

Chapter 10

Compiler I: Parsing

These slides support chapter 10 of the book

The Elements of Computing Systems

By Noam Nisan and Shimon Schocken

MIT Press

The big picture: compilation

high-level program

```
class Main {  
    function void main() {  
        var Point p1, p2, p3;  
        let p1 = Point.new(1,2);  
        let p2 = Point.new(3,4);  
        let p3 = p1.plus(p2);  
        do p3.print();  
        // should print (4,6)  
        do Output.println();  
        do Output.putInt(p1.distance(p3));  
        // should print 5  
        return;  
    }  
}
```

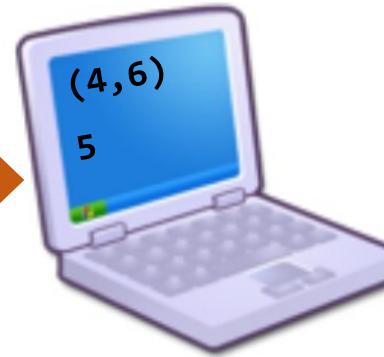
```
/** Represents a Point. */  
class Point {  
    field int x, y;  
    static int pointCount;  
    /** Constructs a new point */  
    constructor Point new(int ax,  
                         int ay) {  
        let x = ax;  
        let y = ay;  
        let pointCount =  
            pointCount + 1;  
        return this;  
    }  
    // ... more Point methods
```

Compiler

machine code

```
000000000010000  
1110111111001000  
0000000000010001  
1110101010001000  
000000000010000  
111111000010000  
000000000000000  
1111010011000000  
000000000000000  
1110001100000001  
000000000010000  
111111000010000  
000000000010001  
000000000010000  
1110111111001000  
000000000010001  
1110101010001000  
000000000010000  
111111000010000  
000000000000000  
1111010011010000  
000000000010010  
1110001100000001  
000000000010000  
111111000010000  
000000000010001  
...  
...
```

execute



Two-tier compilation

high-level program

```
class Main {  
    function void main() {  
        var Point p1, p2, p3;  
        let p1 = Point.new(1,2);  
        let p2 = Point.new(3,4);  
        let p3 = p1.plus(p2);  
        do p3.print();  
        // should print (4,6)  
        do Output.println();  
        do Output.putInt(p1.distance(p3));  
        // should print 5  
        return;  
    }  
}
```



Compiler

```
/** Represents a Point. */  
class Point {  
    field int x, y;  
    static int pointCount;  
    /** Constructs a new point */  
    constructor Point new(int ax,  
                         int ay) {  
        let x = ax;  
        let y = ay;  
        let pointCount =  
            pointCount + 1;  
        return this;  
    }  
    // ... more Point methods
```

VM code

```
push local 0  
push constant 0  
eq  
not  
push argument 1  
neg  
push local 1  
call d...  
pop argument 3  
push local 1  
neg  
push local 0  
push local 1  
push local 2  
add  
push constant 2  
push local 0  
pop argument 1  
push local 0  
push constant 0  
not  
push local 1  
push local 0  
push local 1  
add  
...
```

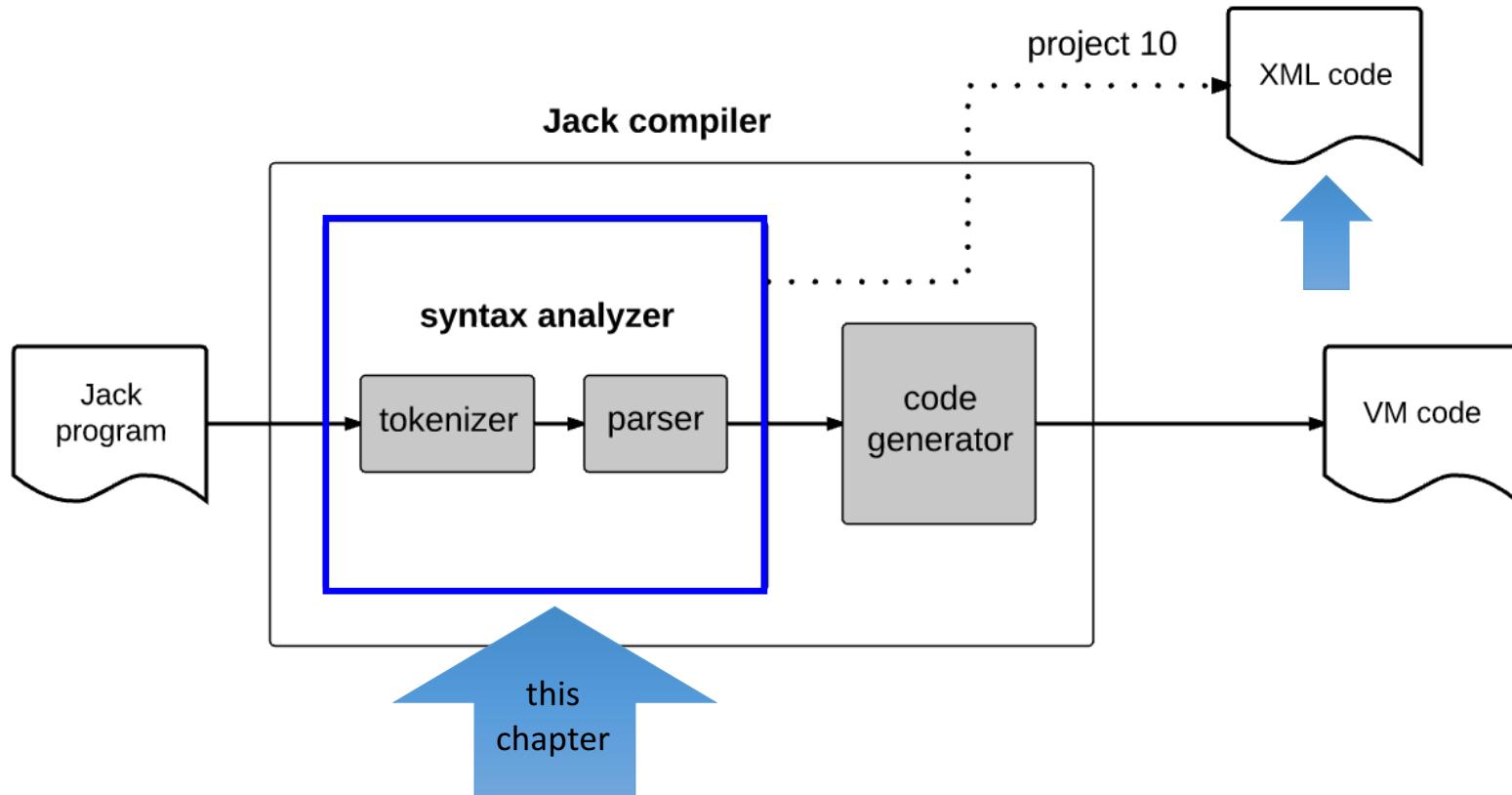
machine code

```
000000000010000  
1110111111001000  
000000000010001  
1110101010001000  
000000000010000  
1111110000010000  
00000000000000000  
1111010011010000  
000000000010010  
1110001100000001  
000000000010000  
1111110000010000  
0000000000000001  
1110111111001000  
000000000010001  
1110101010001000  
000000000010000  
1111110000010000  
00000000000000000  
1111010011010000  
000000000010010  
1110001100000001  
000000000010000  
1111110000010000  
0000000000000001  
...
```



VM translator

Compiler development roadmap



Syntax analyzer implementation:

- Tokenizer
- Parser / compilation engine

Take home lessons

- Tokenizing
- Grammars
- Parsing
- Parse trees
- XML / mark-up
- Handling structured data files
- Compilation.

Compiler I / parsing: lecture plan

Parsing:

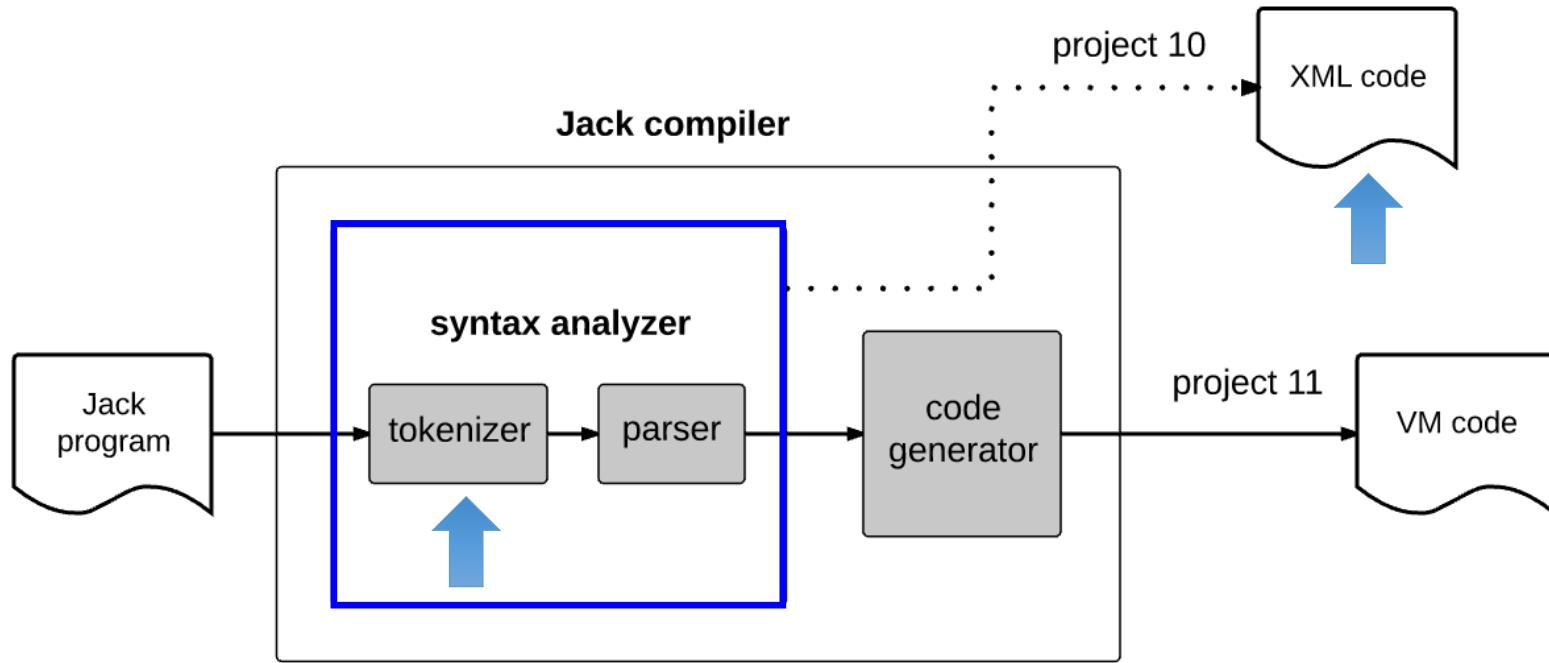
- Overview
- Tokenizer
- Grammar
- Parse trees
- Parsing process



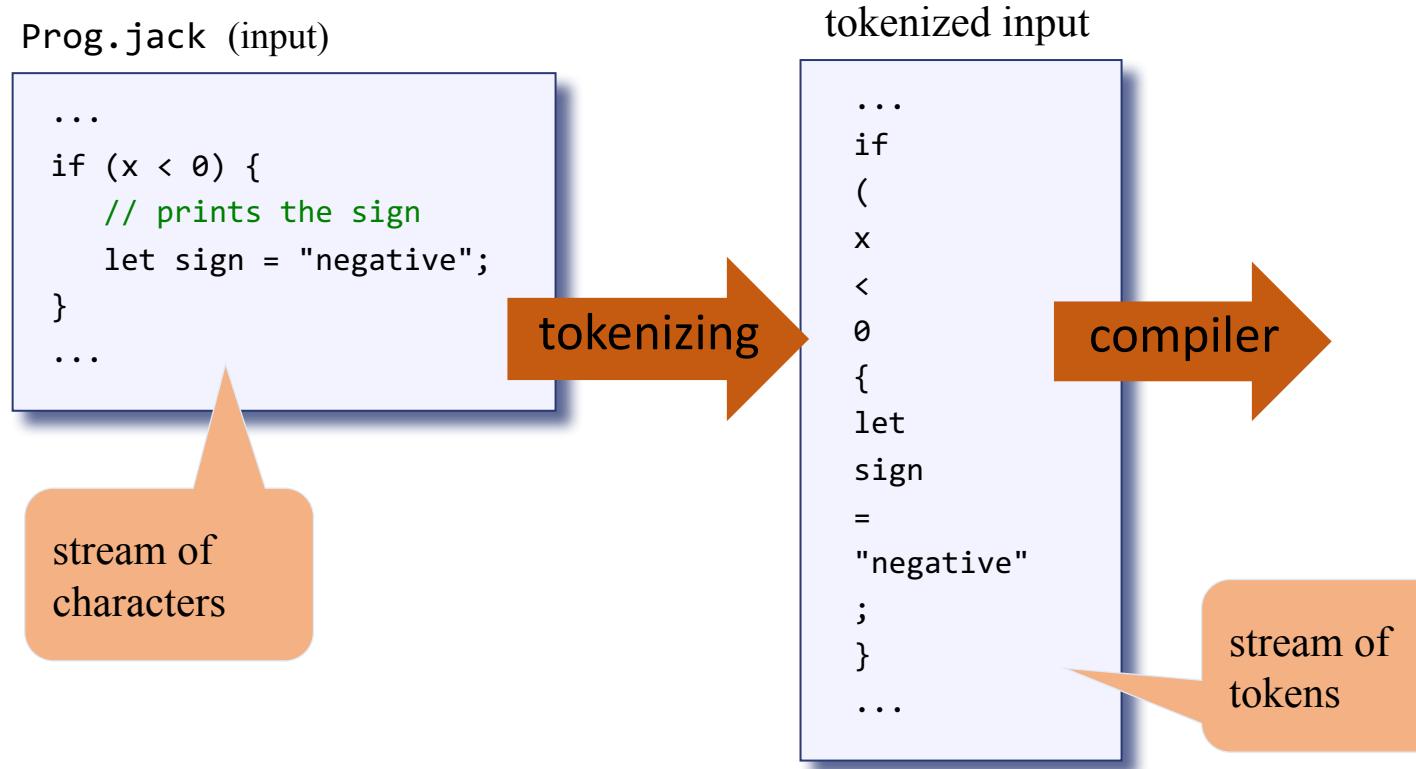
Parsing Jack programs

- The Jack grammar
- The Jack analyzer
 - Overview
 - Proposed implementation
 - Building the Jack Analyzer

Compiler development roadmap



Tokenizing (first approximation)



Tokenizing = grouping characters into tokens

A *token* is a string of characters that has a meaning

A programming language specification must document (among other things) its allowable tokens.

Jack tokens

Prog.jack (input)

```
...
if (x < 0) {
    // prints the sign
    let sign = "negative";
}
...
```

- keywords
- symbols
- integers
- strings
- identifiers

Jack tokens

Prog.jack (input)

```
...
if (x < 0) {
    // prints the sign
    let sign = "negative";
}
...
```

keyword: 'class' | 'constructor' | 'function'
| 'method' | 'field' | 'static' | 'var' | 'int'
| 'char' | 'boolean' | 'void' | 'true' | 'false'
| 'null' | 'this' | 'let' | 'do' | 'if' | 'else'
| 'while' | 'return'

symbol: '{' | '}' | '(' | ')' | '[' | ']' | '.' | ',' | ';' | '+' | '-' | '*' |
'|' | '/' | '&' | '\'' | '<' | '>' | '=' | '~'

integerConstant: a decimal number in the range 0 ... 32767

StringConstant: "" a sequence of Unicode characters,
not including double quote or newline ""

identifier: a sequence of letters, digits, and
underscore ('_ ') not starting with a digit.

Jack tokenizer

Prog.jack

```
...  
if (x < 0) {  
    // prints the sign  
    let sign = "negative";  
}  
...
```

TokenizerTest

output

```
...  
<keyword> if </keyword>  
<symbol> ( </symbol>  
<identifier> x </identifier>  
<symbol> < </symbol>  
<intConst> 0 </intConst>  
<symbol> ) </symbol>  
<symbol> { </symbol>  
<keyword> let </keyword>  
<identifier> sign </identifier>  
<symbol> = </symbol>  
<stringConst> negative </stringConst>  
<symbol> ; </symbol>  
<symbol> } </symbol>  
...
```

keyword: 'class' | 'constructor' | 'function'
| 'method' | 'field' | 'static' | 'var' | 'int'
| 'char' | 'boolean' | 'void' | 'true' | 'false'
| 'null' | 'this' | 'let' | 'do' | 'if' | 'else'
| 'while' | 'return'

symbol: '{' | '}' | '(' | ')' | '[' | ']' | '.' | ',' | ';' | '+' | '-' | '*' |
'|' | '&' | '[' | ']' | '<' | '>' | '=' | '~'

integerConstant: a decimal number in the range 0 ... 32767

StringConstant: "" a sequence of Unicode characters,
not including double quote or newline ""

identifier: a sequence of letters, digits, and
underscore ('_') not starting with a digit.

Tokenizer:

- Handles the compiler's input
- Allows advancing the input
- Supplies the *current token's value* and *type*

(complete API, later)

Jack tokenizer

Prog.jack

```
...  
if (x < 0) {  
    // prints the sign  
    let sign = "negative";  
}  
...
```

TokenizerTest

output

```
...  
<keyword> if </keyword>  
<symbol> ( </symbol>  
<identifier> x </identifier>  
<symbol> < </symbol>  
<intConst> 0 </intConst>  
<symbol> ) </symbol>  
<symbol> { </symbol>  
<keyword> let </keyword>  
<identifier> sign </identifier>  
<symbol> = </symbol>  
<stringConst> negative </stringConst>  
<symbol> ; </symbol>  
<symbol> } </symbol>  
...
```

TokenizerTest (pseudo code)

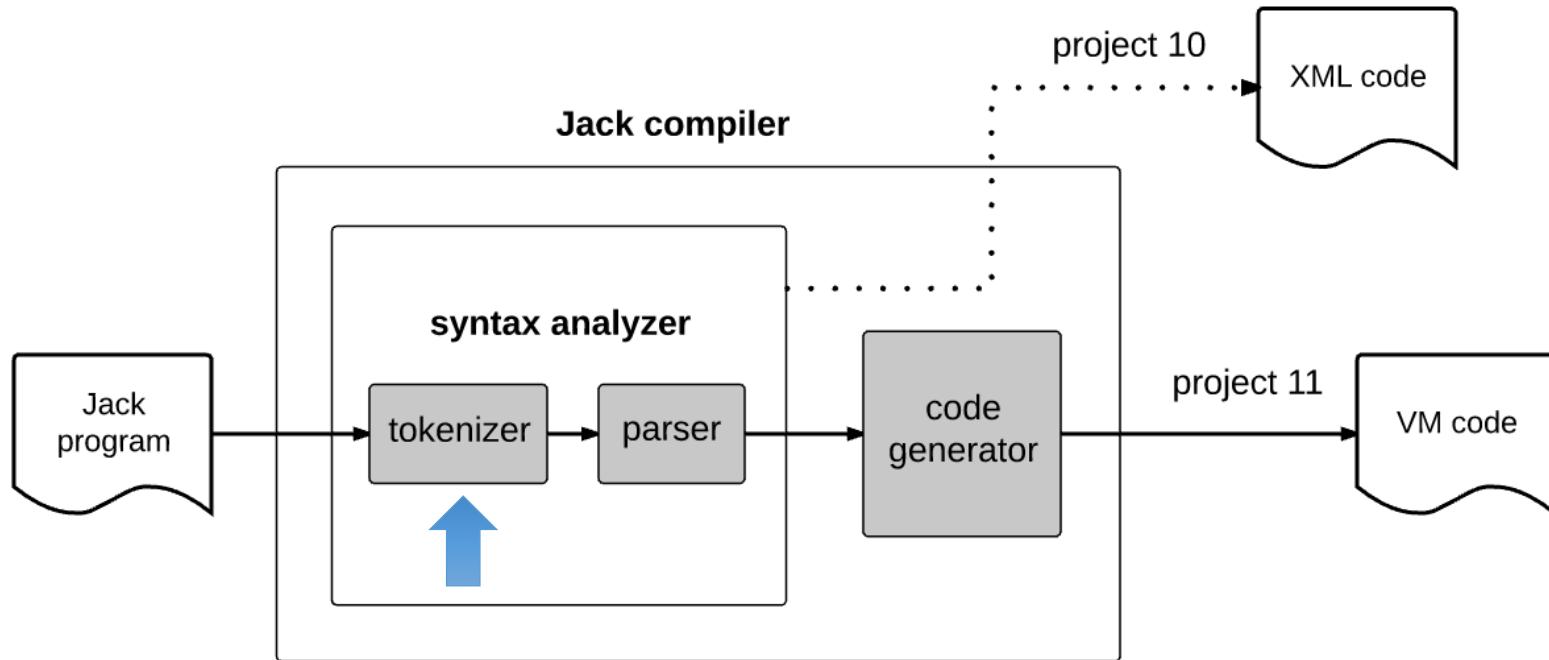
```
tknzr = new JackTokenizer("Prog.jack")  
tknzr.advance();  
while tknzr.hasMoreTokens() {  
    tokenClassification = current token  
        classification  
    print "<" + tokenClassification + ">"  
    print the current token value  
    print "</" + tokenClassification + ">"  
    print newLine  
    tknzr.advance();  
}
```

Tokenizer:

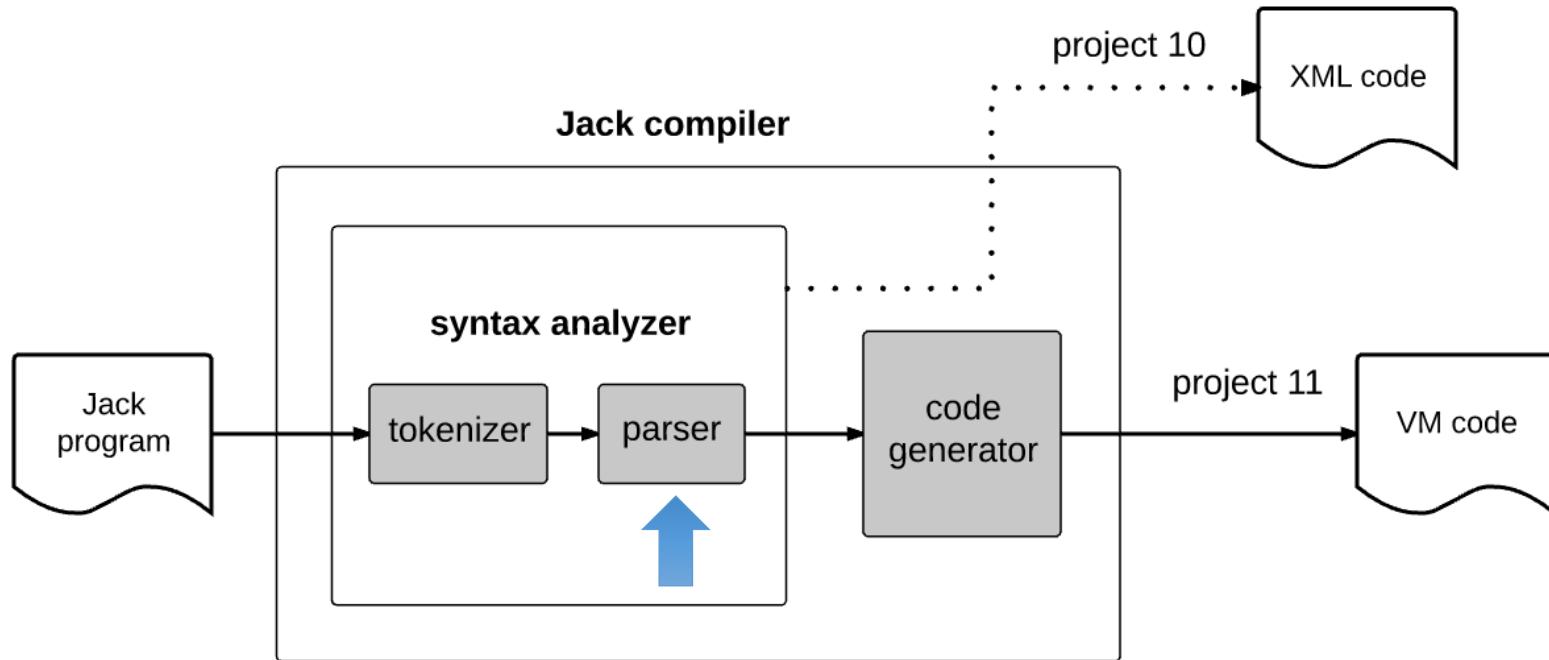
- Handles the compiler's input
- Allows advancing the input
- Supplies the *current token's value* and *type*

(complete API, later)

Compiler development roadmap



Compiler development roadmap



Compiler I / parsing: lecture plan

Parsing:

- Overview
- Tokenizer
- Grammar
- Parse trees
- Parsing process



Parsing Jack programs

- The Jack grammar
- The Jack analyzer
 - Overview
 - Proposed implementation
 - Building the Jack Analyzer

Tokenizing (reminder)

source code

```
/** Represents a Point. */
class Point {
    ...
    /** Constructs a new point */
    constructor Point new(int ax,
                          int ay) {
        let x = ax;
        let y = ay;
        let pointCount = pointCount + 1;
        return this;
    }
    ...
}
```

tokenized code

```
<keyword> class </keyword>
<identifier> Point </identifier>
<symbol> { </symbol>
...
<keyword> constructor </keyword>
<identifier> Point </identifier>
<identifier> new </identifier>
<symbol> ( </symbol>
<keyword> int </keyword>
<identifier> ax </identifier>
<symbol> , </symbol>
<keyword> int </keyword>
<identifier> ay </identifier>
<symbol> ) </symbol>
<symbol> { </symbol>
...
... // tokenizing the next two statements (omitted)
<keyword> let </keyword>
<identifier> pointCount </identifier>
<symbol> = </symbol>
<identifier> pointCount </identifier>
<symbol> + </symbol>
<integerConstant> 1 </integerConstant>
<symbol> ; </symbol>
...
```

tokenizer

Grammar

A *grammar* is a set of rules, describing how tokens can be combined to create valid language constructs

```
sentence: nounPhrase verbPhrase  
nounPhrase: determiner? noun  
verbPhrase: verb nounPhrase  
noun: 'dog' | 'school' | 'dina' | 'he' | 'she' | 'homework' | ...  
verb: 'went' | 'ate' | 'said' | ...  
determiner: 'the' | 'to' | 'my' | ...  
...
```

Each rule has a
left side and a
right side

Dina went to school
She said
The dog ate my homework

Terminal rule: right-hand side includes constants only

Non-terminal rule: all other rules

Grammar

Jack grammar (subset)

```
statement: ifStatement |  
          whileStatement |  
          letStatement
```

Grammar

Jack grammar (subset)

```
statement: ifStatement |  
          whileStatement |  
          letStatement  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' '  
           '{' statements '}'  
  
whileStatement: 'while' '(' expression ')' '  
              '{' statements '}'  
  
letStatement: 'let' varName '=' expression ';' '  
  
expression: term (op term)?  
  
term: varName | constant  
  
varName: a string not beginning with a digit  
  
constant: a decimal number  
  
op: '+' | '-' | '=' | '>' | '<'
```

Input examples

Expressions

```
17  
x  
x + 17  
x - y
```



Grammar

Jack grammar (subset)

statement: ifStatement |
whileStatement |
letStatement

statements: statement*

ifStatement: 'if' '(' expression ')' |
'{' statements '}'

whileStatement: 'while' '(' expression ')' |
'{' statements '}'

letStatement: 'let' varName '=' expression ';'

expression: term (op term)?

term: varName | constant

varName: a string not beginning with a digit

constant: a decimal number

op: '+' | '-' | '=' | '>' | '<'

Input examples

let x = 100;



Grammar

Jack grammar (subset)

statement: ifStatement |
whileStatement |
letStatement

statements: statement*

ifStatement: 'if' '(' expression ')' |
'{' statements '}'

whileStatement: 'while' '(' expression ')' |
'{' statements '}'

letStatement: 'let' varName '=' expression ';'

expression: term (op term)?

term: varName | constant

varName: a string not beginning with a digit

constant: a decimal number

op: '+' | '-' | '=' | '>' | '<'

Input examples

let x = 100;



let x = x + 1;



Grammar

Jack grammar (subset)

statement: ifStatement |
whileStatement |
letStatement

statements: statement*

ifStatement: 'if' '(' expression ')' |
'{' statements '}'

whileStatement: 'while' '(' expression ')' |
'{' statements '}'

letStatement: 'let' varName '=' expression ';' |

expression: term (op term)?

term: varName | constant

varName: a string not beginning with a digit

constant: a decimal number

op: '+' | '-' | '=' | '>' | '<'

Input examples

let x = 100;



let x = x + 1;



while (n < lim)
let n = n + 1;
}



Grammar

Jack grammar (subset)

statement: ifStatement |
whileStatement |
letStatement

statements: statement*

ifStatement: 'if' '(' expression ')' |
'{' statements '}'

whileStatement: 'while' '(' expression ')' |
'{' statements '}'

letStatement: 'let' varName '=' expression ';' |

expression: term (op term)?

term: varName | constant

varName: a string not beginning with a digit

constant: a decimal number

op: '+' | '-' | '=' | '>' | '<'

Input examples

let x = 100;



let x = x + 1;



while (n < lim)
let n = n + 1;
}



if (x = 1) {
let x = 100;
let x = x + 1;
}



Grammar

Jack grammar (subset)

```
statement: ifStatement |  
          whileStatement |  
          letStatement  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' '{' statements '}'  
  
whileStatement: 'while' '(' expression ')' '{' statements '}'  
  
letStatement: 'let' varName '=' expression ';'  
  
expression: term (op term)?  
  
term: varName | constant  
  
varName: a string not beginning with a digit  
  
constant: a decimal number  
  
op: '+' | '-' | '=' | '>' | '<'
```

Input examples

```
while (lim < 100) {  
    if (x = 1) {  
        let z = 100;  
        while (z > 0) {  
            let z = z - 1;  
        }  
    }  
    let lim = lim + 10;  
}
```



Parsing:

Determining if a given input conforms to a grammar

In the process, uncovering the grammatical structure of the given input.

