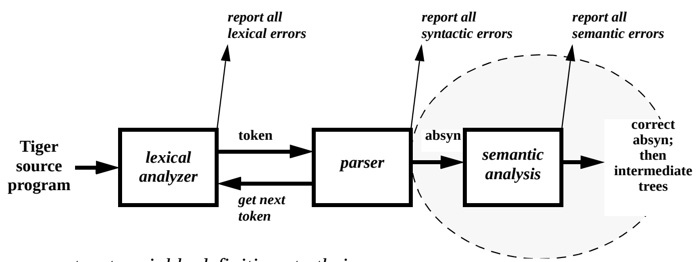
Tiger Semantic Analysis



- *construct variable definitions to their uses*
- *checks that each expression has a correct type*
- *translates the abstract syntax into a simpler intermediate representation suitable for generating machine code.*

Connecting Definition and Use ?

- *Make sure **each variable is defined**; Check the **type consistency** !*

```
.......
function f(v : int) =
 let var v := 6
     function g(x : int) =
          (print (x+v); print "\n")

     function h(v : int) =
          (print v; print "\n")

   in g v;
      let var v := 8 in print v end;
      h v;
  end
```

- ***Solution:** use a **symbol table** --- traverse the **abstract syntax tree** in certain order while maintaining a "(variable -> type)" symbol table.*

Symbol Tables

- *Conceptually, a **symbol table** (also called **environment**) is a set of "(name, attribute)" pairs.*
- *Typical **Names:*** *strings, e.g.,* `"foo"`, `"do_nothing1"`, ...
- *Typical **Attributes** (also called bindings):*

type identifier	type (e.g., `int` , `string`)
variable identifier	type ; access info. or value
function identifier	arg. & result type; access info. or ...

- ***Main Issues** --- for a symbol table **T***

Given an identifier name, how to look up its attribute in T ?
How to insert or delete a pair of new *"(id, attr)"* into the table T?
Efficiency is important !!!

Symbol Tables (cont'd)

- *How to deal with **visibility** (i.e., lexical scoping under nested block structure) ?*

```
       .......                              Initial Table T
v1    function f(v : int) =                   insert v1;
v2     let var v := 6                         insert v2;

         function g(x : int) =
            (print (x+v); ...)                  lookup sees v2

v3       function h(v : int) =                insert v3;
            (print v; ...)                      lookup sees v3
                                              MUST delete v3;
        in g v;                                 lookup sees v2

v4       let var v := 8                       insert v4;
          in print v                            lookup sees v4
         end;                                 MUST delete v4;

         h v;                                   lookup sees v2
      end                                     MUST delete v2;
      ..........
```

Symbol Table Impl.

- ***Hash Table*** *--- efficient, but need explicit "delete" due to side-effects !*

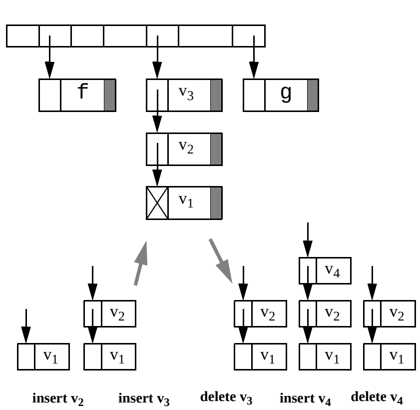
```
Initial Table T
   insert v1;
   insert v2;

      lookup sees v2

   insert v3;
      lookup sees v3
   MUST delete v3;
      lookup sees v2

   insert v4;
      lookup sees v4
   MUST delete v4;

      lookup sees v2
   MUST delete v2;
```



Symbol Table Impl. (cont'd)

- ***Balanced Binary-Tree*** *---- "**persistent**", "**functional**", yet "**efficient**"*

