

Lexical Analysis & Syntax Analysis

1 Overview

In CS323 projects, we will write a compiler for a toy programming language called SPL, the abbreviation for Sustech Programming Language. SPL is a C-like programming language that removes most advanced features in C standard, such as macros or pointers. It is strongly typed, with several primitive types and structure type (as we borrowed from C), and supports C-like control flow such as if-statement and while-statement. Also, it supports basic user interaction by providing two built-in function `read` and `write`, which makes it Turing-complete!

During this semester, you will learn how to build your own compiler from scratch. Our compiler compiles a SPL program into MIPS32 assembly. You are expected to realize it through lexical and syntax analysis, semantics checking, intermediate code and target code generation. At the end of this semester, your compiler will be able to translate a SPL program into MIPS32 code, which can be run on a **REAL** MIPS simulator, in one-shot.

You are suggested to configure the development environment by yourself. Detailed information can be found in Section 2. To make things easier, we also provide you a virtual machine, which already includes tools that are required during this semester.

In the first project, you are required to implement a SPL parser. Specifically, your parser will perform lexical analysis and syntax analysis on the SPL source code. You will use two powerful open-source tools, Flex¹ and Bison², to realize your parser. you will implement it by C programming language. In modern compiler design and implementation, lexical analysis and syntax analysis can be totally automated (so you don't need to implement your NFA/DFA, or parsing algorithms), typical tools are Lex/Flex for generating lexical analyzer, and Yacc/Bison for generating parser. Though you can complete project 1 without too much theoretical knowledge, it doesn't mean the theory is not important. You will learn how to recognize tokens using regular expressions and how to check code structures using context-free grammars in the lecture. As for your project, what you need to do is just specifying the regular expressions and grammar rules.

One thing to note is that, you will finish the subsequent parts of your compiler on top of this work, thus it is important to keep your code maintainable and extensible.

2 Development Environment

To ease your burden, we have made a virtual machine containing necessary dependencies and debugging tools. It is built on top of a Ubuntu 18.04 (64-bit) image, with pure command line interface (you can download the base image [here](#)). We will evaluate your work on exactly

¹<https://github.com/westes/flex>

²<https://www.gnu.org/software/bison/>

the same VM. However, the image is provided as is and it will not be regularly maintained. Therefore, you are highly recommended to set up your own development environment. Here, we list the necessary dependencies as follow:

- GCC version 7.4.0
- GNU Make version 4.1
- GNU Flex version 2.6.4
- GNU Bison version 3.0.4
- Python version 3.6.8
- urwid (Python module) 2.0.1
- Spim version 8.0

You can customize the virtual machine or your own machine to fulfill your requirements during coding, testing and debugging. However, you should ensure that your submitted code can be compiled and run smoothly in our provided environment. We will not install any other software, tools or third-party libraries on the evaluating machine.

2.1 Virtual Machine Setup



We provide you a VMware image of our virtual machine, you can download the zip archive at [this](#) site. You can set up the virtual machine by opening the unzipped archive as a copied virtual machine in VMware workstation. To use the lab vm, login as `student:compiler`, which is already a privileged user.

3 Flex for Lexical Analysis

Flex is a fast lexical analyzer (or *lexer*) generator. You should specify the token patterns to match and actions to apply for each token. Flex takes your specification and generates a combined NFA that recognizes all your patterns, then converts it to an equivalent DFA, minimizes the automaton as much as possible, finally generates C code that implements the lexer. Flex is similar to its predecessor, Lex, designed by Lesk and Schmidt. While we will use Flex in the projects, almost all features we use are present in Lex.

This section is designed to give you a quick introduction to the Flex tool. We hope it serves as a useful reference for the project 1. To learn more about Flex, run `info flex` in the command line, or read the documentation at <http://dinosaur.compilertools.net/flex/>.

3.1 Coding with Flex

Flex is designed for use with C code and generates a lexer/scanner written in C. The lexer is specified using regular expressions for *patterns* and C code for the *actions*. The lexical specification files are identified by a `.l` extension. You invoke `flex` on a `.l` file and it creates `lex.yy.c`, a source file containing C code that implements a finite automaton encoding all your rules and corresponding actions you specified. The file provides an `extern` function `yylex()` that will read the from input stream pointed by `yyin`. You compile that C source file normally, link with the Flex library (by GCC option `-lfl`), then you have built a lexer!

```
%{  
Declarations  
%}  
Definitions  
%%  
Rules  
%%  
User subroutines
```

The optional `Declarations` and `User subroutines` sections are used for ordinary C code that you want copied verbatim to the generated C file. `Declarations` are copied to the top of the file, and `user subroutines` to the bottom. The optional `Definitions` section is where you specify options for the scanner and can set up definitions to give names to regexes as a simple substitution mechanism that allows for more readable code in the `Rules` section that follows. The *required* `Rules` section is where you specify the patterns that identify tokens and corresponding actions to perform upon recognizing each token. Each section is separated by two `%` marks. If the code contains only the required `Rules` section, it should also begin with a line `%%`.

