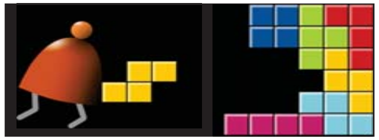
# Compiler I: Syntax Analysis



*Building a Modern Computer From First Principles*

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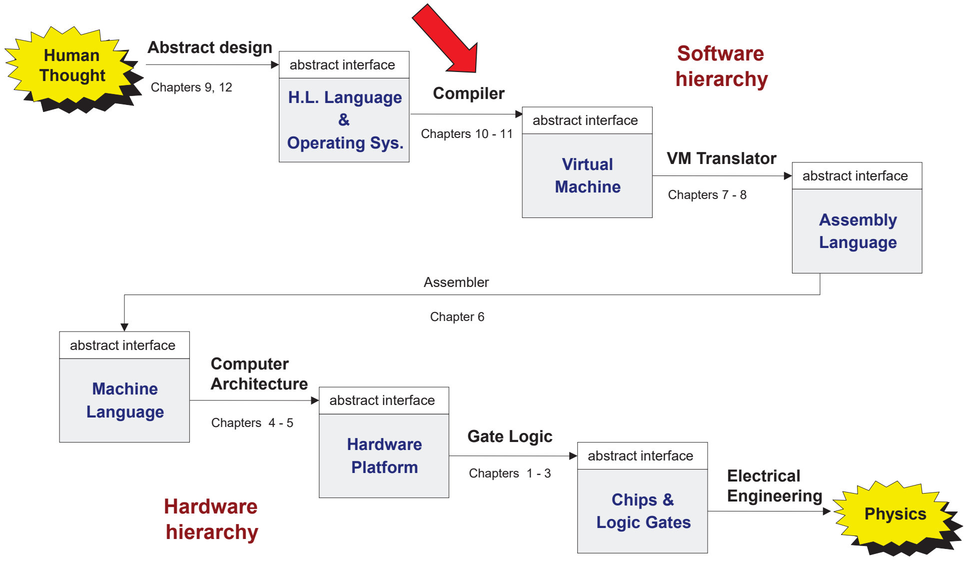
## Course map



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## Motivation: Why study about compilers?

The first compiler is FORTRAN compiler developed by an IBM team led by John Backus (Turing Award, 1977) in 1957. It took 18 man-month.

Because Compilers …

- Are an essential part of applied computer science
- Are very relevant to computational linguistics
- Are implemented using classical programming techniques
- Employ important software engineering principles
- Train you in developing software for transforming one structure to another (programs, files, transactions, …)
- Train you to think in terms of "description languages".
- Parsing files of some complex syntax is very common in many applications.

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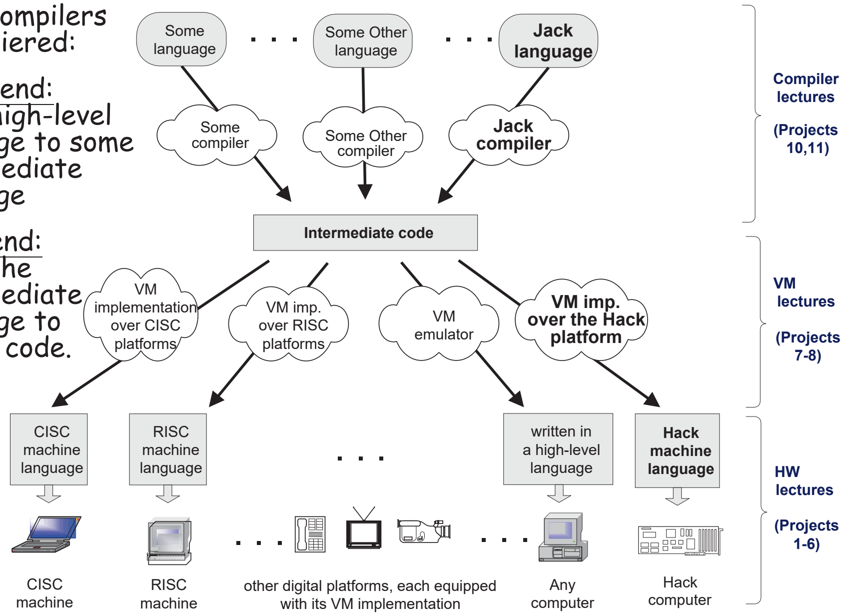
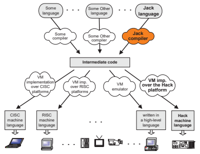
## The big picture

