CMPE 152: Compiler Design

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What Your Current Status Should Be

- Created a grammar for your source language.
- Generated a parser, a scanner, and parse trees using ANTLR 4.
- Incorporated the symbol table code.

What's Left

- Decide what Jasmin assembly code to generate for your language's statements.
- Allow ANTLR to walk the parse tree using the visitor design pattern.
- Override the relevant default visit methods to generate Jasmin assembly code.
- Write sample programs in your source language that you can successfully compile and execute on the JVM.

Pcl2

- Pcl2, a tiny subset of Pascal, version 2.
  - The **`Pcl2.g4`** grammar:

```
grammar Pcl2;  // A tiny subset of Pascal

@header {
    import wci.intermediate.*;
    import wci.intermediate.symtabimpl.*;
}

program   : header mainBlock '.' ;
header    : PROGRAM IDENTIFIER ';' ;
mainBlock : block;
block     : declarations compoundStmt ;

declarations : VAR declList ';' ;
declList     : decl ( ';' decl )* ;
decl         : varList ':' typeId ;
varList      : varId ( ',' varId )* ;
varId        : IDENTIFIER ;
typeId       : IDENTIFIER ;
```

Pcl2.g4

Pcl2, *cont'd*

Pcl2.g4

```
compoundStmt : BEGIN stmtList END ;

stmt : compoundStmt
     | assignmentStmt
     |
     ;

stmtList       : stmt ( ';' stmt )* ;
assignmentStmt : variable ':=' expr ;

variable : IDENTIFIER ;

expr locals [ TypeSpec type = null ]
    : expr mulDivOp expr    # mulDivExpr
    | expr addSubOp expr    # addSubExpr
    | number                # unsignedNumberExpr
    | signedNumber          # signedNumberExpr
    | variable              # variableExpr
    | '(' expr ')'          # parenExpr
    ;
```

Pcl2, *cont'd*

Pcl2.g4

```
mulDivOp : MUL_OP | DIV_OP ;
addSubOp : ADD_OP | SUB_OP ;

signedNumber locals [ TypeSpec type = null ]
    : sign number
    ;
sign : ADD_OP | SUB_OP ;

number locals [ TypeSpec type = null ]
    : INTEGER    # integerConst
    | FLOAT      # floatConst
    ;

PROGRAM : 'PROGRAM' ;
VAR     : 'VAR' ;
BEGIN   : 'BEGIN' ;
END     : 'END' ;
```

Pcl2, *cont'd*

```
IDENTIFIER : [a-zA-Z][a-zA-Z0-9]* ;
INTEGER    : [0-9]+ ;
FLOAT      : [0-9]+ '.' [0-9]+ ;

MUL_OP :   '*' ;
DIV_OP :   '/' ;
ADD_OP :   '+' ;
SUB_OP :   '-' ;

NEWLINE : '\r'? '\n' -> skip  ;
WS      : [ \t]+ -> skip ;
```

Pcl2.g4

Sample Pcl2 Program

- Main program
- Declarations
- Compound statement
- Assignment statements only
- Arithmetic expressions

```
PROGRAM sample;

VAR
    i, j : integer;
    alpha, beta5x : real;

BEGIN
    i := 32;
    j := i;
    i := -2 + 3*j;

    alpha := 9.3;
    beta5x := alpha;
    beta5x := alpha/3.7 - alpha*2.88;
    beta5x := 8.45*(alpha + 9.12)
END.
```

Code Generation in Two Tree Visits

- After the parser and lexer have generated the parse tree and the default visit methods, we will visit the tree <u>twice</u>.

- The <u>first visit</u> will process <u>declarations</u>.
  - Enter identifiers into the <u>symbol tables</u> (Pcl1).
  - Emit `.field` assembly directives for the <u>program variables</u>.
  - Emit boilerplate code for the <u>constructor method</u>.
  - Decorate the parse tree nodes with <u>data type specifications</u>.

