COP 3402 Systems Software

Lexical analysis

Outline

1. Lexical analyzer
2. Designing a Scanner
3. Regular expressions
4. Transition diagrams

Lexical Analyzer

The purpose of the scanner is to decompose the source program into Its elementary symbols or tokens.

1. Read input one character at a time
2. Group characters into tokens
3. Remove white spaces, comments and control characters
4. Encode token types
5. Detect errors and generate error messages

Lexical analyzer

The stream of characters in the assignment statement

\t fahrenheit := 32 + celsious * 1.8;\n /* Hello */

control characters — white spaces — control characters — comments

is read in by the scanner and the scanner translates it into a stream of tokens in order to ease the task of the Parser.

[id, 1] [: =][int, 32][+][id, 2][*][int, 1.8][;]

Scanner eliminates white spaces, comments, and control characters.

Lexical Analyzer

1. Lookahead plays an important role to a lexical analyzer.
2. It is not always possible to decide if a token has been found without looking ahead one character.

   For instance, if only one character, say "i", is used it would be impossible to decide whether we are in the presence of identifier "i" or at the beginning of the reserved word "if".

3. We need to ensure a unique answer and that can be done knowing what is the character ahead.

Designing a scanner

Define the token types (internal representation)

Create tables with initial values:

Reserved words name table: **begin**, **call**, **const**, **do**, **end**, **if**, **odd**, **procedure**, **then**, **var**, **while**.

Special symbols table: ‘**+**’, ‘**-**‘, ‘*’, ‘**/**’, ‘**(**‘, ‘**)**’, ‘**=**’, ’**,**’ , ‘**.**’, ‘ **<**’, ‘>’, ‘**;**’.

Name table (usually known as the symbol table)

Designing a scanner

Examples:

```
#define  norw       15        /* number of reserved words */
#define  imax    32767        /* maximum integer value */
#define  cmax       11        /* maximum number of chars for idents */
#define  nestmax     5        /* maximum depth of block nesting */
#define  strmax    256        /* maximum length of strings */
```

Internal representation of PL/0 Symbols
token types example:

```
tydef enum { nulsym = 1, idsym, numbersym, plussym, minussym,
multsym,  slashsym, oodsym, eqsym, neqsym, lessym, leqsym,
gtrsym, geqsym, lparentsym, rparentsym, commasym, semicolonsym,
periodsym, becomessym, beginsym, endsym, ifsym, thensym,
whilesym, dosym, callsym, constsym, varsym, procsym, writesym
} token_type;
```

Designing a scanner

```
/* list of reserved word names */
char  *word [ ] = {  "null“, "begin“, "call", “const”, “do’ , “else”, “end”, “if”,
                     “odd”, “procedure”, “read”, “then”, “var”, “while”, “write”};

/* internal representation  of reserved words */
int  wsym [ ] =  { nul, beginsym, callsym, constsym, dosym, elsesym, endsym, ifsym,
                   oddsym, procsym, readsym, thensym, varsym, whilesym, writesym};

/* list of special symbols */
Int ssym[256]

ssym['+']=plus;     ssym['-']=minus;    ssym['*']=mult;
ssym['/']=slash;    ssym['(']=lparen;   ssym[')']=rparen;
ssym['=']=eql;      ssym[',']=comma;    ssym['.']=period;
ssym['#']=neq;      ssym['<']=lss;      ssym['>']=gtr;
ssym['$']=leq;      ssym['%']=geq;      ssym[';']=semicolon;
```

Symbol Table

The symbol table or name table records information about each symbol name in the program.

Each piece of information associated with a name is called an attribute. (i.e. type for a variable, number of parameters for a procedure, number of dimensions for an array)

The symbol table can be organized as a linear list, a tree, or using hash tables which is the most efficient method.

