1

Static Semantics

- So far, our parser correctly parses syntactically correct programs
- This Pascal fragment is syntactically correct, but contains a semantic error.
  - We need to implement the type system

```
var i : integer;
begin
   i := 2.0 / 3.0;
end;
```

- Semantic consistency in a programming language is usually implemented via typing entities and checking for the consistent use of the entity
- Implementing the Static Semantics requires:
  - implementation of an identifier table to store information about identifiers
  - implementation of a type module which checks the usage of the identifiers

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Implementing the Type System

- Before proceeding further, we must note that the type checking we are required to implement will be spread throughout the parser.
  - This is the way we build the recursive descent compiler – by a process of enrichment.
- Implementation of the type system requires two things:
  - A specification of the type rules of the language.
  - A suitable representation of the type of entities in the compiler.
- The specification of the type rules will normally be provided by the programming language designer.
  - Type rules can be expressed in many different ways.
- The representation of types by the compiler may at first seem strange, but it is no different from the representation of any other piece of information.

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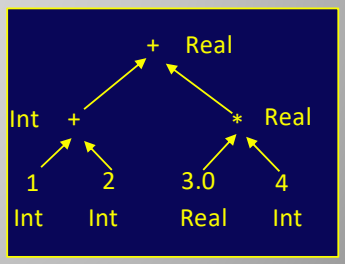
Arithmetic Expressions

- Consider simple arithmetic expressions:
  - this involves the parsers: Expression, Term & Factor.
- A simple evaluator of arithmetic expressions can be built by using a stack.
  - Operands are pushed on to the stack.
  - Operations are performed on the top of the stack.
- If we note the type of the objects, rather than the value we can deduce the type structure.
  - In real terms, we make the sub–parsers E,T & F return the type of the current sub–expression (rather than void).



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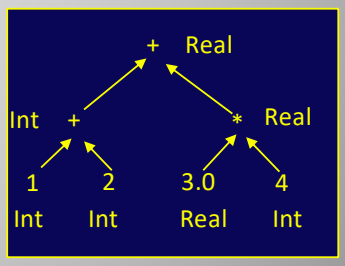
Arithmetic Expressions

- Type information, like the value of the expression is propagated back up the tree.
- We don't generate an explicit parse tree
  – our tree is represented by the run–time stack.
  - Parser methods often return a value such as the type of the exporession being evaluated.



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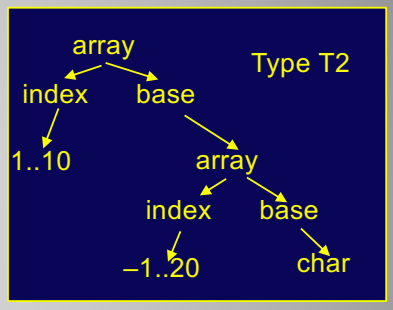
Representing Types

- Types aren't simple – they are structured – and so is their representation
- Example:

```
Type t = array[1..10] of  char;
```

- Our representation would need to record:
  - the fact that it is an array
  - the index type & range
  - the base type of the array
- These descriptions are recursive:

```
Type t2 = array[1..10] of array[-1..20] of char;
```



- Checking types then involves traversing the representation structure
- The representation structure is built out of:
  - the base types
  - the type constructors

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Type Nuts & Bolts

- Note the use of the variant record (discriminated union) type here.
  - Programming languages which support higher order functions need to be able to describe function/ procedures in the type system.

```
Type types is (int, real, char, bool, pointer, arry, recrd, set, file);
Type type_rep;
Type type_rep_ptr is access type_rep;
Type type_rep is record (ty : types) is
        ...
        case ty is
                when pointer => pointer_to : type_rep_ptr;
                when arry => base_ty : type_rep_ptr;
                                range_ty : type_rep_ptr;
                when set => set_of : type_rep_ptr;
                ...
        end case;
end record;
```

  - Simple languages (such as that in your assignment) have no structured types and hence are somewhat simpler.

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Limitations of C++

- C++ does not support discriminated unions as is found in some other languages such as Ada.
- This means that you have to create a struct or a class with all of the fields even though some fields are invalid for some types.
  - See the token class in the starter kit for your project. Not every token has an integer_value, real_value, string_value and identifier_value.
  - Care is necessary to ensure a field is not illegally referenced.
  - Can lead to some strange errors!

