2. Lexical Analysis

2.1 Tasks of a Scanner

2.2 Regular Grammars and Finite Automata

2.3 Scanner Implementation

Tasks of a Scanner

1. Delivers tokens

i	f		(	x	=	=	3	)		

→ scanner → if, lpar, ident, eql, number, rpar, ..., eof

character stream

token stream
(must end with eof)

2. Skips meaningless characters

- blanks
- tabulator characters
- end-of-line characters (CR, LF)
- comments

Tokens have a syntactical structure, e.g.

```
ident =     letter {letter | digit}.
number =    digit {digit}.
if =        "i" "f".
eql =       "=" "=".
...
```

Why is scanning not part of parsing?

Why is Scanning not Part of Parsing?

It would make parsing more complicated
(e.g. difficult distinction between keywords and names)

```
Statement =  ident "=" Expr ";"
          |  "if" "(" Expr ")" ... .
```

One would have to write this as follows:

```
Statement =  "i" (   "f" "(" Expr ")" ...
                 |   notF {letter | digit} "=" Expr ";"
                 )
          |  notI {letter | digit} "=" Expr ";".
```

The scanner must eliminate blanks, tabs, end-of-line characters and comments
(these characters can occur anywhere => would lead to very complex grammars)

```
Statement =  "if" {Blank} "(" {Blank} Expr {Blank} ")" {Blank} ... .
Blank = " " | "\r" | "\n" | "\t" | Comment.
```

Tokens can be described with regular grammars
(simpler and more efficient than context-free grammars)

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Regular Grammars

Definition
A grammar is called regular if it can be described by productions of the form:

```
X = a.
X = b Y.
```

a, b $\in$ TS
X, Y $\in$ NTS

Example Grammar for identifiers

```
Ident  =  letter
       |  letter Rest.
Rest   =  letter
       |  digit
       |  letter Rest
       |  digit Rest.
```

e.g., derivation of the name xy3

Ident $\Rightarrow$ letter Rest $\Rightarrow$ letter letter Rest $\Rightarrow$ letter letter digit

Alternative definition
A grammar is called regular if it can be described by a <u>single non-recursive</u> EBNF production.

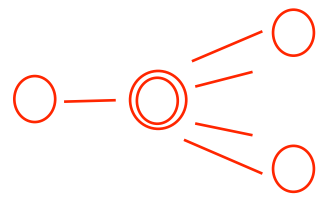
Example Grammar for identifiers

```
Ident  =  letter {letter | digit}.
```

Examples

Can we transform the following grammar into a regular grammar?

```
E = T {"+" T}.
T = F {"*" F}.
F = id.
```



Can we transform the following grammar into a regular grammar?

```
E = F {"*" F}.
F = id | "(" E ")".
```

Limitations of Regular Grammars

Regular grammars cannot deal with *nested structures*
because they cannot handle *central recursion*!

But central recursion is important in most programming languages

• nested expressions	Expr $\Rightarrow^*$ ... "(" Expr ")" ...
• nested statements	Statement $\Rightarrow$ "do" Statement "while" "(" Expr ")"
• nested classes	Class $\Rightarrow$ "class" "{" ... Class ... "}"

For productions like these we need context-free grammars

But most lexical structures are regular

names	letter {letter | digit}
numbers	digit {digit}
strings	"\"" {noQuote} "\""
keywords	letter {letter}
operators	">" "="

Exception: nested comments

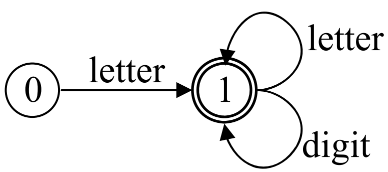
/* ..... /* ... */ ..... */

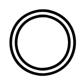
The scanner must treat them in a special way

Deterministic Finite Automaton (DFA)

Can be used to analyze regular languages

Example



 final state

start state is always state 0 by convention

State transition function as a table

δ	letter	digit
s0	s1	error
s1	s1	s1

"finite", because δ can be written down explicitly

Definition

A deterministic finite automaton is a 5 tuple (S, I, δ, s0, F)

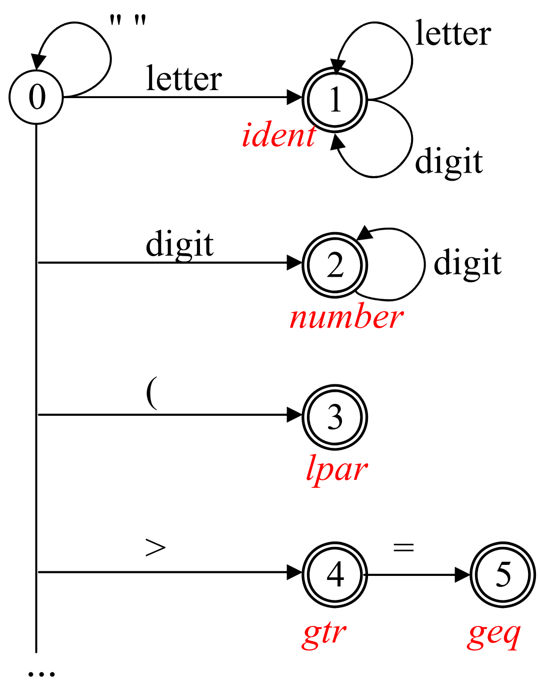
- S — set of states
- I — set of input symbols
- $\delta: S \times I \rightarrow S$ — state transition function
- s0 — start state
- F — set of final states