Code Generation in Two Tree Visits, *cont'd*

- The second visit will emit code for statements.
  - Code for the main program header and epilogue.
  - Code for assignment statements.
  - Code for arithmetic expressions.
- The two visits override different visit methods.
- All generated Jasmin code is written into a `.j` file named after the program name.
  - Example: **`PROGRAM sample`** ➔ **`sample.j`**

Code Generation in Two Tree Visits, *cont'd*

```
public class Pcl2
{
    public static void main(String[] args) throws Exception
    {
        String inputFile = null;

        if (args.length > 0) inputFile = args[0];
        InputStream is = (inputFile != null)
                                ? new FileInputStream(inputFile)
                                : System.in;

        ANTLRInputStream input = new ANTLRInputStream(is);
        Pcl2Lexer lexer = new Pcl2Lexer(input);
        CommonTokenStream tokens = new CommonTokenStream(lexer);
        Pcl2Parser parser = new Pcl2Parser(tokens);
        ParseTree tree = parser.program();

        Pass1Visitor pass1 = new Pass1Visitor();
        pass1.visit(tree);

        PrintWriter jFile = pass1.getAssemblyFile();

        Pass2Visitor pass2 = new Pass2Visitor(jFile);
        pass2.visit(tree);
    }
}
```

Assignment #6

- Begin code generation.
- Generate Jasmin assembly object code for declarations, assignment statements, control statements, and expressions.
- You should be able to assemble and run your generated code.
  - Produce runtime printed output, including the elapsed time at the end.
- Follow the Pcl1 and Pcl2 examples.
- Formal assignment write-up soon in Canvas.

Pascal Procedures and Functions

- Analogous to Java methods.
- Two major simplifications for our Pascal compiler:
  - Standard Pascal is not object-oriented.
  - Therefore, Pascal procedures and functions are more like the private static methods of a Java class.
- Java does not have nested methods.
  - The JVM does not easily implement nested methods.
  - Therefore, we will compile only "top level" (level 1) Pascal procedures and functions.

Procedures and Functions, *cont'd*

- A Pascal program:

```
PROGRAM ADDER;

VAR
  i, j, sum : integer;

FUNCTION add(n1, n2 : integer) : integer;

  VAR
    s : integer;

  BEGIN
    s := i + j + n1 + n2;
    add := s;
  END;

BEGIN
  i := 10;
  j := 20;

  sum := add(100, 200);
  writeln('Sum = ', sum)
END.
```

- The roughly equivalent Java class:
  - Fields and methods are **private static**.

```
public class Adder
{
    private static int i, j, sum;

    private static int add(int n1, int n2)
    {
        int s = i + j + n1 + n2;
        return s;
    }

    public static void main(String args[])
    {
        i = 10;
        j = 20;

        sum = add(100, 200);
        System.out.println("Sum = " + sum);
    }
}
```

Code for a Pascal Main Program

```
PROGRAM Adder;

VAR
  i, j, sum : integer;

FUNCTION add(n1, n2 : integer) : integer;

  VAR
    s : integer;

  BEGIN
    s := i + j + n1 + n2;
    add := s;
  END;

BEGIN
  i := 10;
  j := 20;

  sum := add(100, 200);
  writeln('Sum = ', sum)
END.
```

```
.class public super Adder
.super java/lang/Object

.private field static i I
.private field static j I
.private field static sum I

.method public <init>()V


    aload_0
    invokenonvirtual java/lang/Object/<init>()V
    return

.limit stack 1
.limit locals 1
.end method

...
```

Private static class fields.

Void method. No parameters.

- Each Jasmin class must have a <u>constructor</u> named **<init>**.
  - The local variable in slot #0 contains the value of “this”.
  - Each constructor must call the <u>superclass constructor</u>.

Code for a Pascal Function (Static Method)

```
PROGRAM ADDER;

VAR
  i, j, sum : integer;

FUNCTION add(n1, n2 : integer) : integer;

  VAR
    s : integer;

  BEGIN
    s := i + j + n1 + n2;
    add := s;
  END;

BEGIN
  i := 10;
  j := 20;

  sum := add(100, 200);
  writeln('Sum = ', sum)
END.
```

```
.method static add(II)I

    getstatic Adder/i I
    getstatic Adder/j I
    iadd
    iload_0    ; n1 (slot #0)
    iadd
    iload_1    ; n2 (slot #1)
    iadd
    istore_2   ; s  (slot #2)

    iload_2
    ireturn    ; s

.limit stack 2
.limit locals 3
.end method
```

- Use **`getstatic`** with a <u>fully qualified name and type</u> to push the value of a <u>static field</u> onto the operand stack.

Code to Call a Function (Static Method)

```
PROGRAM ADDER;

VAR
  i, j, sum : integer;

FUNCTION add(n1, n2 : integer) : integer;

  VAR
    s : integer;

  BEGIN
    s := i + j + n1 + n2;
    add := s;
  END;

BEGIN
  i := 10;
  j := 20;

  sum := add(100, 200);
  writeln('Sum = ', sum)
END.
```

```
.method public static main([Ljava/lang/String;)V
.limit stack 4
.limit locals 1

    bipush 10
    putstatic Adder/i I

    bipush 20
    putstatic Adder/j I

    bipush 100
    sipush 200
    invokestatic Adder/add(II)I

    putstatic Adder/sum I

    ...
```

A function call leaves its return value on top of the operand stack of the caller.

