Course Project

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We Will Implement A Simple Compiler

- Our goal in this project is to build a compiler for a simple programming language, called *MICRO*
- *MICRO* is popularly used for teaching students how to build compilers in many universities
- Our compiler will translate a *MICRO* program into a simple <u>two-address assembly program</u>, called *Tiny*

MICRO Language

- For the purpose of this course, we will use a modified version of *MICRO*
- *MICRO* syntax is a bit similar to C
- MICRO is case-sensitive
- Keywords are written using capital letters only
- Function “main” is where the execution starts
- Three data types are used: INT, FLOAT, and STRING
  - STRING variables are read-only and must be initialized when declared
  - INT and FLOAT variables can be read and written and are not initialized when declared

“Hello” Program in *MICRO*

```
PROGRAM hello
BEGIN
    STRING str := “Welcome to MICRO!” ;

    FUNCTION void main ( )
        WRITE ( str ) ;          -- print on the screen
    END

END
```

Tiny Assembly Code

- The output of our compiler is *Tiny*: a two-address assembly code
- We will use a **simulator** to execute and test translated *Tiny* codes
- I will go into more details about *Tiny* later

Compilation is Done in Multiple Passes

- During the translation, compilers **pass** over the source code or the IR several times
- Each pass usually comprises a single task
  - For example, the first pass is scanning, next pass is parsing, next pass is symbol table generation, etc
- The output of each pass is the input of the next pass
- Multi-pass compilers are very popular
  - **We will use the multi-pass scheme in our project**
- Single-pass compilers (where everything is done in one pass) do exist but less commonly used

Coding Language is Java

- We will implement the compiler in Java
- Java is platform-independent
  - We need not worry about OS compatibility
- Java is also known for being easy to learn, write, compile and debug
- Multiple nice IDEs that support Java are available

Coding Tips

- Do the design first, then write the code
- Take advantage of object-oriented programming
- Some of the good programming practices:
    - Keep the code simple
    - Use good naming scheme
    - Keep the code portable and extendable
    - Eliminate redundancy
    - Encapsulate what varies into classes

Project Steps

- Step0: forming teams
- Step1: implementing the scanner
- Step2: implementing the parser
- Step3: building the symbol table
- Step4: generating the IR
- Step5: generating *Tiny* code
- Step6 (not included for BSc): implementing live variables dataflow analysis
- Step7 (not included for BSc): implementing register allocation

Step 0: Forming Teams

- Each team should consist of 2 students
- You may ask other teams questions about Java or the IDE but not about the compiler design or code
- It is really common sense to tell what is cheating and what is not
- Team Registration link: TBD

Step1: Building The Scanner

- We will use ANTLR to automatically obtain the code of the scanner (isn't that great?!)
- ANTLR's input is a text file that specifies the regular expression of each token, as well as the language grammar
  - We will worry about the grammar in Step 2
- To complete step1, you need to learn
  - How to express regular expressions with ANTLR
  - How to use ANTLR tool to generate the scanner code
  - How to integrate the scanner code with your compiler code

Token Types in *MICRO*

- KEYWORD
- OPERATOR
- IDENTIFIER
- INTLITERAL, FLOATLITERAL, STRINGLITERAL
- COMMENT

Keywords in *MICRO*

PROGRAM	declare a program
BEGIN	Similar to an open bracket ‘{’ in C
END	Similar to a closed bracket ‘}’ in C
FUNCTION	declare a function
RETURN	Similar to return in C
READ	Read the input from the user
WRITE	Print on the screen

IF
ELSE
ENDIF
	IF statement keywords

FOR ENDFOR	FOR statement keywords
INT VOID STRING FLOAT	Data type declarations

Operators in *MICRO*

:=	Assignment operator
+	Plus
-	Minus
*	Multiply
/	Divide
=	Test if equal
!=	Test if not equal
<	Test if smaller
>	Test if greater
<=	Test if less or equal
>=	Test if greater or equal
;	Same as C: a code statement must end with a semicolon
,	Same as C: separate parameters using a comma
(	Left parenthesis
)	Right parenthesis

Identifiers in *MICRO*

- An identifiers token will begin with a letter, followed by any number of letters and numbers
  - Letters can be small or capital
  - A number consists of characters 0, 1, …, 9
- Example on valid identifier names:

  N, m, STR, str, Str1, a100
- Example on non-valid identifier names:

  8N, STR!, 1

Literals in *MICRO*

- Three types of literals can be used:

1. INTLITERAL
   - Any integer number
2. FLOATLITERAL
   - Any real number with the format xxx.xxx or .xxx
   - integer and fraction parts can have any number of digits
3. STRINGLITERAL
   - any sequence of characters except ' " ' between ' " ' and ' " '
   - Valid string examples: "Hello!\n" and "****"

Comments in *MICRO*

- Any string that starts with "--" and lasts till the end of line
- The scanner must recognize comments but then ignore them (i.e., skip them)
- Valid comment examples:

  -- this is a comment

  -- $%#4-34455003-7354530

  --999--

Micro.g4

- Micro.g4 will be the input file of the ANTLR tool
- Below is skeleton of Micro.g4 code (your job is to finish it)

```
grammar Micro;

KEYWORD:        ……

OPERATOR:       ……

IDENTIFIER:     ……

INTLITERAL:     ……

FLOATLITERAL:     ……

STRINGLITERAL:    ……

COMMENT:        ……

WS : [ \t\r\n]+ -> skip ;     // skip spaces, tabs, newlines
```

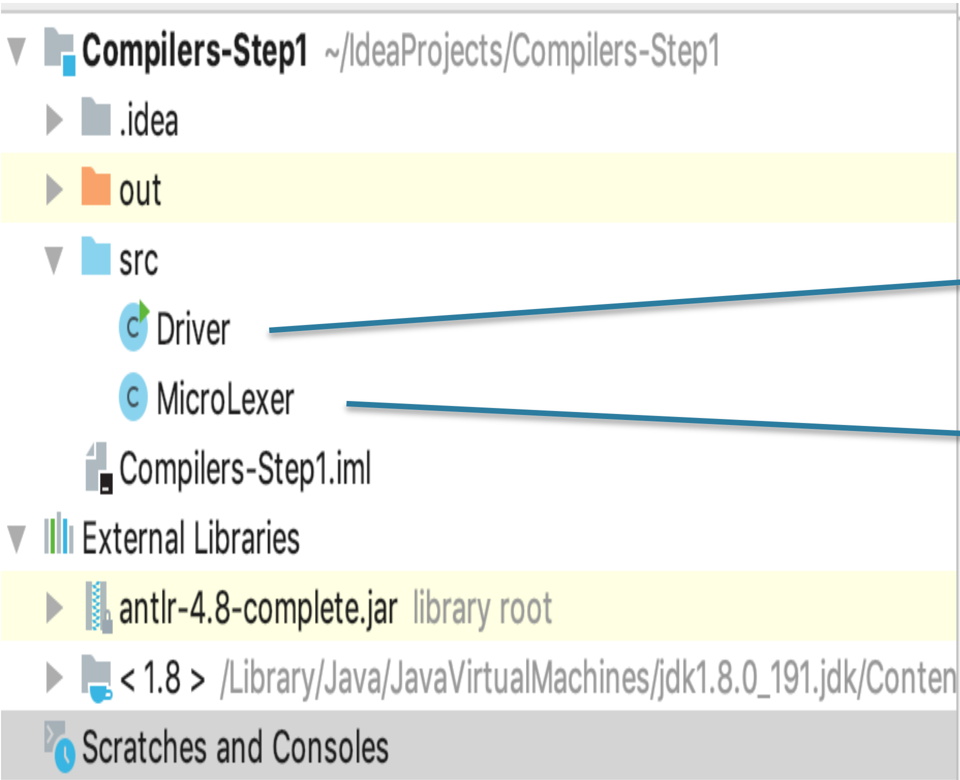
Refer to the ANTLR v4 reference book to learn how write regular expressions with ANTLR

Using ANTLR Tool

- Download ANTLR: https://www.antlr.org/download/antlr-4.13.1-complete.jar
- Use the following command

  java –jar antlr-4.13.1-complete.jar Micro.g4
- Scanner source code is then found in MicroLexer.java
- To use the scanner, simply integrate the scanner source code files with your code

Example: Integrating Scanner Code With Eclipse Project



This is the test file

add scanner class to the project

Do not forget to add ANTLR to the build path

Driver.java

```java
// import antlr
import org.antlr.v4.runtime.ANTLRInputStream;

import java.io.FileInputStream;
import java.io.InputStream;
public class Driver {
    public static void main(String[] args) throws Exception{
        // read input MICRO code
        InputStream is=null;
        try{
            String inputFile;
            inputFile = args[0];
            is = new FileInputStream(inputFile);
        }
        catch ( Exception e){
            System.out.println("You must specify an input file");
            System.exit( status: 0);
        }

        ANTLRInputStream input = new ANTLRInputStream(is);
        MicroLexer lexer = new MicroLexer(input);

        // add code here to print each token’s type and value

    }
}
```