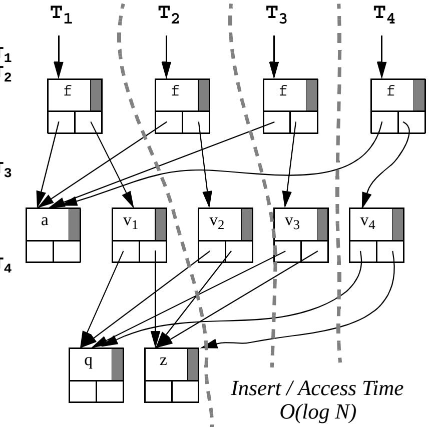
```
Initial Table T0
   insert v1;                 T1
   insert v2;                 T2

      lookup sees v2

   insert v3;                 T3
      lookup sees v3
(* delete v3;*)  use T2
      lookup sees v2

   insert v4;                 T4
      lookup sees v4
(* delete v4;*)  use T2

      lookup sees v2
(* delete v2;*)  use T1
```



Summary: Symbol Table Impl.

- *Using **hash-table** is ok but explicit "delete" is a **big headache** !*
- *We prefer the **functional** approach --- using <u>persistent balanced binary tree</u> --- no need to explicit "delete" ; access and insertion time O(log N)*
- *The **Symbol** signature (symbol table is an abstract datatype --- used to hide the implementation details)*

```
signature SYMBOL =
sig
  eqtype symbol
  val symbol : string -> symbol
  val name : symbol -> string

  type 'a table
  val empty : 'a table
  val enter : 'a table * symbol * 'a -> 'a table
  val look : 'a table * symbol -> 'a option
end
```

No "delete" because we use "functional" approach!

String <==> Symbol

- *Using string as the search key is slow --- involves a string comparison*
- *Associate each string with a integer --- which is used as the key for all access to the symbol table (i.e., binary tree)*

```
type symbol = string * int

exception Symbol
val nextsym = ref 0

structure H = ... a HashTable from STRING to INTEGER ...

fun symbol name =
  case H.find hashtable name
   of SOME i => (name, i)
    | NONE => let val i = !nextsym
               in inc nextsym;
                  H.insert hashtable (name,i);
                  (name,i)
              end

fun name(s,n) = s
```

Summary: Symbol Table

- *A **symbol** is a pair of string and integer* `(s,n)` *where the string* `s` *is the identifier name, the integer* `n` *is its associated search key.*
- *The **mapping** from a string to its corresponding search key (a integer) is implemented using a hash table.*
- *The **symbol table --- ** from a symbol to its attributes --- is implemented using* IntBinaryMap --- *a **persistent balanced binary tree**.*

```
structure Symbol :> SYMBOL = (* see Appel page 110 *)
struct
  type symbol = string * int
  ......
  type 'a table = 'a IntBinaryMap.intmap (* in SML Library *)

  val empty = IntBinaryMap.empty
  fun enter(t,(s,n),a) = IntBinaryMap.insert(t,n,a)
  fun look(t,(s,n)) = IntBinaryMap.look(t,n)
end
```


Environments

- ***Bindings*** ---- *interesting attributes associated with type, variable, or function identifiers during compilations.*
- ***Type bindings*** --- *internal representation of types*

```
structure Types =
struct
  type unique = unit ref

  datatype ty
     = INT
     | STRING
     | RECORD of (Symbol.symbol * ty) list * unique
     | ARRAY of ty * unique
     | NIL
     | UNIT
     | NAME of Symbol.symbol * ty option ref
end
```

- ***Variable/Function Bindings*** --- *type + localtion&access information*

Environments (cont'd)

- *The signature for Environment*

```
signature Env =
struct
  type access
  type level
  type label
  type ty   (* = Type.ty *)

  datatype enventry
     = VARentry of {access : access, ty : ty}
     | FUNentry of {level : level, label : label,
                    formals : ty list, result : ty}

  val base_tenv : ty Symbol.table
  val base_env : enventry Symbol.table
end
```

location of the variable at runtime

static nesting level

the function machine code label ...

Normally we build one environment for each name space !

