Lecture 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, 2021

Compilation: One tier

high-level program

```
/** Creates and uses 2D points. */
class Main {
  function void main() {
     var Point p1, p2, p3;
     let p1 = Point.new(1,2);
     let p2 = Point.new(3,4);
     // Prints p1+p2
     let p3 = p1.plus(p2);
     do p3.print();
     do Output.println();
     // Prints distance(p1,p3)
     do Output.printInt(p1.distance(p3));
     return;
  }
}
```

```
/** Represents a 2D 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
```

machine code

```
      ...
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111110000010000
0000000000010001
      ...
```

Compilation: Two tier

high-level program

```
/** Creates and uses 2D points. */
class Main {
  function void main() {
     var Point p1, p2, p3;
     let p1 = Point.new(1,2);
     let p2 = Point.new(3,4);
     // Prints p1+p2
     let p3 = p1.plus(p2);
     do p3.print();
     do Output.println();
     // Prints distance(p1,p3)
     do Output.printInt(p1.distance(p3));
     return;
  }
}
```

```
/** Represents a 2D 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

projects 10-11

VM code

```
function Main.main 0
   push constant 1
   push constant 2
   call Point.new 2
   pop local 0
   push constant 3
   push constant 4
   call Point.new 2
   pop local 1
   push local 0
   push local 2
   call Point.plus 2
   pop local 2
   push local 2
   cal
   pop
   ...
```

```
function Point.new 0
  push constant 2
  call Memory.alloc 1
  pop pointer 0
  push argument 0
  pop this 0
  push argument 1
  pop this 1
  push static 0
  push constant 1
  add
  pop static 0
  push pointer 0
  return
...
```

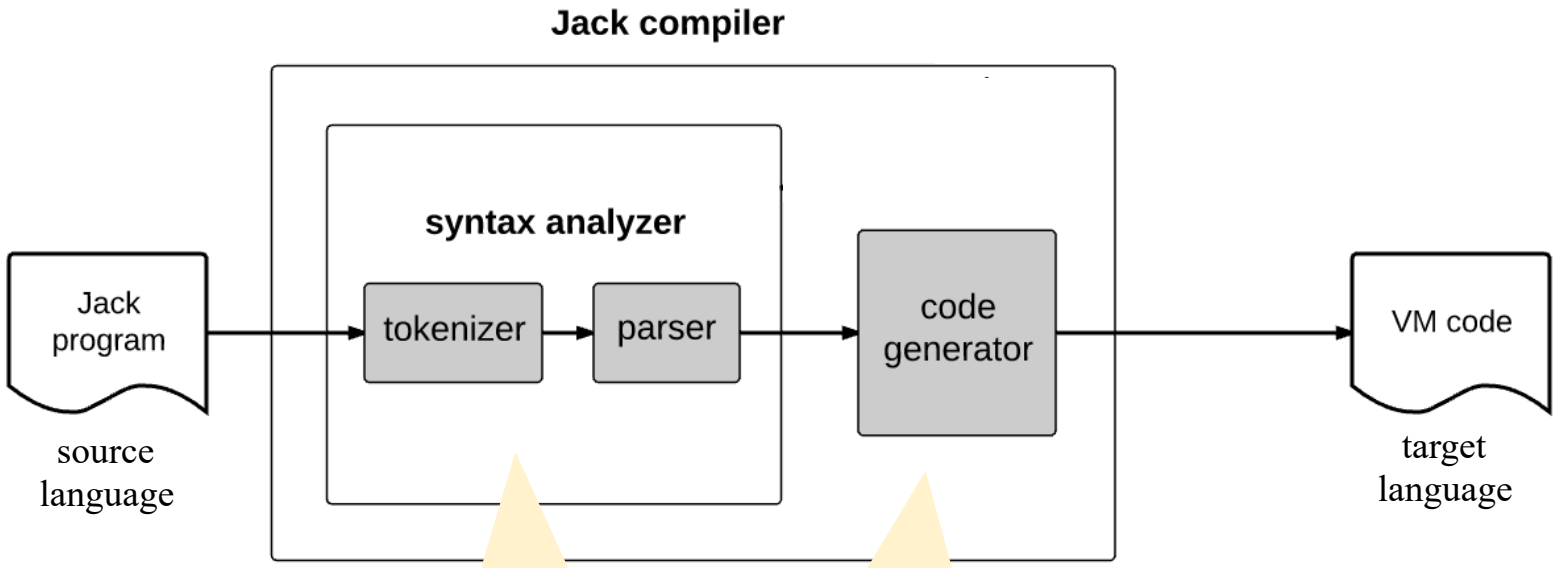
VM translator

projects 7-8

machine code