This code will invoke the lexer automatically

Step 1 Output

- Your code should read an input *MICRO* code, scan it, and then produce an output file that shows each token's type and value
- I uploaded a set of input *MICRO* code examples on the course website
- I also uploaded the expected output for each input code example
- Due: TBD

Step2 : Building The Parser

- We will use ANTLR to automatically obtain the code of the parser

- To complete step 2, you need to:
  1. Use the grammar file (Micro.g4) to write the full grammar of Micro (the language grammar is available on the course webpage)
  2. Use ANTLR to obtain the scanner and parser codes and integrate them with your project
  3. Modify Driver.java to invoke the parser and check for syntax errors

Micro.g4

```
grammar Micro;
KEYWORD:      ……
……
WS : [ \t\r\n]+ -> skip ;
```

These are the regular expressions that you wrote in step 1

```
program:  'PROGRAM' id 'BEGIN' pgm_body 'END’ ;
id: IDENTIFIER ;
….
```

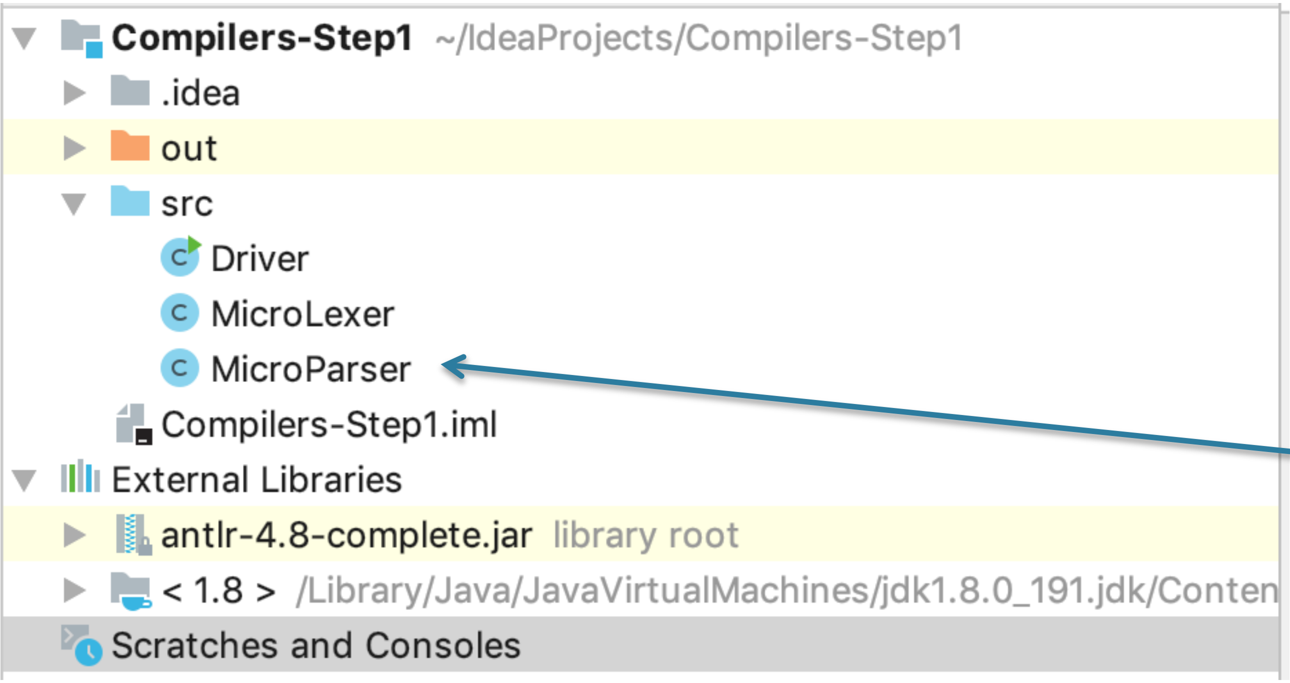
Now, write the grammar rules

Using ANTLR Tool

- Use the following command

  java –jar antlr-4.13.1-complete.jar –no-listener Micro.g4
- The scanner code is found in MicroLexer.java
- The parser code is found in MicroParser.java

