Syntax Errors; Static Semantics

Lecture 14

(from notes by R. Bodik)

Dealing with Syntax Errors

- One purpose of the parser is to filter out errors that show up in parsing
- Later stages should not have to deal with possibility of malformed constructs
- Parser must *identify* error so programmer knows what to correct
- Parser should *recover* so that processing can continue (and other errors found)
- Parser might even *correct* error (e.g., PL/C compiler could "correct" some Fortran programs into equivalent PL/1 programs!)

Identifying Errors

- All of the valid parsers we've seen identify syntax errors "as soon as possible."
- *Valid prefix property:* all the input that is shifted or scanned is the beginning of *some* valid program
- … But the rest of the input might not be
- So in principle, deleting the lookahead (and subsequent symbols) and inserting others will give a valid program.

Automating Recovery

- Unfortunately, best results require using semantic knowledge and hand tuning.
  - E.g., a(i].y = 5 might be turned to a[i].y = 5 if a is statically known to be a list, or a(i).y = 5 if a function.
- Some automatic methods can do an OK job that at least allows parser to catch more than one error.

Bison's Technique

- The special terminal symbol error is never actually returned by the lexer.
- Gets inserted by parser in place of erroneous tokens.
- Parsing then proceeds normally.

Example of Bison's Error Rules

- Suppose we want to throw away bad statements and carry on

```
stmt : whileStmt
     | ifStmt
     | …
     | error NEWLINE
     ;
```

Response to Error

- Consider erroneous text like

  if x y: …
- When parser gets to the y, will detect error.
- Then pops items off parsing stack until it finds a state that allows a shift or reduction on 'error' terminal
- Does reductions, then shifts 'error'.
- Finally, throws away input until it finds a symbol it can shift after 'error'

Error Response, contd.

- So with our example:

```
stmt : whileStmt
     | ifStmt
     | …
     | error NEWLINE
     ;
```

Bad input:

```
if x y: …
  x = 0
```

- We see 'y', throw away the 'if x', so as to be back to where a stmt can start.
- Shift 'error' and away more symbols to NEWLINE. Then carry on.

Of Course, It's Not Perfect

- "Throw away and punt" is sometimes called "panic-mode error recovery"
- Results are often annoying.
- For example, in our example, there's an INDENT after the NEWLINE, which doesn't fit the grammar and causes another error.
- Bison compensates in this case by not reporting errors that are too close together
- But in general, can get *cascade of errors.*

On to Static Semantics

- Lexical analysis
  - Produces tokens
  - Detects & eliminates illegal tokens
- Parsing
  - Produces trees
  - Detects & eliminates ill-formed parse trees
- Static semantic analysis
  - Produces "decorated tree" with additional information attached
  - Detects & eliminates remaining static errors

Static vs. Dynamic

- The term *static* used to indicate properties that the compiler can determine without considering any particular execution.
  - E.g., in

    ```
    def f(x) : x + 1
    ```

    Both uses of x refer to same variable
- *Dynamic* properties are those that depend on particular executions in general. E.g., will x = x/y cause arithmetic exception.

Tasks of the Semantic Analyzer

- Find the declaration that defines each identifier instance
- Determine the static types of expressions
- Perform re-organizations of the AST that were inconvenient in parser, or required semantic information
- Detect errors and fix to allow further processing

Typical Semantic Errors: Java, C++

- Multiple declarations: a variable should be declared (in the same region) at most once
- Undeclared variable: a variable should not be used before being declared.
- Type mismatch: type of the left-hand side of an assignment should match the type of the right-hand side.
- Wrong arguments: methods should be called with the right number and types of arguments.

A sample semantic analyzer

- works in two phases
  - i.e., it traverses the AST created by the parser:

1. For each declarative region in the program:
   - **process the declarations** =
     - add new entries to the symbol table and
     - report any variables that are multiply declared
   - **process the statements** =
     - find uses of undeclared variables, and
     - update the "ID" nodes of the AST to point to the appropriate symbol-table entry.
2. Process all of the statements in the program again,
   - use the symbol-table information to determine the type of each expression, and to find type errors.

