$T.type := array(1..\mathsf{num}.val, T_1.type)$

Insert type of variable to symbol table

```
do {// code in compileVardecl function
      eat(TK_IDENT);
      checkFreshIdent(currentToken->string);
      varObj = createVariableObject(currentToken->string);
      eat(SB_COLON);
      varType = compileType();

      varObj->varAttrs->type = varType;
      declareObject(varObj);

      eat(SB_SEMICOLON);
    } while (lookAhead->tokenType == TK_IDENT);
//data type is returned by function compileType in the next slide.
```

```
Type* compileType(void) {
  Type* type;
  Type* elementType;
  int arraySize;
  Object* obj;
  switch (lookAhead->tokenType)
{
  case KW_INTEGER:
    eat(KW_INTEGER);
    type =  makeIntType();
    break;
  case KW_CHAR:
    eat(KW_CHAR);
    type = makeCharType();
    break;
  case KW_ARRAY:
    eat(KW_ARRAY);
    eat(SB_LSEL);
    eat(TK_NUMBER);
    arraySize = currentToken-
>value;
    eat(SB_RSEL);
    eat(KW_OF);
    elementType =
compileType();
    type =
makeArrayType(arraySize,
elementType);
    break;
  case TK_IDENT:
    eat(TK_IDENT);
    obj =
checkDeclaredType(currentToken-
>string);
    type = duplicateType(obj-
>typeAttrs->actualType);
    break;
  default:
    error(ERR_INVALID_TYPE,
lookAhead->lineNo, lookAhead-
>colNo);
    break;
  }
  return type;}
```

Type checker of expressions

PRODUCTIONS	SEMANTIC RULES
$E \rightarrow \mathsf{literal}$	$E.type := char$
$E \rightarrow \mathsf{num}$	$E.type := int$
$E \rightarrow \mathsf{id}$	$E.type := lookup(\mathsf{id}.entry)$
$E \rightarrow E_1 \ \mathsf{mod}\ E_2$	$E.type :=$ if $E_1.type = int$ and $E_2.type = int$ then int else $type\_error$
$E \rightarrow E_1[E_2]$	$E.type :=$ if $E_2.type = int$ and $E_1.type = array(s,t)$ then t else $type\_error$
$E \rightarrow E_1\uparrow$	$E.type :=$ if $E_1.type = pointer(t)$ then t else $type\_error$

Type checker of statements

PRODUCTIONS	SEMANTIC RULES
$S \rightarrow \text{id} := E$	$S.type :=$ if id.$type = E.type$ then $void$ else $type\_error$
$S \rightarrow \text{if } E \text{ then } S_1$	$S.type :=$ if $E.type = boolean$ then $S_1.type$ else $type\_error$
$S \rightarrow \text{while } E \text{ do } S_1$	$S.type :=$ if $E.type = boolean$ then $S_1.type$ else $type\_error$
$S \rightarrow S_1 ; S_2$	$S.type :=$ if $S_1.type = void$ and $S_2.type = void$ then $void$ else $type\_error$

Type checker of functions

PRODUCTIONS	SEMANTIC RULES
$D \rightarrow \text{id} : T$	$addtype(\text{id}.entry, T.type); D.type := T.type$
$D \rightarrow D_1 ; D_2$	$D.type := D_1.type \times D_2.type$
$Fun \rightarrow \text{fun} \ \ \text{id}(D) : T ; B$	$addtype(\text{id}.entry, D.type{:}T.type)$
$B \rightarrow \{S\}$	
$S \rightarrow \text{id}(EList)$	$E.type :=$ if $lookup(\text{id}.entry){=}t_1 : t_2$ and $EList.type{=}\ t_1$ then t_2 else $type\_error$
$EList \rightarrow E$	$EList.type := E.type$
$EList \rightarrow EList, E$	$EList.type := EList_1.type \times E.type$

Function for checking equivalence of types

```
function sequiv(s, t): boolean;
begin
    if s and t have the same basic type then
          return true;
    else if s = array(s1, s2) and t  = array(t1, t2) then
          return sequiv(s1, t1) and sequiv(s2, t2)
    else if s = s1 x s2 and t  = t1 x t2) then
          return sequiv(s1, t1) and sequiv(s2, t2)
    else if s = pointer(s1) and t  = pointer(t1) then
          return sequiv(s1, t1)
    else if s = s1→ s2 and t  = t1→ t2 then
          return sequiv(s1, t1) and sequiv(s2, t2)
    else
          return false;
end;
```

Type Conversion

- What's the type of "x + i" if:
  1. x is of type real;
  2. i is of type int;
  3. Different machine instructions are used for operations on reals and integers.
- Depending on the language, specific conversion rules must be adopted by the **compiler** to convert the type of one of the operand of +.
- The type checker in a **compiler** can insert these conversion operators into the intermediate code.
- Such an implicit type conversion is called *Coercion*.

