南方科技大学
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CS323 Lab 2

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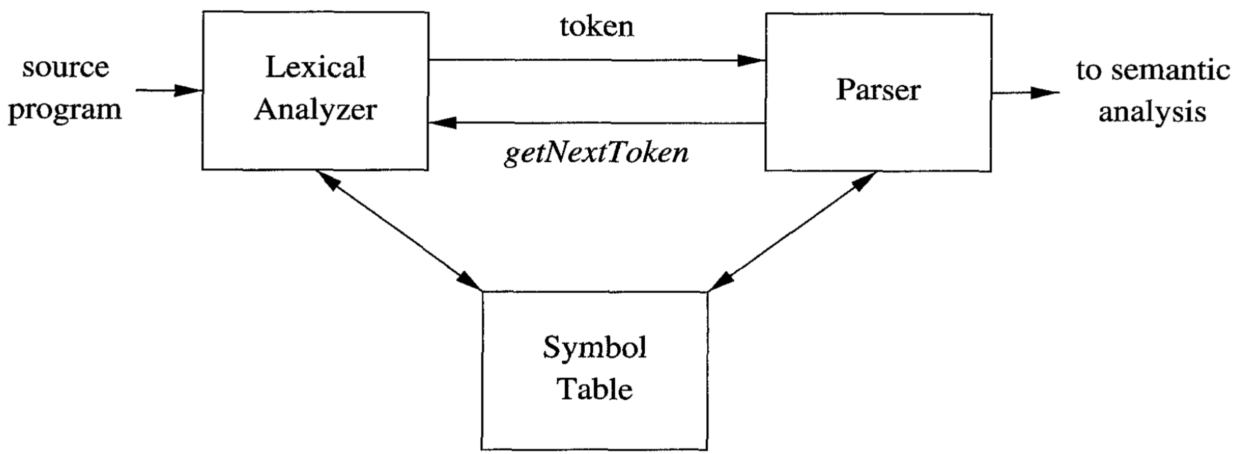
Outline

- The Role of Lexical Analyzer
- Specification of Tokens (Regular Expressions)
- Flex Tutorial
- Introduction to Project (Phase 1)

The Role of Lexical Analyzer

- Read the input characters of the source program, group them into lexemes, and produces a sequence of tokens
- Add lexemes into the symbol table when necessary



The Role of Lexical Analyzer

```
position = initial + rate * 60
```

Lexical Analyzer

```
<id, 1>
<=>
<id, 2>
<+>
<id, 3>
<*>
<60>
```

SYMBOL TABLE

1	position	...
2	initial	...
3	rate	...

Tokens, Patterns, and Lexemes

- A ***lexeme*** is a string of characters that is a lowest-level syntactic unit in programming languages
- A ***token*** is a syntactic category representing a class of lexemes. Formally, it is a pair <token name, attribute value>
  - Token name: an abstract symbol representing the kind of the token
  - Attribute value (optional) points to the symbol table
- Each token has a particular ***pattern***: a description of the form that the lexemes of the token may take

Examples

TOKEN	INFORMAL DESCRIPTION	SAMPLE LEXEMES
if	characters `i`, `f`	`if`
else	characters `e`, `l`, `s`, `e`	`else`
comparison	`<` or `>` or `<=` or `>=` or `==` or `!=`	`<=`, `!=`
id	letter followed by letters and digits	`pi`, `score`, `D2`
number	any numeric constant	`3.14159`, `0`, `6.02e23`
literal	anything but `"`, surrounded by `"`'s	`"core dumped"`

Consider the C statement: `printf("Total = %d\n", score);`

Lexeme	`printf`	`score`	`"Total = %d\n"`	`(`	...
Token	**id**	**id**	**literal**	**left_parenthesis**	...

