Compiler Construction

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http://ssw.jku.at/Misc/CC/

Text Book

N.Wirth: Compiler Construction, Addison-Wesley 1996
http://www.ethoberon.ethz.ch/WirthPubl/CBEAll.pdf

1. Overview

1.1 Motivation

1.2 Structure of a Compiler

1.3 Grammars

1.4 Chomsky's Classification of Grammars

1.5 The MicroJava Language

Why should I learn about compilers?

It's part of the general background of any software engineer

- How do compilers work?
- How do computers work?
  (instruction set, registers, addressing modes, run-time data structures, ...)
- What machine code is generated for certain language constructs?
  (efficiency considerations)
- What is good language design?
- Opportunity for a non-trivial programming project

Also useful for general software development

- Reading syntactically structured command-line arguments
- Reading structured data (e.g. XML files, part lists, image files, ...)
- Searching in hierarchical namespaces
- Interpretation of command codes
- ...

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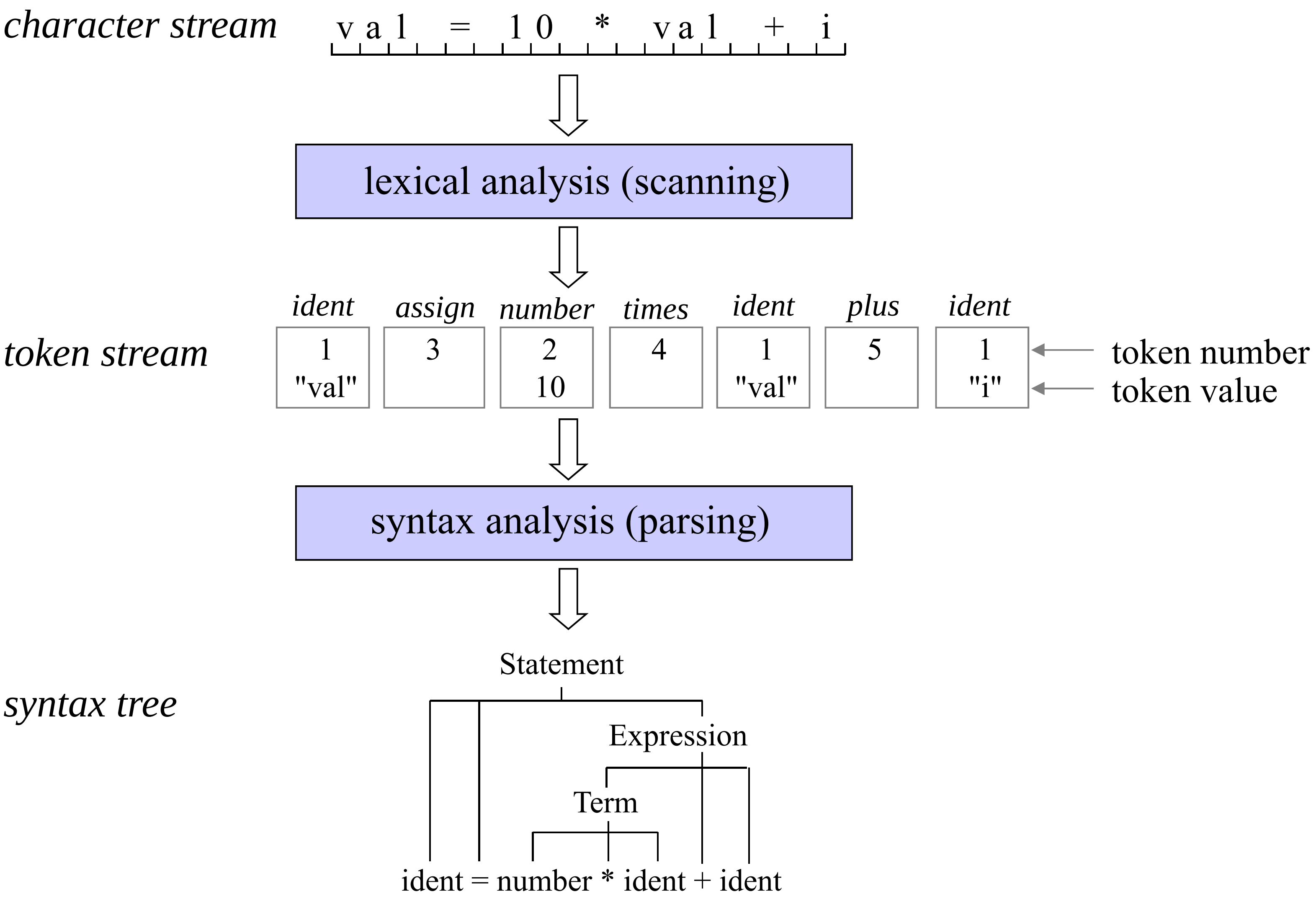
Dynamic Structure of a Compiler