Compiler I / parsing: lecture plan

Parsing:

- Overview
- Tokenizer
- Grammar
- Parse trees
- Parsing process

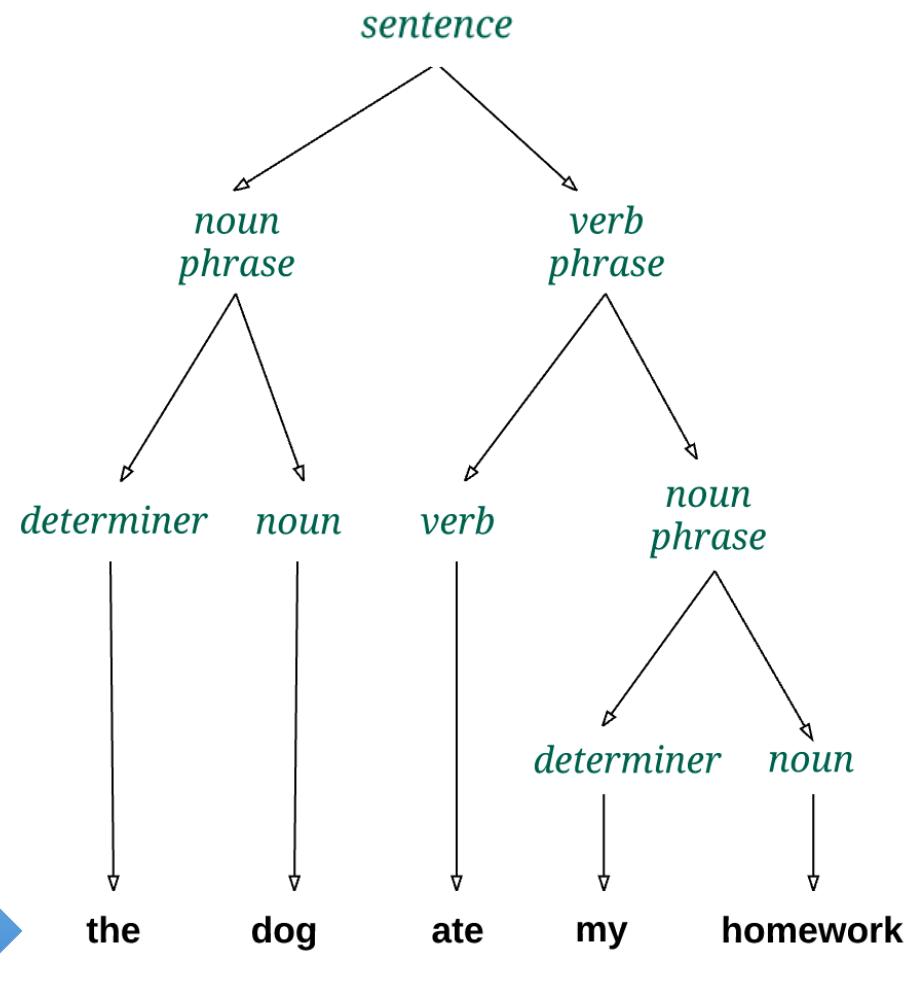


Parsing Jack programs

- The Jack grammar
- The Jack analyzer
 - Overview
 - Proposed implementation
 - Building the Jack Analyzer

Parse tree

```
sentence: nounPhrase verbPhrase  
nounPhrase: determiner? noun  
verbPhrase: verb nounPhrase  
noun: 'dog' | 'school' | 'dina' |  
      'he' | 'she' | 'homework' | ...  
verb: 'went' | 'ate' | 'said' | ...  
determiner: 'the' | 'to' | 'my' | ...  
...
```



Parsing

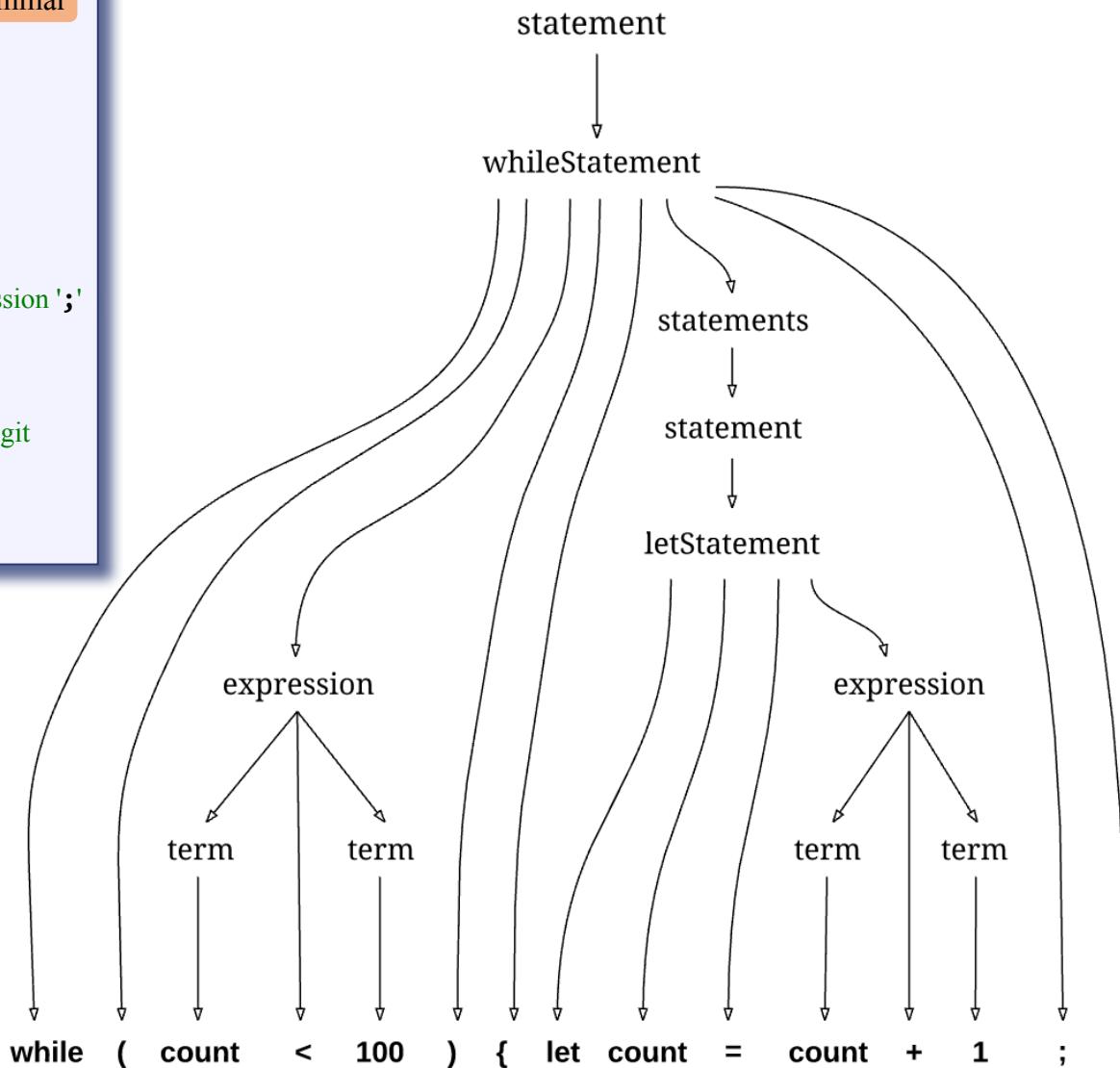
- Determine if the given input conforms to the grammar
- In the process, construct the grammatical structure of the input

Parse tree

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input →



Parse tree

```
statement: ifStatement | grammar  
         whileStatement |  
         letStatement  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' '  
           '{' statements '}'  
  
whileStatement: 'while' '(' expression ')' '  
             '{' statements '}'  
  
letStatement: 'let' varName '=' expression ';' '  
  
expression: term (op term)?  
  
term: varName | constant  
  
varName: a string not beg. with a digit  
  
constant: a decimal number  
  
op: '+' | '-' | '=' | '>' | '<'
```

Same parse tree,
in XML

```
<whileStatement> parser output  
  <keyword> while </keyword>  
  <symbol> ( </symbol>  
  <expression>  
    <term>  
      <identifier> count </identifier>  
    </term>  
    <symbol> < </symbol>  
    <term>  
      <intConstant> 100 </intConstant>  
    </term>  
  </expression>  
  <symbol> ) </symbol>  
  <symbol> { </symbol>  
  <statements>  
    <letStatement>  
      <keyword> let </keyword>  
      <identifier> count </identifier>  
      <symbol> = </symbol>  
      <expression>  
        <term> <identifier> count </identifier> </term>  
        <symbol> + </symbol>  
        <term> <intConstant> 1 </intConstant> </term>  
      </expression>  
      <symbol> ; </symbol>  
    </letStatement>  
  </statements>  
  <symbol> } </symbol>  
</whileStatement>
```

Compiler I / parsing: lecture plan

Parsing:

- Overview
- Tokenizer
- Grammar
- Parse trees
- • Parsing process

Parsing Jack programs

- The Jack grammar
- The Jack analyzer
 - Overview
 - Proposed implementation
 - Building the Jack Analyzer

Parser design (sneak preview)

```
statement: ifStatement | grammar  
         whileStatement |  
         letStatement  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' |  
           '{' statements '}'  
  
whileStatement: 'while' '(' expression ')' |  
              '{' statements '}'  
  
letStatement: 'let' varName '=' expression ';' |  
             expression: term (op term)?  
               term: varName | constant  
             varName: a string not beg. with a digit  
             constant: a decimal number  
             op: '+' | '-' | '=' | '>' | '<'
```

The parser consists of a set of `compilexxx` methods;
each `compilexxx` method
implements the right hand side of
the grammar rule describing `xxx`

Parser

```
class CompilationEngine {  
    compileStatements() {  
        // code for compiling statements  
    }  
    compileIfStatement() {  
        // code for compiling an if statement  
    }  
  
    compileWhileStatement() {  
        // code for compiling an while statement  
    }  
    ...  
    compileTerm() {  
        // code for compiling a term  
    }  
}
```

Parsing process

```
statement: ifStatement | grammar  
         whileStatement |  
         letStatement  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' |  
            '{' statements '}'  
  
whileStatement: 'while' '(' expression ')' |  
              '{' statements '}'  
  
letStatement: 'let' varName '=' expression ';' |  
            expression: term (op term)?  
            term: varName | constant  
            varName: a string not beg. with a digit  
            constant: a decimal number  
            op: '+' | '-' | '=' | '>' | '<'
```

Parsing process

- Follow the right-hand side of the rule, and parse the input accordingly
- If the right-hand side specifies a non-terminal rule *xxx*, call `compileXXX`
- Do this recursively.

Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '
'{ statements '}'
whileStatement: 'while' '(' expression ')' '
'{ statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

Parsing process

- Follow the right-hand side of the rule, and parse the input accordingly
- If the right-hand side specifies a non-terminal rule *xxx*, call `compileXXX`
- Do this recursively.

Example:

input

Parsing process

```
statement: ifStatement | grammar  
         whileStatement |  
         letStatement  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' { statements '}'  
  
whileStatement: 'while' '(' expression ')' { statements '}'  
  
letStatement: 'let' varName '=' expression ';'  
  
expression: term (op term)?  
term: varName | constant  
varName: a string not beg. with a digit  
constant: a decimal number  
op: '+' | '-' | '=' | '>' | '<'
```

Parsing process

- Follow the right-hand side of the rule, and parse the input accordingly
- If the right-hand side specifies a non-terminal rule *xxx*, call `compileXXX`
- Do this recursively.

Example:

Let us assume that we read `while`,
so we know that we have to call the method
`compileWhileStatement`

input

Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '
'{ statements '}'
whileStatement: 'while' '(' expression ')' '
'{ statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

compileWhileStatement

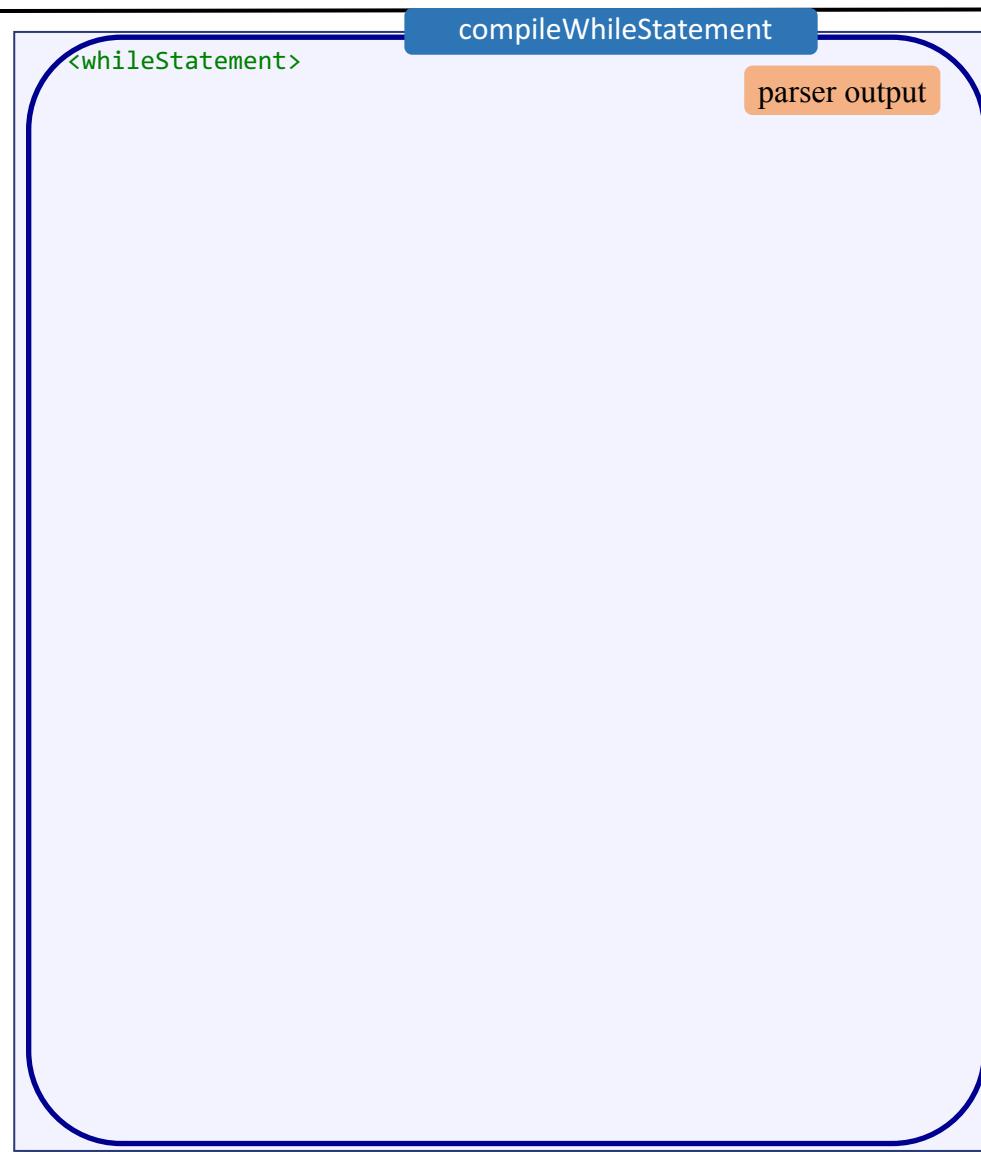
parser output

input

while

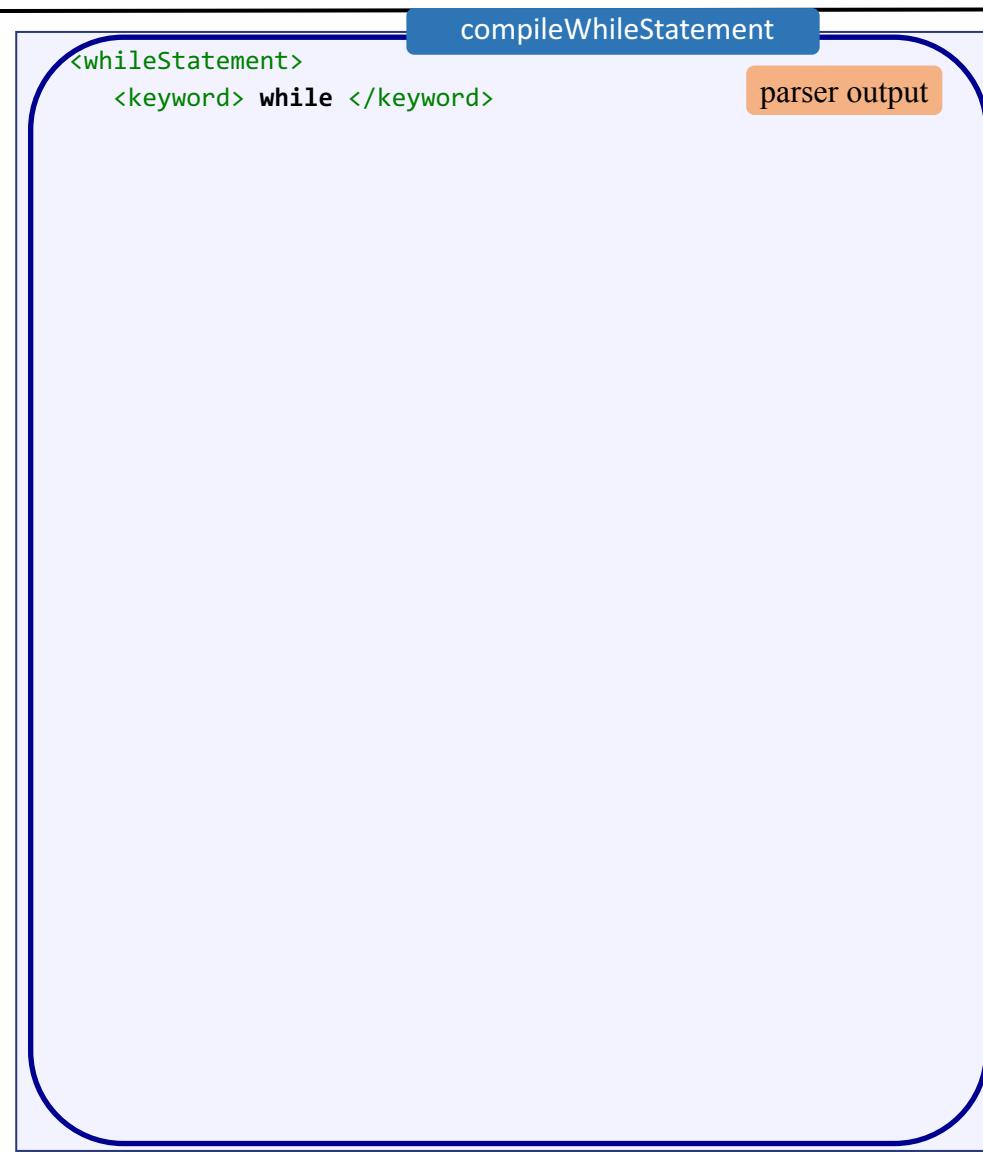
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '
'{ statements '}'
whileStatement: 'while' '(' expression ')' '
'{ statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '
'{ statements '}'
whileStatement: 'while' '(' expression ')' '
'{ statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



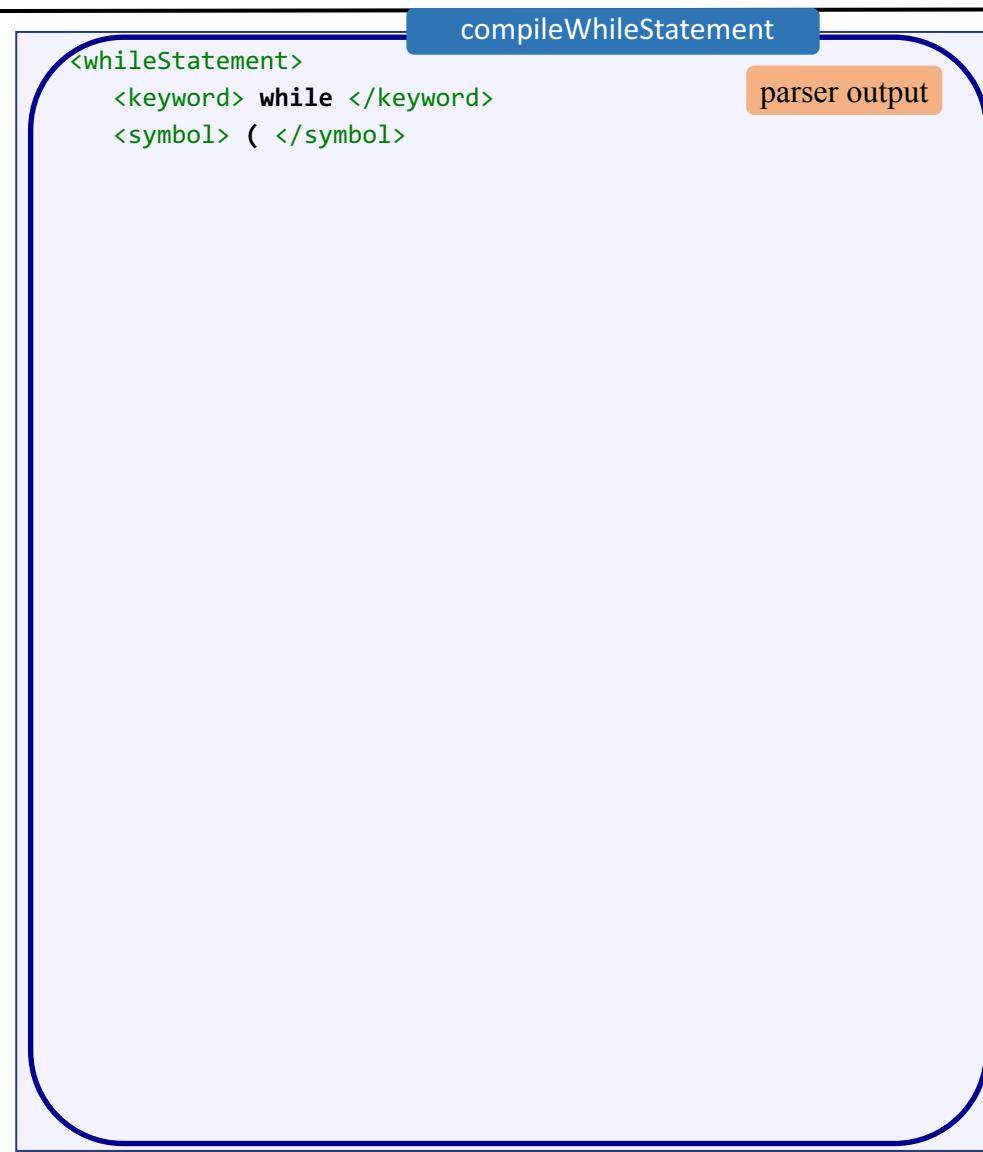
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '
'{ statements '}'
whileStatement: 'while' '(' expression ')' '
'{ statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



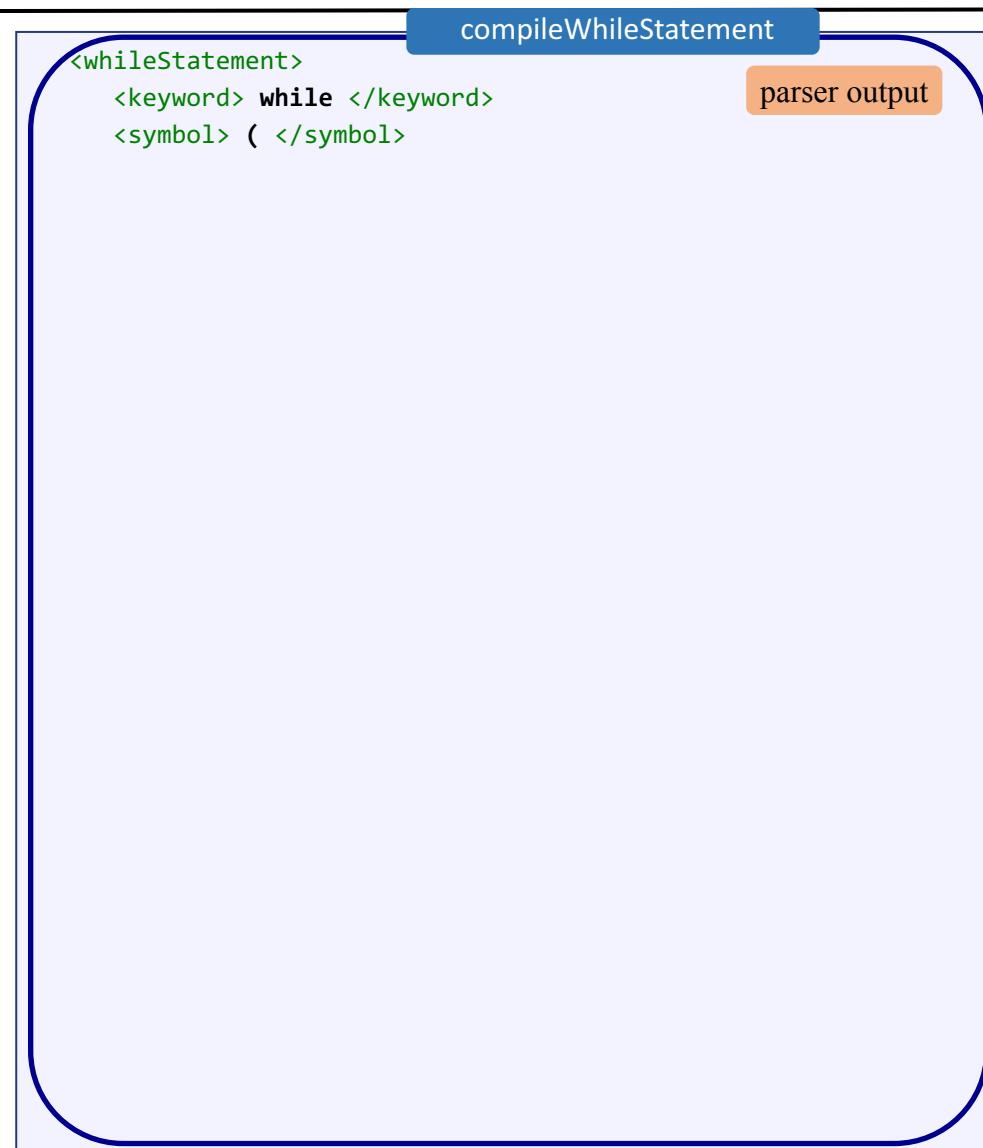
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '
'{ statements '}'
whileStatement: 'while' '(' expression ')' '
'{ statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



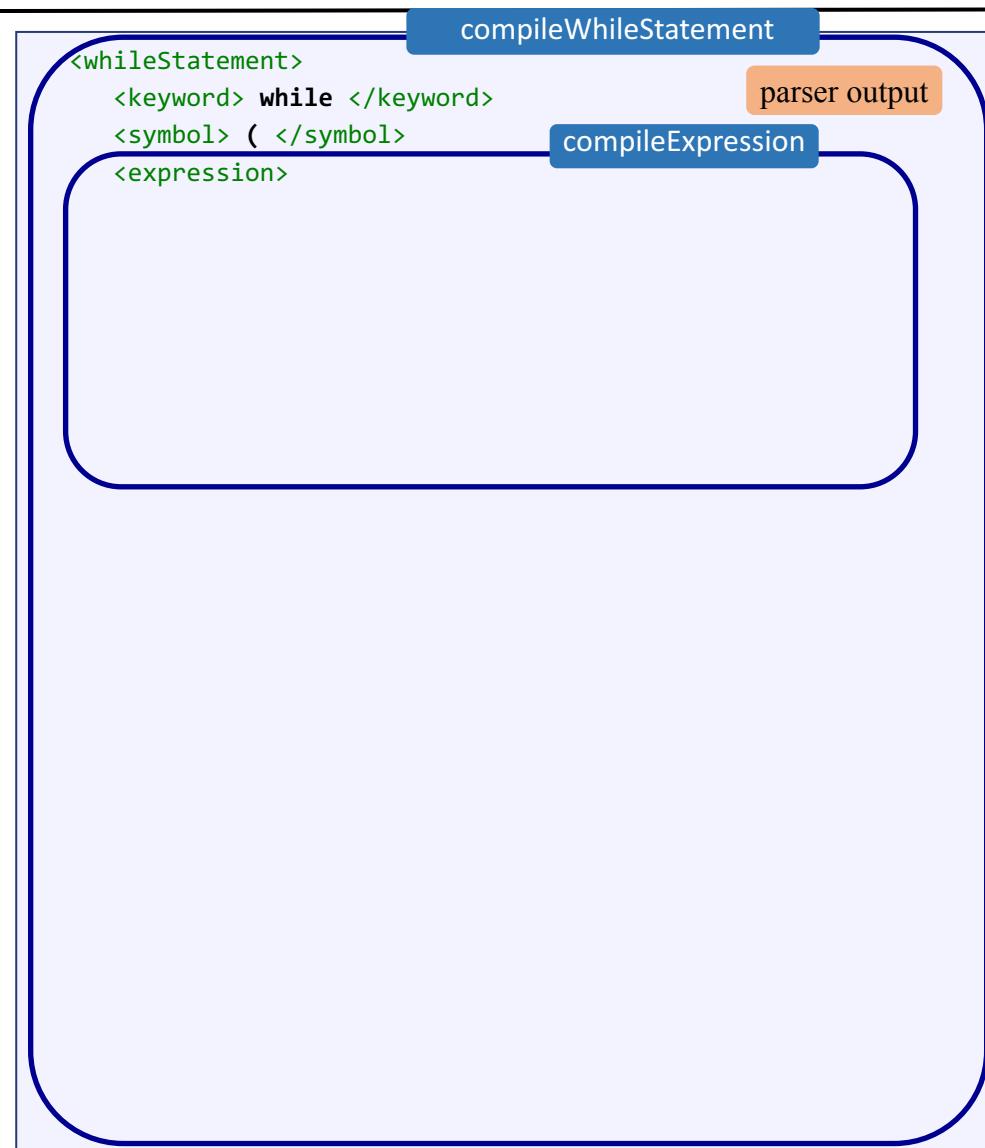
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '
'{ statements '}'
whileStatement: 'while' '(' expression ')' '
'{ statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



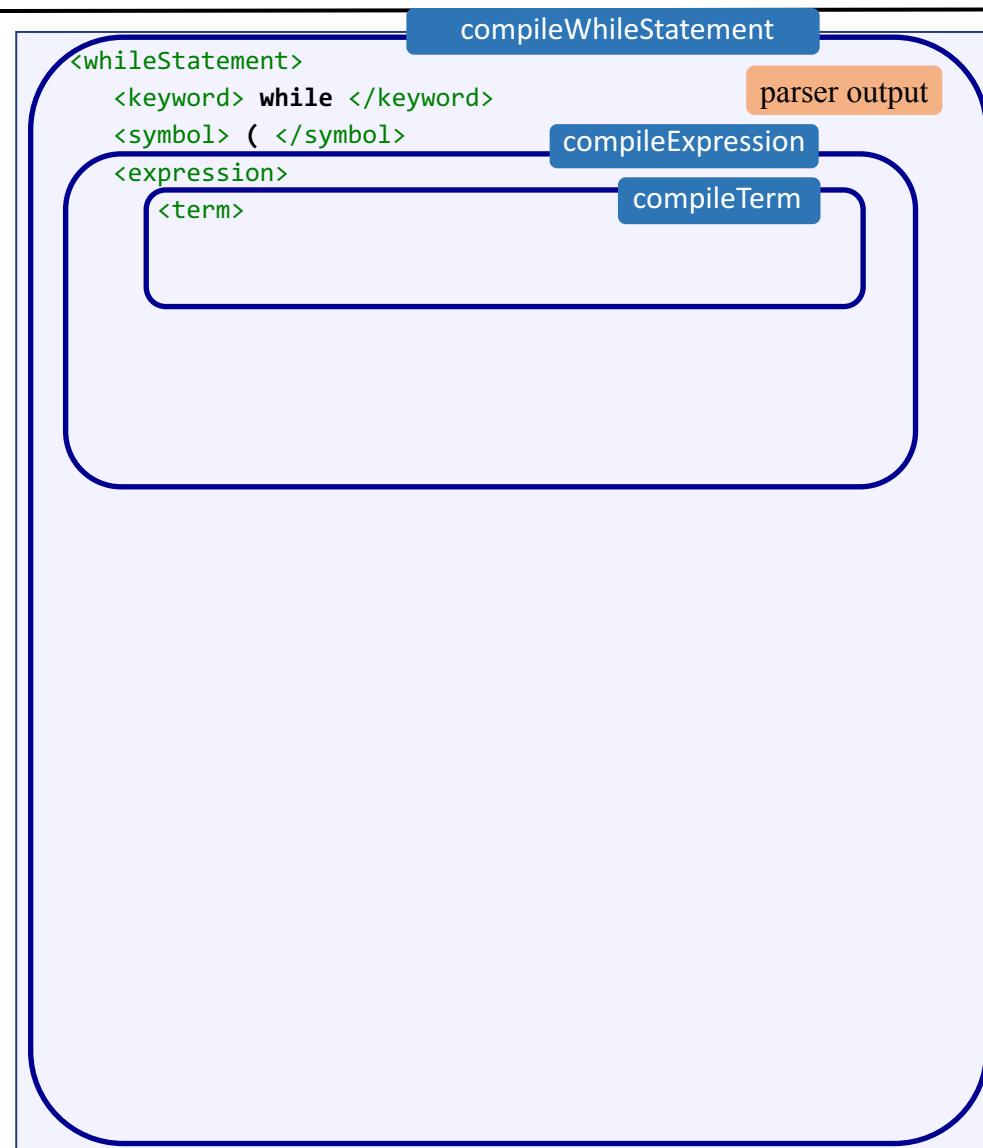
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



