Assignment #2: AST Generation and Static Semantic Analysis

COMP321 Compiler, Spring 2023

Assignment #2 Due date: Wednesday, June. 21, 2023, 23:59 (tentative).

1 Due Date

- The due date for Assignment 2 is **Wednesday, June. 21, 2023, 23:59**.

2 Introduction

AST Generation

We will extend our recursive descent parser from Assignment 1-(2) to produce Abstract Syntax Trees (ASTs) for MiniC. If a program is syntactically legal, then the parser must build the AST for the program exactly as specified below. Otherwise, the parser can print any error message and exit without completing the AST for the illegal input program.

Static Semantic Analysis

Consecutively we will perform static semantic analysis of the ASTs that we generated. Specifically, we check whether a program conforms to the static semantic specification of the MiniC language. To keep the workload manageable at this stage of the semester, you are provided with a visitor for the complete MiniC language, where you will have to fill in your code at specific places. Semantic analysis of arrays will only be done as a bonus assignment. This assignment spec walks you through the complete semantic analysis process, to ensure your understanding of this part of a compiler. Emphasis is on comprehension, the coding effort on your side will be less than 100 lines of Java code.

3 Environment

- We use Java JDK **version 17**. You can solve this assignment on any computer that has this Java development environment installed.
- We will also provide the **VirtualBox Linux image**.

4. AST Generation

4-1. Building ASTs

The package MiniC.AstGen contains our class hierarchy of AST nodes. We will use this class hierarchy to create AST nodes for MiniC programs. The following list describes all 53 classes of the class hierarchy. The arguments for the constructors are given also. Classes prefixed with "+" are abstract classes, classes marked with "=" are concrete classes. All classes inherit the instance variable "position" (of type SourcePos) from the base class AST. For space considerations, this argument is omitted in the following list (to be specific, it is the last argument with each constructor).

```
+AST
 =Program(Decl D)

 +Decl
  =EmptyDecl()
  =EmptyFormalParamDecl()
  =FormalParamDecl(Type astType, ID astIdent)
  =FormalParamDeclSequence(Decl lAST, Decl rAST)
  =VarDecl(Type tAST, ID idAST, Expr eAST)
  =DeclSequence(Decl d1AST, Decl d2AST)
  =FunDecl(Type tAST, ID idAST, Decl paramsAST, Stmt stmtAST)

 +Type
  =ArrayType(Type astType, Expr astExpr)
  =IntType()
  =BoolType()
  =FloatType()
  =VoidType()
  =StringType()
  =ErrorType()

 +Expr
  =EmptyExpr()
  =ExprSequence(Expr lAST, Expr rAST)
  =AssignExpr(Expr lAST, Expr rAST)
  =IntExpr(IntLiteral astIL)
  =BoolExpr(BoolLiteral astBL)
  =FloatExpr(FloatLiteral astFL)
  =StringExpr(StringLiteral astSL)
  =ArrayExpr(Expr idAST, Expr indexAST)
  =BinaryExpr(Expr lAST, Operator oAST, Expr rAST)
  =UnaryExpr(Operator oAST, Expr eAST)
  =CallExpr(ID idAST, Expr paramAST)
   =VarExpr(ID Ident)
  =EmptyActualParam()
  =ActualParam(Expr pAST)
   =ActualParamSequence(Expr lAST, Expr rAST)

 +Stmt
```

```
 =EmptyStmt()
 =EmptyCompoundStmt()
 =CompoundStmt(Decl astDecl, Stmt astStmt)
 =StmtSequence(Stmt s1AST, Stmt s2AST)
 =ReturnStmt(Expr eAST)
 =AssignStmt(Expr lAST, Expr rAST)
 =IfStmt(Expr eAST, Stmt thenAST)
 =IfStmt(Expr eAST, Stmt thenAST, Stmt elseAST)
 =WhileStmt(Expr eAST, Stmt stmtAST)
 =ForStmt(Expr e1AST, Expr e2AST, Expr e3AST, Stmt stmtAST)
 =CallStmt(Expr eAST)

+Terminal
 =ID(String Lexeme)
 =Operator(String Lexeme)
 =IntLiteral(String Lexeme)
 =BoolLiteral(String Lexeme)
 =FloatLiteral(String Lexeme)
 =StringLiteral(String Lexeme)
```

AST is the base class for this class hierarchy. Each concrete class provides one constructor (except class IfStmt, which provides 2). Your parser will use these constructors for generating new AST nodes.

Package MiniC.AstGen contains a design pattern in the interface in file visitor.java. This design pattern will be used to traverse the AST (in Assignments 2 (this assignment) and 3). For this assignment, understanding of this design pattern is not strictly necessary. But feel free to have a look already now, in case you are curious.

You can draw from a large number of examples to see how to build ASTs for all MiniC language constructs. You find these testcases in Parser/tst/base/AST_testcases. You can conveniently view their AST images on LMS (TBA).