```
        ...
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
0000000000010000
1110111111001000
0000000000010001
1110101010001000
0000000000010000
1111110000010000
0000000000000000
1111010011010000
0000000000010010
1110001100000001
0000000000010000
1111110000010000
0000000000010001
1111110000010000
0000000000010001
        ...
```

Compiler development roadmap



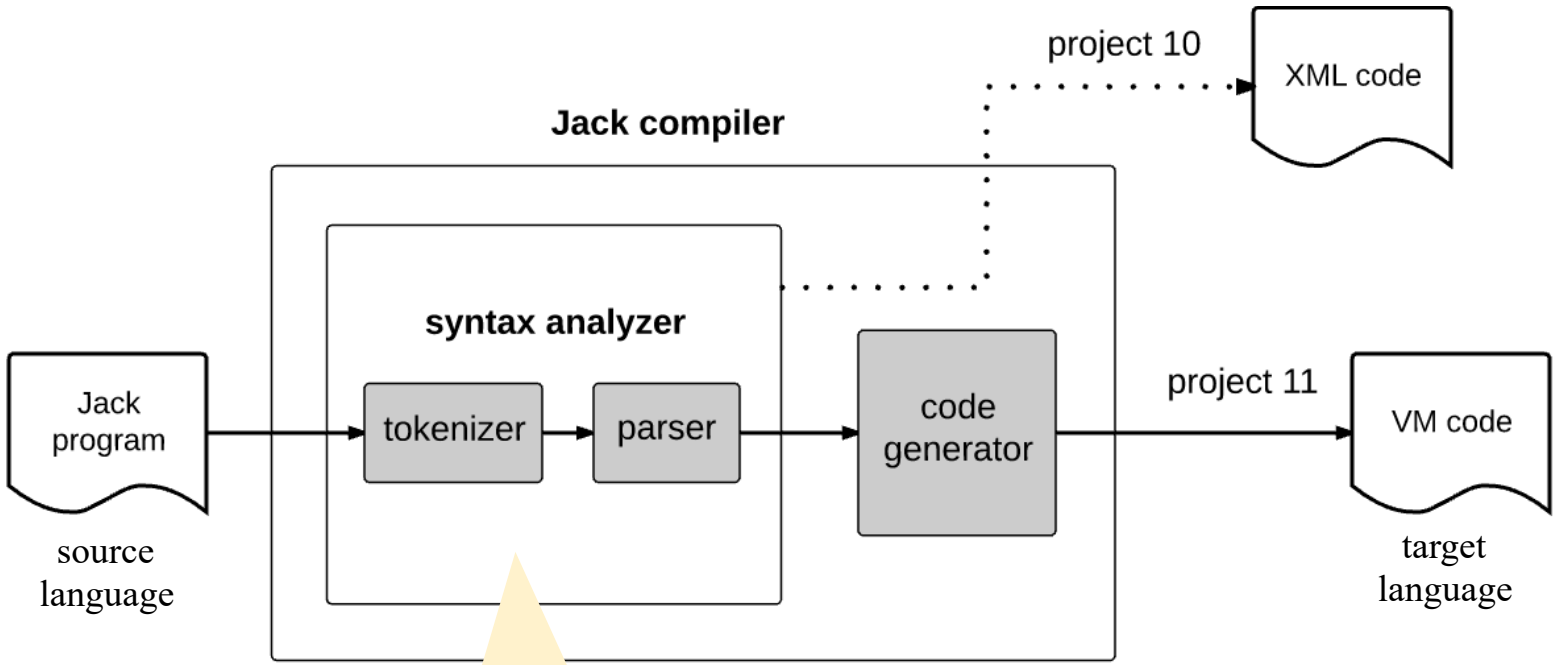
Understanding / parsing the semantics of the *source code*

project 10

Expressing the parsed semantics using the *target language*

project 11

Compiler development roadmap



Understanding / parsing the semantics of the *source code*

project 10

In project 10 we "only" parse the source code, without generating VM code;

To unit-test that the syntax analyzer parses correctly, we'll have it generate XML code that represents the source code semantics.

Compiler I / Syntax Analysis

Take home lessons

- Grammars
- Tokenizing
- Parsing
- XML / mark-up
- Handling structured data files

Applications

- Compilation
- Computational linguistics
- Natural language processing
- Communications
- Bioinformatics
- Fintech
- Blockchain
- Generative AI
- ...

Lecture plan

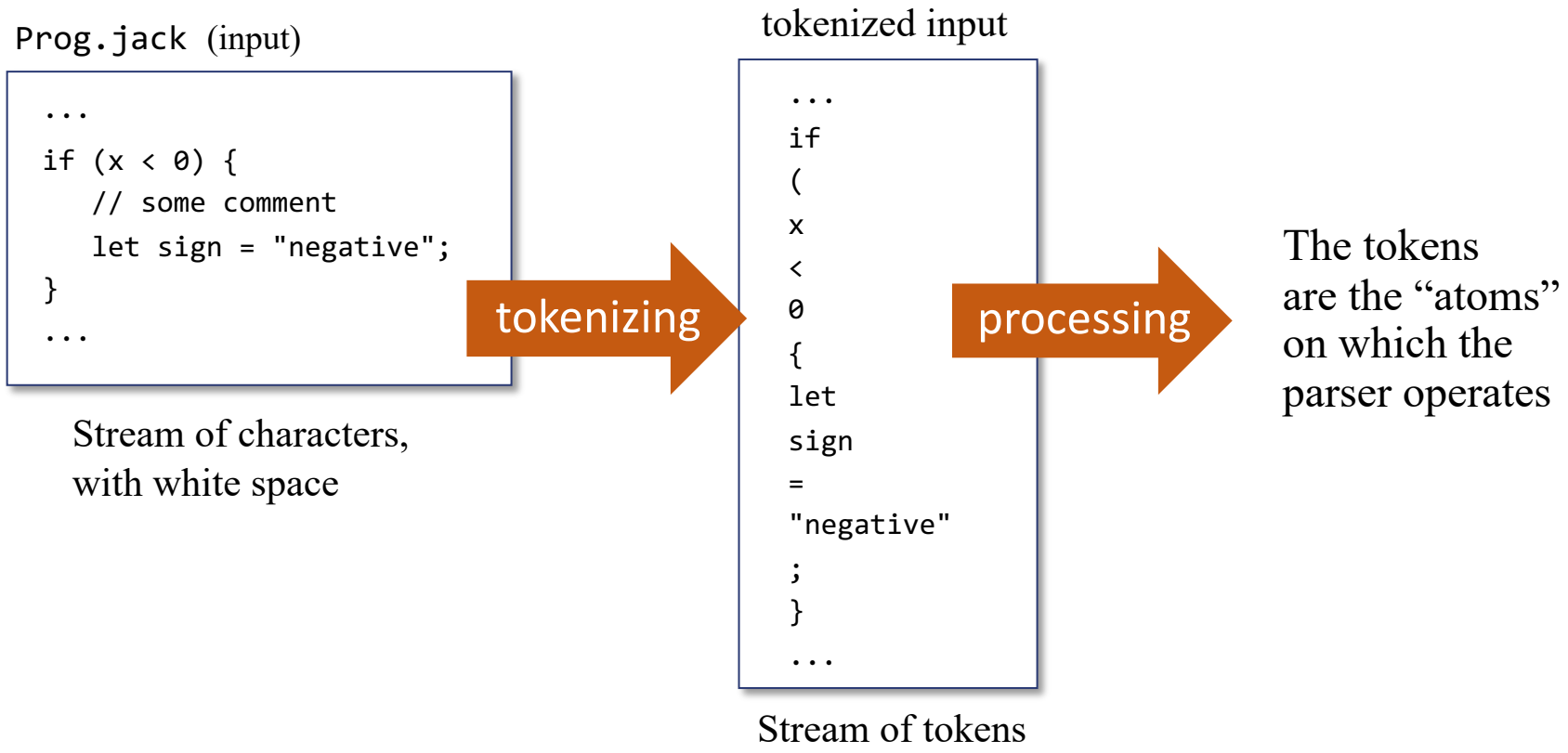
Syntax analysis

- Overview
- Tokenizing
- Grammar
- Parsing

Building a syntax analyzer

- Software design
- The Jack grammar
- The Jack analyzer
  - Overview
  - Implementation
  - Project 10

Tokenizing



Tokenizing: facilitates access to an input stream, one token at a time

Lexicon: set of valid tokens.

Tokenizing

`Prog.jack` (input)

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

Jack lexicon:

- keywords
- symbols
- integers
- strings
- identifiers

Tokenizing

`Prog.jack` (input)

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

Jack lexicon:

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 characters '"'
(not including double quote or newline)

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

Tokenizing

`Prog.jack` (input)

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

JackAnalyzer (V.0)

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>
...
```