Parsing process

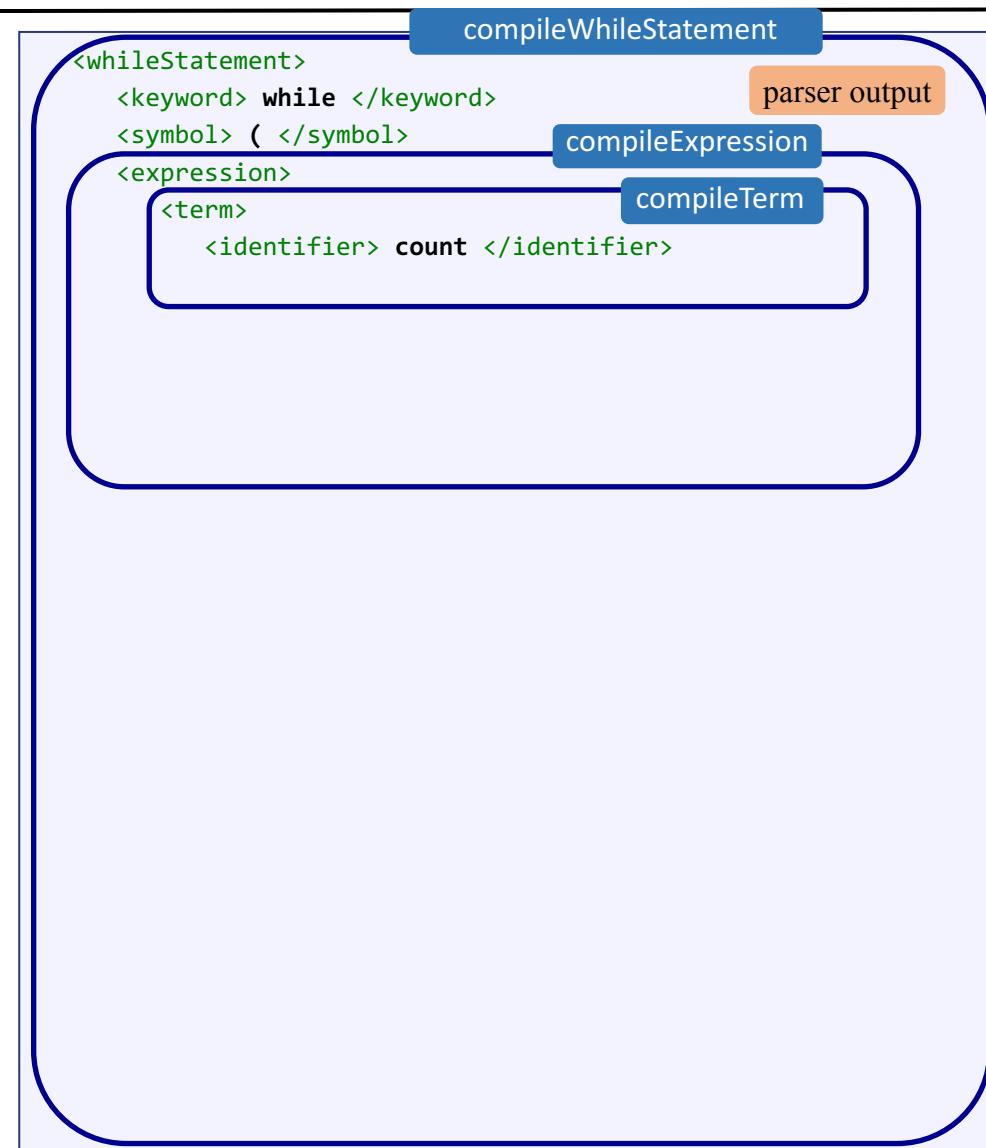
statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



input

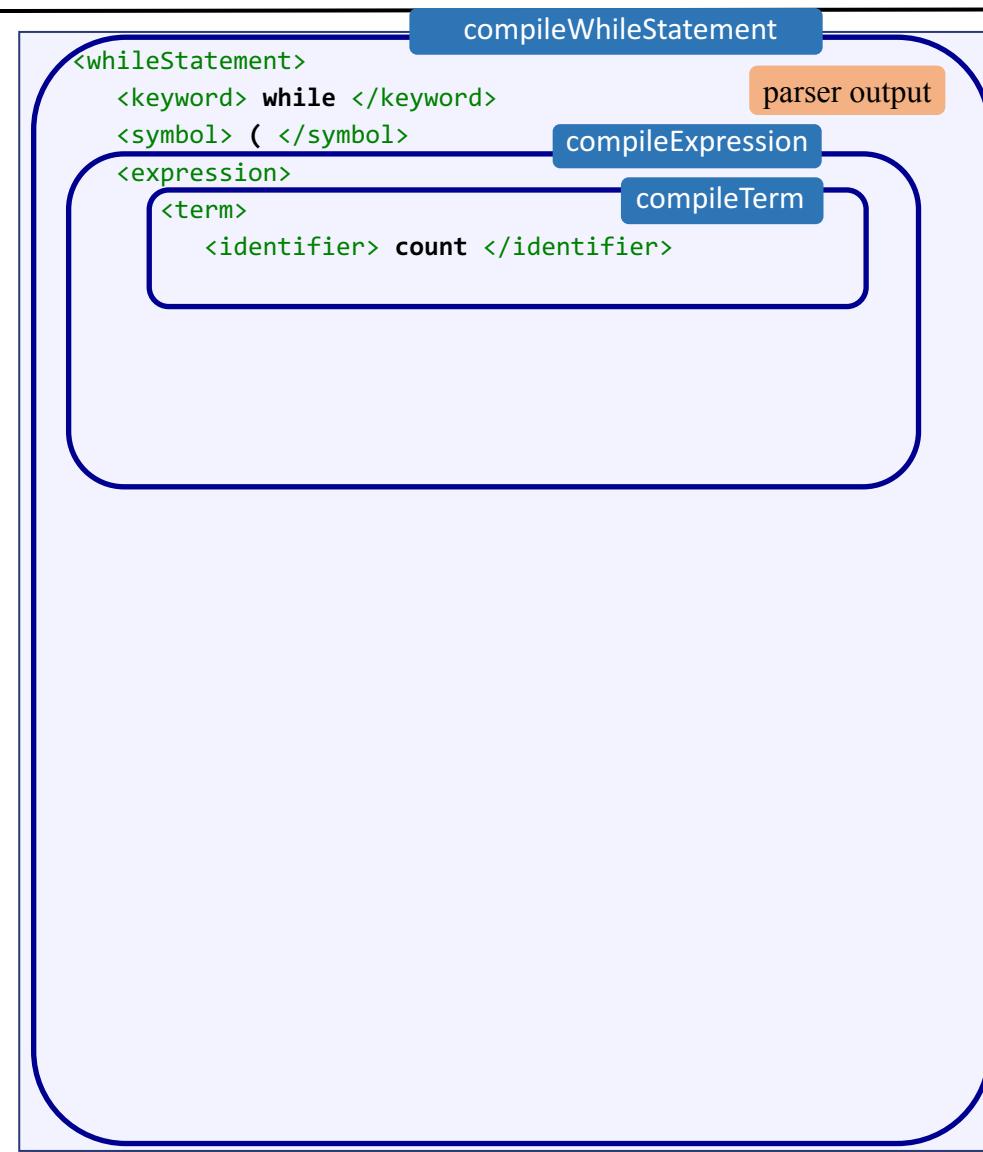
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



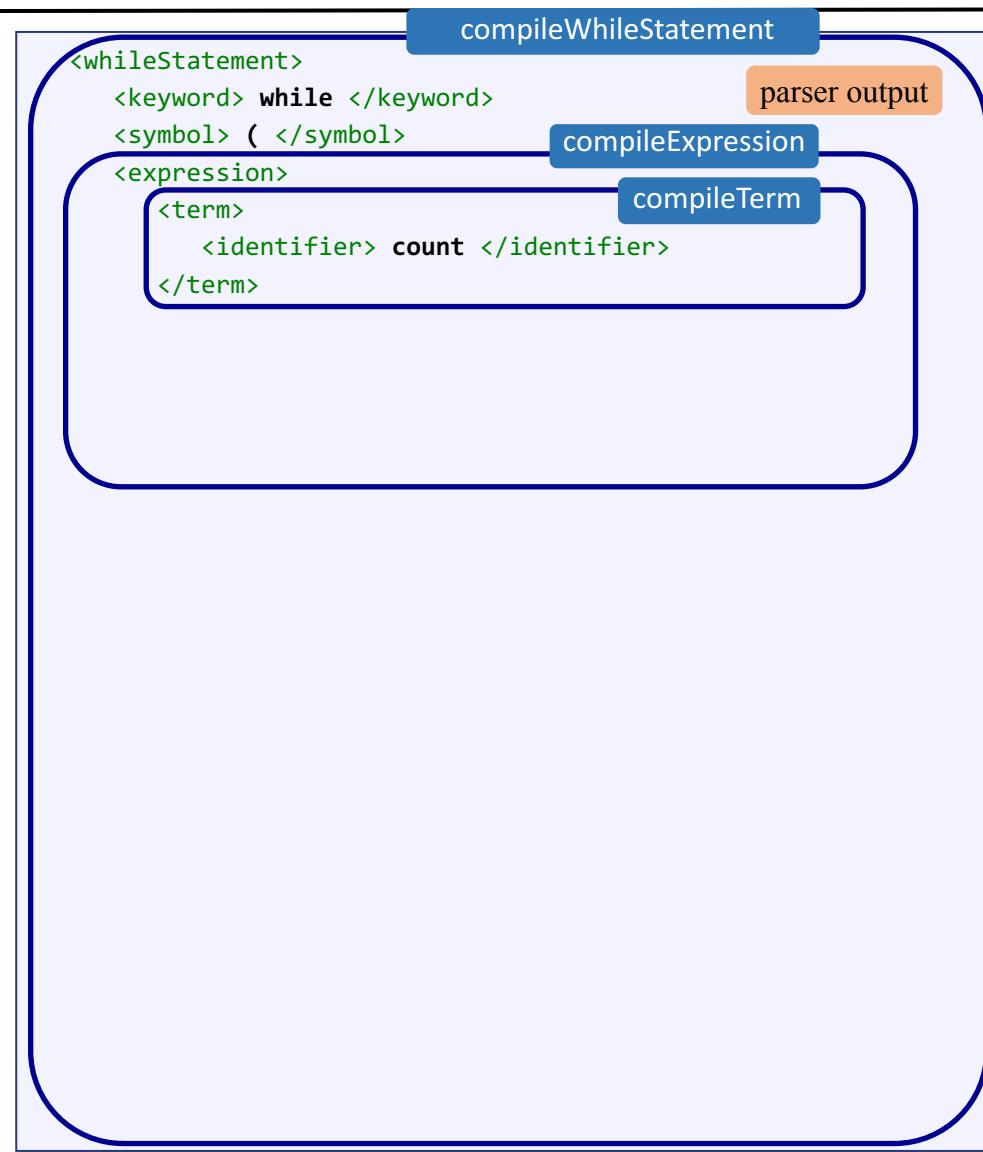
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



Parsing process

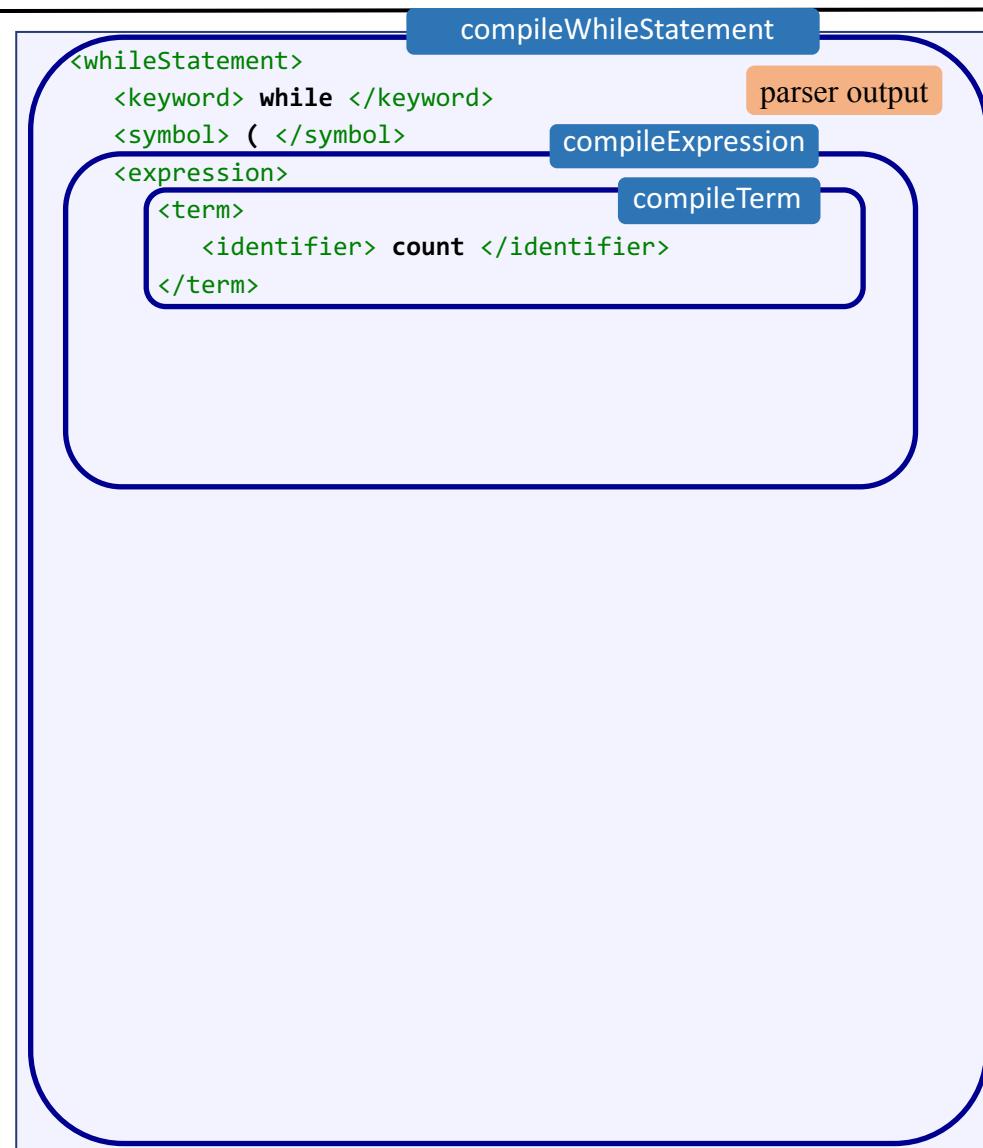
statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



Parsing process

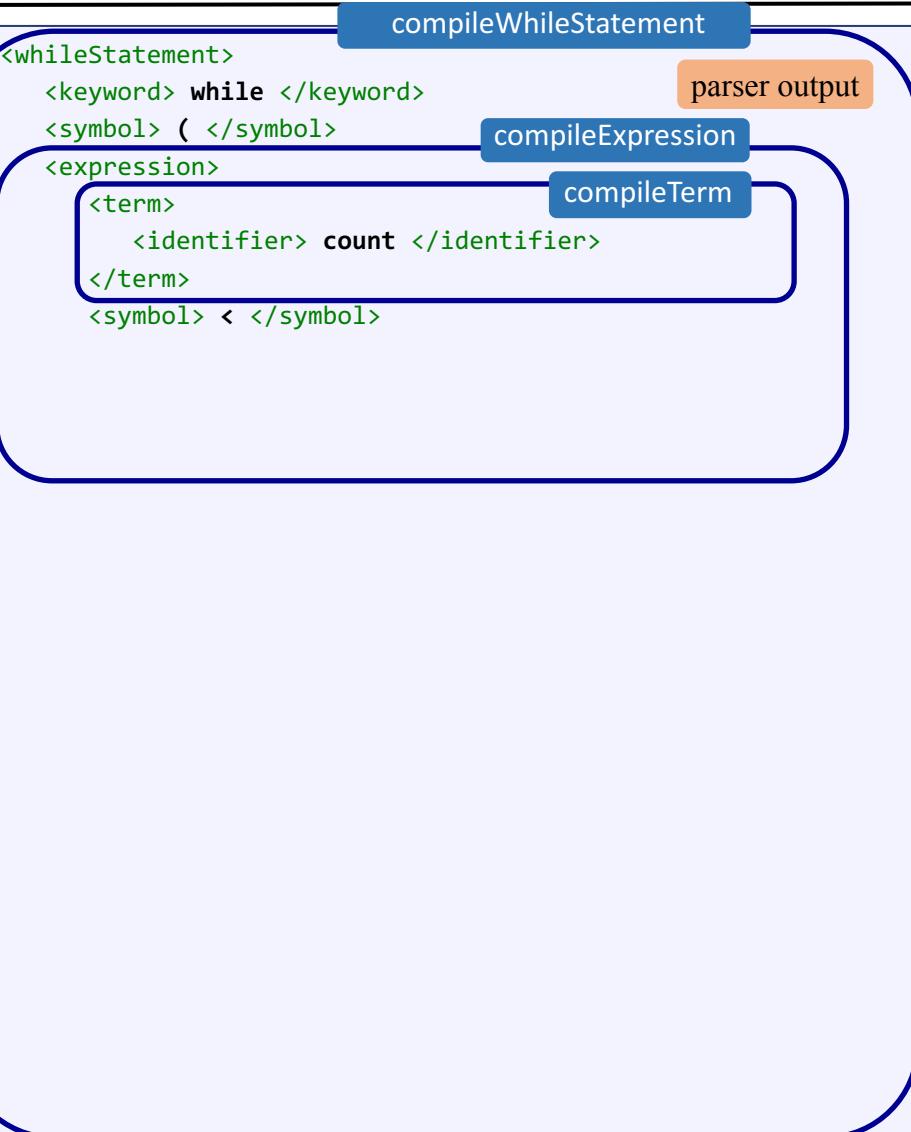
statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';' expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

input



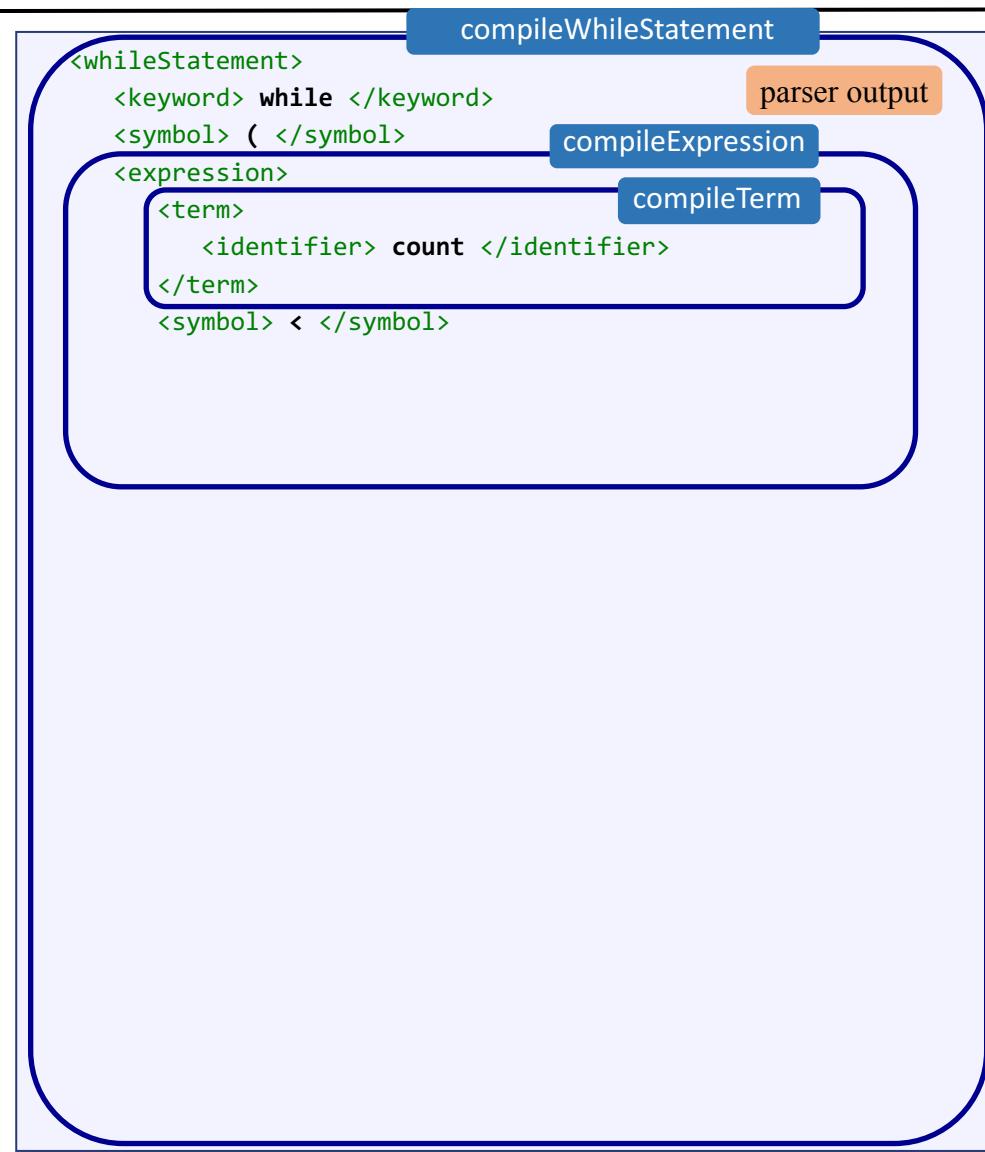
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';' expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



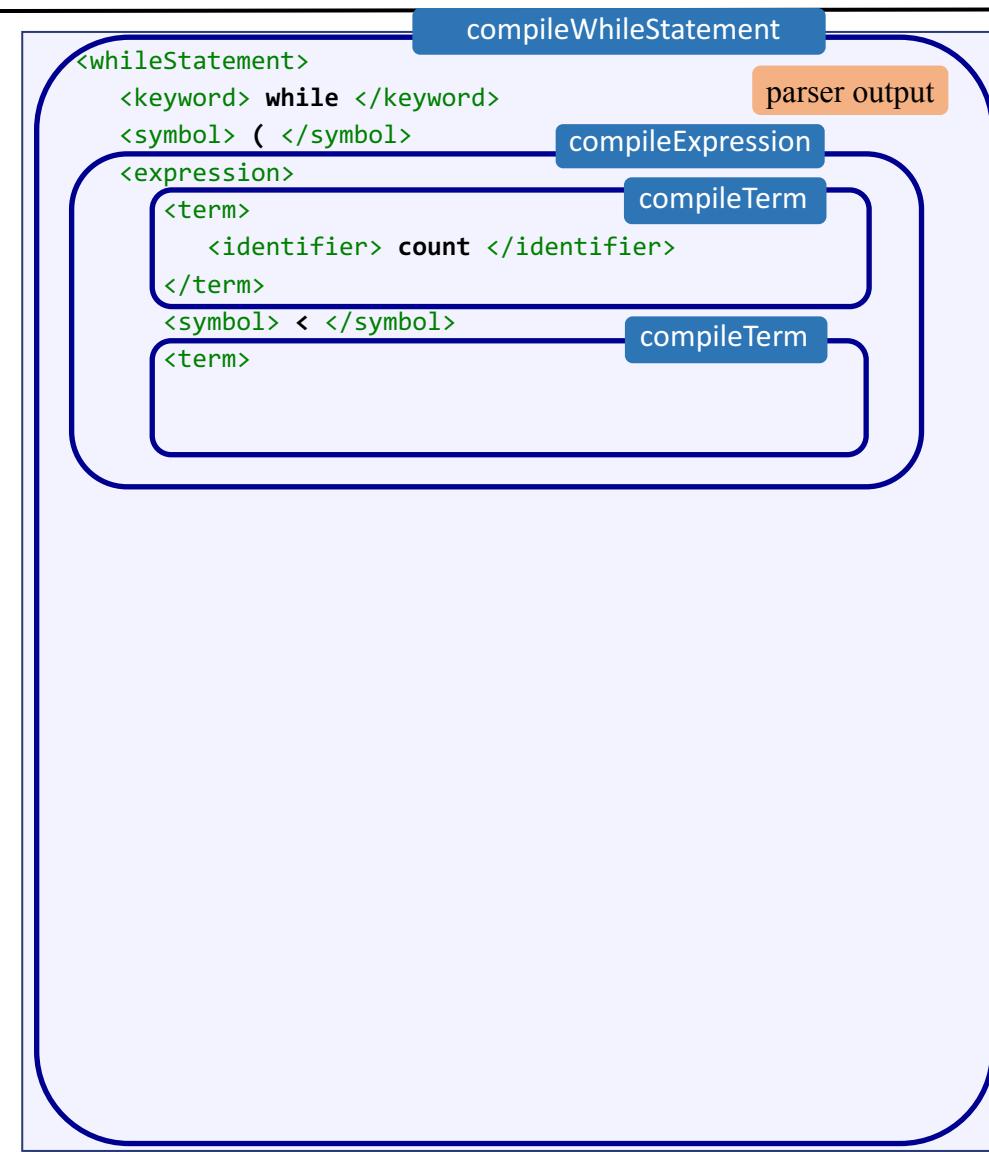
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';' expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



Parsing process

statement: ifStatement |
whileStatement |
letStatement
grammar

statements: statement*

ifStatement: 'if' '(' expression ')' '{' statements '}'

whileStatement: 'while' '(' expression ')' '{' statements '}'

letStatement: 'let' varName '=' expression ';'

expression: term (op term)?

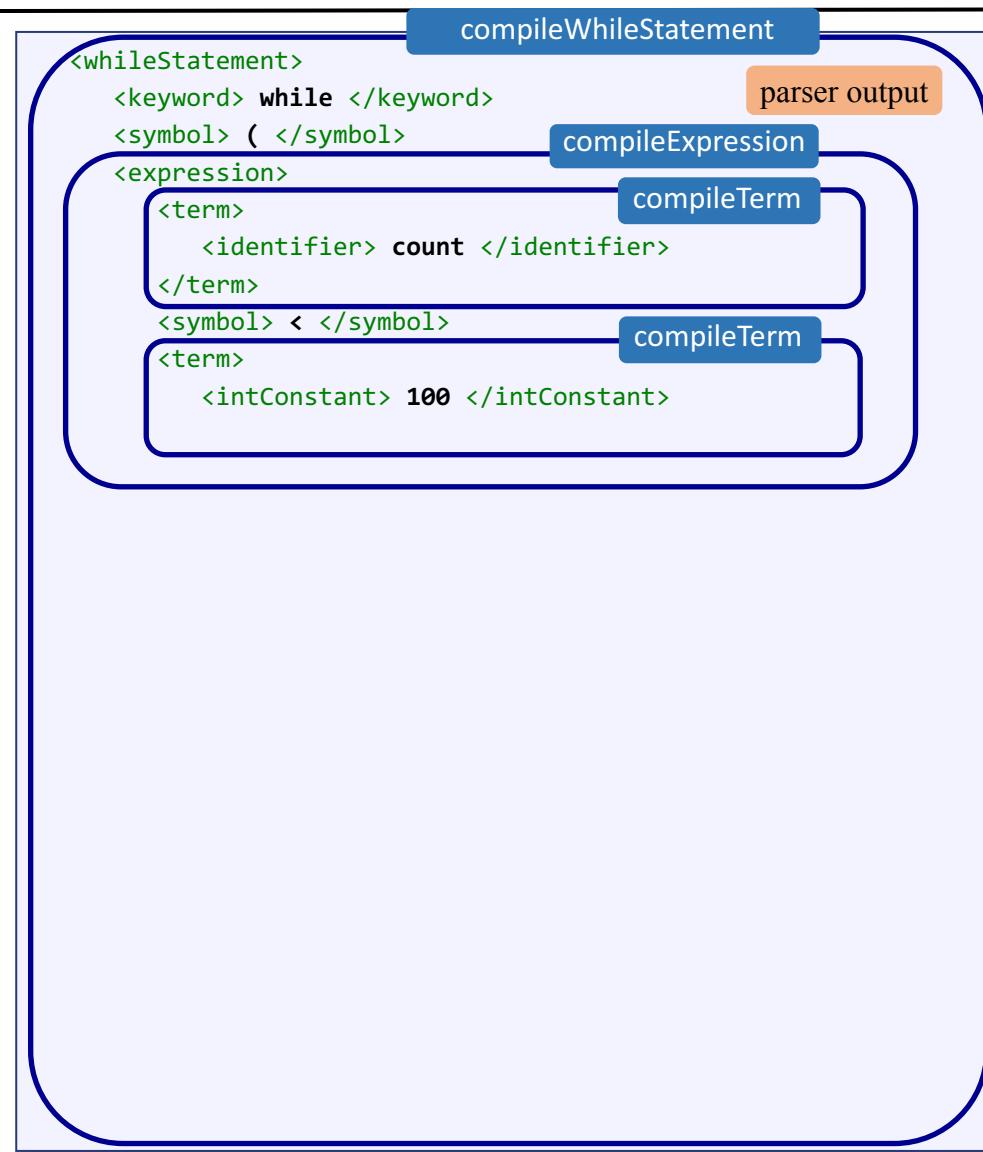
term: varName | constant

varName: a string not beg. with a digit

constant: a decimal number

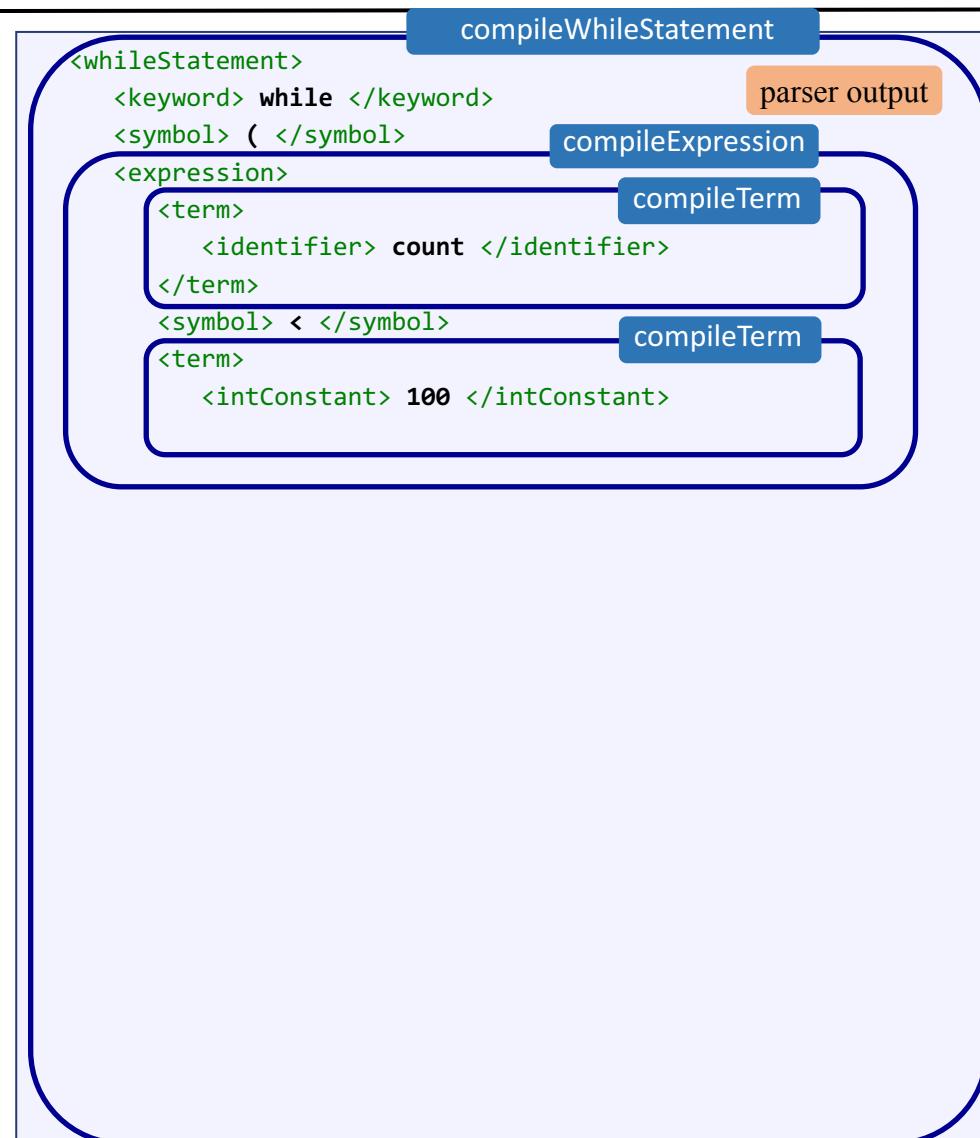
op: '+' | '-' | '=' | '>' | '<'

input



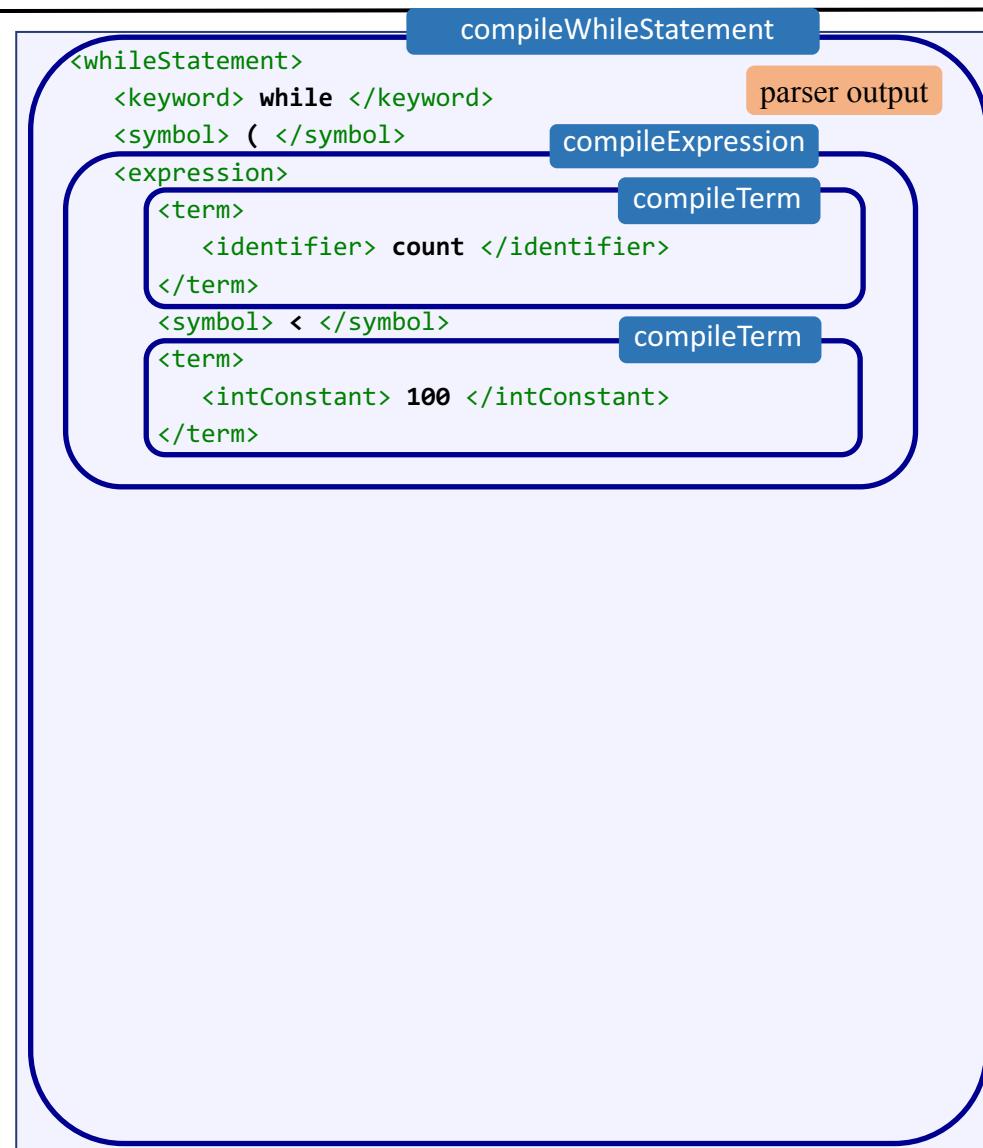
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



