Type Checking

Roadmap (Where are we?)

Last lecture
- Context-sensitive analysis
  - → Motivation
  - → Attribute grammars
  - → Ad hoc Syntax-directed translation

This lecture ←
- Type checking
  - → Type systems
  - → Using syntax directed translation
- Symbol tables
  - → Lexical scoping
  - → Implementation
    - Stack
    - Threaded stack

Types

Type: A set of values and meaningful operations on them

Types provide semantic "sanity checks" (consistency checks) and determine efficient implementations for data objects

Types help identify

- → errors, if an operator is applied to an incompatible operand
  - dereferencing of a non-pointer
  - adding a function to something
  - incorrect number of parameters to a procedure
  - ...
- → which operation to use for overloaded names and operators, or what type coercion to use (e.g.: 3.0 + 1)
- → identification of polymorphic functions

Type Systems

Type system: Each language construct (operator, expression, statement, ...) is associated with a type expression. The type system is a collection of rules for assigning type expressions to these constructs.

Type expressions for

- → basic types
  - `integer, char, real, boolean, typeError`
- → constructed types // T is a type expression
  - `array(lb…ub, T)` // array of T
  - `pointer(T)` // pointer to T
  - T1 **x** T2 // tuple of T1, T2
  - T1 → T2 // function w/ arg T1 returning T2

Type System Properties

- Progress
  - → Given expression e, either
    - e is a value with some type T
    - e -> e' (e can be evaluated to produce expression e')
  - → I.e., prevent expressions such as (2 3) that cannot be evaluated
- Preservation
  - → Given expression e with type T
    - If e -> e' then e' must also have type T
  - → I.e., prevents type of expression e from changing at run time
- Soundness
  - → If a type system supports progress & preservation, then
    - Given expression e, e ->* v (for some value v) or e diverges
  - → I.e., well-typed programs don't go wrong

Type Checker

- A type checker implements a type system. It computes or "constructs" type expressions for each language construct

- Static type checking
  - → Detects type errors at compile time
  - → No run time overhead
  - → Not always possible (e.g., A[i])

- Dynamic type checking
  - → Performed at run time
  - → More flexible, allows prototyping
  - → Run-time overhead to maintain & check tags

Type Inference (for Expressions)

- Specifies the type of an expression
- Example
  - → If operands of addition are of type integer, result is of type integer
  - → Result of unary & operator is pointer to type of operand
- Denotational semantics of type inference rule

$$\frac{E \qquad e_1 : \text{integer} \qquad E \qquad e_2 : \text{integer}}{E \qquad (e_1 + e_2) : \text{integer}}$$

where E is a type environment that maps constants and variables to their type expressions.

- Question
  - → How to specify rules that allow type coercion (type widening) from integers to reals in arithmetic expressions?

3.0 + 1 or 1 + 3.0

Type Inference (in General)

- Goal
  - → Given expression with no type annotations, reconstruct valid type for the expression, or determine there is no valid typing
- Approach
  - → Use type variables for unknown types
  - → Generate equality constraints among types and type variables
  - → Solve constraints to determine valid typing (unification)
  - → May require general Constraint Logic Programming (CLP)

Type Equivalence

Structural - type equivalence: type names are expanded
Name - type equivalence: type names are not expanded

Example:

```
type A is  array(1..10) of integer;
type B is  array(1..10) of integer;
a : A;
b : B;
c, d: array(1..10) of integer;
e: array(1..10) of integer;
```

Answer: structural equivalence: **(a, b, c, d, e)**
name equivalence: **(a), (b), (c, d, e)**

Syntax Directed Translation Scheme (in CUP)

Revisit our type inference rule for "+".

```
exp  ::=  exp:e1  PLUS exp:e2
   {: if (e1 == sym.INT && e2 == sym.INT )
         RESULT = sym.INT ;
      else {
         RESULT = typeError;
         System.out.println("Error: illegal operand types");
      } :}
```

- The definition of type expression as Java types (static final int fields in class sym) should be done in mycc.cup.
- The assignment of type expression Java types to terminals and nonterminals of the grammar is done in mycc.cup.

Syntax Directed Translation Scheme (in Yacc)

Revisit our type inference rule for "+".

```
exp  :  exp '+' exp  {  if ($1 == integer && $3 == integer)
                            $$ = integer;
                        else {
                            $$ = typeError;
                            printf("Error: illegal operand types\n");
                        } }
```

- The definition of type expression as C types (structs) should be done in attr.h . attr.c may contain helper functions.
- The assignment of type expression C types to terminals and nonterminals of the grammar is done in parse.y.