character stream

v a l = 1 0 * v a l + i

lexical analysis (scanning)

token stream

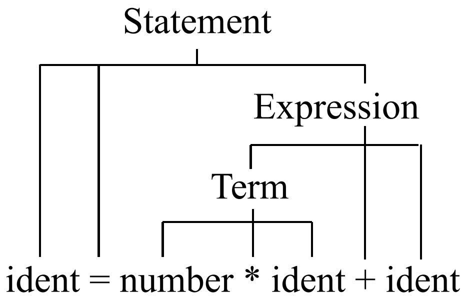
ident	*assign*	*number*	*times*	*ident*	*plus*	*ident*	
1	3	2	4	1	5	1	token number
"val"		10		"val"		"i"	token value

syntax analysis (parsing)

syntax tree

Dynamic Structure of a Compiler

syntax tree



⇩

semantic analysis (type checking, ...)

⇩

intermediate representation

syntax tree, symbol table, ...

⇩

optimization

⇩

code generation

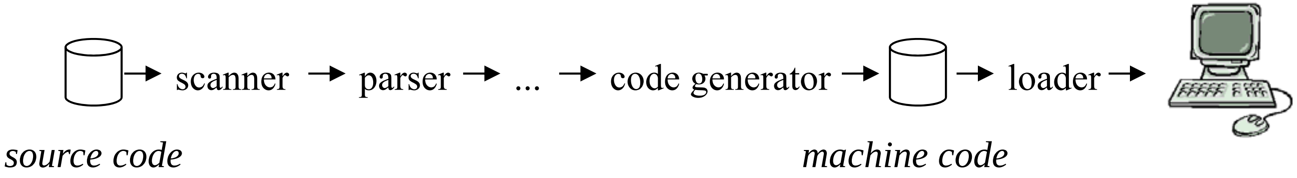
⇩

machine code

```
const 10
load  1
mul
...
```

Compiler versus Interpreter

Compiler translates to machine code

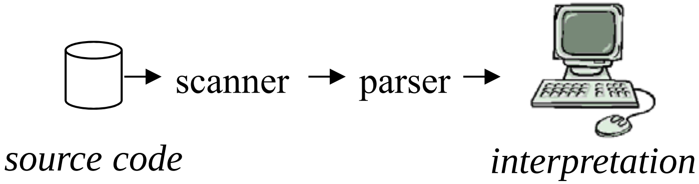


scanner → parser → ... → code generator → loader →

source code

machine code

Interpreter executes source code "directly"



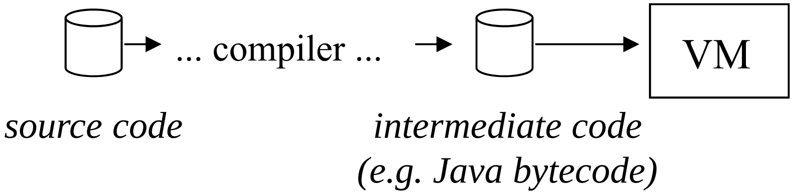
scanner → parser →

source code

interpretation

- statements in a loop are scanned and parsed again and again

Variant: interpretation of intermediate code



... compiler ...