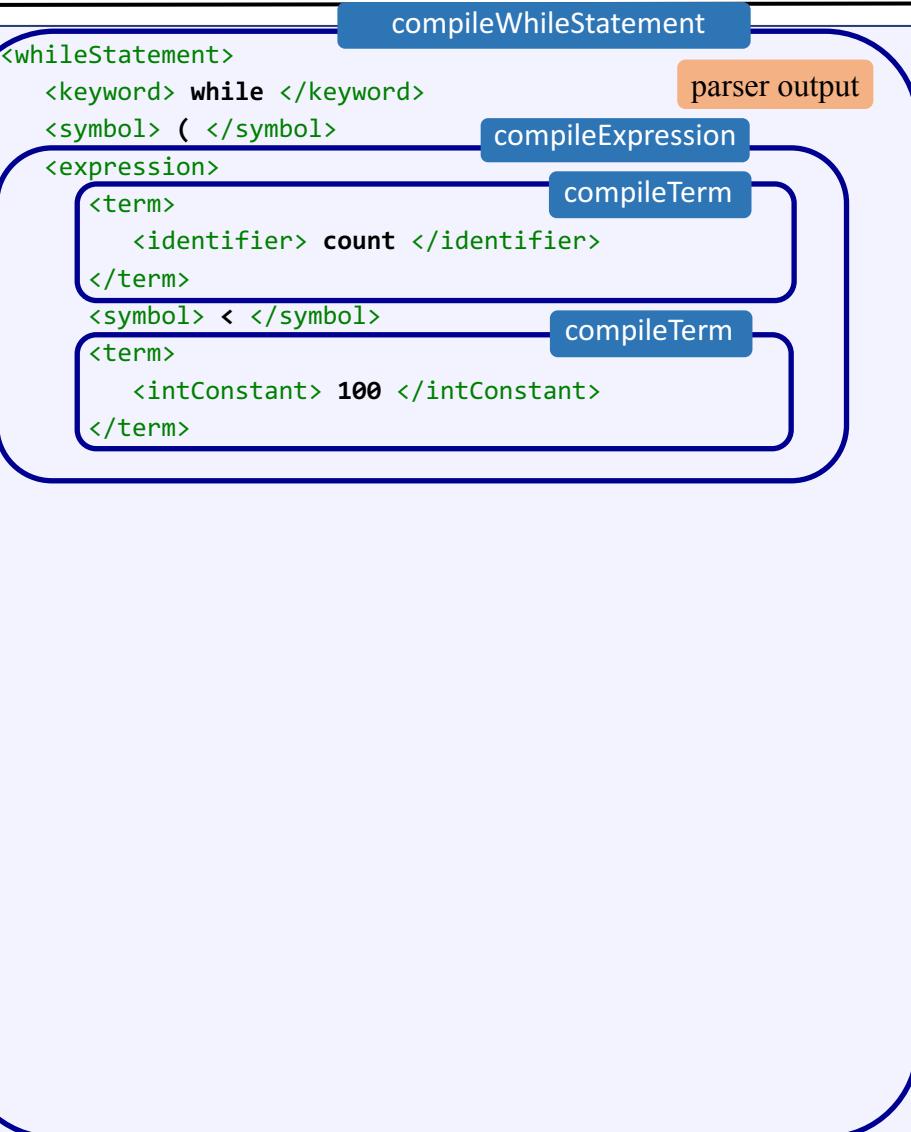
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



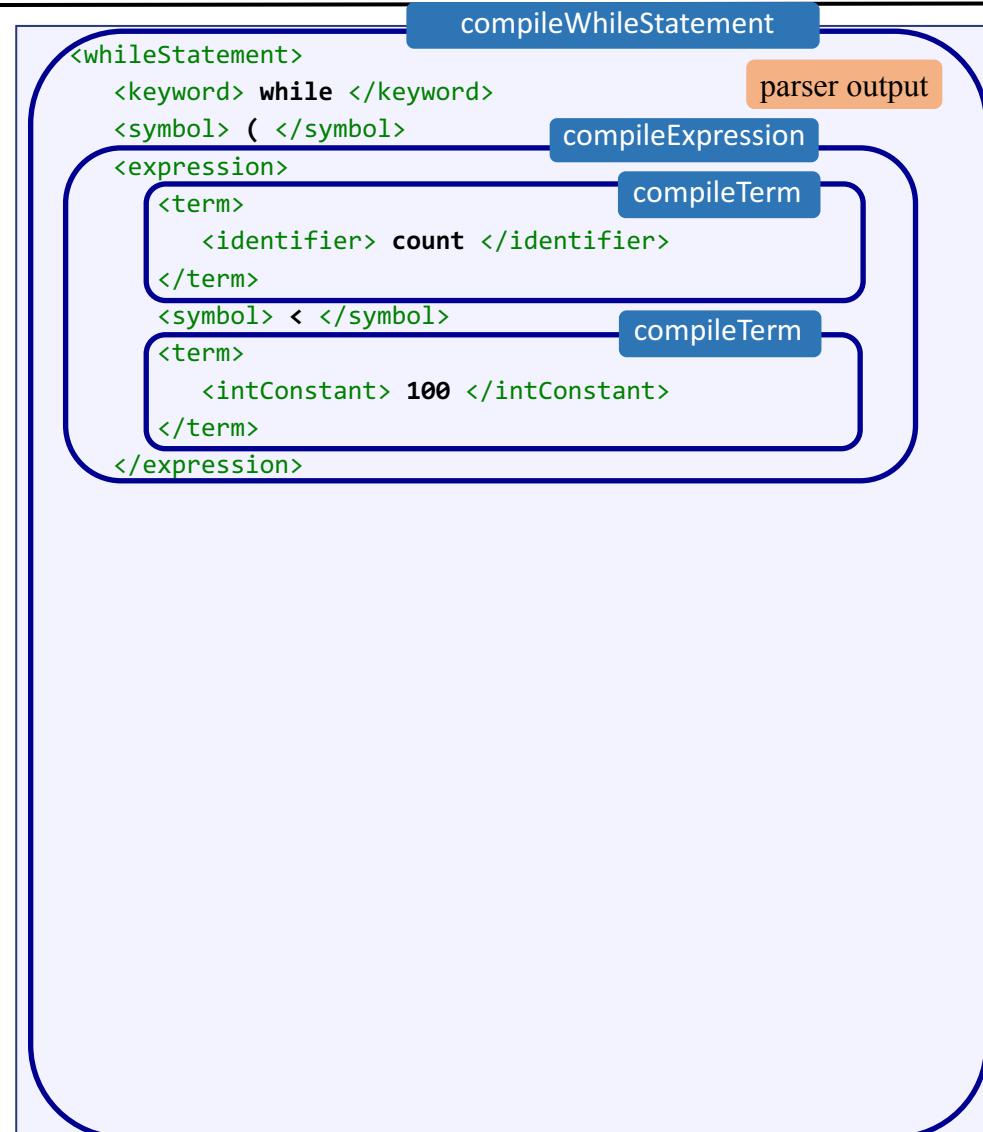
Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';' expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



Parsing process

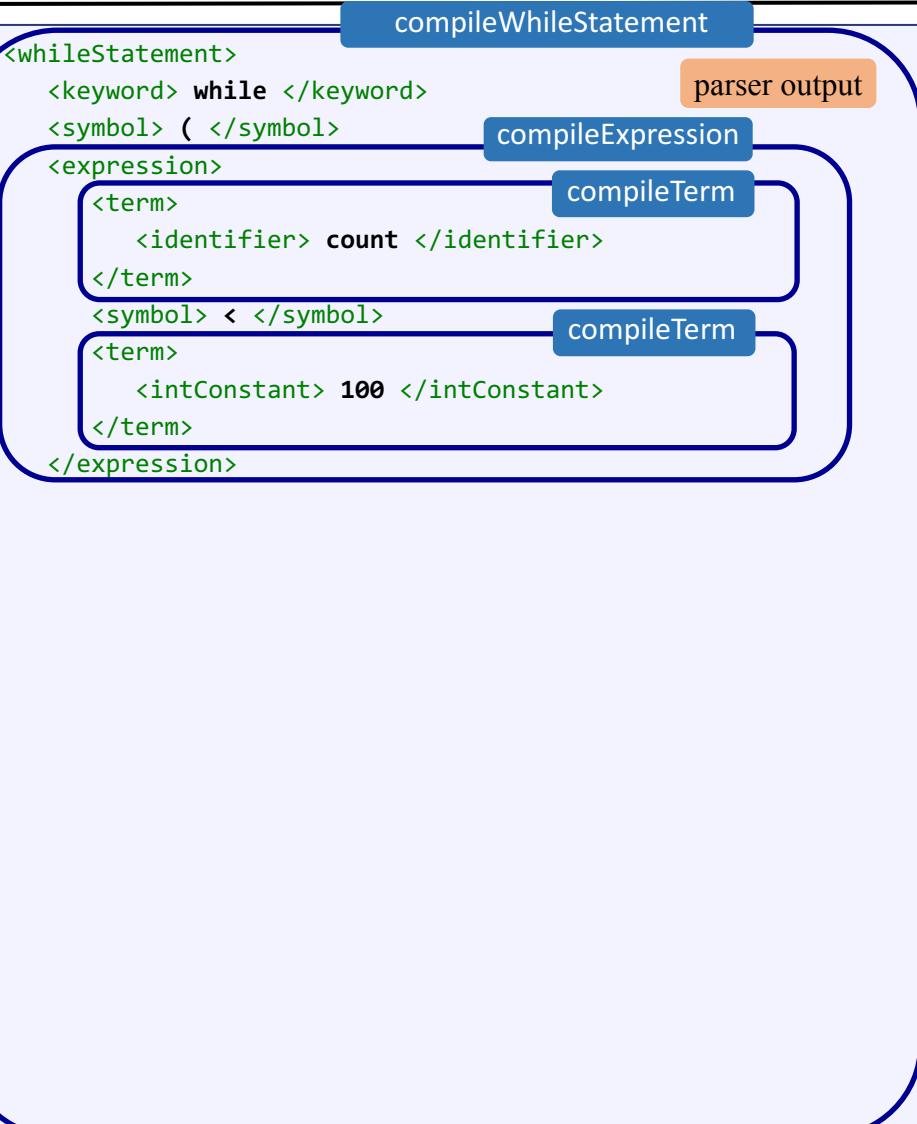
statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';' expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'



Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

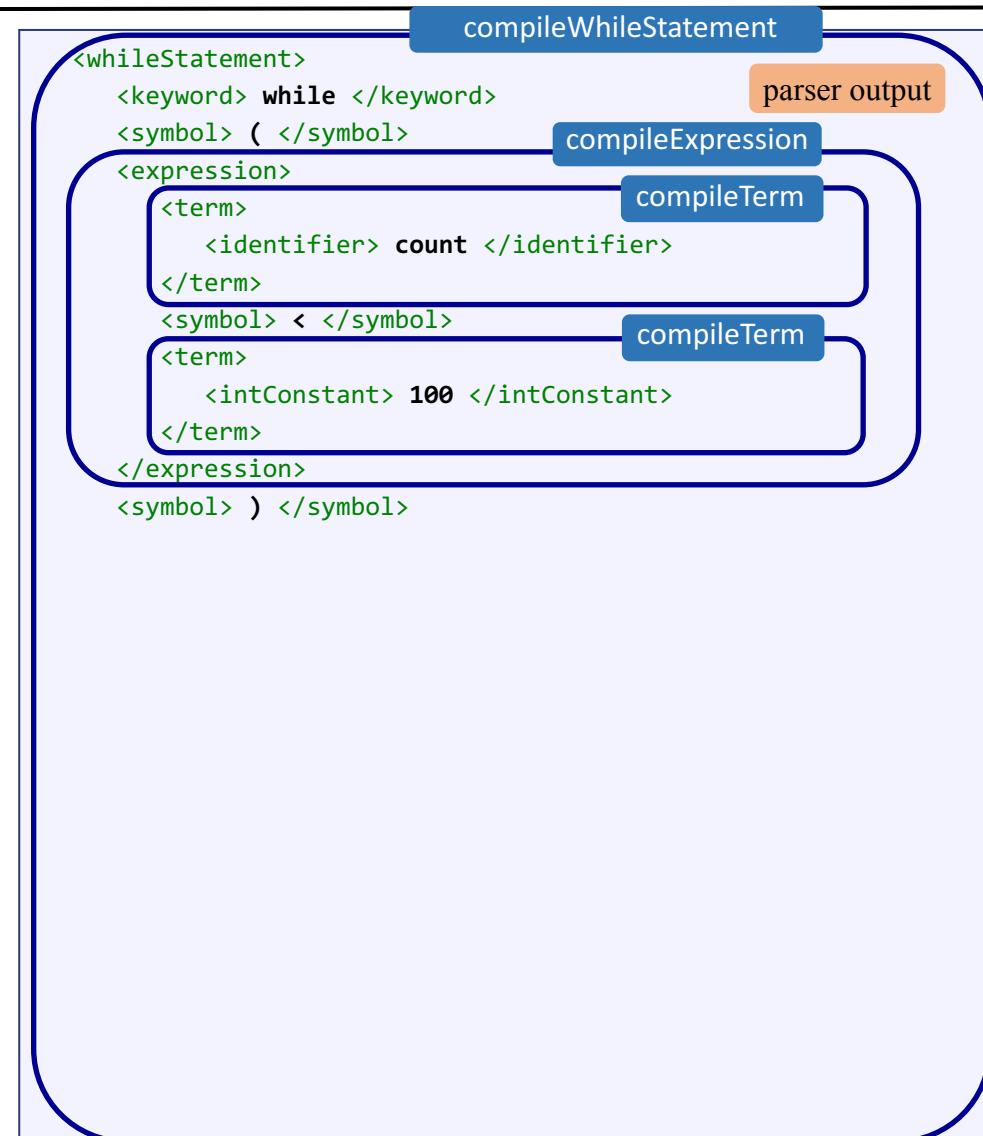


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

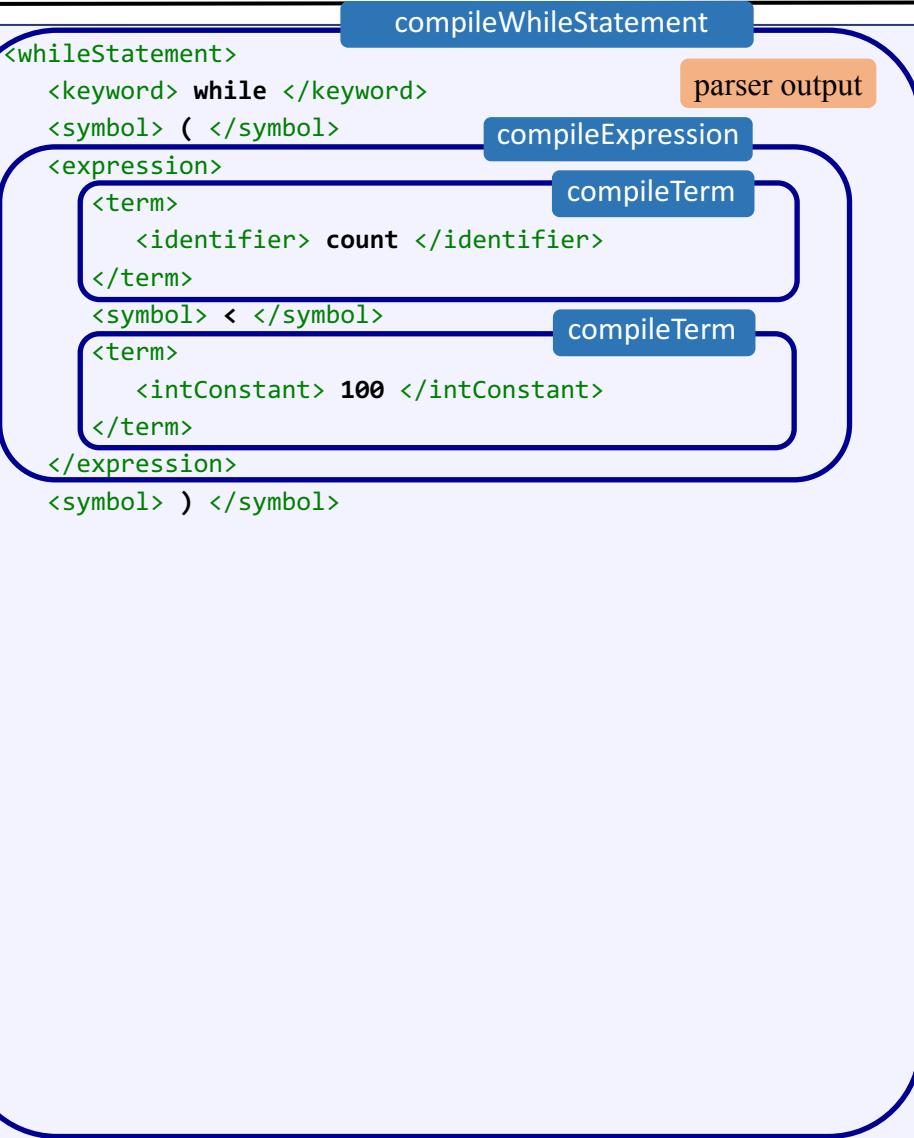
input



Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

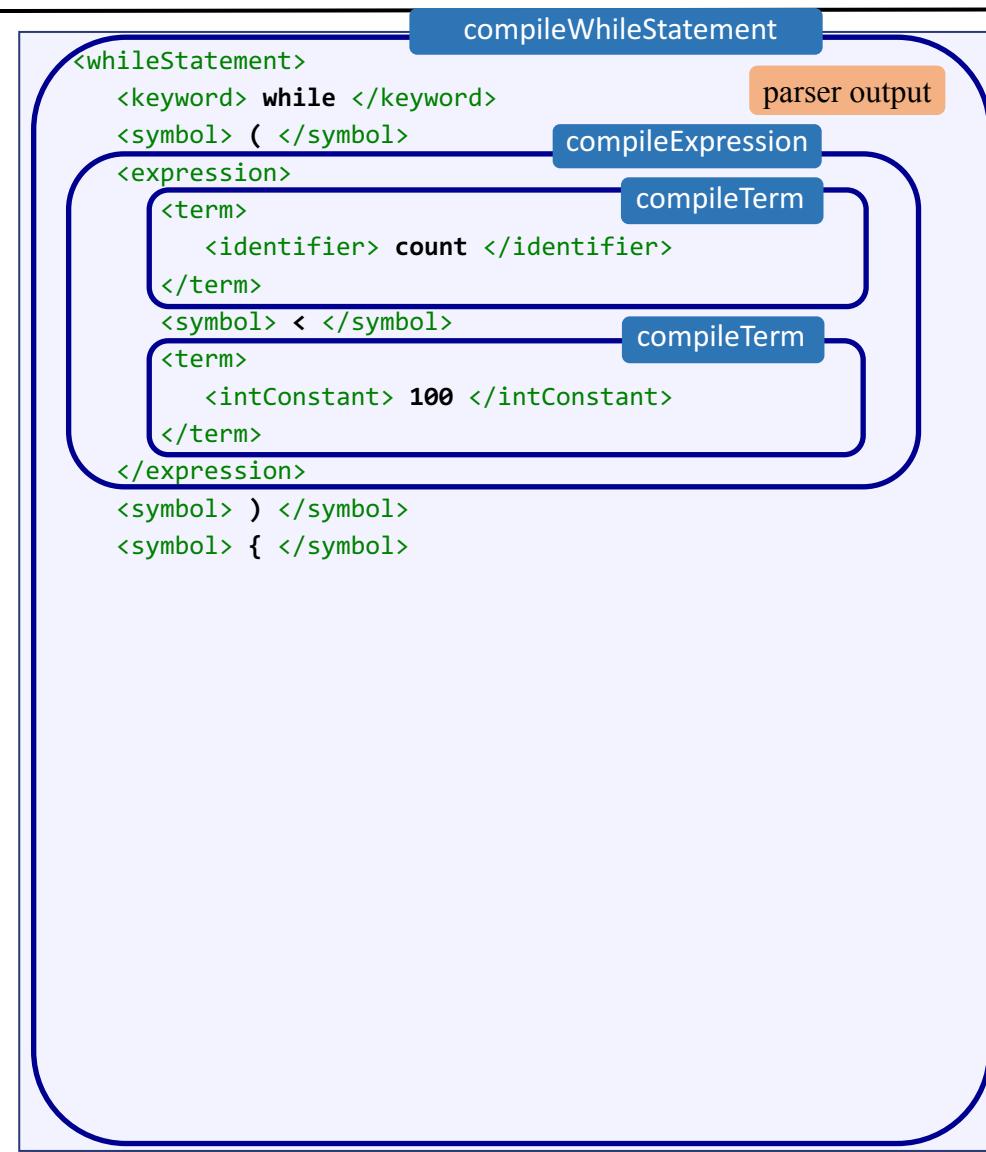


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

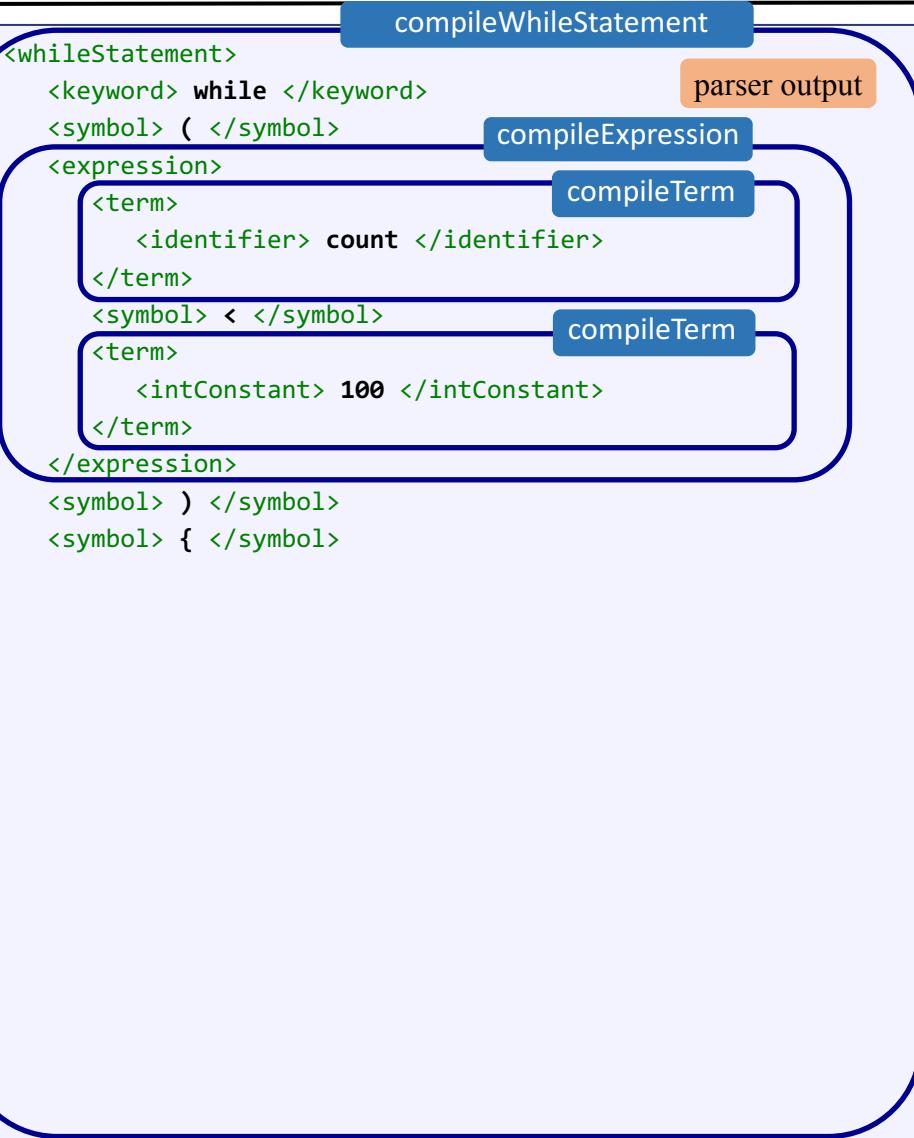
input



Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

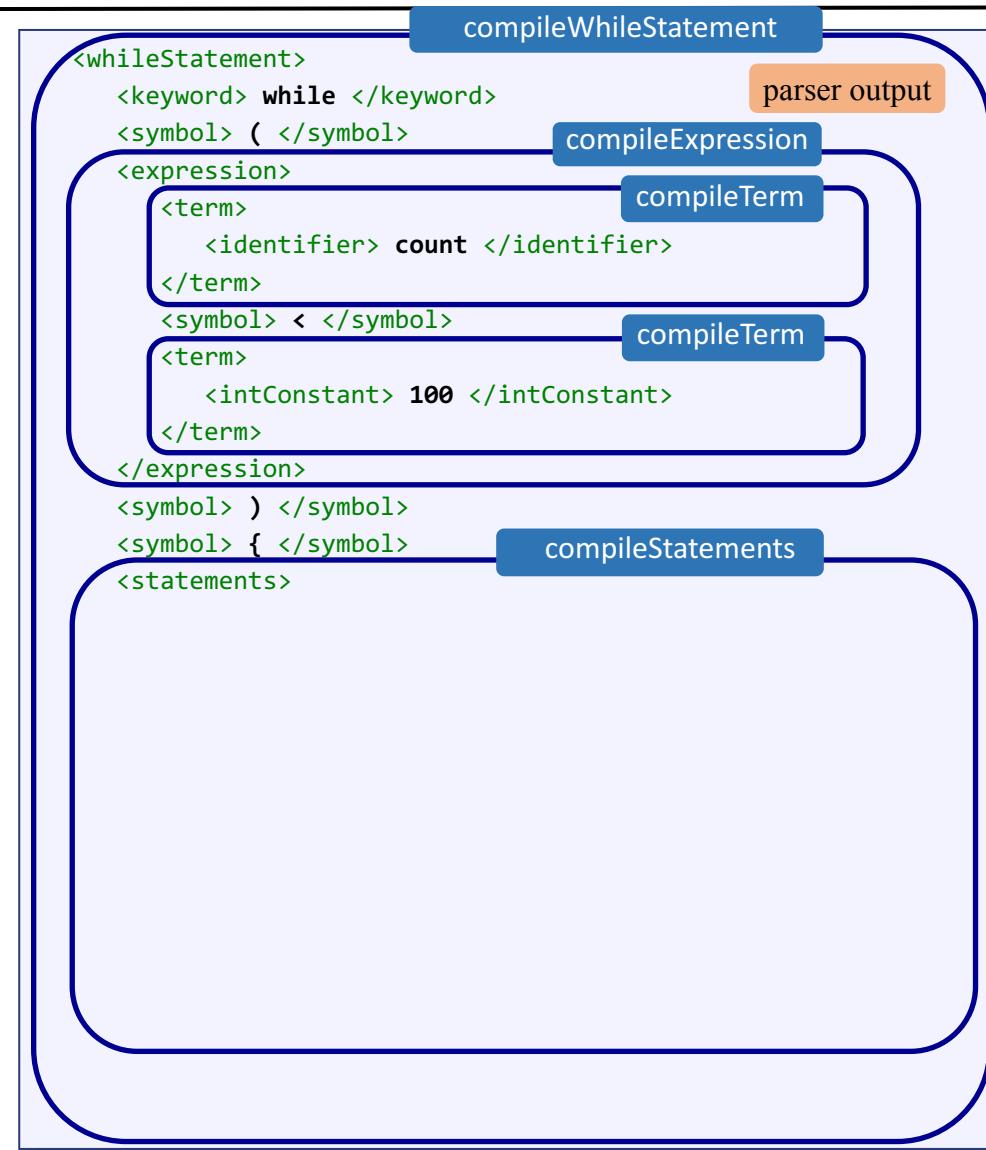
grammar



Parsing process

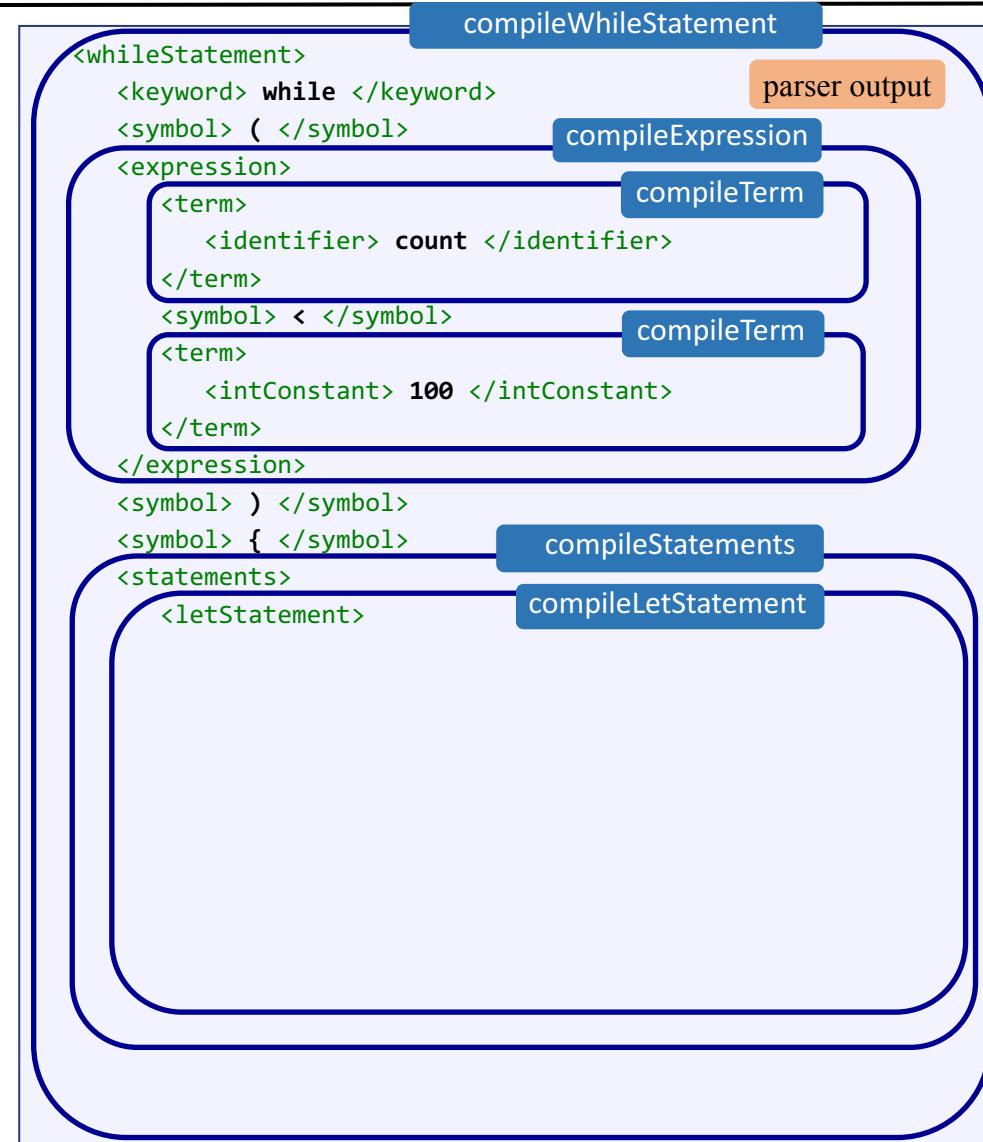
statement: ifStatement | grammar
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';' expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

input



Parsing process

statement: ifStatement | grammar
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';' **input**
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

