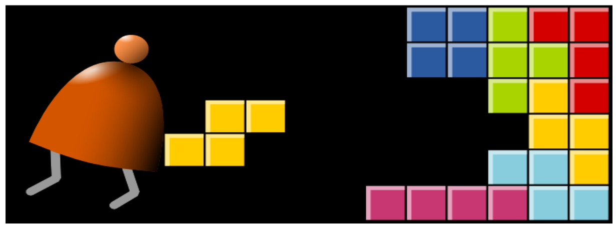
Compiler I: Syntax Analysis



Building a Modern Computer From First Principles

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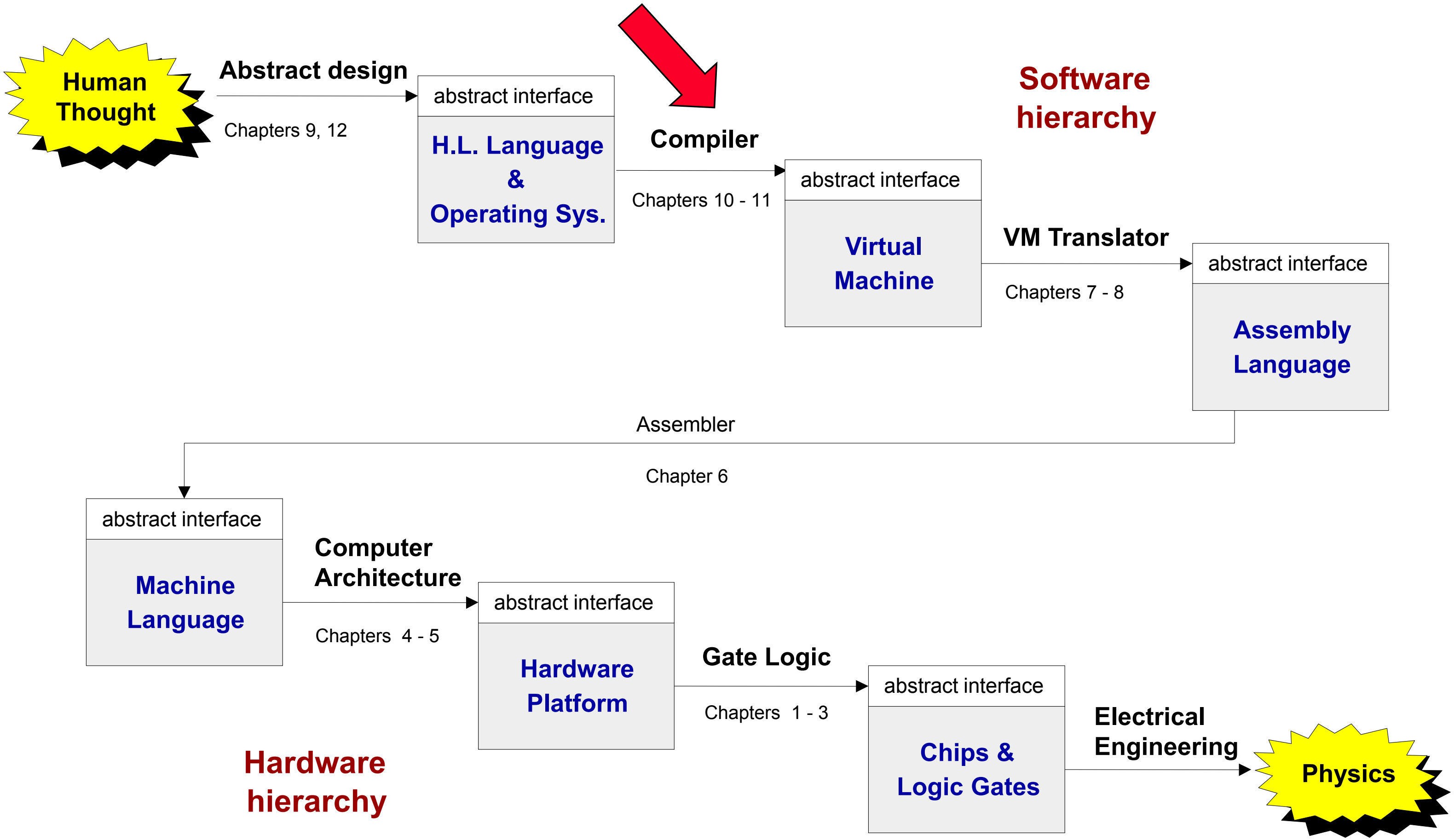
Course map



