

## a. 实验目的

本实验旨在设计并实现一个针对自定义小型编程语言的分析器。通过该实验，深入理解程序设计语言的语法结构与词法分析，从而提高对编译原理核心算法的实践能力。

## b. 实验内容

- 设计一个简单的编程语言的语法和词法规则。
- 实现该语言的词法分析器，能够将源代码转换为一系列的记号（tokens）。
- 实现该语言的语法分析器，能够根据词法分析器生成的记号构建抽象语法树（AST）。
- 编写测试用例，验证词法分析器和语法分析器的正确性。

## c. 设计思路

### 语言设计

该实验所虚构的语言具有以下基本特性：

- 支持变量声明和赋值（使用let关键字）。
- 支持 if-else 条件语句。
- 支持 read() 和 write() 输入输出操作。
- 支持基本的算术运算（加、减、乘、除）。
- 支持使用语句块`^^`表达式来表示重复执行的代码段。
- 支持单行注释。

### 词法分析器设计

词法分析器的设计基于正则表达式，用于识别以下记号类型：

- 关键字：let, if, else, read, write
- 标识符：变量名，由字母和数字组成，且以字母开头
- 数字：整数或浮点数
- 运算符：+，-，\*，/，=，==，!=，<，>，<=，>=，`^^`
- 分隔符：;，，0，{}

- 注释：以 // 开头的单行注释

## 语法分析器设计

语法分析器采用LL(1)分析方法，主要语法规则详见 e 部分。语法分析器将根据词法分析器生成的记号流，构建抽象语法树（AST）。

## d. 假设条件

- 类型检查：假设 ^^ 右侧表达式的结果必须能求值为整数，代表循环次数。
- 声明顺序：假设 let 语句必须出现在变量被赋值或引用之前的物理位置。
- 关键字限制：假设 read 和 print 作为保留字，不能被用作用户定义的变量名。

## e. 相关有限自动机描述

### 正规表达式

- 标识符

```
ID    = [A-Za-z_][A-Za-z0-9_]*
```

- 数字

```
NUM   = [0-9]+(\.[0-9]+)?
```

- 注释

```
COMMENT = "//" [^\n]*
```

- 双字符运算符

```
POW2 = "^^" EQ = "==" NEQ = "!=" GE = ">=" LE = "<="
```

- 单字符运算符

```
POW1 = "^"
```

```
ASSIGN = "="
```

```
PLUS   = "+"
```

```
MINUS  = "-"
```

```
MUL    = "*"
```

```
DIV    = "/"
```

```
GT     = ">"
```

```
LT     = "<"
```