Attributes for Tokens

- When more than one lexeme match a pattern, the lexical analyzer must provide additional information, named *attribute values*, to the subsequent compiler phases
  - Token names influence parsing decisions
  - Attribute values influence semantic analysis, code generation etc.
- For example, an **id** token is often associated with: (1) its lexeme, (2) type, and (3) the location at which it is first found. Token attributes are stored in the symbol table.

```
A = B * 2  →  <id, pointer to symbol-table entry for A>
              <assign_op>
              <id, pointer to symbol-table entry for B>
              <mult_op> <number, integer value 2>
```

Lexical Errors

- When none of the patterns for tokens match any prefix of the remaining input

- Example: `int 3a = a * 3;`

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Specification of Tokens

- **Regular expression (正则表达式, regexp for short)** is an important notation for specifying lexeme patterns

- Content of this part
  - Strings and Languages (串和语言)
  - Operations on Languages (语言上的运算)
  - Regular Expressions
  - Regular Definitions (正则定义)
  - Extensions of Regular Expressions

Strings and Languages

- **Alphabet (字母表)**: any finite set of symbols
  - Examples of symbols: letters, digits, and punctuations
  - Examples of alphabets: {1, 0}, ASCII, Unicode

- A **string (串)** over an alphabet is a finite sequence of symbols drawn from the alphabet
  - The length of a string *s*, denoted $|s|$, is the number of symbols in *s* (i.e., cardinality)
  - Empty string (空串): the string of length 0, ϵ

Terms (using banana for illustration)

- **Prefix (前缀) of string *s*:** any string obtained by removing 0 or more symbols from the end of *s* (ban, banana, ϵ)
- **Proper prefix (真前缀):** a prefix that is not ϵ and not *s* itself (ban)
- **Suffix (后缀):** any string obtained by removing 0 or more symbols from the beginning of *s* (nana, banana, ϵ).
- **Proper suffix (真后缀):** a suffix that is not ϵ and not equal to *s* itself (nana)

Terms Cont.

- **Substring (子串) of s:** any string obtained by removing any prefix and any suffix from s (banana, nan, ϵ)
- **Proper substring (真子串):** a substring that is not ϵ and not equal to s itself (nan)
- **Subsequence (子序列):** any string formed by removing 0 or more not necessarily consecutive symbols from s (bnn)

How many substrings does banana have?

(Two substrings are different as long as they have different start/end index)

String Operations (串的运算)

- **Concatenation (连接)**: the concatenation of two strings x and y, denoted xy, is the string formed by appending y to x
  - x = dog, y = house, xy = doghouse

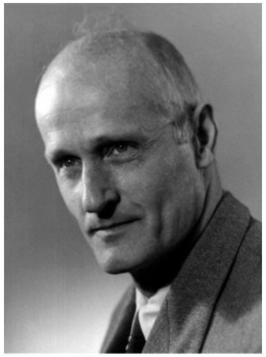
- **Exponentiation (幂/指数运算):** $s^0 = \epsilon$, $s^1 = s$, $s^i = s^{i-1}s$
  - x = dog, $x^0 = \epsilon$, x^1 = dog, x^3 = dogdogdog

Language (语言)

- A **language** is any **countable set**[1] of strings over some fixed alphabet
  - The set containing only the empty string, that is $\{\epsilon\}$, is a language, denoted $\emptyset$
  - The set of all grammatically correct English sentences
  - The set of all syntactically well-formed C programs

[1] In mathematics, a countable set is a set with the same cardinality (number of elements) as some subset of the set of natural numbers. A countable set is either a finite set or a countably infinite set.

Operations on Languages (语言的运算)



- 并，连接，Kleene闭包，正闭包

OPERATION	DEFINITION AND NOTATION
Union of L and M	$L \cup M = \{s \mid s \text{ is in } L \text{ or } s \text{ is in } M\}$
Concatenation of L and M	$LM = \{st \mid s \text{ is in } L \text{ and } t \text{ is in } M\}$
Kleene closure of L	$L^* = \cup_{i=0}^{\infty} L^i$
Positive closure of L	$L^+ = \cup_{i=1}^{\infty} L^i$

The exponentiation of L can be defined using concatenation. L^n means concatenating L n times.

https://en.wikipedia.org/wiki/Stephen_Cole_Kleene

Examples

- L = {A, B, …, Z, a, b, …, z}
- D = {0, 1, …, 9}

$L \cup D$	{A, B, …, Z, a, b, …, z, 0, 1, …,9}
LD	the set of 520 strings of length two, each consisting of one letter followed by one digit
L^4	the set of all 4-letter strings
L^*	the set of all strings of letters, including ϵ
$L(L \cup D)^*$	?
D^+	?