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Virtual Machine
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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.

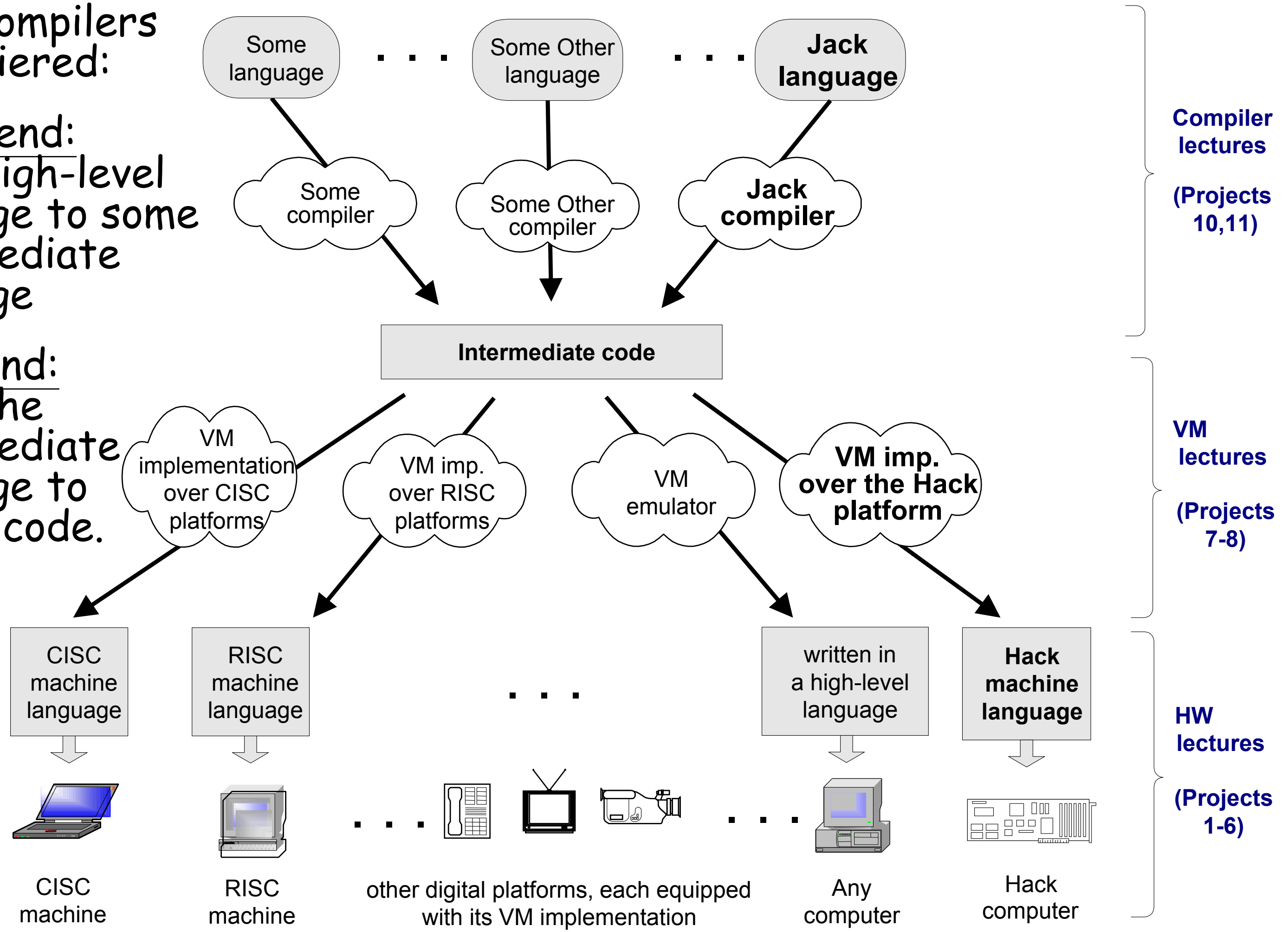
Because Compilers …

- 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.