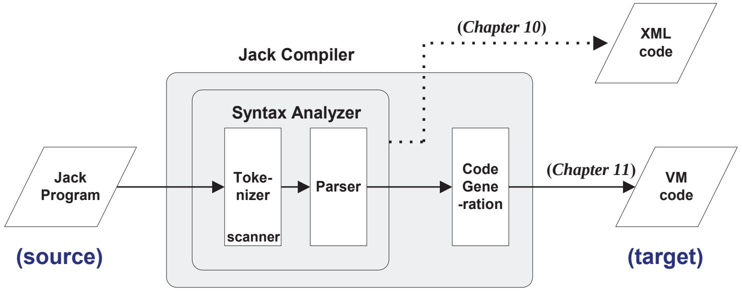
Modern compilers are two-tiered:

- Front-end: from high-level language to some intermediate language
- Back-end: from the intermediate language to binary code.



## Compiler architecture (front end)





- **Syntax analysis:** understanding the structure of the source code
  - **Tokenizing**: creating a stream of "atoms"
  - **Parsing**: matching the atom stream with the language grammar

  XML output = one way to demonstrate that the syntax analyzer works
- **Code generation:** reconstructing the semantics using the syntax of the target code.

---

## Tokenizing / Lexical analysis / scanning

***C code***

```
while (count <= 100) { /** some loop */
   count++;
   // Body of while continues
   ...
```

**tokenizing**

***Tokens***

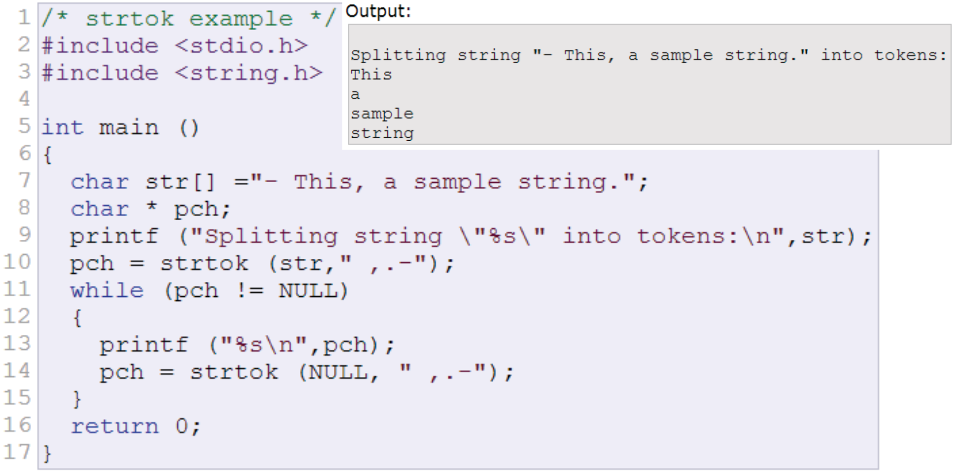
```
while
(
count
<=
100
)
{
count
++
;
...
```

- Remove white space
- Construct a token list (language atoms)
- Things to worry about:
  - Language specific rules: e.g. how to treat "++"
  - Language-specific classifications: keyword, symbol, identifier, integerConstant, stringConstant,...
- While we are at it, we can have the tokenizer record not only the token, but also its lexical classification (as defined by the source language grammar).

---

## C function to split a string into tokens

- `char* strtok(char* str, const char* delimiters);`
  - `str`: string to be broken into tokens
  - `delimiters`: string containing the delimiter characters



```
/* strtok example */
#include <stdio.h>
#include <string.h>

int main ()
{
  char str[] ="- This, a sample string.";
  char * pch;
  printf ("Splitting string \"%s\" into tokens:\n",str);
  pch = strtok (str," ,.-");
  while (pch != NULL)
  {
    printf ("%s\n",pch);
    pch = strtok (NULL, " ,.-");
  }
  return 0;
}
```

Output:

```
Splitting string "- This, a sample string." into tokens:
This
a
sample
string
```

---

## Jack Tokenizer

```
if (x < 153) {let city = ”Paris”;}
```

Source code

**Tokenizer**

Tokenizer's output

```
<tokens>
  <keyword> if </keyword>
  <symbol> ( </symbol>
  <identifier> x </identifier>
  <symbol> &lt; </symbol>
  <integerConstant> 153 </integerConstant>
  <symbol> ) </symbol>
  <symbol> { </symbol>
  <keyword> let </keyword>
  <identifier> city </identifier>
  <symbol> = </symbol>
  <stringConstant> Paris </stringConstant>
  <symbol> ; </symbol>
  <symbol> } </symbol>
</tokens>
```

## Parsing

- The tokenizer discussed thus far is part of a larger program called *parser*
- Each language is characterized by a *grammar.* The parser is implemented to recognize this grammar in given texts
- The parsing process:
  - A text is given and tokenized
  - The parser determines weather or not the text can be generated from the grammar
  - In the process, the parser performs a complete structural analysis of the text
- The text can be in an expression in a :
  - Natural language (English, ...)
  - Programming language (Jack, ...).