- The empty program: c1.mc
- Global variable declarations: c2.mc, c3.mc
- Function declarations: c4.mc, c5.mc
- Local variable declarations: c6.mc, c7.mc, c8.mc
- Statements: c9.mc, c10.mc, c11.mc
- Formal parameters: c12.mc, c13.mc, c14.mc
- Actual parameters: c15.mc, c16.mc, c17.mc
- Assignments: c18.mc, ..., c22.mc
- If statements: c23.mc, ..., c27.mc
- For loops: c28.mc, c29.mc
- While loops: c30.mc, c31.mc
- Multiple variable declarations: c32.mc, c33.mc, c34.mc, c35.mc
- Whole programs: c36.mc, c37.mc
- Arrays:
    - Global variable declarations: c38.mc
    - Local variable declarations: c39.mc
    - Formal array parameters: c40.mc

- Array expressions: c41.mc

Note that global and local variable declarations use exactly the same class (VarDecl). However, they are displayed differently by the TreeDrawer, depending on whether it is a local declaration or a global declaration. Local declarations are shown as ``L.VarDecl'', whereas global declarations are shown as ``G.VarDecl''.

Every declaration in which multiple variables are declared is treated as if the variables had been declared in separate statements (in the order they appear in the source code). The AST for ```int a, b`'' is therefore the same as

```
int a;
int b;
```

This holds for local and global variables.

Multiple syntactic constructs of the same kind (e.g., multiple variable declarations as in the above example) are strung together as binary subtrees by *sequence classes*. The sequence classes are `DeclSequence`, `FormalParamDeclSequence`, `ActualParamSequence`, `ExprSequence` and `StmtSequence`. The provided examples show you how the sequence classes are used. With sequence classes, the first construct from the source appears at the top of the tree, and the last construct is always at the bottom of the tree. See e.g., c5.mc, where functions `foo` is the highest in the tree, followed by function `f` and function `g`. Sequences are always terminated by the corresponding Empty* AST node.

The AST class ErrorType will not be used in this assignment. We will use it in Assignment 4.

The AST class StringType will not be used in this assignment, because MiniC does not allow the declaration of variables of type string. In Assignment 4, string literals will be assigned this type during type checking.

4-2 Implementing AST Generation in Your Parser

We provide you with an updated version of the skeleton compiler that you should extend to create your MiniC parser.

In the following, you find a description of the skeleton-files that have been added or changed compared to Assignment 1.

Package MiniC (directory MiniC)

MiniC.java: the new version of the compiler driver. This version supports now several command line switches (see “Testing your parser” below).

Package Scanner (directory MiniC/Scanner)

Scanner.java: empty scanner implementation which you should **replace** by **your own scanner** from **Assignment 1-(1)**. In case your scanner from Assignment 1-(1) does not work properly, you can use scanner classfiles provided with this assignment instead (see Section "Scanner" below).

Package Parser (directory MiniC/Parser)

Parser.java: the skeleton parser for you to complete (you will need to augment this skeleton parser with your parser-code from Assignment 1-(2). You should extend your parser-code from Assignment 1-(2) to build ASTs for MiniC input programs). The lecture on Syntax Analysis contains ample examples on AST construction.

tst/base/AST_testcases: the testcases for this assignment. All testcases are syntactically legal MiniC programs.
tst/base/AST_solutions_image: the solutions for this assignment, as png images.
tst/base/AST_solutions_unparsed: the solutions for this assignment as unparsed trees. During marking, we will compare the unparsed solutions produced by your parser to the unparsed solutions provided by our parser.
tst/base/AST_solutions_trees: the solutions for this assignment as ASTs in ASCII format.

The provided parser compiles out-of-the-box. It parses a subset of the MiniC language and handles the following test cases from directory AST_testcases correctly: c1.mc, c4.mc, c5.mc, c6.mc, c9.mc, c12.mc, c13.mc, c14.mc, c40.mc.
After **adding your code from Assignment 1-(2)**, you will have to write about 400 lines of additional Java code for building ASTs.

Each AST node represents a language construct, i.e., a phrase, for the MiniC language. The position of a construct can then be defined by using an object of the class `SourcePos` (see also our lecture on Syntax Analysis, in particular, on AST generation). A `SourcePos` object contains four fields:

```
StartLine: the line where the construct begins
EndLine: the line where the construct ends
StartCol: the column where the construct begins
EndCol: the column where the construct ends
```

The supplied file `Parser.java` demonstrates how to make use of the two helper methods `start()` and `finish()` to fill in the position information for AST nodes. We use dummy positions for "empty" AST nodes that have no counterpart in the actual input program.

Package TreeDrawer (directory MiniC/TreeDrawer)

The Java classes to draw graphic representations of MiniC ASTs on-screen. It is not necessary to understand how ASTs are actually drawn. However, if you are interested in Java graphics programming, you are encouraged to take a look at this package.
Note that the TreeDrawer abbreviates the names of many AST classes in its output to save space. You can find the exact spellings in file LayoutVisitor.java.