Symbol Table = set of entries

- purpose:
  - keep track of names declared in the program
  - names of
    - variables, classes, fields, methods,
- symbol table entry:
  - associates a name with a set of attributes, e.g.:
    - kind of name (variable, class, field, method, etc)
    - type (int, float, etc)
    - nesting level
    - memory location (i.e., where will it be found at runtime).

Scoping

- symbol table design influenced by what kind of scoping is used by the compiled language
- Scope of a declaration: section of text where it applies
- Declarative region: section of text that bounds scopes of declarations (we'll say "region" for short)
- In most languages, the same name can be declared multiple times
  - if its declarations occur in different declarative regions, and/or
  - involve different kinds of names.

Scoping: example

- Java: can use same name for
  - a class,
  - field of the class,
  - a method of the class, and
  - a local variable of the method
- ***legal Java program:***

```
class Test {
   int Test;
   Test( ) { double Test; }
}
```

Scoping: overloading

- Java and C++ (but not in Pascal, C, or Pyth):
  - can use the same name for more than one method
  - as long as the number and/or types of parameters are unique.

```
int add(int a, int b);
float add(float a, float b);
```

Scoping: general rules

- The scope rules of a language:
  - determine which declaration of a named object corresponds to each use of the object.
  - i.e., scoping rules map uses of objects to their declarations.
- C++ and Java use ***static scoping***:
  - mapping from uses to declarations is made at compile time.
  - C++ uses the "most closely nested" rule
    - a use of variable x matches the declaration with the most closely enclosing scope.
    - a deeply nested variable x hides x declared in an outer region.
  - in Java:
    - inner regions cannot define variables defined in outer regions

Scope levels

- In Java, each function has two or more declarative regions:
  - one for the parameters,
  - one for the function body,
  - and possibly additional regions in the function
    - for each *for* loop and
    - each nested block (delimited by curly braces)
- In Pyth, each function has one per function (possibly plus more for nested functions)

Example (assume C++ rules)

```
void f( int k ) {          // k is a parameter
    int k = 0;             // also a local variable (not legal in Java)
    while (k) {
        int k = 1;         // another local var, in a loop (not ok in Java)
    }
}
```

- the outermost region includes just the name "f", and
- function f itself has three (nested) regions:
  1. The outer region for f just includes parameter k.
  2. The next region is for the body of f, and includes the variable k that is initialized to 0.
  3. The innermost region is for the body of the while loop, and includes the variable k that is initialized to 1.

Dynamic scoping

- Not all languages use static scoping.
- Original Lisp, APL, and Snobol use **dynamic** scoping.
- Dynamic scoping:
  - A use of a variable that has no corresponding declaration in the same function corresponds to the declaration in the **most-recently-called still active** function.
- With this rule, difficult for compiler to determine much about identifiers

Example

- For example, consider the following code:

```
void main() { f1(); f2(); }
void f1() { int x = 10; g(); }
void f2() { String x = "hello"; f3();g(); }
void f3() { double x = 30.5; }
void g() { print(x); }
```

- With static scoping, illegal.
- With dynamic scoping, prints 10 and hello

Used before declared?

- Can names be used before they are defined?
  - Java: a method or field name *can* be used before the definition appears; *not* true for a variable.
  - In Pyth, almost anything can be used before declaration, where syntactically possible

Simplification

- From now on, assume that our language:
  - uses static scoping
  - requires that *all* names be declared before they are used
  - does not allow multiple declarations of a name in the same region
    - even for different kinds of names
  - *does* allow the same name to be declared in multiple nested regions
    - but only once per region
  - uses the same region for a method's parameters and for the local variables declared at the beginning of the method

- Rules in Project 3 will differ!

Symbol Table Implementations

- In addition to the above simplification, assume that the symbol table will be used to answer two questions:

  1. Given a declaration of a name, is there already a declaration of the same name in the current region
     - i.e., is it multiply declared?