Jack lexicon:

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 characters '"'
(not including double quote or newline)

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

JackAnalyzer (version 0):

Using the services of a `JackTokenizer`, prints the list of tokens in a given input file, and their types.

Tokenizing

Prog.jack (input)

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

JackAnalyzer (V.0)

output

```
...
<keyword>     if        </keyword>
<symbol>      (         </symbol>
<identifier>  x         </identifier>
<symbol>      <         </symbol>
<intConst>    0         </intConst>
...
```

```
JackTokenizer {  // API  (details: later)

   // Constructs a tokenizer
   JackTokenizer(filename)

   // Checks if there are more lines to process
   boolean hasMoreTokens()

   // Gets the current token and advances the input
   void advance()

   // Returns the type of the current token
   String tokenType()
   ...
}
```

```
// Version 0: Designed to test the JackTokenizer
JackAnalyzer {
   tknzr = new JackTokenizer("Prog.jack")
   tknzr.advance();  // gets the first token
   while tknzr.hasMoreTokens() {
      tokenType = type of the current token
      print "<" + tokenType + ">"
      print the current token
      print "</" + tokenType + ">"
      print newLine
      tknzr.advance();
   }
}
```

(pseudo code)

Lecture plan

Syntax analysis

- Overview
- Tokenizing
- Grammar
- Parsing

Building a syntax analyzer

- Software design
- The Jack grammar
- The Jack analyzer
  - Overview
  - Implementation
  - Project 10

Grammar

Tiny English grammar

sentence: *nounPhrase verbPhrase*

nounPhrase: *determiner noun*

verbPhrase: *verb nounPhrase*

noun: `'dog'|'school'|'girl'|`
`'he'|'she'|'homework'|` ...

verb: `'went'|'ate'|'said'|` ...

determiner: `'the'|'to'|'my'|` ...

...

valid sentences (examples)

```
the girl went to school

she said

the dog ate my homework
```

Grammar

A set of rules of the form *ruleName*: *ruleDefinition*

Each rule specifies how valid tokens can be arranged to form valid language patterns.

Grammar

Tiny English grammar

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

Grammar conventions (rules' right-hand side)

'x'	:	text that appears verbatim
x	:	lexical element
x y	:	*x* appears, then *y* appears
x | *y*	:	either *x* or *y* appear
x?	:	*x* appears 0 or 1 times
*x**	:	*x* appears 0 or more times
(*x y*)	:	grouping of *x* and *y*

Grammar

A set of rules of the form *ruleName*: *ruleDefinition*

Each rule specifies how valid tokens can be arranged to form valid language patterns.

Grammar

Jack grammar (subset)

statement: *letStatement* | *ifStatement* | *whileStatement*

statements: *statement**

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

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

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

expression: *term* (*op term*)?

term: *varName* | *constant*

varName: a string not beginning with a digit

constant: a decimal number

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

Grammar conventions (rules' right-hand side)

'**x**' : text that appears verbatim

x : lexical element

x y : *x* appears, then *y* appears

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x? : *x* appears 0 or 1 times

*x** : *x* appears 0 or more times

(*x y*) : grouping of *x* and *y*

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input examples

```
let x = 100;
```

Grammar

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input examples

```
let x = 100;
```

```
let n = n + 1;
```

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

input examples

```
let x = 100;
```

```
let n = n + 1;
```

```
if (n < lim)
   let n = n + 1;
}
```

Grammar

Jack grammar (subset)

statement: *letStatement* | *ifStatement* | *whileStatement*

statements: *statement**

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

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expression: *term* (*op term*)?

term: *varName* | *constant*

varName: a string not beginning with a digit

constant: a decimal number

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

input example

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

Grammar

Jack grammar (subset)

statement: *letStatement* | *ifStatement* | *whileStatement*

statements: *statement**

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

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expression: *term* (*op term*)?

term: *varName* | *constant*

varName: a string not beginning with a digit

constant: a decimal number

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

Grammars consist of two kinds of rules:

"nonterminals"

(rules whose definitions mention other rules)

"terminals"

Lecture plan

Syntax analysis

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  - Overview
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  - Project 10

Parsing

Tiny English grammar

sentence: *nounPhrase verbPhrase*

nounPhrase: *determiner noun*

verbPhrase: *verb nounPhrase*

noun: `'dog'|'school'|'girl'|`
`'he'|'she'|'homework'|` ...

verb: `'went'|'ate'|'said'|` ...

