Module 02

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Module 02: CS31003: Compilers:

Lexical Analyzer Generator: Flex / Lex

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Module Objectives

- Understand Flex Specification
- Understand Lexical Analysis

Module Outline

- Lexical Analysis Outline
- Flex Specification
  - Sample
  - Regular Expressions
  - Common Errors in Flex
  - Line Count Example
- Interactive Flex
- Flex–Bison Flow
- Start Condition in Flex

Lexical Analysis Algorithm

- RE[1] for every Token Class
- Convert Regular Expression to an NFA[2]
- Convert NFA to DFA[3]
- Lexical Action for every final state of DFA

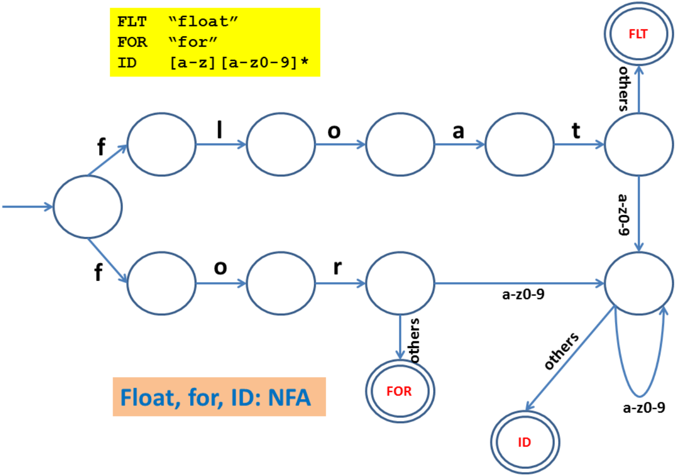
[1] Regular Expression

[2] Non-deterministic Finite Automata

[3] Deterministic Finite Automata

Lexical Analysis Algorithm

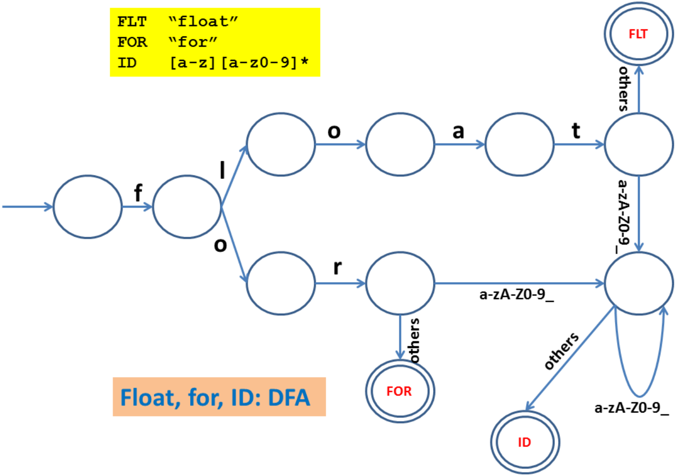
```
FLT   "float"
FOR   "for"
ID    [a-z][a-z0-9]*
```



Float, for, ID: NFA

Lexical Analysis Algorithm


```
FLT   "float"
FOR   "for"
ID    [a-z][a-z0-9]*
```



Float, for, ID: DFA

Lexical Analysis Rules

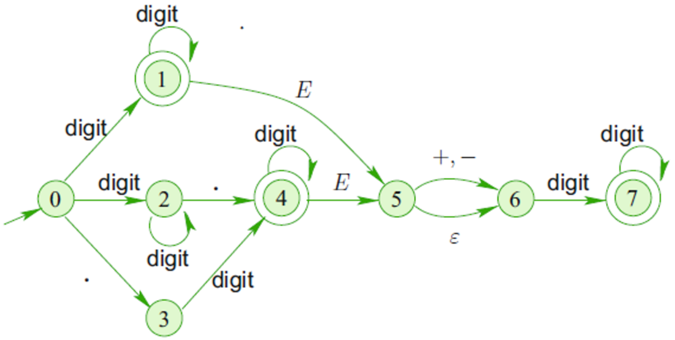
number → digits optFrac optExp
digit → 0 | 1 | 2 | …| 9
digits → digit digit*
optFrac → . digit | ε
optExp → (E (+ | - | ε) digit) | ε

integer and float constants

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

Character class

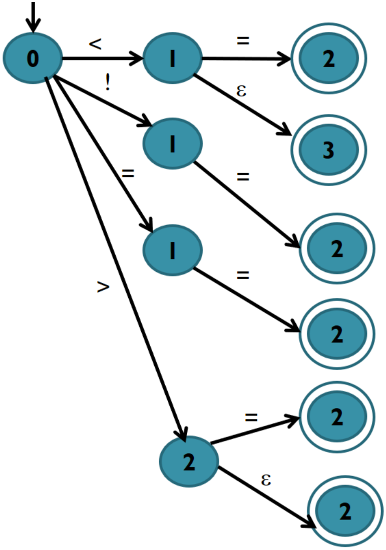
FSM for Integer and Floating Point Constants



