# Describing Syntax and Semantics

## of

## Programming Languages

## Part I

# Programming Language Description

Description must

- be **concise** and **understandable**
- be useful to both **programmers** and **language implementors**
- cover both
  - **syntax** (forms of expressions, statements, and program units) and
  - **semantics** (meanings of expressions, statements, and program units

*Example*: Java `while-statement`

**Syntax:** `while (boolean_expr) statement`

**Semantics:** if `boolean_expr` is true then statement is executed and control returns to the expression to repeat the process; if `boolean_expr` is false then control is passed on to the statement following the while-statement.

# Lexemes and Tokens

Lowest-level syntactic units are called **lexemes**. Lexemes include identifiers, literals, operators, special keywords etc.

A **token** is a category of the lexemes (i.e. similar lexemes belong to a token)

*Example*: Java `statement: index = 2 * count + 17;`

| Lexeme | Token |
|---|---|
| `index` | IDENTIFIER |
| `=` | EQUALS |
| `2` | NUMBER |
| `*` | MUL |
| `count` | IDENTIFIER |
| `+` | PLUS |
| `17` | NUMBER |
| `;` | SEMI |

IDENTIFIER **tokens**: `index, count`

NUMBER **tokens**: `2, 17`

remaining 4 lexemes (`=, *, +, ;`) are lone examples of their corresponding token!

# Lexemes and Tokens: Another Example

*Example*: SQL `statement`

```
select sno, sname
from   suppliers
where  sname = 'Smith'
```

| Lexeme | Token |
|---|---|
| `select` | SELECT |
| `sno` | IDENTIFIER |
| `,` | COMMA |
| `sname` | IDENTIFIER |
| `from` | FROM |
| `suppliers` | IDENTIFIER |
| `where` | WHERE |
| `sname` | IDENTIFIER |
| `=` | EQUALS |
| `'Smith'` | SLITERAL |

IDENTIFIER **tokens**: `sno, same, suppliers`

SLITERAL **tokens**: `'Smith'`

remaining lexemes (`select, from, where, ,, =`)

are lone examples of their corresponding token!

# Lexemes and Tokens: A third Example

*Example*: WAE expressions

```
{with {{x 5} {y 2}} {+ x y}};
```

| **Lexeme** | **Token** |
|---|---|
| `{` | LBRACE |
| `with` | WITH |
| `{` | LBRACE |
| `{` | LBRACE |
| `x` | ID |
| 5 | NUMBER |
| `}` | RBRACE |
| `{` | LBRACE |
| `y` | ID |
| 2 | NUMBER |

| **Lexeme** | **Token** |
|---|---|
| `}` | RBRACE |
| `}` | RBRACE |
| `{` | LBRACE |
| + | PLUS |
| `x` | ID |
| `y` | ID |
| `}` | RBRACE |
| `}` | RBRACE |
| `;` | SEMI |
| | |

TOKENS:

LBRACE
RBRACE
PLUS
MINUS
TIMES
DIV
**ID**
WITH
IF
**NUMBER**
SEMI

# Lexical Analyzer

A **lexical analyzer** is a **program** that reads an input program/expression/query and extracts each lexeme from it (classifying each as one of the tokens).

Two ways to write this lexical analyzer program:

1. Write it from scratch! i.e. choose your favorite programming language (python!) and write a program in python that reads input string (which contain the input program, expression, or query) and extracts the lexemes.
2. Use a code-generator (Lex, Yacc, PLY, ANTLR, Bison, …) that reads a high-level specification (in the form of **regular expressions**) of all tokens and generates a lexical analyzer program for you!
3. We will see how to write the lexical analyzer from scratch later.
4. Now, we will learn how to do it using PLY: http://www.dabeaz.com/ply/

# Regular Expressions in Python

https://docs.python.org/3/library/re.html
https://www.w3schools.com/python/python_regex.asp

Meta Characters used in Python regular expressions:

<table>
<tr><th>Meta</th><th>Description</th><th>Examples</th></tr>
<tr><td>[]</td><td>A set of characters</td><td>[a-z], [0-9], [xyz012]</td></tr>
<tr><td>.</td><td>Any one character (except newline)</td><td>he..o,</td></tr>
<tr><td>^</td><td>starts with</td><td>^hello</td></tr>
<tr><td>$</td><td>ends with</td><td>world$</td></tr>
<tr><td>*</td><td>zero or more occurrences</td><td>[a-z]*</td></tr>
<tr><td>+</td><td>one or more occurrences</td><td>[a-zA-Z]+</td></tr>
<tr><td>?</td><td>one or zero occurrence</td><td>[-+]?</td></tr>
<tr><td>{}</td><td>specify number of occurrences</td><td>[0-9]{5}</td></tr>
<tr><td>|</td><td>either or</td><td>[a-z]+ | [A-Z]+</td></tr>
<tr><td>()</td><td>capture and group</td><td>([0-9]{5}) use \1 \2 etc. to refer</td></tr>
<tr><td>\</td><td>begins special sequence; also used to escape meta characters</td><td>\d, \w, etc. (see documentation)</td></tr>
</table>

# PLY (Python Lex/Yacc): WAE Lexer

```
import ply.lex as lex

reserved = { 'with': 'WITH', 'if': 'IF' }

tokens =
['NUMBER','ID','LBRACE','RBRACE','SEMI','PLUS',\
 'MINUS','TIMES','DIV'] + list(reserved.values())

t_LBRACE = r'\{'
t_RBRACE = r'\}'
t_SEMI = r';'
t_WITH = r'[wW][iI][tT][hH]'
t_IF = r'[iI][fF]'
t_PLUS = r'\+'
t_MINUS = r'-'
t_TIMES = r'\*'
t_DIV = r'/'
```

pip install ply

or

pip3 install ply

```
def t_NUMBER(t):
  r'[-+]?[0-9]+(\.([0-9]+)?)?'
  t.value = float(t.value)
  t.type = 'NUMBER'
  return t

def t_ID(t):
  r'[a-zA-Z][_a-zA-Z0-9]*'
  t.type = reserved.get(t.value.lower(),'ID')
  return t

# Ignored characters
t_ignore = " \r\n\t"
t_ignore_COMMENT = r'\#.*'

def t_error(t):
  print("Illegal character '%s'" % t.value[0])
  t.lexer.skip(1)

lexer = lex.lex()
```

# WAE Lexer continued

```
# Test it out
data = '''
{with {{x 5} {y 2}} {+ x y}};
'''

# Give the lexer some input
print("Tokenizing: ",data)
lexer.input(data)

# Tokenize
while True:
    tok = lexer.token()
    if not tok:
        break      # No more input
    print(tok)
```

- The lexer object has just two methods: `lexer.input(data)` and `lexer.token()`
- Usually, the Lexical Analyzer is used in tandem with a Parser (the parser calls `lexer.token()).`
- So, the code on this page is written just to debug the Lexical Analyzer.
- Once satisfied we can/should comment out this code.

# WAE Lexer continued

```
{with {{x 5} {y 2}} {+ x y}};
```

The PLY Lexer program we wrote will generate the following sequence of pairs of token types and their values:

```
(‘LBRACE’,’{‘), (‘WITH’,’with’), (‘LBRACE’,’{‘), (‘LBRACE’,’{‘), (‘ID’,’x’),
(‘NUMBER’,’5’), (‘RBRACE’,’}’), (‘LBRACE’,’{‘), (‘ID’,’y’), (‘NUMBER’,’2’),
(‘RBRACE’,’{‘), (‘RBRACE’,’}’), (‘LBRACE’,’{’), (‘PLUS’,’+’), (‘ID’,’x’)
(‘ID’,’y’), (‘RBRACE’,’}’), (‘RBRACE’,’}’), (‘SEMI’,’;’)
```

Let us see this program (`WAELexer.py`) in action!

# Language Generators and Recognizers

Now that we know how to describe tokens of a program, let us learn how to describe a "valid" sequence of tokens that constitutes a program. A valid program is referred to as a **sentence** in formal language theory.

Two ways to describe the syntax:

(1) **Language Generator**: a mechanism that can be used to generate sentences of a language. This is usually referred to as a **Context-Free-Grammar** (CFG). Easier to understand.

(2) **Language Recognizer**: a mechanism that can be used to verify if a given string, p, of characters (grouped in a sequence of tokens) belongs to a language L. The syntax analyzer in a compiler is a language recognizer.

