Languages and Compilers (SProg og Oversættere)

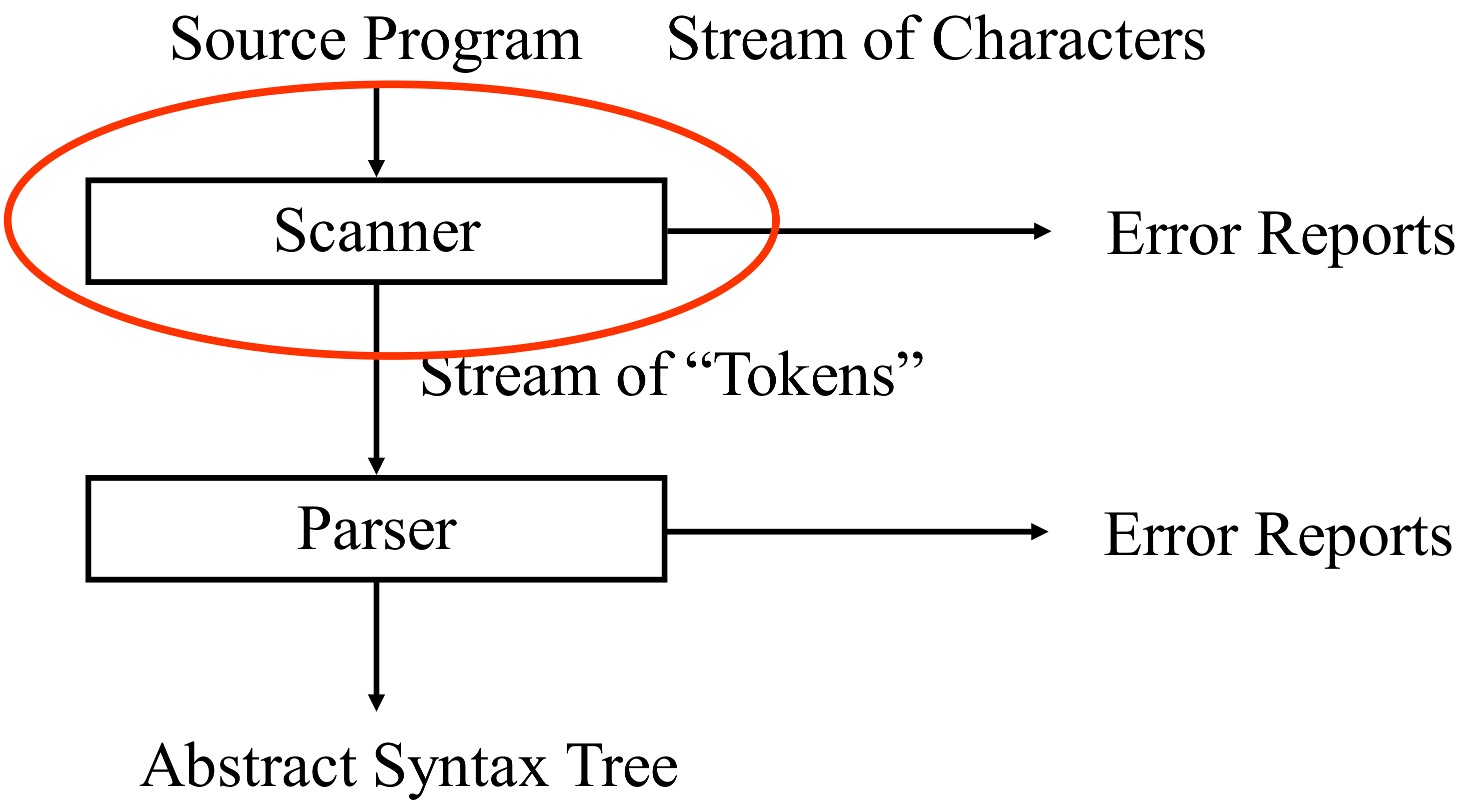
Lexical analysis

Lexical analysis

a. Describe the role of the lexical analysis phase
b. Describe lexemes and tokens
c. Describe how a scanner can be implemented by hand
d. Describe how a scanner can be auto-generated
e. Describe regular expressions and finite automata and how they relate to implementations of scanners

Syntax Analysis: Scanner

Dataflow chart



1) Scan: Divide Input into Tokens

An example ac source program:

```
f b
i a
a = 5
b = a + 3.2
p b
```

Lexems are “words” in the input, for example keywords, operators, identifiers, literals, etc.
Tokens is a datastructure for lexems and additional information

scanner

floatdl	*id*	*intdcl*	*id*	*id*	*assign*	*inum*
f	b	i	a	a	=	5

...