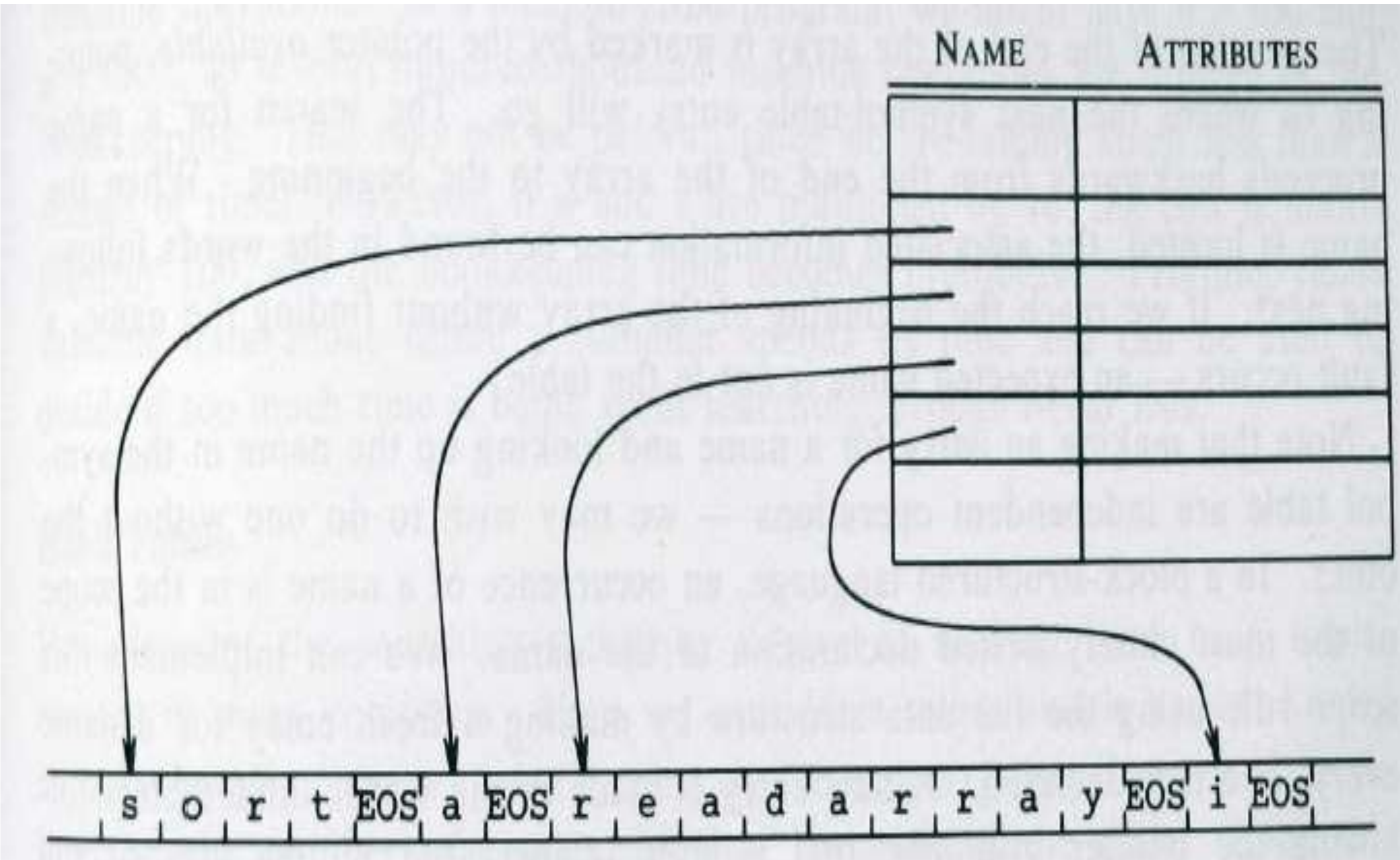
Type coercion rules

PRODUCTIONS	SEMANTIC RULES
$E \rightarrow \text{num}$	$E.type := int$
$E \rightarrow \text{num.num}$	$E.type := real$
$E \rightarrow \text{id}$	$E.type := lookup(\text{id}.entry)$
$E \rightarrow E_1 \text{ op } E_2$	$E.type :=$ if $E_1.type = int$ and $E_2.type = int$ then int else if $E_1.type = int$ and $E_2.type = real$ then $real$ else if $E_1.type = real$ and $E_2.type = int$ then $real$ else if $E_1.type = real$ and $E_2.type = real$ then $real$ else $type\_error$