Package AstGen (directory MiniC/AstGen)

This package contains the class hierarchy of AST nodes.

Package Unparser (directory MiniC/Unparser)

This class is written for automated marking and debugging. It contains an unparser that takes an AST as input, visits the AST nodes in depth-first left-to-right order, and produces an equivalent MiniC program. This program is usually different from the original one (see Section “Marking Criteria” below).

Package TreePrinter (directory MiniC/TreePrinter)

The TreePrinter dumps an AST in text format to a file.
The TreeDrawer, TreePrinter and Unparser are implemented using visitor classes. For Assignment 3 knowledge of the Visitor Design Pattern is not needed; we will however use this design pattern for Assignments 4 and 5, based on the discussion in the lecture.

Scanner

In case your scanner from Assignment 1 does not work properly, you can use the scanner classfiles provided in the ``resources'' sub-directory of the Assignment_2.zip archive. Compile using the ``jarNoScanner'' build task. See the Assignment 1-(2) specification on further details on the provided scanner classfiles.

4-3 Building, Running and Testing Your Parser

Like with the previous assignments, we use the Gradle build automation system to compile our MiniC compiler. The build tasks ``jar'' and ``jarNoScanner'' are the same as with Assignment 2.

The MiniC compiler now accepts a set of command-line switches:

- **-ast** to display the AST on-screen.
- **-astp** to display the AST, including source positions.
- **-t <file>** prints the AST in file <file>, using the TreePrinter.
- **-u <file>** unparses the AST into file <file>.

The provided testcases demonstrate how to build ASTs for MiniC language constructs. You are encouraged to find additional testcases for debugging purposes.
A way to test your parser works as follows:

```
(1.)  java -jar build/libs/MiniC-AstGen.jar -u mytest.mc.u mytest.mc
(2.)  java -jar build/libs/MiniC-AstGen.jar -u mytest.mc.u.u mytest.mc.u
(3.)  diff mytest.mc.u mytest.mc.u.u
```

If the two files differ, then you obviously have a problem in your AST generation. If the two files are the same, there might still be a problem! (Why?)

To make sure that your compiler works correctly for the provided testcases, you are strongly recommended to use the Linux **diff** utility (or similar tools that supports the same features as diff) to do a byte-by-byte comparison of the ASTs generated by your compiler versus the provided solutions. For example:

```
(1.)  java -jar ../build/libs/MiniC-AstGen.jar -t my_c1.mc.ast
      Parser/tst/base/AST_testcases/c1.mc
(2.)  diff --brief my_c1.mc.ast Parser/tst/base/AST_solutions_trees/c1.mc.ast
(3.)  echo $?
      0
```

If diff returns zero (checked by the **echo** command), then the content of your file **`my_c1.mc.ast`** is byte-by-byte identical to the solution in file **`c1.mc.ast`**.

Otherwise, diff will tell you that the files differ. In this case, you can use diff to show the line-by-line differences:

```
diff -u my_c1.mc.ast Parser/tst/base/AST_solutions_trees/c1.mc.ast
```

To find out how to read the output of the diff command, please refer to the GNU diffutils manual.

The most efficient way to test your parser using diff is to adapt the provided test script of Assignment 1-(1) or Assignment 1-(2). You are allowed to share your **test script(s)** with our colleagues through our Q&A board.

Please note: ASTs that fail the diff comparison described above will receive zero score.

4-4 Marking: AST Generation

Please note that all assignments are *individual* assignments. You are most welcome to discuss your ideas with your colleagues, but ``code sharing'' and ``code reuse'' are not allowed. Assignments are designed to facilitate understanding of the course contents. Assignments are also a part of the preparation for the exams.

Your parser will be assessed by examining whether it can build the correct AST for syntactically legal MiniC programs.

You will not be marked up or down for how your parser behaves on syntactically illegal MiniC programs. You will not be marked up or down for the precision of the position information recorded with AST nodes (i.e., position information is optional with this assignment). However, accurate position information will facilitate debugging of your static semantic analysis component that we will develop in Assignment 4.

This assignment will be automatically marked by comparing the AST produced by your compiler (invoked with the -t option) to the solution.

5 Static Semantic Analysis

5-1 Specification

MiniC static semantic analysis ensures two types of constraints, namely (1) scope rules and (2) type rules. Therefore static semantic analysis consists of two subphases:

1) *Identification:* Here we apply the scope rules of MiniC (discussed in the lecture) to relate each applied occurrence of an identifier to its declaration.

2) *Type checking*: we apply the type rules of MiniC to determine the type of each construct. We compare that the type we have found is compatible to the type that is expected in that context.

This assignment involves developing a visitor class in file `SemanticAnalysis.java` that implements the visitor methods from the visitor interface in the file `MiniC.AstGen.Visitor.java`. Our semantic analyzer is a visitor object that performs type checking and identification while it visits the AST in a depth-first traversal. In case of ill-typed constructs, appropriate error messages must be issued. As before, if no lexical, syntactic or semantic error is found, the compiler should print "`Compilation was successful`.", otherwise it should print "`Compilation was unsuccessful`.".