The hashing technique will allow us to find a numerical value for the identifier. For example:

We can used the formula: H(id) = ord (first letter) + ord (last letter)

ASCII Character Set

The ordinal number of a character *ch* is computed from its coordinates (X,Y) in the table as:

ord(*ch*) = 16 * X + Y

Example:

ord(‘A’ **)** = 16 * 4 + 1 = 65

X

Y

	0	1	2	3	4	5	6	7
0	NUL	DLE	SP	0	@	P	`	p
1	SOH	DC1	!	1	A	Q	a	q
2	STX	DC2	"	2	B	R	b	r
3	ETX	DC3	#	3	C	S	c	s
4	EOT	DC4	$	4	D	T	d	t
5	ENQ	NAK	%	5	E	U	e	u
6	ACK	SYN	&	6	F	V	f	v
7	BEL	ETB	'	7	G	W	g	w
8	BS	CAN	(	8	H	X	h	x
9	HT	EM	)	9	I	Y	i	y
10(A)	LF	SUB	*	:	J	Z	j	z
11(B)	VT	ESC	+	;	K	[	k	{
12(C)	FF	FS	,	<	L	\	l	|
13(D)	CR	GS	-	=	M	]	m	}
14(E)	SO	RS	.	>	N	^	n	~
15(F)	SI	US	/	?	O	_	o	DEL

Designing a scanner

/* structure of the symbol table record ***/**

```
typedef struct
   {
          int kind;            /* const = 1, var = 2, proc = 3.
          char name[10];       /* name up to 11 chars
          int val;             /* number (ASCII value)
          int level;           /* L  level
          int adr;             /* M  address
   } namerecord_t;

symbol_ table [MAX_NAME_TABLE_SIZE];
```

Symbol Table

Symbol table operations:

Enter (insert)

Lookup (retrieval)

Enter: When a declaration is processed the name is inserted into the the symbol table. If the programming language does not require declarations, then the name is inserted when the first occurrence of the name is found.

Lookup: Each subsequent use of the name cause a lookup operation.

Regular expressions

An **alphabet** is any finite set of symbols and usually the greek letter ***sigma*** (Σ) is used to denote it.

For example:

$\Sigma = \{0,1\}$ → **the binary alphabet**

Note: **ASCII** is an important example of an alphabet; it is used in many software systems

A **string** (string = sentence = word) over an alphabet is a finite sequence of symbols drawn from an alphabet.

For example:

$\Sigma = \{0,1\}$ **s = 1011** → denotes a string called **s**

Note: any sequence of **0** and **1** is a string over the alphabet $\Sigma = \{0,1\}$

Regular expressions

Example 2:

Alphabet	**Strings**
Σ = {a, b, c, …, z}	**while, for, const**

The **length** of a string **s**, usually written **| s |**, is the number of occurrences of symbols in s.

For example:

If s = **while** the value of $| s | = 5$

Note: the empty string, denoted ε ***(epsilon)***, is the string of length zero.

$| \varepsilon | = 0$

Regular expressions

A *language* is any countable set of strings over some fixed alphabet.

For example:
Let **L** be the alphabet of letters and **D** be the alphabet of digits:

L = { A, B, …, Z, a, b, …, z} and **D** = {0, 1, 2, 3, …, 8, 9}

Note: **L** and **D** are languages all of whose strings happen to be of length one. Therefore, and equivalent definition is:

L is the alphabet of uppercase and lowercase letters.
D is the alphabet of digits.

Regular expressions

Other languages that can be constructed from **L** and **D** are:

1) **L U D** → the language with 62 strings of length one.

2) **L D** → is the set of 520 strings of length two each containing a letter followed by a digit.

3) $\mathbf{L^3}$ → is the set of all 3-letter strings.

4) **L*** → is the set of all strings (of any length) of letters, including **e** the empty string. Formally this is called Kleene closure of L.

The star means "zero or more occurrences".

$$L^* = L^0 \cup L^1 \cup L^2 \cup \ldots$$

Regular expressions

5) **D^+** → is the set of all strings of one or more digits.

$$D^+ = D\,D^* = D^1\ \mathbf{U}\ D^2\ \mathbf{U}\ D^3\ \mathbf{U} \ldots$$

6) **L (L** U **D)*** → is the set of all strings of letters and digits beginning with a letter.