Regular Expressions

Rules that define regexps over an alphabet Σ:

- **BASIS**: two rules form the basis:
  - ϵ is a regexp, $L(\epsilon) = \{\epsilon\}$
  - If a is a symbol in Σ, then a is a regexp, and $L(a) = \{a\}$
- **INDUCTION:** Suppose r and s are regexps denoting the languages $L(r)$ and $L(s)$
  - $(r)|(s)$ is a regexp denoting the language $L(r) \cup L(s)$
  - $(r)(s)$ is a regexp denoting the language $L(r)L(s)$
  - $(r)^*$ is a regexp denoting $(L(r))^*$
  - (r) is a regexp denoting $L(r)$. Additional parentheses do not change the language an expression denotes.

Regular Expressions Cont.

- Following the rules, regexps often contain unnecessary pairs of parentheses. We may drop some if we adopt the conventions:
  - **Precedence:** closure * > concatenation > union |
  - **Associativity:** All three operators are left associative, meaning that operations are grouped from the left, e.g., a | b | c would be interpreted as (a | b) | c
- Example: $(a) \mid ((b)^*(c)) = a \mid b^*c$

Regular Expressions Cont.

- Examples: Let $\Sigma = \{a, b\}$
  - a|b denotes the language {a, b}
  - (a|b)(a|b) denotes {aa, ab, ba, bb}
  - a^* denotes $\{\epsilon$, a, aa, aaa, …}
  - $(a|b)^*$ denotes the set of all strings consisting of 0 or more *a*'s or *b*'s: $\{\epsilon$, a, b, aa, ab, ba, bb, aaa, …}
  - $a|a^*b$ denotes the string *a* and all strings consisting of 0 or more *a*'s and ending in *b*: {a, b, ab, aab, aaab, …}

Regular Language (正则语言)

- A **regular language** is a language that can be defined by a regexp
- If two regexps r and s denote the same language, they are *equivalent*, written as $r = s$

Regular Language Cont.

- Each algebraic law below asserts that expressions of two different forms are equivalent

LAW	DESCRIPTION
$r\|s = s\|r$	$\|$ is commutative
$r\|(s\|t) = (r\|s)\|t$	$\|$ is associative
$r(st) = (rs)t$	Concatenation is associative
$r(s\|t) = rs\|rt;\ (s\|t)r = sr\|tr$	Concatenation distributes over $\|$
$\epsilon r = r\epsilon = r$	ϵ is the identity for concatenation
$r^* = (r\|\epsilon)^*$	ϵ is guaranteed in a closure
$r^{**} = r^*$	$*$ is idempotent

Is (**a** | **b**)(**a** | **b**) = **aa** | **ab** | **ba** | **bb** true?

Regular Definitions (正则定义)

- For notational convenience, we can give names to certain regexps and use those names in subsequent expressions

If Σ is an alphabet of basic symbols, then a ***regular definition*** is a sequence of definitions of the form:

$$d_1 \rightarrow r_1$$
$$d_2 \rightarrow r_2$$
$$\ldots$$
$$d_n \rightarrow r_n$$

where:

- Each d_i is a new symbol not in Σ and not the same as the other d's
- Each r_i is a regexp over the alphabet $\Sigma \cup \{d_1, d_2, \ldots, d_{i-1}\}$

Each new symbol denotes a regular language. The second rule means that you may reuse previously-defined symbols.

Examples

- Regular definition for C identifiers

$$
\begin{array}{rcl}
letter\_ & \rightarrow & \mathtt{A} \mid \mathtt{B} \mid \cdots \mid \mathtt{Z} \mid \mathtt{a} \mid \mathtt{b} \mid \cdots \mid \mathtt{z} \mid \_ \\
digit & \rightarrow & \mathtt{0} \mid \mathtt{1} \mid \cdots \mid \mathtt{9} \\
id & \rightarrow & letter\_ \ (\ letter\_ \mid digit\ )^*
\end{array}
$$

`_hello` valid?