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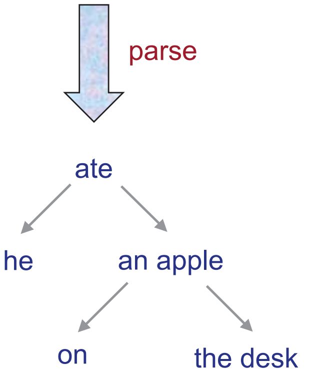
## Parsing examples

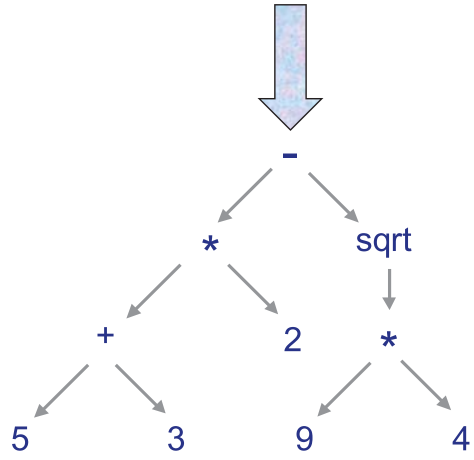
English

```
He ate an apple on the desk.
```



Jack

```
(5+3)*2 – sqrt(9*4)
```



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## Regular expressions

- a|b*

{ε, “a”, “b”, “bb”, “bbb”, ...}

- (a|b)*

{ε, “a”, “b”, “aa”, “ab”, “ba”, “bb”, “aaa”, ...}

- ab*(c|ε)

{a, “ac”, “ab”, “abc”, “abb”, “abbc”, ...}

---

## Lex

- A computer program that generates lexical analyzers (scanners or lexers)
- Commonly used with the yacc parser generator.
- Structure of a Lex file

```
Definition section
%%
Rules section
%%
C code section
```

## Example of a Lex file

```
/*** Definition section ***/
%{
/* C code to be copied verbatim */
#include <stdio.h>
%}

/* This tells flex to read only one input file */
%option noyywrap

/*** Rules section ***/
%%

[0-9]+  {
            /* yytext is a string containing the
               matched text. */
            printf("Saw an integer: %s\n", yytext);
        }
.|\n    {   /* Ignore all other characters. */   }
```

---

## Example of a Lex file

```
%%
/*** C Code section ***/

int main(void)
{
    /* Call the lexer, then quit. */
    yylex();
    return 0;
}
```

---

## Example of a Lex file

```
> flex test.lex
  (a file lex.yy.c with 1,763 lines is generated)

> gcc lex.yy.c
  (an executable file a.out is generated)

> ./a.out < test.txt
Saw an integer: 123
Saw an integer: 2
Saw an integer: 6
```

test.txt

```
abc123z.!&*2gj6
```

---

## Another Lex example

```
%{
int num_lines = 0, num_chars = 0;
%}

%option noyywrap

%%
\n      ++num_lines; ++num_chars;
.       ++num_chars;

%%
main() {
  yylex();
  printf( "# of lines = %d, # of chars = %d\n",
          num_lines, num_chars );
}
```

## A more complex Lex example

```
%{
/* need this for the call to atof() below */
#include <math.h>
%}
%option noyywrap

DIGIT    [0-9]
ID       [a-z][a-z0-9]*

%%
{DIGIT}+    {
            printf( "An integer: %s (%d)\n", yytext,
                    atoi( yytext ) );
            }

{DIGIT}+"."{DIGIT}*        {
            printf( "A float: %s (%g)\n", yytext,
                    atof( yytext ) );
            }
```

## A more complex Lex example

```
if|then|begin|end|procedure|function  {
            printf( "A keyword: %s\n", yytext );
            }

{ID}        printf( "An identifier: %s\n", yytext );

"+"|"-"|"="|"("|")"  printf( “Symbol: %s\n", yytext );

[ \t\n]+   /* eat up whitespace */

.          printf("Unrecognized char: %s\n", yytext );

%%
void main(int argc, char **argv ) {
    if ( argc > 1 ) yyin = fopen( argv[1], "r" );
    else yyin = stdin;

    yylex();
}
```