Token Representation

Lexemes	Token Name	Attribute Value
Any ws	-	-
if	**if**	-
then	**then**	-
else	**else**	-
Any id	**id**	Pointer to ST
Any number	**number**	Pointer to ST
<	**relop**	LT
<=	**relop**	LE
==	**relop**	EQ
!=	**relop**	NE
>	**relop**	GT
>=	**relop**	GE

FSM for Logical Operators



return (relop, LE)

return (relop, LT)

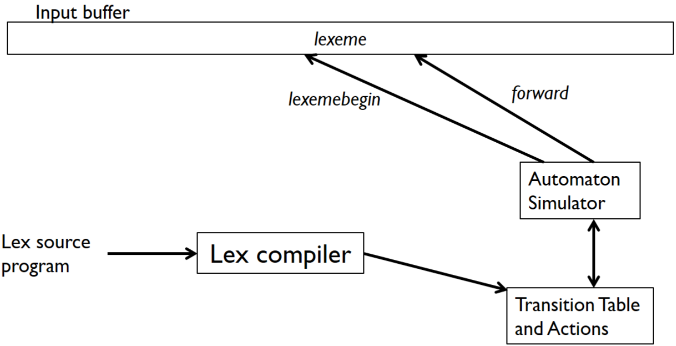
return (relop, NE)

return (relop, EQ)

return (relop, GE)

return (relop, GT)

Flex Flow



Lex program → Transition table and actions → FA simulator

Our Sample for Flex

- This is a simple block with declaration and expression statements
- We shall use this as a running example

```
{
    int x;
    int y;
    x = 2;
    y = 3;
    x = 5 + y * 4;
}
```

Structure of Flex Specs


```
Declarations
%%
Translation rule
%%
Auxiliary functions
```

Flex Specs for our sample

- C Declarations and definitions
- Definitions of Regular Expressions
- Definitions of Rules & Actions
- C functions

```
%{
/* C Declarations and Definitions */
%}
 /* Regular Expression Definitions */
INT          "int"
ID           [a-z][a-z0-9]*
PUNC         [;]
CONST        [0-9]+
WS           [ \t\n]
/* Definitions of Rules \& Actions */
%%
{INT}        { printf("<KEYWORD, int>\n"); /* Keyword Rule */ }
{ID}         { printf("<ID, %s>\n", yytext); /* Identifier Rule */}
"+"          { printf("<OPERATOR, +>\n"); /* Operator Rule */ }
"*"          { printf("<OPERATOR, *>\n"); /* Operator Rule */ }
"="          { printf("<OPERATOR, =>\n"); /* Operator Rule */ }
"{"          { printf("<SPECIAL SYMBOL, {>\n"); /* Scope Rule */ }
"}"          { printf("<SPECIAL SYMBOL, }>\n"); /* Scope Rule */ }
{PUNC}       { printf("<PUNCTUATION, ;>\n"); /* Statement Rule */ }
{CONST}      { printf("<INTEGER CONSTANT, %s>\n",yytext); /* Literal Rule */ }
{WS}         /* White-space Rule */ ;
%%
/* C functions */
main() { yylex(); /* Flex Engine */ }
```

Flex I/O for our sample

I/P Character Stream

```
{
    int x;
    int y;
    x = 2;
    y = 3;
    x = 5 + y * 4;
}
```

O/P Token Stream

```
<SPECIAL SYMBOL, {>
<KEYWORD, int> <ID, x> <PUNCTUATION, ;>
<KEYWORD, int> <ID, y> <PUNCTUATION, ;>
<ID, x> <OPERATOR, => <INTEGER CONSTANT, 2> <PUNCTUATION, ;>
<ID, y> <OPERATOR, => <INTEGER CONSTANT, 3> <PUNCTUATION, ;>
<ID, x> <OPERATOR, => <INTEGER CONSTANT, 5> <OPERATOR, +>
<ID, y> <OPERATOR, *> <INTEGER CONSTANT, 4> <PUNCTUATION, ;>
<SPECIAL SYMBOL, }>
```