To see how Flex works, we have a simple application that includes all aforementioned sections in a `.l` source file. For those optional sections, Flex has default routine to handle with their absence, which will be introduced later.

Listing 1: A `wc` application in Flex

```

1  %{
2      // just let you know you have macros!
3      #define EXIT_OK 0
4      #define EXIT_FAIL 1
5      // and global variables
6      int chars = 0;
7      int words = 0;
8      int lines = 0;
9  %}
10 letter [a-zA-Z]
11 %%
12 {letter}+ { words++; chars+=strlen(yytext); }
13 \n { chars++; lines++; }
14 <<EOF>> { if(yyleng > 1){ lines++; } return 0; }
15 . { chars++; }
16 %%
17 int main(int argc, char **argv){
18     char *file_path;
19     if(argc < 2){
20         fprintf(stderr, "Usage: %s <file_path>\n", argv[0]);
21         return EXIT_FAIL;
22     }
23     else if(argc == 2){
24         file_path = argv[1];
25         if(!(yyin = fopen(file_path, "r"))){
26             perror(argv[1]);
27             return EXIT_FAIL;
28         }
29         yylex();
30         printf("%-8d%-8d%-8d%s\n", lines, words, chars, file_path);
31         return EXIT_OK;
32     }
33     else{
34         fputs("Too much arguments!\n", stderr);
35         return EXIT_FAIL;
36     }
37 }

```

The program above works like a `wc` utility presented in most Unix systems. In the **Declarations** section, we define two macros `EXIT_OK` and `EXIT_FAIL`, and three global variables that store the number of characters, words and lines, respectively. Just like coding with C, you can also include libraries, declare external variables in this section. Then the **Definitions** section follows. The general format of this section is:

name definition

which means you *name* a regex specified by the *definition*. You can define multiple definitions here. The **Definitions** section is optional, since you can always write the full regexes in the **Rules** section. A single rule is defined as:

pattern {action}

As the lexer reads characters from the input stream, it will gather them until it forms the longest possible match for any of the available patterns. If two or more patterns match an

equally long sequence, the pattern listed first in the source code is applied. The *action* is written in C, it depends on what procedure you are trying to do with each token. For a lexer designed to be used by a compiler, the action will usually record the token attributes and return a code that identifies the token type.

In code listing 1, we define the name `letter`, which corresponds to the alphabetic characters, then we specify four action rules that reference global variables defined by both Flex library and ourselves. The global variables `yytext` and `yylen` store the matched lexeme and its length. Action for each pattern is intuitive. In 3.2, we will show more available patterns supported by Flex. The third pattern is a special pattern provided by Flex, it is matched when the input stream reaches the end, it will return 0 by default. In the customized rule, 0 should also be returned to signal the end-of-file, otherwise the lexer will never stop scanning.

We defined our own `main` function at the bottom. By default, Flex provides a simple `main` that will repeatedly calls `yylex` until it reaches EOF. You should compile and link the lexer into your project and use your own `main` to control the behavior whenever tokens are matched. In the main routine, we reference the variable `yyin` and invoke the library function `yylex`. The former is a pointer pointing to the input file descriptor and is `stdin` by default; the latter is the entry point to our lexing procedure. More library-defined global variables and functions will be introduced later in 3.3.

3.2 Patterns in Flex

We show you some useful patterns supported by Flex in Table 1, while not yet complete, they are sufficient for your compiler construction. For more details about the supported regex patterns, please refer to the Flex manual.

3.3 More Flex Features

In this section, we will introduce more features supported by Flex, which can reduce your workload during coding. However, they are totally optional since you can still complete your lexer without these advanced features.

1. The `yylineno` option

A compiler often needs to record information of line number of the source file, in case of error reporting, debugging, etc. To support this functionality, you can maintain a global variable `lineno` with initial value 1, and increment it when a new line character is encountered, i.e., `lineno++` for pattern `"\n"`.

However, Flex has already provided built-in mechanism for this, by a global variable `yylineno` which will automatically increase by 1 after scanning each line. To use this feature, you should add a single line in the **Definitions** section:

```
%option yylineno
```

Table 1: Patterns supported by Flex (not complete)

Pattern	Regex	Description
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	.	Matches any single character except newline .
Selection	x y	Either x or y can be matched.
Single repetition	x?	0 or 1 occurrence of x.
Nonzero 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 reuse pattern pieces and define more readable patterns.

2. The library function input and unput

Flex library function `input()` takes no input, which will read a single character from the input buffer and return it. By this function, you are able to realize some actions without specifying the concrete regex. For example, you can discard all characters behind `"//"` in the line by the following code:

```
"//" { char c; while((c=input()) != '\n'); }
```

Inversely, the function `unput(char c)` puts c back into the input buffer. You can realize multiple-lines comment with this function, which is an optional implementation in this project. Note that pushing characters back should be done reversely.