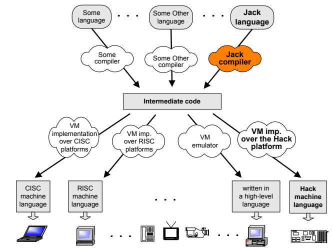
The big picture

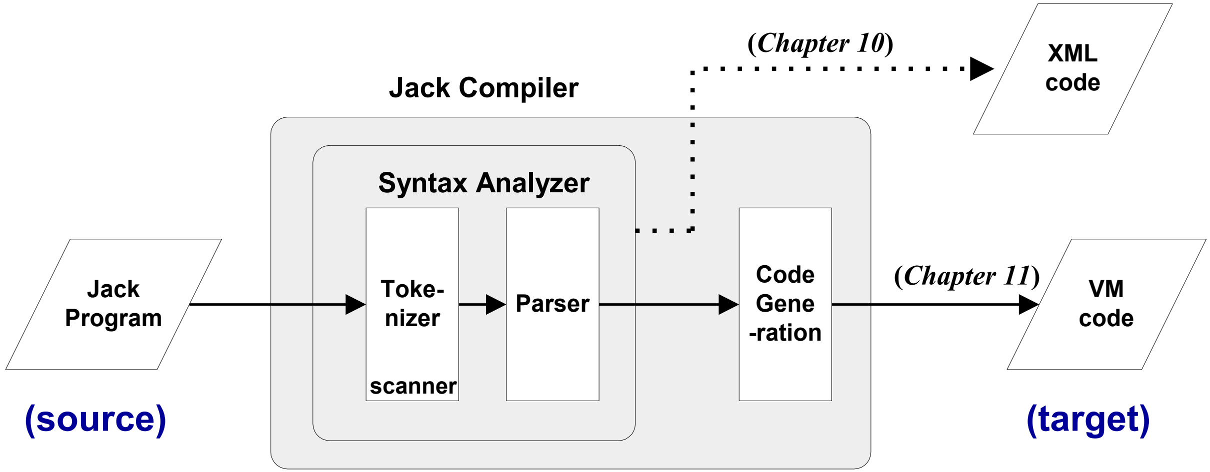
Modern compilers are two-tiered:

- **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

```c
/* 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;
}
```

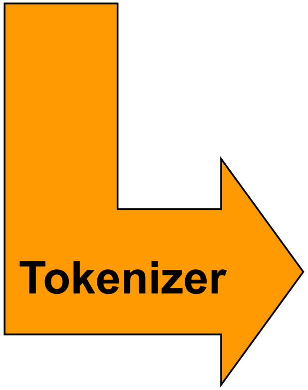
Output:

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

Jack Tokenizer

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

Source code



Tokenizer'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>
```

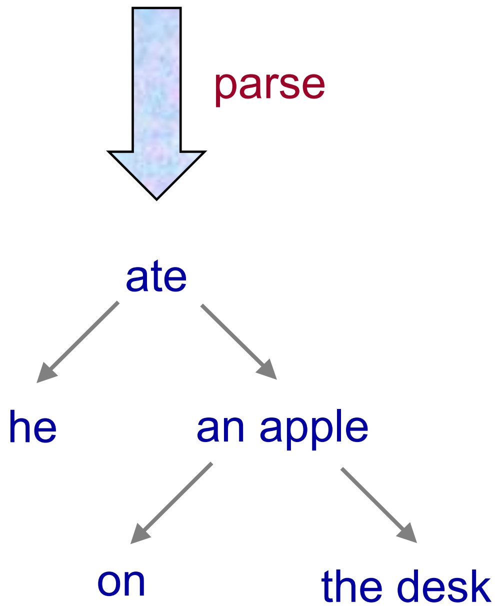
Parsing

- 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, …).

Parsing examples

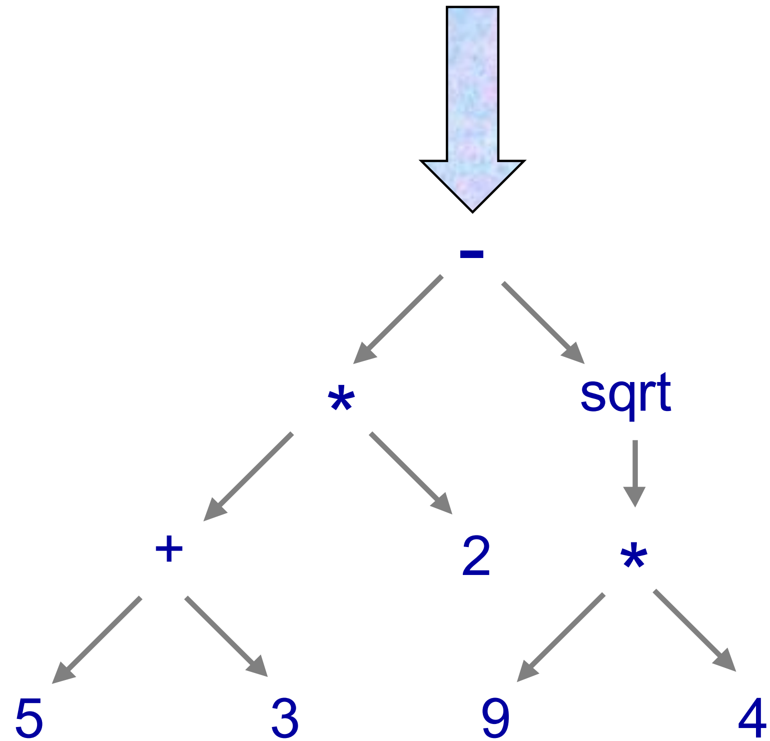
English

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



Jack