## A more complex Lex example

pascal.txt

```
if (a+b) then
  foo=3.1416
else
  foo=12
```

output

```
A keyword: if
Symbol: (
An identifier: a
Symbol: +
An identifier: b
Symbol: )
A keyword: then
An identifier: foo
Symbol: =
A float: 3.1416 (3.1416)
An identifier: else
An identifier: foo
Symbol: =
An integer: 12 (12)
```

## Context-free grammar

- Terminals: 0, 1, #
- Non-terminals: A, B
- Start symbol: A
- Rules:
  - $A \rightarrow 0A1$
  - $A \rightarrow B$
  - $B \rightarrow \#$

- Simple (terminal) forms / complex (non-terminal) forms
- Grammar = set of rules on how to construct complex forms from simpler forms
- Highly recursive.

## Examples of context-free grammar

- S→()
  S→(S)
  S→SS
- S→a|aS|bS

  strings ending with 'a'
- S → x
  S → y
  S → S+S
  S → S-S
  S → S*S
  S → S/S
  S → (S)
  (x+y)*x-x*y/(x+x)

---

## Examples of context-free grammar

- non-terminals: S, E, Elist
- terminals: ID, NUM, PRINT, +, :=, (, ), ;
- rules:

S → S; S
S → ID := E
S → PRINT ( Elist )

E → ID
E → NUM
E → E + E
E → ( S , Elist )

Elist → E
Elist → Elist , E

Try to derive: ID = NUM ; PRINT ( NUM )

slide credit: David Walker

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## Examples of context-free grammar

- non-terminals: S, E, Elist
- terminals: ID, NUM, PRINT, +, :=, (, ), ;
- rules:

S → S; S
S → ID := E
S → PRINT ( Elist )

E → ID
E → NUM
E → E + E
E → ( S , Elist )

Elist → E
Elist → Elist , E

left-most derivation

S
S ; S
ID = E ; S
ID = NUM ; S
ID = NUM ; PRINT ( Elist )
ID = NUM ; PRINT ( E )
ID = NUM ; PRINT ( NUM )

right-most derivation

S
S ; S
S ; PRINT ( Elist )
S ; PRINT ( E )
S ; PRINT ( NUM )
ID = E ; PRINT ( NUM )
ID = NUM ; PRINT ( NUM )

slide credit: David Walker

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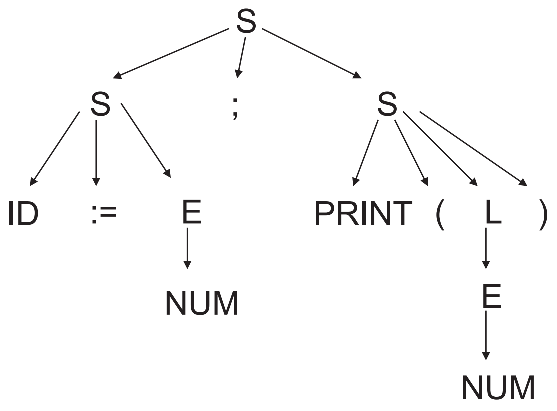
## Parse tree

- Two derivations, but 1 tree

S
S ; S
ID = E ; S
ID = NUM ; S
ID = NUM ; PRINT ( Elist )
ID = NUM ; PRINT ( E )
ID = NUM ; PRINT ( NUM )

S
S ; S
S ; PRINT ( Elist )
S ; PRINT ( E )
S ; PRINT ( NUM )
ID = E ; PRINT ( NUM )
ID = NUM ; PRINT ( NUM )



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## Ambiguous Grammars

- a grammar is ambiguous if the same sequence of tokens can give rise to two or more parse trees

- non-terminals: E
- terminals: ID, NUM, PLUS, MUL
- rules:
  E → ID
  E → NUM
  E → E + E
  E → E * E

characters: 4 + 5 * 6
tokens: NUM(4) PLUS NUM(5) MUL NUM(6)

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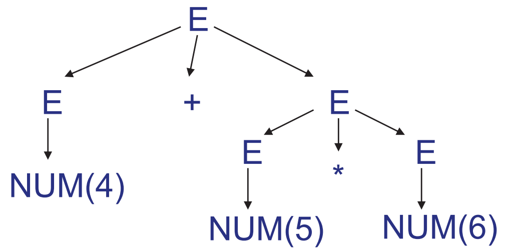
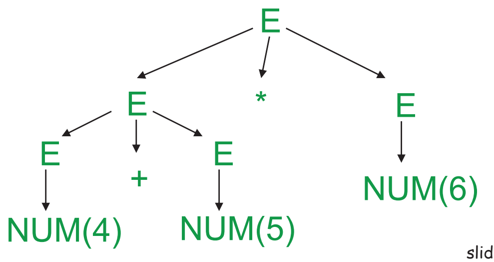
## Ambiguous Grammars

characters: 4 + 5 * 6
tokens: NUM(4) PLUS NUM(5) MUL NUM(6)