3. The library function `yylless` and `yymore`

`yylless(int n)` returns the `yyleng-n` characters in the postfix of current lexeme back to the input buffer, where they will be rescanned when the lexer looks for the next match. `yytext` and `yyleng` are adjusted appropriately (e.g., `yyleng` will now be equal to `n`).

`yymore()` tells the lexer that the next time it matches a rule, the corresponding token should be appended onto the current value of `yytext` rather than replacing it.

If you want to support string literal, you should consider the case when there are nested double-quotation mark in the lexeme, for example, "And God said, \"Let there be light,\" and there was light." By cooperating `yylless` and `yymore`, your lexer is able to recognize string literals:

```
\"[^\"]*\" {
    if(yytext[yyleng-2] == '\\\\') {
        yylless(yyleng-1);
        yymore();
    } else {
        /* process the string literal */
    }
}
```

3.4 Writing Your Lexer

To realize your lexer, you should firstly (and carefully) read the token specification of SPL in Appendix A and the detailed explanation. You should write regular expressions for the first four tokens, while the remaining part of the specification is rather simple. In this stage, your job is only to recognize each token, hence you can simply print out the tokens in their corresponding actions:

```
"TYPE" { printf("TYPE %s\n", yytext); }
```

To report lexical error, you can add a fallback rule:

```
. { printf("Error type A at Line %d: Unknown characters \'%s\'\\n",
        yylineno, yytext); }
```

Here is a sample program of SPL:

Listing 2: A sample SPL source code

```
1  int test_spl()
2  {
3      int i = 0, j = 1;
4      float i = 1;
5  }
```

For this source code, your lexer should print:

```
TYPE int
ID test_spl
LP
RP
LC
TYPE int
ID i
ASSIGN
INT 0
COMMA
ID j
ASSIGN
INT 1
SEMI
TYPE float
ID i
ASSIGN
INT 1
SEMI
RC
```

4 Bison for Syntax Analysis

Bison is a parser generator. You provide the input of a grammar specification and Bison will generate an LALR(1) parser to recognize sentences in that grammar. The name is a great example of a CS in-joke. Bison is an upgraded version of the older tool Yacc (“Yet Another Compiler Compiler”). It is probably the most common LALR tool. Our programming projects are configured to use the updated version Bison, a close relative of the yak, but all features we use are also present in the original tool. So this handout serves as a brief overview of both. For those who really want to dig deep and learn everything about parser generators, please refer to Bison’s official manual: <https://www.gnu.org/software/bison/manual/bison.html>.

Bison generates a parser, which accepts the input token stream from Flex, to recognize code in the specified context-free grammar (CFG). By default, Bison generates a LALR(1) parser. Note that the programmer is always shielded from the parsing algorithm applied by the compiler. For example, JTB³ by Java generates an LL(1) parser for the JavaCC. As a compiler designer, what you are going to do is writing the grammar/syntax specification, and the action for each production. In theory, the output of a parser is a parse tree, though we are able to go beyond, i.e., analyzing the code semantics with Bison.

³<http://compilers.cs.ucla.edu/jtb/>

4.1 Interacting Flex and Bison

Bison source code has a similar structure as Flex source code, which also contains optional `Declarations`, `Definitions` and `User routines` sections.

```
%{  
Declarations  
%}  
Definitions  
%%  
Productions  
%%  
User subroutines
```

In Bison, just as you utilize Flex, you can associate an action with each pattern (this time a production), which allows you to do whatever processing as you reduce using that production. Unlike in Flex, the optional `Definitions` section is where we configure various parser features such as defining token codes, establishing operator precedence and associativity, and setting up the global variables used to communicate between the lexer and parser.

To see how Bison compiles a CFG into an executable, we provide example Bison code in Listing 3. It implements a simple calculator with conventional precedence for each operation:

Listing 3: The Bison source code `syntax.y` for `calc`

```
1  %{  
2      #include"lex.yy.c"  
3      void yyerror(const char*);  
4  %}  
5  %token INT  
6  %token ADD SUB MUL DIV  
7  %%  
8  Calc: /* empty */  
9      | Exp { printf("= %d\n", $1); }  
10     ;  
11  Exp: Factor  
12     | Exp ADD Factor { $$ = $1 + $3; }  
13     | Exp SUB Factor { $$ = $1 - $3; }  
14     ;  
15  Factor: Term  
16     | Factor MUL Term { $$ = $1 * $3; }  
17     | Factor DIV Term { $$ = $1 / $3; }  
18     ;  
19  Term: INT  
20     ;  
21  %%  
22  void yyerror(const char *s){  
23      fprintf(stderr, "%s\n", s);  
24  }  
25  int main(){  
26      yyparse();  
27  }
```

We define our `main` function at the end of the source file. We invoke the Bison function `yyparse`, in which the token stream will be read via `yylex`. The routine `yyerror` is called when parser encounters an error, in which the next token cannot be shifted during parsing. Though `yyerror` is invoked every time an error occurs, it should be defined by ourselves. You should be able to report more than general syntax error messages in the `yyerror` function.