```
(5+3)*2 – sqrt(9*4)
```



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

- $S \to ()$
  $S \to (S)$
  $S \to SS$
- $S \to a|aS|bS$
  strings ending with 'a'
- $S \to x$
  $S \to y$
  $S \to S+S$
  $S \to S-S$
  $S \to S*S$
  $S \to S/S$
  $S \to (S)$
  $(x+y)*x-x*y/(x+x)$

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)

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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)

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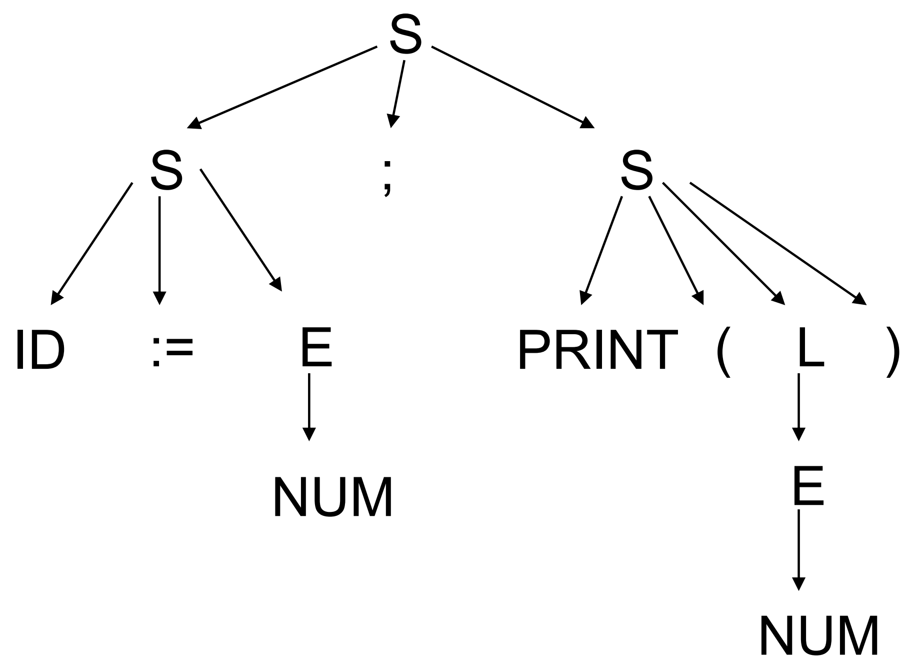
Parse tree

- 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:

$$E \rightarrow ID$$
$$E \rightarrow NUM$$
$$E \rightarrow E + E$$
$$E \rightarrow E * E$$

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

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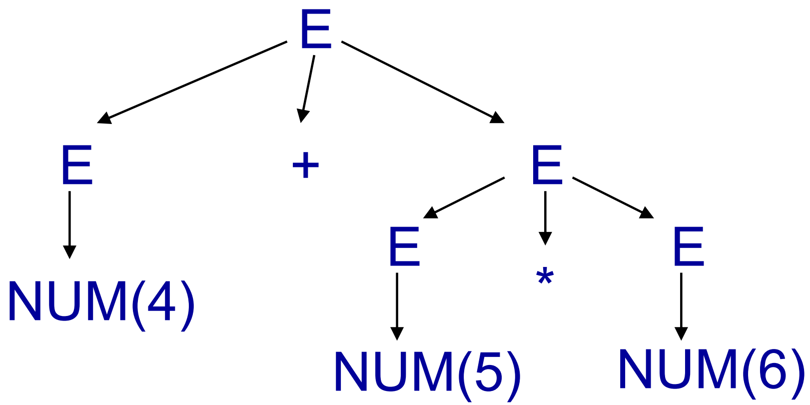
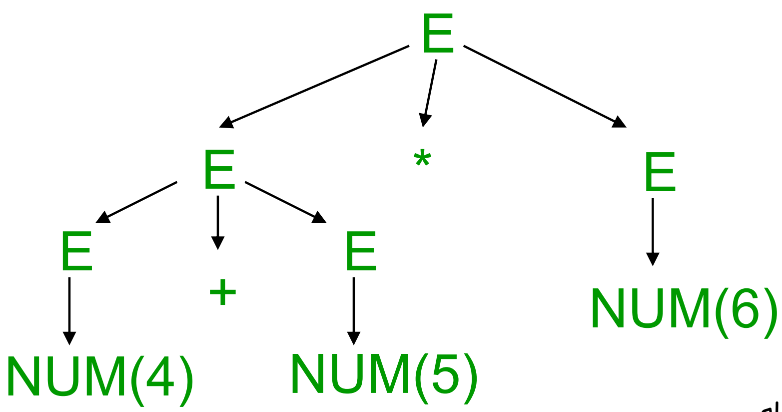
Ambiguous Grammars

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

$E \rightarrow ID$
$E \rightarrow NUM$
$E \rightarrow E + E$
$E \rightarrow E * E$





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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
- 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

```
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;
  }
}
```

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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
- 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