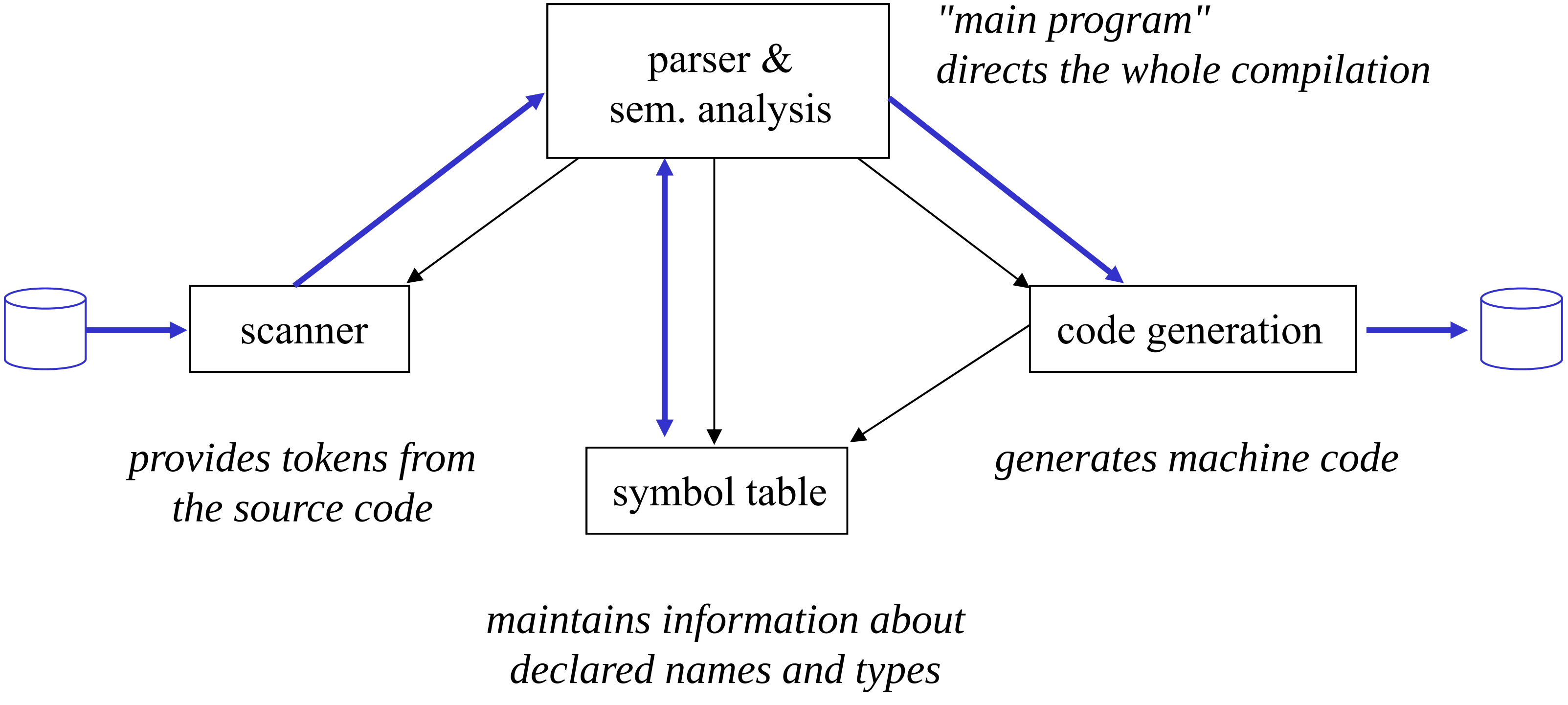
VM

source code

intermediate code (e.g. Java bytecode)

- source code is translated into the code of a *virtual machine* (VM)
- VM interprets the code simulating the physical machine

Static Structure of a Compiler



parser & sem. analysis

"main program" directs the whole compilation

scanner

provides tokens from the source code

symbol table

maintains information about declared names and types

code generation

generates machine code

→ uses

➞ data flow

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What is a grammar?