Integrating Parser Code



Add the parser code to the project you already created in step1

Driver.java

```java
public class Driver {

    public static void main(String[] args) throws Exception{
        // read input MICRO code
        InputStream is=null;
        try{
            String inputFile;
            inputFile = args[0];
            is = new FileInputStream(inputFile);
        }
        catch ( Exception e){
            System.out.println("You must specify an input file");
            System.exit( status: 0);
        }

        ANTLRInputStream input = new ANTLRInputStream(is);
        MicroLexer lexer = new MicroLexer(input);
        MicroParser parser = new MicroParser(new CommonTokenStream(lexer));
        System.out.println("number of errors is " + parser.getNumberOfSyntaxErrors());
    }
}
```

Step 2 Output

- By the end of this step, your compiler should be able to take a source Micro code, parse it and show number of syntax errors
- I uploaded a set of input *MICRO* code examples on the course website, as well as the expected output for each code example
- Due: One week from today

Step3 : Building The Symbol Table

- In this step, you will implement a **semantic action pass** for building the symbol table
- Our symbol table only needs to store information about declared variables in the program
  - For *INT* and *FLOAT* variables, the symbol table should store their types and names
  - For *STRING* variables, the symbol table should store their types, names and values

Variables Declaration In Micro

- In Micro, there are multiple *scopes* where variables can be declared:
  - Variables declared at the begging of the program before any functions are global – visible to all functions
  - Variables declared as part of a function's parameter list are local to this function, and cannot be accessed by any other function
  - Variables declared at the beginning of a function body are local to this function as well.
  - Variables declared at the beginning of an ***if***, ***else*** or ***while*** blocks are local to the block itself. Other blocks, even in the same function, cannot access these variables.

Symbol Table Organization

- You will implement an individual symbol table for each ***scope*** that store its *local* variables
- Variables with the same name cannot appear in the same scope
- Duplicate variable names across different scopes are allowed
- Note that *scopes* can be nested, therefore, variables in outer scopes are implicitly visible to inner scopes
- The compiler should keep track of the relationship between nested scopes

Implementing Semantic Actions

- Semantic actions are routines that the compiler invokes while traversing the **parse tree**

- ANTLR provides multiple mechanisms for implementing semantic actions:
  - Inserting actions in the grammar
  - Inserting actions in a parse-tree visitor
  - Inserting actions in a parse-tree listener

We will use this method

Calculator Grammar

- I will use the following grammar to demonstrate how to implement semantic actions
- The grammar describes an algebraic expression of integers that are added or subtracted to each other

```
// Calculator.g4
grammar Calculator;
expr :  INT  expr_tail;
expr_tail :      '+'  INT expr_tail
              |     '-'  INT expr_tail
              |
              ;
INT : [0-9] | [1-9] [0-9] ([0-9]?) ;     // up to 3-digit integers
WS : [ \t\r\n]+ -> skip ;                 // skip spaces, tabs, newlines
```

Our goal is to write semantic actions that compute the sum of the integers in the expression

Embedding Semantic Actions Into **Parse-Tree Visitors**

- To generate the Visitor class, use the following option when running ANTLR tool:

$ java –jar antlr.jar –no-listener –visitor Calculator.g4

This option deactivate Listener

This option generates Visitor classes

- Output files are:
  - CalculatorLexer.java
  - CalculatorLexer.tokens
  - CalculatorParser.java
  - CalculatorVisitor.java
  - CalculatorBaseVisitor.java

Looking Inside CalculatorBaseVistor.java

- By default, ANTLR generate only one visit function for each **non-terminal**, regardless of how many rules it has
- However, as we studied in class, it is better to generate a separate visit function for each **rule**
- We can add directives in the grammar file to guide ANTLR into generating separate visit functions for separate rules (see next slide)

Embedding Semantic Actions Into **Parse-Tree Visitors**

- Conceptually, ANTLR Visitor is similar to the Visitor pattern we studied in lecture 7

```
// Calculator.g4
grammar Calculator;
expr :  operand=INT  expr_tail;
expr_tail :      '+'  operand=INT expr_tail       #AdditionOperation
              |   '-'  operand=INT expr_tail       #SubtractionOperation
              |                                    #EmptyOperation
              ;
INT : [0-9] | [1-9] [0-9] ([0-9]?) ;      // up to 3-digit integers
WS : [ \t\r\n]+ -> skip ;                 // skip spaces, tabs, newlines
```

Let us do a demo

You Are Ready

- Use ANTLR's Visitor to implement semantic actions for building the symbol table
- Hints:
  - **Look carefully at all the rules inside Micro grammar and decide**
    - Which rules that indicate that a new scope has started
    - Which rules that indicate that a scope has ended
    - Which rules that indicate that new variables are being declared
    - Add hashtags to your grammar file to generate rule-based visit functions
  - **Think abut the design of your code**
    - Is it a good idea to create a class for Symbol? If yes, what are the methods needed in that class?
    - Is it a good idea to create a class for Scope? If yes, what are the methods needed in that class?