`base_tenv` *is the initial type environment*
`base_env` *is the initial variable+function environment*

Tiger Absyn

```
datatype 'a option = NONE | SOME of 'a

datatype var = ...
and exp
  = ...
  | OpExp of {left: exp, oper: oper, right: exp,...
  | LetExp of {decs: dec list, body: exp, ...

and dec
  = FunctionDec of fundec list
  | TypeDec of tydec list
  | VarDec of vardec

withtype
    field = {name: symbol, typ: symbol, pos: pos}

and fundec = {name: symbol, params: field list,
              result : (symbol * pos) option,
              body: exp, pos: pos}
```

multually-recursive declarations
(must be consecutive in the source)

Type-Checking Expressions

```
type tenv = Types.ty Symbol.table
type env = enventry Symbol.table

(* transexp : env * tenv -> exp -> ty *)
fun transexp (env,tenv) =
  let fun g(OpExp{left,oper=A.plusOp,right,pos}) =
              (checkInt(g left, pos);
               checkInt(g right, pos);
               Types.INT)
        | g(LetExp{decs, body, pos}) =
            let val (env',tenv') =
                  transdecs (env,tenv) decs
             in transexp (env',tenv') body
            end
        | ....
   in g
  end
```

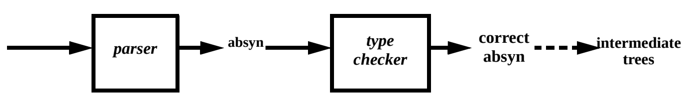

Type-Checking Declarations

```
(* transdec : env * tenv -> dec -> env * tenv *)
fun transdec (env,tenv) =
  let fun g(VarDec{var,typ=NONE,init}) =
           let val ty = transexp (env,tenv) init
               val b = VARentry{access=(),ty=ty}
            in (enter(env,var,b), tenv)
           end
        | g(FunctionDec[{name,params,body,pos,result=_}])=
           let val b = FUNentry{...}
               val env' = enter(env,name,b)
               val env'' = enterparams(params,env')
            in transexp (env'',tenv) body;
               (env', tenv)
           end
        | g ...
   in g
  end

(* transdecs : env * tenv -> dec list -> env * tenv *)
fun transdecs (env, tenv) [] = (env,tenv)
  | transdecs (env, tenv) (a::r) =
       let val (env', tenv') = transdec (env, tenv) a
        in trandsdecs (env', tenv') r
       end
```


Type-Checking

- *The **type** of an expression tells us the values it can denote and the operations that can be applied to it.*
- ***Type system** --- definition of well-formed types + a set of **typing rules** that define what type-consistency means.*
- ***Type-checking** ensures that the operations in a program are applied properly. A program that executes without type errors is said to be **type safe.***
- ***Static** Type-checking **:** type are checked at <u>compile time</u>. **(once and for all)***



- ***Dynamic** Type-checking **:** types are checked at <u>run time</u>. **(inside the code)***

Type Safety

- *Modern programming languages are always equipped with a **strong type system** ------ meaning a program will either run successfully, or the compiler & the runtime system will report the type error.*

  strongly-typed languages: Modula-3, Scheme, ML, Haskell
  weakly-typed languages: C, C++

- ***Safety ----** a language feature is **unsafe** if its misuse can corrupt the runtime system so that further execution of the program is not faithful to the language semantics. (e.g., no array bounds checking, ...)*
- *A **statically-typed** language (e.g., ML, Haskell) does most of its type-checking at compile time (except array-bounds checking).*
- *A **dynamically-typed** language (e.g., Scheme, Lisp) does most of its type-checking at run time.*

Main Issues

- ***What are valid type expressions ?***

  e.g., int, string, unit, nil, array of int, record {...

- ***How to define two types are equivalent ?***

  name equivalence or structure equivalence

- ***What are the typing rules ?***
- ***How much type info should be specified in the source program?***

  implicitly-typed lang., e.g., ML ----- uses type inference

  explicitly-typed lang. e.g., Tiger, Modula-3 ----- must specify the type of each newly-introduced variables.