```
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

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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
2. A -> ID := E
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
- 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

```
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())
- Rules:

1. S -> A EOF
2. A -> ID := E
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
  2. A -> ID := E
  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++;
      // ...
```

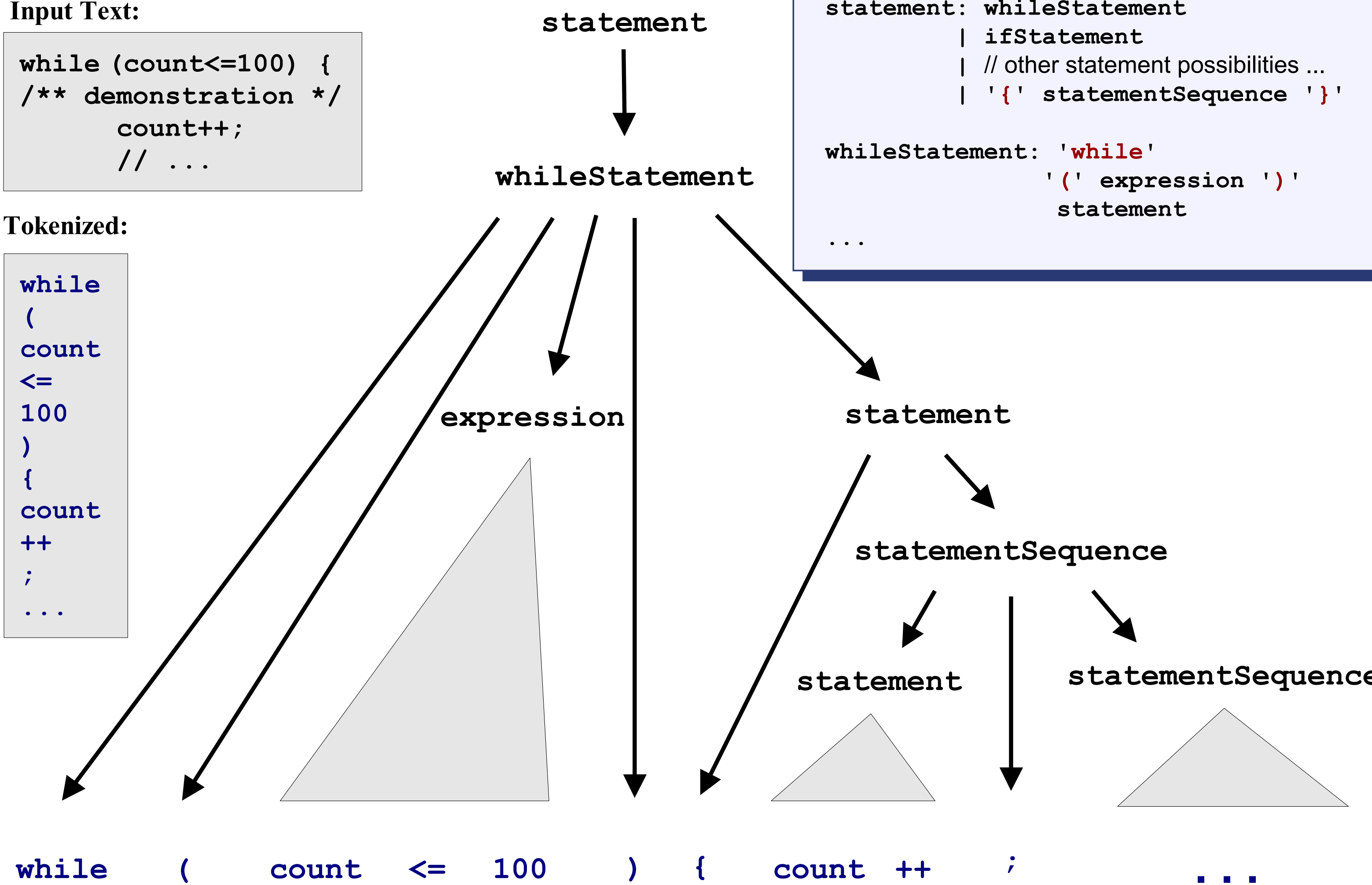
Tokenized:

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

```
program:   statement;

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

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



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'

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Jack syntax analyzer in action

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

Syntax analyzer

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.