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Type Nuts & Bolts

- This is an example of a type comparison routine which implements structure equivalence.
  - Some languages use a simpler name equivalent system.
  - Some languages use a mixture of the two!

```
function comp_types(t1,t2 : type_rep_ptr) return boolean is
  begin – –  comp_types
    if t1.ty /= t2.ty then
      return false;
    else
      case t1.ty is
        when pointer => return comp_types(t1.pointer_to, t2.pointer_to);
        when arry => return comp_types(t1.range_ty, t2.range_ty) and then
          comp_types(t1.base_ty, t2.base_ty);
        ...
      end case;
    end if;
  end comp_types;
```


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Type Checking

- Look at the body of the parser for Term.

```
lhs, rhs : Type_Rep;
begin – – Term
  lhs := Factor;
  while member(symbol, mult) loop
    op := symbol;
    rhs := Factor;
    case op is
      when div => if comp_types(lhs, rhs)
                    and comp_types(lhs, TYPE_INTEGER) then
                    ...
                  else
                    syntax("Type error");
                  end if;
      when and => if comp_types(lhs, rhs)
                    and comp_types(lhs, TYPE_BOOLEAN) then
                    ...
                  else
                    syntax("Type error");
                  end if;
    ...
```


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Storing Type Information

- Information about user defined types must be stored somewhere.
- Two choices:
  - a type table which maps type names to type structures
  - a type table merged into the identifier table
- Different languages require different approaches, e.g.:
- Ada:

```
type foo is (a,b,c);
foo : foo;
```

- Pascal would disallow this declaration : it stores the type identifiers in the identifier table.
- SUMMARY:
  - Managing the type information is easy.
  - Formal type rules describe where you need to put type checking.
  - Types are represented internally using a tree structure.

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The identifier table

- Management of identifiers is one of the most pivotal aspects of the compiler.
- The identifier table stores:
  - Each identifier.
  - Information about that identifier:
    - Kind of object: variable, constant, parameter, ...
    - Type of object.
    - Address information etc.
- The organization of the identifier table depends on the language being used
  - in particular, we need to consider the scope rules of the language.
  - In a block structured language (Ada, Pascal, etc) when we enter a new scope level we can declare entities which are homomorphs to entities at outer scope levels.
  - In a language like FORTRAN, redeclaration would be an error (there is only one scope level).

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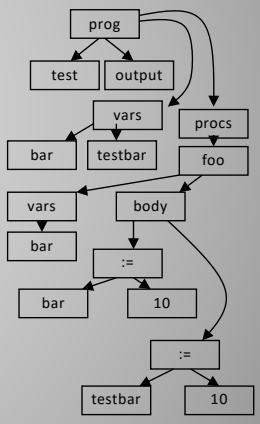
Identifiers

- We can now implement type information, but we need to determine which identifiers are valid (and their meaning) in our program.
  - We can use an abstract syntax tree:
- ```
  Program test(output);
  var bar, testbar : integer;
  procedure foo;
  var bar : integer;
  begin (* foo *)
    bar := 10;
    testbar := 10;
  end; (* foo *)
  begin (* test *)
    foo;
  end.
  ```



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The Identifier table

- To access the information needed, we need an auxiliary data structure
  - We need to know what things are in scope
- Aside: Scope rules
- The scope rules of the language define the *referencing environment* the module sees.
- Pascal has a scope environment that chains back through the nested modules
  - In the example, the local identifier `bar` and the main program's `testbar` identifiers are in scope inside procedure `foo`.
  - The identifier table also needs to implement the scope rules of the language.
- Observation: number the scope regions, the scopes *nest*.
  - We have only *one* thing contributing to the referencing environment at any given level
  - Our scope regions are therefore a simple linear list of blocks in scope.