...

assign	*id*	*plus*	*fnum*	*print*	*id*	*eot*
=	a	+	3.2	p	b	

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scanner

floatdl	*id*	*intdcl*	*id*	*id*	*assign*	*inum*	…
	b		a	a		5	

…	*assign*	*id*	*plus*	*fnum*	*print*	*id*	*eot*
		a		3.2		b	

Implement Scanner based on RE by hand

1) Express the “lexical” grammar as RE

   (sometimes it is easier to start with a BNF or an EBNF and do necessary transformations)

- For each variant make a switch on the first character by peeking the input stream
- For each repetition (..)* make a while loop with the condition to keep going as long as peeking the input still yields an expected character
- Sometimes the “lexical” grammar is not reduced to one single RE but a small set of REs – in this case a switch or if-then-else case analysis is used to determine which rule is being recognized, before following the first two steps

Developing a Scanner

- Express the "lexical" grammar in EBNF

Token ::= Identifier | Integer-Literal | Operator |
; | : | := | ~ | (|) | eot
Identifier ::= Letter (Letter | Digit)*
Integer-Literal ::= Digit Digit*
Operator ::= + | - | * | / | < | > | =
Separator ::= Comment | space | eol
Comment ::= ! Graphic* eol

Now perform substitution and left factorization...

Token ::= Letter (Letter | Digit)*
| Digit Digit*
| + | - | * | / | < | > | =
| ; | : (=|ε) | ~ | (|) | eot
Separator ::= ! Graphic* eol | space | eol

```
Token ::= Letter (Letter | Digit)*
        | Digit Digit*
        | + | - | * | / | < | > | =
        | ; | : (=|ε) | ~ | ( | ) | eot
```

```
private byte scanToken() {
  switch (currentChar) {
    case 'a': case 'b': ... case 'z':
    case 'A': case 'B': ... case 'Z':
      scan Letter (Letter | Digit)*
      return Token.IDENTIFIER;
    case '0': ... case '9':
      scan Digit Digit*
      return Token.INTLITERAL ;
    case '+': case '-': ... : case '=':
      takeIt();
      return Token.OPERATOR;
    ...etc...
  }
```

Developing a Scanner

Let’s look at the identifier case in more detail

```
    ...
    return ...
  case 'a': case 'b': ... case 'z':
  case 'A': case 'B': ... case 'Z':
    acceptIt();
    while (isLetter(currentChar)
           || isDigit(currentChar) )
      acceptIt();
    return Token.IDENTIFIER;
  case '0': ... case '9':
    ...
```