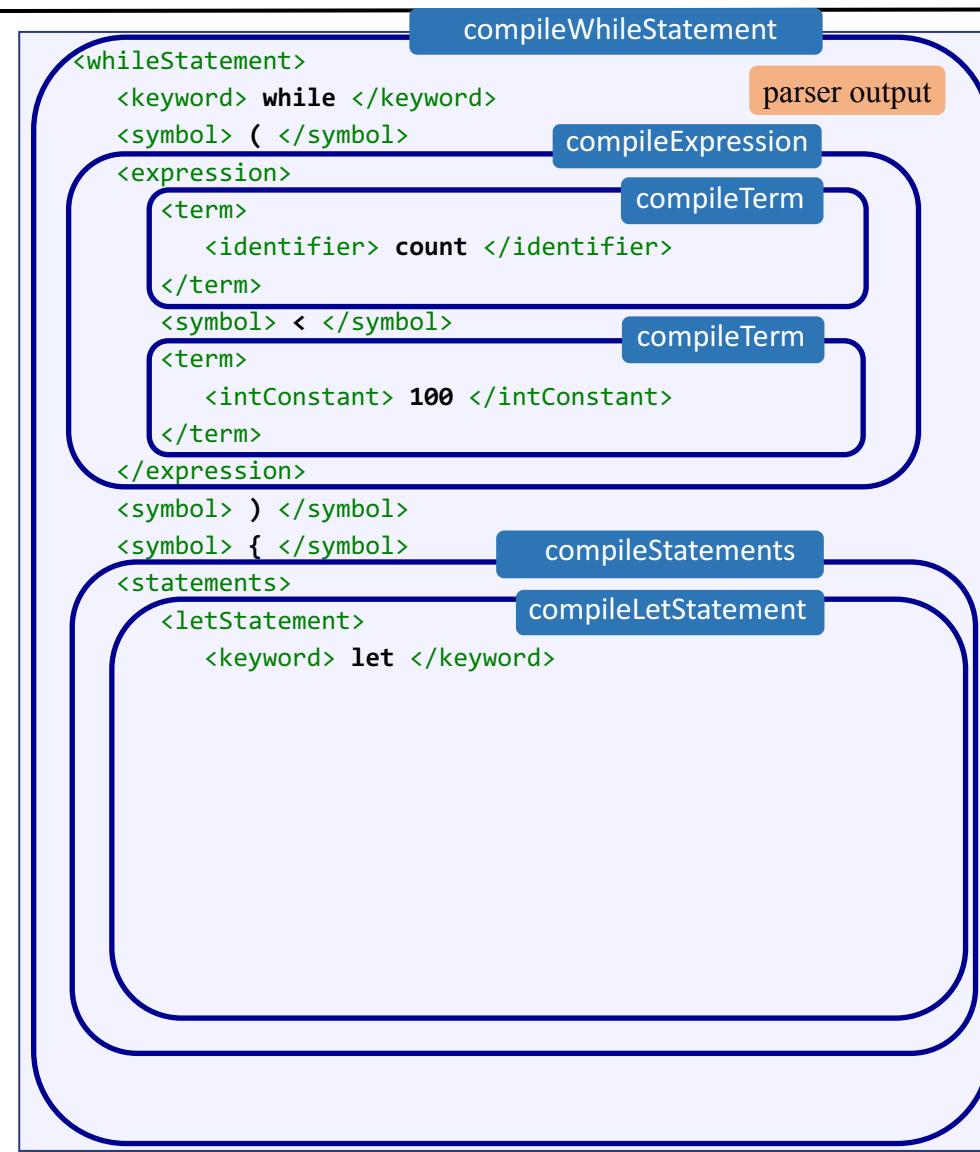


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input

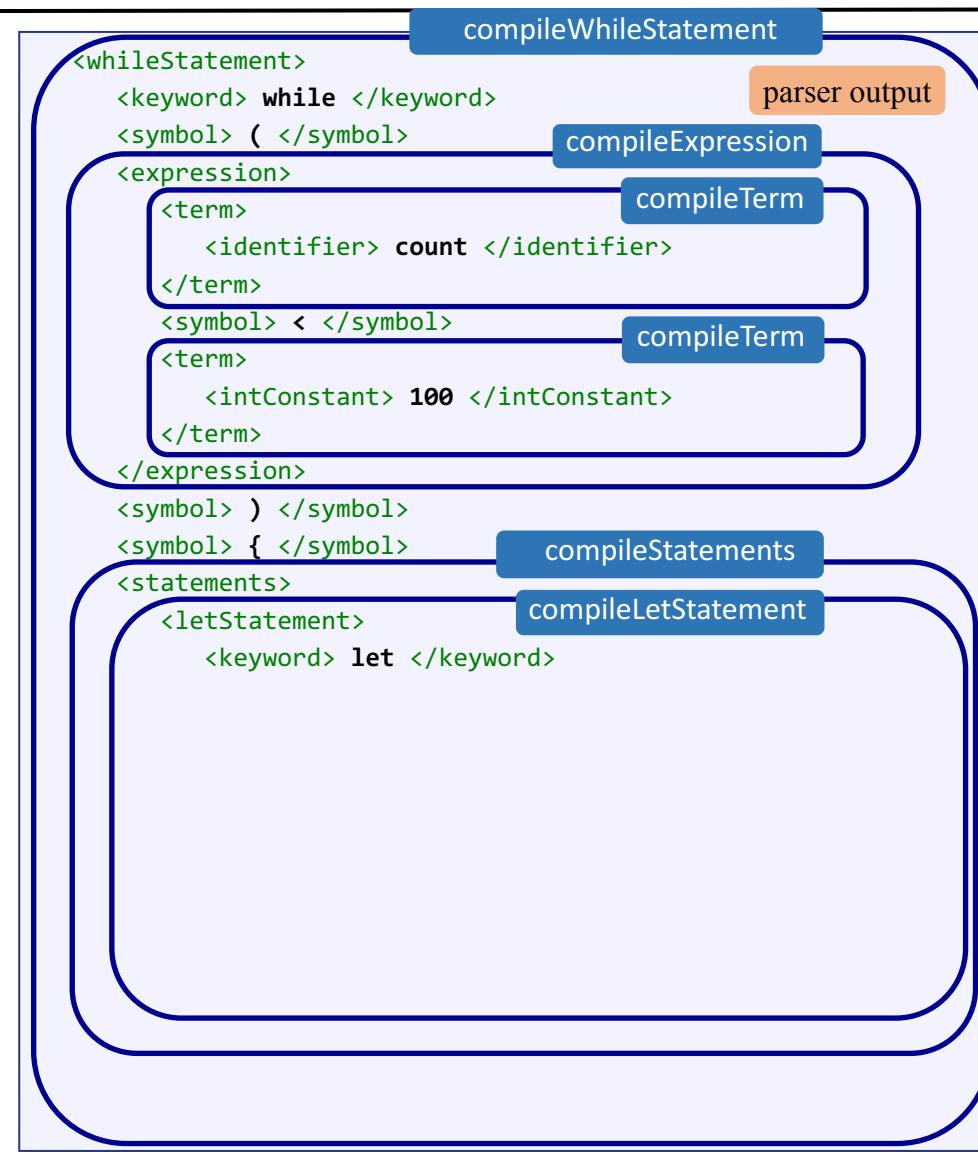


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input

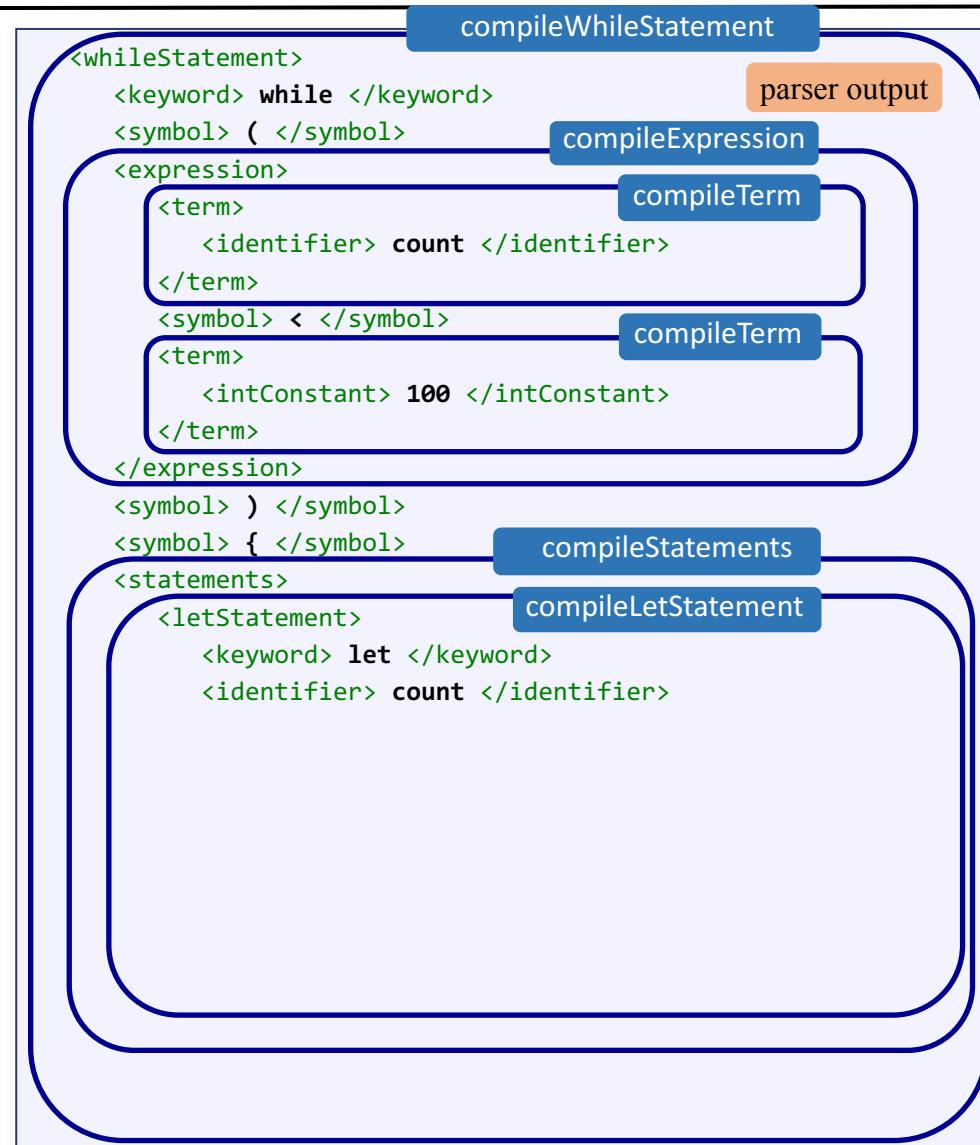


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input

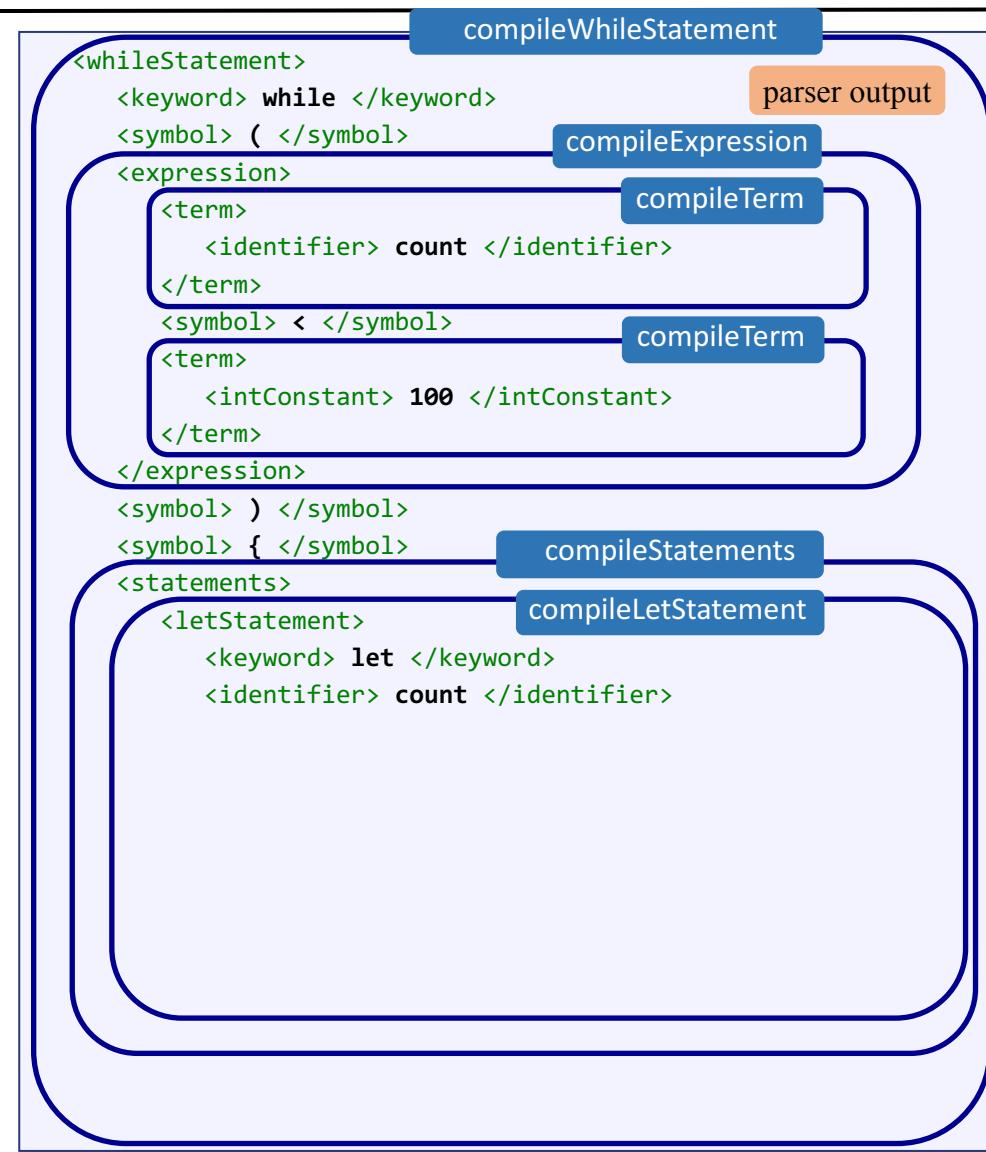


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input

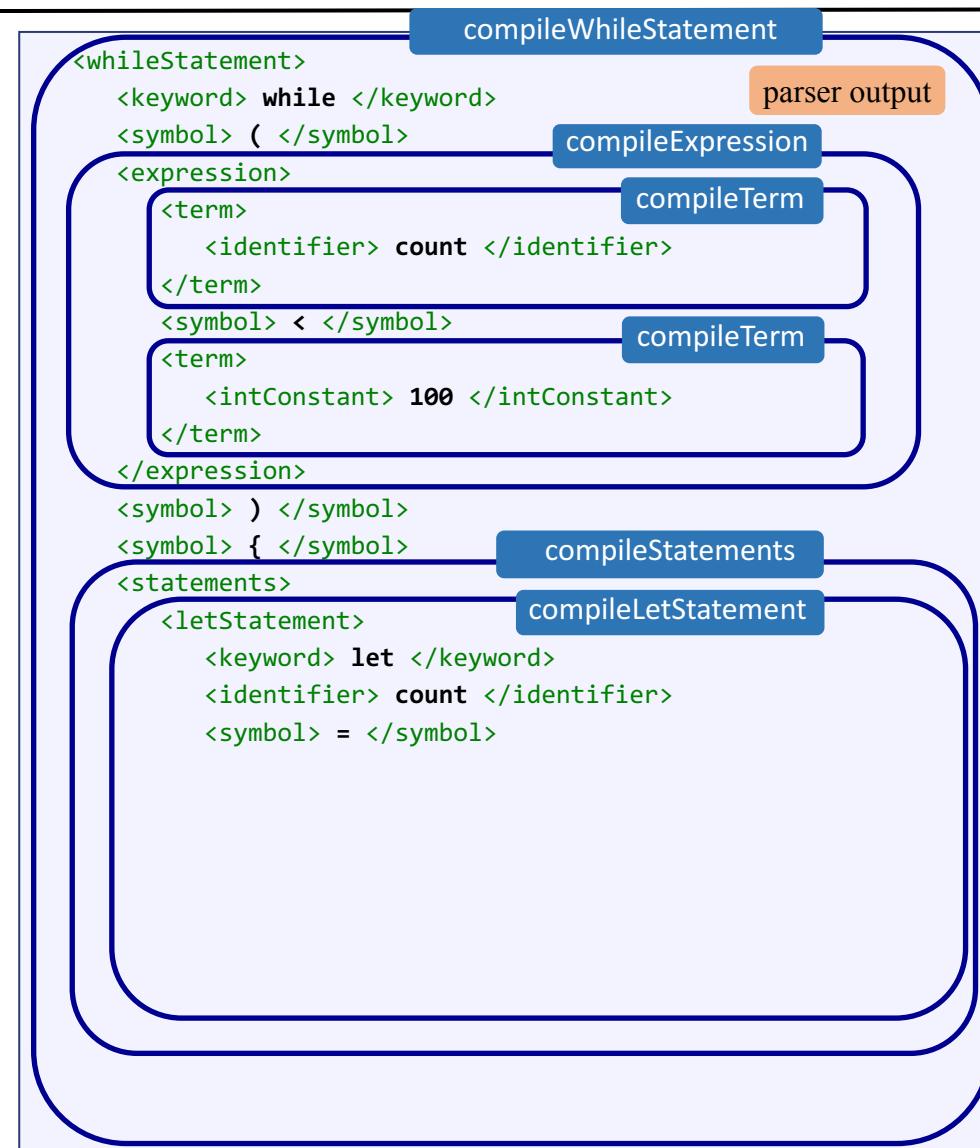


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input

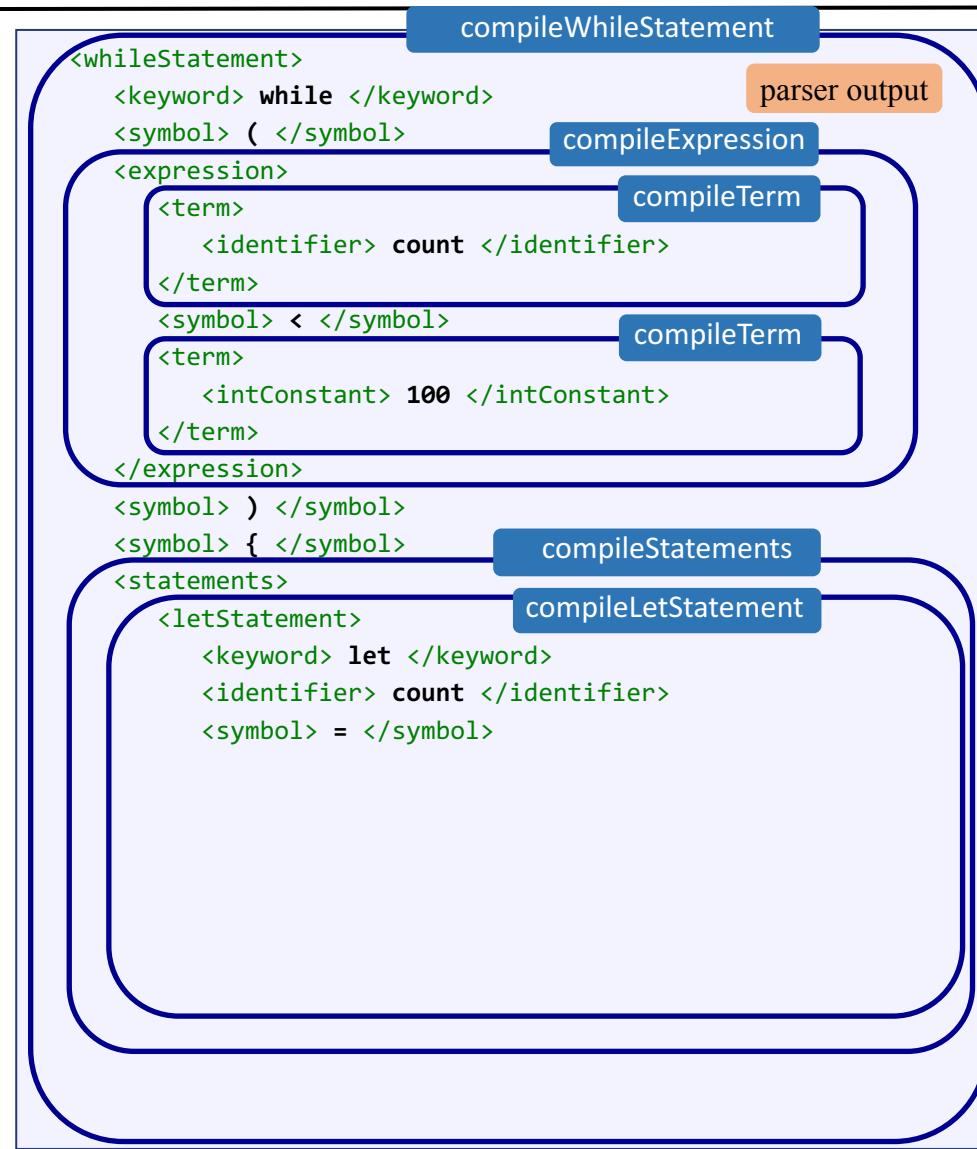


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

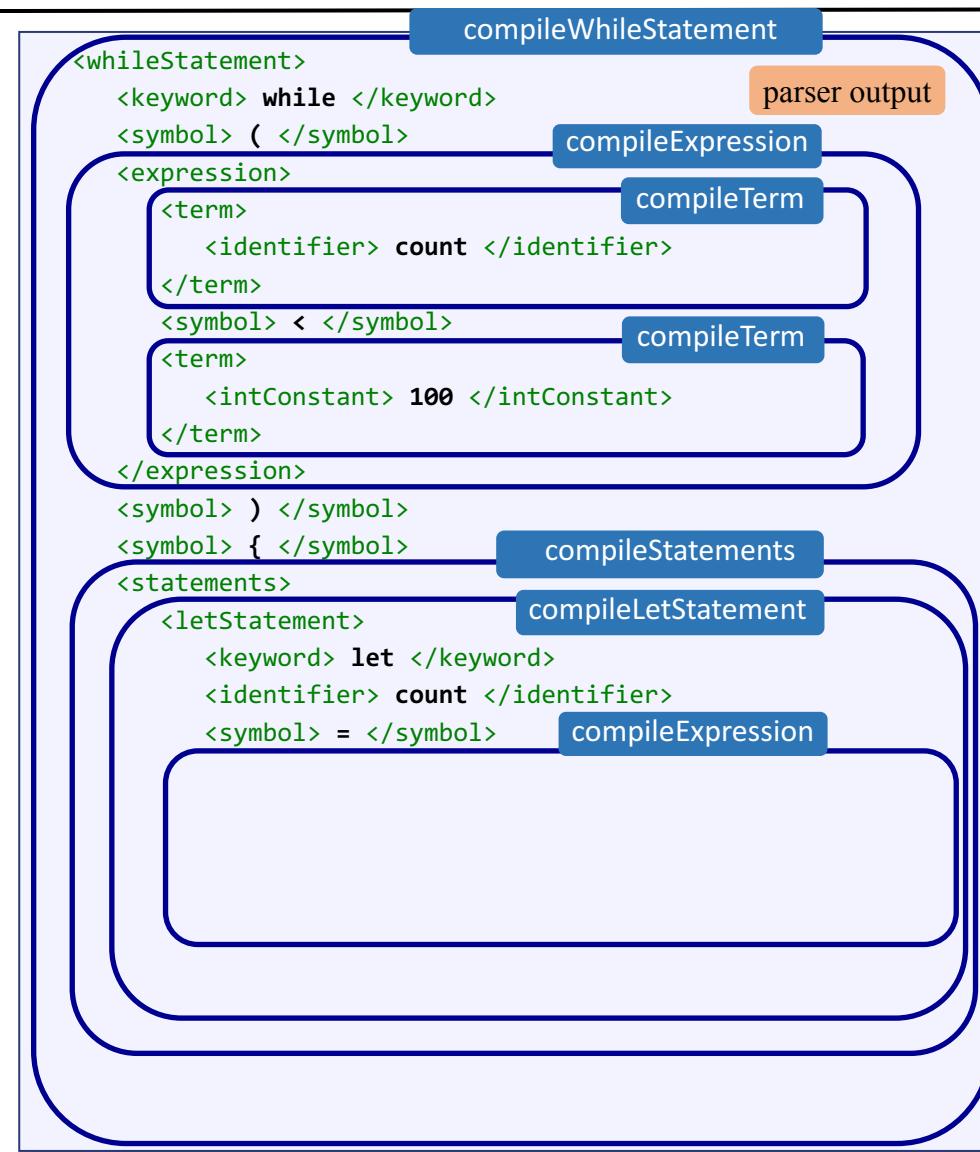
input



Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';' grammar
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<' expression

input



Parsing process

statement: ifStatement | grammar
whileStatement |
letStatement

statements: statement*

ifStatement: 'if' '(' expression ')' '{' statements '}'

whileStatement: 'while' '(' expression ')' '{' statements '}'

letStatement: 'let' varName '=' expression ';' expression: term (op term)?

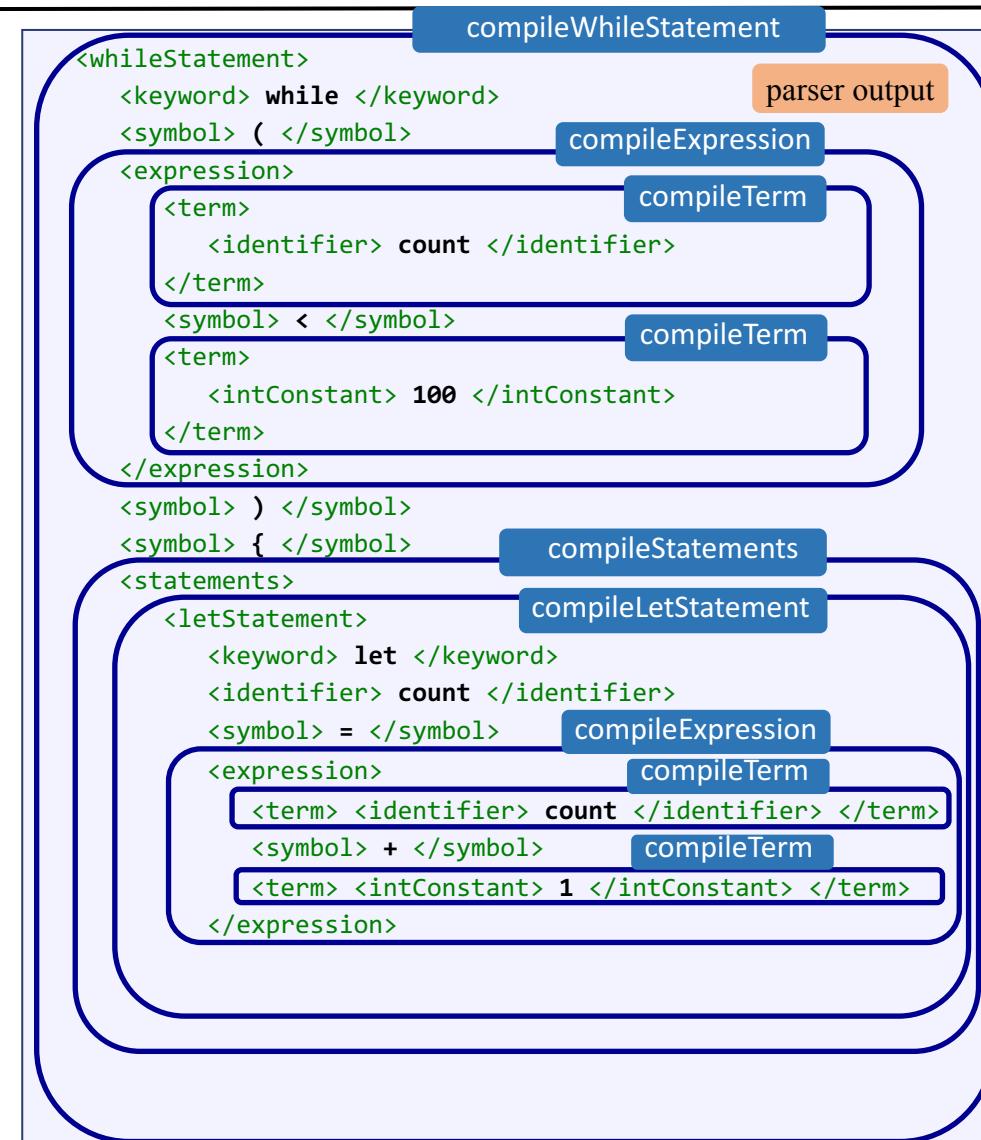
term: varName | constant

varName: a string not beg. with a digit

constant: a decimal number

op: '+' | '-' | '=' | '>' | '<'