Type Checker Example

Grammar for source language:

P ::= D ; E
D ::= D ; E | id: T
T ::= char | integer | array [num] of T | $\uparrow$ T
E ::= literal | num | id | E mod E | E[E] | E $\uparrow$

T ::= T $\rightarrow$ T   declaration
E ::= E (E)   application

- Basic types *char*, *integer*, *typeError*
- assume all arrays start at 1, *e.g.*,
  array [256] of char
  results in the type expression $array(1 \ldots 256, char)$
- $\uparrow$ builds a pointer type, so $\uparrow$ integer
  results in the type expression *pointer(integer)*

Type Checker Example (cont.)

- Handling declarations

D	::=	id: T	$\{ addtype(\text{id}.entry,\ T.type) \}$
T	::=	char	$\{ T.type \leftarrow char \}$
T	::=	integer	$\{ T.type \leftarrow integer \}$
T	::=	$\uparrow \mathrm{T}_1$	$\{ T.type \leftarrow pointer(T_1.type) \}$
T	::=	array [num] of T_1	$\{ T.type \leftarrow array(1 \ldots \text{num}.val,\ T_1.type) \}$

Type Checker Example (cont.)

- Handling expressions

E	::=	literal	$\{ E.type \leftarrow char \}$
E	::=	num	$\{ E.type \leftarrow integer \}$
E	::=	id	$\{ E.type \leftarrow lookup(\text{id}.entry) \}$
E	::=	E_1 mod E_2	$\{ E.type \leftarrow$ if $E_1.type = integer$ and $E_2.type = integer$ then $integer$ else $typeError \}$
E	::=	$\mathrm{E}_1[\mathrm{E}_2]$	$\{ E.type \leftarrow$ if $E_2.type = integer$ and $E_1.type = array(s,t)$ then t else $typeError \}$
E	::=	$\mathrm{E}_1 \uparrow$	$\{ E.type \leftarrow$ if $E_1.type = pointer$ then t else $typeError \}$

Type Checker Example (cont.)

- Handling statements

$S ::= \mathsf{id} \leftarrow E \quad \{ S.type \leftarrow \text{ if id}.type = E.type$
$\quad \text{then } void$
$\quad \text{else } typeError \}$

$S ::= \text{if } E \text{ then } S_1 \quad \{ S.type \leftarrow \text{ if } E.type = boolean$
$\quad \text{then } S_1.\mathrm{type}$
$\quad \text{else } typeError \}$

$S ::= \text{while } E \text{ do } S_1 \quad \{ S.type \leftarrow \text{ if } E.type = boolean$
$\quad \text{then } S_1.\mathrm{type}$
$\quad \text{else } typeError \}$

$S ::= S_1 \,;\, S_2 \quad \{ S.type \leftarrow \text{ if } S_1.type = void$
$\quad \text{then } void$
$\quad \text{else } typeError \}$

Type Checker Example (cont.)

- Handling functions

$T ::= T_1 \rightarrow T_2 \quad \{ T.type \leftarrow (T_1.type \rightarrow T_2.type) \}$

$E ::= E_1 \,(\, E_2 \,) \quad \{ E.type \leftarrow \text{ if } E_1.type = s \rightarrow t$
$\quad \text{and } E_2.type = s \text{ then } t$
$\quad \text{else } typeError \}$

Symbol Tables

- Symbol table
  - → Compile-time structures for resolving references to names
    - Will look at run-time structures later
  - → Can also associate attributes with name
- Attributes possibly associated with name
  - → Type
  - → Declaring procedure
  - → Lexical level
  - → If array, number and size of dimensions
  - → If function, number and type of parameters

Lexically-scoped Symbol Tables § 5.7 in EaC

The problem
- The compiler needs a distinct record for each declaration
- Nested lexical scopes admit duplicate declarations

The interface
- insert(*name, level*) – creates record for *name* at *level*
- lookup(*name, level*) – returns pointer or index
- delete(*level*) – removes all names declared at *level*

Many implementation schemes have been proposed (see § B.4)
- We'll stay at the conceptual level
- Hash table implementation is tricky, detailed, & fun

Example

```
procedure p {
    int a, b, c
    procedure q {
        int v, b, x, w
        procedure r {
            int x, y, z
            ....
        }
        procedure s {
            int x, a, v
            ...
        }
        ... r ... s
    }
    ... q ...
}
```

```
B0: {
     int a, b, c
B1:  {
          int v, b, x, w
B2:            {
               int x, y, z
               ....
          }
B3:            {
               int x, a, v
               ...
          }
          ...
     }
   ...
   }
```


Example

```
procedure p {
    int a, b, c
    procedure q {
        int v, b, x, w
        procedure r {
            int x, y, z
            ....
        }
        procedure s {
            int x, a, v
            ...
        }
        ... r ... s
    }
    ... q ...
}
```

c

b, w

x, a, v

```
B0: {
     int a_0, b_1, c_2
B1:  {
          int v_3, b_4, x_5, w_6
B2:            {
               int x_7, y_8, z_9
               ....
          }
B3:            {
               int x_10, a_11, v_12
               ...
          }
          ...
     }
   ...
   }
```