We include the Flex-generated `lex.yy.c` file at the **Declarations** section, since we will apply `yylex` defined in it. It's worth mentioning that, the **Declarations** section will be copied verbatim into the generated `C` file, rather than statically linked during Bison compilation, hence we are able to compile our `.y` file successfully with the absence of `lex.yy.c` file. Lines 5–6 define tokens of the language. In this case, they are number literals and arithmetic operators. These tokens can be returned by Flex actions.

All defined tokens are terminals in the language, where the nonterminals are specified in the **Productions** section. The first nonterminal presented is assumed to identify the start symbol for the grammar. For each rule, a colon is used in place of the arrow, a vertical bar separates the various productions, and a semicolon terminates the rule. The action for each production is enclosed by braces. If no rules are assigned, Bison will insert a default action `{ $$ = $1 }`. The variables whose name starts with the dollar sign (`'$'`) are associated with each variable's attribute value at each production and the order increases from left to right. As an example, in Listing 3, Line 12 evaluates the result of add operator. The `'$$'` is the attribute of the left-side of the production, i.e., `Exp`, while `'$1'` and `'$3'` correspond to the attributes of right-side nonterminals `Exp` and `Factor`.

Since we read the token stream from lexer-defined functions, we should update Flex source code accordingly:

Listing 4: The Flex source code `lex.l` for `calc`

```
1  %{
2      #include "syntax.tab.h"
3  %}
4  %%
5  [0-9]+ { yylval = atoi(yytext); return INT; }
6  "+" { return ADD; }
7  "-" { return SUB; }
8  "*" { return MUL; }
9  "/" { return DIV; }
```

In each action, we return the tokens defined in `syntax.tab.h`, which is generated from Bison source code. `yylval` is a predefined Flex variable, which indicates the attribute of the current token, while the return value tells the parser what kind of token is scanned at the moment.

In order to compile the calculator, we should firstly compile the Bison source code into C code, and split it into header file and implementation file (by Bison `“-d”` option):

```
bison -d syntax.y
```

This command will produce two files, `syntax.tab.h` and `syntax.tab.c`. Then we can compile the Flex code:

```
flex lex.l
```

Next we put them together and compile the source files with GCC:

```
gcc syntax.tab.c -lfl -ly -o calc.out
```

The options `-lfl` and `-ly` tell GCC to include Flex and Bison/Yacc library, respectively. After that, we have an executable, which accepts a single arithmetic expression from standard input and outputs its result to the console. You can validate the calculator by feeding simple test cases:

```
echo "1 + 1" | ./calc.out
> = 2
echo "10 - 2*3" | ./calc.out
> = 4
echo "92+1c" | ./calc.out
> syntax error
```

4.2 More on Bison

1. Token/nonterminal attributes

In the above, we mentioned that, the attribute of the symbol is assigned to the global variable `yylval`, but we did not clarify its data type. This variable is declared as of type `YYSTYPE`, which has a default value `int`. That's why we are able to assign a integer value to `yylval` in the aforementioned Flex source code. However, in our parser, the attribute of each nonterminal/token should be abstracted into a syntax tree node. How can we implement it?

One way to do so is to explicitly redefine the `YYSTYPE` macro. In other words, you can insert the following line in the **Bison Declarations**:

```
#define YYSTYPE float
```

to ensure each production results in a floating-point value. To support multi-typed attribute, you may consider `union/struct` type.

However, there are more flexible approaches for this goal. Bison provides the `%union` directive to indicate the token's data type, which goes to the **Definitions** section. For example, the following `union` type will be copied as the value of `YYSTYPE`:

```
%union{
    int int_value;
    float float_value;
    char *string_value;
}
```

To indicate the token type, we should modify the token definition. In the **Definitions** section, by preceding the token name with the union field name enclosed in a pair of angle brackets, we are able to assign type to a particular token. The same usage applies to nonterminal symbols, which should be specified by the `%type` directive.

```
%token <int_value> INT
%token ADD SUB MUL DIV
%type <float_value> Exp Factor
```

As an example, the code above assigns an integer value to the `INT` token, and a floating-point value to `Exp` and `Factor` nonterminals. The arithmetic operators are defined without data type, since their attributes are not significant during expression parsing.

2. Symbol position

At the beginning of this section, we have shown that we can access the attribute of each symbol (token or nonterminal) via `$n`, where `n = $` refers to the left-side nonterminal of production, while numerical `n` refers to the `n`-th symbol at the right side.

Similarly, we are able to access the location information of each symbol with `@n` notation. These two notations are totally in parallel, i.e.,

- `$n` refers to a `YYSTYPE` variable `yylval`, which is the attribute of the symbol
- `@n` refers to a `YYLTYPE` variable `yylloc`, which is the position of the symbol

The default definition of `YYLTYPE` is a structure containing the first line/column and the last line/column of the grammar symbol. The information provided is already sufficient. However, if you directly read the information via `@n` notation, you will find that the location value never gets updated! The reason is that, the parser only reduces the token stream, while the position information is gathered by the lexer. So, in order to update the location, you have to manage it in the Flex code.