5-2 Identification

A scope stack has already been implemented for you. Identification relates each applied occurrence of an identifier to its declaration, by applying the scope rules of MiniC. We use the scope stack to associate identifiers with their declaration. In the MiniC compiler, the identifier's declaration is represented as a pointer to the AST subtree (`FunDecl`, `VarDecl`, or `FormalParamDecl`) that represents that declaration. This attribute is represented by the instance variable *declAST* in `MiniC.AstGen.ID.java`:

```
public class ID extends Terminal {

    public AST declAST;

    public ID (String Lexeme, SourcePos pos) {
     super (pos);
     this.Lexeme = Lexeme;
     declAST = null;
    }

    public void accept(Visitor v) {
     v.visit(this);
    }

}
```

During identification, we use the scope stack to store identifiers and their declarations for later lookup. (We perform look-ups when we encounter applied occurrences of identifiers.) The scope stack consists of two classes.

1) `MiniC.SemanticAnalysis.IdEntry.java` is the internal data structure for stack entries of the scope stack.
2) `MiniC.SemanticAnalysis.ScopeStack.java` defines all methods that the scope stack supports.

The scope stack is used as follows during identification:

- Whenever the semantic analyzer visits an AST corresponding to a declaration (`FunDecl`, `VarDecl` and `FormalParmDecl` ASTs), it will call `enter()` to enter the identifier of the declaration (i.e., the defining occurrence of that identifier) into the scope stack. MiniC does not allow declarations of the **same** identifier within a single block. To detect duplicates (i.e., re-declarations), the scope stack's `enter()` method will return `false` if an identifier of that name is already present in the current scope. Your code needs to check this return value to report re-declarations.

  Example 1:
  ```
  {
  int f;
  int f; // Error: re-declaration of f in the current block.
  }
  ```
  Another slightly more complicated example addresses the re-declaration of a formal parameter as a local variable:

  Example 2:
  ```
  void foo (int f) {
  int f; // Error: re-declaration of f.
  }
  ```
- Whenever the semantic analyzer visits an applied occurrence of an identifier I, it will call `retrieve(I)` to retrieve the declaration of I from the scope stack. The scope stack will return the pointer to the AST subtree that corresponds to I's declaration. This pointer will be stored with the ID node for I. If no declaration is found, the scope stack will return a `null` pointer. This indicates the use of an identifier that has not been declared. Of course this is a MiniC semantic error that has to be reported.
- Whenever the semantic analyzer visits a compound statement `{...}`, it calls `scopeStack.openScope()` at the start of the block to open a new scope. At the end of the block it will call `scopeStack.closeScope()` to close this scope again.

The scope stack is already pre-loaded with the entries for the Standard Environment of MiniC (many programming languages provide the programmer with a set of pre-defined types, constants and functions that the programmer can use without having to declare them). The

MiniC standard environment contains 9 built-in functions and several primitive types. The declarations of these constructs do not appear in the printout of your ASTs, but you can use the MiniC compiler's `-envast` option to print the AST of the standard environment. In order to make the use of built-in functions such as `putInt()` possible from within MiniC programs, the ASTs for those functions and primitive types are constructed in the constructor of package `MiniC.StdEnvironment`. Before semantic analysis, the semantic analyzer initializes the scope stack with the identifiers for those functions and primitive types.

Identifier	Scope Stack Level	Attribute
`int`	1	ptr to the int type AST
`bool`	1	ptr to the bool type AST
`float`	1	ptr to the float type AST
`void`	1	ptr to the void type AST
`getInt`	1	ptr to the getInt AST
`putInt`	1	ptr to the putInt AST
`getBool`	1	ptr to the getBool AST
`putBool`	1	ptr to the putBool AST
`getFloat`	1	ptr to the getFloat AST
`putFloat`	1	ptr to the putFloat AST
`getString`	1	ptr to the getString AST
`putString`	1	ptr to the putString AST
`putLn`	1	ptr to the putLn AST
here the identifiers from the source code of the program follow...		

It is recommended that you read `MiniC.SemanticAnalysis.IdEntry.java`, `MiniC.SemanticAnalysis.ScopeStack.java`, `MiniC.StdEnvironment.java` and the constructor of `MiniC.SemanticAnalysis.SemanticAnalysis.java` to understand the details of the MiniC scope stack mechanism.