E → ID
E → NUM
E → E + E
E → E * E





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## Ambiguous Grammars

- problem: compilers use parse trees to interpret the meaning of parsed expressions
  - different parse trees have different meanings
  - eg: (4 + 5) * 6 is not 4 + (5 * 6)
  - languages with ambiguous grammars are DISASTROUS; The meaning of programs isn't well-defined! You can't tell what your program might do!
- solution: rewrite grammar to eliminate ambiguity
  - fold precedence rules into grammar to disambiguate
  - fold associativity rules into grammar to disambiguate
  - other tricks as well

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## Recursive descent parser

- Recursive Descent Parsing
  - aka: predictive parsing; top-down parsing
  - simple, efficient
  - can be coded by hand in ML quickly
  - parses many, but not all CFGs
    - ❑ parses LL(1) grammars
      - Left-to-right parse; Leftmost-derivation; 1 symbol lookahead
  - key ideas:
    - ❑ one recursive function for each non terminal
    - ❑ each production becomes one clause in the function

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## Recursive descent parser

- Non-terminals: S, E, L
- Terminals: NUM, IF, THEN, ELSE, BEGIN, END, PRINT, =, ;
- Rules:
  1. S -> IF E THEN S ELSE S
  2. | BEGIN S L
  3. | PRINT E
  4. L -> END
  5. | ; S L
  6. E -> NUM = NUM

slide credit: David Walker

---

## Recursive descent parser

- Non-terminals: S, E, L
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  3. | PRINT E
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```
S()
{
  switch (next()) {
    case IF:
      eat(IF); E(); eat(THEN);
      S(); eat(ELSE); S();
      break;
    case BEGIN:
      eat(BEGIN); S(); L();
      break;
    case PRINT:
      eat(PRINT); E();
      break;
  }
}
```

slide credit: David Walker

---

## Recursive descent parser

- Non-terminals: S, E, L
- Terminals: NUM, IF, THEN, ELSE, BEGIN, END, PRINT, EQ(=), SEMI(;)
- Rules:
  1. S -> IF E THEN S ELSE S
  2. | BEGIN S L
  3. | PRINT E
  4. L -> END
  5. | ; S L
  6. E -> NUM = NUM

```
L()
{
  switch (next()) {
    case END:
      eat(END);
      break;
    case SEMI:
      eat(SEMI); S(); L();
      break;
    default:
      error();
  }
}
```

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## Recursive descent parser

- Non-terminals: S, E, L
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- Rules:
  1. S -> IF E THEN S ELSE S
  2. | BEGIN S L
  3. | PRINT E
  4. L -> END
  5. | ; S L
  6. E -> NUM = NUM

```
E()
{
  eat(NUM);
  eat(EQ);
  eat(NUM);
}
```

slide credit: David Walker

## Recursive descent parser

- Non-terminals: S, A, E, L
- Terminals: EOF, ID, NUM, ASSIGN(:=), PRINT, LPAREN((), RPAREN())
- Rules:
  1. S -> A EOF
  2. A -> ID := E
  3. | PRINT(L)
  4. E -> ID
  5. | NUM
  6. L -> E
  7. | L, E

slide credit: David Walker

---

## Recursive descent parser

- Non-terminals: S, A, E, L
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  3. | PRINT(L)
  4. E -> ID
  5. | NUM
  6. L -> E
  7. | L, E

```
S()
{
   A();
   eat(EOF);
}
```

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---

## Recursive descent parser

- Non-terminals: S, A, E, L
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  3. | PRINT(L)
  4. E -> ID
  5. | NUM
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  7. | L, E

```
A()
{
   switch (next()) {
      case ID:
         eat(ID); eat(ASSIGN);
         E();
         break;
      case PRINT:
         eat(PRINT); eat(LPAREN);
         L(); eat(RPAREN);
         break;
   }
}
```

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---

## Recursive descent parser

- Non-terminals: S, A, E, L
- Terminals: EOF, ID, NUM, ASSIGN(:=), PRINT, LPAREN((), RPAREN())
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  1. S -> A EOF
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  3. | PRINT(L)
  4. E -> ID
  5. | NUM
  6. L -> E
  7. | L, E