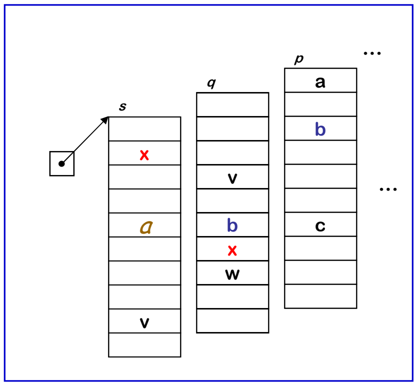
a_{11}, b_4, c_2, v_{12}, w_6, x_{10}, *no y or z*

Picturing it as a series of Algol-like procedures

Lexically-scoped Symbol Tables

High-level idea

- Create a new table for each scope
- Chain them together for lookup



"Chain of tables" implementation

- ***insert()*** **may need to create table**
- **it always inserts at current level**
- ***lookup()*** **walks chain of tables & returns first occurrence of name**
- ***delete()*** **throws away table for level** ***p*****, if it is top table in the chain**

Individual tables can be hash tables.

Lexically-scoped Symbol Tables

High-level idea

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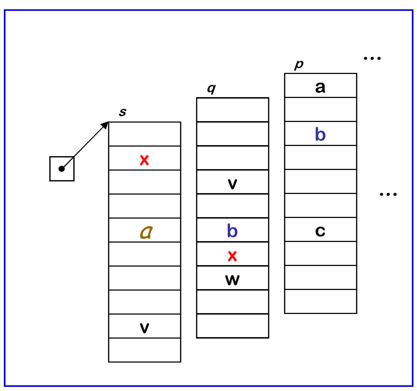


Remember

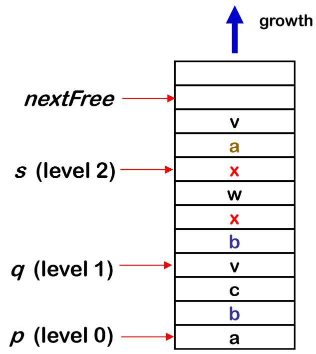
a_{11}, b_4, c_2, v_{12}, w_6, x_{10}, *no y or z*

the names visible in s

If we add the subscripts, the relationship between the code and the table becomes clear

Implementing Lexically Scoped Symbol Tables

Stack organization



Implementation

- insert () creates new level pointer if needed and inserts at nextFree
- lookup () searches linearly from nextFree-1 forward
- delete () sets nextFree to the equal the start location of the level deleted.

Advantage

- Uses <u>much</u> less space

Disadvantage

- Lookups can be expensive

Implementing Lexically Scoped Symbol Tables

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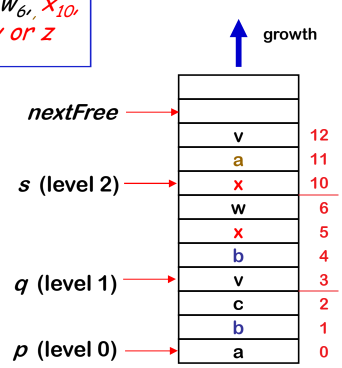

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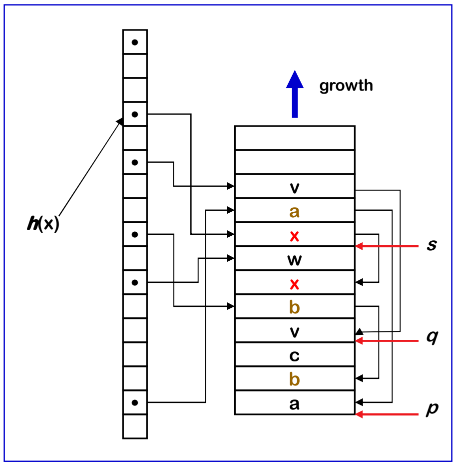
Implementing Lexically Scoped Symbol Tables

Threaded stack organization



Implementation

- insert () puts new entry at the head of the list for the name
- lookup () goes direct to location
- delete () processes each element in level being deleted to remove from head of list

Advantage

- lookup is fast

Disadvantage

- delete takes time proportional to number of declared variables in level

Implementing Lexically Scoped Symbol Tables

Threaded stack organization

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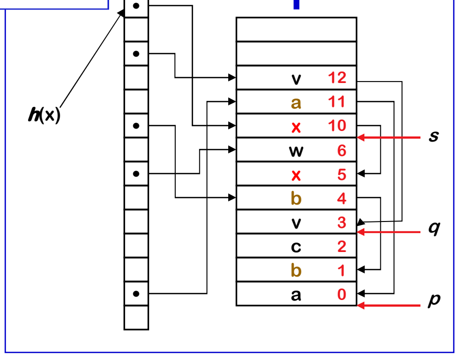

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