(3) There is a close connection between a language generator and a language recognizer.

# Chomsky Hierarchy and Backus-Naur Form

- Chomsky, a noted Linguist, defined a hierarchy of language generator mechanisms or grammars for four different classes of languages. Two of them are used to describe the syntax of programming languages:
  - **Regular Grammars**: describe the tokens and are equivalent to regular expressions.
  - **Context-free Grammars**: describe the syntax of programming languages
- John Backus invented a similar mechanism, which was extended by Peter Naur later and this mechanism is referred to as the Backus-Naur Form (BNF)
- Both these mechanisms are similar and we may use CFG or BNF to refer to them interchangeably.

# Fundamentals of Context Free Grammars

CFGs are a **meta-language** to describe another language. They are meta-languages for programming languages!

A context-free grammar G has 4 components (N,T,P,S):

1) N, a set of non-terminal symbols or just called **non-terminals;** these denote abstractions that stand for syntactic constructs in the programming language.

2) T, a set of terminal symbols or just called **terminals;** these denote the **tokens** of the programming language

3) P, a set of **production rules** of the form

   $X \rightarrow \alpha$

   where X is a non-terminal and $\alpha$ (**definition** of X) is a string made up of terminals or non-terminals. The production rules define the "valid" sequence of tokens for the programming language.

4) S, a non-terminal, that is designated as the **start symbol;** this denotes the highest level abstraction standing for all possible programs in the programming language.

# CFGs: Examples of Production rules

Note: We will use lower-case for non-terminals and upper-case for terminals.

(1) A Java assignment statement may be represented by the abstraction `assign`. The definition of `assign` may be given by the production rule

```
assign → VAR EQUALS expression
```

(2) A Java if statement may be represented by the abstraction `ifstmt` and the following production rules:

```
ifstmt → IF LPAREN logic_expr RPAREN stmt
```

```
ifstmt → IF LPAREN logic_expr RPAREN stmt ELSE stmt
```

These two rules have the same LHS; They can be combined into one rule with "or" on the RHS:

```
ifstmt → IF LPAREN logic_expr RPAREN stmt |
          IF LPAREN logic_expr RPAREN stmt ELSE stmt
```

In the above examples, we have to introduce production rules that define the various abstractions used such as `expression`, `logic_expr`, and `stmt`

# CFGs: Examples of Production rules

(3) A list of identifiers in Java may be represented by the abstraction `ident_list`. The definition of `ident_list` can be given by the following **recursive** production rules:

```
ident_list → IDENTIFIER
ident_list → ident_list COMMA IDENTIFIER
```

IMPORTANT PATTERN!

Notice that the second rule is recursive because the non-terminal `ident_list` on the LHS also appears in the RHS.

It is time to learn how these production rules are to be used! The production rules are a type of "replacement" or "rewrite" rules, where the LHS is replaced by the RHS. Consider the following replacements/rewrites starting with `ident_list`:

```
  ident_list
⇒ ident_list COMMA IDENTIFIER
⇒ ident_list COMMA IDENTIFIER COMMA IDENTIFIER
⇒ ident_list COMMA IDENTIFIER COMMA IDENTIFIER COMMA IDENTIFIER
⇒ IDENTIFIER COMMA IDENTIFIER COMMA IDENTIFIER COMMA IDENTIFIER
```

substituting these token types by their values, we may get: `x, y, z, u`

# WAE PLY Grammar

Note: In PLY, we use : instead of →

**PRODUCTION RULES (P)**

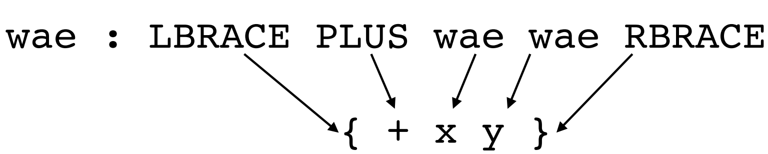
```
waeStart : wae SEMI

wae : NUMBER
wae : ID
wae : LBRACE PLUS wae wae RBRACE
wae : LBRACE MINUS wae wae RBRACE
wae : LBRACE TIMES wae wae RBRACE
wae : LBRACE DIV wae wae RBRACE
wae : LBRACE IF wae wae wae RBRACE
wae : LBRACE WITH LBRACE alist RBRACE wae RBRACE

alist : LBRACE ID wae RBRACE
alist : LBRACE ID wae RBRACE alist
```

