CS 412
Introduction to Compilers

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Lecture 9: ASTs and symbol tables
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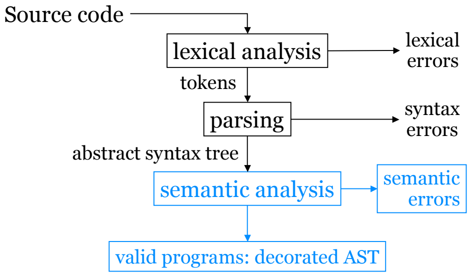
Outline

- Abstract syntax trees
- Type checking
- Symbol tables
- Using symbol tables for analysis

Semantic Analysis



Building the AST bottom-up

- Semantic actions are attached to grammar statements
- E.g. CUP: Java statement attached to each production

```
non terminal Expr expr; …
expr ::= expr:e1 PLUS expr:e2
     {: RESULT = new Add(e1,e2); :}
```

grammar production

semantic action

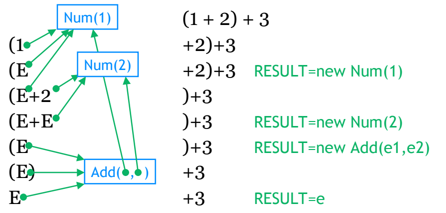
- *Semantic action* executed when parser reduces a production
- Variable RESULT is *value* of non-terminal symbol being reduced (in yacc: $$)
- AST is built bottom-up along with parsing

Actions in S-R parser

```
non terminal Expr expr; …
expr ::= expr:e1 PLUS expr:e2
     {: RESULT = new Add(e1,e2); :}
```

$E \rightarrow \mathbf{num} \models (E) \mid E + E$

- Parser stack stores value of each non-terminal



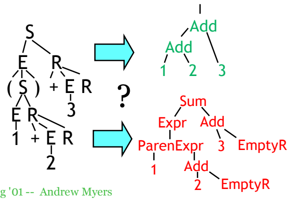
	(1 + 2) + 3	
(1	+2)+3	
(E	+2)+3	RESULT=new Num(1)
(E+2	)+3	
(E+E	)+3	RESULT=new Num(2)
(E	)+3	RESULT=new Add(e1,e2)
(E)	+3	
E	+3	RESULT=e

How not to design an AST

- Introduce a tree node for every node in parse tree
  - not very abstract
  - creates a lot of useless nodes to be dealt with later

$$\begin{array}{c} S \rightarrow E\,R \\ R \rightarrow \varepsilon \mid + E\,R \\ E \rightarrow \text{num} \mid (S) \end{array}$$

(1 + 2) + 3



How not to design the AST, part II

- Simple(minded) approach: have one class AST_node
- E.g. need information for if, while, +, *, ID, NUM

```
class AST_node {
    int node_type;
    AST_node[ ] children;
    String name; int value; …etc…
}
```

- Problem: must have fields for every different kind of node with attributes
- Not extensible, Java type checking no help

Using class hierarchy

- Can use subclassing to solve problem
  - write *abstract* class for each “interesting” non-terminal in grammar
  - write non-abstract subclass for (almost) every prod’n

$$E \rightarrow E + E \mid E * E \mid -E \mid (E)$$

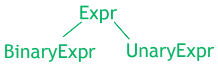
```
abstract class Expr { … } // E
class Add extends Expr { Expr left, right; … }
class Mult extends Expr { Expr left, right; … }
// or: class BinExpr extends Expr { Oper o; Expr l, r;  }
class Negate extends Expr { Expr e; …}
```

Creating the AST

```
non terminal Expr expr; ...
expr ::= expr:e1 PLUS expr:e2
    {: RESULT = new BinaryExpr(plus, e1, e2); :}
| expr:e1 TIMES expr:e2
    {: RESULT = new BinaryExpr(times, e1, e2); :}
| MINUS expr:e
    {: RESULT = new UnaryExpr(negate, e); :}
| LPAREN expr:e RPAREN
    {: RESULT = e; :}
```