For example: **while**, **for**, **salary**, **intel486**

Definition: A **Regular Expressions** is a notation for describing all valid strings (of a language) that can be built from an alphabet. (or a set of characters that specify a pattern)

Regular expressions

Each regular expression r denotes a language L(r)

Rules that define a regular expression:

1) ε ***(epsilon)*** is a regular expression denoting the language **$L(\varepsilon) = \{ \varepsilon \}$.**

2) Every element in Σ ***(sigma)*** is a regular expression. If **a** is a symbol in Σ , then **a** is a regular expression, and **L(a) = {a}.**

3) Given two regular expressions **r** and **s**, **rs** is a regular expression denoting the language **L(r) L(s).**

4) Given two regular expressions **r** and **s**, ***r* U *s*** is a regular expression denoting the language **L(r) U L(s).**

5) Given a regular expression **r**, **r^*** is a regular expression.

6) Given a regular expression **r**, **r^+** is a regular expression.

7) Given a regular expression **r**, **(r)** is a regular expression.

Regular expressions

For example, given the alphabet:

Σ = { A, B, …, Z, a, b, …, z, 0, 1, 2, 3, …, 8, 9}

ε is a regular expression denoting { **ε** }, the empty string.

a is a regular expression denoting { **a** }.

Any symbol from Σ is a regular expression.

If **a** and **b** are regular expressions, then:

a | b denotes the language { **a, b** }. ← choice among alternatives

For example:
(a | b) (a | b) denotes { **aa, ab, ba, bb** }
The language of all strings of length two over the alphabet Σ.

Regular expressions

a . b denotes the regular expression { **ab** }. ← concatenation

The language (L^2) consisting of the string { **ab** }.
(we will use the notation **a b** instead of **a . b)**

a* denotes the language consisting of all strings of zero or more **a' s**, that is:

{ ε, a, aa, aaa, aaaa, …}

(a | b)* denotes the set of all strings consisting of zero or more instances of **a** or **b**.

For example:

{ ε, a, b, aa, ab, ba, bb, aaa, …}

Regular expressions

What is the language denoted by **a | a* b** ?

{ a, b, ab, aab, aaab, …}

There are different notations to describe a language. For example,

L^2 = { **aa**, **ab**, **ba**, **bb**}

Or using the regular expression:

L^2 → **aa** | **ab** | **ba** | **bb**

This will allow us to describe identifiers in PL/0 as:

letter → A | B | C | … | Z| a | b | … | z
digit → 0 | 1 | 2 | … | 9
id → letter (letter | digit)*

Regular expressions

Remember !

A *language* is any countable set of strings over some fixed alphabet.

Each string from the language is called a word or sentence.

Given the following alphabet $\Sigma = \{a, b\}$, each one of the following sets is a language over the fixed alphabet $\{a, b\}$:

$L = \{a, b, ab\}$ $M = \{a, b, ab, aab, aaab, \ldots\}$

Language L can be defined by explicit enumeration but M can not.

A regular expression is a type of grammar that specifies a set of strings and can be used to denote a language over an alphabet .

(i.e.,The regular expression $a \mid a^* b$ denotes the language M over Σ)

Regular expressions

Extensions of regular expressions notation:

1) One or more repetitions: "**+**" .

   For example: $(a \mid b)^+ = (a \mid b)(a \mid b)^*$

2) Zero or one instance: "**?**"

   For example: $(+ \mid -)?\,(digit)^+ = (digit)^+ \mid +\,(digit)^+ \mid -\,(digit)^+$

3) A range of characters: "**[… - …]**"

   For example: $a \mid b \mid c \mid \ldots \mid z = [a - z]$

Example: letter → [A – Za – z]
digit → [0 – 9]
id → letter (letter | digit)*

Lexemes, Patterns and Tokens

A **Lexeme** is the sequence of input characters in the source program that matches the pattern for a token (the sequence of input characters that the token represents).

A **Pattern** is a description of the form that the lexemes of a token may take.

A **Token** is the internal representation of a lexeme. Some tokens may consist only of a name (internal representation) while others may also have some associated values (attributes) to give information about a particular instance of a token.