`3times` valid?

- Regexp for C identifiers

```
(A|B|...|Z|a|b|...|z|_)((A|B|...|Z|a|b|...|z|_)|(0|1|
...|9))*
```

Extensions of Regular Expressions

- **Basic operators:** union $|$, concatenation, and Kleene closure * (proposed by Kleene in 1950s)
- A few **notational extensions**:
  - One of more instances: the unary, postfix operator $^+$
    - $r^+ = rr^*$, $r^* = r^+ \mid \epsilon$
  - Zero or one instance: the unary postfix operator ?
    - $r? = r \mid \epsilon$
  - Character classes: shorthand for a logical sequence
    - $[a_1 a_2 \ldots a_\mathrm{n}] = a_1 \mid a_2 \mid \ldots \mid a_n$
    - $[a\text{-}e] = a \mid b \mid c \mid d \mid e$
- The extensions are only for notational convenience, they do not change the descriptive power of regexps

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The Lexical-Analyzer Generator `Lex`

- `Lex`, or a more recent tool `Flex`, allows one to specify a lexical analyzer by specifying regexps to describe patterns for tokens

- Often used with Yacc/Bison to create the frontend of compiler

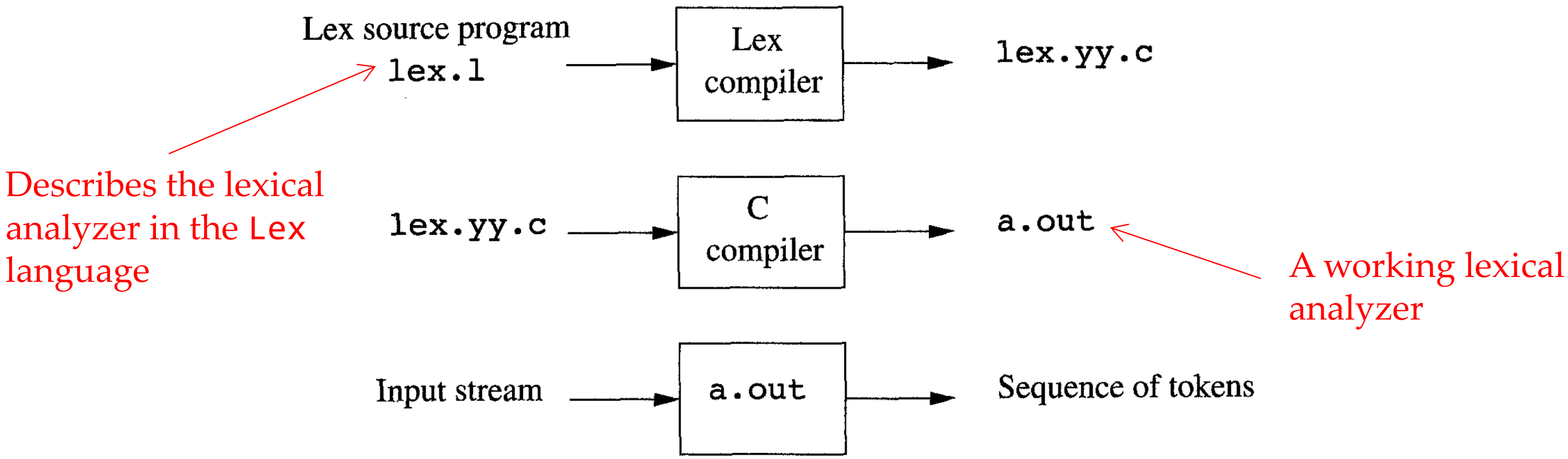

Figure 3.22: Creating a lexical analyzer with Lex

Structure of Lex Programs

- **A Lex program has three sections separated by %%**
  - Declaration (声明)
    - Variables, constants (e.g., token names)
    - Regular definitions
  - Translation rules (转换规则) in the form "Pattern {Action}"
    - Each pattern (模式) is a regexp (may use the regular definitions of the declaration section)
    - Actions (动作) are fragments of code, typically in C, which are executed when the pattern is matched
  - Auxiliary functions section (辅助函数)
    - Additional functions that can be used in the actions

Lex Program Example

```
%{
    /* definitions of manifest constants
    LT, LE, EQ, NE, GT, GE,
    IF, THEN, ELSE, ID, NUMBER, RELOP */
%}

/* regular definitions */
delim       [ \t\n]
ws          {delim}+
letter      [A-Za-z]
digit       [0-9]
id          {letter}({letter}|{digit})*
number      {digit}+(\.{digit}+)?(E[+-]?{digit}+)?

%%
```

Anything in between `%{` and `}%` is copied directly to `lex.yy.c`.