”RESULT has type Expr in all semantic actions for expr”

plus, times, negate: Oper



Another Example

expr ::= *num* | (*expr*) | *expr* + *expr* | **id**

stmt ::= *expr* ; | *if* (*expr*) *stmt* |
 if (expr) *stmt* else *stmt* | **id** = *expr* ; | ;

```
abstract class Expr { … }
class Num extends Expr { Num(int value) … }
class Add extends Expr { Add(Expr e1, Expr e2) … }
class Id extends Expr { Id(String name) … }
abstract class Stmt { … }
class If extends Stmt { If(Expr cond, Stmt s1, Stmt s2) }
class EmptyStmt extends Stmt { EmptyStmt() … }
class Assign extends Stmt { Assign(String id, Expr e)…}
```

And…top-down

- parse_*X* method for each non-terminal *X*
- Return type is abstract class for *X*

```
Stmt parseStmt() {
   switch (next_token) {
     case IF: eat(IF); eat(LPAREN);
       Expr e = parseExpr;
       eat(RPAREN);
       Stmt s2, s1 = parseStmt();
       if (next_token == ELSE) { eat(ELSE);
                                  s1 = parseStmt(); }
       else s2 = new EmptyStmt();
       return new IfStmt(e, s1,s2); }
     case ID: …
```

Goals of Semantic Analysis

- Find all possible remaining errors that would make program invalid
  - undefined variables, types
  - type errors that can be caught *statically*
- Figure out useful information for later compiler phases
  - types of all expressions
  - data layout

Recursive semantic checking

- Program is tree, so…
  - recursively traverse tree, checking each component
  - traversal routine returns information about node checked

```
class Add extends Expr {
   Expr e1, e2;
   Type typeCheck() throws SemanticError {
        Type t1 = e1.typeCheck(), t2 = e2.typeCheck();
        if (t1 == Int && t2 == Int) return Int;
        else throw new TypeCheckError("type error +");
   }
```

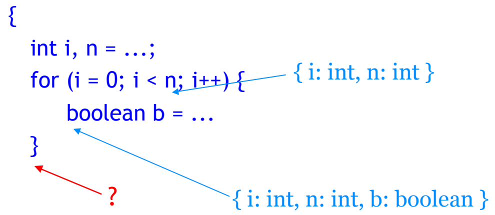
Type-checking identifiers

```
class Id extends Expr {
   String name;
   Type typeCheck() {
        return ?
   }
}
```

- Need a *environment* that keeps track of types of all identifiers in scope: *symbol table*

Symbol table

- Can write formally as set of *identifier* : *type* pairs: { x: int, y: array[string] }



```
{
   int i, n = ...;
   for (i = 0; i < n; i++) {
        boolean b = ...
   }
```

{ i: int, n: int }

?

{ i: int, n: int, b: boolean }

Specification

- Symbol table maps identifiers to types

```
class SymTab {
  Type lookup(String id) ...
  void add(String id, Type binding) ...
 }
```

Using the symbol table

- Symbol table is argument to all checking routines

```
class Id extends Expr {
   String name;
   Type typeCheck(SymTab s) {
     try {
        return s.lookup(name);
     } catch (NotFound exc) {
        throw new UndefinedIdentifier(this);
     }
   }
}
```

Propagation of symbol table

```
class Add extends Expr {
   Expr e1, e2;
   Type typeCheck(SymTab s) {
        Type t1 = e1.typeCheck(s),
             t2 = e2.typeCheck(s);
        if (t1 == Int && t2 == Int) return Int;
        else throw new TypeCheckError("+");
   }
```

- Same variables in scope – same symbol table used
- When do we add new entries to symbol table?