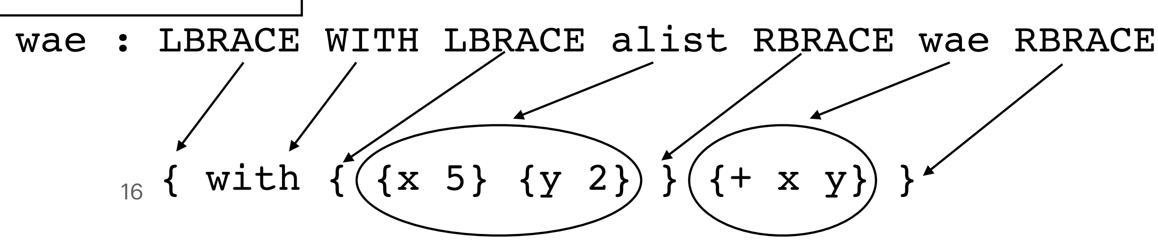
**TERMINALS (T)**

```
LBRACE
RBRACE
PLUS
MINUS
TIMES
DIV
ID
WITH
IF
NUMBER
SEMI
```

**NON-TERMINALS (N)**

```
waeStart
wae
alist
```



# Grammars and Derivations

The sentences of the language are generated through a sequence of applications of the production rules, starting with the start symbol. This sequence of rule applications is called a **derivation**. In a derivation, each successive string is derived from the previous string by replacing one of the nonterminals with one of that nonterminal's definitions.

Consider the string: `{+ x y};`

Here is a derivation for this string (starting from waeStart we are able to derive `{+ x y};`)

```
  waeStart
⇒ wae ;                  using rule waeStart : wae SEMI
⇒ { + wae wae } ;        using rule wae : LBRACE PLUS wae wae RBRACE
⇒ { + x wae } ;          using rule wae : ID
⇒ { + x y } ;            using rule wae : ID
```

We have highlighted in red the non-terminal that is being replaced/rewritten. Since we have a successful derivation for the string, `{+ x y};` we say that the string, `{+ x y};` is a "valid" WAE expression.

# Another Derivation Example

Consider the string: `{WITH {{x 5} {y 2}} {+ x y}};`

Here is a derivation for this string:

| | Production Rule Used |
|---|---|
| waeStart | `waeStart : wae SEMI` |
| ⇒ wae ; | `wae : LBRACE WITH LBRACE alist RBRACE wae RBRACE` |
| ⇒ { WITH { alist } wae } ; | `alist : LBRACE ID wae RBRACE alist` |
| ⇒ { WITH { { x wae } alist } wae }; | `wae : NUMBER` |
| ⇒ { WITH { { x 5 } alist } wae }; | `alist : LBRACE ID wae RBRACE` |
| ⇒ { WITH { { x 5 } { y wae } } wae }; | `wae : NUMBER` |
| ⇒ { WITH { { x 5 } { y 2 } } wae }; | `wae : LBRACE PLUS wae wae RBRACE` |
| ⇒ { WITH { { x 5 } { y 2 } } {+ wae wae} }; | `wae : ID` |
| ⇒ { WITH { { x 5 } { y 2 } } {+ x wae} }; | `wae : ID` |
| ⇒ { WITH { { x 5 } { y 2 } } {+ x y} }; | |

# Derivations continued

- Each string in a derivation, including the start symbol, is referred to as a **sentential form**.
- A derivation continues until the sentential form does not contain any non-terminals.
- A **leftmost derivation** is one in which the replaced nonterminal is always the leftmost nonterminal.
- In addition to leftmost, a derivation may be **rightmost** or in an order that is **neither leftmost nor rightmost**.
- Derivation order has no effect on the language generated by a grammar.
- By choosing alternative rules with which to replace non-terminals in the derivation, different sentences in the language can be generated.
- By exhaustively choosing all combinations of choices, the entire language can be generated.