Example:

Lexeme	**Pattern**	**Token**	**Attribute**
Any identifier	letter(letter | digit)*	idsym	pointer to symbol table
If	if	ifsym	--
>=	< | <= | > | >= | = | <>	relopsym	GE

Transition Diagrams

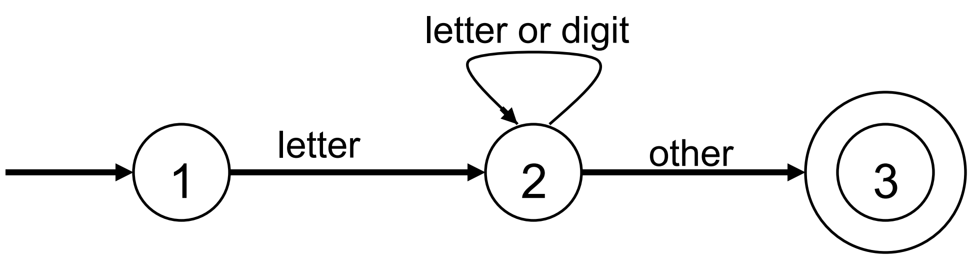
Transition diagrams or transition graphs are used to attempt to match a lexeme to a pattern.

Each Transition diagram has:

States → represented by circles.
Actions → represented by arrows between the states.
Start state → represented by an arrowhead (beginning of a pattern)
Final state → represented by two concentric circles (end of pattern).

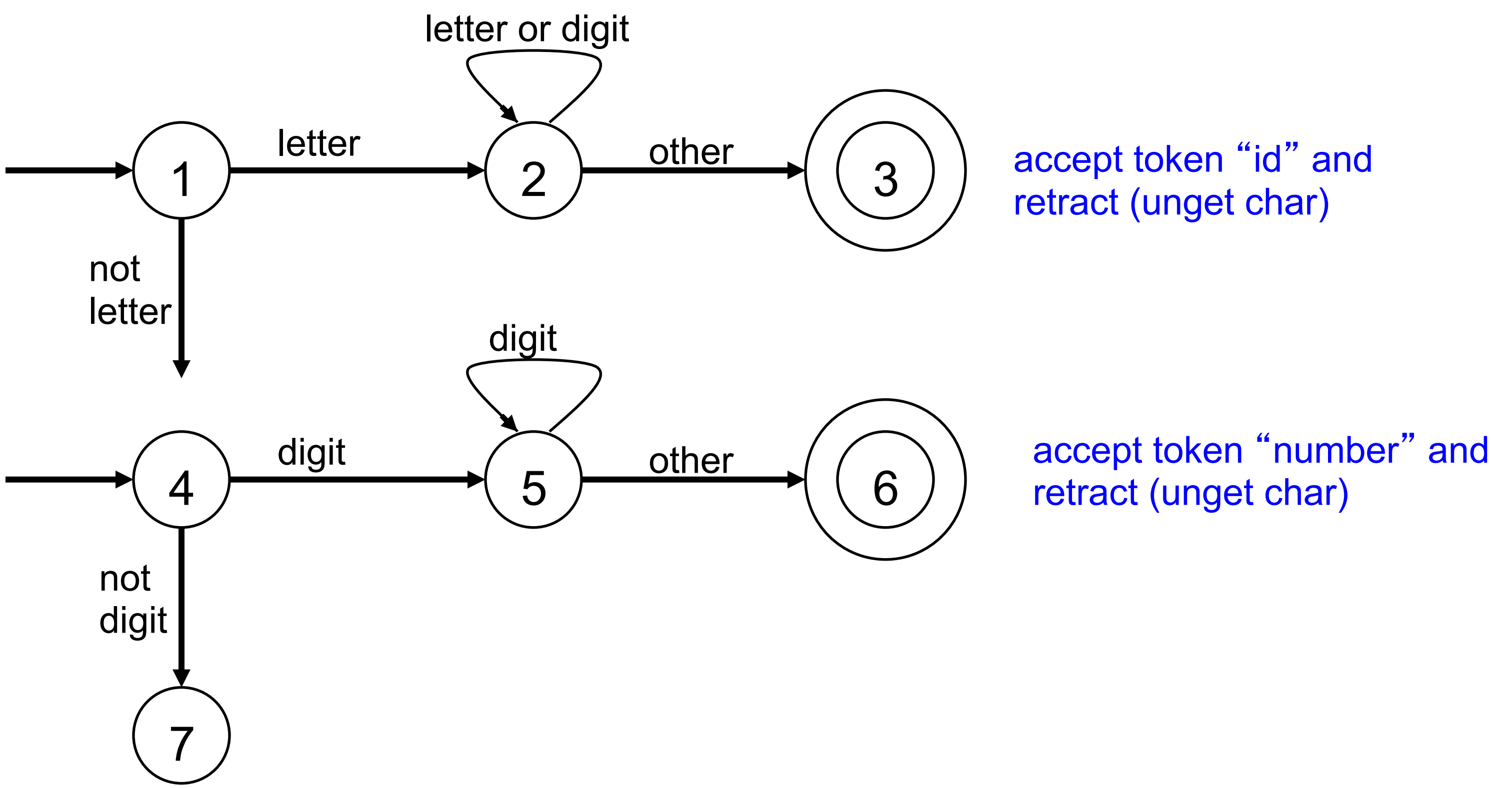
All transition diagrams are deterministic, which means that there is no need to choose between two different actions for a given input.