Step 3 Test Cases and Output

- To test the correctness of this step, your compiler should print the symbol table for each scope
- I uploaded a set of input *MICRO* code examples on the course website, as well as the expected output for each code example
- Due: TBA

Step4 : Generating The Intermediate Representation

- In this step, you will implement a **semantic action pass** for generating the intermediate representation

- We will choose **the three-address code** to be the compiler's intermediate representation in this project

- Our three-address code properties:
  - Low-level abstraction level: resembles assembly code
  - Linear representation: can be implemented as a linked list of **IR nodes**, where each node corresponds to a single instruction

IR Node Format
Arithmetic Instructions

opcode	operand 1	Operand 2	result/label

- ADDI OP1 OP2 RESULT //integer add
- ADDF OP1 OP2 RESULT //float point add
- SUBI OP1 OP2 RESULT //integer subtract
- SUBF OP1 OP2 RESULT //float point subtract
- MULTI OP1 OP2 RESULT //integer multiply
- MULTF OP1 OP2 RESULT //float point multiply
- DIVI OP1 OP2 RESULT //integer divide
- DIVF OP1 OP2 RESULT //float point divide

IR Node Format
Branch Operations

opcode	operand 1	Operand 2	result/label

• GT	OP1	OP2	LABEL	//if (OP1 > OP2) goto LABEL
• GE	OP1	OP2	LABEL	//if (OP1 ≥ OP2) goto LABEL
• LT	OP1	OP2	LABEL	//if (OP1 < OP2) goto LABEL
• LE	OP1	OP2	LABEL	//if (OP1 ≤ OP2) goto LABEL
• NE	OP1	OP2	LABEL	//if (OP1 ≠ OP2) goto LABEL
• EQ	OP1	OP2	LABEL	//if (OP1 = OP2) goto LABEL
• JUMP			LABEL	//unconditional jump to LABEL
• LABEL			STRING	//set a label

IR Node Format
Write and Read Operations

opcode	operand 1	Operand 2	result/label

- READI RESULT //read integer inputted by user
- READF RESULT //read float point inputted by user
- WRITEI RESULT //print integer on screen
- WRITEF RESULT //print float point on screen
- WRITES RESULT //print string on screen

IR Node Format
Move Operations

opcode	operand 1	Operand 2	result/label

- STOREI OP1 RESULT //store integer OP1 to RESULT
- STOREF OP1 RESULT //store float point OP1 to RESULT
- RETURN RESULT //return execution to caller

Assumptions

- To simplify the implementation of the compiler, we will only consider compiling the following *MICRO* programs in step 4 (as well as step 5):
  - *MICRO* programs that have a single *main()* function, which calls no other functions (i.e., there are no function call expressions)
  - *MICRO* programs where all variables are only declared as global variables, i.e., no additional variables will be declared in *main*( )

Code Example

MICRO code

```
PROGRAM test
BEGIN

    INT a, b , e ;
    STRING newline := "\n";

    FUNCTION VOID main( )
    BEGIN
        READ(a,b);

         e := a * b + 1;

         WRITE(e, newline);
    END
END
```

Three-address code

```
LABEL  main
READI  a
READI  b
MULTI  a  b  $T1
ADDI  $T1  1  $T2
STOREI  $T2  e
WRITEI  e
WRITES  newline
```

Refer to lecture 7 to see more examples

Implementation Hints

Think about the following when implementing the semantic action pass for generating the three-address code:

- Determine which parts of *MICRO's* grammar is used for generating three-address code for expressions, assignment statements, if statements, while statements, etc
- Remember that the global symbol table has all variable types, which helps determine the opcode
- **Take advantage of recursion**

Step 4 Test Cases and Output

- To test the correctness of this step, your compiler should print the three-address code
- I uploaded a set of input *MICRO* code examples on the course website, as well as the expected output for each code example
- Due: TBA