```
<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>
    ...
```

Jack syntax analyzer in action

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

Syntax analyzer

- 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>
```

```
<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>
    ...
```

The Jack grammar

Expressions:

expression:	term (op term)*
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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);
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                  eat(VAR);
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From parsing to code generation

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```
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   switch (next())
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EXP() :
   TERM();
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      OP();
      TERM();
```

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

From parsing to code generation

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

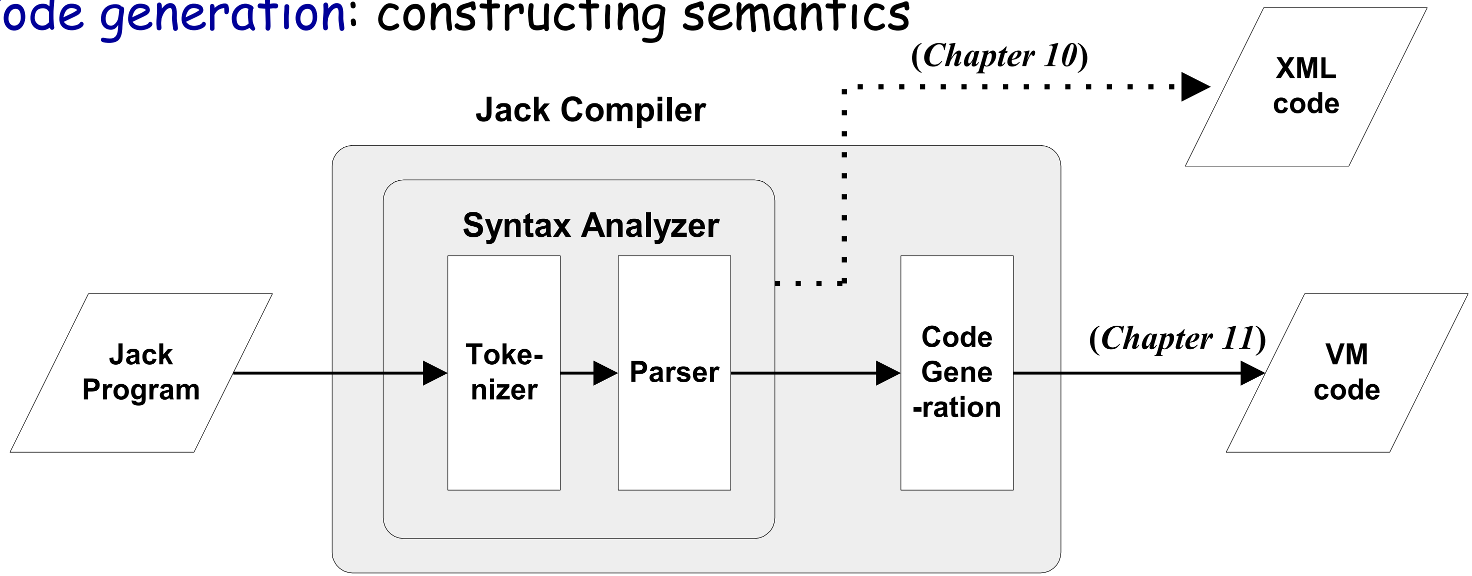
```
OP(): print('<op>');
   switch (next())
     case +: eat(ADD);
               print('<sym> + </sym>');
     case -: eat(SUB);
               print('<sym> - </sym>');
     case *: eat(MUL);
               print('<sym> * </sym>');
     case /: eat(DIV);
               print('<sym> / </sym>');
   print('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