The **language** recognized by a DFA is the set of all symbol sequences that lead from the start state into one of the final states

A DFA has recognized a sentence
- if it is in a final state
- <u>and</u> if the input is totally consumed <u>or</u> there is no possible transition with the next input symbol

The Scanner as a DFA

The scanner can be viewed as a big DFA



Example input: max >= 30

$$s0 \xrightarrow{m} s1 \xrightarrow{a} s1 \xrightarrow{x} s1$$

- no transition with " " in s1
- *ident* recognized

$$s0 \xrightarrow{\text{" "}} s0 \xrightarrow{>} s4 \xrightarrow{=} s5$$

- skips blanks at the beginning
- does not stop in s4
- no transition with " " in s5
- *geq* recognized

$$s0 \xrightarrow{\text{" "}} s0 \xrightarrow{3} s2 \xrightarrow{0} s2$$

- skips blanks at the beginning
- no transition with " " in s2
- *number* recognized

After every recognized token the scanner starts in s0 again

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Scanner Interface

```
class Scanner {
    static void     init (Reader r) {...}
    static Token  next () {...}
}
```

For efficiency reasons methods are static (there is just one scanner per compiler)

Initializing the scanner

```
InputStream s = new FileInputStream("myfile.mj");
Reader r = new InputStreamReader(s);
Scanner.init(r);
```

Reading the token stream

```
for (;;) {
    Token t = Scanner.next();
    ...
}
```

Tokens

```
class Token {
    int kind;       // token code
    int line;       // token line (for error messages)
    int col;        // token column (for error messages)
    int val;        // token value (for number and charCon)
    String string;  // token string
}
```

Token codes for MicroJava

error token | token classes | operators and special characters | keywords | end of file

static final int

```
none = 0,

ident = 1,
number = 2,
charCon = 3,

plus   = 4,  /* + */     assign    = 15, /* = */
minus  = 5,  /* - */     semicolon = 16, /* ; */
times  = 6,  /* * */     comma     = 17, /* , */
slash  = 7,  /* / */     period    = 18, /* . */
rem    = 8,  /* % */     lpar      = 19, /* ( */
eql    = 9,  /* == */    rpar      = 20, /* ) */
neq    = 10, /* != */    lbrack    = 21, /* [ */
lss    = 11, /* < */     rbrack    = 22, /* ] */
leq    = 12, /* <= */    lbrace    = 23, /* { */
gtr    = 13, /* > */     rbrace    = 24, /* } */
geq    = 14, /* >= */

class_    = 25,
else_     = 26,
final_    = 27,
if_       = 28,
new_      = 29,
print_    = 30,
program_  = 31,
read_     = 32,
return_   = 33,
void_     = 34,
while_    = 35,

eof       = 36;
```

Scanner Implementation

Static variables in the scanner

```
static Reader in;                    // input stream
static char ch;                      // next input character (still unprocessed)
static int line, col;                // line and column number of the character ch

static final int eofCh = '\u0080';   // character that is returned at the end of the file
```

init()

```
public static void init (Reader r) {
    in = r;
    line = 1; col = 0;
    nextCh();  // reads the first character into ch and increments col to 1
}
```

nextCh()

```
private static void nextCh() {
    try {
        ch = (char) in.read(); col++;
        if (ch == '\n') { line++; col = 0; }
        else if (ch == '\uffff') ch = eofCh;
    } catch (IOException e) { ch = eofCh; }
}
```

- *ch* = next input character
- returns *eofCh* at the end of the file
- increments *line* and *col*

next()

```
public static Token next() {
    while (ch <= ' ') nextCh();  // skip blanks, tabs, eols
    Token t = new Token(); t.line = line; t.col = col;
    switch (ch) {
```

```
        case 'a': case 'b': ... case 'z': case 'A': case 'B': ... case 'Z':
                    readName(t); break;
```

names, keywords

```
        case '0': case '1': ... case '9':
                    readNumber(t); break;
```

numbers

```
        case ';':   nextCh(); t.kind = semicolon; break;
        case '.':   nextCh(); t.kind = period; break;
        case eofCh: t.kind = eof; break;  // no nextCh() any more
        ...
```

simple tokens

```
        case '=':   nextCh();
                    if (ch == '=') { nextCh(); t.kind = eql; } else t.kind = assign;
                    break;
        ...
```

compound tokens

```
        case '/':   nextCh();
                    if (ch == '/') {
                        do nextCh(); while (ch != '\n' && ch != eofCh);
                        t = next();  // call scanner recursively
                    } else t.kind = slash;
                    break;
```

comments

```
        default:    nextCh(); t.kind = none; break;
```

invalid character

```
    }
    return t;
} // ch holds the next character that is still unprocessed
```

Further Methods

private static void readName(Token t)

- At the beginning *ch* holds the first letter of the name
- Reads further letters and digits and stores them in *t.string*
- Looks up the name in a keyword table (using hashing or binary search)
  if found: t.kind = *token number of the keyword*;
  otherwise: t.kind = ident;
- At the end *ch* holds the first character after the name

private static void readNumber(Token t)

- At the beginning *ch* holds the first digit of the number
- Reads further digits, converts them into a number and stores the number value to *t.val*.
  if overflow: report an error
- t.kind = number;
- At the end *ch* holds the first character after the number