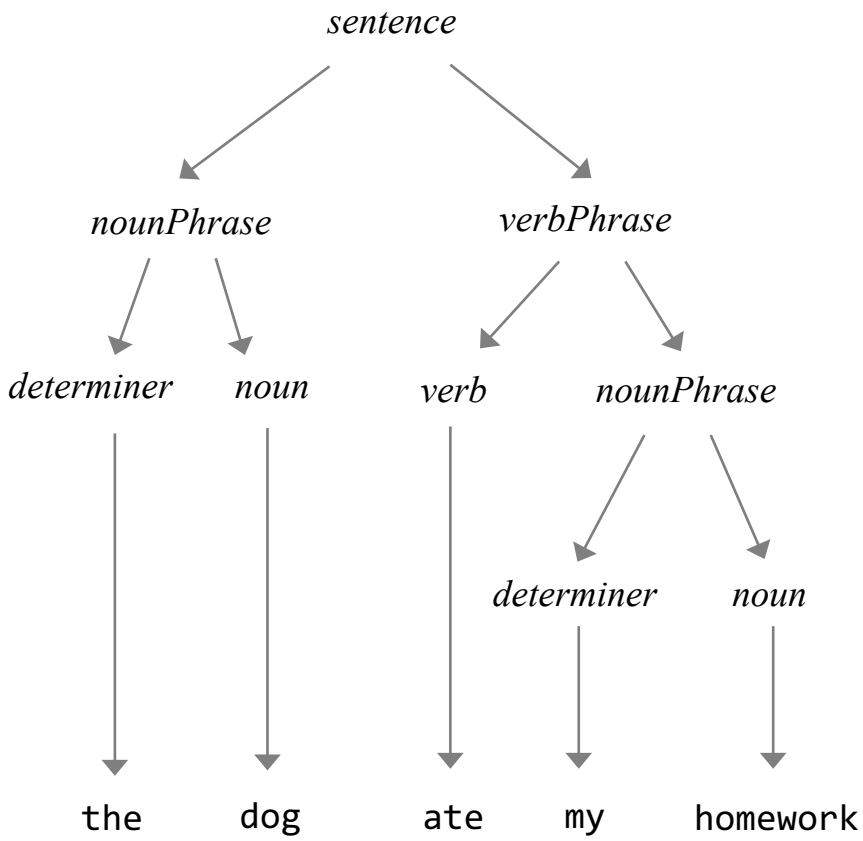
determiner: `'the'|'to'|'my'|` ...

...

Input

`The dog ate my homework`

parse



pare tree

Parsing:

Checking if a given input is accepted by the grammar

In the process, uncovering the input's grammatical structure

Parsing

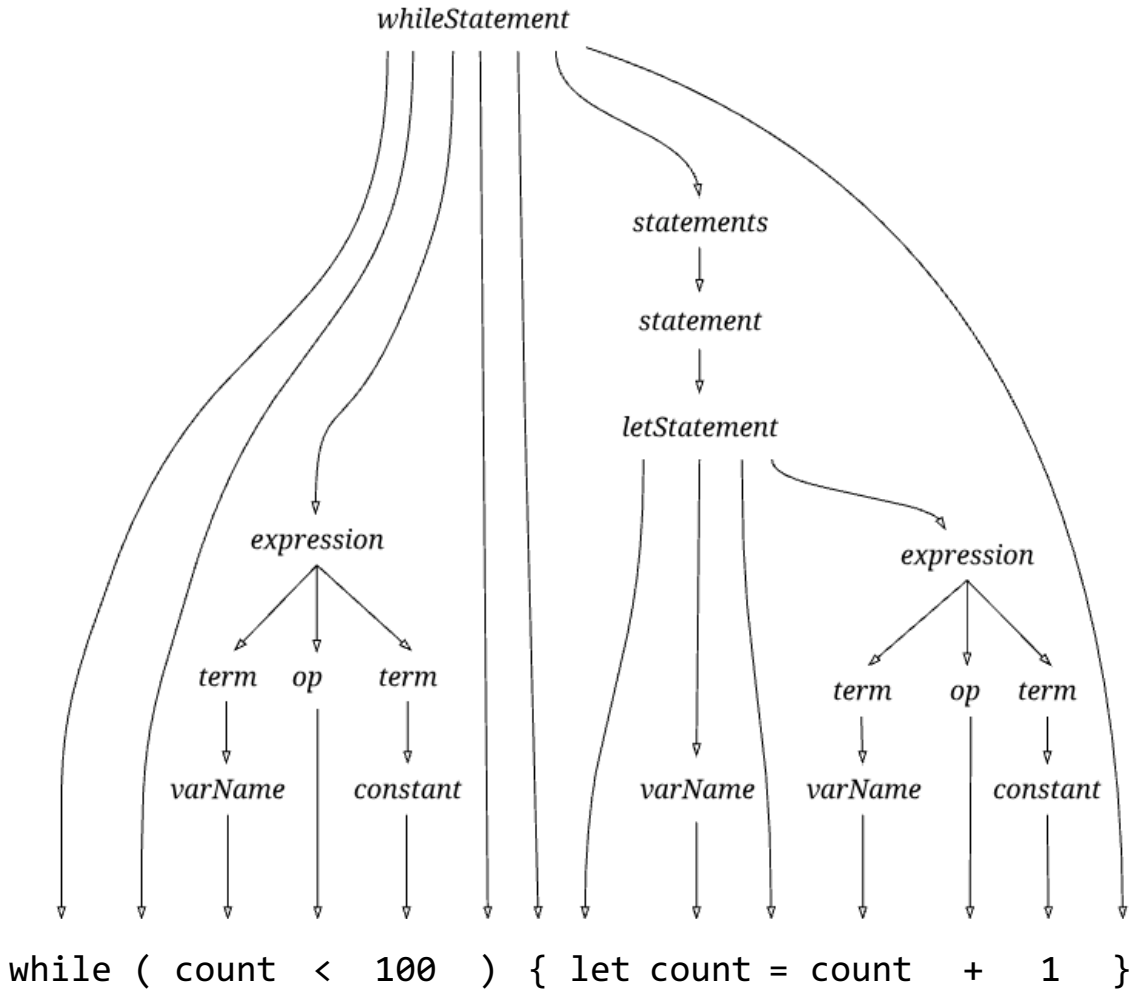
Jack grammar (subset)