  2. Given a use of a name, to which declaration does it correspond (using the "most closely nested" rule), or is it undeclared?

Symbol Table is Just Means to an End

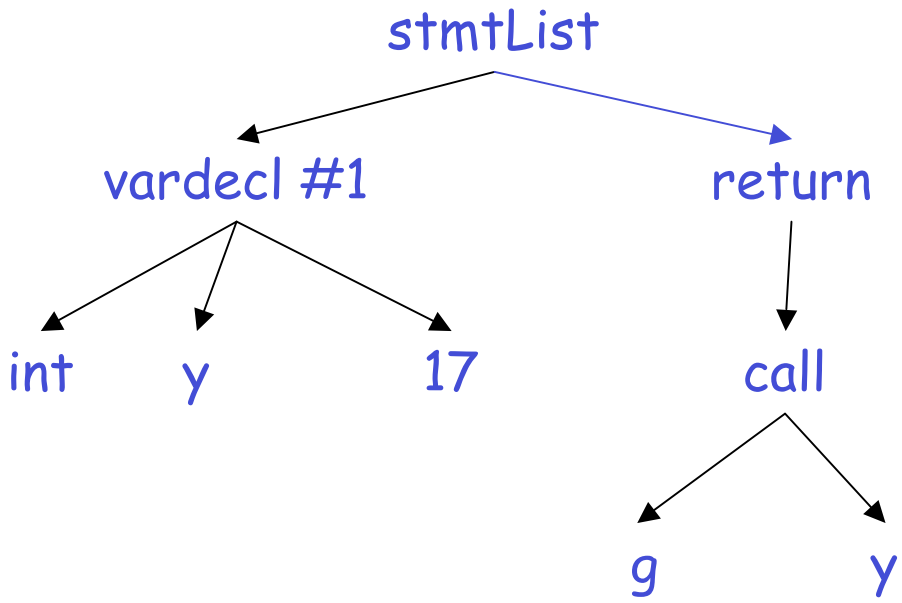
- The symbol table is only needed to answer those two questions, i.e.
  - once all declarations have been processed to build the symbol table,
  - and all uses have been processed to link each ID node in the abstract-syntax tree with the corresponding symbol-table entry,
  - then the symbol table itself is no longer needed
    - because no more lookups based on name will be performed

Decorating a Tree

- Program:

  int y = 17;

  return g(y);



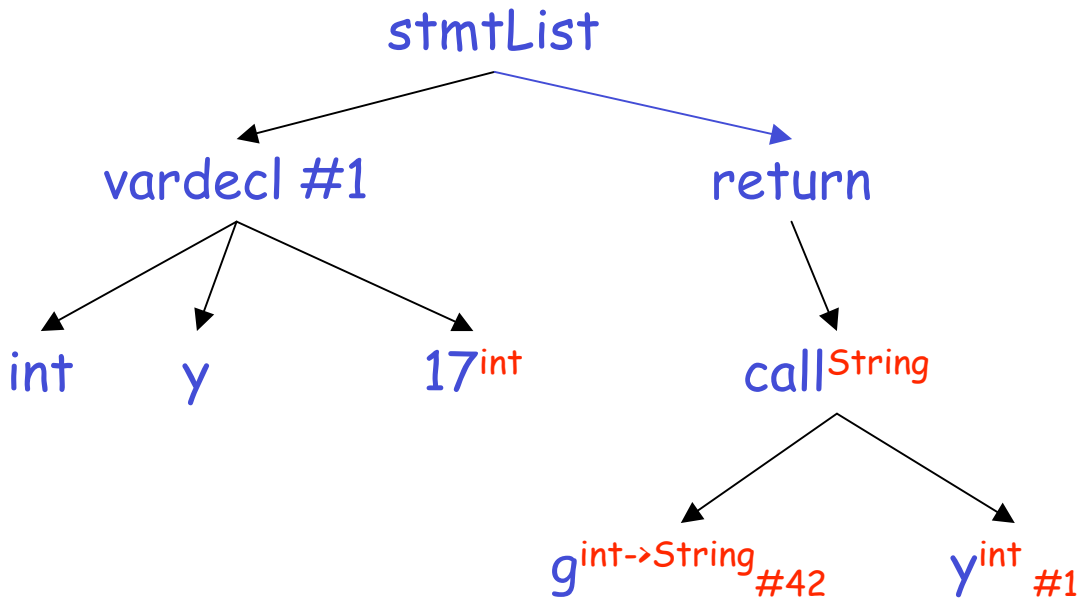
Decorating a Tree

- Program:

  int y = 17;

  return g(y);