Example:



Transition Diagrams

The following state diagrams recognize identifiers and numbers (integers)



Transition Diagrams

This will be the translation of the transition diagrams to a programming language notation:

```
{state 1}    ch = getchar
             If isletter (ch) then {

{state 2}    while isletter(ch) or isdigit(ch) do{
               ch := getchar;
             }
{state 3}    retract  /* we have scanned
                      /*  one character too far
             token := (id, index in ST)}
             accept
             return(token)
             }
             else {
              Fail /* look for a different token
             }
```

```
{state 4}    ch = getchar
             if isdigit(ch) then {
               value := convert (ch)

{state 5}    ch = getchar
             while isdigit (ch) do{
               value := 10 * value + conver (ch)
               ch := getchar
             }

{state 6}    retract
             token := (int, value)
             accept
             return (token)
             }

{state 7}    else{
              Fail /* look for a different token
             }
```

Transition Diagrams

Convert() turns a character representation of a digit into an integer in the range 0 -9.

```
ch = getchar
while isdigit (ch) do
   value := 10 * value + conver (ch)
   ch := getchar
endwhile
```

Example:

Value := 10 * value + ch – ‘0’ ;

or

Value := 10 * value + (ord(5) – ord(0))

53 **48** **← ASCII values for five and zero**

ASCII Character Set

The ordinal number of a character ***ch*** is computed from its coordinates (X,Y) in the table as:

ord(*ch*) = 16 * X + Y

Example:

ord('5' **)** = 16 * 4 + 1 = 53

	0	1	2	3	4	5	6	7
0	NUL	DLE	SP	0	@	P	`	p
1	SOH	DC1	!	1	A	Q	a	q
2	STX	DC2	"	2	B	R	b	r
3	ETX	DC3	#	3	C	S	c	s
4	EOT	DC4	$	4	D	T	d	t
5	ENQ	NAK	%	5	E	U	e	u
6	ACK	SYN	&	6	F	V	f	v
7	BEL	ETB	'	7	G	W	g	w
8	BS	CAN	(	8	H	X	h	x
9	HT	EM	)	9	I	Y	i	y
10(A)	LF	SUB	*	:	J	Z	j	z
11(B)	VT	ESC	+	;	K	[	k	{
12(C)	FF	FS	,	<	L	\	l	|
13(D)	CR	GS	-	=	M	]	m	}
14(E)	SO	RS	.	>	N	^	n	~
15(F)	SI	US	/	?	O	_	o	DEL

Transition Diagrams

“Transitions diagrams” are an implementation of a formal model called Finite Automata (FA) or Finite State Machine (FSM).