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

Input

```
while (count < 100) {
   let count = count + 1;
}
```

parse



Parsing

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term: *varName* | *constant*

varName: a string not beginning with a digit

constant: a decimal number

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

Input

```
while (count < 100) {
   let count = count + 1;
}
```

parse

Same parse tree, expressed linearly using mark-up tags

```
...
<whileStatement>
   <keyword> while </keyword>
   <symbol> ( </symbol>
   <expression>
      <term> <varName> count </varName> </term>
      <op> <symbol> < </symbol> </op>
      <term> <constant> 100 </constant> </term>
   </expression>
   <symbol> ) </symbol>
   <symbol> { </symbol>
   <statements>
      <statement> <letStatement>
         <keyword> let </keyword>
         <varName> count </varName>
         <symbol> = </symbol>
         <expression>
            <term> <varName> count </varName> </term>
            <op> <symbol> + </symbol> </op>
            <term> <constant> 1 </constant> </term>
         </expression>
         <symbol> ; </symbol>
      </letStatement> </statement>
   </statements>
   <symbol> } </symbol>
</whileStatement>
...
```

Lecture plan

Syntax analysis

- Overview
- Tokenizer
- Grammar
- Parsing

Building a syntax analyzer

- Software design
- The Jack grammar
- The Jack analyzer
  - Overview
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  - Project 10

Syntax analyzer

Jack grammar (subset)

statement: *letStatement* | *ifStatement* | *whileStatement*

statements: *statement**

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

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

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

expression: *term* (*op term*)?

term: *varName* | *constant*

varName: a string not beginning with a digit

constant: a decimal number

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

Syntax Analyzer (also known as *parser*)

Accepts / rejects a given input (program);

In the process, builds the program's parse tree.

`prog.jack` (input)

```
...
while (count < 100) {
   let count = count + 1;
}
...
```

JackAnalyzer

Parse tree (output)

```
...
<whileStatement>
   <keyword> while </keyword>
   <symbol> ( </symbol>
   <expression>
      <term> <varName> count </varName> </term>
      <op> <symbol> < </symbol> </op>
      ...
```

Syntax analyzer design

Jack grammar (subset)

statement: *letStatement* | *ifStatement* | *whileStatement*

statements: *statement**

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

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expression: *term* (*op term*)?

term: *varName* | *constant*

varName: a string not beginning with a digit

constant: a decimal number

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

Syntax analyzer (main module)

```
CompilationEngine {
    ...
    compileLet() {
        // parses a let statement
    }
    ...
    compileWhile() {
        // parses a while statement
    }
    ...
    compileTerm() {
        // parses a term
    }
    ...
}
```

The Parser's software design:
Informed by the language's grammar.

prog.jack (input)

```
...
while (count < 100) {
   let count = count + 1;
}
...
```

JackAnalyzer

Parse tree (output)

```
...
<whileStatement>
   <keyword> while </keyword>
   <symbol> ( </symbol>
   <expression>
      <term> <varName> count </varName> </term>
      <op> <symbol> < </symbol> </op>
      ...
```

Syntax analyzer design

Jack grammar (subset)

statement: *letStatement* | *ifStatement* | *whileStatement*

statements: *statement**

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

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

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

expression: *term* (*op term*)?

term: *varName* | *constant*

varName: a string not beginning with a digit

constant: a decimal number

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

Syntax analyzer (main module)

```
CompilationEngine {
    ...
    compileLet() {
        // parses a let statement
    }
    ...
    compileWhile() {
        // parses a while statement
    }
    ...
    compileTerm() {
        // parses a term
    }
    ...
}
```

The Parser's software design:
Informed by the language's grammar.

Grammar rules are realized by parsing methods

prog.jack (input)

```
...
while (count < 100) {
   let count = count + 1;
}
...
```

JackAnalyzer

Parse tree (output)

```
...
<whileStatement>
   <keyword> while </keyword>
   <symbol> ( </symbol>
   <expression>
      <term> <varName> count </varName> </term>
      <op> <symbol> < </symbol> </op>
      ...
```

Syntax analyzer design

Jack grammar (subset)

statement: *letStatement* | *ifStatement* | *whileStatement*

statements: *statement**

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

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varName: a string not beginning with a digit

constant: a decimal number

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

Parsing method (typical)

```
// Parses a while statement:
// 'while' '(' expression ')' '{' statements '}'
// Should be called if the current token is 'while'.
compileWhile()
```

pseudo code

`prog.jack` (input)

```
...
while (count < 100) {
   let count = count + 1;
}
...
```

JackAnalyzer

Parse tree (output)

```
...
<whileStatement>
   <keyword> while </keyword>
   <symbol> ( </symbol>
   <expression>
      <term> <varName> count </varName> </term>
      <op> <symbol> < </symbol> </op>
      ...
```

Syntax analyzer design

Jack grammar (subset)

statement: *letStatement* | *ifStatement* | *whileStatement*

statements: *statement**

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

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

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

expression: *term* (*op term*)?

term: *varName* | *constant*

varName: a string not beginning with a digit

constant: a decimal number

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

Parsing method (typical)

pseudo code

```
// Parses a while statement:
// 'while' '(' expression ')' '{' statements '}'
// Should be called if the current token is 'while'.
compileWhile()
   print("<whileStatement>")
   process("while")
   process("(")
   compileExpression()
   process(")")
   process("{")
   compileStatements()
   process("}")
   print("</whileStatement>")
```

```
// Helper method:
// Handles the current input token,
// and advances the input.
process(str)
   if (currentToken == str)
      printXMLToken(str)
   else
      print("syntax error")
   currentToken =
      tokenizer.advance()
```

prog.jack (input)

```
...
while (count < 100) {
   let count = count + 1;
}
...
```