- Use **putstatic** with a fully qualified field name and type signature to pop a value off the operand stack and store it into a static field.
- Use **invokestatic** with a fully-qualified method name and a type signature to call a static method.

Code to Call `System.out.println()`

- What does the method call
  `System.out.println("Hello, world!")`
  require on the operand stack?
  - A reference to the `java.io.PrintStream` object `System.out`.
  - A reference to the `java.lang.String` object `"Hello, world!"`

object

type descriptor of object

```
getstatic     java/lang/System/out Ljava/io/PrintStream;
ldc           "Hello, world!"
invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
```

Note: `invokevirtual`

method

parm type descriptor

no return type (void)

System.out.println(), *cont'd*

- Compile the Pascal call

```
writeln('Sum = ', sum)
```

as if it were the Java

Remember to use **javap**!

```
System.out.println(
    new StringBuilder(" Sum = ")
        .append(sum)
        .toString()
);
```

Each call to **invokevirtual** requires an object reference and then any required actual parameter values on the operand stack.

```
getstatic java/lang/System/out Ljava/io/PrintStream;
new       java/lang/StringBuilder
dup
ldc "Sum = "
invokenonvirtual java/lang/StringBuilder/<init>(Ljava/lang/String;)V
getstatic     Adder/sum I
invokevirtual java/lang/StringBuilder/append(I)Ljava/lang/StringBuilder;
invokevirtual java/lang/StringBuilder/toString()Ljava/lang/String;
invokevirtual java/io/PrintStream/println(Ljava/lang/String;)V
```

Why do we need this **dup** instruction?

String.format()

- A more elegant way to compile a call to Pascal's standard **`writeln()`** procedure is to use Java's **`String.format()`** method.

- Compile Pascal

```
writeln('The square root of ', n:4,
        ' is ', root:8:4);
```

as if it were the Java

```
System.out.print(
    String.format(
        "The square root of %4d is %8.4f\n",
        n, root)
);
```

`String.format()`, *cont'd*

- The Java `String.format()` method has a variable-length parameter list.
- The first parameter is the format string.
- Similar to C's format strings for `printf()`.

- The code generator must construct the format string.
  - Pascal:

```
('The square root of ', n:4, ' is ', root:8:4)
```

  - Equivalent Java:

```
("The square root of %4d is %8.4f\n", n, root)
```

`String.format()`, *cont'd*

- The remaining parameters are the <ins>values to be formatted</ins>, one for each format specification in the format string.

- Jasmin passes these remaining parameters as a <ins>one-dimensional array</ins> of objects.

- Therefore, we must emit code to <ins>create and initialize the array</ins> and <ins>leave its reference</ins> on the operand stack.

String.format(), *cont'd*

```
s = String.format(
        "The square root of %4d is %8.4f\n",
        n, root);
```

- Instruction **aastore** operands on the stack:
  - Array reference
  - Index value
  - Element value (object reference)

```
ldc            "The square root of %4d is %8.4f\n"
iconst_2
anewarray      java/lang/Object
dup
iconst_0
getstatic      FormatTest/n I
invokestatic   java/lang/Integer.valueOf(I)Ljava/lang/Integer;
aastore
dup
iconst_1
getstatic      FormatTest/root F
invokestatic   java/lang/Float.valueOf(F)Ljava/lang/Float;
aastore
invokestatic   java/lang/String.format(Ljava/lang/String;[Ljava/lang/Object;)
                                                                Ljava/lang/String;
putstatic      FormatTest/s Ljava/lang/String;
```

Create an **array of size 2** and leave the array reference on the operand stack.

Store **element 0:** The value of **n**.

Why the **dup** instructions?

Store **element 1:** The value of **root**.

String.format(), *cont'd*

```
System.out.print(
    String.format("The square root of %4d is 8.4f\n",
                  n, root);
);
```

```
getstatic     java/lang/System/out Ljava/io/PrintStream;
ldc           "The square root of %4d is %8.4f\n"
iconst_2
anewarray     java/lang/Object
dup
iconst_0
getstatic      FormatTest/n I
invokestatic   java/lang/Integer.valueOf(I)Ljava/lang/Integer;
aastore
dup
iconst_1
getstatic      FormatTest/root F
invokestatic   java/lang/Float.valueOf(F)Ljava/lang/Float;
aastore
invokestatic   java/lang/String.format(Ljava/lang/String;
                                       [Ljava/lang/Object;)Ljava/lang/String;
invokevirtual java/io/PrintStream.print(Ljava/lang/String;)V
```

Easier: Use the newer `System.out.printf()`.