5-3 Error Messages

Semantic errors must be reported to the user. The file `SemanticAnalysis.java` contains predefined error messages that you should use.

```
private String errMsg[] = {
        "#0: main function missing",
        "#1: return type of main must be int",

        //defining occurrences of identifiers,
        //for local, global variables and for formal parameters:
        "#2: identifier redeclared",
        "#3: identifier declared void",
        "#4: identifier declared void[]",

```

```
        //applied occurrences of identifiers:
        "#5: undeclared identifier",

        //assignment statements:
        "#6: incompatible types for =",
        "#7: invalid lvalue in assignment",

        //expression types:
        "#8: incompatible type for return statement",
        "#9: incompatible types for binary operator",
        "#10: incompatible type for unary operator",

        //scalars:
        "#11: attempt to use a function as a scalar",

        //arrays:
        "#12: attempt to use scalar/function as an array",
        "#13: wrong type for element in array initializer",
        "#14: invalid initializer: array initializer for scaler",
        "#15: invalid initializer: scalar initializer for array",
        "#16: too many elements in array initializer",
        "#17: array subscript is not an integer",
        "#18: array size missing", (not used)

        //functions:
        "#19: attempt to reference a scalar/array as a function",

        //conditional expressions:
        "#20: "if" conditional is not of type boolean",
        "#21: "for" conditional is not of type boolean",
        "#22: "while" conditional is not of type boolean",

        //parameters:
        "#23: too many actual parameters",
        "#24: too few actual parameters",
        "#25: wrong type for actual parameter"
    };
```

If a semantic error is detected, you can report it using the ErrorReporter as follows: `reporter.reportError(errMsg[index] + "what else you want to say", "", sourcepos);` See the class `ErrorReporter.java` for further details. You are not allowed to change the error messages in array `errMsg[],` otherwise automated marking won't work anymore!

5-3 Writing Your Semantic Analyzer

We provide you with an updated version of the skeleton compiler that you should extend to create your MiniC semantic analyzer. You will find the new skeleton on the LMS. Please set up your programming environment as specified in Assignment 1.

Package MiniC (directory MiniC)

`MiniC.java`: the new version of the compiler driver. The TreeDrawer incorporates type information into the AST. This can be helpful for debugging a semantic analyzer.
`StdEnvironment.java`: The standard environment of the MiniC language.

Package Scanner (directory MiniC/Scanner)

Scanner.java: empty scanner implementation which you should **replace** by **your own scanner** from **Assignment 1**. In case your scanner from Assignment 1 does not work properly, you can use scanner classfiles provided with this assignment instead (see Section ``Provided Classfiles'' below).

Package Parser (directory MiniC/Parser)

`Parser.java`: empty Parser implementation which you should replace by your own parser from Assignment 3. In case your parser from Assignment 3 does not work properly, you can use scanner and parser classfiles provided with this assignment instead (see Section "Provided Classfiles" below).

Package SemanticAnalysis (directory MiniC/SemanticAnalysis)

`SemanticAnalysis.java`: this is the skeleton of a visitor to perform semantic analysis on MiniC ASTs. You will add your code at specific places in this file. Those places are already marked (see below).
`IdEntry.java, ScopeStack.java`: the files implementing the scope stack (see the section on identification).
Subdirectory tst/base/testcases: contains MiniC testcases. Several testcases are semantically invalid! **Note that testcases with a number higher than c26*.mc belong to the bonus assignment (see section below).**
Subdirectory tst/base/solutions: contains the **output** that your compiler should generate for each of the testcases (see section on "Marking" below).
The decorated images for the AST testcases are provided online, like with AST Generation part, at LMS (TBA).

Package TreeDrawer (directory MiniC/TreeDrawer)

Has been updated to include type information with AST nodes, e.g. <int> for an integer type, <?> for an unknown type, and <error> for an error type.

Package AstGen (directory MiniC/AstGen)

A few classes had to be extended for semantic analysis.

The following list contains typical static semantic constraints that we have to check:
(1.) Identifiers must be declared before they are used.
(2.) An Identifier cannot be declared more than once in a block.

(3.) No identifier can be declared to have type `void` or type `void[]`.
(4.) Operands in expressions must be compatible with operators.
(5.) Left-hand and right-hand sides of assignments must be type-compatible.
(6.) A function must be called with the correct number of arguments. The type of an actual parameter must be assignment-compatible with the corresponding formal parameter.
(7.) The type of a return value must be assignment-compatible with the result type of the corresponding function.
(8.) Conditions in `if/for/while` statements must be of type `bool`. For example:

```
while(1) {} //ERROR #22.
```

For an expression, the analyzer will determine the type of the expression and store it in the corresponding expression node (that's "decorating the AST"). An expression may actually consist of several nodes which form an AST subtree. The MiniC *type* attribute is evaluated bottom up in this expression subtree (i.e., type information is synthesized). For each node in the expression subtree, this synthesized type attribute is stored in the instance variable **type** that is defined in the abstract class MiniC.AstGen.Expr.java and inherited in all expression classes. For every expression tree node, you compute this type information from the type information of the children (this requires of course that children have already been visited, which is ensured by our depth-first traversal).

During semantic analysis, we often need to check whether two types are equal or whether one type can be assigned to the other type. For this purpose AST classes `IntType, FloatType, BoolType, StringType` and `ErrorType` contain methods `Tequal()` and `AssignableTo()`.

Let e1Type and e2Type be the types of two expressions.