# Another Grammar Example

PRODUCTION RULES:

```
<assign> : <id> = <expr>
<expr> : <id> + <expr>
<expr> : <id> * <expr>
<expr> : ( <expr> )
<expr> : <id>
<id> : A
<id> : B
<id> : C
```

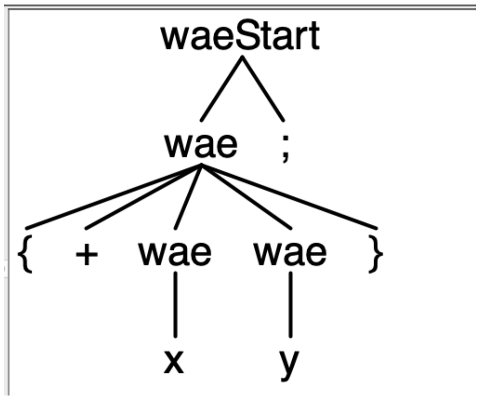
A leftmost derivation for A = B * ( A + C )

```
  <assign>
⇒ <id> = <expr>
⇒ A = <expr>
⇒ A = <id> * <expr>
⇒ A = B * <expr>
⇒ A = B * ( <expr> )
⇒ A = B * ( <id> + <expr> )
⇒ A = B * ( A + <expr> )
⇒ A = B * ( A + <id> )
⇒ A = B * ( A + C )
```

# Parse Tree

- A derivation can be represented graphically in the form of a **parse tree**.
- The root node is the start symbol of the grammar.
- Each step of the derivation expands a non-terminal node by creating one child node for each symbol in the RHS of the production rule used in the derivation.
- Every internal node is labeled with a non-terminal and every leaf is labeled with a terminal.
- A pre-order traversal of just the leaves is called the **yield** and should equal the terminal string whose derivation the parse tree represents.

```
waeStart
⇒ wae ;
⇒ { + wae wae } ;
⇒ { + x wae } ;
⇒ { + x y } ;
```



# Parse Tree: Another Example

waeStart

⇒ wae ;

⇒ { WITH { alist } wae } ;

⇒ { WITH { { x wae } alist } wae };

⇒ { WITH { { x 5 } alist } wae };

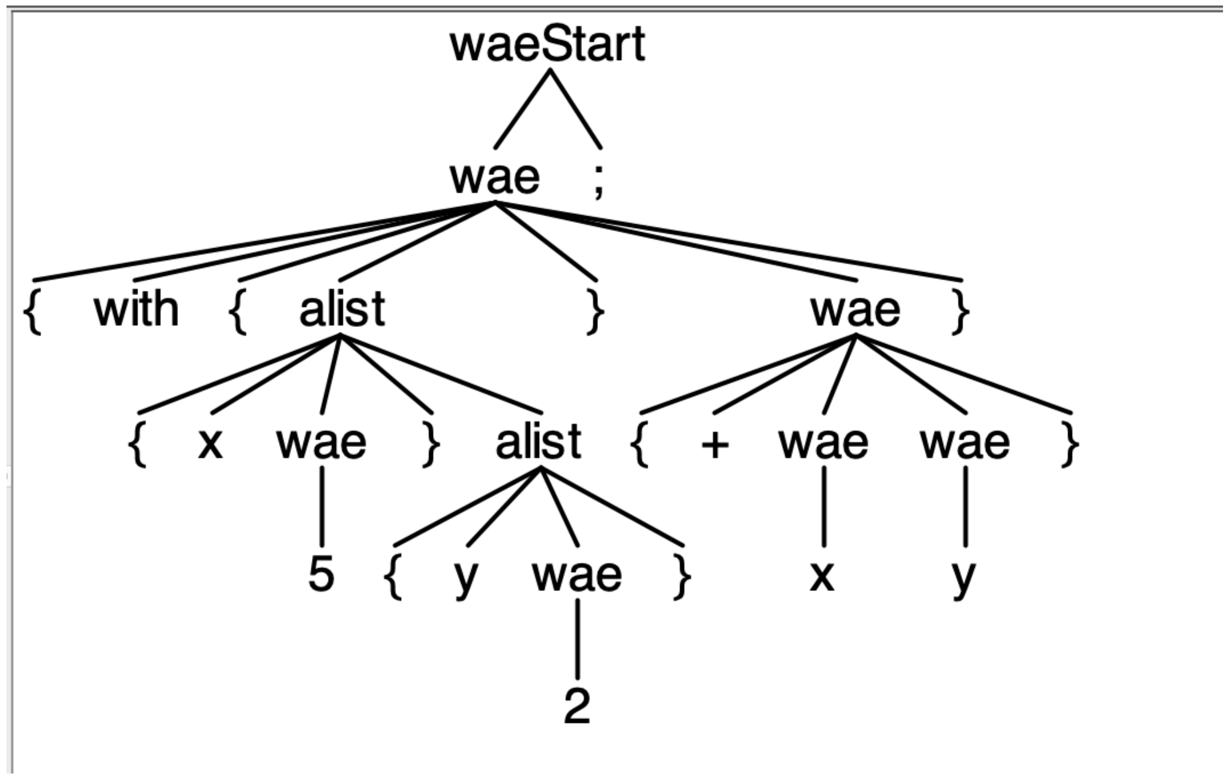
⇒ { WITH { { x 5 } { y wae } } wae };