- Every token is a doublet showing the token class and the specific token information
- The output is generated as one token per line. It has been rearranged here for better readability

Variables in Flex

`yylex`	Flex generated lexer driver
`yyin`	File pointer to Flex input
`yyout`	File pointer to Flex output
`yytext`	Pointer to Lexeme
`yyleng`	Length of the Lexeme

Regular Expressions – Basic

Expr.	Meaning
x	Character x
.	Any character except newline
[xyz]	Any characters amongst x, y or z.
[a-z]	Denotes any letter from a through z
[^0-9]	Stands for any character which is not a decimal digit, including new-line
\x	If x is an a, b, f, n, r, t, or v, then the ANSI-C interpretation of \x. Otherwise, a literal x (used to escape operators such as *)
\0	A NULL character
\num	Character with octal value num
\xnum	Character with hexadecimal value num
"string"	Match the literal string. For instance "/*" denotes the character / and then the character *, as opposed to /* denoting any number of slashes
<<EOF>>	Match the end-of-file

Regular Expressions - Operators

Expr.	**Meaning**
(r)	Match an r; parentheses are used to override precedence
rs	Match the regular expression r followed by the regular expression s. This is called *concatenation*
r|s	Match either an r or an s. This is called *alternation*
{*abbreviation*}	Match the expansion of the abbreviation definition. Instead of:

```
%%
[a-zA-Z_][a-zA-Z0-9_]* return IDENTIFIER;
%%
```

Use

```
id [a-zA-Z_][a-zA-Z0-9_]*
%%
{id} return IDENTIFIER;
%%
```

Regular Expressions - Operators

Expr.	Meaning
	quantifiers
r*	zero or more r's
r+	one or more r's
r?	zero or one r's
r{[num]}	num times r
r{min,[max]}	Anywhere from min to max (defaulting to no bound) r's
r/s	Match an r but only if it is followed by an s. This type of pattern is called *trailing context*. For example: Distinguish DO1J=1,5 (a for loop where I runs from 1 to 5) from DO1J=1.5 (a definition/assignment of the floating variable DO1J to 1.5) in FORTRAN. Use DO/[A-Z0-9]*=[A-Z0-9]*
^r	Match an r at the beginning of a line
r$	Match an r at the end of a line

Wrong Flex Specs for our sample

- Rules for ID and INT have been swapped.
- No keyword can be tokenized as keyword now.

```
%{
/* C Declarations and Definitions */
%}
 /* Regular Expression Definitions */
INT         "int"
ID          [a-z][a-z0-9]*
PUNC        [;]
CONST       [0-9]+
WS          [ \t\n]

%%
{ID}        { printf("<ID, %s>\n", yytext); /* Identifier Rule */}
{INT}       { printf("<KEYWORD, "int">\n"); /* Keyword Rule */ }
"+"         { printf("<OPERATOR, +>\n"); /* Operator Rule */ }
"*"         { printf("<OPERATOR, *>\n"); /* Operator Rule */ }
"="         { printf("<OPERATOR, =>\n"); /* Operator Rule */ }
"{"         { printf("<SPECIAL SYMBOL, {>\n"); /* Scope Rule */ }
"}"         { printf("<SPECIAL SYMBOL, }>\n"); /* Scope Rule */ }
{PUNC}      { printf("<PUNCTUATION, ;>\n"); /* Statement Rule */ }
{CONST}     { printf("<INTEGER CONSTANT, %s>\n",yytext); /* Literal Rule */ }
{WS}        /* White-space Rule */ ;
%%

main() {
    yylex(); /* Flex Engine */
}
```

Wrong Flex I/O for our sample

I/P Character Stream

```
{
    int x;
    int y;
    x = 2;
    y = 3;
    x = 5 + y * 4;
}
```

O/P Token Stream

```
<SPECIAL SYMBOL, {>
<ID, int> <ID, x> <PUNCTUATION, ;>
<ID, int> <ID, y> <PUNCTUATION, ;>
<ID, x> <OPERATOR, => <INTEGER CONSTANT, 2> <PUNCTUATION, ;>
<ID, y> <OPERATOR, => <INTEGER CONSTANT, 3> <PUNCTUATION, ;>
<ID, x> <OPERATOR, => <INTEGER CONSTANT, 5> <OPERATOR, +>
<ID, y> <OPERATOR, *> <INTEGER CONSTANT, 4> <PUNCTUATION, ;>
<SPECIAL SYMBOL, }>
```

- Both `int`'s have been taken as `ID`!