Example Statement = "if" "(" Condition ")" Statement ["else" Statement].

Four components

terminal symbols	are atomic	"if", ">=", ident, number, ...
nonterminal symbols	are decomposed into smaller units	Statement, Condition, Type, ...

productions	rules how to decompose nonterminals	Statement = Designator "=" Expr ";".
		Designator = ident ["." ident].
		...

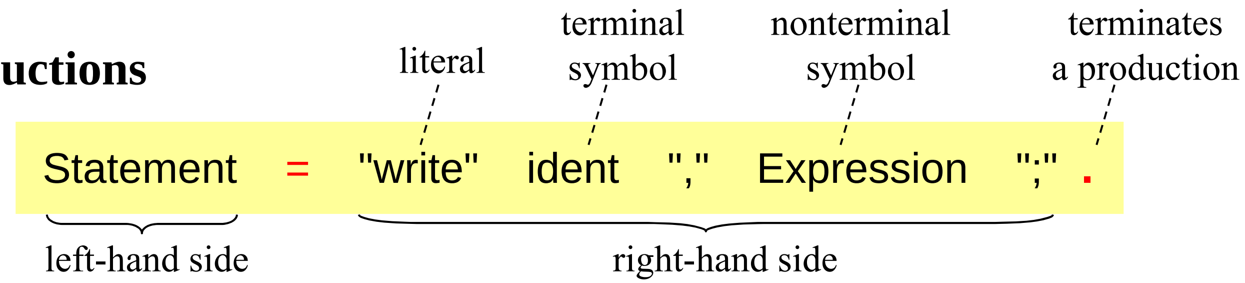
start symbol	topmost nonterminal	Java

EBNF Notation

Extended Backus-Naur form for writing grammars

John Backus: developed the first Fortran compiler
Peter Naur: edited the Algol60 report

Productions



literal
terminal symbol
nonterminal symbol
terminates a production

Statement = "write" ident "," Expression ";" .

left-hand side
right-hand side

by convention

- terminal symbols start with lower-case letters
- nonterminal symbols start with upper-case letters

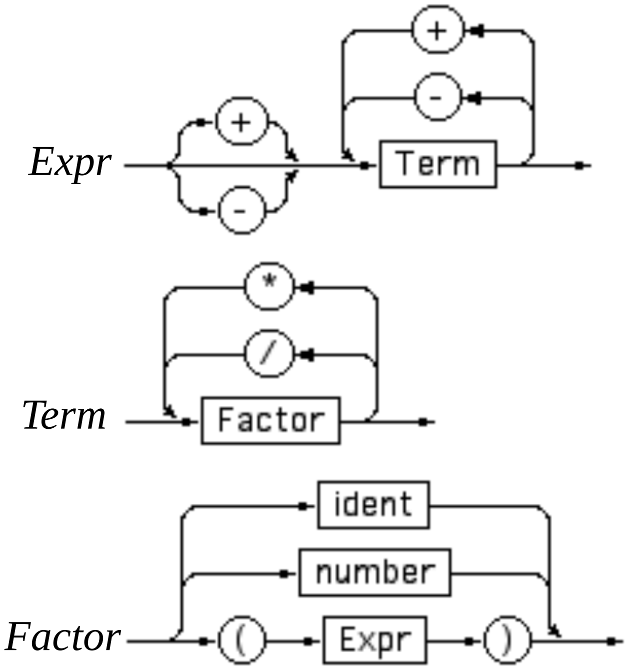
Metasymbols

|	separates alternatives	a | b | c	≡ a or b or c
(...)	groups alternatives	a (b | c)	≡ ab | ac
[...]	optional part	[a] b	≡ ab | b
{...}	iterative part	{a}b	≡ b | ab | aab | aaab | ...