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  ```

Scope

```
Program Scope(output);
var bar, testbar : integer;

  procedure one;
    var bar : integer;

    procedure two;
    begin (* two *)
         bar := 1;
    end; (* two *)

  begin (* one *)
    bar := 10;
    two;
    testbar := 10;
  end; (* one *)

    procedure three;
    begin (* three *)
        one;
    end; (* three *)

begin (* scope *)
  three;
end.
```

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Scope

```
Program Scope(output);
var bar, testbar : integer;

  procedure one;
    var bar : integer;

    procedure two;
    begin (* two *)
         bar := 1;
    end; (* two *)

  begin (* one *)
    bar := 10;
    two;
    testbar := 10;
  end; (* one *)

    procedure three;
    begin (* three *)
        one;
    end; (* three *)

begin (* scope *)
  foo;
end.
```

RE: bar(one), testbar(Scope), one, two

RE: bar(one), testbar(Scope), one, two

RE: bar(Scope), testbar(Scope), one, three

RE: bar(Scope), testbar(Scope), one, three

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Scope

- Note carefully how the local declaration of bar in procedure one hides the more global version in the main program.
  - But the other non-hidden entities are still visible, of course.
- Implementing this is not very hard!
- Look at the compilation process:
  - We see, in order, the following blocks:

    Scope, one , two, one, three, scope
  - Including the bodies!

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Scope

- While compiling one, we need Scope and one.
  - While doing two, we need Scope, one and two.
  - While doing three we need Scope…
- We can implement this by using an array structure where the n^{th} element has the module at scope level n
  - We simply search this from end to beginning!

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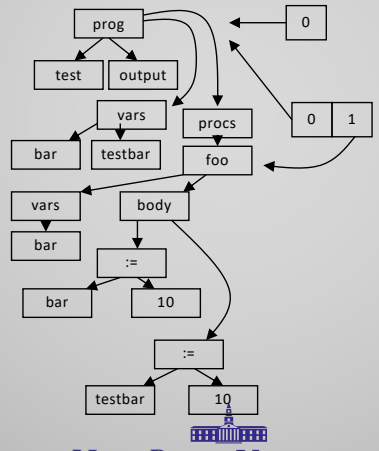
The Identifier Table

- As we traverse the abstract syntax tree, we need to resolve each identifier – build up the idtable array as we enter each new scope region.




```
Program test(output);
var bar, testbar : integer;
procedure foo;
var bar : integer;
begin (* foo *)
  bar := 10;
  testbar := 10;
end; (* foo *)
begin (* test *)
  foo;
end.
```

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Using the IDtable

- We discover an entity is undeclared by falling off the start of the idtable array
  - At this point, we need to enter the id into the idtable with type set to unknown
    - Prevent spurious errors from happening on every future reference
- Once we have determined which identifier it is, the lookup() method should return a reference to the identifier.

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Using the IDtable

- This reference should be written into the tree so that when we perform further work on the tree, we can directly locate what entity is being referenced.
  - You don't strictly need to do this, of course.
    - We could just use the lookup() method again, but this is somewhat wasteful
- IMPORTANT – our AST is now a DAG

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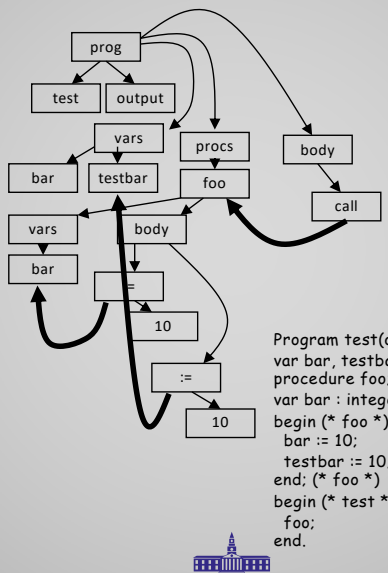
Tree with resolved IDs




```
Program test(output);
var bar, testbar : integer;
procedure foo;
var bar : integer;
begin (* foo *)
  bar := 10;
  testbar := 10;
end; (* foo *)
begin (* test *)
  foo;
end.
```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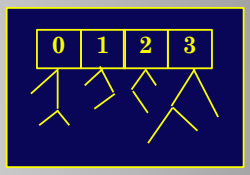
Id–table Organization

- Since we need to search the idtable frequently, we need an efficient storage regime.
  - We will use a sorted binary tree.
- Such a structure allows us to search in *O(logn)* time.
- We need a means of coping with multiple instances of an identifier at different scope levels, however.
  - Use an array of binary trees, indexed by scope level.



