Language Design and Optimizations

By – Louis Jenkins

Presentation Summary

- Create our own programming language
  - Demystify and Explore how they are created
    - Grammars, Lexers, Syntax Trees, etc.
- Define semantics for our language
- Interpret and run programs written in our language
- High-Level overview of program execution
  - Control Flow Graphs

Defining Our Language

- Domain Specific Language
  - Language created to solve a particular problem domain
    - Our domain is academic research
  - Opposite of a general-purpose language
    - C, C++, Java, Go, etc.
- Grammars
  - Defines our actual language
  - Lexers tokenizes input defined in the grammar
    - Lexer is also known as *scanner* or *tokenizer*
    - Determines syntactic correctness
  - Parsers infer meaning from sequences of tokens
    - Also determine syntactic correctness
  - Lexer and Parser provide different granularities in providing syntactic correctness.

Building the Parser

- YACC
  - Yet Another Compiler Compiler
  - A LALR Parser generator
    - Look Ahead Left To Right
    - Can look ahead K symbols to determine the right action to take.
  - Reads in BNF grammar
    - Backus-Naur Form is a context-free grammar capable of defining any language
      - Also known as *meta* syntax that can even define itself.
- Shift-Reduce Parser
  - *Shift* pushes the symbol on the stack
  - *Reduce* combines the symbols on the top of the stack into a single symbol if it satisfies a grammar rule.
  - Is a push-down automaton

The Grammar Pt.1

- Lexer
    - Also known as a *scanner* or *tokenizer*
    - Deals with parsing characters into streams of *tokens*
        - Tokens are the primitives that make up a language
            - Example: *'var', 'this', 'if', 'else', 'while', 'for'*
        - Tokens are also referred to as *lexemes*
    - Determines syntactic correctness
        - If input cannot be tokenized, it is syntactically invalid.

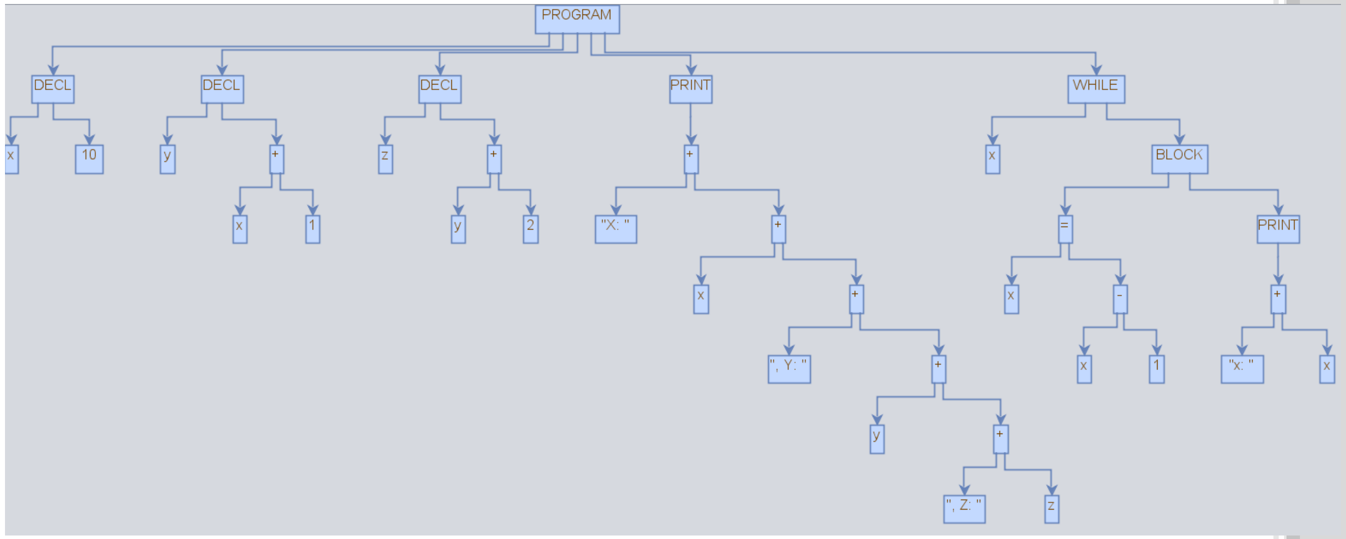
```java
// String literal
if (tok.startsWith("\"")) {
    // In case String was chunked, need to collect next lines up to ending '"'
    // Also drop the excess '"'
    String str = tok.substring(1);
    while (!str.endsWith("\"")) {
        String nextStr = tokens.poll();
        if (nextStr == null) {
            yyerror("Unterminated String!");
        }

        str += " " + nextStr;
    }
    yylval = new ConstantASTNode(str.substring(0, str.length() - 1));
    return token = STRING;
}

// Integer literal
if (tok.matches("0") || tok.matches("[1-9][0-9]*")) {
    yylval = new ConstantASTNode(Integer.parseInt(tok));
    return token = INTEGER;
}

// 'var' declaration
if (tok.equals("var")) {
    // Check next token for name...
    String t = tokens.element();
    if (t == null) {
        yyerror("Need NAME after 'var'");
    }
    return token = VAR;
}

if (tok.equals("print")) {
    String t = tokens.element();
    if (t == null) {
        yyerror("Need EXPR after 'print'");
    }
    return token = PRINT;
}

if (tok.equals("while")) {
    String t = tokens.element();
    if (t == null) {
        yyerror("Need EXPR after 'while'");
    }
    return token = WHILE;
}
```