Example: Grammar for Arithmetic Expressions

Productions

```
Expr    = ["+" | "-"] Term {("+" | "-") Term}.
Term    = Factor {("*" | "/") Factor}.
Factor  = ident | number | "(" Expr ")".
```



Terminal symbols

simple TS: "+", "-", "*", "/", "(", ")"
(just 1 instance)

terminal classes: ident, number
(multiple instances)

Nonterminal symbols

Expr, Term, Factor

Start symbol

Expr

Operator Priority

Grammars can be used to define the priority of operators

```
Expr   = ["+" | "-"] Term {("+" | "-") Term}.
Term   = Factor {("*" | "/") Factor}.
Factor = ident | number | "(" Expr ")".
```

input: - a * 3 + b / 4 - c

$\Rightarrow$ - ident * number + ident / number - ident

$\Rightarrow$ $-\ \underbrace{\text{Factor * Factor}}\ +\ \underbrace{\text{Factor / Factor}}\ -\ \underbrace{\text{Factor}}$

$\Rightarrow$ $\underbrace{-\ \text{Term}\ +\ \text{Term}\ -\ \text{Term}}$

$\Rightarrow$ Expr

"*" and "/" have higher priority than "+" and "-"

"-" does not refer to *a*, but to *a**3

How must the grammar be transformed, so that "-" refers to *a*?

Terminal Start Symbols of Nonterminals

What are the terminal symbols with which a nonterminal can start?

```
Expr   = ["+" | "-"] Term {("+" | "-") Term}.
Term   = Factor {("*" | "/") Factor}.
Factor = ident | number | "(" Expr ")".
```

First(Factor) = ident, number, "("

First(Term) = First(Factor)
= ident, number, "("

First(Expr) = "+", "-", First(Term)
= "+", "-", ident, number, "("

Terminal Successors of Nonterminals

Which terminal symbols can follow a nonterminal in the grammar?

```
Expr    = ["+" | "-"] Term {("+" | "-") Term}.
Term    = Factor {("*" | "/") Factor}.
Factor  = ident | number | "(" Expr ")".
```

Where does *Expr* occur on the right-hand side of a production? What terminal symbols can follow there?

Follow(Expr) = ")", eof

Follow(Term) = "+", "-", Follow(Expr)

= "+", "-", ")", eof

Follow(Factor) = "*", "/", Follow(Term)

= "*", "/", "+", "-", ")", eof

Strings and Derivations

String

A finite sequence of symbols from an alphabet.
Alphabet: all terminal and nonterminal symbols of a grammar.

Strings are denoted by greek letters (α, β, γ, ...)
e.g: α = ident + number
β = - Term + Factor * number

Empty String

The string that contains no symbol (denoted by ε).

Derivation

$\alpha \Rightarrow \beta$ (direct derivation)

$$\overbrace{\text{Term + }\underbrace{\text{Factor}}_{\text{NTS}}\text{ * Factor}}^{\alpha} \Rightarrow \overbrace{\text{Term + }\underbrace{\text{ident}}_{\text{right-hand side of a production of NTS}}\text{ * Factor}}^{\beta}$$

$\alpha \Rightarrow^{*} \beta$ (indirect derivation)

$$\alpha \Rightarrow \gamma_1 \Rightarrow \gamma_2 \Rightarrow \ldots \Rightarrow \gamma_n \Rightarrow \beta$$

Recursion

A production is recursive if $\boxed{X \Rightarrow^* \omega_1\ X\ \omega_2}$

Can be used to represent repetitions and nested structures

Direct recursion $\boxed{X \Rightarrow \omega_1\ X\ \omega_2}$

Left recursion	X = b | X a.	X ⇒ X a ⇒ X a a ⇒ X a a a ⇒ b a a a a a ...
Right recursion	X = b | a X.	X ⇒ a X ⇒ a a X ⇒ a a a X ⇒ ... a a a a a b
Central recursion	X = b | "(" X ")".	X ⇒ (X) ⇒ ((X)) ⇒ (((X))) ⇒ (((... (b)...)))