Firstly, you should insert the code below at the header sections in the `.l` file:

```
%{
    /* library inclusions */
    int yycolno = 1;
    #define YY_USER_ACTION \
        yylloc.first_line = yylineno; \
        yylloc.first_column = yycolno; \
        yylloc.last_line = yylineno; \
        yylloc.last_column = yycolno + yyleng; \
        yycolno += yyleng;
%}
```

The variable `yycolno` is managed by yourself, which should be reset every time a new line occurs:

```
"\n" { yycolno = 1; }
```

The macro `YY_USER_ACTION` is executed at each token recognized by Flex, which is an empty macro by default.

3. Conflict resolution

The grammar can be ambiguous, and Bison will not throw exception under such a situation, but will record all potential conflicts in the table, and handle conflicts in such ways:

- For a shift/reduce conflict, always choosing shift
- For a reduce/reduce conflict, reducing with the rule declared first in the `.y` file

These strategies may change the accepted language, which is undesirable. Even if everything happens to work out, it is not recommended to adopt this default mechanism. You should resolve conflicts by specifying the precedence and associativity for the operators. The precedence and associativity for SPL operators are enumerated in Appendix [C.2](#).

Consider our calculator example. If we modify the grammar to make it ambiguous:

```
Exp: INT
    | Exp ADD Exp
    | Exp SUB Exp
    | Exp MUL Exp
    | Exp DIV Exp
    ;
```

When you compile the grammar, Bison will report:

```
syntax.y: warning: 16 shift/reduce conflicts [-Wconflicts-sr]
```

The parser generated from this grammar may then exhibit strange behavior:

```
echo "3 * 4 + 5" | ./calc.out
> = 27
echo "5 + 3 * 4" | ./calc.out
> = 17
```

To understand the reason, consider why shift/reduce conflict occurs. For the first expression, when token stream `3 * 4` is on the stack, followed by the tokens `+ 5`, the parser can choose either reducing with `Exp -> Exp MUL Exp` or shifting the next token. For such a shift/reduce conflict, Bison will always shift, hence the parser shifts `+ 5` and reduces with `Exp -> Exp ADD Exp`. To resolve the conflict, we should explicitly assign precedence and associativity to each operator. See the following token definition code:

```
%left ADD SUB
%left MUL DIV
```

The code states the associativity for arithmetic operators, i.e., all of them associate from left to right. Similarly, you can apply `%right` directive to indicate a right-to-left operator, and `%nonassoc` for a non-associative operator. The code also assigns precedence for the operators by ordering the token definition: the lower-precedence operator appears earlier, so `MUL` has a higher precedence than `ADD` and `SUB`.

Assigning precedence and associativity resolves the conflicts. For a shift/reduce conflict, if the precedence of the token to be shifted is higher than that of the rule to reduce, it chooses to shift and vice versa. The precedence of a rule is determined by the precedence of the rightmost terminal on the right-hand side. So if a `5 + 3` is on the stack and `*` is coming up, the `*` has a higher precedence than the `5 + 3`, so it shifts. If `3 * 4` is on the stack and `+` is coming up, it reduces. If `5 + 3` is on the stack and `+` is coming up, the associativity breaks the tie: a left-to-right associativity will reduce the rule and then go on; a right-to-left associativity will shift and postpone the reduction.

The associativity of the production can also be explicitly set with the `%prec` directive. When `%prec` is placed at the end of a production with a terminal as argument, it explicitly sets the precedence of the production to the same precedence as that terminal. This is useful where the production's right side has no terminals, or when you want to explicitly assign precedence to the production. This feature may help you to eliminate the shift/reduce conflict warning for a *dangling-else ambiguity* (it is present in our SPL specification), even if Bison's default strategy for this conflict is consistent with the C language standard.

4. Error recovery

Bison supports error recovery by providing a special `error` token. When the Bison-generated parser encounters an error, it triggers the following error recovery routine:

1. Invoke `yyerror` reporting function (which you may overwrite)
2. Pop out all un-reduced tokens, until the `error` can be shifted
3. Shift `error`, then drop tokens until one can be pushed after `error` (re-synchronization)
4. If three symbols can be successfully shifted, continue parsing, otherwise, back to step 2

To recover from an error state, you should place the `error` in a correct context. For example, the following recovery patterns help the parser recover from programs that have missing semicolons, right curly brackets or right parentheses.

```
Stmt: Exp error
CompSt: LC DefList StmtList error
Exp: ID LP Args error
```

However, where to put the `error` token is more of an art than a science: putting error at fairly high levels tends to protect you from all sorts of errors, while putting error at a lower

level can help minimize the number of tokens to be discarded. For compiler construction, one reasonable strategy is to put it before ending the statement, and use punctuation as the synchronizing tokens. Another practice is to add incorrect productions into the syntax specification, which allows your parser to recognize these illegal forms.