In the example, there is only a comment, not real C code to define manifest constants

Regular definitions that can be used in translation rules

Section separator

Lex Program Example Cont.

Continue to recognize other tokens

Return token name to the parser

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

Literal strings*

Place the lexeme found in the symbol table

A global variable that stores a pointer to the symbol table entry for the lexeme. Can be used by the parser or a later component of the compiler.

* The characters inside have no special meaning (even if it is a special one such as *).

Lex Program Example Cont.

- Everything in the auxiliary function section is copied directly to the file `lex.yy.c`
- Auxiliary functions may be used in actions in the translation rules

```
int installID() {/* function to install the lexeme, whose
                    first character is pointed to by yytext,
                    and whose length is yyleng, into the
                    symbol table and return a pointer
                    thereto */
}

int installNum() {/* similar to installID, but puts numer-
                     ical constants into a separate table */
}
```

Variables defined and set automatically by the lexical analyzer `Lex` generates

Conflict Resolution

- When the generated lexical analyzer runs, it analyzes the input looking for prefixes that match any of its patterns. *

- **Rule 1:** If it finds multiple such prefixes, it takes the longest one
  - The analyzer will treat <= as a single lexeme, rather than < as one lexeme and = as the next

- **Rule 2:** If it finds a prefix matching different patterns, the pattern listed first in the `Lex` program is chosen.
  - If the keyword patterns are listed before identifier pattern, the lexical analyzer will not recognize keywords as identifiers

* See Flex manual for details (Chapter 8: How the input is matched) at http://dinosaur.compilertools.net/flex/

Flex

- Flex的前身是Lex。Lex是1975年由Mike Lesk和当时还在贝尔实验室做暑期实习的Eric Schmidt（前谷歌CEO），共同完成的一款基于Unix环境的词法分析程序生成工具。虽然Lex很出名并被广泛使用，但它的低效和诸多问题也使其颇受诟病。
- 1987年伯克利实验室（隶属美国能源部的国家实验室）的Vern Paxson使用C语言重写Lex，并将这个新程序命名为Flex（Fast Lexical Analyzer Generator）。无论从效率上还是稳定性上，Flex都远远好于它的前辈Lex。

*我们在Linux下使用的是`Flex`在BSD License下的版本（和Bison不同，Flex不属于GNU计划）。

An Example Flex Program

- A word-count program (see the code under lab2/wc)
- Build the program with the following commands (or "`make wc`")
  - `flex lex.l` (you will see a lex.yy.c file generated)
  - `gcc lex.yy.c -lfl -o wc.out`

```
yepang@Ubuntu-LYP:~/Desktop/CS323-2021F/lab2/wc$ ./wc.out inferno3.txt
#lines  #words  #chars  file path
162     1088    6525    inferno3.txt
```

A Closer Look

```
%{
    // just let you know you have macros!
    // C macro tutorial in Chinese: http://c.biancheng.net/view/446.html
    #define EXIT_OK 0
    #define EXIT_FAIL 1

    // global variables
    int chars = 0;
    int words = 0;
    int lines = 0;
%}
letter [a-zA-Z]

%%
{letter}+ { words++; chars+=strlen(yytext); }
\n { chars++; lines++; }
. { chars++; }

%%
int main(int argc, char **argv){
    char *file_path;
    if(argc < 2){
        fprintf(stderr, "Usage: %s <file_path>\n", argv[0]);
        return EXIT_FAIL;
    } else if(argc == 2){
        file_path = argv[1];
        if(!(yyin = fopen(file_path, "r"))){
            perror(argv[1]);
            return EXIT_FAIL;
        }
        yylex();
        printf("%-8s%-8s%-8s%s\n", "#lines", "#words", "#chars", "file path");
        printf("%-8d%-8d%-8d%s\n", lines, words, chars, file_path);
        return EXIT_OK;
    } else{
        fputs("Too many arguments! Expected: 2.\n", stderr);
        return EXIT_FAIL;
    }
}
```