Indirect recursion $\boxed{X \Rightarrow^* \omega_1\ X\ \omega_2}$

Example

```
Expr   = Term {"+" Term}.
Term   = Factor {"*" Factor}.
Factor = id | "(" Expr ")".
```

Expr ⇒ Term ⇒ Factor ⇒ "(" Expr ")"

How to Remove Left Recursion

Left recursion cannot be handled in topdown parsing

X = b | X a.

Both alternatives start with *b*.
The parser cannot decide which one to choose

Left recursion can always be transformed into iteration

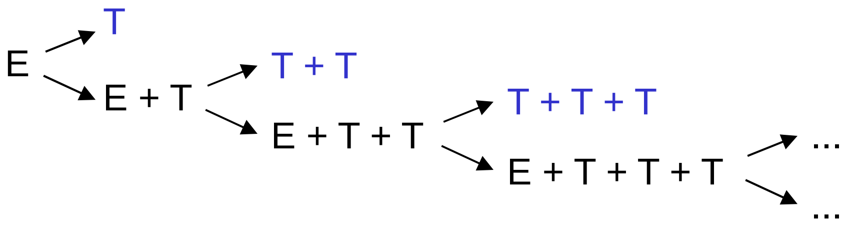
X ⇒ baaaa...a

X = b {a} .

Another example

E = T | E "+" T.

What phrases can be derived?



E
T
E + T
T + T
E + T + T
T + T + T
E + T + T + T
...
...

Thus

E = T {"+" T}.

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Classification of Grammars

Due to Noam Chomsky (1956)

Grammars are sets of productions of the form $\alpha = \beta$.

class 0 **Unrestricted grammars** (α and β arbitrary)

e.g: X = a X b | Y c Y.
aYc = d.
dY = bb.

$X \Rightarrow aXb \Rightarrow aYcYb \Rightarrow dYb \Rightarrow bbb$

Recognized by Turing machines

class 1 **Context-sensitive grammars** ($|\alpha| \leq |\beta|$)

e.g: a X = a b c.

Recognized by linear bounded automata

class 2 **Context-free grammars** (α = NT, $\beta \neq \varepsilon$)

e.g: X = a b c.

Recognized by push-down automata

class 3 **Regular grammars** (α = NT, β = T or T NT)

e.g: X = b | b Y.

Recognized by finite automata

} Only these two classes are relevant in compiler construction

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Sample MicroJava Program

```
program P
    final int size = 10;
    class Table {
        int[] pos;
        int[] neg;
    }
    Table val;
{
    void main()
        int x, i;
    {   //---------- initialize val ----------
        val = new Table;
        val.pos = new int[size];
        val.neg = new int[size];
        i = 0;
        while (i < size) {
            val.pos[i] = 0; val.neg[i] = 0; i = i + 1;
        }
        //---------- read values ----------
        read(x);
        while (x != 0) {
            if (x >= 0) val.pos[x] = val.pos[x] + 1;
            else if (x < 0) val.neg[-x] = val.neg[-x] + 1;
            read(x);
        }
    }
}
```

main program; no separate compilation

classes (without methods)

global variables

local variables

Lexical Structure of MicroJava

Names ident = letter {letter | digit | '_'}.