```
E()
{
   switch (next()) {
      case ID:
         eat(ID);
         break;
      case NUM:
         eat(NUM);
         break;
   }
}
```

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## Recursive descent parser

- Non-terminals: S, A, E, L
- Terminals: EOF, ID, NUM, ASSIGN(:=), PRINT, LPAREN((), RPAREN())
- Rules:
  1. S -> A EOF
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  3. | PRINT(L)
  4. E -> ID
  5. | NUM
  6. L -> E
  7. | L, E

```
L()
{
   switch (next()) {
      case ID:
         ???
      case NUM:
         ???
   }
}
```

Problem:
E could be ID
L could be E could be ID

## Recursive descent parser

- Non-terminals: S, A, E, L
- Terminals: EOF, ID, NUM, ASSIGN(:=), PRINT, LPAREN((), RPAREN())
- Rules:
  1. S -> A EOF
  2. A -> ID := E
  3. | PRINT(L)
  4. E -> ID
  5. | NUM
  6. L -> E
  7. | L, E

Problem:
E could be ID
L could be E could be ID

L -> E M
M -> , E M
| ε

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## A typical grammar of a typical C-like language

### Code samples

```
while (expression) {
  if (expression)
     statement;
     while (expression) {
        statement;
        if (expression)
           statement;
     }
  while (expression) {
     statement;
     statement;
  }
}
```

```
if (expression) {
   statement;
   while (expression)
      statement;
      statement;
   }
   if (expression)
      if (expression)
         statement;
}
```

## A typical grammar of a typical C-like language

```
program:          statement;

statement:          whileStatement
                  | ifStatement
                  | // other statement possibilities ...
                  | '{' statementSequence '}'

whileStatement: 'while' '(' expression ')' statement

ifStatement:        simpleIf
                  | ifElse

simpleIf:         'if' '(' expression ')' statement

ifElse:           'if' '(' expression ')' statement
                 'else' statement

statementSequence:    ''   // null, i.e. the empty sequence
                      | statement ';' statementSequence

expression:        // definition of an expression comes here
```

## Parse tree

**Input Text:**

```
while (count<=100) {
/** demonstration */
      count++;
      // ...
```

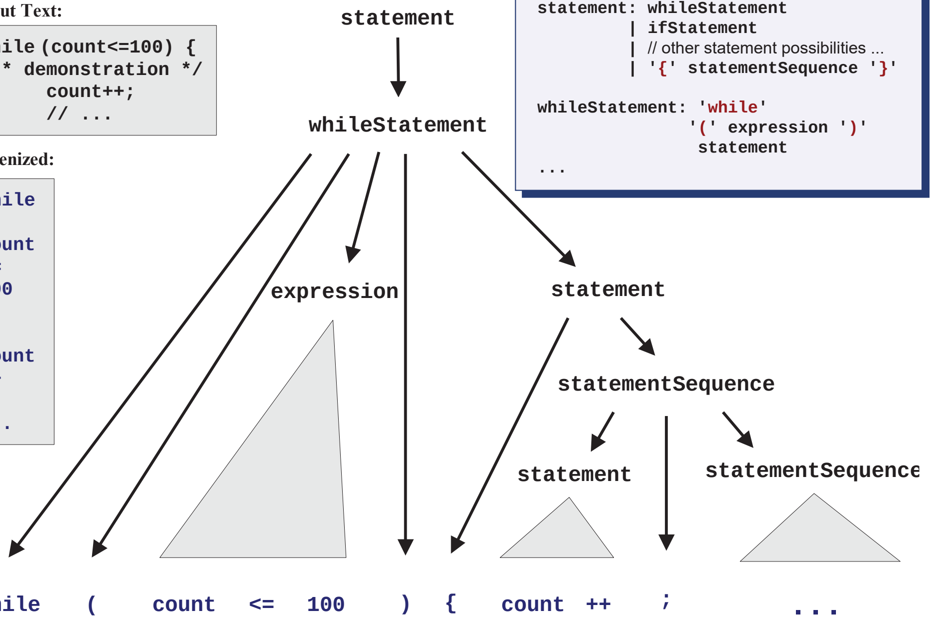
**Tokenized:**

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