The structure is the same as in a Lex program:

1. Declaration
2. Translation rules
3. Auxiliary functions

More on Flex patterns

Flex supports a rich set of conveniences:

Character classes	**`[0-9]`**	This means alternation of the characters in the range listed (in this case: **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9**). More than one range may be specified, e.g. **`[0-9A-Za-z]`** as well as specifying individual characters, as with **`[aeiou0-9]`**.
Character exclusion	**^**	The first character in a character class may be **^** to indicate the complement of the set of characters specified. For example, **`[^0-9]`** matches any non-digit character.
Arbitrary character	**.**	The period matches any single character **except newline**.
Single repetition	**`x?`**	0 or 1 occurrence of **`x`**.

More on Flex patterns

Non-zero repetition	**x+**	**x** repeated one or more times; equivalent to **xx***.
Specified repetition	**x{n,m}**	**x** repeated between **n** and **m** times.
Beginning of line	^x	Match **x** at beginning of line only.
End of line	**x$**	Match **x** at end of line only.
Context-sensitivity	**ab/cd**	Match **ab** but only when followed by **cd**. The lookahead characters are left in the input stream to be read for the next token.
Literal strings	**"x"**	This means **x** even if **x** would normally have special meaning. Thus, **"x*"** may be used to match **x** followed by an asterisk. You can turn off the special meaning of just one character by preceding it with a backslash, .e.g. **\\.** matches exactly the period character and nothing more.
Definitions	**{name}**	Replace with the earlier defined pattern called **name**. This kind of substitution allows you to re-use pattern pieces and define more readable patterns.

https://web.stanford.edu/class/archive/cs/cs143/cs143.1128/handouts/050%20Flex%20In%20A%20Nutshell.pdf

Flex Exercise: C Identifier

- Count the occurences of valid C identifiers
  - A valid C identifier starts with an English letter or an underscore followed by any number of English letters, digits, or underscores
- We make some assumptions to simplify the task
  - Only these reserved words may appear: char, int, return, while, if, else
  - There are no preprocessor commands (e.g., #include <stdio.h>)
  - There are no function calls

Flex Exercise: C Identifier

- Please modify the lex.l under lab2/identifier directory
- Build the lexer
  - `make idcount`
- Run the counting program
  - `./idcount.out test.c`
- If you get the following output, your implementation is correct.

```
line 1: main
line 3: a
line 4: BBA
line 4: a_
line 5: _
line 7: a0
line 7: _
line 7: b0
line 8: _
line 8: b0
line 9: b
line 9: b1
line 9: b0
line 9: b2
line 10: c
There are 15 occurrences of valid identifiers
```

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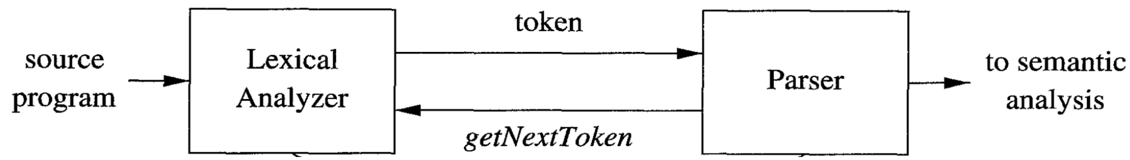
Project Goal

- Design & implement a compiler for SUSTech Programming Language (SPL), a Turing-complete C-like programming language without advanced features (e.g., macros, pointers)

- **Compiler input:** A piece of SPL source code

- **Compiler output:** MIPS32 assembly code (runnable in the Spim simulator)

Phase 1



- Implement a SPL parser, which can perform lexical analysis and syntax analysis on SPL source code
  - Flex will be used to implement the lexical analysis module
  - Bison will be used to implement the syntax analysis module
  - The syntax analysis module invokes the lexical analysis module during parsing
- Parser output:
  - For a syntactically valid SPL program, your parser should output the parse tree (will be introduced in Chapter 3)
  - Otherwise, your parser should output all lexical & syntax errors