input

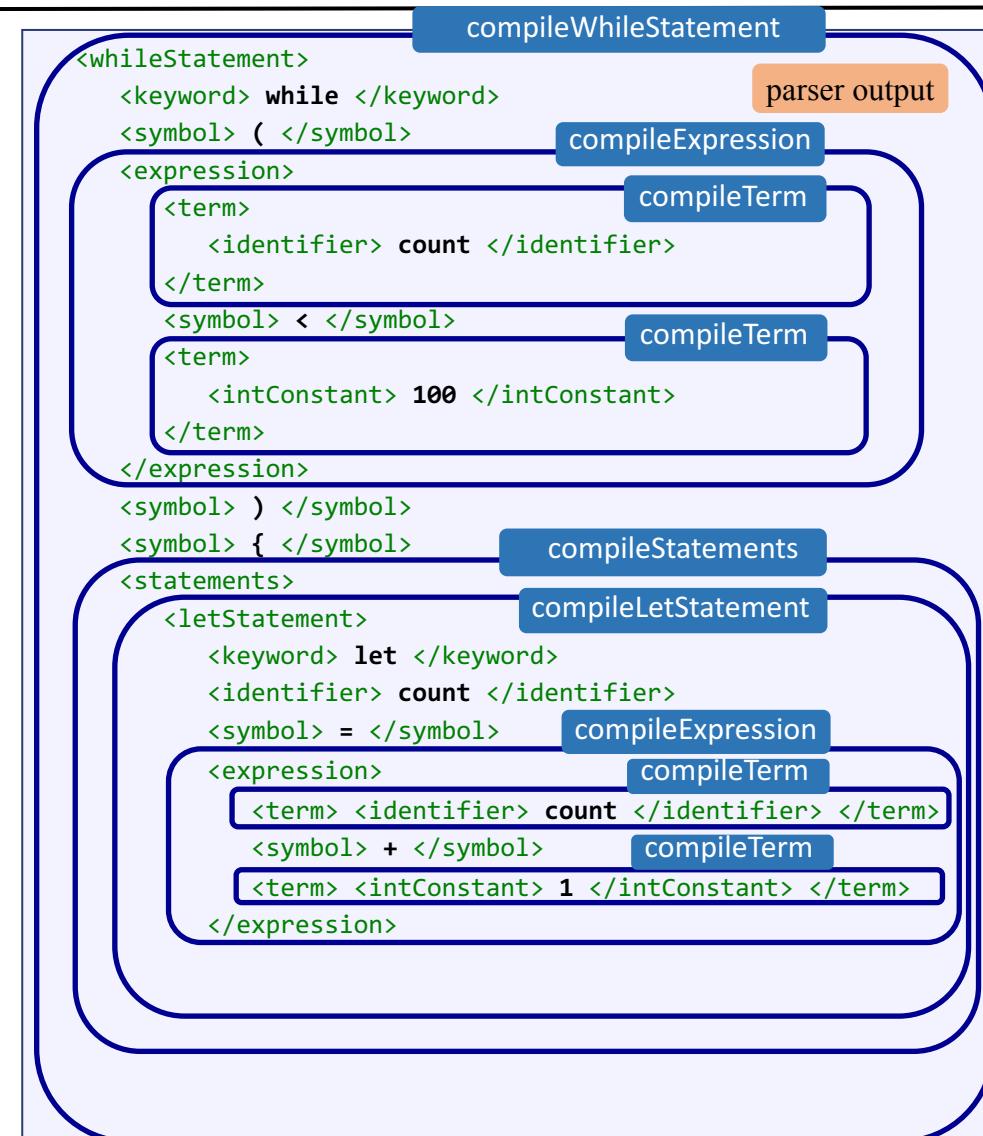


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input

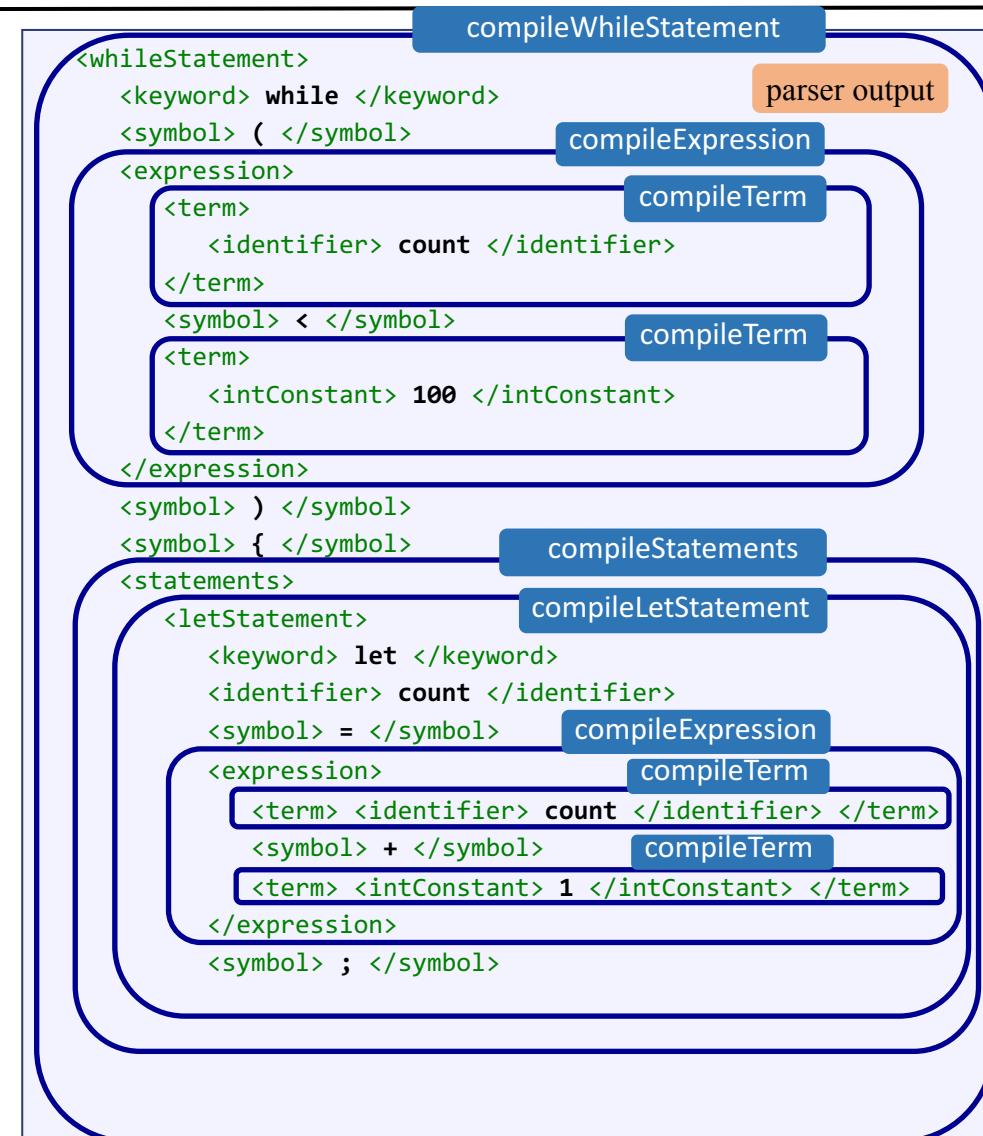


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input

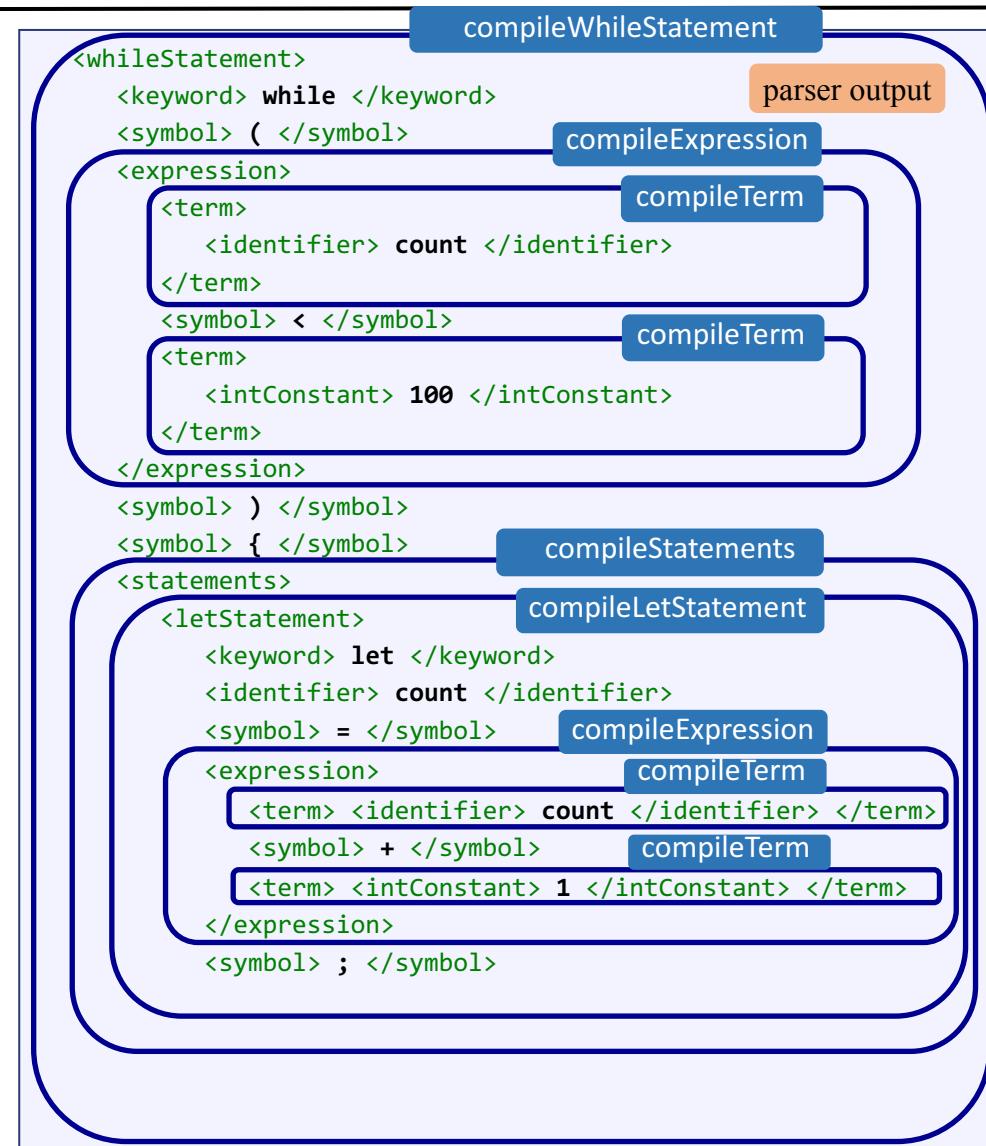


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input

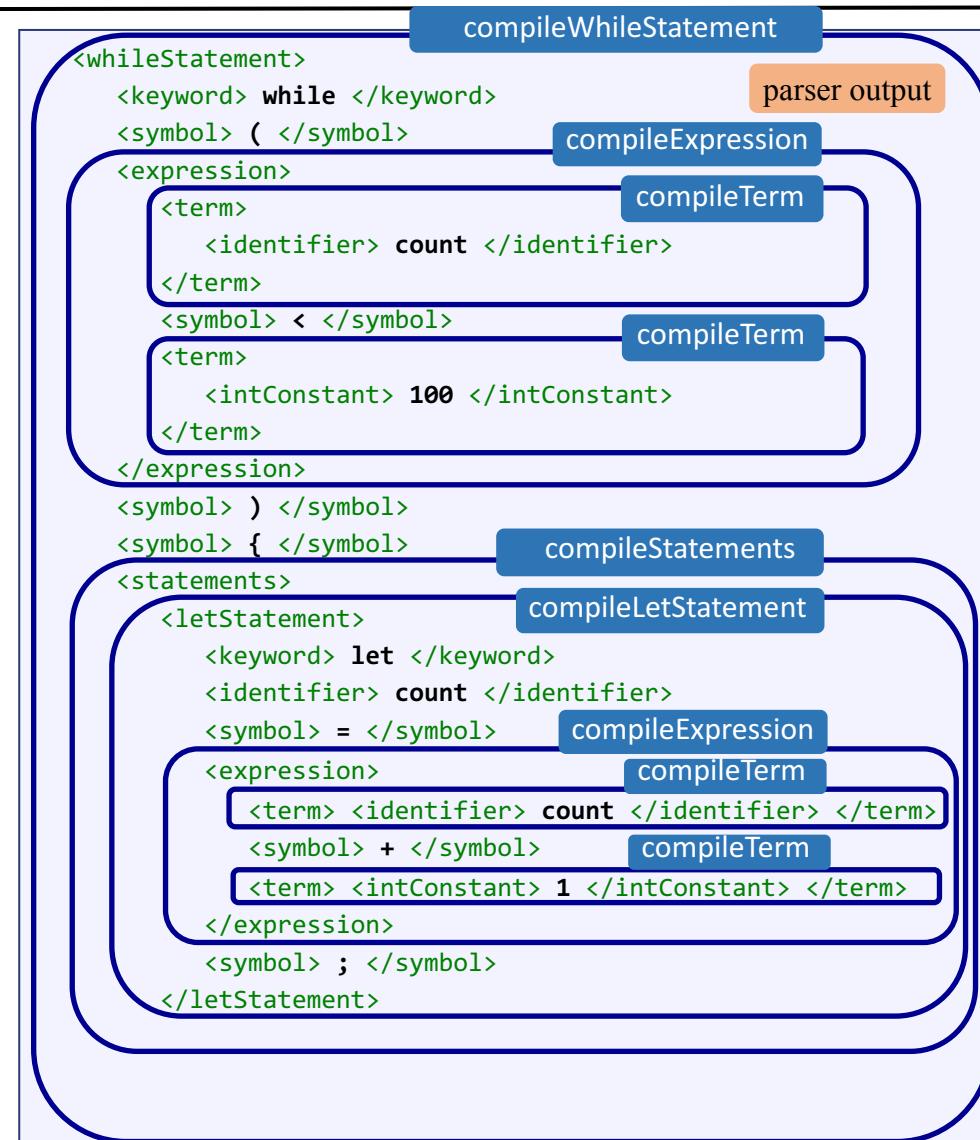


Parsing process

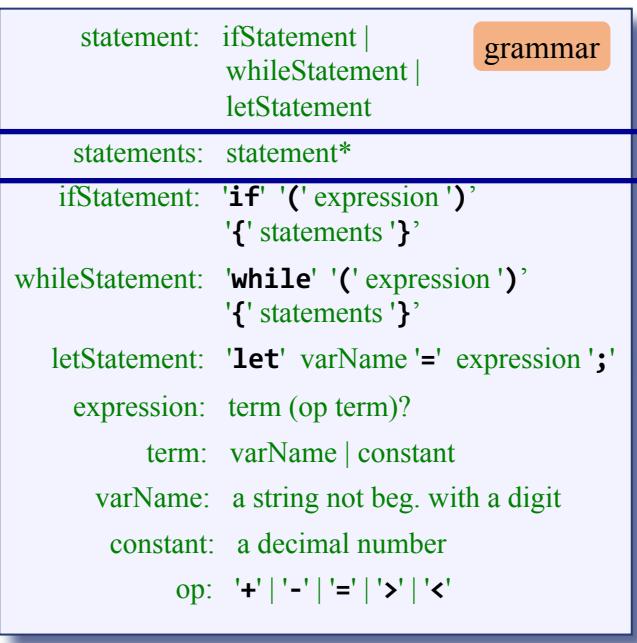
statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

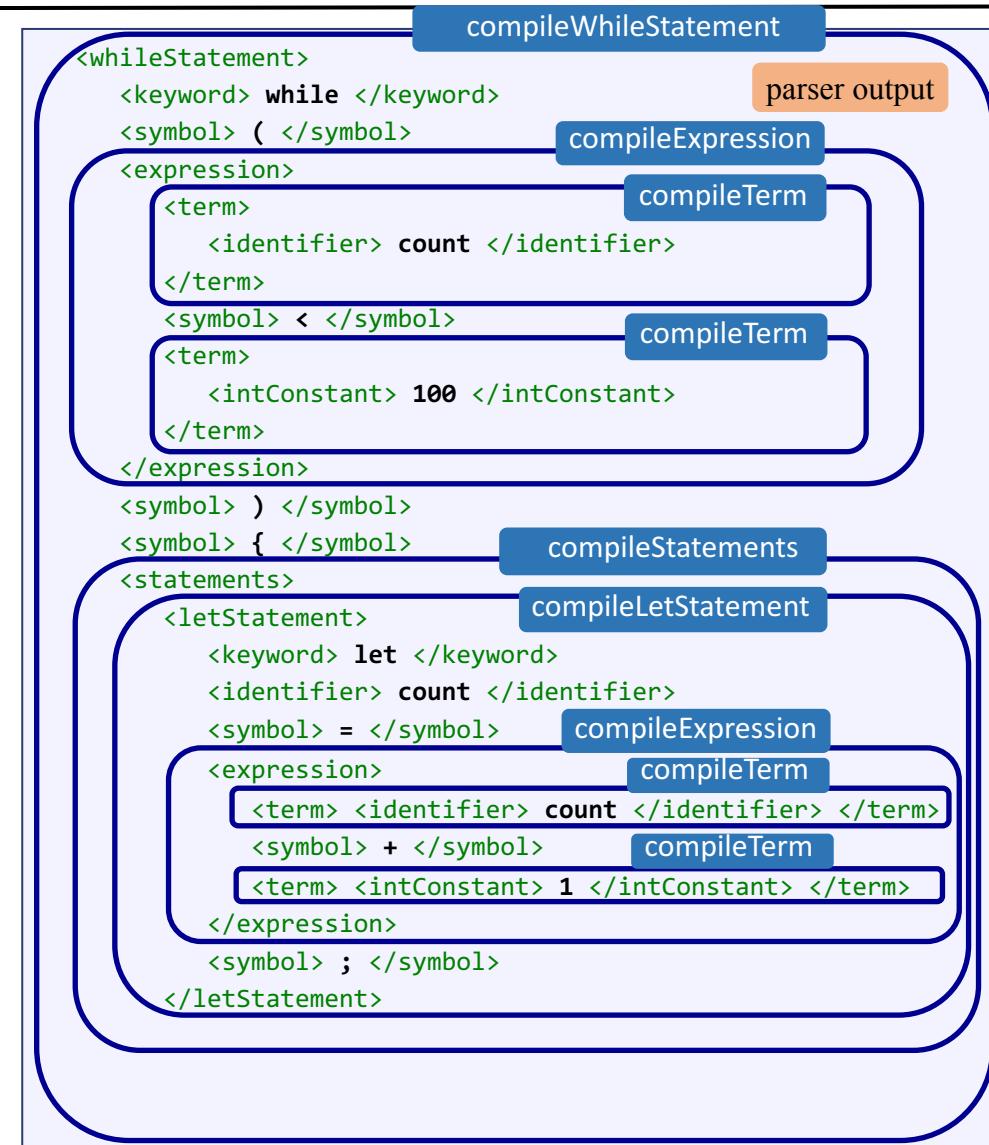
input



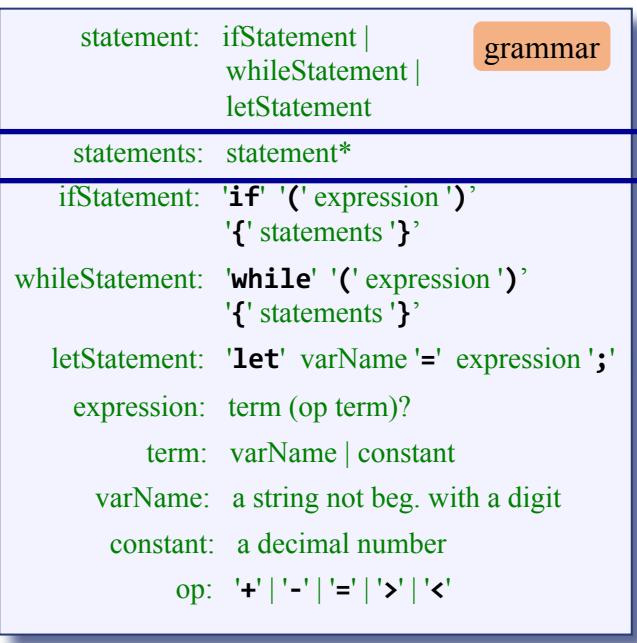
Parsing process



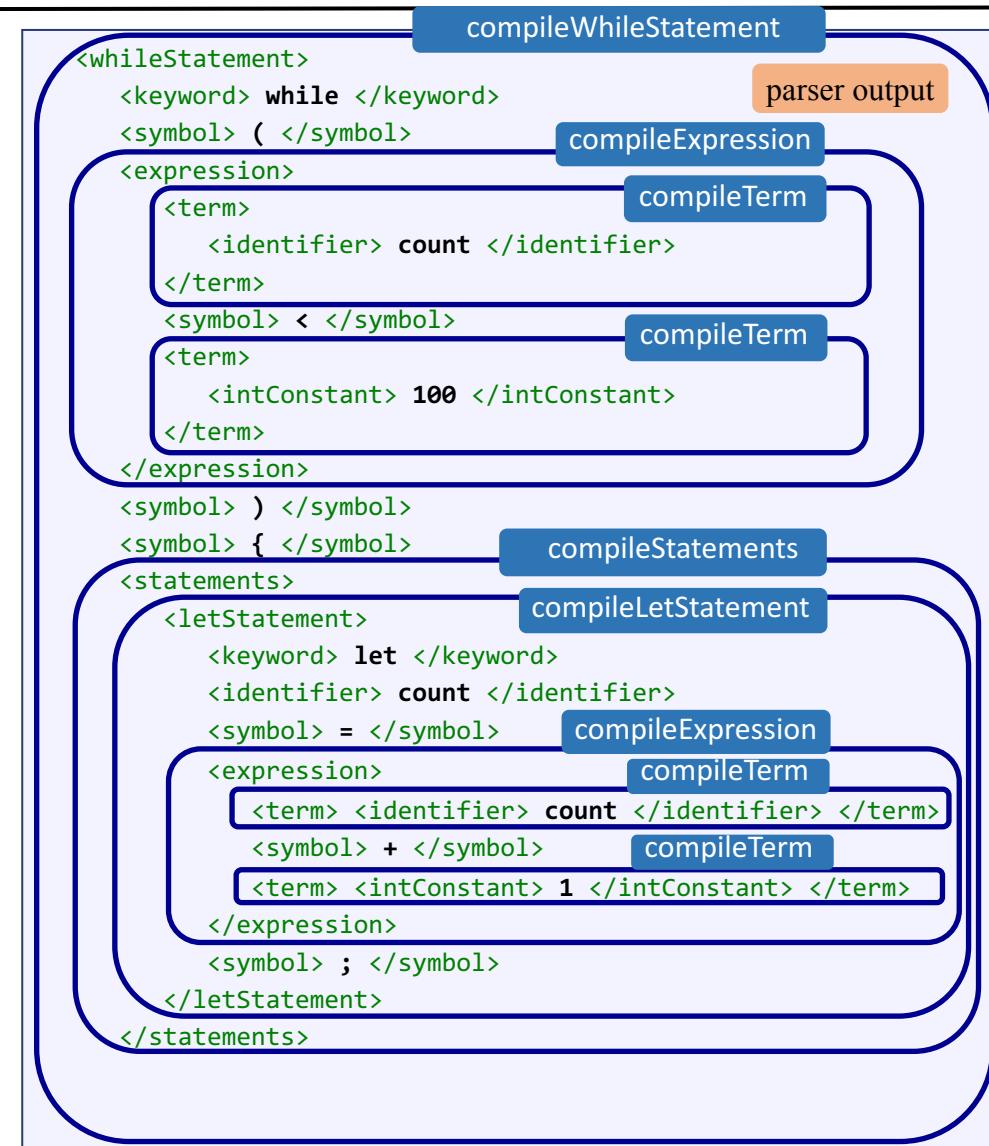
input



Parsing process



input

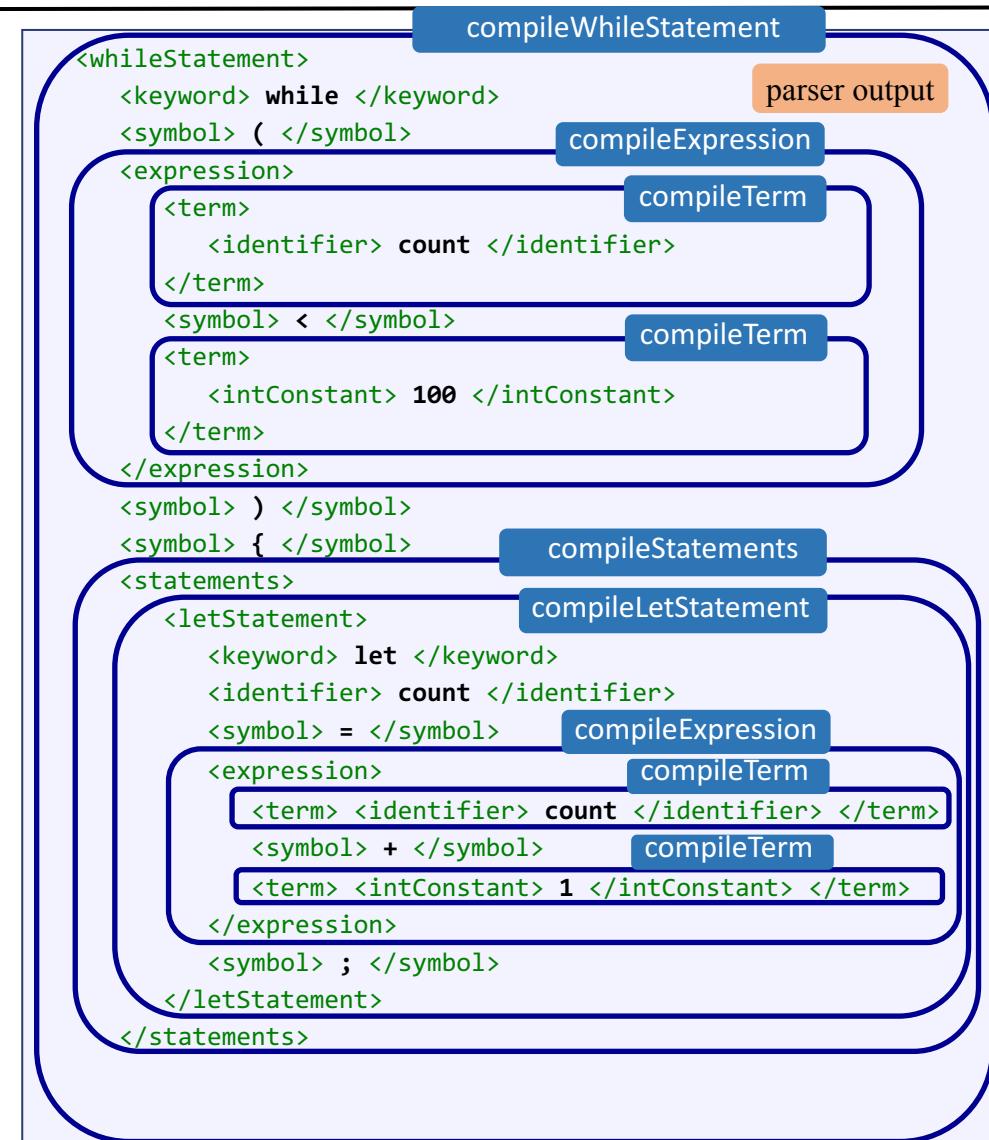


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input

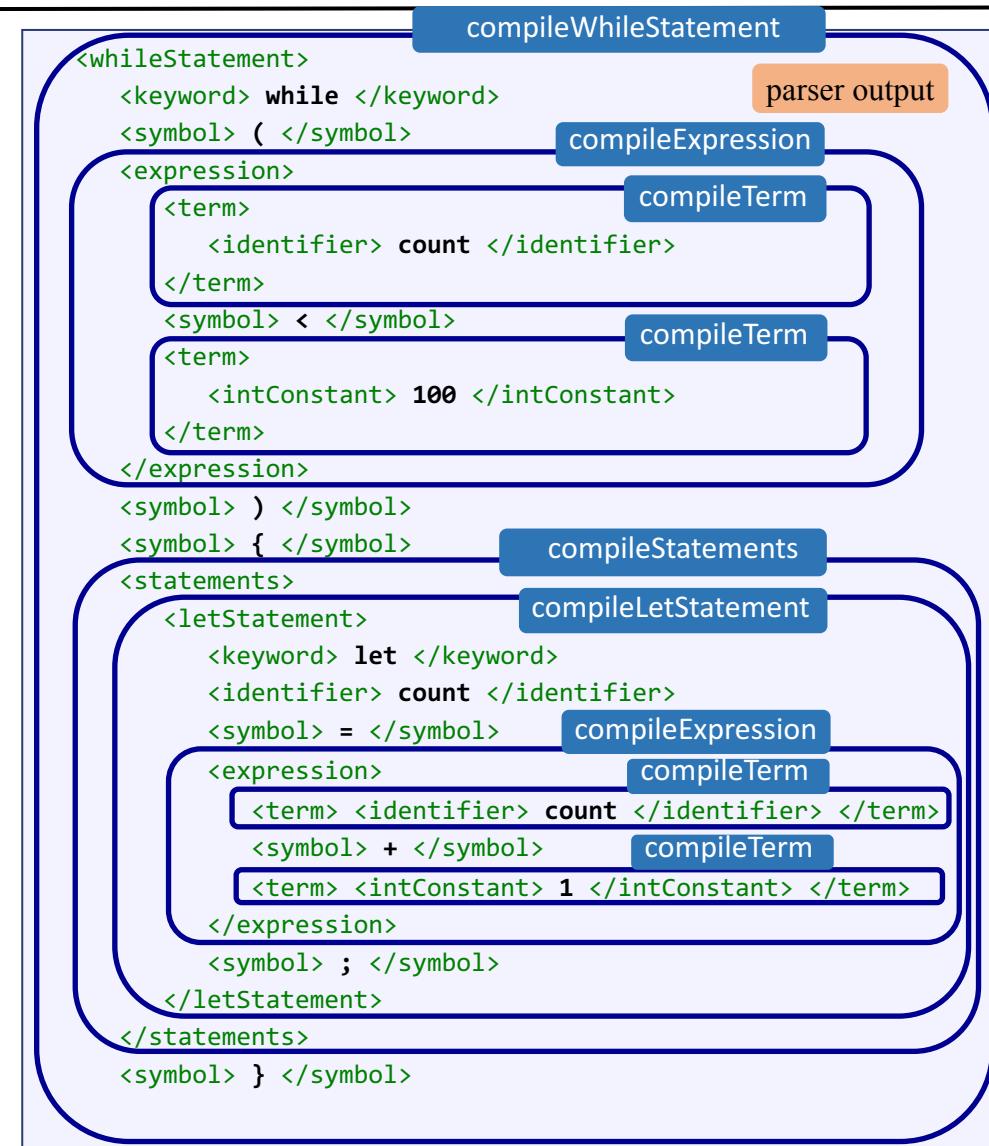


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input

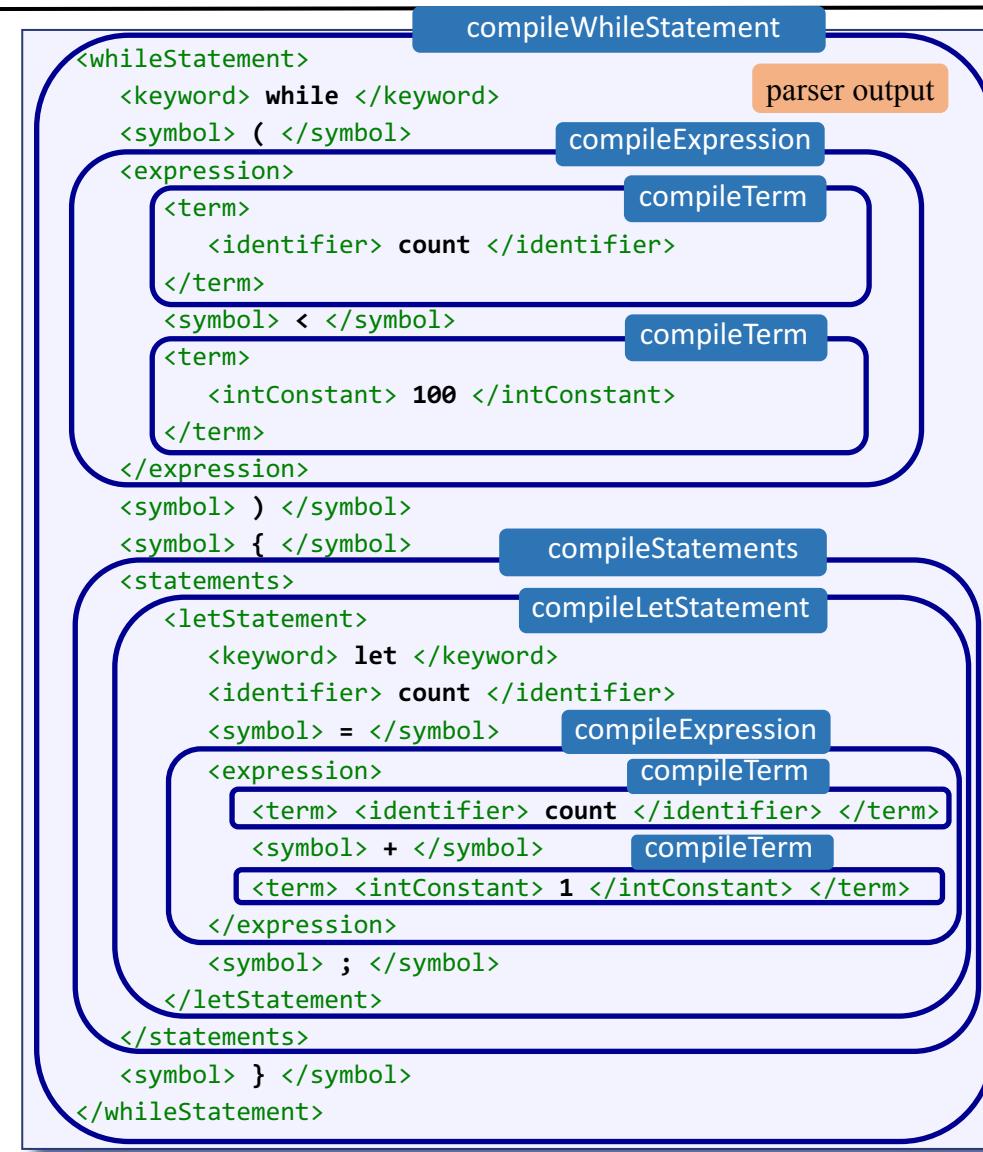


Parsing process

statement: ifStatement |
whileStatement |
letStatement
statements: statement*
ifStatement: 'if' '(' expression ')' '{' statements '}'
whileStatement: 'while' '(' expression ')' '{' statements '}'
letStatement: 'let' varName '=' expression ';'
expression: term (op term)?
term: varName | constant
varName: a string not beg. with a digit
constant: a decimal number
op: '+' | '-' | '=' | '>' | '<'

grammar

input



Parsing process

```
statement: ifStatement | grammar  
         whileStatement |  
         letStatement  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' { statements }'  
  
whileStatement: 'while' '(' expression ')' { statements }'  
  
letStatement: 'let' varName '=' expression ';'  
  
expression: term (op term)?  
  
term: varName | constant  
  
varName: a string not beg. with a digit  
  
constant: a decimal number  
  
op: '+' | '-' | '=' | '>' | '<'
```

input

```
<whileStatement>  
  <keyword> while </keyword> parser output  
  <symbol> ( </symbol>  
  <expression>  
    <term>  
      <identifier> count </identifier>  
    </term>  
    <symbol> < </symbol>  
    <term>  
      <intConstant> 100 </intConstant>  
    </term>  
  </expression>  
  <symbol> ) </symbol>  
  <symbol> { </symbol>  
  <statements>  
    <letStatement>  
      <keyword> let </keyword>  
      <identifier> count </identifier>  
      <symbol> = </symbol>  
      <expression>  
        <term> <identifier> count </identifier> </term>  
        <symbol> + </symbol>  
        <term> <intConstant> 1 </intConstant> </term>  
      </expression>  
      <symbol> ; </symbol>  
    </letStatement>  
  </statements>  
  <symbol> } </symbol>  
</whileStatement>
```

Parser design

Grammar

```
statement: ifStatement |  
          whileStatement |  
          letStatement  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' '  
           '{' statements '}'  
  
whileStatement: 'while' '(' expression ')' '  
               '{' statements '}'  
  
letStatement: 'let' varName '=' expression ';'  
  
expression: term (op term)?  
  
term: varName | constant  
  
varName: a string not beg. with a digit  
  
constant: a decimal number  
  
op: '+' | '-' | '=' | '>' | '<'
```

Parser

```
class CompilationEngine {  
  
    compileStatements() {  
        // code for compiling statements  
    }  
  
    compileIfStatement() {  
        // code for compiling an if statement  
    }  
  
    compileWhileStatement() {  
        // code for compiling an while statement  
    }  
  
    ...  
  
    compileTerm() {  
        // code for compiling a term  
    }  
}
```

Parser's design:

- A set of `compilexxx` methods;
- each `compilexxx` method implements the right hand side of the grammar rule describing `xxx`

Parser design

Grammar

```
statement: ifStatement |  
          whileStatement |  
          letStatement  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' '  
           '{' statements '}'  
  
whileStatement: 'while' '(' expression ')' '  
                '{' statements '}'  
  
letStatement: 'let' varName '=' expression ';'  
  
expression: term (op term)?  
          term: varName | constant  
varName: a string not beg. with a digit  
constant: a decimal number  
op: '+' | '-' | '=' | '>' | '<'
```

Parsing process

```
class CompilationEngine {  
    ...  
    compileWhileStatement() {  
        eat('while'); code to handle 'while';  
        eat('('); code to handle '(';  
        compileExpression();  
        eat(')'); code to handle ')';  
        ...  
  
        eat(string) {  
            if (currentToken <> string)  
                error...  
            else  
                advance...  
        }  
    }  
}
```

- The code of each `compile xxx` method follows the right-hand side of the rule xxx
- Each `compile xxx` method is responsible for advancing and handling its own part of the input.

LL grammar

Grammar

```
statement: ifStatement |  
          whileStatement |  
          letStatement  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' '  
           '{' statements '}' '  
  
whileStatement: 'while' '(' expression ')' '  
              '{' statements '}' '  
  
letStatement: 'let' varName '=' expression ';' '  
  
expression: term (op term)?  
  
term: varName | constant  
  
varName: a string not beg. with a digit  
  
constant: a decimal number  
  
op: '+' | '-' | '=' | '>' | '<'
```

- LL grammar: can be parsed by a recursive descent parser without backtracking
- $\text{LL}(k)$ parser: a parser that needs to look ahead at most k tokens in order to determine which rule is applicable
- The grammar that we saw so far is $\text{LL}(1)$.