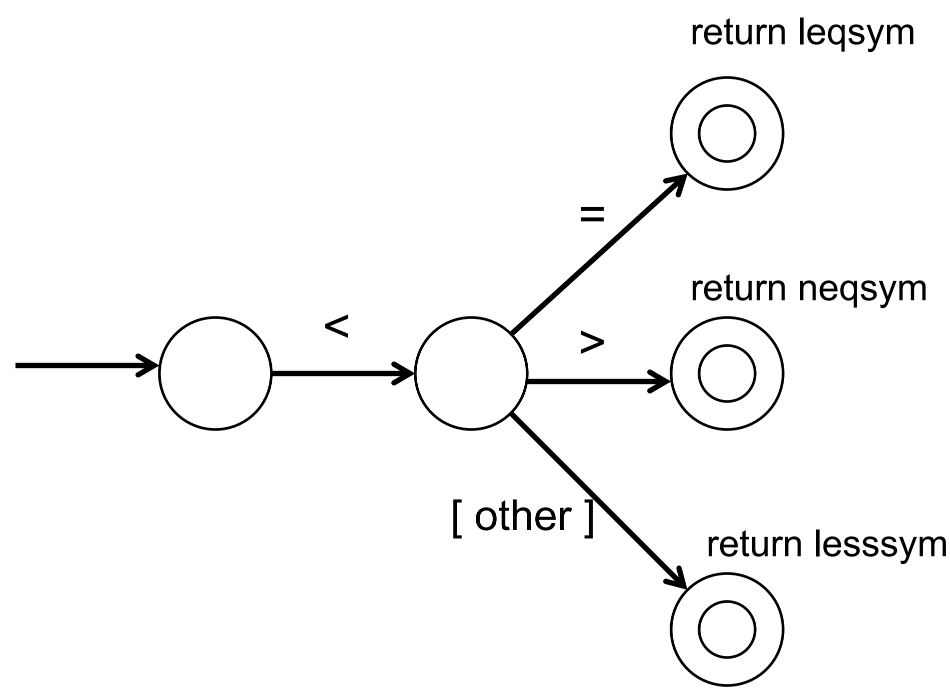
Any language that can be denoted by a regular expression can be recognized by a Finite State Machine (FSM)

Lexical Analyzer

Example of a lexical analyzer implementation:

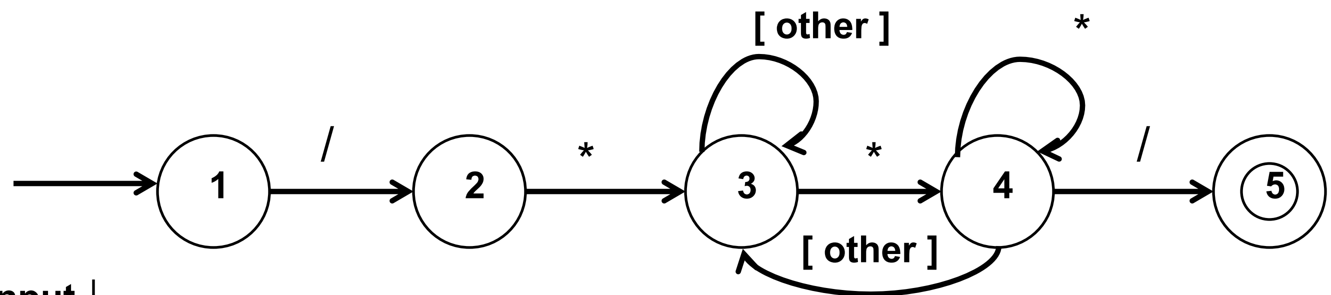
In this example we show you the algorithm to recognize the symbols “<“, “<=“, and “<>”:

```
ch := getch;
If ch = ‘<‘ then
   begin
      ch := getch;
      if ch = ‘=‘ then
         begin
            token := leqsym;
            ch := getch
         end
      else
         if ch = ‘>’ then
            begin
              token := neqsym;
              ch := getch
            end
         else token := lessym
   end;
```



Lexical Analyzer

Transition diagram for C comments.



state \ input	/	*	[other]	accepting
1	2			no
2		3		no
3	3	4	3	no
4	5	4	3	no
5				yes

Transition table