Error recovery is largely a trial-and-error process, you can experiment with real-world compilers to see how good they are at recognizing errors (they are expected to hit this one perfectly), reporting errors clearly (less perfect), and gracefully recovering (far from perfect).

4.3 Parser Implementation

Realizing a parser is more complicated than a lexer. You have to carefully read and understand each production to handle potential syntax conflicts/errors as much as possible.

We highly recommend you to build your parser without any action for all productions at the beginning. For a syntactically correct SPL program, this parser should run smoothly and exit without any output or error message; as for a program with syntax errors, your parser at this stage will only output `"syntax error"`. Then you can handle general issues for parser, such as conflict resolution and error recovery.

To ensure that your parser can be compiled smoothly and run correctly, we provide you some hints for debugging your Bison programs:

- Compile your `.y` file with `-v` option, which generates a `syntax.output` text file that illustrates the LALR automaton, about its states, transitions, etc.
- Compile `.y` with `-t`, and add `yydebug = 1`; before invoking `yyparse`, which enables your parser with verbose output.

After that, you should construct a parse tree in the action of each production. As we've done in Listing 3, for a nonterminal symbol, you can assign a tree node to attribute `$$` and insert its children nodes one-by-one by some sort of `insert($$, $n)` (alternatively, consider [variadic function](#) for node constructor). For a terminal symbol, assign it with tree node via `yylval` in the Flex code, the usage of which is already shown in Listing 4.

Printing out the parse tree can be implemented as a pre-order traversal from the root node. In a object-oriented design paradigm, this method should be a member of type `node`, rather than the routine completed by the `main` function.

5 Project Requirements

5.1 Parser Requirements

5.1.1 Basic requirements

You are required to implement a parser that accepts a single command line argument (the SPL file path), and outputs the parse tree for a syntactically valid SPL program, or the

message reporting all existing lexical/syntax errors in the code. You should compile your parser as the `splc` target in `make`, and move the executable to the `bin` directory.

For example, the `Makefile` is placed under the project root directory, then we make the `splc` target by:

```
make splc
```

which generates the parser executable. Then we run the parser by:

```
bin/splc test/test_1_r01.spl
```

the parser should output the corresponding result specified in the text file `test/test_1_r01.out`, and we will verify the output by the `diff` utility.

5.1.2 Required features

Your parser should be able to recognize the following errors:

- Lexical error (error type A) when there are undefined characters or tokens in the SPL program, or identifiers starting with digits.
- Syntax error (error type B) when the program has an illegal structure, such as missing closing symbol. Please find as many syntax errors as possible.

For a syntactically correct SPL program, your parser should print out its parse tree. Consider the following SPL code:

Listing 5: SPL test case 1

```
1  int test_1_r01(int a, int b)
2  {
3      c = 'c';
4      if (a > b)
5      {
6          return a;
7      }
8      else
9      {
10         return b;
11     }
12 }
```

This program is free from syntax errors, while there is a semantic error: the local variable `c` is referenced without a definition, which is not allowed in C standard. Your parser should print its corresponding parse tree as follows (a caliper is helpful):

```
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

```

Listing 6: SPL test case 2

```

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  }

```

The program in Listing 6 contains two lexical errors and one syntax error, so your parser should report all of them:

```

Error type A at Line 4: Mysterious lexeme $
Error type B at Line 7: Missing semicolon ';'
Error type A at Line 8: Mysterious lexeme @

```

Note that the syntax error is reported at Line 7, while, intuitively, it appears to be at the end of Line 6. We do not require the exact position for a syntax error. In such a case, either Line 6 or Line 7 is fine.

Additionally, you should implement these capabilities:

- Supporting hexadecimal representation of integers such as `0x12`. You should be able to detect illegal form of hex-int, like `0x5gg`, and report lexical errors.
- Supporting hex-form characters, such as `\x90`, also, you need to detect its illegal form like `\xt0` and report lexical errors.

5.1.3 Bonus features

You are encouraged to implement other features that are not mentioned before, you may receive bonus points for implementing additional features. To show your parser's ability, you should provide your own testcases in the submitted files, and clearly introduce them in the report. You may consider the following features adopted by most general-purpose programming languages:

- single- and/or multi-line comment (C.3)
- macro **preprocessor**
- file inclusion
- **for** statements
- ...

5.2 Self-written Test Cases

You are required to write **5** test cases (i.e., SPL programs and the corresponding parser outputs) for overall evaluation. We will evaluate your compiler with all test cases written by the students enrolled in this course. Your test cases should strictly follow the SPL specification in the Appendix.

For evaluation purpose, your test cases should contain at least **2** type A errors and **2** type B errors. They can appear in the same SPL program, or distribute across individual test cases. We will provide you a set of sample test cases for reference. You can write arbitrarily complex programs and the only requirement is that they should follow the SPL specification, or you should point out its lexical/syntax errors. The grading of this part will be based on the quality and the creativeness of your test cases.