Count Number of Lines – Flex Specs

```
/* C Declarations and definitions */
%{
    int charCount = 0, wordCount = 0, lineCount = 0;
%}

/* Definitions of Regular Expressions */
word   [^ \t\n]+

/* Definitions of Rules \& Actions */
%%
{word}    { wordCount++; charCount += yyleng; }
[\n]      { charCount++; lineCount++; }
.         { charCount++; }
%%

/* C functions */
main() {
    yylex();
    printf("Characters: %d Words: %d Lines %d\n",charCount, wordCount, lineCount);
}
```

Count Number of Lines – lex.yy.c


```
char *yytext;
int charCount = 0, wordCount = 0, lineCount = 0; /* C Declarations and definitions */
/* Definitions of Regular Expressions & Definitions of Rules & Actions */
int yylex (void) { /** The main scanner function which does all the work. */
// ...
    if ( ! (yy_start) ) (yy_start) = 1;    /* first start state */
    if ( ! yyin ) yyin = stdin;
    if ( ! yyout ) yyout = stdout;
// ...
    while ( 1 ) {        /* loops until end-of-file is reached */
// ..
     yy_current_state = (yy_start);
yy_match: // ...
yy_find_action: // ...
do_action:
        switch ( yy_act ) { /* beginning of action switch */
            case 0: /* must back up */ // ...
            case 1: { wordCount++; charCount += yyleng; } YY_BREAK
            case 2: { charCount++; lineCount++; } YY_BREAK
            case 3: { charCount++; } YY_BREAK
            case 4: ECHO; YY_BREAK
            case YY_STATE_EOF(INITIAL): yyterminate();
            case YY_END_OF_BUFFER:
            default: YY_FATAL_ERROR("fatal flex scanner internal error--no action found" );
        } /* end of action switch */
    } /* end of scanning one token */
} /* end of yylex */
main() { /* C functions */
    yylex();
    printf("Characters: %d Words: %d Lines %d\n",charCount, wordCount, lineCount);
}
```

Modes of Flex Operations

Flex can be used in two modes:

- **Non-interactive**: Call `yylex()` only once. It keeps spitting the tokens till the end-of-file is reached. So the actions on the rules do not have `return` and falls through in the `switch` in `lex.yy.c`.
  This is convenient for small specifications. But does not work well for large programs because:
  - Long stream of spitted tokens may need a further tokenization while processed by the parser
  - At times tokenization itself, or at least the information update in the actions for the rules, may need information from the parser (like pointer to the correctly scoped symbol table)
- **Interactive**: Repeatedly call `yylex()`. Every call returns one token (after taking the actions for the rule matched) that is consumed by the parser and `yylex()` is again called for the next token. This lets parser and lexer work hand-in-hand and also eases information interchange between the two.

Flex Specs (non-interactive) for our sample

- C Declarations and definitions
- Definitions of Regular Expressions
- Definitions of Rules & Actions
- C functions

```
%{
/* C Declarations and Definitions */
%}
 /* Regular Expression Definitions */
INT         "int"
ID          [a-z][a-z0-9]*
PUNC        [;]
CONST       [0-9]+
WS          [ \t\n]
/* Definitions of Rules \& Actions */
%%
{INT}       { printf("<KEYWORD, int>\n"); /* Keyword Rule */ }
{ID}        { printf("<ID, %s>\n", yytext); /* Identifier Rule */}
"+"         { printf("<OPERATOR, +>\n"); /* Operator Rule */ }
"*"         { printf("<OPERATOR, *>\n"); /* Operator Rule */ }
"="         { printf("<OPERATOR, =>\n"); /* Operator Rule */ }
"{"         { printf("<SPECIAL SYMBOL, {>\n"); /* Scope Rule */ }
"}"         { printf("<SPECIAL SYMBOL, }>\n"); /* Scope Rule */ }
{PUNC}      { printf("<PUNCTUATION, ;>\n"); /* Statement Rule */ }
{CONST}     { printf("<INTEGER CONSTANT, %s>\n",yytext); /* Literal Rule */ }
{WS}        /* White-space Rule */ ;
%%
/* C functions */
main() { yylex(); /* Flex Engine */ }
```