JackAnalyzer

Parse tree (output)

```
...
<whileStatement>
   <keyword> while </keyword>
   <symbol> ( </symbol>
   <expression>
      <term> <varName> count </varName> </term>
      <op> <symbol> < </symbol> </op>
      ...
```

Syntax analyzer design

Jack grammar (subset)

statement: *letStatement* | *ifStatement* | *whileStatement*

statements: *statement**

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

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

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

expression: *term* (*op term*)?

term: *varName* | *constant*

varName: a string not beginning with a digit

constant: a decimal number

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

Parsing method (typical)

```
// Parses a while statement:
// 'while' '(' expression ')' '{' statements '}'
// Should be called if the current token is 'while'.
compileWhile()
   print("<whileStatement>")
   process("while")
   process("(")
   compileExpression()
   process(")")
   process("{")
   compileStatements()
   process("}")
   print("</whileStatement>")
```

pseudo code

```
// Helper method:
// Handles the current input token,
// and advances the input.
process(str)
   if (currentToken == str)
      printXMLToken(str)
   else
      print("syntax error")
   currentToken =
      tokenizer.advance()
```

Recursive descent parsing

The parser is designed as a set of `compile`*xxx* methods (of which `compileWhile` is one);

The design of each `compile`*xxx* method is informed by a corresponding grammar rule;

Each `compile`*xxx* method is responsible for advancing, and handling, its own part of the input;

The `compile`*xxx* methods call each other, recursively.

How do we know which rule to invoke at each step?

Syntax analyzer design

Jack grammar (subset)

statement: *letStatement* | *ifStatement* | *whileStatement*

statements: *statement**

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

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

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

expression: *term* (*op term*)?

term: *varName* | *constant*

varName: a string not beginning with a digit

constant: a decimal number

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

LL Grammars (a bit of theory)

LL: Parsing the input from Left to right, performing Leftmost derivation of the input

LL(*k*): Looking ahead *k* tokens is sufficient for knowing which parsing rule to invoke next

LL(1) grammar: The first token informs which rule to invoke next

LL(1) grammars can be handled simply and elegantly by recursive descent parsing algorithms, without backtracking.

The Jack grammar is LL(1), barring one exception that can be easily handled (later).

Lecture plan

Syntax analysis

- Overview
- Tokenizer
- Grammar
- Parsing

Building a syntax analyzer

- Software design
- The Jack grammar
- The Jack analyzer
  - Overview
  - Implementation
  - Project 10

Jack grammar: Tokens

The Jack language has 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.

Parsing tip 1

This part of the Jack grammar informs the implementation of the Jack Tokenizer;

(informs how to group characters into tokens).

Jack grammar: Program structure

A Jack class declaration is a set of variable and subroutine declarations:

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

Parsing tip 2

Some rules specify a sequence of elements whose length is not known;

For example, the *class* rule specifies a sequence of zero or more *classVardDec* elements;

To handle, the corresponding parsing methods can use iteration;

For example, `compileClass` can use a loop to parse as many *classVarDec* elements as there are in the input.

Jack grammar: Program structure

A Jack class declaration is a set of variable and subroutine declarations:

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

Parsing tip 3

Some rules specify two or more parsing possibilities;

For example, the first token of a *classVarDec* is either `static`, or `field`;

The `process` method shown before can be refined to accommodate such choices;
For example, we can change its parameter to a list/set of possible valid tokens.

Jack grammar: Statements

A Jack subroutine's body is a sequence of 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? '**;**'

Parsing tip 4

The *letStatement* rule accepts patterns like `let x =` *expression* as well as `let x[`*expression*`] =` *expression*

This implies that in the corresponding parsing method `compileLet`, after handling the *varName*, we should expect to see either the token `=`, or the token `[`, and continue the parsing accordingly;

To support such choices (in this and in other rules), see "Parsing Tip 3".

Jack grammar: Expressions

Jack statements can include 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'

Parsing tip 5

A *subroutine call* occurs in two places only:

- when parsing a *term* in an *expression*. For example: `x + calc(…) + y`
- when parsing a `do` statement. For example: `do play(…)`

To simply things, instead of writing a separate `compileSubroutineCall` method:

- Have your `compileTerm` method parse subroutine calls directly;
- Parse `do` *subroutineCall* statements as if they were `do` *expression*.

Jack grammar: Expressions

Jack statements can include 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'

Parsing tip 6

According to the definitions of *term* and *subroutineCall*,
if the current token is a *varName*, say `foo`, it can be one of 5 possible things:
`foo`, `foo[`*expression*`]`, `foo(`*expressionList*`)`, `Foo.bar(`*expressionList*`)`, or `foo.bar(`*expressionList*`)`

Notice that the token following the *varName* (in this example, `foo`) is sufficient to resolve which option we are in. Therefore, if the current token is a *varName*, the syntax analyzer must:

1. save the current token, and
2. advance to get the next token

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

Jack grammar: Complete

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.

tokens

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

program structure

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? **';'**

statements

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'**

expressions

Lecture plan

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- Overview
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Building a syntax analyzer

- Software design
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- The Jack analyzer
  - Overview
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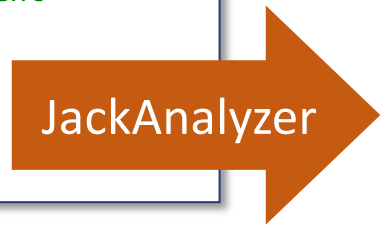
  - Project 10

Jack analyzer

Example: `Point.jack`

```
/** Represents a 2D Point. */
class Point {
   ...
   method int getx() {
      // some comment
      return x;
   }
   ...
}
```