⇒ { WITH { { x 5 } { y 2 } } wae };

⇒ { WITH { { x 5 } { y 2 } } {+ wae wae} };

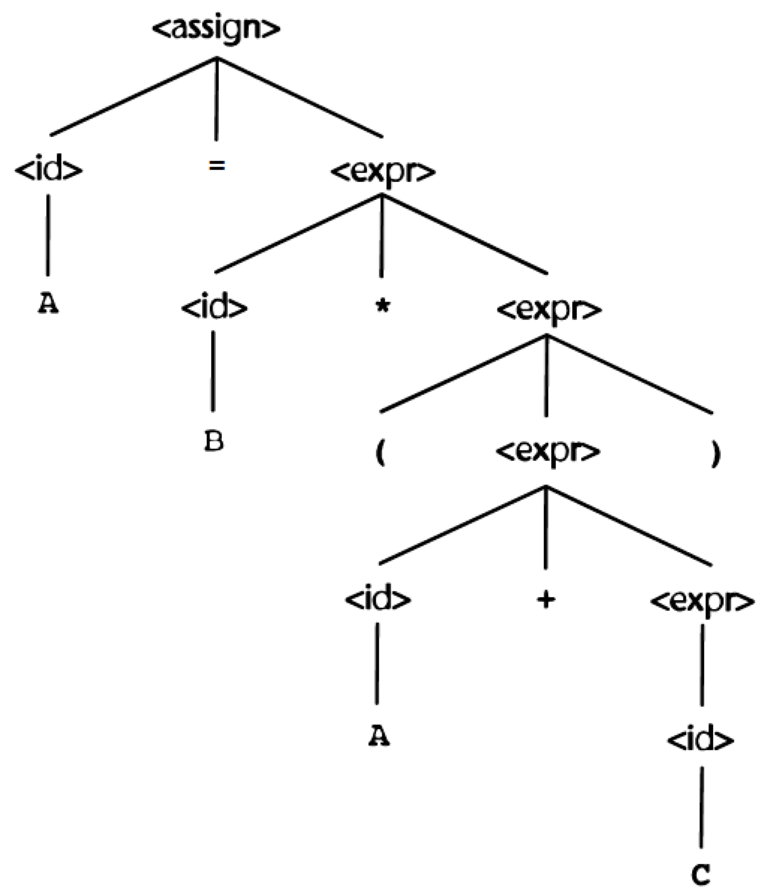
⇒ { WITH { { x 5 } { y 2 } } {+ x wae} };

⇒ { WITH { { x 5 } { y 2 } } {+ x y} };



# Parse Tree: A third example

```
  <assign>
⇒ <id> = <expr>
⇒ A = <expr>
⇒ A = <id> * <expr>
⇒ A = B * <expr>
⇒ A = B * ( <expr> )
⇒ A = B * ( <id> + <expr> )
⇒ A = B * ( A + <expr> )
⇒ A = B * ( A + <id> )
⇒ A = B * ( A + C )
```



# PLY Parser

- In addition to the Lexer (ply.lex) module, PLY also provides a Parser module (**ply.yacc**)
- The Parser module requires a CFG specification of the language
- PLY **automatically** generates a Parser program from the CFG.
- The Parser program calls the PLY Lexer object (created by the Lexer module) to read tokens from the input string.
- The Parser program verifies that the input string can be derived from the grammar by trying to construct a parse tree.
- PLY also provides the ability to evaluate "attribute" values for non-terminals in the parse tree. This ability can be used by the programmer to construct a data structure that stores the essential parts of the input string. This data structure is sometimes called an **abstract syntax tree**