Numbers number = digit {digit}. all numbers are of type *int*

Char constants charConst = '\'' char '\''. all character constants are of type *char* (may contain \r, \n, \t)

no strings

Keywords

```
program  class
if       else    while   read    print   return   void
final    new
```

Operators

```
+    -    *    /    %
==   !=   >    >=   <    <=
(    )    [    ]    {    }
=    ;    ,    .
```

Comments // ... eol

Types *int* *char* arrays classes

Syntactical Structure of MicroJava

Programs

```
Program  =  "program" ident
            {ConstDecl | VarDecl | ClassDecl}
            "{" {MethodDecl} "}".
```

```
program P
    ... declarations ...
{   ... methods ...
}
```

Declarations

```
ConstDecl     =  "final" Type ident "=" (number | charConst) ";".
VarDecl       =  Type ident {"," ident} ";".
MethodDecl    =  (Type | "void") ident "(" [FormPars] ")"
                 {VarDecl} Block.

Type          =  ident [ "[" "]" ].
FormPars      =  Type ident {"," Type ident}.
```

just one-dimensional arrays

Syntactical Structure of MicroJava

Statements

```
Block        = "{" {Statement} "}".
Statement    = Designator  (   "=" Expr ";"
                           |   "(" [ActPars] ")" ";"
                           )
             |  "if" "(" Condition ")" Statement ["else" Statement]
             |  "while" "(" Condition ")" Statement
             |  "return" [Expr] ";"
             |  "read" "(" Designator ")" ";"
             |  "print" "(" Expr ["," number] ")" ";"
             |  Block
             |  ";".
ActPars      = Expr {"," Expr}.
```

- input from *System.in*
- output to *System.out*

Syntactical Structure of MicroJava

Expressions

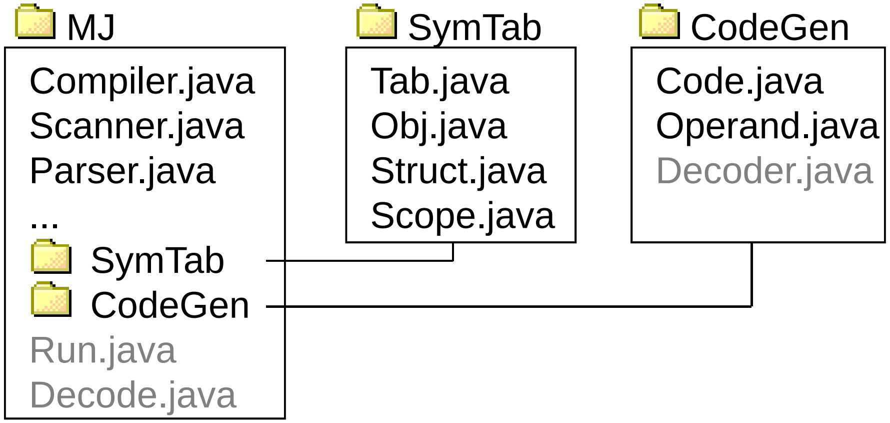
```
Condition     =  Expr Relop Expr.
Relop         =  "==" | "!=" | ">" | ">=" | "<" | "<=".
```

```
Expr          =  ["-"] Term {Addop Term}.
Term          =  Factor {Mulop Factor}.
Factor        =  Designator [ "(" [ActPars] ")" ]
              |  number
              |  charConst
              |  "new" ident [ "[" Expr "]" ]
              |  "(" Expr ")".
Designator    =  ident { "." ident | "[" Expr "]" }.
Addop         =  "+" | "-".
Mulop         =  "*" | "/" | "%".
```

no constructors

The MicroJava Compiler

Package structure



MJ
Compiler.java
Scanner.java
Parser.java
...
SymTab
CodeGen
Run.java
Decode.java

SymTab
Tab.java
Obj.java
Struct.java
Scope.java

CodeGen
Code.java
Operand.java
Decoder.java

Compilation of a MicroJava program

```
java MJ.Compiler  myProg.mj
```

myProg.mj → compiler → myProg.obj

Execution

```
java MJ.Run  myProg.obj  -debug
```

myProg.obj → interpreter

Decoding

```
java MJ.Decode  myProg.obj
```

myProg.obj → decoder → myProg.code