- `e1Type.Tequal(e2Type)` returns true iff e1Type and e2Type are identical. Example: If both e1Type and e2Type are of type int, `Tequal()` will return true. If one type is int and the other type is float, `Tequal()` will return false.
- `e1Type.AssignableTo(e2Type)` will return true if e1Type is assignment-compatible with e2Type (for a definition of assignment-compatibility, see below).

In addition, both tests return true if e1Type or e2Type is the `errorType`. This avoids generating too many error messages with large expressions (there is no use complaining at each AST expression node up the tree after we have reported the initial type error, see also our lecture slides on "Semantic Analysis").

To use the above methods, the StdEnvironment already provides the six predefined types

```
StdEnvironment.intType
StdEnvironment.boolType
StdEnvironment.floatType
StdEnvironment.stringType
StdEnvironment.voidType
StdEnvironment.errorType
```

You find those types in file StdEnvironment.java.
Example: if you want to find out whether some type `e1Type` is int, you would use

```
if (e1Type.Tequal(StdEnvironment.intType))....
```

5-4 Type Coercions and Assignment Compatibility

An expression is a *mixed-mode* expression if it has operands of different types, e.g.,

```
1 + 2.0  //type int and type float
```

In MiniC, like in C, C++ and Java, certain kinds of mixed-mode expressions are permitted. When an operator has operands of different types, they will be automatically converted by the compiler to a common type, if this mixed-mode expression is legal according to the language semantic rules. Such an automatic (also called "implicit") type conversion is called *type coercion*. This is different from an explicit type conversion or *type cast* like

```
2.0 + (float) 1
// the int literal is type-cast to a float literal 1.0
```

Type casts do not exist in MiniC, but they exist in C, C++ and Java. In MiniC, the following operators allow **int** or **float** operands:
`+  -  *  /  <  <=  >  >=  ==  !=`
If one operand is of type **float**, the compiler will perform coercion to convert the other operand to **float**. Therefore, if at least one operand of a binary operator is of type **float**, then the operation is a floating-point operation (and not an integer operation). If both operands are of type **int**, then the operation is an integer operation. We must implement these semantic rules in our semantic analyzer. Specifically, the above rules are implemented in the `visit()` routine for `BinaryExpr` nodes.

Assignment coercions can occur when the value of an expression is assigned to a variable. In that case the value of the right-hand side expression is converted to the type of the left-hand side of the assignment statement, e.g.,

```
float a; int b; a = b;  // coercion of b from int to float.
```

The following rules apply to assignment coercions in MiniC:
(R1) If the type of the left-hand side variable is **int**, the type of the right-hand side must be **int.**
(R2) If the type of the left-hand side variable is **float,** the type of the right-hand side must be **int** or **float**. In case of **int,** it is coerced to **float** by the compiler.
(R3) If the type of the left-hand side variable is **bool,** then the right-hand side must be of type **bool.**

If the type of a right-hand side is compatible according to the above rules, then we say the right-hand side expression is *assignment-compatible* to the left-hand side. As already mentioned, the MiniC types provide the method `AssignableTo() to` check for assignment compatibility. Note that if `AssignableTo()` returns true, it may require you to insert an **int**-to-**float** coercion if you are facing Case (R2) above.

Because an argument of a function call is an expression, assignment coercions may also be required when arguments are passed to functions. Our semantic analyzer must check the actual arguments of a function-call versus the formal parameters of the called function. The same holds for return statements that return a value.

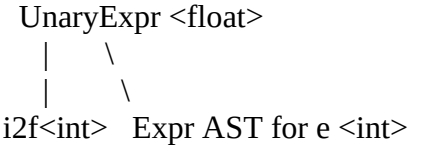
We achieve **int**-to-**float** type coercions by introducing extra conversion nodes into the program's AST. This is done in the `visit()` routines for `AssignStmt, CallExpr, BinaryExpr` and `ReturnStmt`. We use a special unary operator `i2f` to convert an int value to a float value. SemanticAnalysis.java already provides a routine that does exactly that:

```
private Expr i2f (Expr e) {
      Operator op = new Operator ("i2f", new SourcePos());
      op.type = StdEnvironment.intType;
      UnaryExpr eAST = new UnaryExpr (op, e, new SourcePos());
      eAST.type = StdEnvironment.floatType;
      return eAST;
}
```

It generates an operator "`i2f`" and sets its type to **int.** It generates a UnaryExpr node with two children, the "`i2f`" operator and the argument expression e. The (return) type of the new UnaryExpr is **float**.

Example:

Expr AST for e <int>
=>



AST node annotations <...> denote the value of the *type-attribute* of a node.

5-5 Overloaded Operators

Several MiniC operators, e.g., * and /, can be applied to either a pair of floating-point numbers, or a pair of integer numbers. Such operators are said to be overloaded. Our semantic analyzer must replace each overloaded operator by the appropriate operator required in the specific situation (e.g., *<int> for integer multiplication with expression 2 * 3).