Flex Specs (interactive) for our sample


```
%{
#define    INT         10
#define    ID          11
#define    PLUS        12
#define    MULT        13
#define    ASSIGN      14
#define    LBRACE      15
#define    RBRACE      16
#define    CONST       17
#define    SEMICOLON   18
%}

INT        "int"
ID         [a-z][a-z0-9]*
PUNC       [;]
CONST      [0-9]+
WS         [ \t\n]

%%
{INT}    { return INT; }
{ID}     { return ID; }
"+"      { return PLUS; }
"*"      { return MULT; }
"="      { return ASSIGN; }
"{"      { return LBRACE; }
"}"      { return RBRACE; }
{PUNC}   { return SEMICOLON; }
{CONST}  { return CONST; }
{WS}     {/* Ignore
              whitespace */}
%%
```

```
main() { int token;
    while (token = yylex()) {
        switch (token) {
            case INT: printf("<KEYWORD, %d, %s>\n",
                token, yytext); break;
            case ID: printf("<IDENTIFIER, %d, %s>\n",
                token, yytext); break;
            case PLUS: printf("<OPERATOR, %d, %s>\n",
                token, yytext); break;
            case MULT: printf("<OPERATOR, %d, %s>\n",
                token, yytext); break;
            case ASSIGN: printf("<OPERATOR, %d, %s>\n",
                token, yytext); break;
            case LBRACE: printf("<SPECIAL SYMBOL, %d, %s>\n",
                token, yytext); break;
            case RBRACE: printf("<SPECIAL SYMBOL, %d, %s>\n",
                token, yytext); break;
            case SEMICOLON: printf("<PUNCTUATION, %d, %s>\n",
                token, yytext); break;
            case CONST: printf("<INTEGER CONSTANT, %d, %s>\n",
                token, yytext); break;
        }
    }
}
```

– Input is taken from `stdin`. It can be changed by opening the file in `main()` and setting the file pointer to `yyin`.
– When the lexer will be integrated with the YACC generated parser, the `yyparse()` therein will call `yylex()` and the `main()` will call `yyparse()`.

Flex I/O (interactive) for our sample

I/P Character Stream

```
{
    int x;
    int y;
    x = 2;
    y = 3;
    x = 5 + y * 4;
}
```

```
#define     INT          10
#define     ID           11
#define     PLUS         12
#define     MULT         13
#define     ASSIGN       14
#define     LBRACE       15
#define     RBRACE       16
#define     CONST        17
#define     SEMICOLON    18
```

O/P Token Stream

```
<SPECIAL SYMBOL, 15, {>
<KEYWORD, 10, int>
<IDENTIFIER, 11, x>
<PUNCTUATION, 18, ;>
<KEYWORD, 10, int>
<IDENTIFIER, 11, y>
<PUNCTUATION, 18, ;>
<IDENTIFIER, 11, x>
<OPERATOR, 14, =>
<INTEGER CONSTANT, 17, 2>
<PUNCTUATION, 18, ;>
<IDENTIFIER, 11, y>
<OPERATOR, 14, =>
<INTEGER CONSTANT, 17, 3>
<PUNCTUATION, 18, ;>
<IDENTIFIER, 11, x>
<OPERATOR, 14, =>
<INTEGER CONSTANT, 17, 5>
<OPERATOR, 12, +>
<IDENTIFIER, 11, y>
<OPERATOR, 13, *>
<INTEGER CONSTANT, 17, 4>
<PUNCTUATION, 18, ;>
<SPECIAL SYMBOL, 16, }>
```

- Every token is a triplet showing the token class, token manifest constant and the specific token information.

Managing Symbol Table

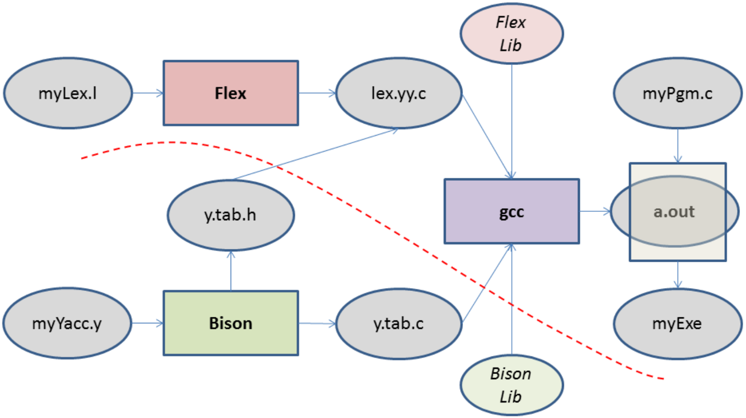

```
%{
    struct symbol {
        char *name;
        struct ref *reflist;
    };
    struct ref {
        struct ref *next;
        char *filename;
        int flags;
        int lineno;
   };

   #define NHASH 100
   struct symbol symtab[NHASH];
   struct symbol *lookup(char *);
   void addref(int, char*, char*, int);
%}
```