5.3 Grading Policy

The maximum score of this project, excluding the bonus part, is 100 points. Your score depends on the number of test cases your parser can pass, the quality of your provided test cases, and the quality of your report. Your parser will be evaluated with the test cases written by the students enrolled in this course. If your parser passes all submitted test cases, you will get 80 points. Failing to pass some test cases may result in a decrease of the grade. Your submitted test cases will be graded independently, with a maximum score of 10 points, according to the quality and the creativeness. Your project report accounts for the remaining 10 points.

If you implemented other bonus features, you should provide extra test cases. Note that these test cases will not be used to evaluate the parsers written by other students, since they may not choose to implement those bonus features. The bonus points you can get depend on the difficulty of the features and how well you have implemented and tested them. The maximum bonus you can get for this project is 20 points. The bonus points can only be used to redeem the points you lose for projects or programming assignments.

There may be multiple members in your team. In that case, we will evaluate the contribution of each member and rate his/her contribution using four levels: A (significant), B (moderate), C (low), and D (very little contribution). If the rating is A, the member will get 100% of the grade obtained by the team as a whole (G). If the rating is B, the member will get 85% of G . If the rating is C, the member will get 60% of G . If the rating is D, the member will get 30% of G . We hope everyone gets rated as A or B.

6 Submission

What to submit You are required to submit your C/flex/bison source code and other related files in a .zip archive with file name format: **StudentID-projectNumber.zip** (e.g., 11849180-project1.zip). Each team only needs to make one submission. In this project, the zip file tree is:

```
StudentID-project1/
  bin/
    splc      // generated
  report/
    StudentID-project1.pdf
  test/
    test_StudentID_1.spl
    test_StudentID_1.out
    test_StudentID_2.spl
    test_StudentID_2.out
    ...      // your self-written testcases
  test-ex/
    test_1.spl
    test_1.out
    ...      // your extra testcases
  Makefile
  ...      // C/Flex/Bison source code
```

- **bin** directory contains a single executable file named `splc`, which is generated by an `splc` target in the `Makefile`. Make sure it works properly in our environment (Section 2).
- **report** directory contains a pdf file that illustrates your design and implementation, you should focus on the optional/bonus features you have realized, since the required part is rather simple and straight-forward. Your report should not exceed **4 pages**, we suggest you to use 11pt font size and single-line spacing for main content.
- **test** directory is your self-written testcases. Make sure to include your output files in the directory, which records the message follow the output requirements (Section 5.1.2). The

code file name should end with `.spl` extension and output file name should end with `.out`. Remember to include your student ID in the file names.

- `test-ex` stores all your extra testcases. We **will not** use these testcases to evaluate other students' parsers. The only purpose of them is just to examine your parser's bonus features.
- The `Makefile` is provided. You can add any targets, but most importantly, **you have to guarantee the `splc` target compiles and generates a single executable `splc` (the parser) in the `bin/` directory**. Otherwise, we cannot evaluate your work and you will get 0 for this project.
- In this project, you will write code in C/Flex/Bison, you can place them directly under the submitted directory, or under separate folders like `src` and `include`. Again, it's your job to ensure the code can be compiled successfully.

How to submit You should upload your zip file on SAKAI before the **11:55 PM, October 11, 2021**. We will check and grade in-time submissions during the lab session on October 12, 2021. Late submissions are still allowed within 2 weeks after the deadline (grace period). If you submit your project before October 18 (11:55 PM), your score will be 80% of the score you could get if the submission was made before the deadline. If you make submission before October 25 (11:55 PM), you will get only 60%. Any submissions after October 25 will not be graded, meaning that you will get a zero for project 1.

Contact For any question regarding this project, feel free to contact our teaching team via emails (typically reply within 24 hours). Please use the following subject:

[CS323] Project 1 (YourName-StudentID)

e.g., [CS323] Project 1 (WangSinan-11849180)

7 Resources

Here we list some links that you may find useful information during this course.

- C language tutorial: <http://www.stat.cmu.edu/~brian/cprog.html>
- Simple Makefile tutorial: <http://www.cs.colby.edu/maxwell/courses/tutorials/maketutor/>
- Compiler tools (Flex & Bison) introduction: <http://dinosaur.compilertools.net/>
- Flex & Bison introduction: https://aquamentus.com/flex_bison.html
- Stanford University CS143 Compilers: <https://web.stanford.edu/class/archive/cs/cs143/cs143.1128/>

- GNU C Compiler Internals/GNU C Compiler Architecture: https://en.wikibooks.org/wiki/GNU_C_Compiler_Internals/GNU_C_Compiler_Architecture
- Buffer Overflow Exploit - Dhaval Kapil: <https://dhavalkapil.com/blogs/Buffer-Overflow-Exploit/>
- Assemblers, Linkers, and the SPIM Simulator: http://pages.cs.wisc.edu/~larus/HP_AppA.pdf
- Kempe's graph-coloring algorithm <https://www.cs.princeton.edu/~appel/Color.pdf>

Appendix

A Token Specification

The following token specification defines the valid token in SPL. You can easily make a lexer with Flex by following the specification. However, we do not specify the patterns of the first four tokens: INT, FLOAT, CHAR and ID, it is your job to carefully design and write their regular expressions.