Compiler I / parsing: lecture plan

Parsing:

- Overview
- Tokenizer
- Grammar
- Parse trees
- Parsing process



Parsing Jack programs

- The Jack grammar
- The Jack analyzer
 - Overview
 - Proposed implementation
 - Building the Jack Analyzer

Grammar notation

```
statement: ifStatement |  
          whileStatement |  
          letStatement  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' '  
'{' statements '}'  
  
whileStatement: 'while' '(' expression ')' '  
'{' statements '}'  
  
letStatement: 'let' varName '=' expression ';' '  
  
expression: term (op term)?  
  
term: varName | constant  
  
varName: a string not beg. with a digit  
  
constant: a decimal number  
  
op: '+' | '-' | '=' | '>' | '<'
```

'xxx' : quoted boldface is used to list language tokens that appear verbatim ("terminals");
xxx : Regular typeface represents names of non-terminals;
() : used for grouping;
x | y : indicates that either x or y appear;
x y : indicates that x appears, and then y appears;
x? : indicates that x appears 0 or 1 times;
x* : indicates that x appears 0 or more times.

Jack grammar

Lexical elements:	The Jack language includes five types of terminal elements (tokens):
keyword:	'class' 'constructor' 'function' 'method' 'field' 'static' 'var' 'int' 'char' 'boolean' 'void' 'true' 'false' 'null' 'this' 'let' 'do' 'if' 'else' 'while' 'return'
symbol:	'{' '}' '(' ')' '[' ']' ';' '+' '-' '*' '/' '&' ' ' '<' '>' '=' '~'
integerConstant:	A decimal number in the range 0 .. 32767.
StringConstant	"" A sequence of Unicode characters not including double quote or newline ""
identifier:	A sequence of letters, digits, and underscore ('_') not starting with a digit.
Program structure:	A Jack program is a collection of classes, each appearing in a separate file. The compilation unit is a class. A class is a sequence of tokens structured according to the following context free syntax: class: 'class' className '{' classVarDec* subroutineDec* '}' classVarDec: ('static' 'field') type varName (, varName)* ; type: 'int' 'char' 'boolean' className subroutineDec: ('constructor' 'function' 'method') ('void' type) subroutineName ('parameterList') subroutineBody parameterList: ((type varName) (, type varName)*)? subroutineBody: '{' varDec* statements '}' varDec: 'var' type varName (, varName)* ; className: identifier subroutineName: identifier varName: identifier
Statements:	statements: statement* statement: letStatement ifStatement whileStatement doStatement returnStatement letStatement: 'let' varName ('[expression]')? '=' expression ; ifStatement: 'if' (' expression ') '{' statements '}' ('else' '{' statements '}')? whileStatement: 'while' (' expression ') '{' statements '}' doStatement: 'do' subroutineCall ; ReturnStatement: 'return' expression? ;
Expressions:	expression: term (op term)* term: integerConstant stringConstant keywordConstant varName varName '[' expression '] ' subroutineCall '(' expression ')' unaryOp term subroutineCall: subroutineName '(' expressionList ')' (className varName). subroutineName '(' expressionList ')' expressionList: (expression (, expression)*)? op: '+' '-' '*' '/' '&' ' ' '<' '>' '=' unaryOp: '-' '~' KeywordConstant: 'true' 'false' 'null' 'this'

Jack grammar: lexical elements

The Jack language includes five categories of terminal elements (*tokens*):

keyword: `'class'|'constructor'|'function'|'method'|'field'|'static'|
'var'|'int'|'char'|'boolean'|'void'|'true'|'false'|'null'|'this'|
'let'|'do'|'if'|'else'|'while'|'return'`

symbol: `'{'|'}'|'('|')'|'['|']'|'.'|','|';'|'+'|'-'|'*'|'/'|'&'|' '| '<'|'>'|'='|'~'`

integerConstant: a decimal number in the range 0 ... 32767.

StringConstant `"" a sequence of Unicode characters not including double quote or newline ""`

identifier: a sequence of letters, digits, and underscore ('_') not starting with a digit.

Jack grammar: program structure

A Jack program is a collection of *classes*, each appearing in a separate file, and each compiled separately. Each class is structured as follows:

```
class:      'class' className '{' classVarDec* subroutineDec* '}'
classVarDec: ('static' | 'field') type varName (',' varName)* ';' 
type:       'int' | 'char' | 'boolean' | className
subroutineDec: ('constructor' | 'function' | 'method') ('void' | type) subroutineName
               '(' parameterList ')' subroutineBody
parameterList: ( (type varName) (',' type varName)* )?
subroutineBody: '{' varDec* statements '}'
varDec:      'var' type varName (',' varName)* ';' 
className:   identifier
subroutineName: identifier
varName:    identifier
```

Jack grammar: statements

A Jack program includes *statements*, as follows:

```
statements: statement*
statement: letStatement | ifStatement | whileStatement | doStatement | returnStatement
letStatement: 'let' varName '[' expression ']'? '=' expression ';'
ifStatement: 'if' '(' expression ')' '{' statements '}' ('else' '{' statements '}')?
whileStatement: 'while' '(' expression ')' '{' statements '}'
doStatement: 'do' subroutineCall ';'
returnStatement: 'return' expression? ';'
```

Jack grammar: expressions

A Jack program includes *expressions*, as follows:

```
expression: term (op term)*  
term: integerConstant | stringConstant | keywordConstant | varName |  
varName '[' expression ']' | subroutineCall | '(' expression ')' | unaryOp term  
subroutineCall: subroutineName '(' expressionList ')' |  
( className | varName ) '.' subroutineName '(' expressionList ')' |  
expressionList: (expression (',' expression)* )?  
op: '+' | '-' | '*' | '/' | '&' | '|' | '<' | '>' | '='  
unaryOp: '-' | '~'  
keywordConstant: 'true' | 'false' | 'null' | 'this'
```

End note: parsing

Lexical elements:	The Jack language includes five types of terminal elements (tokens):
keyword:	'class' 'constructor' 'function' 'method' 'field' 'static' 'var' 'int' 'char' 'boolean' 'void' 'true' 'false' 'null' 'this' 'let' 'do' 'if' 'else' 'while' 'return'
symbol:	'{' '}' '(' ')' '[' ']' ';' '+' '-' '*' '/' '&' '!' '<' '>' '=' '~'
integerConstant:	A decimal number in the range 0 .. 32767.
StringConstant:	" " A sequence of Unicode characters not including double quote or newline "
identifier:	A sequence of letters, digits, and underscore ('_') not starting with a digit.
Program structure:	A Jack program is a collection of classes, each appearing in a separate file. The compilation unit is a class. A class is a sequence of tokens structured according to the following context free syntax:
class:	'class' className '{' classVarDec* subroutineDec* '}'
classVarDec:	('static' 'field') type varName (, varName)* ;
type:	'int' 'char' 'boolean' className
subroutineDec:	('constructor' 'function' 'method') ('void' type) subroutineName (parameterList) subroutineBody
parameterList:	((type varName) (, type varName)*)?
subroutineBody:	{' varDec* statements '}
varDec:	'var' type varName (, varName)* ;
className:	identifier
subroutineName:	identifier
varName:	identifier
Statements:	
statements:	statement*
statement:	letStatement ifStatement whileStatement doStatement returnStatement
letStatement:	'let' varName ([' expression ']?) '=' expression ;
ifStatement:	'if' ([' expression ']?) '{' statements '}' ('else' ([' statements '])?)
whileStatement:	'while' ([' expression ']?) '{' statements '}'
doStatement:	'do' subroutineCall ;
ReturnStatement:	'return' expression? ;
Expressions:	
expression:	term (op term)*
term:	integerConstant stringConstant keywordConstant varName varName '[' expression ']' subroutineCall '(' expression ')' unaryOp term
subroutineCall:	subroutineName '(' expressionList ')' (className varName) '.' subroutineName '(' expressionList ')'
expressionList:	(expression (, expression)*)?
op:	'+' '-' '*' '/' '&' '!' '<' '>' '='
unaryOp:	'-' '~'
KeywordConstant:	'true' 'false' 'null' 'this'

Parser's design

- A set of **compilexxx** methods, structured according to the grammar rules defining *xxx*
- Each method outputs some of the parse tree (XML), and advances the input
- The parsing logic of each method follows the right-hand side of the rule that it implements.

End note: parsing expressions

Lexical elements:	The Jack language includes five types of terminal elements (tokens):
keyword:	'class' 'constructor' 'function' 'method' 'field' 'static' 'var' 'int' 'char' 'boolean' 'void' 'true' 'false' 'null' 'this' 'let' 'do' 'if' 'else' 'while' 'return'
symbol:	'()' '()' '[' ']' ';' '+' '-' '*' '/' '&' '!' '<' '>' '=' '~'
integerConstant:	A decimal number in the range 0 .. 32767.
StringConstant:	" " A sequence of Unicode characters not including double quote or newline "
identifier:	A sequence of letters, digits, and underscore ('_') not starting with a digit.
Program structure:	A Jack program is a collection of classes, each appearing in a separate file. The compilation unit is a class. A class is a sequence of tokens structured according to the following context free syntax:
class:	'class' className '{' classVarDec* subroutineDec* '}'
classVarDec:	('static' 'field') type varName (, varName)* ;
type:	'int' 'char' 'boolean' className
subroutineDec:	('constructor' 'function' 'method') ('void' type) subroutineName (parameterList) subroutineBody
parameterList:	((type varName) (, type varName)*)?
subroutineBody:	{ varDec* statements }
varDec:	'var' type varName (, varName)* ;
className:	identifier
subroutineName:	identifier
varName:	identifier
Statements:	
statements:	statement*
statement:	letStatement ifStatement whileStatement doStatement returnStatement
letStatement:	'let' varName ([expression]) ? = expression ;
ifStatement:	'if' (expression) ({ statements }) ('else' ({ statements })) ?
whileStatement:	'while' (expression) ({ statements })
doStatement:	'do' subroutineCall ;
ReturnStatement:	'return' expression? ;
Expressions:	
expression:	term (op term)*
term:	integerConstant stringConstant keywordConstant varName varName [expression] subroutineCall (expression) unaryOp term
subroutineCall:	subroutineName (expressionList) (className varName) . subroutineName (expressionList)
expressionList:	(expression (, expression)*)?
op:	'+' '-' '*' '/' '&' '!' '<' '>' '='
unaryOp:	'-' '~'
KeywordConstant:	'true' 'false' 'null' 'this'

Parser's design

- A set of **compilexxx** methods, structured according to the grammar rules defining *xxx*
- Each method outputs some of the parse tree (XML), and advances the input
- The parsing logic of each method follows the right-hand side of the rule that it implements.

End note: parsing expressions

```
expression: term (op term)*  
term: integerConstant | stringConstant | keywordConstant | varName |  
      varName '[' expression ']' | subroutineCall | '(' expression ')' | unaryOp term  
subroutineCall: subroutineName '(' expressionList ')' |  
               ( className | varName ) '.' subroutineName '(' expressionList ')' |  
expressionList: (expression (',' expression)* )?  
op: '+' | '-' | '*' | '/' | '&' | '|' | '<' | '>' | '='  
unaryOp: '-' | '~'  
keywordConstant: 'true' | 'false' | 'null' | 'this'
```

When the current token is a *varName* (some identifier), it can be the first token in any one of these possibilities:

```
foo  
foo[expression]  
foo.bar(expressionList)  
Foo.bar(expressionList)  
bar(expressionList)
```

To resolve which possibility we are in, the parser should “look ahead”:

- save the current token, and
- advance to get the next one.

This is the only case in the Jack grammar in which the language becomes LL(2) rather than LL(1).

Compiler I / parsing: lecture plan

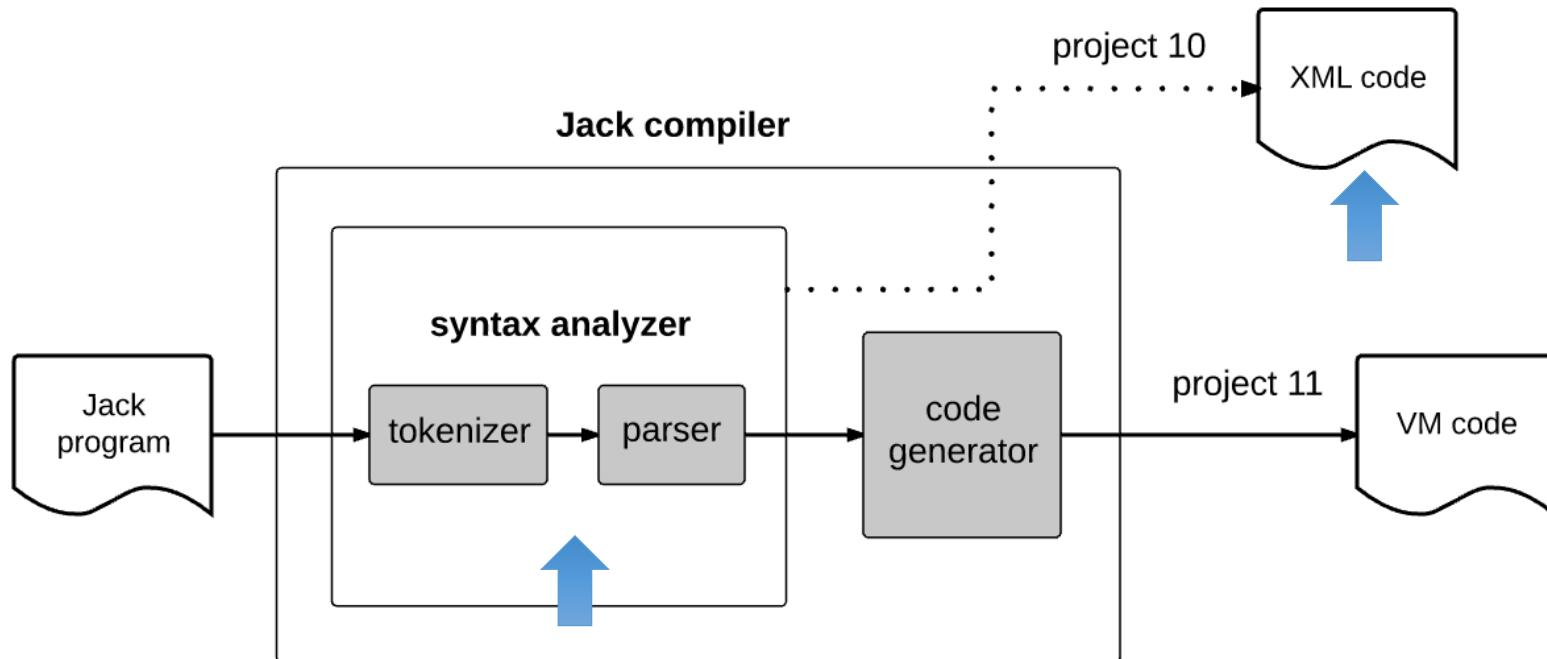
Parsing:

- Overview
- Tokenizer
- Grammar
- Parse trees
- Parsing process

Parsing Jack programs

- The Jack grammar
 - The Jack analyzer
- 
- Overview
 - Proposed implementation
 - Building the Jack Analyzer

Compiler development roadmap



- How can we unit-test that the analyzer “understands” the source code?
- We can have it output the the source code in some structured way

Jack analyzer

input

```
/** Represents a Point. */
class Point {
    ...
    /** Returns the x value */
    method int getx() {
        return x;
    }
    ...
}
```

parser

XML output

```
<class>
    <keyword> class </keyword>
    <identifier> Point </identifier>
    <symbol> { </symbol>
    ...
    <subroutineDec>
        <keyword> method </keyword>
        <keyword> int </keyword>
        <identifier> getx </identifier>
        <symbol> ( </symbol>
        <parameterList>
        </parameterList>
        <symbol> ) </symbol>
        <subroutineBody>
            <symbol> { </symbol>
            <statements>
                <returnStatement>
                    <keyword> return </keyword>
                    <expression>
                        <term>
                            <identifier> x </identifier>
                        </term>
                    </expression>
                    <symbol> ; </symbol>
                </returnStatement>
            </statements>
            <symbol> } </symbol>
        </subroutineBody>
    </subroutineDec>
    ...
    <symbol> } </symbol>
</class>
```

- The parser generates marked-up output
- The mark up creates a textual parse tree
- Generated according to the Jack grammar

Jack grammar

Lexical elements:	The Jack language includes five types of terminal elements (tokens):
keyword:	'class' 'constructor' 'function' 'method' 'field' 'static' 'var' 'int' 'char' 'boolean' 'void' 'true' 'false' 'null' 'this' 'let' 'do' 'if' 'else' 'while' 'return'
symbol:	'{' '}' '(' ')' '[' ']' ';' '+' '-' '*' '/' '&' ' ' '<' '>' '=' '~'
integerConstant:	A decimal number in the range 0 .. 32767.
StringConstant:	"" A sequence of Unicode characters not including double quote or newline ""
identifier:	A sequence of letters, digits, and underscore ('_') not starting with a digit.
Program structure:	A Jack program is a collection of classes, each appearing in a separate file. The compilation unit is a class. A class is a sequence of tokens structured according to the following context free syntax: class: 'class' className '{' classVarDec* subroutineDec* '}' classVarDec: ('static' 'field') type varName (, varName)* ; type: 'int' 'char' 'boolean' className subroutineDec: ('constructor' 'function' 'method') ('void' type) subroutineName ('parameterList') subroutineBody parameterList: ((type varName) (, type varName)*)? subroutineBody: '{' varDec* statements '}' varDec: 'var' type varName (, varName)* ; className: identifier subroutineName: identifier varName: identifier
Statements:	statements: statement* statement: letStatement ifStatement whileStatement doStatement returnStatement letStatement: 'let' varName ('[expression]')? '=' expression ; ifStatement: 'if' (' expression ') '{' statements '}' ('else' '{' statements '}')? whileStatement: 'while' (' expression ') '{' statements '}' doStatement: 'do' subroutineCall ; ReturnStatement: 'return' expression? ;
Expressions:	expression: term (op term)* term: integerConstant stringConstant keywordConstant varName varName '[' expression '] ' subroutineCall '(' expression ')' unaryOp term subroutineCall: subroutineName '(' expressionList ')' (className varName). subroutineName '(' expressionList ')' expressionList: (expression (, expression)*)? op: '+' '-' '*' '/' '&' ' ' '<' '>' '=' unaryOp: '-' '~' KeywordConstant: 'true' 'false' 'null' 'this'

Jack analyzer: handling inputs that correspond to terminal rules

If the parser encounters a *terminalElement* xxx of type
keyword, *symbol*, *integer constant*, *string constant*, or *identifier*,

the parser generates the output:

```
<terminalElement>  
    xxx  
</terminalElement>
```

where *terminalElement* is:

keyword,
symbol,
integerConstant,
stringConstant,
identifier

Examples:

```
<keyword> method </keyword>  
  
<symbol> { </symbol>  
  
<integerConstant> 42 </integerConstant>  
  
<stringConstant> xkcd </stringConstant>  
  
<symbol> { </symbol>
```

Jack analyzer: handling inputs that correspond to non-terminal rules

If the parser encounter a *nonTerminal* element of type *class declaration*, *class variable declaration*, *subroutine declaration*, *parameter list*, *subroutine body*, *variable declaration*, *statements*, *let statement*, *if statement*, *while statement*, *do statement*, *return statement*, *an expression*, *a term*, or *an expression list*,

the parser generates the output:

```
<nonTerminal>
  Recursive output for the non-terminal body
</nonTerminal>
```

where *nonTerminal* is:

```
class, classVarDec, subroutineDec,
parameterList, subroutineBody,
varDec; statements, LetStatement,
ifStatement, whileStatement,
doStatement, returnStatement;
expression, term, expressionList
```

Example: if the input is `return x;`

```
<returnStatement>
  <keyword>
    return
  </keyword>
  <expression>
    <term>
      <identifier> x </identifier>
    </term>
  </expression>
  <symbol> ; </symbol>
</returnStatement>
```

Jack analyzer: handling inputs that correspond to non-terminal rules

If the parser encounter a *nonTerminal* element of type *type, class name, subroutine name, variable name, statement, or subroutine call*,

The parser handles it directly, without recursing.

Example:

Jack grammar:

```
...
letStatement: 'let' varName '=' expression ';'
varName: identifier
identifier: a sequence of letters, digits, ..., not starting with a digit
...
```

Suppose the input is `let x = 17;`

```
<letStatement>
  <keyword> let </keyword>
  <identifier> x </identifier>
  <symbol> = </symbol>
  <expression>
  ...
...
```

varName is handled directly

Compiler I / parsing: lecture plan

Parsing:

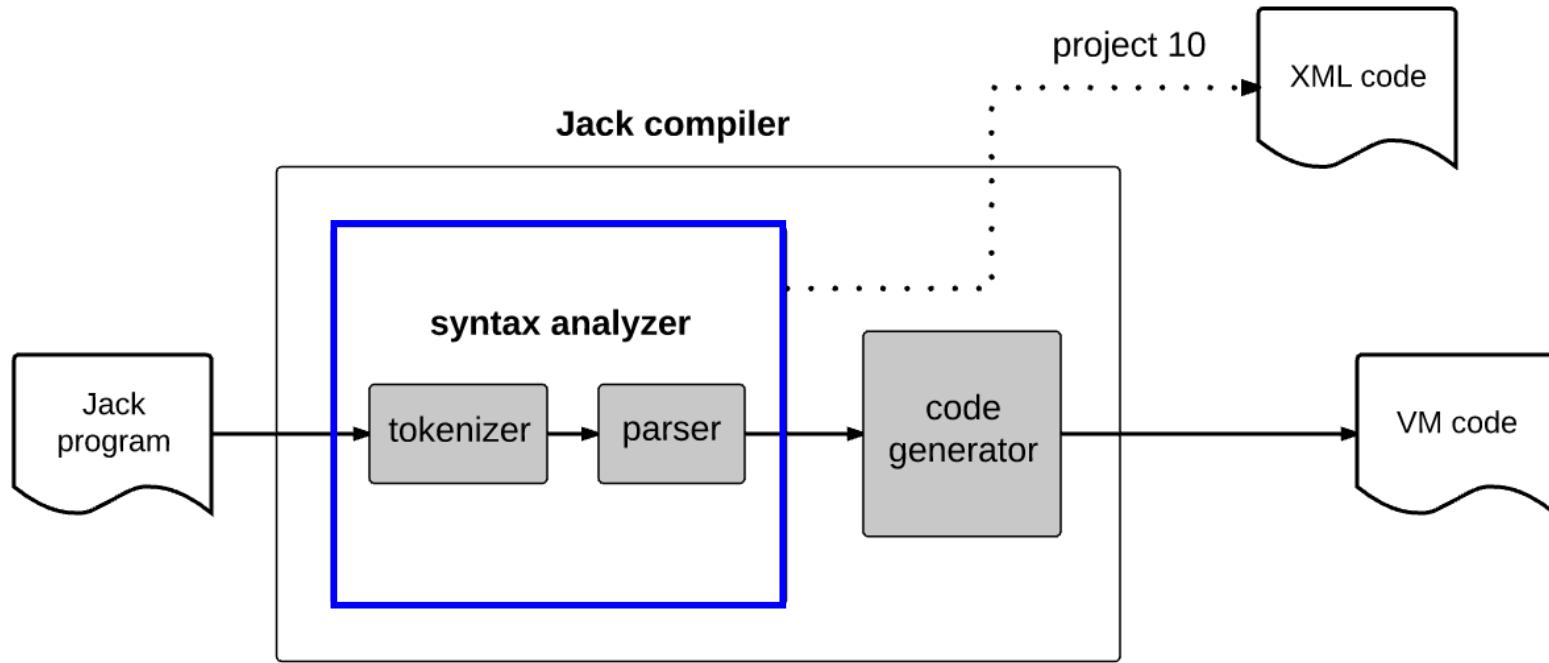
- Overview
- Tokenizer
- Grammar
- Parse trees
- Parsing process

Parsing Jack programs

- The Jack grammar
- The Jack analyzer
 - Overview
- Proposed implementation
- Building the Jack Analyzer



Compiler development roadmap



Implementation plan:

- `JackTokenizer`
- `CompilationEngine`
- `JackAnalyzer` (top-most / main module)

JackAnalyzer: usage

prompt> JackAnalyzer *input*

Input:

- ❑ *fileName.jack*: name of a single source file, or
- ❑ *directoryName*: name of a directory containing one or more .jack source files

Output:

- ❑ if the input is a single file: *fileName.xml*
- ❑ if the input is a directory: one .xml file for every .jack file, stored in the same directory

JackAnalyzer in action

Point.jack

```
/** Represents a Point. */
class Point {
    ...
    /** Returns the x value */
    method int getx() {
        return x;
    }
    ...
}
```

JackAnalyzer

Point.xml

```
<class>
    <keyword> class </keyword>
    <identifier> Point </identifier>
    <symbol> { </symbol>
    ...
    <subroutineDec>
        <keyword> method </keyword>
        <keyword> int </keyword>
        <identifier> getx </identifier>
        <symbol> ( </symbol>
        <parameterList>
        </parameterList>
        <symbol> ) </symbol>
        <subroutineBody>
            <symbol> { </symbol>
            <statements>
                <returnStatement>
                    <keyword> return </keyword>
                    <expression>
                        <term>
                            <identifier> x </identifier>
                        </term>
                    </expression>
                    <symbol> ; </symbol>
                </returnStatement>
            </statements>
            <symbol> } </symbol>
        </subroutineBody>
    </subroutineDec>
    ...
    <symbol> } </symbol>
</class>
```

The JackAnalyzer

- Uses the services of a JackTokenizer
- Written according to the Jack grammar

Jack grammar (guideline for writing the JackAnalyzer)

Lexical elements:	The Jack language includes five types of terminal elements (tokens):
keyword:	'class' 'constructor' 'function' 'method' 'field' 'static' 'var' 'int' 'char' 'boolean' 'void' 'true' 'false' 'null' 'this' 'let' 'do' 'if' 'else' 'while' 'return'
symbol:	'{}()' '[]()' '()' ';' '+' '-' '*' '/' '&' ' ' '<' '>' '=' '~'
integerConstant:	A decimal number in the range 0 .. 32767.
StringConstant	"" A sequence of Unicode characters not including double quote or newline ""
identifier:	A sequence of letters, digits, and underscore ('_') not starting with a digit.
Program structure:	A Jack program is a collection of classes, each appearing in a separate file. The compilation unit is a class. A class is a sequence of tokens structured according to the following context free syntax:
class:	'class' className '{' classVarDec* subroutineDec* '}'
classVarDec:	('static' 'field') type varName (, varName)* ;
type:	'int' 'char' 'boolean' className
subroutineDec:	('constructor' 'function' 'method') ('void' type) subroutineName (parameterList) subroutineBody
parameterList:	((type varName) (, type varName)*)?
subroutineBody:	{ varDec* statements }
varDec:	'var' type varName (, varName)* ;
className:	identifier
subroutineName:	identifier
varName:	identifier
Statements:	
statements:	statement*
statement:	letStatement ifStatement whileStatement doStatement returnStatement
letStatement:	'let' varName '[' expression ']'? '=' expression ;
ifStatement:	'if' '(' expression ')' '{' statements '}' 'else' '{' statements '}'
whileStatement:	'while' '(' expression ')' '{' statements '}'
doStatement:	'do' subroutineCall ;
ReturnStatement	'return' expression? ;
Expressions:	
expression:	term (op term)*
term:	integerConstant stringConstant keywordConstant varName varName '[' expression ']' subroutineCall '(' expression ')' unaryOp term
subroutineCall:	subroutineName '(' expressionList ')' (className varName) '.' subroutineName '(' expressionList ')'
expressionList:	(expression (, expression)*)?
op:	'+' '-' '*' '/' '&' ' ' '<' '>' '='
unaryOp:	'-' '~'
KeywordConstant:	'true' 'false' 'null' 'this'

JackTokenizer

CompilationEngine

JackAnalyzer

input

```
/** Represents a Point. */
class Point {
    ...
    /** Returns the x value */
    method int getx() {
        return x;
    }
    ...
}
```

JackAnalyzer

XML output

```
<class>
    <keyword> class </keyword>
    <identifier> Point </identifier>
    <symbol> { </symbol>
    ...
    <subroutineDec>
        <keyword> method </keyword>
        <keyword> int </keyword>
        <identifier> getx </identifier>
        <symbol> ( </symbol>
        <parameterList>
        </parameterList>
        <symbol> ) </symbol>
        <subroutineBody>
            <symbol> { </symbol>
            <statements>
                <returnStatement>
                    <keyword> return </keyword>
                    <expression>
                        <term>
                            <identifier> x </identifier>
                        </term>
                    </expression>
                    <symbol> ; </symbol>
                </returnStatement>
            </statements>
            <symbol> } </symbol>
        </subroutineBody>
    </subroutineDec>
    ...
    <symbol> } </symbol>
</class>
```

JackTokenizer

input

```
/** Represents a Point. */
class Point {
    ...
    /** Returns the x value */
    method int getx() {
        return x;
    }
    ...
}
```

JackAnalyzer

XML output

```
<keyword> class </keyword>
<identifier> Point </identifier>
<symbol> { </symbol>
...
<keyword> method </keyword>
<keyword> int </keyword>
<identifier> getx </identifier>
<symbol> ( </symbol>

<symbol> ) </symbol>

<symbol> { </symbol>

<keyword> return </keyword>

<identifier> x </identifier>

<symbol> ; </symbol>

<symbol> } </symbol>

...
<symbol> } </symbol>
```

tokens
only

JackTokenizer

input

```
/** Represents a Point. */
class Point {
    ...
    /** Returns the x value */
    method int getx() {
        return x;
    }
    ...
}
```

JackAnalyzer

XML output

```
<keyword> class </keyword>
<identifier> Point </identifier>
<symbol> { </symbol>
...
<keyword> method </keyword>
<keyword> int </keyword>
<identifier> getx </identifier>
<symbol> ( </symbol>
...
```

tokens
only

Jack tokens:

keyword: 'class' | 'constructor' | 'function' | 'method' |
'field' | 'static' | 'var' | 'int' | 'char' | 'boolean'
'void' | 'true' | 'false' | 'null' | 'this' | 'let' | 'do'
'if' | 'else' | 'while' | 'return'

symbol: '{}' | '()' | '[]' | '.' | ',' | ';' | '+' | '-' | '*' |
'/' | '&' | '!' | '<' | '>' | '=' | '~'

integerConstant: a decimal number in the range 0 ... 32767

StringConstant: "" a sequence of Unicode characters,
not including double quote or newline ""

identifier: a sequence of letters, digits, and
underscore ('_') not starting with a digit.

JackTokenizer:

Handles the compiler's input.

Allows:

- Ignoring white space
- Advancing the input, one token at a time
- Getting the *value* and *type* of the *current token*

JackTokenizer

input

```
/** Represents a Point. */
class Point {
    ...
    /** Returns the x value */
    method int getx() {
        return x;
    }
    ...
}
```

JackAnalyzer

XML output

```
<keyword> class </keyword>
<identifier> Point </identifier>
<symbol> { </symbol>
...
<keyword> method </keyword>
<keyword> int </keyword>
<identifier> getx </identifier>
<symbol> ( </symbol>
...
```

tokens
only

Jack tokens:

keyword: 'class' | 'constructor' | 'function' | 'method' |
'field' | 'static' | 'var' | 'int' | 'char' | 'boolean'
'void' | 'true' | 'false' | 'null' | 'this' | 'let' | 'do'
'if' | 'else' | 'while' | 'return'

symbol: '{' | '}' | '(' | ')' | '[' | ']' | '.' | ',' | ';' | '+' | '-' | '*' |
'/' | '&' | '!' | '<' | '>' | '=' | '~'

integerConstant: a decimal number in the range 0 ... 32767

StringConstant: "" a sequence of Unicode characters,
not including double quote or newline ""

identifier: a sequence of letters, digits, and
underscore ('_') not starting with a digit.

JackTokenizer

```
class JackTokenizer {

    // Constructor (code omitted)

    hasMoreTokens()

    advance()

    tokenType()

    ...

}
```

JackTokenizer API

JackTokenizer: Ignores all comments and white space in the input stream, and serializes it into Jack-language tokens. The token types are specified according to the Jack grammar.

Routine	Arguments	Returns	Function
Constructor	input file / stream		Opens the input .jack file and gets ready to tokenize it.
hasMoreTokens	—	boolean	Are there more tokens in the input?
advance	—		Gets the next token from the input, and makes it the current token. This method should be called only if hasMoreTokens is true. Initially there is no current token.
tokenType	—	KEYWORD, SYMBOL, IDENTIFIER, INT_CONST, STRING_CONST	Returns the type of the current token, as a constant.

JackTokenizer API

JackTokenizer: Ignores all comments and white space in the input stream, and serializes it into Jack-language tokens. The token types are specified according to the Jack grammar.

Routine	Arguments	Returns	Function
keyword	—	CLASS, METHOD, FUNCTION, CONSTRUCTOR, INT, BOOLEAN, CHAR, VOID, VAR, STATIC, FIELD, LET, DO, IF, ELSE, WHILE, RETURN, TRUE, FALSE, NULL, THIS	Returns the keyword which is the current token, as a constant. This method should be called only if <code>tokenType</code> is KEYWORD.
symbol	—	char	Returns the character which is the current token. Should be called only if <code>tokenType</code> is SYMBOL.
identifier	—	string	Returns the identifier which is the current token. Should be called only if <code>tokenType</code> is IDENTIFIER.
intVal	—	int	Returns the integer value of the current token. Should be called only if <code>tokenType</code> is INT_CONST.
stringVal	—	string	Returns the string value of the current token, without the two enclosing double quotes. Should be called only if <code>tokenType</code> is STRING_CONST.