`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 analyzer outputs a parse tree, represented by XML markup

Jack analyzer

Example: `Point.jack`

```
/** Represents a 2D Point. */
class Point {
   ...
   method int getx() {
      // some comment
      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 analyzer outputs a parse tree, represented by XML markup

The analyzer handles:

- Terminals (tokens)
- Nonterminals

Jack analyzer: Terminals

Terminal elements *xxx* generate the output:

<*tokenType*> *xxx* </*tokenType*>

where *tokenType* is:

`keyword`, `symbol`, `integerConstant`, `stringConstant`, `identifier`

Output examples

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

Jack analyzer: Nonterminals

Nonterminal element *xxx* generates the output:

<*nonTerminal*>

Recursive output from parsing *xxx*

</*nonTerminal*>

where *nonTerminal* is:

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

Output example: parsing `return x;`

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

Jack analyzer: Nonterminals

Nonterminal element *xxx* generates the output:

```
<nonTerminal>
    Recursive output from parsing xxx
</nonTerminal>
```

where *nonTerminal* is:

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

Output example: parsing `return x;`

```
<returnStatement>                    output by compileReturn
   <keyword> return </keyword>
   <expression>
      <term>
         <identifier> x </identifier>
      </term>                        output by compileExpression
   </expression>
   <symbol> ; </symbol>
</returnStatement>                   output by compileReturn
```

Produced by:

```
// Parses a return statement. Implements the rule:
// 'return' expression ';'
compileReturn()
   print("<returnStatement>")
   process("return")
   compileExpression()
   process(";")
   print("</returnStatement>")
```

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Proposed implementation

Modules

`JackTokenizer` : Handles the input

`CompilationEngine`: Handles the parsing

`JackAnalyzer`: Drives the process.

JackTokenizer API

JackTokenizer: Provides routines that skip comments and white space, get the next token, and advance the input exactly beyond it. Other routines return the type of the current token, and its value.

Routine	*Arguments*	*Returns*	*Function*
Constructor / initializer	input file / stream	–	Opens the input `.jack` file / stream 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.
`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 `tokenType` is `KEYWORD`.
`symbol`	–	char	Returns the character which is the current token. Should be called only if `tokenType` is `SYMBOL`.
`identifier`	–	string	Returns the string which is the current token. Should be called only if `tokenType` is `IDENTIFIER`.
`intVal`	–	int	Returns the integer value of the current token. Should be called only if `tokenType` is `INT_CONST`.
`stringVal`	–	string	Returns the string value of the current token, without the opening and closing double quotes. Should be called only if `tokenType` is `STRING_CONST`.

Proposed implementation

Modules

`JackTokenizer` : Handles the input

`CompilationEngine`: Handles the parsing

`JackAnalyzer`: Drives the process.

CompilationEngine API

CompilationEngine: Gets its input from a JackTokenizer and emits its output to an output file, using a set of parsing routines. Each `compile`*xxx* 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*.

Routine	*Arguments*	*Returns*	*Function*
Constructor / initializer	Input stream/file Output stream/file	–	Creates a new compilation engine with the given input and output. The next routine called (by the `JackAnalyzer` module) must be `compileClass`.
`compileClass`	–	–	Compiles a complete class.
`compileClassVarDec`	–	–	Compiles a static variable declaration, or a field declaration.
`compileSubroutine`	–	–	Compiles a complete method, function, or constructor.
`compileParameterList`	–	–	Compiles a (possibly empty) parameter list. Does not handle the enclosing parentheses tokens `(` and `)`.
`compileSubroutineBody`	–	–	Compiles a subroutine's body.
`compileVarDec`	–	–	Compiles a `var` declaration.
`compileStatements`	–	–	Compiles a sequence of statements. Does not handle the enclosing curly bracket tokens `{` and `}`.

API continues in next slide

CompilationEngine API

CompilationEngine: Gets its input from a JackTokenizer and emits its output to an output file, using a set of parsing routines. Each `compile`*xxx* 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*.

Routine	*Arguments*	*Returns*	*Function*
`compileLet`	–	–	Compiles a `let` statement.
`compileIf`	–	–	Compiles an `if` statement, possibly with a trailing `else` clause.
`compileWhile`	–	–	Compiles a `while` statement.
`compileDo`	–	–	Compiles a `do` statement.
`compileReturn`	–	–	Compiles a `return` statement.

API continues in next slide

CompilationEngine API

CompilationEngine: Gets its input from a JackTokenizer and emits its output to an output file, using a set of parsing routines. Each `compile`*xxx* 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*.

Routine	*Arguments*	*Returns*	*Function*
`compileExpression`	–	–	Compiles an expression.
`compileTerm`	–	–	Compiles a *term*. If the current token is an *identifier*, the routine must resolve it into a *variable*, an *array entry*, or a *subroutine call*. A single lookahead token, which may be `[`, `(`, or `.`, suffices to distinguish between the possibilities. Any other token is not part of this term and should not be advanced over.
`compileExpressionList`	–	int	Compiles a (possibly empty) comma-separated list of expressions. Returns the number of expressions in the list.

Parsing tip 7

The nonterminal elements *subroutineCall, subroutineName*, *variableName*, *className*, *type,* and *statement* are parsed directly, by other parsing methods that mention them;

Therefore, these rules have no corresponding `compile`*xxx* methods;

This makes the analyzer's implementation simpler.

Proposed implementation

Modules

`JackTokenizer` : Handles the input

`CompilationEngine`: Handles the parsing

`JackAnalyzer`: Drives the process.

Jack analyzer

Usage

`% JackAnalyzer` *input*

input: *fileName*`.jack`: name of a single file containing a Jack class, or
folderName: name of a folder containing one or more `.jack` files

output: If the input is a single file: *fileName*`.xml`
If the input is a folder: One `.xml` file for every `.jack` file, stored in that folder

Implementation

`JackAnalyzer` is the main module. For each file in the input, it:

1. Creates a `JackTokenizer` from *fileName*`.jack`
2. Creates an output file named *fileName*`.xml`
3. Creates a `CompilationEngine`, and calls the `compileClass` method
   (`compileClass` will then do the rest of the parsing, recursively)
4. Closes the output file.

No API is given, implement your own design.

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Project 10

Implementation stages

- Build a Jack tokenizer, and a basic Jack analyzer (V.0) that tests it
- Complete the Jack analyzer:

  Version 1 (handles no expressions and no array syntax)

  Version 2 (complete)

Jack tokenizer

Prog.jack

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

JackAnalyzer (V.0)

Unit-tests the `JackTokenizer`:

Prints a list of tokens

ProgT.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>
```