Code Generation for Arrays and Subscripts

- Code to allocate memory for an <u>array variable</u>.
- Code to allocate memory for each <u>non-scalar</u> array element.
- Code for a subscripted variable in an <u>expression</u>.
- Code for a subscripted variable that is an <u>assignment target</u>.

Arrays and Subscripts, *cont'd*

- Allocate memory for single-dimensional arrays:
  - Instruction **`newarray`** for scalar elements.
  - Instruction **`anewarray`** for non-scalar elements.
- Allocate memory for multidimensional arrays:
  - Instruction **`multianewarray`**.

Allocating Memory for Arrays

- Recall the code template for a Jasmin method.

Code to allocate **arrays** here!

Routine header

```
.method private static signature return-type-descriptor
```

Code for local variables

Code for structured data allocations

Code for compound statement

Code for return

Routine epilogue

```
.limit locals n
.limit stack m
.end method
```

- Pascal <u>automatically allocates</u> memory for arrays declared in the main program or locally in a procedure or function.
  - The memory allocation occurs whenever the routine is called.
  - This is separate from <u>dynamically allocated</u> data using pointers and **new**.

Therefore, our generated Jasmin code must implement this automatic runtime behavior.

Example: Allocate Memory for Scalar Arrays

```
PROGRAM ArrayTest;

TYPE
    vector = ARRAY[0..9] OF integer;
    matrix = ARRAY[0..4, 0..4] OF integer;
    cube   = ARRAY[0..1, 0..2, 0..3] OF integer;

VAR
    i, j, k, n : integer;
    a1         : vector;
    a2         : matrix;
    a3         : cube;

BEGIN
    ...
END.
```

```
bipush   10
newarray int
putstatic        arraytest/a1 [I

iconst_5
iconst_5
multianewarray   [[I 2
putstatic        arraytest/a2 [[I

iconst_2
iconst_3
iconst_4
multianewarray   [[[I 3
putstatic        arraytest/a3 [[[I
```

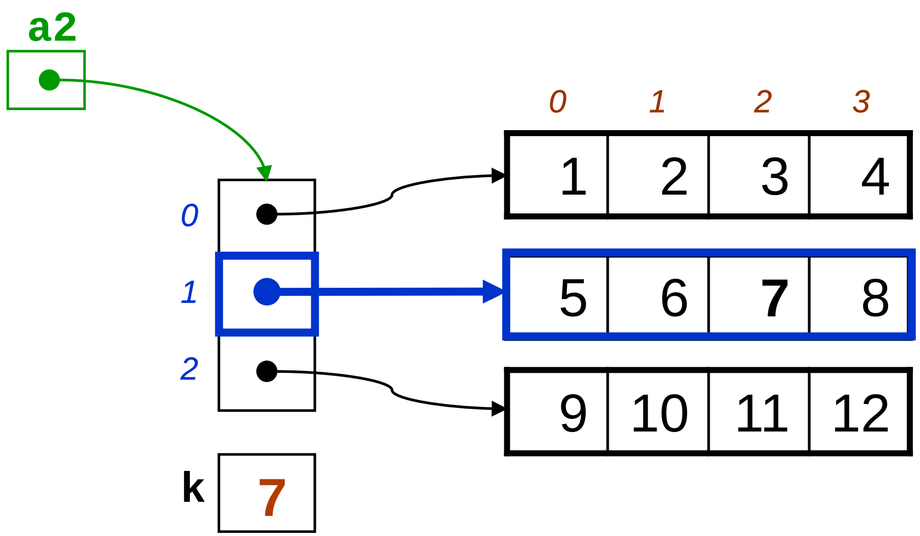
Access an Array Element of a 2-D Array

```
PROGRAM ArrayTest;

TYPE
  matrix = ARRAY[0..2, 0..3]
             OF integer;

VAR
  i, j, k : integer;
  a2      : matrix;

BEGIN
  ...
  i := 1;
  j := 2;
  k := a2[i, j];
  ...
END.
```




```
getstatic  arraytest/a2 [[I
getstatic  arraytest/i I
aaload
getstatic  arraytest/j I
iaload
putstatic  arraytest/k I
```

1	2	3	4
5	6	7	8
9	10	11	12