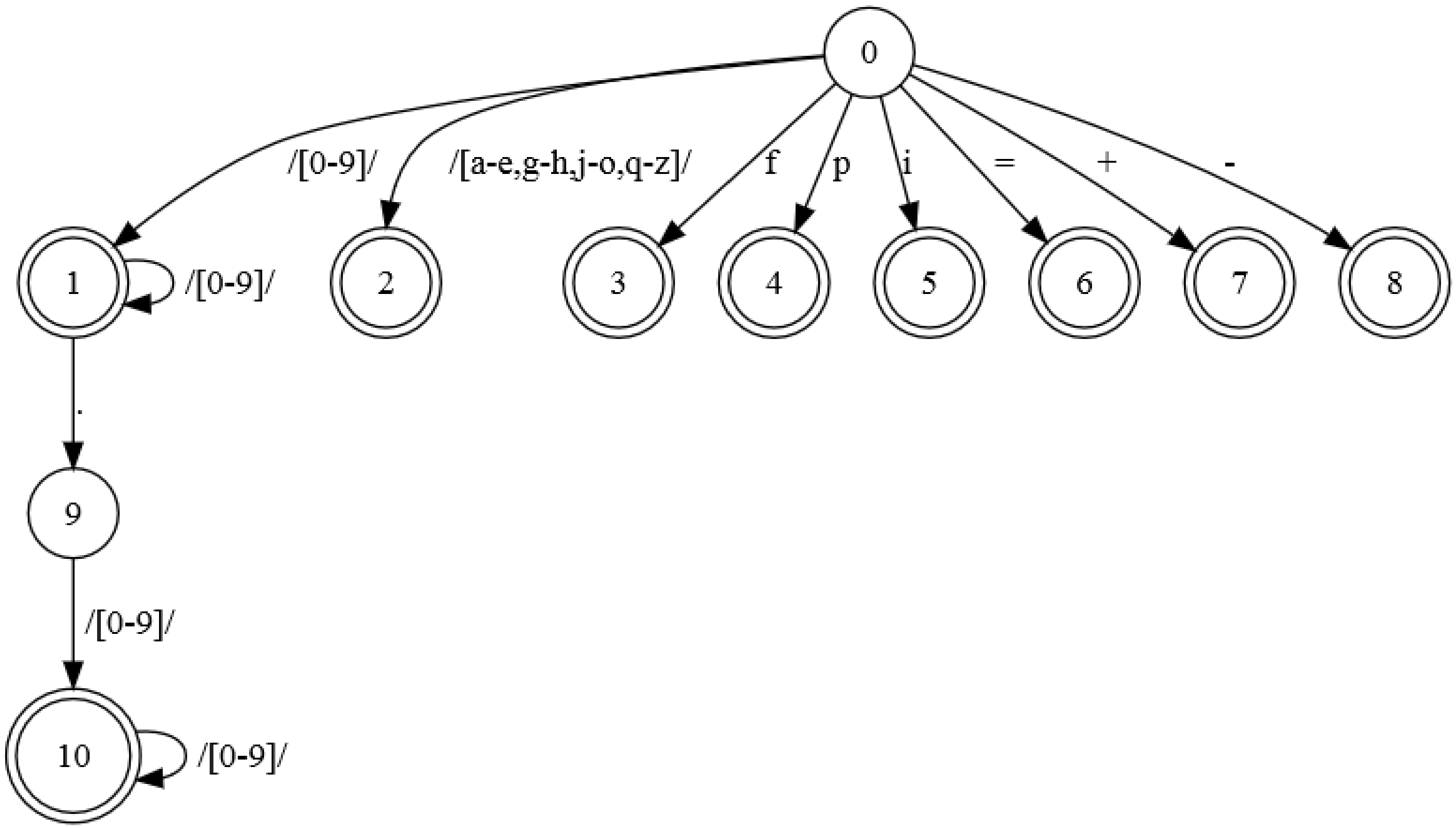
Thus developing a scanner is a mechanical task.

Token Specification

Terminal	Regular Expression
floatdcl	"f"
intdcl	"i"
print	"p"
id	[a – e] | [g – h] | [j – o] | [q – z]
assign	"="
plus	"+"
minus	"-"
inum	$[0-9]^+$
fnum	$[0-9]^+ . [0-9]^+$
blank	$(" ")^+$

Figure 2.3: Formal definition of ac tokens.

[0-9]+ | [0-9]+.[0-9]+ | [a-e,g-h,j-o,q-z] | f | p | i | = | \+ | -



```
function SCANNER( ) returns Token
    while s.PEEK( ) = blank do call s.ADVANCE( )
    if s.EOF( )
    then ans.type ← $
    else
        if s.PEEK( ) ∈ { 0, 1, . . . , 9 }
        then ans ← SCANDIGITS( )
        else
            ch ← s.ADVANCE( )
            switch (ch)
                case { a, b, . . . , z } − { i, f, p }
                    ans.type ← id
                    ans.val ← ch
                case f
                    ans.type ← floatdcl
                case i
                    ans.type ← intdcl
                case p
                    ans.type ← print
                case =
                    ans.type ← assign
                case +
                    ans.type ← plus
                case -
                    ans.type ← minus
                case default
                    call LEXICALERROR( )
    return (ans)
end
```

Figure 2.5: Scanner for the ac language. The variable s is an input stream of characters.

```
function ScanDigits( ) returns token
    tok.val ← " "
    while s.peek( ) ∈ {0, 1, . . . , 9} do
        tok.val ← tok.val + s.advance( )
    if s.peek( ) ≠ "."
    then  tok.type ← inum
    else
        tok.type ← fnum
        tok.val ← tok.val + s.advance( )
        while s.peek( ) ∈ {0, 1, . . . , 9} do
            tok.val ← tok.val + s.advance( )
    return (tok)
end
```