Types in Tiger

Tiger types *are* `ty -> type-id | array of type-id | {}`
`| {id : type-id {,id : type-id}}`

type-id *is defined by type declarations:*
`tydec -> type type-id = ty`

Typechecker must translate all source-level type specification (in absyn) into the following internal type representation:

```
structure Types =
struct  type unique = unit ref

        datatype ty
           = RECORD of (Symbol.symbol * ty) list * unique
           | NIL
           | INT
           | STRING
           | ARRAY of ty * unique
           | NAME of Symbol.symbol * ty option ref
           | UNIT
end
```

implementing Name Equivalence

for recursive type declarations

Type Equivalence

When are two type expressions equivalent ?

- ***Name equivalence*** *(NE) : T_1 and T_2 are equivalent iff T_1 and T_2 are identical type names defined by the exact same type declaration.*
- ***Structure equivalence*** *(SE) : T_1 and T_2 are equivalent iff T_1 and T_2 are composed of the same constructors applied in the same order.*

Here `point` ***and*** `ptr` ***are equivalent under SE but not equivalent under NE***

```
type point = {x : int, y : int}
type ptr = {x : int, y : int}
function f(a : point) = a
```

Here the redeclaration of `point` ***defines a new type under NE; thus it is a type error when function*** `f` ***is applied to*** `p`

```
type point = {x : int, y : int}
var p : point = point {x=3, y=5}
var q : point = f(p)
```


Typing Rules in Tiger

- *Tiger uses* ***name equivalence;*** *type constraints must be a* ***type-id*** *(used on variable declarations, function parameters and results, array elements, and record fields)*
- *The expression* **nil** *has the special type* ***NIL***. ***NIL*** *belongs to every record type ---- it is equivalent to any record type.* ***nil*** *must be used in a context where its type can be determined.*

```
var p : point := nil           OK
if p <> nil then ...           OK
var a := nil                   Illegal
```

- *For variable declaration:* `var id : type-id := exp` *the type of expression* `exp` *must be equivalent to type* `type-id`.
- *Assignment expression* `id := exp` *--- id & exp have equivalent type.*

Typing Rules in Tiger (cont'd)

- *Function call: the types of formal parameters must be equivalent to the types of actual arguments.*
- *Array subscript must has integer type.*
- *Array creation* `type-id [exp1] of exp2` — exp_1 has type int, exp_2 must have type equivalent to that of the element of `type-id`
- *Record creation* `type-id {id = exp1, ...}` — the type of each field (exp_i) must have type equivalent to that defined in `type-id`
- *If-expression* **if** exp_1 **then** exp_2 **else** exp_3 — *the type of* exp_1 *must be integer, the type of* exp_2 *and* exp_3 *should be equivalent.*
- *For-expression* **for** *id* := exp_1 **to** exp_2 **do** exp_3 — *the type of* exp_1 *and* exp_2 *must be integer.* exp_3 *should produce no value ...*
- *For more info, read* ***Appendix in Appel.***

Recursive Type Declarations

- *How to convert the following declaration into the internal type representations ?*

```
type list = {first : int, rest : list}
```

Problem*: when we do the conversion of the r.h.s., "*`list`*" is not defined in the* `tenv` *yet.*

Solution*: use the special* **`Name`** *type*

```
datatype ty = NAME of Symbol.symbol * ty option ref
            | ......
```

First, enter a "header" type for `list`

```
val tenv' = enter(tenv,name, NAME(name,ref NONE))
```

Then, we process the body (i.e., r.h.s) of the type declarations, and assign the result into the reference cell in the **`NAME`** *type*

Recursive Function Declarations

- ***Problem****: when we process the right hand side of function declarations, we may encounter symbols that are not defined in the* `env` *yet*

```
function do_nothing1(a: int, b: string)= do_nothing2(a+1)
function do_nothing2(d: int) = do_nothing1(d, "str")
```

- ***Solution****: first put all function names (on the l.h.s.) with their header information (e.g., parameter list, function name, type, etc., all can be figured out easily) into the* `env` --------- *then process each function's body in this augmented* `env`.

Other Semantic Check

Many other things can be done in the type-checking phase:

- *resolve overloading operators*
- *type inference*
- *check if all identifiers are defined*
- *check correct nesting of* **`break`** *statements .*

Comming soon ---

Assignment 5 is to write the type-checker.