Jack grammar

Lexical elements:	The Jack language includes five types of terminal elements (tokens):
keyword:	'class' 'constructor' 'function' 'method' 'field' 'static' 'var' 'int' 'char' 'boolean' 'void' 'true' 'false' 'null' 'this' 'let' 'do' 'if' 'else' 'while' 'return'
symbol:	'(' ')' '[' ']' '.' ';' '+' '-' '*' '/' '&' '!' '<' '>' '=' '~'
integerConstant:	A decimal number in the range 0 .. 32767.
StringConstant	"" A sequence of Unicode characters not including double quote or newline ""
identifier:	A sequence of letters, digits, and underscore ('_') not starting with a digit.
Program structure:	A Jack program is a collection of classes, each appearing in a separate file. The compilation unit is a class. A class is a sequence of tokens structured according to the following context free syntax:
class:	'class' className '{' classVarDec* subroutineDec* '}'
classVarDec:	('static' 'field') type varName (, varName)* ;
type:	'int' 'char' 'boolean' className
subroutineDec:	('constructor' 'function' 'method') ('void' type) subroutineName (parameterList) subroutineBody
parameterList:	((type varName) (, type varName)*)?
subroutineBody:	{ varDec* statements }
varDec:	'var' type varName (, varName)* ;
className:	identifier
subroutineName:	identifier
varName:	identifier
Statements:	
statements:	statement*
statement:	letStatement ifStatement whileStatement doStatement returnStatement
letStatement:	'let' varName ('[' expression ']')? '=' expression ;
ifStatement:	'if' ('expression') '{' statements '}' ('else' '{' statements '}')
whileStatement:	'while' ('expression') '{' statements '}'
doStatement:	'do' subroutineCall ;
ReturnStatement	'return' expression? ;
Expressions:	
expression:	term (op term)*
term:	integerConstant stringConstant keywordConstant varName varName '[' expression ']' subroutineCall '(' expression ')' unaryOp term
subroutineCall:	subroutineName '(' expressionList ')' (className varName) '.' subroutineName '(' expressionList ')'
expressionList:	(expression (, expression)*)?
op:	'+' '-' '*' '/' '&' '!' '<' '>' '='
unaryOp:	'-' '~'
KeywordConstant:	'true' 'false' 'null' 'this'

Tokenizer



CompilationEngine

CompilationEngine design

Grammar

```
...  
  
statement: ifStatement |  
          whileStatement |  
          letStatement | ...  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' '  
'{ statements '}'  
  
whileStatement: 'while' '(' expression ')' '  
'{ statements '}'  
  
...
```

CompilationEngine

```
class CompilationEngine {
```

- Gets its input from a `JackTokenizer`, and emits its output to an output file

CompilationEngine design

Grammar

```
...
statement: ifStatement |
           whileStatement |
           letStatement | ...
statements: statement*
ifStatement: 'if' '(' expression ')'
           '{' statements '}'
whileStatement: 'while' '(' expression ')'
               '{' statements '}'
...
...
```

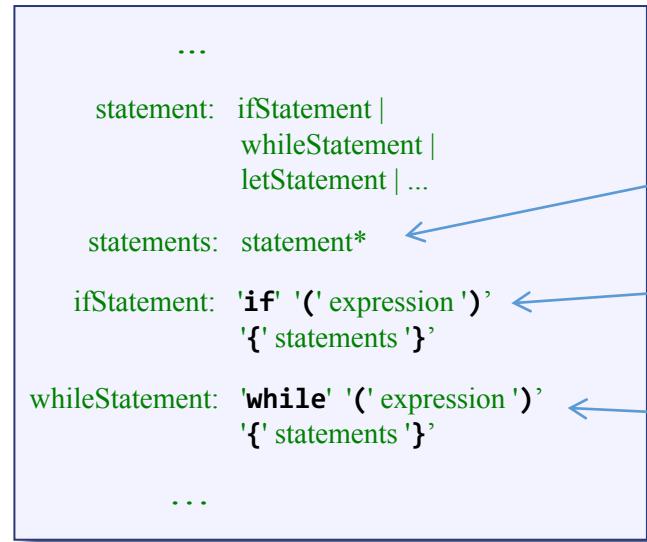
CompilationEngine

```
class CompilationEngine {
    // Constructor (code omitted)
```

- Gets its input from a `JackTokenizer`, and emits its output to an output file

CompilationEngine design

Grammar



CompilationEngine

```
class CompilationEngine {  
    // Constructor (code omitted)  
    compileStatements() {  
        // code for compiling statements  
    }  
    compileIfStatement() {  
        // code for compiling an if statement  
    }  
    compileWhileStatement() {  
        // code for compiling an while statement  
    }  
    ...  
}
```

- Gets its input from a `JackTokenizer`, and emits its output to an output file
- The output is generated by a series of `compilexxx` routines, structured according to the grammar rules that define `xxx`
- Each `compilexxx` routine is responsible for handling all the tokens that make up `xxx`, advancing the tokenizer exactly beyond these tokens, and outputting the parsing of `xxx`

CompilationEngine API

`CompilationEngine`: generates the compiler's output.

Routine	Arguments	Returns	Function
Constructor	Input stream/file Output stream/file		Creates a new compilation engine with the given input and output. The next routine called must be <code>compileClass</code> .
<code>CompileClass</code>	—	—	Compiles a complete class.
<code>CompileClassVarDec</code>	—	—	Compiles a static variable declaration, or a field declaration.
<code>CompileSubroutineDec</code>	—	—	Compiles a complete method, function, or constructor.
<code>compileParameterList</code>	—	—	Compiles a (possibly empty) parameter list. Does not handle the enclosing “()”.
<code>compileSubroutineBody</code>	—	—	Compiles a subroutine’s body.
<code>compileVarDec</code>	—	—	Compiles a <code>var</code> declaration.
<code>compileStatements</code>	—	—	Compiles a sequence of statements. Does not handle the enclosing “{}”.

CompilationEngine API

`CompilationEngine`: generates the compiler's output.

Routine	Arguments	Returns	Function
<code>compileLet</code>	—	—	Compiles a <code>let</code> statement.
<code>compileIf</code>	—	—	Compiles an <code>if</code> statement, possibly with a trailing <code>else</code> clause.
<code>compileWhile</code>	—	—	Compiles a <code>while</code> statement.
<code>compileDo</code>	—	—	Compiles a <code>do</code> statement.
<code>compileReturn</code>	—	—	Compiles a <code>return</code> statement.

CompilationEngine API

CompilationEngine: generates the compiler's output.

Routine	Arguments	Returns	Function
CompileExpression	--	--	Compiles an expression.
CompileTerm	--	--	Compiles a <i>term</i> . If the current token is an <i>identifier</i> , the routine must distinguish between a <i>variable</i> , an <i>array entry</i> , or a <i>subroutine call</i> . A single look-ahead token, which may be one of “[”, “(“, or “.”, suffices to distinguish between the possibilities. Any other token is not part of this term and should not be advanced over.
CompileExpressionList	--	--	Compiles a (possibly empty) comma-separated list of expressions.

CompilationEngine (end-note)

The following rules in the Jack grammar have no corresponding `compilexxx` methods:

- *type*
- *className*
- *subroutineName*
- *variableName*
- *statement*
- *subroutineCall*



the parsing logic of these rules is handled by the rules that invoke them

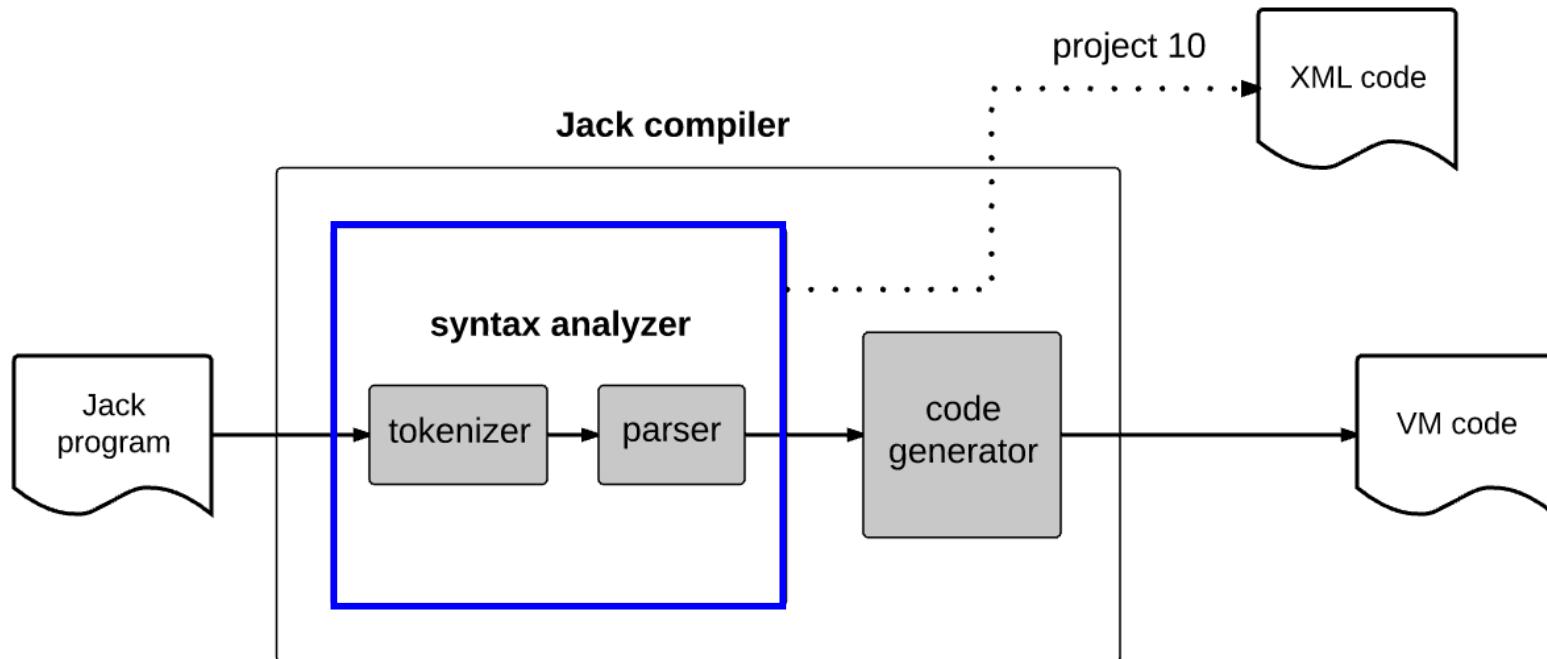
Example:

```
...
statement: ifStatement |  
          whileStatement |  
          letStatement | ...  
  
statements: statement*  
  
ifStatement: 'if' '(' expression ')' '  
           {' statements '}'  
  
whileStatement: 'while' '(' expression ')' '  
             {' statements '}'  
  
...
```

compileStatements:

- Uses a loop to handle 0 or more *statement* instances, according to the left-most token
- If the left-most token is "if", "while", ... it invokes `compileIf`, `compileWhile`, ...
- There is no `compileStatement` method

Recap



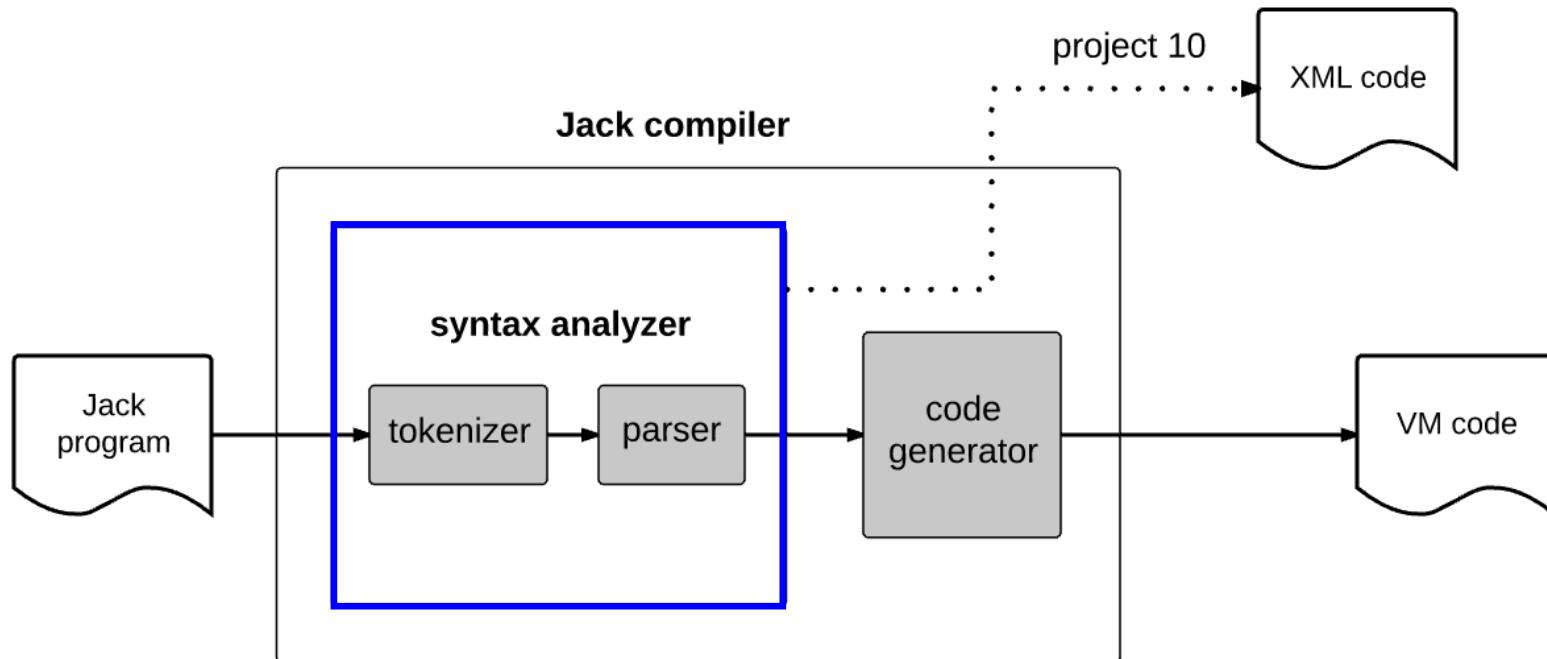
Implementation plan:

- ✓ **JackTokenizer**
- ✓ **CompilationEngine**
 - **JackAnalyzer** (top-most module)

JackAnalyzer

- The top-most / main module
- Input: a single `fileName.jack`, or a directory containing 0 or more such files
- For each file, goes through the following logic:
 1. Creates a `JackTokenizer` from `fileName.jack`
 2. Creates an output file named `fileName.xml` and prepares it for writing
 3. Creates and uses a `compilationEngine` to compile the input `JackTokenizer` into the output file.

Recap



Implementation plan:

- ✓ **JackTokenizer**
- ✓ **CompilationEngine**
- ✓ **JackAnalyzer** (top-most module)

Compiler I / parsing: lecture plan

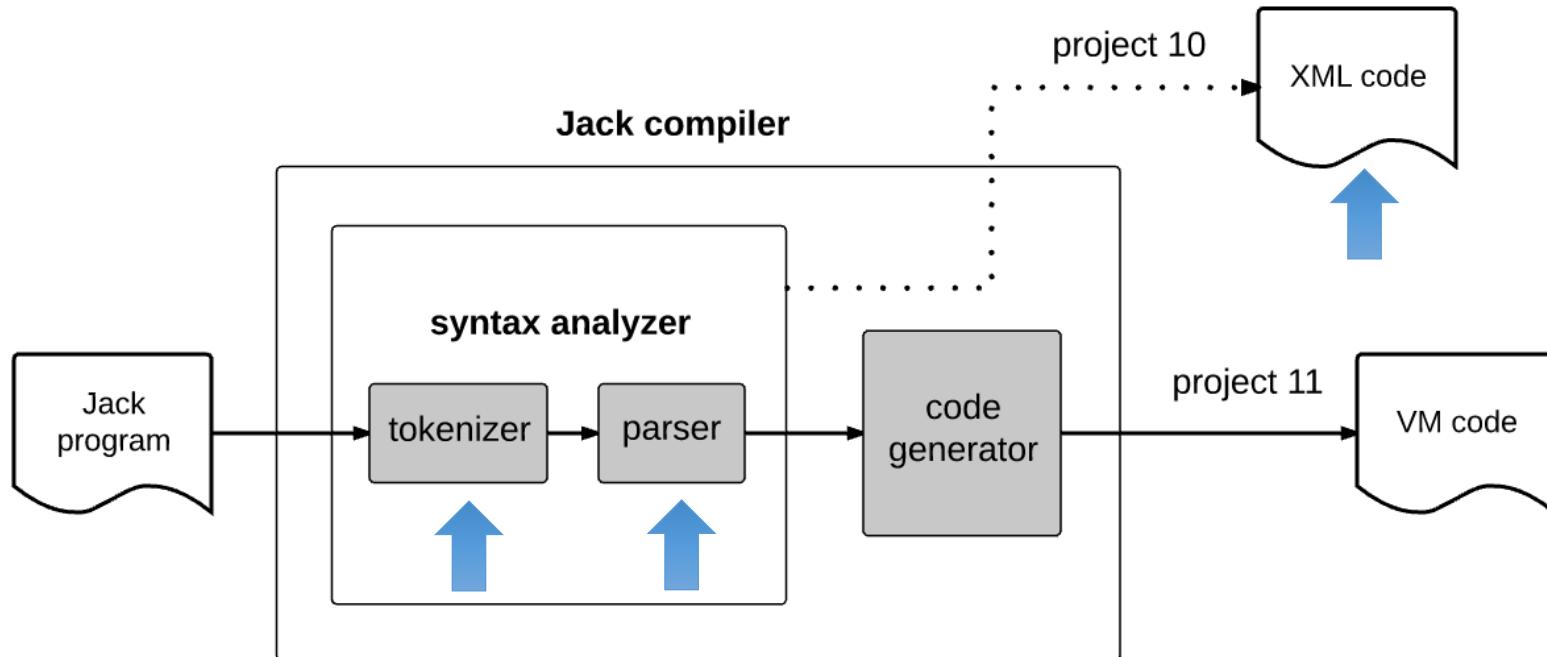
Parsing:

- Overview
- Tokenizer
- Grammar
- Parse trees
- Parsing process

Parsing Jack programs

- The Jack grammar
- The Jack analyzer
 - Overview
 - Proposed implementation
- • Building the Jack Analyzer

Goal: develop a syntax analyzer for the Jack language



Goal: develop a syntax analyzer for the Jack language

Contract:

- Implement a syntax analyzer for the Jack language
- Use it to parse all the supplied test .jack class files
- For each test .jack file, your analyzer should generate an .xml output file, identical to the supplied compare file.

Tools and resources:

- Test programs and compare files: [nand2tetris/projects/10](#)
- TextComparer: [nand2tetris/tools](#)
- XML file viewer: browser, text editor, ...
- Programming language: Java, Python, ...
- Reference: chapter 10 in *The Elements of Computing Systems*

Implementation plan

- Build a Jack Tokenizer
- Build a compilation engine
(a Jack analyzer that makes use of the Tokenizer's services):
 - Basic version
 - Complete version

Jack tokenizer

TestClass.jack

```
...  
if (x < 0) {  
    let sign = "negative";  
}  
...
```

tokenizer

TestClassT.xml

```
<tokens>  
    <keyword> if </keyword>  
    <symbol> ( </symbol>  
    <identifier> x </identifier>  
    <symbol> &lt; </symbol>  
    <integerConstant> 0 </integerConstant>  
    <symbol> ) </symbol>  
    <symbol> { </symbol>  
    <keyword> let </keyword>  
    <identifier> sign </identifier>  
    <symbol> = </symbol>  
    <stringConstant> negative </stringConstant>  
    <symbol> ; </symbol>  
    <symbol> } </symbol>  
</tokens>
```

string constants are outputted
without the double-quotes

<, >, ", and & are outputted as
<, >, ", and &

Implementation tips:

Implement the Tokenizer API (described earlier)

You may use class library services (e.g. for handling strings etc.)

Jack analyzer

TestClass.jack

```
...  
let x = x * (x + 1);  
...
```

tokenizer

TestClass.xml

```
...  
<letStatement>  
  <keyword> let </keyword>  
  <identifier> x </identifier>  
  <symbol> = </symbol>  
  <expression>  
    <term>  
      <identifier> x </identifier>  
    </term>  
    <symbol> * </symbol>  
    <term>  
      <symbol> ( </symbol>  
    <expression>  
      <term>  
        <identifier> x </identifier>  
      </term>  
      <symbol> * </symbol>  
      <term>  
        <integerConstant> 1 </integerConstant>  
      </term>  
    </expression>  
    <symbol> ) </symbol>  
  </term>  
</expression>  
  <symbol> ; </symbol>  
</letStatement>  
...
```

Implementation:

- Build a basic `CompilationEngine` that handles everything except expressions
- Add the handling of expressions
(we supply test files to unit-test both stages)

Sample test class file

projects/10/Square/Square.jack

```
class Square {  
  
    field int x, y;    // location on the screen  
    field int size;    // The size of the square  
    ...  
    // Increments the square size by 2.  
    method void incSize() {  
        if (((y + size) < 254) & ((x + size) < 510)) {  
            do erase();  
            let size = size + 2;  
            do draw();  
        }  
        return;  
    }  
    ...  
    // Moves the square up by 2 pixels.  
    method void moveUp() {  
        if (y > 1) {  
            do Screen.setColor(false);  
            do Screen.drawRectangle(x, (y + size) - 1, x + size, y + size);  
            let y = y - 2;  
            do Screen.setColor(true);  
            do Screen.drawRectangle(x, y, x + size, y + 1);  
        }  
        return;  
    }  
    // More Square methods  
}
```

Sample test class file (expressions highlighted)

projects/10/Square/Square.jack

```
class Square {  
  
    field int x, y;    // location on the screen  
    field int size;    // The size of the square  
    ...  
    // Increments the square size by 2.  
    method void incSize() {  
        if (((y + size) < 254) & ((x + size) < 510)) {  
            do erase();  
            let size = size + 2;  
            do draw();  
        }  
        return;  
    }  
    ...  
    // Moves the square up by 2 pixels.  
    method void moveUp() {  
        if (y > 1) {  
            do Screen.setColor(false);  
            do Screen.drawRectangle(x, (y + size) - 1, x + size, y + size);  
            let y = y - 2;  
            do Screen.setColor(true);  
            do Screen.drawRectangle(x, y, x + size, y + 1);  
        }  
        return;  
    }  
    // More Square methods  
}
```

Sample test class file (expressionless version)

projects/10/Square/Square.jack

```
class Square {  
  
    field int x, y;    // location  
    field int size;    // The size  
    ...  
    // Increments the square size  
    method void incSize() {  
        if (((y + size) < 254) & ((  
            do erase();  
            let size = size + 2;  
            do draw();  
        })  
        return;  
    }  
    ...  
    // Moves the square up by 2 pixels  
    method void moveUp() {  
        if (y > 1) {  
            do Screen.setColor(false)  
            do Screen.drawRectangle(  
                let y = y - 2;  
                do Screen.setColor(true)  
                do Screen.drawRectangle(  
            })  
            return;  
        }  
        // More Square methods  
    }  
}
```

projects/10/ExpressionLessSquare/Square.jack

```
class Square {  
  
    field int x, y;    // location on the screen  
    field int size;    // The size of the square  
    ...  
    // Increments the square size by 2.  
    method void incSize() {  
        if (x) {  
            do erase();  
            let size = size;  
            do draw();  
        }  
        return;  
    }  
    ...  
    // Moves the square up by 2 pixels.  
    method void moveUp() {  
        if (y) {  
            do Screen.setColor(x);  
            do Screen.drawRectangle(x, y, x, y);  
            let y = y;  
            do Screen.setColor(x);  
            do Screen.drawRectangle(x, y, x, y);  
        }  
        return;  
    }  
    // More Square methods  
}
```

Purpose:
tests the analyzer's
ability to parse
everything except
expressions.

Basic Jack analyzer

Main.jack (expressionless)

```
...  
let x = x;  
...
```

tokenizer

Main.xml

```
...  
<letStatement>  
  <keyword> let </keyword>  
  <identifier> x </identifier>  
  <symbol> = </symbol>  
  <expression>  
    <term>  
      <identifier> x </identifier>  
    </term>  
  </expression>  
  <symbol> ; </symbol>  
</letStatement>  
...
```

The expressionless code
is meaningless, but is
grammatically valid

Implementation plan

- Build a Jack Tokenizer
- Build a compilation engine
(a Jack analyzer that makes use of the Tokenizer's services):
 - Basic version (handles everything except expressions)
 - □ Complete version (handles everything)

Reminder: handling expressions

```
expression: term (op term)*  
term: integerConstant | stringConstant | keywordConstant | varName |  
varName '[' expression ']' | subroutineCall | '(' expression ')' | unaryOp term  
subroutineCall: subroutineName '(' expressionList ')' |  
( className | varName ) '.' subroutineName '(' expressionList ')' |  
expressionList: (expression (',' expression)* )?  
op: '+' | '-' | '*' | '/' | '&' | '|' | '<' | '>' | '='  
unaryOp: '-' | '~'  
keywordConstant: 'true' | 'false' | 'null' | 'this'
```

- When the current token is a *varName* (some identifier), it can be either a variable name, an array entry, or a subroutine call
- To resolve which possibility we are in, the parser should “look ahead”: save the current token, and advance to get the next one.

Reminder: handling expressions

```
expression: term (op term)*  
term: integerConstant | stringConstant | keywordConstant | varName |  
      varName '[' expression ']' | subroutineCall | '(' expression ')' | unaryOp term  
subroutineCall: subroutineName '(' expressionList ')' |  
               ( className | varName ) '.' subroutineName '(' expressionList ')' |  
expressionList: (expression (',' expression)* )?  
op: '+' | '-' | '*' | '/' | '&' | '|' | '<' | '>' | '='  
unaryOp: '-' | '~'  
keywordConstant: 'true' | 'false' | 'null' | 'this'
```

- When the current token is a *varName* (some identifier), it can be either a variable name, an array entry, or a subroutine call
- To resolve which possibility we are in, the parser should “look ahead”: save the current token, and advance to get the next one
- There is no `compileSubroutineCall` method;
rather, the subroutine call logic is handled in `compileTerm`

The ArrayTest class

Main.jack

```
/** Computes the average of a sequence of integers. */
class Main {
    function void main() {
        var Array a;
        var int length;
        var int i, sum;

        let length = Keyboard.readInt("HOW MANY NUMBERS? ");
        let a = Array.new(length);
        let i = 0;

        while (i < length) {
            let a[i] = Keyboard.readInt("ENTER THE NEXT NUMBER: ");
            let i = i + 1;
        }

        let i = 0;  let sum = 0;

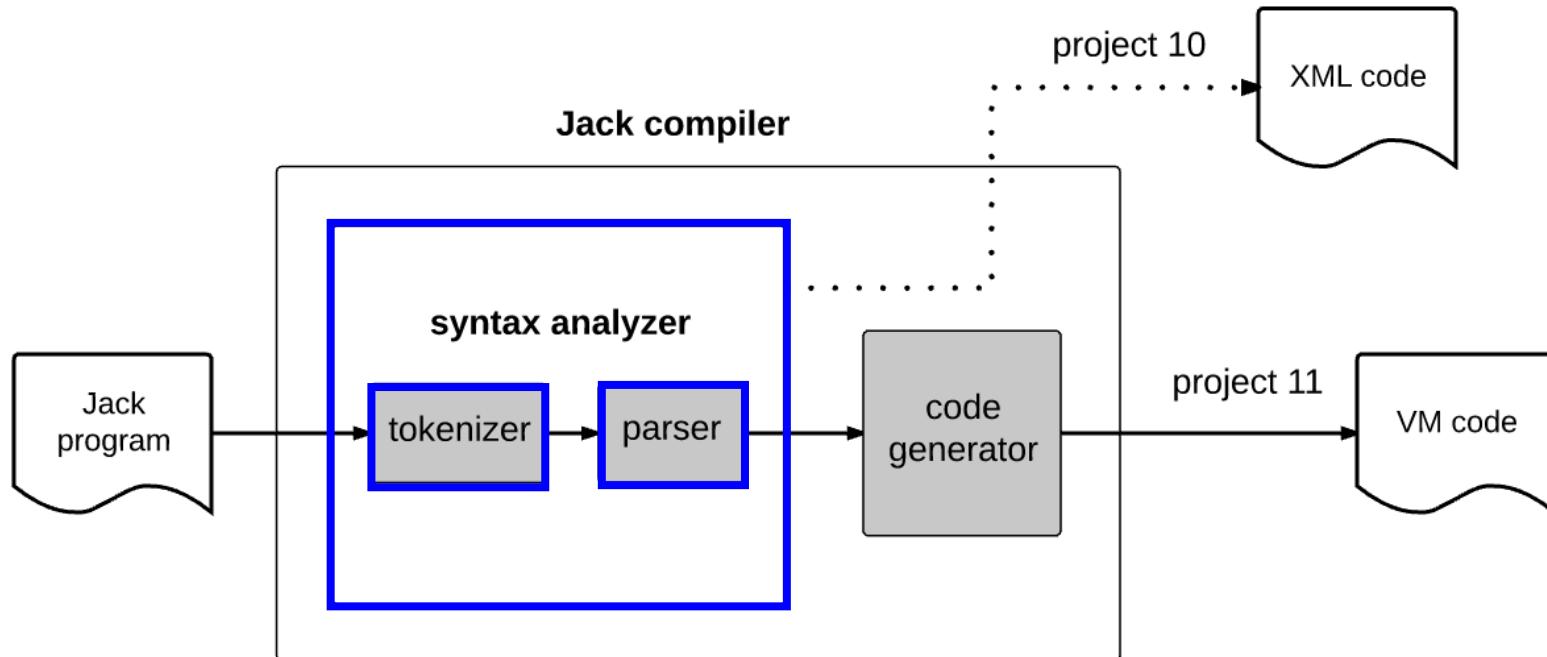
        while (i < length) {
            let sum = sum + a[i];
            let i = i + 1;
        }

        do Output.printString("THE AVERAGE IS: ");
        do Output.printInt(sum / length);
        do Output.println();
        return;
    }
}
```

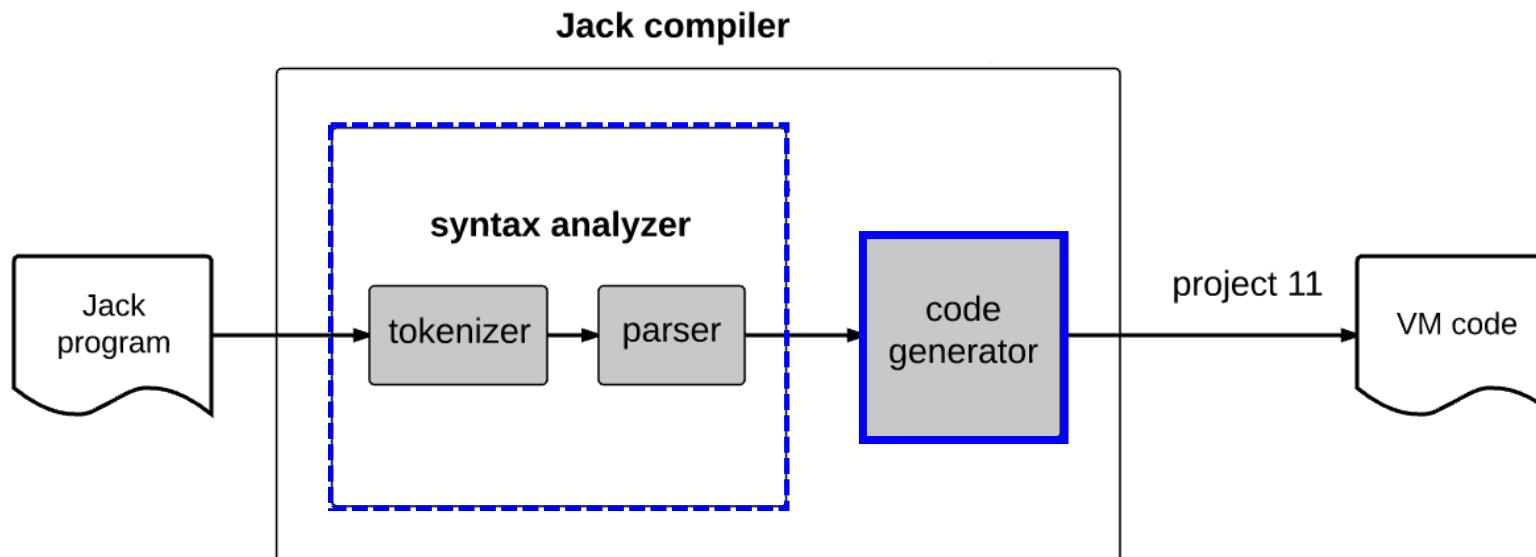
Purpose:

Tests the analyzer's ability to handle array processing code.

Compiler's development roadmap (project 10)



Compiler's development roadmap (project 11)



Perspective

Errors

- Detection
- Handling
- Reporting

Parsing strategies

- Top-down
- Bottom-up

Parsing applications

- Compilation
- Linguistics
- Natural language processing
- Bioinformatics
- Financial services
- ...

Parsing tools

- LEX / YACC
- Why didn't we use them?