First Flex Program

```
$ flex myLex.l
$ cc lex.yy.c -lfl
$ ./a.out
...
$
```

Flex-Bison Flow



Start Condition in Flex

Flex provides a mechanism for conditionally activating rules. Any rule whose pattern is prefixed with <sc> will only be active when the scanner is in the start condition named sc. For example,

```
<STRING>[^"]*             { /* eat up the string body ... */
                            ...
                            }
```

will be active only when the scanner is in the STRING start condition, and

```
<INITIAL,STRING,QUOTE>\.  { /* handle an escape ... */
                            ...
                            }
```

will be active only when the current start condition is either INITIAL, STRING, or QUOTE.

Source: http://flex.sourceforge.net/manual/Start-Conditions.html

Start Condition in Flex - Specs

- *Declaration*: Declared in the definitions section of the input
- `BEGIN` *Action*: A start condition is activated using the `BEGIN` action. Until the next `BEGIN` action is executed, rules with the given start condition will be active and rules with other start conditions will be inactive.
- *Inclusive Start Conditions*: Use unindented lines beginning with '%s' followed by a list of names. If the start condition is inclusive, then rules with no start conditions at all will also be active.
- *Exclusive Start Conditions*: Use unindented lines beginning with '%x' followed by a list of names. If it is exclusive, then only rules qualified with the start condition will be active.

  A set of rules contingent on the same exclusive start condition describe a scanner which is independent of any of the other rules in the flex input. Because of this, exclusive start conditions make it easy to specify mini-scanners which scan portions of the input that are syntactically different from the rest (for example, comments).

Source: http://flex.sourceforge.net/manual/Start-Conditions.html

Start Condition in Flex - Example

The set of rules:

```
%s example
%%
<example>foo   do_something();
bar            something_else();
```

is equivalent to

```
%x example
%%
<example>foo             do_something();
<INITIAL,example>bar     something_else();
```

Without the <INITIAL,example> qualifier, the bar pattern in the second example wouldn't be active (that is, couldn't match) when in start condition example. If we just used <example> to qualify bar, though, then it would only be active in example and not in `INITIAL`, while in the first example it's active in both, because in the first example the example start condition is an inclusive (%s) start condition.

Source: http://flex.sourceforge.net/manual/Start-Conditions.html

Handling Comments


```
%x comment
%%
int line_num = 1;

"/*"                      BEGIN(comment);

<comment>[^*\n]*          /* eat anything that's not a '*' */
<comment>"*"+[^*/\n]*     /* eat up '*'s not followed by '/'s */
<comment>\n               ++line_num;
<comment>"*"+"/"          BEGIN(INITIAL);
```

Source: http://flex.sourceforge.net/manual/Start-Conditions.html

Start Condition in Flex - Specs

- *Declaration*: Declared in the definitions section of the input
- `BEGIN` *Action*: A start condition is activated using the `BEGIN` action. Until the next `BEGIN` action is executed, rules with the given start condition will be active and rules with other start conditions will be inactive.
- *Inclusive Start Conditions*: Use unintended lines beginning with '%s' followed by a list of names. If the start condition is inclusive, then rules with no start conditions at all will also be active.
- *Exclusive Start Conditions*: Use unintended lines beginning with '%x' followed by a list of names. If it is exclusive, then only rules qualified with the start condition will be active.

  A set of rules contingent on the same exclusive start condition describe a scanner which is independent of any of the other rules in the flex input. Because of this, exclusive start conditions make it easy to specify mini-scanners which scan portions of the input that are syntactically different from the rest (for example, comments).

Source: http://flex.sourceforge.net/manual/Start-Conditions.html

Module Summary

- Lexical Analysis process is introduced
- Flex specification for Lexical Analyzer generation is discussed in depth
- Flow of Flex and Bison explained
- Special Flex feature of Start Condition discussed