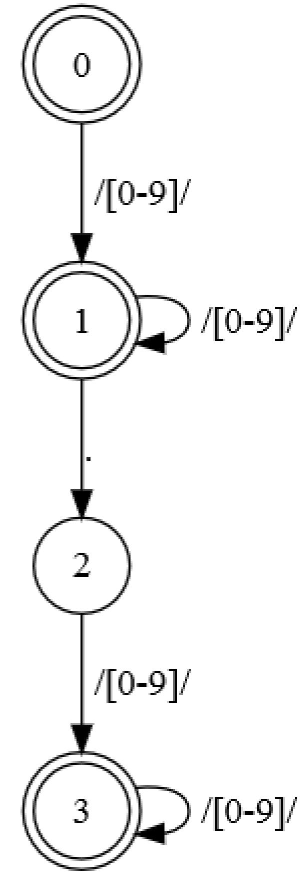


Figure 2.6: Finding inum or fnum tokens for the ac language.

Generating Scanners

- Generation of scanners is based on
  - Regular Expressions: to describe the tokens to be recognized
  - Finite State Machines: an execution model to which RE's are "compiled"

A possible algorithm:
- Convert RE into NDFA-ε
- Convert NDFA-ε into NDFA
- Convert NDFA into DFA
- generate Java/C/... code

Implementing a DFA

/$\star$ Assume *CurrentChar* contains the first character to be scanned $\star$/

$State \leftarrow StartState$

while true do

  $NextState \leftarrow \mathrm{T}[State, CurrentChar]$

  if $NextState =$ error

  then break

  $State \leftarrow NextState$

  $CurrentChar \leftarrow$ READ( )

if $State \in AcceptingStates$

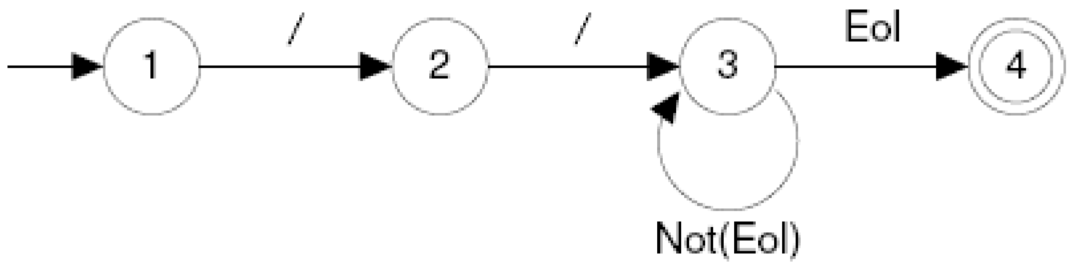
then /$\star$ Return or process the valid token $\star$/

else /$\star$ Signal a lexical error $\star$/

Figure 3.3: Scanner driver interpreting a transition table.

Comment -> //(Not(Eol))*Eol

(a)



(b)

State	Character				
	/	Eol	a	b	...
1	2				
2	3				
3	3	4	3	3	3
4					

Figure 3.2: DFA for recognizing a single-line comment. (a) transition diagram; (b) corresponding transition table.

Implementing a Scanner as a DFA

Slightly different from previously shown implementation (but similar in spirit):

- Not the goal to match entire input
  => when to stop matching?
  - Token(if), Token(Ident i) vs. Token(Ident ifi)

  Match longest possible token

  Report error (and continue) when reaching error state.
- How to identify matched token class (not just true|false)

  Final state determines matched token class

Performance considerations

- Performance of scanners is important for production compilers, for example:
  - 30,000 lines per minute (500 lines per second)
  - 10,000 characters per second (for an average line of 20 characters)
  - For a processor that executes 10,000,000 instructions per second, 1,000 instructions per input character
  - Considering other tasks in compilers, 250 instructions per character is more realistic
- Size of scanner sometimes matters
  - Including keyword in scanner increases table size
    - E.g. Pascal has 35 keywords, including them increases states from 37 to 165
    - Uncompressed this increases table entries from 4699 to 20955