Technical notes

- String constants (like `"negative"`) are outputted without the double-quotes
- The symbols <, >, ", and & are outputted as `<`, `>`, `&quot;`, and `&`
- The begin and end tags (`tokens`) are needed for XML integrity.

Jack tokenizer

Prog.jack

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

JackAnalyzer (V.0)

Unit-tests the `JackTokenizer`:

Prints a list of tokens

ProgT.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>
```

Implementation plan

- Write a `JackTokenizer` (implement the `JackTokenizer` API)
- Write a `JackAnalyzer` (version 0) that uses a loop to iterate the input file and print one token at a time, using the services of a `JackTokenizer`

Project 10

Implementation stages

- Build a Jack tokenizer, and a basic Jack analyzer (V.0) that tests it
- Complete the Jack analyzer:

  Version 1 (handles no expressions and no array syntax)

  Version 2 (complete)

Jack analyzer

Prog.jack

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

JackAnalyzer

Uses the services of a `JackTokenizer`, and a `CompilationEngine`

Prog.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>
...
```

Stages

1. Build a `CompilationEngine` that handles everything except for expressions and array syntax
2. Add the handling of expressions and array syntax

We supply Jack files for unit-testing each stage.

Test file example

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;
         ...
```

Test file example (with and without expressions)

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
         let y = y - 2;
         ...
```

projects/10/ExpressionLessSquare/Square.jack

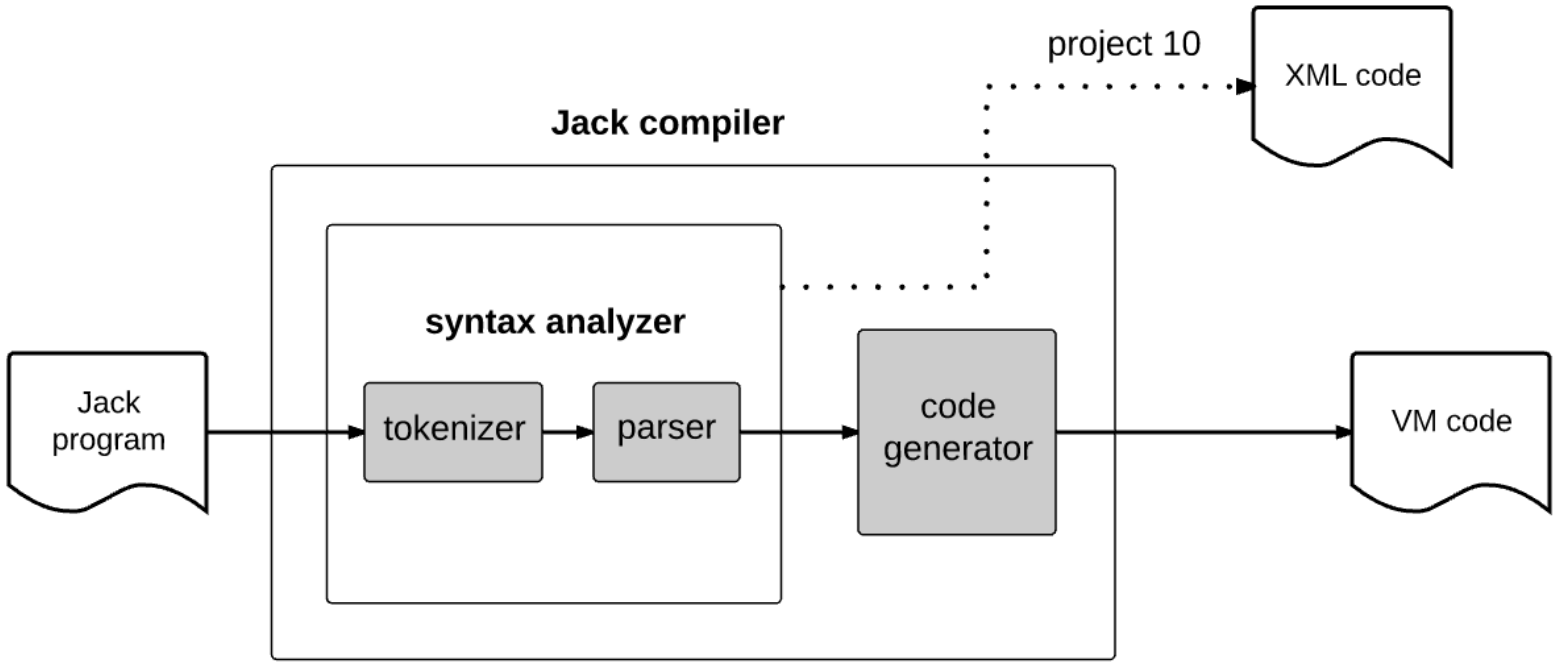
```
class Square {

   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
   method void moveUp(
      if (y) {
         do Screen.setColor(false);
         do Screen.drawRectangle(x, y, x, y);
         let y = y;
         ...
```

All expressions were replaced with variables in scope;

The resulting code is meaningless, but grammatically valid.

The expressionless files supports unit-testing the analyzer's ability to parse everything, except for expressions and array syntax.

What's Next: Code Generation



Project 10 Project 11

Same parsing logic!