INT	->	/* integer in 32-bits (decimal or hexadecimal) */
FLOAT	->	/* floating point number (only dot-form) */
CHAR	->	/* single character (printable or hex-form) */
ID	->	/* valid 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	->	}

B Grammar Specification⁴

```
/* high-level definition */
Program -> ExtDefList
ExtDefList -> ExtDef ExtDefList
           | $
ExtDef -> Specifier ExtDecList SEMI
        | Specifier SEMI
        | Specifier FunDec CompSt
ExtDecList -> VarDec
            | VarDec COMMA ExtDecList

/* specifier */
Specifier -> TYPE
           | StructSpecifier
StructSpecifier -> STRUCT ID LC DefList RC
                | STRUCT ID

/* declarator */
VarDec -> ID
        | VarDec LB INT RB
FunDec -> ID LP VarList RP
        | ID LP RP
VarList -> ParamDec COMMA VarList
        | ParamDec
ParamDec -> Specifier VarDec

/* statement */
CompSt -> LC DefList StmtList RC
StmtList -> Stmt StmtList
          | $
Stmt -> Exp SEMI
      | CompSt
      | RETURN Exp SEMI
      | IF LP Exp RP Stmt
      | IF LP Exp RP Stmt ELSE Stmt
      | WHILE LP Exp RP Stmt

/* local definition */
DefList -> Def DefList
        | $
```

⁴The dollar sign “\$” represents the empty string terminal.


```
Def -> Specifier DecList SEMI
DecList -> Dec
        | Dec COMMA DecList
Dec -> VarDec
        | VarDec ASSIGN Exp

/* Expression */
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
Args -> Exp COMMA Args
    | Exp
```

C Additions

C.1 Tokens

We have already listed the token specification of SPL in Appendix [A](#). You need to write regular expressions for the first four tokens, the remaining tokens correspond to the lexemes specified at the arrows' right side. (except the **TYPE** which can be one of the **int**, **float** or **char**) Here, we give more details about the tokens.

- **INT** represents an unsigned-integer literal. You can assume that they are always in 32-bits range. We have two types of integer literals, decimal (base 10) and hexadecimal (base 16) forms. An integer lexeme in decimal form is a consecutive sequence of digits 0-9, and it cannot start with “0”, except 0 itself. A hexadecimal integer lexeme always starts with “0x” or “0X”, followed by a sequence of hex-digits (0-9, a-f), again, the digit sequence cannot start with “0”, except 0x0 itself.
- **FLOAT** represents an unsigned floating-point⁵ number in IEEE-754 standard. You can assume that they are always in valid single-precision format. We do not consider the scientific notation, which is represented by a number’s base-10 mantissa and exponent. A valid floating-point number always contains a single dot character (i.e., “.”), and there must be always digit sequence on the dot’s both side.
- **CHAR** represents a single character contained in a pair of single-quotes. We do not consider those characters represented by escape sequence, e.g., “\n” (the newline character) or “\t” (the horizontal tab character).
- **ID** stands for *identifier*, which consists of 3 types of characters: the underscore (_), digits (0-9), and letters (A-Z and a-z). A valid identifier cannot start with digit. You can assume that the length of identifiers will not exceed 32.

C.2 Grammar rules

Here we explain the general definition of each set of productions. You should understand the meaning of each production before implementing the parser.

- **High-level definition** specifies the top-level syntax for a SPL program, including global variable declarations and function definitions.
- **Specifier** is related to the type system, in SPL, we have primitive types (**int**, **float** and **char**) and structure type.
- **Declarator** defines the variable and function declaration. Note that the array type is specified by the declarator.
- **Statement** specifies several program structures, such as branching structure or loop structure. They are mostly enclosed by curly braces, or end with a semicolon.
- **Local definition** includes the declaration and assignment of local variables.
- **Expression** can be a single constant, or operations on variables. Note that these operators have their precedence and associativity, as shown in Table 2.

⁵<http://754r.ucbtest.org/background/>

Table 2: Operators in SPL

Precedence	Operator	Associativity	Description
1	()	left to right	parenthesis or function invocation
	[]		array indexing
	.		structure member accessing
2	-	right to left	negative number
	!		logical NOT
3	*	left to right	multiplication
	/		division
4	+		addition
	-		subtraction
5	<		less than
	<=		less than or equal to
	>		greater than
	>=		greater than or equal to
	==		equal to
	!=		not equal to
6	&&		logical AND
7			logical OR
8	=	right to left	assignment

C.3 Comments

You can optionally implement your compiler to support comments. There are two types of comment styles for SPL, single-line and multi-line comments.

A single-line comment starts with two slashes “//”, all symbols followed until a newline character will be dropped by the lexer.

A multi-line comment starts with “/*”, and ends with the first “*/” after that. Note that multi-line comments cannot be nested, i.e., you cannot put another multi-line comment within “/*” and “*/”.