The Grammar Pt. 2

- Semantics
  - Parser Expressions
    - Snippets of code called upon reduction
      - Define semantics
    - Create our Abstract Syntax Tree here
      - Each node has defined with it semantics
        - Has an Action
          - AdditionBinaryASTNode performs type checking and handles addition of both expression operators.

```
prog : prog stmt { $$ = $2; $$.execute(); ASTGraph.graph($$);}
  | stmt { $$ = $1; $$.execute(); ASTGraph.graph($$);}
  | /* Empty */
  ;

conditional : WHILE expr block { $$ = new WhileConditionalASTNode($2, $3); }
    ;

stmt : VAR NAME '=' expr ';' { $$ = new DefinitionASTNode($2, $4); }
    | NAME '=' expr ';' { $$ = new AssignmentASTNode($1, $3); }
    | conditional { $$ = $1; }
    | PRINT expr ';' { $$ = new PrintASTNode($2); }
    | error ';'
    ;

stmt_list : stmt stmt_list { ((StatementASTNode)$2).body.add(0, $1); $$ = $2; }
    | /* Empty */   { $$ = new StatementASTNode(); }
    ;

block : '{' stmt_list '}' { $$ = $2; }
    ;


expr : expr '+' expr { $$ = new AdditionBinaryASTNode($1, $3); }
    | expr '-' expr { $$ = new SubtractionBinaryASTNode($1, $3); }
    | expr '*' expr { $$ = new MultiplicationBinaryASTNode($1, $3); }
    | expr '/' expr { $$ = new DivisionBinaryASTNode($1, $3); }
    | expr EQ expr { $$ = new EqualBinaryASTNode($1, $3); }
    | '(' expr ')' { $$ = $2; }
    | INTEGER { $$ = $1; }
    | STRING { $$ = $1; }
    | NAME { $$ = $1; }
    ;
```

```
var x = 10;
var y = x + 1;
var z = y + 2;
print "X: " + x + ", Y: " + y + ", Z: " + z;
while (x) {
     x = x - 1;
     print "x: " + x;
}
```



