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!

```haskell
function f(v : int) =
  let var v := 6
```

```haskell
function g(x : int) =
  (print (x+v); print "\n")
```

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

```haskell
in g v;
let var v := 8 in print v end;
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)?

```haskell
Initial Table T
```

| v₁ | function f(v : int) =
|    |   let var v := 6 |
| v₂ |   function g(x : int) =
|    |     (print (x+v); ...) |
| v₃ |   function h(v : int) =
|    |     (print v; ...) |
|    | in g v;
|    | let var v := 8 in print v end;
|    | end
| v₄ |   h v;
|    | end |

```

```haskell
Initial Table T
```

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|    |   let var v := 6 |
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|    |     (print (x+v); ...) |
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```

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Initial Table T
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|    | end
| v₄ |   h v;
|    | end |

```haskell
Initial Table T
```
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;
- MUST delete v3;
- Lookup sees v2
- Insert v4;
- Lookup sees v2
- MUST delete v2;
- Lookup sees v2

Symbol Table Impl. (cont’d)

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

Initial Table T0

- Insert v1;
- Insert v2;
- Lookup sees v2
- Insert v3;
- (* delete v3; *) use T2
- Lookup sees v2
- Insert v4;
- (* delete v4; *) use T2
- Lookup sees v2
- (* delete v2; *) use T1

Insert / Access Time O(log N)

Summary: Symbol Table Impl.

- Using hash-table is ok but explicit "delete" is a big headache!
- We prefer the functional approach --- using persistent balanced binary tree --- 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)

```plaintext
signature SYMBOL = sig
  eqtype symbol
  val symbol : string -> symbol
  val name : symbol -> string
  val 'a table : '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)

```plaintext
type symbol = string * int
exception Symbol

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.

```ml
structure Symbol = SYMBOL
  (* see Appel page 110 *)
structure symbol = string * int
......
val empty = IntBinaryMap.empty
fun enter(t, (s, n), a) = IntBinaryMap.insert(t, n, a)
fun look(t, (s, n)) = IntBinaryMap.look(t, n)
```

Environments

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

```ml
structure Types =
  struct
    type unique = unit ref
    datatype ty
      = INT
      | STRING
      | RECORD of (Symbol.symbol * ty) list * unique
      | ARRAY of ty * unique
      | UNIT
      | NAME of Symbol.symbol * ty option ref
  end
```

- Variable/Function Bindings --- type + location&access information

Environments (cont’d)

- The signature for Environment

```ml
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
```

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

```ml
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}
```
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 *)

defun 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 *)

defun 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 compile time, (once and for all)

  parser --------> absyn --------> type checker --------> correct absyn --------> intermediate trees

- Dynamic Type-checking : types are checked at run time, (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

\[ ty -> \text{type-id} | \text{array of type-id} | \{\} \]
\[ | \{ id : \text{type-id}, \ldots \} \]

\text{type-id} is defined by type declarations:

\[ \text{tydec} -> \text{type type-id} = ty \]

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

\[ \text{structure Types} = \]
\[ \text{struct type unique = unit ref} \]
\[ \text{datatype ty} = \]
\[ \text{RECORD of} \{(\text{Symbol.symbol} * \text{ty}) \text{ list} * \text{unique}\} \]
\[ \text{NIL} \]
\[ \text{INT} \]
\[ \text{STRING} \]
\[ \text{ARRAY of ty * unique} \]
\[ \text{NAME of Symbol.symbol * ty option ref} \]
\[ \text{UNIT} \]
\[ \text{end} \]

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:

\[ \text{type point} = \{x : \text{int}, y : \text{int}\} \]
\[ \text{type ptr} = \{x : \text{int}, y : \text{int}\} \]
\[ \text{function f}(x : \text{point}) = a \]

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

\[ \text{type point} = \{x : \text{int}, y : \text{int}\} \]
\[ \text{var p : point} = \text{point} \{x=3, y=5\} \]
\[ \text{var q : point} = f(p) \]

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.

\[ \text{var p : point} = \text{nil} \text{ OK} \]
\[ \text{if p <> nil} \text{ then ...} \text{ OK} \]
\[ \text{var a} = \text{nil} \text{ Illegal} \]

• For variable declaration: \[ \text{var id : type-id} = \text{exp} \text{ the type of expression exp must be equivalent to type type-id.} \]

• Assignment expression \[ \text{id} := \text{exp} \text{ -- id & exp have equivalent type.} \]
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 [exp] of exp has type int, exp must have type equivalent to that of the element of type-id.

• Record creation type-id {id = exp,...} the type of each field (exp) must have type equivalent to that defined in type-id.

• If-expression if exp then exp2 else exp3 the type of exp must be integer, the type of exp2 and exp3 should be equivalent.

• For-expression for id := exp1 to exp2 do exp3 the type of exp1 and exp2 must be integer. exp3 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?

```plaintext
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

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

First, enter a “header” type for `list`

```plaintext
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

```plaintext
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.

Coming soon ---

Assignment 5 is to write the type-checker.