Adding entries

- Java, Iota: statement may declare new variables. `{ a = b; int x = 2; a = a + x }`
- Suppose {*stmt*$_1$; *stmt*$_2$; *stmt*$_3$…} represented by AST nodes:

```
abstract class Stmt { … }
class Block { Vector/*Stmt*/ stmts; … }
```

- And declarations are a kind of statement:

```
class Decl extends Stmt {
    String id; TypeExpr typeExpr; ...
```

A stab at adding entries

```
class Block { Vector stmts;
   Type typeCheck(SymTab s) { Type t;
        for (int i = 0; i < stmts.length(); i++) {
            t = stmts[i].typeCheck(s);
            if (stmts[i] instanceof Decl)
                Decl d = (Decl) stmts[i];
                s.add(d.id, d.typeExpr.interpret());
        }
        return t;
   }
}
```

Does it work?

Restoring Symbol Table

```
{ int x = 5;
  { int y = 1; }
  x = y;          // should be illegal!
}
```

scope of y

Handling declarations

```
class Block { Vector stmts;
   Type typeCheck(SymTab s) { Type t;
        SymTab s1 = s.clone();
        for (int i = 0; i < stmts.length(); i++) {
            t = stmts[i].typeCheck(s1);
            Decl d = (Decl) stmts[i];
                s1.add(d.id, d.typeExpr.interpret());
        }
        return t;
   }
}
```

Declarations added in block (to s1) don't affect code after the block

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Storing Symbol Tables

- Many symbol tables constructed during checking
  - May keep track of more than just variables: type definitions, break & continue labels, …
  - Top-level symbol table contains global variables, type & module declarations,
  - Nested scopes result in extended symbol tables containing add'l definitions for those scopes.
- Can reconstruct symbol tables, but useful to save in corresponding AST nodes to avoid recomputation

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How to implement Symbol Table?

- Imperative? Three operations:

```
Object lookup(String name);
void add (String name, Object type);
SymTab clone(); // expensive?
```

- Functional? Two operations:

```
Object lookup(String name);
SymTab add (String, Object); // expensive?
```

Imperative: Linked list of tables

```
class SymTab {
   SymTab parent;
   HashMap table;
   Object lookup(String id) {
     if (table.get(id) != null) return table.get(id);
     else return parent.lookup(id); // can cache..
   }
   void add(String id, Object t)
     { table.add(id,t); }
   SymTab(Symtab p)
     { parent = p; } // =clone
}
```

Functional: Binary trees

- Discussed in Appel Ch. 5
- Implements the two-operation interface

```
Object lookup(String name);
SymTab add (String, Object);
```

  - non-destructive add so no cloning is needed
  - O(lg n) performance: clones only the path from added node to the root.

Decorating the tree

- How to remember expression type?
- One approach: record in the node

```
abstract class Expr {
     protected Type type = null;
     public Type typeCheck();
}
class Add extends Expr { Type typeCheck() {
     Type t1 = e1.typeCheck(), t2 = e2.typeCheck();
     if (t1 == Int && t2 == Int)
            { type = Int; return type; }
     else throw new TypeCheckError(“+”);
}
```

- Maybe useful to record: symbol table

Structuring Analysis

- Analysis is a traversal of AST
- Technique used in lecture: recursion using methods of AST node objects—object-oriented style

```
class Add extends Expr {
     Type typeCheck(SymTab s) {
     Type t1 = e1.typeCheck(s),
            t2 = e2.typeCheck(s);
     if (t1 == Int && t2 == Int) return Int;
     else throw new TypeCheckError(“+”);
   }}
```

Redundancy

- There will be several more compiler phases like typeCheck and foldConstants
  - constant folding
  - translation to intermediate code
  - optimization
  - final code generation
- Object-oriented style: each phase is a method in AST node objects
- Weakness 1: code for each phase spread
- Weakness 2: traversal logic replicated

Separating Syntax, Impl.