Abstract Syntax Tree

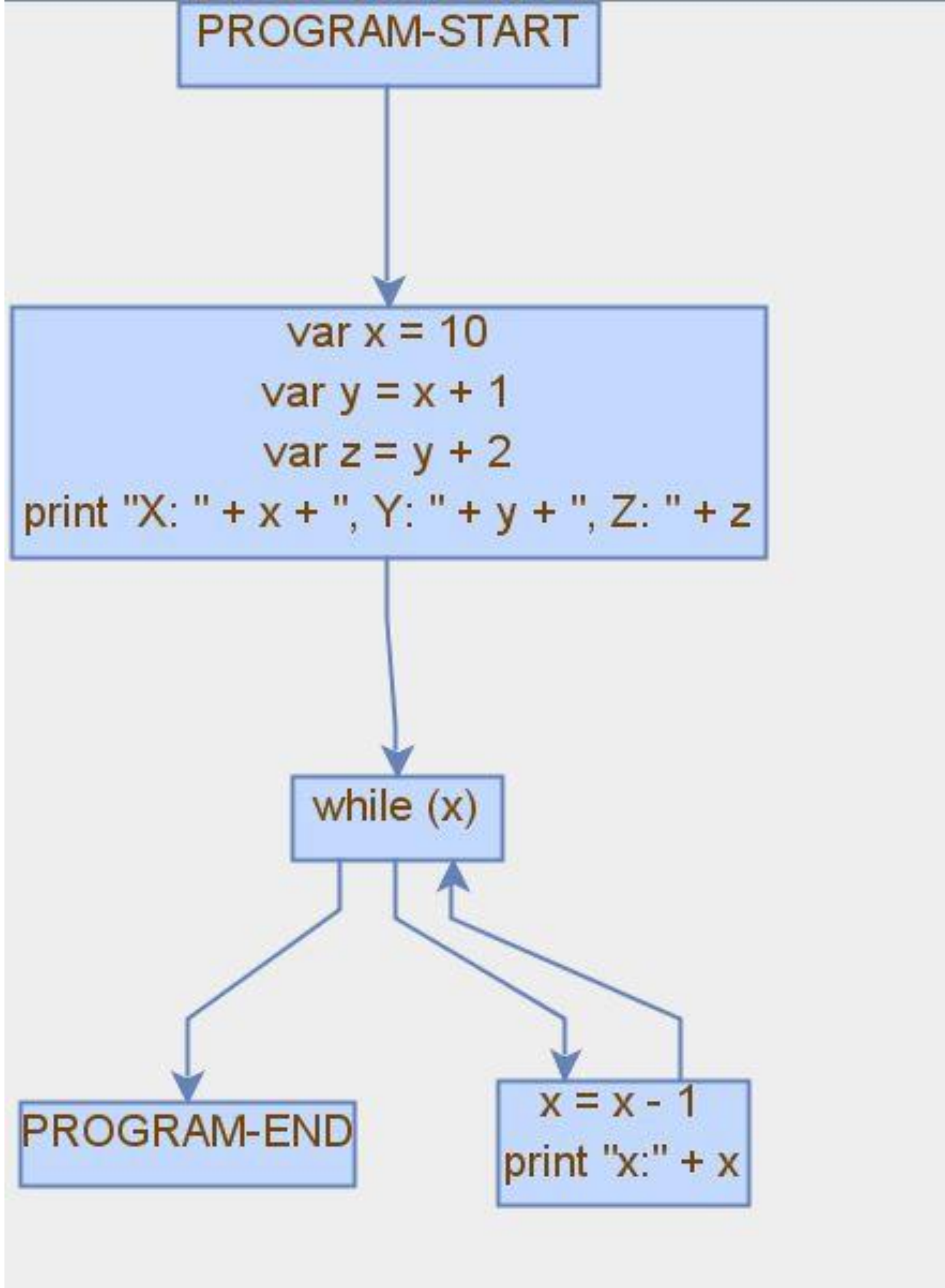
- Tree representation of the syntactic structure of a program
  - Each node represents some constant in the source code
- Why is it Abstract
  - Does not contain all details, only what is important
    - Difference between '+' and 'AdditionBinaryASTNode'
- Applications and Uses
  - "Walking" the syntax tree
    - Also known as the 'visitor' pattern
    - Allows us to make interesting observations and compile-time checks
      - Type-Checking, Definitions, Etc.
      - Could even be *interpreted*