Symbol Table

- The **Symbol Table** is the major inherited attribute and the major data structure as well.
- Symbol Tables store information about the name, type, scope and allocation size.
- Symbol Table must maintain efficiency against insertion and lookup.
- Dynamic data structures must be used to implement a symbol table: Linear Lists and Hash Tables are the most used.
- Each entry has the form of a record with a field for each peace of information.

Storing names



Symbol Tables and Scope Rules

- A **Block** in a programming language is any set of language constructs that can contain declarations.
- A language is **Block Structured** if
  1. Blocks can be *nested* inside other blocks, and
  2. The *Scope* of declarations in a block is limited to that block and the blocks contained in that block.
- **Most Closely Nested Rule.** Given several different declarations for the same identifier, the declaration that applies is the one in the most closely nested block.

Symbol Tables and Scope Rules (con’d)

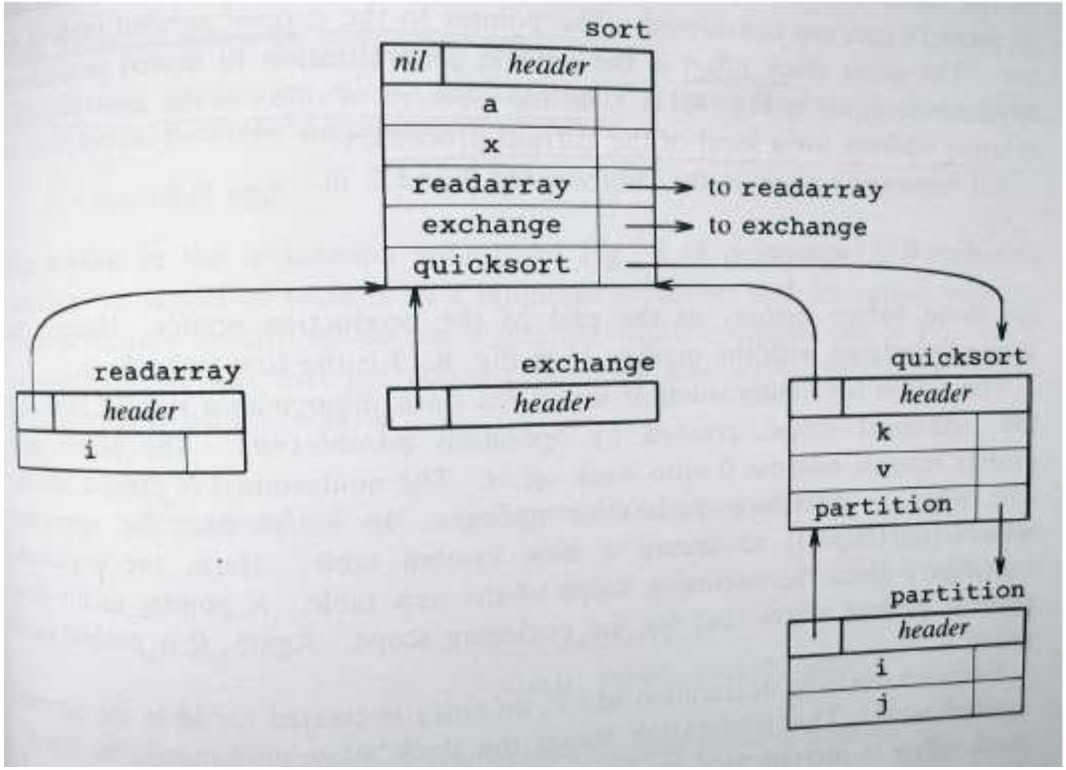
- To implement symbol tables complying with nested scopes
  1. The *insert* operation into the symbol table must not overwrite previous declarations;
  2. The *lookup* operation into the symbol table must always refer to the most close block rule;
  3. The *delete* operation must delete only the most recent declarations.
- The symbol table behaves in a stack-like manner.