# PLY Parser continued

- Each grammar rule is defined by a Python function where the **docstring** to that function contains the grammar rule.
- The Python function name **must** begin with a `p_` and it is typical to include the non-terminal on the LHS of the grammar rule as part of the function name.
- Here is one such function for the WAE Grammar:

```
def p_wae_8(p):
  'wae : LBRACE WITH LBRACE alist RBRACE wae RBRACE'
  # ^       ^     ^     ^     ^      ^     ^     ^
  #p[0]    p[1]  p[2] p[3]  p[4]   p[5]  p[6]  p[7]
  p[0] = ['with',p[4],p[6]]
```

- As can be observed, the function is named `p_wae_8.` The `8` is used to indicate that this is the 8th grammar rule with `wae` on the LHS.
- The second line is the docstring containing the grammar rule.
- The function has one parameter, `p`, which is a list of "values" of each of the symbols in the grammar rule. p[0] holds the value of the LHS non-terminal and p[1], p[2], etc. hold the values of the symbols of the RHS, as shown in the two comment lines.

# PLY Parser continued

```
def p_wae_8(p):
  'wae : LBRACE WITH LBRACE alist RBRACE wae RBRACE'
  # ^       ^     ^    ^     ^      ^     ^     ^
  #p[0]    p[1]  p[2] p[3]  p[4]   p[5]  p[6]  p[7]
  p[0] = ['with',p[4],p[6]]
```

- For RHS <u>tokens or terminals</u>, the "value" of the corresponding `p[i]` is the *same* as the `t.value` attribute assigned in the lexer module.
- For RHS <u>non-terminals</u>, the value of the corresponding `p[i]` is determined by whatever is placed in `p[0]` in the function for the rule that is used in the derivation to replace this non-terminal. This value can be anything, decided by the programmer.

| **p[i]** | **value of p[i]** |
|---|---|
| p[1] | "{" |
| p[2] | "with" |
| p[3] | "{" |
| p[4] | value assigned to p[0] in one of the alist-functions |
| p[5] | "}" |
| p[6] | value assigned to p[0] in one of the wae-functions |
| p[7] | "}" |

# WAE Parser

WAEParser.py

```
import ply.yacc as yacc
from WAELexer import tokens

def p_waeStart(p):
  'waeStart : wae SEMI'
  p[0] = p[1]

def p_wae_1(p):
  'wae : NUMBER'
  p[0] = ['num',p[1]]

def p_wae_2(p):
  'wae : ID'
  p[0] = ['id',p[1]]

def p_wae_3(p):
  'wae : LBRACE PLUS wae wae RBRACE'
  p[0] = ['+',p[3],p[4]]

def p_wae_4(p):
  'wae : LBRACE MINUS wae wae RBRACE'
  p[0] = ['-',p[3],p[4]]

def p_wae_5(p):
  'wae : LBRACE TIMES wae wae RBRACE'
  p[0] = ['*',p[3],p[4]]

def p_wae_6(p):
  'wae : LBRACE DIV wae wae RBRACE'
  p[0] = ['/',p[3],p[4]]

def p_wae_7(p):
  'wae : LBRACE IF wae wae wae RBRACE'
  p[0] = ['if',p[3],p[4],p[5]]

def p_wae_8(p):
  'wae : LBRACE WITH LBRACE alist RBRACE wae RBRACE'
  p[0] = ['with',p[4],p[6]]
```

# WAE Parser (continued)

## WAEParser.py (continued)

```
def p_alist_1(p):
  'alist : LBRACE ID wae RBRACE'
  p[0] = [[p[2],p[3]]]

def p_alist_2(p):
  'alist : LBRACE ID wae RBRACE alist'
  p[0] = [[p[2],p[3]]] + p[5]

def p_error(p):
  print("Syntax error in input!")

parser = yacc.yacc()
```