- Can write each traversal in a *single* method

```
Type typeCheck(Node n, SymTab s) {
  if (n instanceof Add) {
      Add a = (Add) n;
      Type t1 = typeCheck(a.e1, s),
             t2 = typeCheck(a.e2, s);
      if (t1 == Int && t2 == Int) return Int;
      else throw new TypeCheckError(“+”);
  } else if (n instanceof Id) {
      Id id = (Id)n;
      return s.lookup(id.name); …
```

- Now, code for a given *node* spread all over!

Modularity Conflict

- No good answer!
- Two orthogonal organizing principles: node types and phases (rows or columns)

phases

node types

	typeCheck	foldConst	codeGen
Add	×	×	×
Num	×	×	×
Id	×	×	×
Stmt	×	×	×

Constant Folding

- AST optimization: replaces constant expressions with constants they would compute
- Traverses (and modifies) AST

```
abstract class Expr {
  Expr foldConstants();
}
class Add extends Expr { Expr e1, e2;
  Expr foldConstants() {
    e1 = e1.foldConstants(); e2 = e2.foldConstants();
    if (e1 instanceof IntConst && e2 instanceof IntConst)
        return new IntConst(e1.value + e2.value);
    else return new Add(e1, e2);
  }
```

Which is better?

- Neither completely satisfactory
- Both involve repetitive code
  - modularity by objects (rows): different traversals share basic traversal code—boilerplate code
  - modularity by operations (columns): lots of boilerplate:

```
if (n instanceof Add)  { Add a = (Add) n; …}
else if (n instanceof Id)  { Id x = (Id) n; … }
else …
```

Visitors

- Idea: avoid repetition by providing one set of standard traversal code
- Knowledge of particular phase embedded in *visitor* object
- Standard traversal code is done by object methods, reused by every phase
- Visitor invoked at every step of traversal to allow it to do phase-specific work

A Visitor Methodology

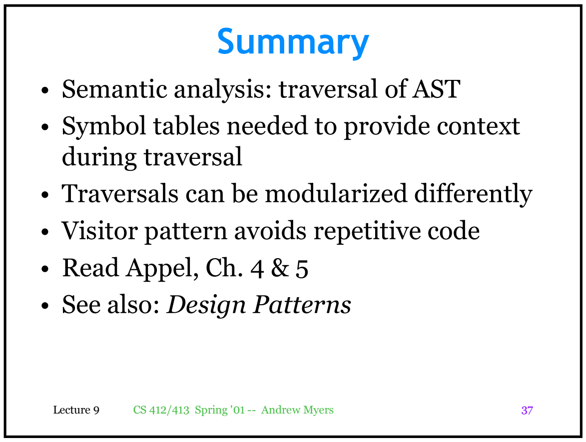
- Class Node is superclass for all AST nodes
- NodeVisitor is superclass for all visitor classes (one visitor class per phase)

```
abstract class Node {
   public final Node visit (NodeVisitor v) {
       Node n = v.override (this);         // default: null
       if (n != null) return n;
       else {
           NodeVisitor v_ = v.enter(this);  // default: v_=v
           n = visitChildren (v_);          // visit children
           return v.leave(this, n, v_);     // default: n
       }}
   abstract Node visitChildren(NodeVisitor v);
```

Folding constants with visitors

```
public class ConstantFolder extends NodeVisitor {
  public Node leave (Node old, Node n, NodeVisitor v) {
    return n.foldConstants();
          // note: all children of n already folded
  }
}

class Node { Node foldConstants( ) { return this; } }
class BinaryExpression {
   Node foldConstants( ) { switch(op) {…} } }
class UnaryExpression {
   Node foldConstants( ) { switch(op) {…} } }
```



Summary

- Semantic analysis: traversal of AST
- Symbol tables needed to provide context during traversal
- Traversals can be modularized differently
- Visitor pattern avoids repetitive code
- Read Appel, Ch. 4 & 5
- See also: *Design Patterns*