- Idea: decorate tree with type, declaration data.



What operations do we need?

- Essentially, we need a data structure like environment diagrams in CS61A, minus dynamic information (i.e., variable values).
- So we will need to:
  1. Look up a name in the current declarative region only to check if it is multiply declared
  2. Look up a name in the current and enclosing regions
     - to check for a use of an undeclared name, and
     - to link a use with the corresponding symbol-table entry
  3. Insert a new name into the symbol table with its attributes.
  4. Do what must be done when entering a new region.
  5. Do what must be done when leaving a region.

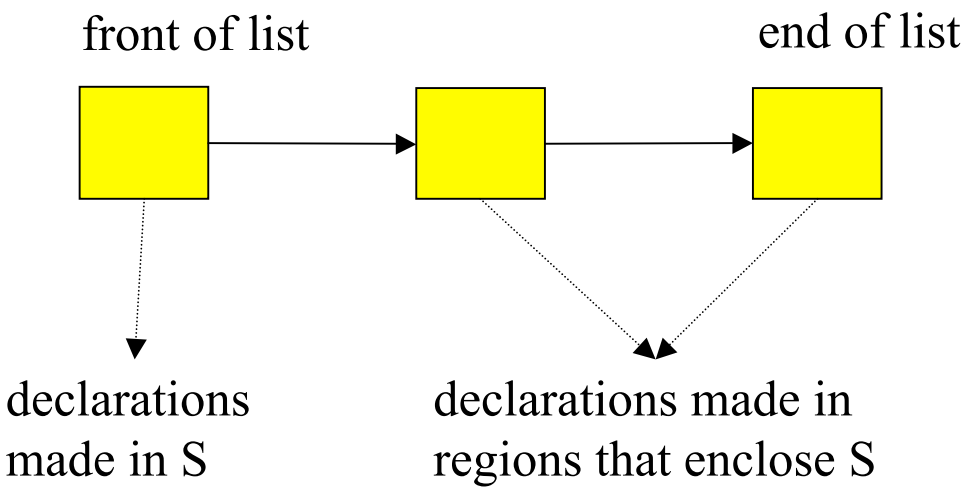
Two possible symbol table implementations

1. a list of tables
2. a table of lists

- For each approach, we will consider
  - what must be done when entering and exiting a region,
  - when processing a declaration, and
  - when processing a use.
- Simplification:
  - assume each symbol-table entry includes only:
    - the symbol name
    - its type
    - the nesting level of its declaration

Method 1: List of Dictionaries

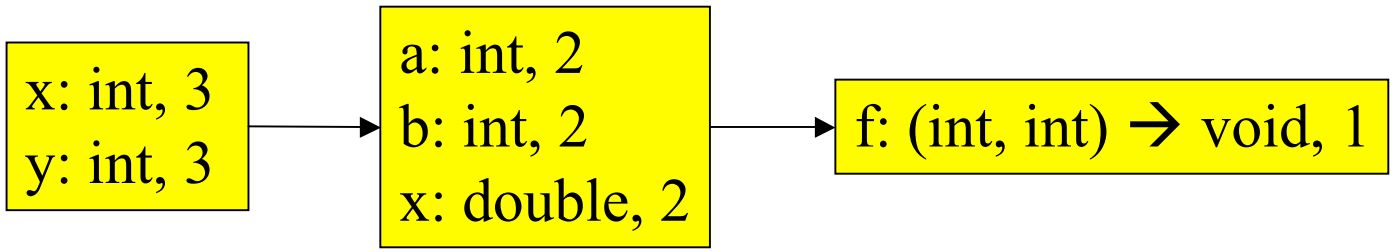
- The idea:
  - symbol table = a list of dictionaries,
  - one dictionary for each currently visible region.
- When processing a declarative region S:



Example:

```
void f(int a, int b) {
   double x;
   while (...) { int x, y; ... }
}
void g() { f(); }
```

- After processing declarations inside the while loop:



List of Dictionaries: The Operations

1. On entry to a declarative region:
   - increment the current level number and add a new empty dictionary to the front of the list.
2. To process a declaration of x:
   - look up x in the first dictionary in the list.
     - If it is there, then issue a "multiply declared variable" error;
     - otherwise, add x to the first table in the list.

… continued

3. To process a use of x:
   - look up x starting in the first dictionary in the list;
     - if it is not there, then look up x in each successive dictionary in the list.
     - if it is not in *any* dictionary then issue an "undeclared variable" error.
4. On leaving a region,
   - remove the first dictionary from the list and decrement the current level number.

Class Members

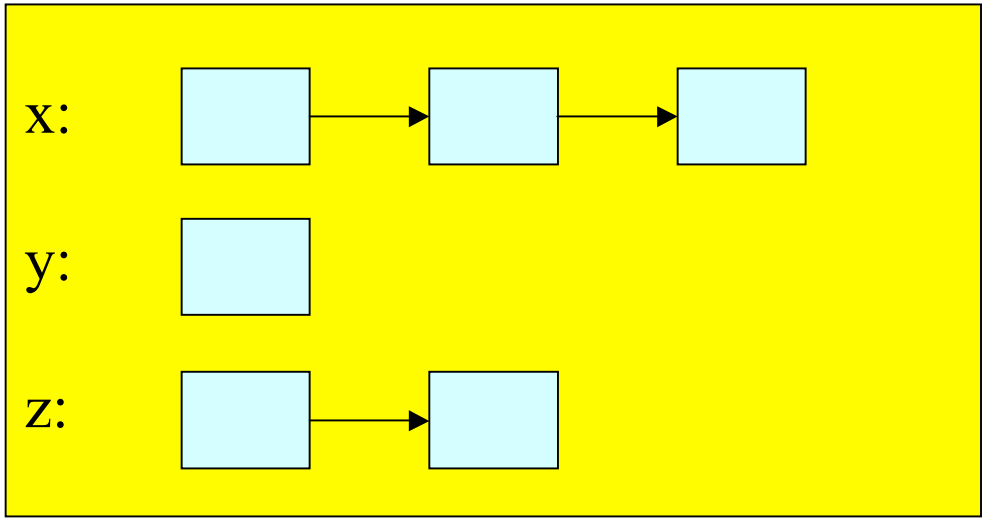
- For each class, associate a dictionary containing entries for each member.
- So given an expression such as x.clear (), we
  - find declaration for x in current dictionary
  - find type of x from its declaration, and
  - look up clear in dictionary associated with x's type.

The running times for each operation:

1. **Region entry**:
   - time to initialize a new, empty dictionary;
   - probably proportional to the size of the dictionary.
2. **Process a declaration:**
   - using hashing, constant expected time ($O(1)$).
3. **Process a use**:
   - using hashing to do the lookup in each dictionary in the list, the worst-case time is O(depth of nesting), when every table in the list must be examined.
4. **Region exit**:
   - time to remove a dictionary from the list, which should be $O(1)$ if garbage collection is ignored

Method 2: Dictionary of Lists

- the idea:
  - when processing a region, S, the structure of the symbol table is:



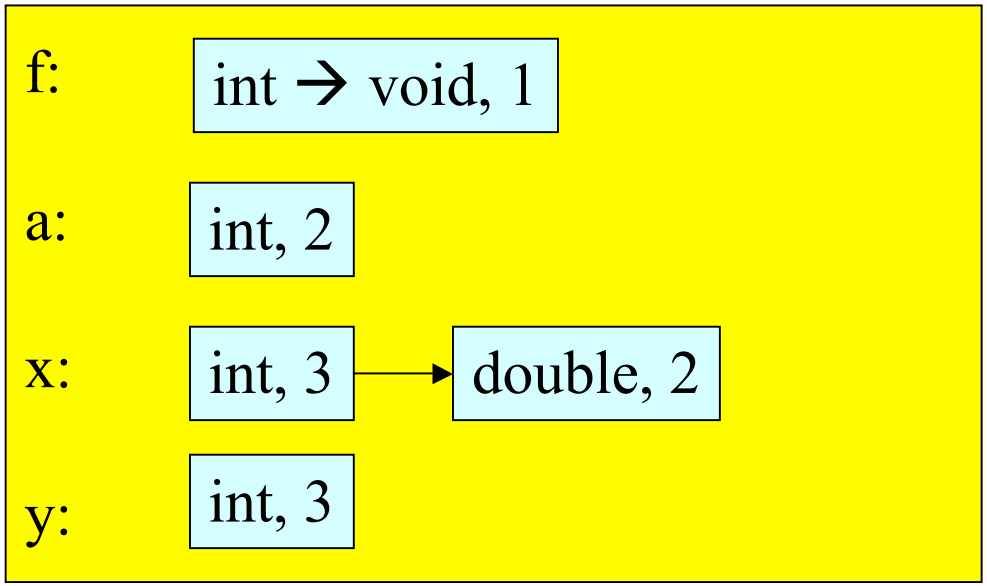
Definition

- there is just one big dictionary, containing an entry for each variable for which there is
  - some declaration in region S or
  - in a region that encloses S.
- Associated with each variable is a list of symbol-table entries.
  - The first list item corresponds to the most closely enclosing declaration;
  - the other list items correspond to declarations in enclosing regions.

Example

```
void f(int a) {
    double x;
    while (...) { int x, y; ... }
    void g() { f(); }
}
```

- After processing the declarations inside the while loop:



Nesting level information is crucial

- The level-number attribute stored in each list item enables us to determine whether the most closely enclosing declaration was made
  - in the current region or
  - in an enclosing region.

Dictionary of lists: the operations

1. On region entry:
   - increment the current level number.
2. To process a declaration of x:
   - look up x in the symbol table.
     - If x is there, fetch the level number from the first list item.
       - If that level number = the current level then issue a "multiply declared variable" error;
       - otherwise, add a new item to the front of the list with the appropriate type and the current level number.

… continue

1. To process a use of x:
   - look up x in the symbol table.
   - If it is not there, then issue an "undeclared variable" error.
2. On region exit:
   - scan all entries in the symbol table, looking at the first item on each list. If that item's level number = the current level number, then remove it from its list (and if the list becomes empty, remove the entire symbol-table entry). Finally, decrement the current level number.

Running times

1. **Scope entry**:
   - time to increment the level number, $O(1)$.
2. **Process a declaration**:
   - using hashing, constant expected time ($O(1)$).
3. **Process a use**:
   - using hashing, constant expected time ($O(1)$).
4. **Scope exit**:
   - time proportional to the number of names in the symbol table (assuming we can find the all names in linear time).

Type Checking

- the job of the type-checking phase is to:
  - Determine the type of each expression in the program
    - (each node in the AST that corresponds to an expression)
  - Find type errors
- The **type rules** of a language define
  - how to determine expression types, and
  - what is considered to be an error.
- The type rules specify, for every operator (including assignment),
  - what types the operands can have, and
  - what is the type of the result.

Type Errors

- The type checker must also
  1. find type errors having to do with the **context** of expressions,
     - e.g., the context of some operators must be boolean,
  2. type errors having to do with method calls.
- Examples of the context errors:
  - the condition of an *if* not boolean (Java)
  - type of returned value not function's return type
- Examples of method errors:
  - calling something that is not a method
  - calling a method with the wrong number of arguments
  - calling a method with arguments of the wrong types