In the Java Virtual Machine (JVM), the Boolean values true and false are represented by integer values. Therefore all MiniC operators acting on bool values must be set to type **int!** The MiniC operators that can act on Boolean values are &&, ||, !, ==, and !=. Our semantic analyzer sets the type of an operator by decorating the type attribute of an operator AST node (see e.g., `i2f` in the example above).

Resolving overloaded operators is straight-forward:

(1.) **&&,** || and **!**: These operators can only act on bool values. Because of the above JVM requirement their type is therefore int.

(2.) **+ - * / < <= > >=** (where +, - are both unary and binary): These must be resolved from the operands. An operator is of type float only if at least one of the operands is of type float.

(3.) **==** and **!=**: These operators can be applied to either a pair of bool values, integers or floating-point numbers. Because of the above JVM requirement their type is again int.

```
// Example type coercion:
void foo() {
  float f;
  int i;
  f = i + 2;
}
```

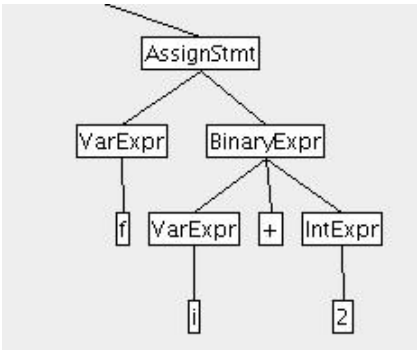


Figure 2: AST before Coercion

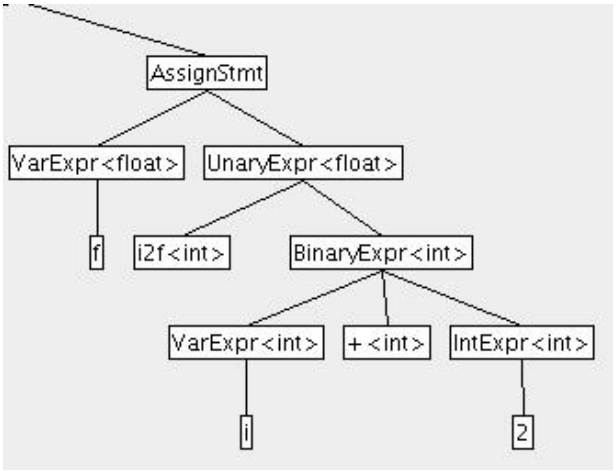


Figure 1: AST after coercion and overload resolution.

5-6 Your Task:

File `SemanticAnalysis.java` contains a visitor to perform static semantic analysis of MiniC ASTs. This analyzer is not complete yet—it has to be completed by you. At specific places in the code you find instructions on what you should do to complete this semantic analyzer. Those instructions are easy to spot, they all start with a comment as follows:

```
// STEP [123]
```

Your task can be divided into three subtasks:

- **STEP 1:** instructions given under STEP 1 tell you how to complete the identification of our semantic analyzer (i.e., scope stack handling).
- **STEP 2:** instructions given under STEP 2 tell you where you have to perform type checking, and what to do there. In STEP 2 you'll compute type information for MiniC expressions and pass them up the AST.
- **STEP 3:** this step involves several additional MiniC static semantic checks, such as to ensure that a MiniC file contains a `main()` routine.

It is strongly recommended to proceed in the order STEP1→STEP2→STEP3.

Whenever during semantic analysis you detect an error, you must report an error message from the `errMsg[]` array, using the `reporter` object.

One word of caution: the `SemanticAnalysis.java` code skeleton compiles as is. It can already produce un-decorated ASTs for some of the test cases. However, because no type information is contained in the AST yet, the type tags <..> contain only question marks or error types. Because type information is missing in the AST, some test cases may make the semantic analyzer skeleton crash. (Some code already provided to you assumes the presence of type information that you'll have to provide yet; Especially `BinExpr` where the left-hand side is a literal are likely to cause problems)

A second word of caution: the code skeletons contain many `assert()` statements to ensure that preconditions are satisfied. That way it is usually easy to find run-time errors right at the place they occur. You are strongly advised to (1) use this programming style for your own code, and (2) to run Java programs with the `-ea` flag, i.e., java `-ea` ..., to enable checking of `assert()` statements at run-time.

Provided Classfiles

In case your scanner and/or parser do not work properly, you can use the classfiles provided in the ``resources/'' directory-tree of the Assignment_2.zip. The following two Gradle tasks are provided:

1) `jarNoScanner`: uses the classfiles in resources/scanner_only to provide a working scanner implementation. (The parser must be provided by the course participant.)
2) `jarNoScannerNoParser`: uses the classfiles in resources/scanner_and_parser to provide a working scanner and parser implementation.

Building, Running and Testing Your Semantic Analyzer

Like with the previous assignments, we use the Gradle build automation system to compile our MiniC compiler. The build tasks ``jar'' and ``jarNoScanner'' are the same as with Assignment 2. Build task "jarNoScannerNoParser" has been added (see Section ``Provided Classfiles").