```
program:  statement;

statement: whileStatement
         | ifStatement
         | // other statement possibilities ...
         | '{' statementSequence '}'

whileStatement: 'while'
               '(' expression ')'
                statement
...
```



statement

whileStatement

expression

statement

statementSequence

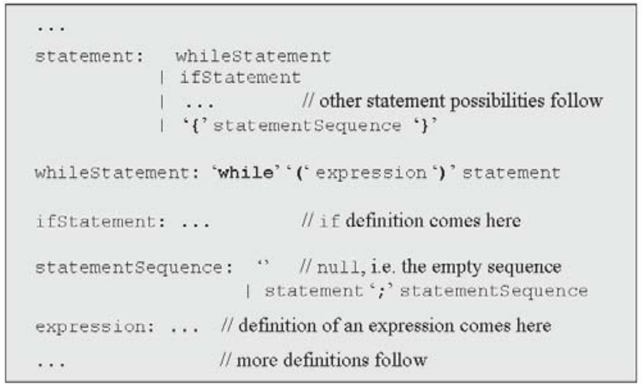
statement

statementSequence

while ( count <= 100 ) { count ++ ; ...

---

## Recursive descent parsing



```
...
statement:   whileStatement
           | ifStatement
           | ...          // other statement possibilities follow
           | ‘{’ statementSequence ‘}’

whileStatement: ‘while’ ‘(’ expression ‘)’ statement

ifStatement: ...          // if definition comes here

statementSequence: ‘’     // null, i.e. the empty sequence
                 | statement ‘;’ statementSequence

expression: ...   // definition of an expression comes here
...               // more definitions follow
```

code sample

```
while (expression) {
    statement;
    statement;
    while (expression) {
        while (expression)
            statement;
            statement;
    }
}
```

- Highly recursive
- LL(0) grammars: the first token determines in which rule we are
- In other grammars you have to look ahead 1 or more tokens
- Jack is almost LL(0).

Parser implementation: a set of parsing methods, one for each rule:

- `parseStatement()`
- `parseWhileStatement()`
- `parseIfStatement()`
- `parseStatementSequence()`
- `parseExpression()`.

---

## The 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.

'x': x appears verbatim
x: x is a language construct
x?: x appears 0 or 1 times
x*: x appears 0 or more times
x|y: either x or y appears
(x,y): x appears, then y.

---

## The Jack grammar

**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

'x': x appears verbatim
x: x is a language construct
x?: x appears 0 or 1 times
x*: x appears 0 or more times
x|y: either x or y appears
(x,y): x appears, then y.

## The Jack grammar

**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? '**;**'

'x': x appears verbatim
x: x is a language construct
x?: x appears 0 or 1 times
x*: x appears 0 or more times
x|y: either x or y appears
(x,y): x appears, then y.

---

## The Jack grammar

**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**'

'x': x appears verbatim
x: x is a language construct
x?: x appears 0 or 1 times
x*: x appears 0 or more times
x|y: either x or y appears
(x,y): x appears, then y.

---

## Jack syntax analyzer in action

```
Class Bar {
   method Fraction foo(int y)
     var int temp; // a varia
     let temp = (xxx+12)*-63;
     ...
   ...
```

Syntax analyzer

```
<varDec>
  <keyword> var </keyword>
  <keyword> int </keyword>
  <identifier> temp </identifier>
  <symbol> ; </symbol>
</varDec>
<statements>
  <letStatement>
    <keyword> let </keyword>
    <identifier> temp </identifier>
    <symbol> = </symbol>
    <expression>
      <term>
        <symbol> ( </symbol>
        <expression>
          <term>
            <identifier> xxx </identifier>
          </term>
          <symbol> + </symbol>
          <term>
            <int.Const.> 12 </int.Const.>
          </term>
        </expression>
    ...
```

Syntax analyzer

- With the grammar, we can write a syntax analyzer program (parser)
- The syntax analyzer takes a source text file and attempts to match it on the language grammar
- If successful, it can generate a parse tree in some structured format, e.g. XML.

---

## Jack syntax analyzer in action

```
Class Bar {
   method Fraction foo(int y)
     var int temp; // a varia
     let temp = (xxx+12)*-63;
     ...
   ...
```

Syntax analyzer

```
<varDec>
  <keyword> var </keyword>
  <keyword> int </keyword>
  <identifier> temp </identifier>
  <symbol> ; </symbol>
</varDec>
<statements>
  <letStatement>
    <keyword> let </keyword>
    <identifier> temp </identifier>
    <symbol> = </symbol>
    <expression>
      <term>
        <symbol> ( </symbol>
        <expression>
          <term>
            <identifier> xxx </identifier>
          </term>
          <symbol> + </symbol>
          <term>
            <int.Const.> 12 </int.Const.>
          </term>
        </expression>
    ...
```

- If **xxx** is non-terminal, output:

  **<xxx>**
  Recursive code for the body of **xxx**
  **</xxx>**

- If **xxx** is terminal (keyword, symbol, constant, or identifier) , output:

  **<xxx>**
  **xxx** value
  **</xxx>**

## The Jack grammar

**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'

'x': x appears verbatim
x: x is a language construct
x?: x appears 0 or 1 times
x*: x appears 0 or more times
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---

## Recursive descent parser (simplified expression)

- EXP → TERM (OP TERM)*
- TERM → integer | variable
- OP → + | - | * | /

---

## From parsing to code generation

- EXP → TERM (OP TERM)*
- TERM → integer | variable
- OP → + | - | * | /