## WAE.py (main program)

```
from WAEParser import parser

def read_input():
  result = ''
  while True:
    data = input('WAE: ').strip()
    if ';' in data:
      i = data.index(';')
      result += data[0:i+1]
      break
    else:
      result += data + ' '
  return result

def main():
  while True:
    data = read_input()
    if data == 'exit;':
      break
    try:
      tree = parser.parse(data)
    except Exception as inst:
      print(inst.args[0])
      continue
    print(tree)
```

## Grammar (subset)

```
waeStart : wae SEMI
wae : ID
wae : LBRACE PLUS wae wae RBRACE
```

## Input String

```
{ + x y } ;
```

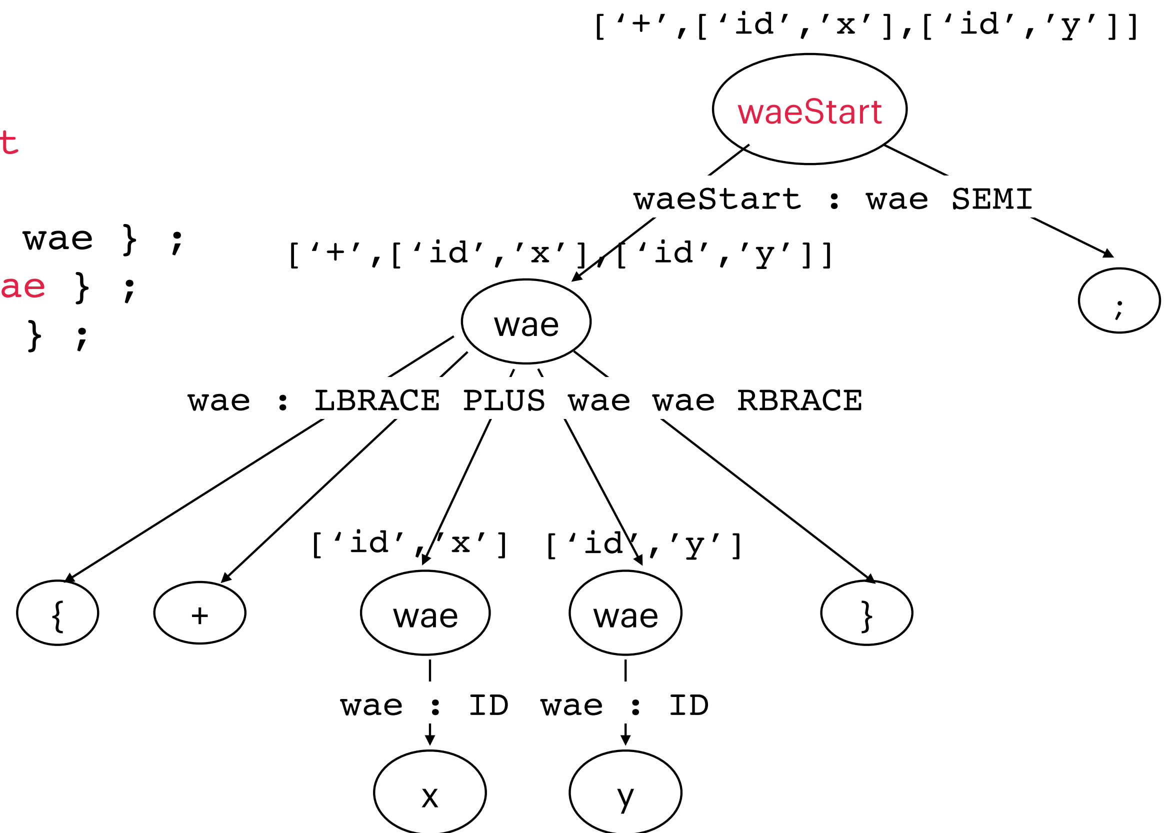
## Derivation

```
   waeStart
⇒ wae ;
⇒ { + wae wae } ;
⇒ { + x wae } ;
⇒ { + x y } ;
```

## PLY functions (subset)

```
def p_waeStart(p):
  'waeStart : wae SEMI'
  p[0] = p[1]

def p_wae_2(p):
  'wae : ID'
  p[0] = [‘id’,p[1]]

def p_wae_3(p):
  'wae : LBRACE PLUS wae wae RBRACE'
  p[0] = ['+',p[3],p[4]]
```

## Parse Tree



# PLY: In a nutshell