The MiniC compiler now accepts a set of command-line switches:

- -ast1 to display the AST from the parser on-screen.
- -ast2 to display the AST from semantic analysis on-screen.
- -envast to display the AST of the MiniC standard environment on-screen.
- -t <file> prints the AST from the parser in file <file>, using the TreePrinter.
- -u <file> unparses the AST from the parser into file <file>.

Using option -ast2, you can compare the annotations produced by your semantic analyzer to the annotations provided on our LMS.

The most efficient way to test your semantic analyzer is to automatically run it on the provided testcases and ``diff'' the output with the solutions provided in directory MiniC/SemanticAnalysis/tst/base/solutions. You may adapt the test scripts provided with Assignment 1 and 2 for this purpose. You are allowed to share test scripts on LMS. The most useful test scripts will be awarded a participation point. (Please do **not** share any other code on LMS!)

5-7 Bonus Assignment

Semantic analysis of initializing expressions and arrays. This is done as a bonus assignment that will give you 10% extra if you solve the testcases c27*.mc and above. The places in the SemanticAnalysis.java code skeleton that have to be extended for the bonus assignment are marked as “STEP4”.

MiniC arrays have been derived and simplified from C arrays. MiniC permits only one-dimensional arrays. Array subscripts start at 0. If an array has n elements, then valid subscripts are from 0..n-1. With this assignment, checking of valid subscripts is however not attempted in the compiler! A subscript can be any expression of type int. The element type of an array can only be **bool**, **int** or **float**.
In MiniC it is mandatory to specify the array range with formal parameters. (E.g., `void foo(int a[]){}` is not allowed, but `void foo(int a[2]){}` is.)
An array variable itself without square brackets [] cannot appear in any MiniC expression, except as an argument in a function call. MiniC requires that a formal array parameter exactly matches the argument provided at the function call-site:

```
void foo(int x[22]) {}

int main(){
 int a[21];
 int b[22];
 int c;
 foo(a); // ERROR (array range does not match)
 foo(b); // semantically correct
 c = a;  // ERROR
}
```

Arrays can be initialized with an initializer list between curly braces:

```
int a, b[3] = {1+a, 2, 3};     // ok
int c[2] = {1.0};              // type error
```

Every element in the list must be of the element type of the array. Type coercions of initializing expressions from int to float apply as with assignment statements. It is permissible that the list of initializing expressions contains fewer elements than the array's range specifies. It is however not allowed to have more expressions.

Non-array variables can be initialized with a single expression, e.g.,

```
int a, b = 22*a;
```

It is not permitted in MiniC to initialize an array variable without curly braces, and it is not permitted to initialize a non-array variable with curly braces, e.g.,

```
int a = {1};          // ERROR
int b[1] = 1;         // ERROR
```

The provided testcases and the error messages in file SemanticAnalysis.java provide additional information for arrays and initializing expressions.

5-8 Marking: Static Semantic Analysis

Please note that all assignments are *individual* assignments. You are most welcome to discuss your ideas with your colleagues, but ``code-sharing'' and ``code-reuse'' are not allowed. Assignments are designed to facilitate understanding of the course contents. Assignments are also a part of the preparation for the exams.

Your semantic analyzer will be assessed by how well it handles various semantically legal and illegal MiniC programs. Only *syntactically* legal programs will be used. Your type checker will not be marked on how well it recovers from errors or whether it outputs spurious error messages.

We will use small test cases, so that each test case contains **at most** one semantic error. We will use the UNIX grep command to search your output for the ``ERROR…'' message specific to a particular semantic error in the input program. Consider the following example:

```
int main() {
  int i;
  i = 1.0+true;
}
```

Our semantic analyzer reports

```
********** MiniC Compiler **********
Syntax Analysis ...
Semantic Analysis ...
ERROR: #9: incompatible types for binary operator 7..14,
           line 3.
Compilation was unsuccessful.
```

Error #9 is the one that is required in this case. If semantic analysis is continued in the presence of errors, then the further spurious error message is possible:

```
ERROR: #6: incompatible types for =
```

Whether your semantic analyzer reports spurious error messages or not will not be assessed.

Positional information (line numbers and column numbers) will not be assessed.

6 Deliverables and Submission

You should extend the parser in file Parser.java so that it constructs ASTs for the complete MiniC specification. Note that for this assignment it is only necessary to modify file Parser.java (for AST generation) and SemanticAnalysis.java (for Static Semantic Analysis). Submission will therefore be restricted to these two files (with its header files). *It is not allowed to modify other files, e.g., the AST class hierarchy, Token.java also, otherwise automated testing of your parser might no longer work. For the same reason, you are not allowed to modify the error messages in the errMsg[] array.*

To solve this assignment, it is not necessary nor allowed to use packages and libraries other than the ones already imported in file Parser.java and SemanticAnalysis.java.

If you have questions, don't hesitate to contact us. ☺

All the best!