Procedure Activations: Example

```
program sort;
   var a : array[0..10] of integer;
        x : integer;
   procedure readarray;
       var i : integer;
       begin … a … end { readarray };
   procedure exchange( i:integer; j : integer );
       begin
           x := a[i]; a[i] := a[j]; a[j] := x
       end { exchange };
   procedure quicksort( m: integer; n: integer );
       var k, v : integer;
   function partition( y:integer; z: integer ): integer;
       var i, j : integer;
       begin… a …
             … v …
             … exchange( i, j ); …
       end { partition };
   begin … end { quicksort };
begin … end { sort };
```

Maintain separate symbol tables for each scope

- Tables must be linked both from inner to outer scope, and from outer to inner



Lexical- Vs. Syntactic-Time Construction

- Information is first entered into a symbol table by the lexical analyzer only if the programming language does not allow for different declarations for the same identifier (scope).
- If scoping is allowed, the lexical analyzer will only return the name of the identifier together with the token
- The identifier is inserted into the symbol table when the syntactic role played by the identifier is discovered.

Relative Address

- **Relative Address.** Is a storage allocation information consisting of an offset from a base (usually zero) address: The Loader will be responsible for the run-time storage.

Computes relative address

Use a global variable called *offset*.

$$P \rightarrow \{\text{offset} := 0\}\ D$$

$$D \rightarrow D; D$$

$$D \rightarrow \mathsf{id} : T \qquad \{enter(\mathsf{id}.name,\ T.type,\ offset);$$
$$\textbf{offset := offset + T.width}\}$$

$$T \rightarrow \mathsf{int} \qquad \{T.type := int;\ T.width := 4\}$$

$$T \rightarrow \mathsf{real} \qquad \{T.type := real;\ T.width := 8\}$$

$$T \rightarrow \mathsf{array}[\mathsf{num}]\ \mathsf{of}\ T_1 \qquad \{T.type := array(\mathsf{num}.val, T_1.type);$$
$$T.width := \mathsf{num}.val * T_1.width\}$$

$$T \rightarrow \uparrow T_1 \qquad \{T.type := pointer(T_1.type);\ T.width := 4\}$$

Computes relative address

- The global variable *offset* keeps track of the next available address.
- Before the first declaration, *offset* is set to 0
- As each new identifier is seen it is entered in the symbol table and *offset* is incremented.
- *type* and *width* are synthesized attributes for non-terminal T.

Keeping Track of Scope Information

- Consider *Nested Procedures*: When a nested procedure is seen processing of declarations in the enclosing procedure is suspended.
- To keep track of nesting a stack is maintained.
- We associate a new symbol table for each procedure:
- When we need to *enter* a new identifier into a symbol table we need to specify which symbol table to use.

Processing declarations in nested procedures

$P \rightarrow \mathbf{M}\ D$	$\{addwidth(top(tblptr), top(offset));$ $pop(tblptr);\ pop(offset)\}$
$\mathbf{M} \rightarrow \epsilon$	$\{t := mktable(nil);$ $push(t, tblptr);\ push(0, offset)\}$
$D \rightarrow D; D$	
$D \rightarrow \text{proc id;}\mathbf{N}\ D_1; S$	$\{t := top(tblptr);\ addwidth(t, top(offset));$ $pop(tblptr);\ pop(offset);$ $enterproc(top(tblptr), \text{id}.name, t)\}$
$D \rightarrow \text{id} : T$	$\{enter(top(tblptr), \text{id}.name,\ T.type,\ top(offset));$ $top(offset) := top(offset) + T.width\}$
$\mathbf{N} \rightarrow \epsilon$	$\{t := mktable(top(tblptr));$ $push(t, tblptr);\ push(0, offset)\}$

Keeping Track of Scope Information

- The semantic rules make use of the following procedures and stack variables:
  1. *mktable(previous)* creates a new symbol table and returns its pointer. The argument *previous* is the pointer to the enclosing procedure.
  2. The stack *tblptr* holds pointers to symbol tables of the enclosing procedures.
  3. The stack *offset* keeps track of the relative address w.r.t. a given nesting level.
  4. *enter(table,name,type,offset)* creates a new entry for the identifier *name* in the symbol table pointed to by *table*, specifying its *type* and *offset*.
  5. *addwidth(table,width)* records the cumulative *width* of all the entries in *table* in the header of the symbol table.
  6. *enterproc(table,name,newtable)* creates a new entry for procedure *name* inthe symbol table pointed to by *table*. The argument *newtable* points to the symbol table for this procedure *name*.