```
EXP() :
   TERM();
   while (next()==OP)
      OP();
      TERM();
```

---

## From parsing to code generation

- EXP → TERM (OP TERM)*
- TERM → integer | variable
- OP → + | - | * | /

```
EXP() :
   TERM();
   while (next()==OP)
      OP();
      TERM();
```

```
TERM():
   switch (next())
     case INT:
                eat(INT);
     case VAR:
                eat(VAR);
```

## From parsing to code generation

- EXP → TERM (OP TERM)*
- TERM → integer | variable
- OP → + | - | * | /

```
OP():
   switch (next())
     case +: eat(ADD);

     case -: eat(SUB);

     case *: eat(MUL);

     case /: eat(DIV);
```

```
EXP() :
   TERM();
   while (next()==OP)
       OP();
      TERM();

TERM():
   switch (next())
     case INT:
                  eat(INT);
     case VAR:
                  eat(VAR);
```

---

## From parsing to code generation

- EXP → TERM (OP TERM)*
- TERM → integer | variable
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     case VAR:
                  eat(VAR);
```

---

## From parsing to code generation

- EXP → TERM (OP TERM)*
- TERM → integer | variable
- OP → + | - | * | /

```
OP(): print(‘<op>’);
   switch (next())
     case +: eat(ADD);
            print(‘<sym> + </sym>’);
     case -: eat(SUB);
            print(‘<sym> - </sym>’);
     case *: eat(MUL);
            print(‘<sym> * </sym>’);
     case /: eat(DIV);
            print(‘<sym> / </sym>’);
   print(‘</op>’);
```

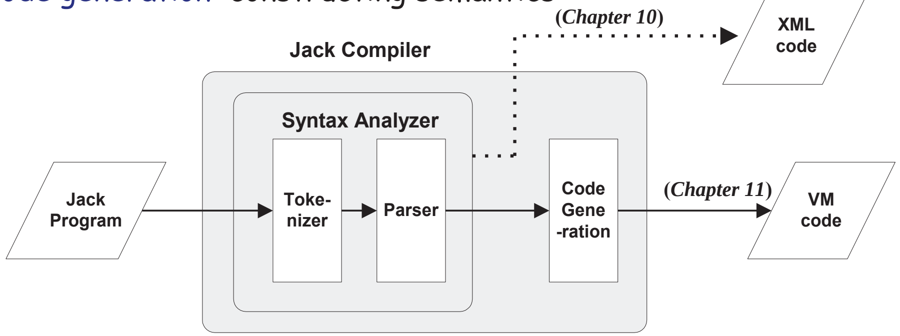
```
EXP() : print(‘<exp>’);
   TERM();
   while (next()==OP)
       OP();
      TERM();
   print(‘</exp>’);

TERM(): print(‘<term>’);
   switch (next())
     case INT: print(‘<int> next() </int>’);
                  eat(INT);
     case VAR: print(‘<id> next() </id>’);
                  eat(VAR);
   print(‘</term>’);
```

---

## Summary and next step

- Syntax analysis: understanding syntax
- Code generation: constructing semantics



The code generation challenge:

- Extend the syntax analyzer into a full-blown compiler that, instead of passive XML code, generates executable VM code
- Two challenges: (a) handling data, and (b) handling commands.

## Perspective

- The parse tree can be constructed on the fly
- The Jack language is intentionally simple:
  - Statement prefixes: **`let`**, **`do`**, ...
  - No operator priority
  - No error checking
  - Basic data types, etc.
- The Jack compiler: designed to illustrate the key ideas that underlie modern compilers, leaving advanced features to more advanced courses
- Richer languages require more powerful compilers

---

## Perspective

- Syntax analyzers can be built using:
  - **`Lex`** tool for tokenizing (flex)
  - **`Yacc`** tool for parsing (bison)
  - Do everything from scratch (our approach ...)
- Industrial-strength compilers: (LLVM)
  - Have good error diagnostics
  - Generate tight and efficient code
  - Support parallel (multi-core) processors.