Interpreter – Executing our Language

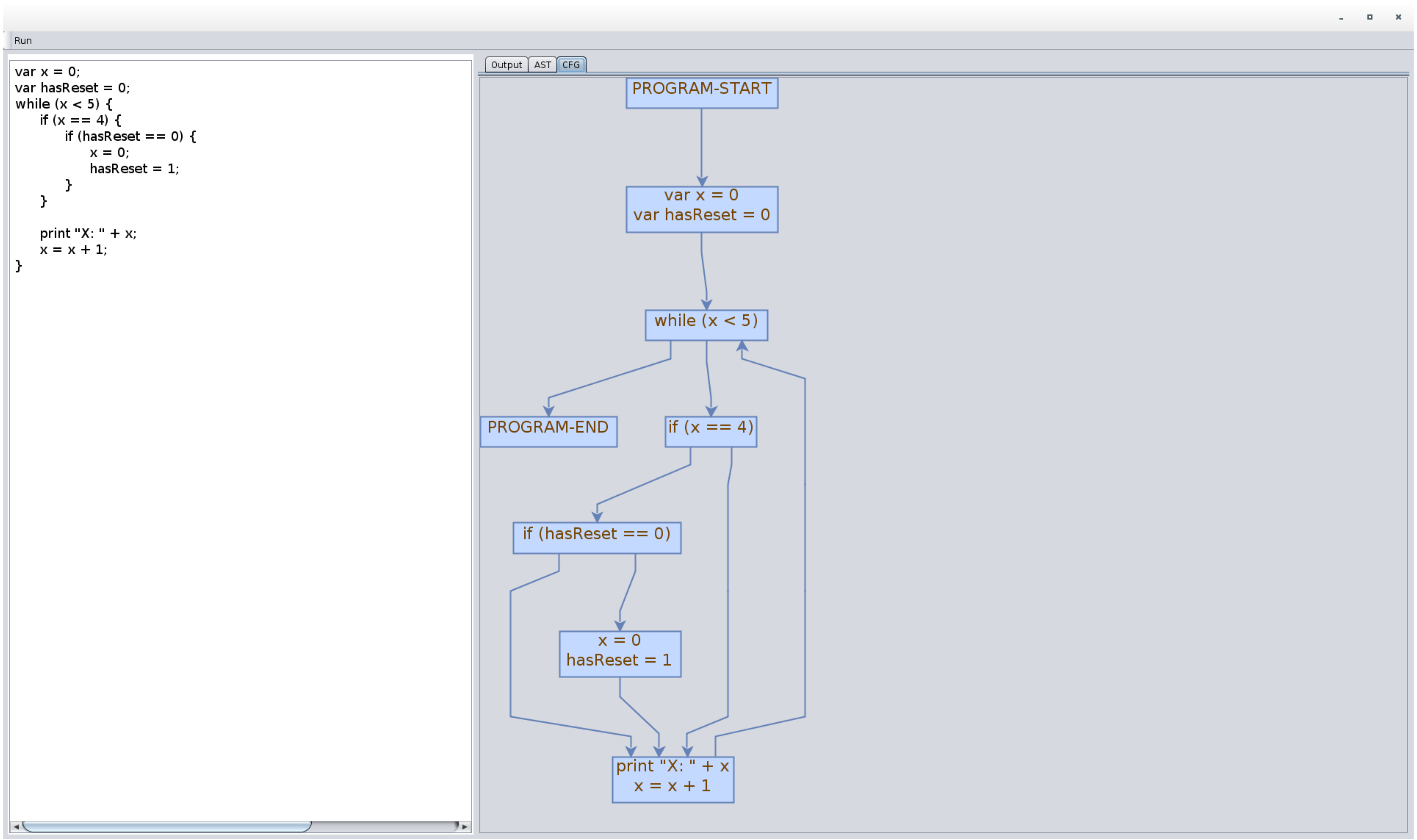
- Symbol Table
  - Mapping from a *name* to it’s *symbol*
    - In the interpreter, the symbol keeps track of it’s value
  - We do not support lexical scoping
    - Only one instance of a variable name can exist in the program at one time.
- ‘Visitor’ execution
  - Walking the tree allows us to obtain the structure of the program
    - This structure can be used to interpret the intent behind the original instructions and executed
  - Similar style can be used to construct the Control Flow Graph
    - Each root of a statement subtree can be used to reconstruct the intent of the original statement
      - Each statement is a node with an edge to the next statement node.
    - But what about loops and conditional statements?

Control Flow Graph

- A directed graph that shows flow of control from one statement to another
  - Normal statements, Conditional Statements, Loops
- Basic Blocks
  - Sequence of statements that are *dominated* by a predecessor
    - A statement s_1 is said to *dominate* s_2 if all path of execution must flow through s_1 to reach s_2
      - Denoted $s_1 \; dom \; s_2$
    - A basic block is a sequence $(s_1, s_2, \ldots, s_n)$ such that $\forall i \in [1, N-1] \;\; s_i \; dom \; s_{i+1}$
  - A Control Flow Graph composed solely of basic blocks is said to be a *reduced* control flow graph.



Live Demo – Screenshot



Language Test – Duff's Device

- Duff's device is a loop unrolling optimization that reduces the number of conditional evaluations in a loop
  - By unrolling the loop, we do not need to explicitly check on each pass
    - I.E: 1000 checks vs 1000 / N checks
      - N is the amount of the loop duplicated/unrolled on each iteration
        - In most cases 8
  - Trade-Off
    - Larger program size
- The Test
  - Implement loop unrolling in our language as the ultimate test
    - Tests everything needed to prove we are Turing Complete

Turing Completeness

- A language is Turing Complete if it can *simulate* a single-tape Turing-Machine
  - *read* and *write* values to a tape
    - Variables do precisely this.
      - Given a variable X and a tape position Y, then the concatenation of the variable and position XY can store information at that tape position.
        - 1st Tape Position: $X1$
        - N^{th} Tape Position: XN
      - To maintain state, a variable q can be defined
  - Act conditionally based on current state and tape contents
    - Conditional statements do precisely this.
      - Wrap in a while loop
        - Now we can simulate the *halting problem*
      - Chain *if-else* statements to check current state
      - Read and write variables and transition states as needed
- Our Domain Specific Language is Turing Complete

Conclusion

- Recap
  - Created our own language by defining it’s grammar
  - Created the Abstract Syntax Tree from the grammar
    - Interpreted and ran ACTUAL code in our language by walking the syntax tree
  - Created the Control Flow Graph
    - Reduced it into basic blocks, handles loops and conditionals
  - Established Turing Completeness of our language
- Was it fun?
  - Yep
    - Taught myself everything in a compiler design course