SPL Specification

Allowed tokens:

```
INT     -> /* integer in 32-bits (decimal or hexadecimal) */
FLOAT   -> /* floating point number (only dot-form) */
CHAR    -> /* single character (printable or hex-form) */
ID      -> /* identifier */
TYPE    -> int | float | char
STRUCT  -> struct
IF      -> if
ELSE    -> else
WHILE   -> while
RETURN  -> return
DOT     -> .
SEMI    -> ;
COMMA   -> ,
ASSIGN  -> =
```

```
LT       -> <
LE       -> <=
GT       -> >
GE       -> >=
NE       -> !=
EQ       -> ==
PLUS     -> +
MINUS    -> -
MUL      -> *
DIV      -> /
AND      -> &&
OR       -> ||
NOT      -> !
LP       -> (
RP       -> )
LB       -> [
RB       -> ]
LC       -> {
RC       -> }
```

https://github.com/sqlab-sustech/CS323-2022F/blob/main/spl-spec/token.txt

SPL Specification

The grammar rules:

```
Stmt -> Exp SEMI
      | CompSt
      | RETURN Exp SEMI
      | IF LP Exp RP Stmt
      | IF LP Exp RP Stmt ELSE Stmt
      | WHILE LP Exp RP Stmt
```

https://github.com/sqlab-sustech/CS323-2022F/blob/main/spl-spec/syntax.txt

```
Exp -> Exp ASSIGN Exp
     | Exp AND Exp
     | Exp OR Exp
     | Exp LT Exp
     | Exp LE Exp
     | Exp GT Exp
     | Exp GE Exp
     | Exp NE Exp
     | Exp EQ Exp
     | Exp PLUS Exp
     | Exp MINUS Exp
     | Exp MUL Exp
     | Exp DIV Exp
     | LP Exp RP
     | MINUS Exp
     | NOT Exp
     | ID LP Args RP
     | ID LP RP
     | Exp LB Exp RB
     | Exp DOT ID
     | ID
     | INT
     | FLOAT
     | CHAR
```

The parse tree:

```
Program (1)
  ExtDefList (1)
    ExtDef (1)
      Specifier (1)
        TYPE: int
      FunDec (1)
        ID: test_1_r01
        LP
        VarList (1)
          ParamDec (1)
            Specifier (1)
              TYPE: int
            VarDec (1)
              ID: a
          COMMA
          VarList (1)
            ParamDec (1)
              Specifier (1)
                TYPE: int
              VarDec (1)
                ID: b
        RP
      CompSt (2)
        LC
        StmtList (3)
          Stmt (3)
            Exp (3)
              Exp (3)
                ID: c
              ASSIGN
              Exp (3)
                CHAR: 'c'
            SEMI
          StmtList (4)
            Stmt (4)
              IF
              LP
              Exp (4)
                Exp (4)
                  ID: a
                GT
                Exp (4)
                  ID: b
              RP
              Stmt (5)
                CompSt (5)
                  LC
                  StmtList (6)
                    Stmt (6)
                      RETURN
                      Exp (6)
                        ID: a
                      SEMI
                  RC
              ELSE
              Stmt (9)
                CompSt (9)
                  LC
                  StmtList (10)
                    Stmt (10)
                      RETURN
                      Exp (10)
                        ID: b
                      SEMI
                  RC
        RC
```

Example

```
int test_1_r01(int a, int b)
{
  c = 'c';
  if (a > b)
  {
    return a;
  }
  else
  {
    return b;
  }
}
```

A syntactically valid program*

* Here, the vairable c is used without definition.
This error will be caught during semantic analysis.

Example

```
1  int test_1_r03()
2  {
3          int i = 0, j = 1;
4    float i = $;
5    if(i < 9.0){
6      return 1
7    }
8    return @;
9  }
```

```
Error type A at Line 4: unknown lexeme $
Error type B at Line 6: Missing semicolon ';'
Error type A at Line 8: unknown lexeme @
```