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Id–table Organization

- Implementing the scope rules is now easy:
  - We search for the identifier at the current level, and if not found we search the array backwards.
  - If still not found, it hasn't been declared!
- Question: how big an array do we need?
  - Not big, 10 to 12 is ample.
  - We can use an unconstrained array to avoid imposing a fixed limit on the number of scope levels!

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Id–table Contents

- What information is stored in the identifier table?
  - the name of the identifier (this is the search key!)
  - the kind of identifier: constant, type, variable, proc, func, etc
  - depending on the kind of identifier we will have other things:
    - value (if a constant)
    - list of parameters (if a function or a procedure)
    - result type (if a function)
    - the type of the identifier
    - the address of the identifier (if appropriate)
    - the scope level of the identifier
    - etc etc

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I d–Table details

- To manage our ID table, we will implement an Abstract Data Type/class.
  - The ADT will export some operations on the table entries.
  - The ADT will make use of a private variable which will refer to an idtable entry.
- Our idtable abstraction will maintain the scope level information as well.

```
with types, scanner;
use types, scanner;
package id_table is
    type idtable is private;
    idtable_error : exception;

    procedure enter_new_scope;
    procedure exit_scope;
    function lookup(s : str_ptr) return idtable;
```

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I d–Table details

- All of our compiler code should be self–checking: when the idtable module detects an inconsistency, it raises an exception.
- In addition to the 3 operations implemented above, there is an operation for entering a new identifier into the table and a collection of operations which return pieces of information about a particular identifier.

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Using the Id–table

- By using the idtable & the type system, we are able to choose the right alternative in statement
- Note the use of the selector operations kind and tipe.
  - Remember, the idtable is an abstract data type (class in C++)!

```
...
if symbol = identifier then
    id := lookup(token.ident_value);
    if (kind(id) = variable) or (kind(id) = func) then
        mustbe(becomes);
        if not type_equal(tipe(id), expression) then
            syntax("Type mismatch");
        end if;
    elsif kind(id) = proc then
        ...
    end if;
elsif have(begin_sym) then
```


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Using the Id–table

- QUESTION: What if the identifier wasn't yet declared?
  - Won't "lookup" fail??
  - NO! Our lookup routine will insert the identifier into the table & issue an error message when this happens!
  - The inserted ID is of type "unknown" - used to help error recovery.

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Using the Id–table

- Extracting information from the id–table is easier than putting it in!
- Consider the block parser in Pascal.
  - When we process a variable declaration:

```
var i, j, k : integer;
```

  - We don't know the type of the identifier `i` until we process the entire declaration!
  - There are a number of solutions to the problem, but the best is to enter the identifiers into the table (as they are encountered) and to then "fix–up" the type information.
  - Doing it this way, will cause errors about duplicate declarations to appear in the correct place.
  - Implementation of this scheme requires us to maintain a list of idtable type objects in the parser and the provision of a "fix–up" operation in the identifier table ADT.
    - Different languages require different sorts of fix–ups, Pascal and *lille* needs them for variable declarations and procedure/function declarations.

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Using the Id–table

```
– function enter_id(id : str_ptr; kind: id_kind := unknown;
                    ty : lang_type := type_unknown) return idtable;
...
    list := null;
    loop
        if symbol = identifier then
            add_to_list(list, enter_id(id => token.ident_value,
                                       kind => variable); get_token;
        else
            syntax("identifier expected");
        end if;
        ...
    end loop;
    if symbol = identifier then
        ty := lookup(token.ident_value); ...
    end if;
    while list /= null loop
        this_id := next_from_list(list);
        fix_up(this_id, ty);
        next(list);
    end loop;
```

Note how the use of default values makes this operation simpler

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Using the Id–table

- C++ has a limited form of default parameters. It can be used to some advantage, but it is not as versatile as the mechanism permitted in some other languages.

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Simple Coding tips for the id–table

- There are many coding tips for making life easier…
  - By choosing sensible default values for parameters, you can avoid having to make several similar procedures.
    - enter_id for example would also have several parameters for the value of a constant – all with defaults, and it is only when the object being entered is of kind = constant that these are used. You choose the appropriate one based on the type of the constant being entered!
  - Make all your idtable code self checking!
  - Implement a dump procedure which will print the identifier table
    - Make this callable from the parser.
    - You might like to make it be able to dump just the current scope level as an option. VERY useful wen debugging!

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