- 单字符分隔符

```
SEP = [();,]
```

- 空格

```
WS   = [ \t\n\r]+
```

- 关键字

```
KEY = (let|print|read|if|else)
```

## NFA

---

```
1 ID_NFA:
2   states: {s0, s1}
3   start: s0
4   accept: {s1}
5   transitions:
6     s0 --[A-Zabcdefghijklmnopqrstuvwxyz_]--> s1
7     s1 --[A-Za-z0-9_]--> s1
8
9 NUM_NFA:
10  states: {s0, s1, s2, s3}
11  start: s0
12  accept: {s1, s3}
13  transitions:
14    s0 --[0-9]--> s1
15    s1 --[0-9]--> s1
16    s1 --[.]--> s2
17    s2 --[0-9]--> s3
18    s3 --[0-9]--> s3
19
20 COMMENT_NFA:
21  states: {s0, s1, s2}
22  start: s0
23  accept: {s2}
24  transitions:
25    s0 --[/]--> s1
26    s1 --[/]--> s2
27    s2 --[\n]--> s2
28
29 POW2_NFA:
30  states: {s0, s1, s2}
31  start: s0
32  accept: {s2}
33  transitions:
34    s0 --[\^]--> s1
35    s1 --[\^]--> s2
36
37 POW1_NFA:
38  states: {s0, s1}
39  start: s0
40  accept: {s1}
41  transitions:
42    s0 --[\^]--> s1
43
44 EQ_NFA:
45  states: {s0, s1, s2}
46  start: s0
47  accept: {s2}
48  transitions:
49    s0 --[=]--> s1
50    s1 --[=]--> s2
```

```
51
52 NEQ_NFA:
53     states: {s0, s1, s2}
54     start: s0
55     accept: {s2}
56     transitions:
57         s0 --[!]--> s1
58         s1 --[=]--> s2
59
60 GE_NFA:
61     states: {s0, s1, s2}
62     start: s0
63     accept: {s2}
64     transitions:
65         s0 --[>]--> s1
66         s1 --[=]--> s2
67
68 LE_NFA:
69     states: {s0, s1, s2}
70     start: s0
71     accept: {s2}
72     transitions:
73         s0 --[<]--> s1
74         s1 --[=]--> s2
75
76 ASSIGN_NFA:
77     states: {s0, s1}
78     start: s0
79     accept: {s1}
80     transitions:
81         s0 --[=]--> s1
82
83 PLUS_NFA:
84     states: {s0, s1}
85     start: s0
86     accept: {s1}
87     transitions:
88         s0 --[+]--> s1
89
90 MINUS_NFA:
91     states: {s0, s1}
92     start: s0
93     accept: {s1}
94     transitions:
95         s0 --[-]--> s1
96
97 MUL_NFA:
98     states: {s0, s1}
99     start: s0
100    accept: {s1}
101    transitions:
102        s0 --[*]--> s1
103
104 DIV_NFA:
105    states: {s0, s1}
106    start: s0
107    accept: {s1}
108    transitions:
```

```

109    s0 --[/]--> s1
110
111 GT_NFA:
112     states: {s0, s1}
113     start: s0
114     accept: {s1}
115     transitions:
116         s0 --[>]--> s1
117
118 LT_NFA:
119     states: {s0, s1}
120     start: s0
121     accept: {s1}
122     transitions:
123         s0 --[<]--> s1
124
125 SEP_NFA:
126     states: {s0, s1}
127     start: s0
128     accept: {s1}
129     transitions:
130         s0 --[()]--> s1
131         s0 --[()]-> s1
132         s0 --[{}]-> s1
133         s0 --[{}]-> s1
134         s0 --[;]-> s1
135         s0 --[,]-> s1
136
137 WS_NFA:
138     states: {s0, s1}
139     start: s0
140     accept: {s1}
141     transitions:
142         s0 --[ \t\n\r]-> s1
143         s1 --[ \t\n\r]-> s1
144
145 KEY_NFA:
146     states: {s0, s1, s2, s3, s4, s5, s6, s7, s8, s9, s10, s11, s12, s13, s14}
147     start: s0
148     accept: {s3, ID}
149     transitions:
150
151         s3 --[A-Za-z0-9_]-> ID
152         ID --[A-Za-z0-9_]-> ID
153         # "let"
154         s0 --[l]-> s1
155         s1 --[A-Za-df-z0-9_]-> ID
156         s1 --[e]-> s2
157         s2 --[A-Za-su-z0-9_]-> ID
158         s2 --[t]-> s3
159
160         # "print"
161         s0 --[p]-> s4
162         s4 --[A-Za-qs-z0-9_]-> ID
163         s4 --[r]-> s5
164         s5 --[A-Za-hj-z0-9_]-> ID
165         s5 --[i]-> s6
166         s6 --[A-Za-mo-z0-9_]-> ID

```

```

167 s6 --[n]--> s7
168 s7 --[A-Za-su-z0-9_]--> ID
169 s7 --[t]--> s3
170
171 # "read"
172 s0 --[r]--> s9
173 s9 --[A-Za-qst-z0-9_]--> ID
174 s9 --[e]--> s10
175 s10 --[A-Zb-z0-9_]--> ID
176 s10 --[a]--> s11
177 s10 --[A-Za-ce-z0-9_]--> ID
178 s11 --[d]--> s3
179
180 # "if"
181 s0 --[i]--> s13
182 s13 --[A-Za-eg-z0-9_]--> ID
183 s13 --[f]--> s3
184
185 # "else"
186 s0 --[e]--> s15
187 s15 --[A-Za-km-z0-9_]--> ID
188 s15 --[l]--> s16
189 s16 --[A-Za-rt-z0-9_]--> ID
190 s16 --[s]--> s17
191 s17 --[A-Za-df-z0-9_]--> ID
192 s17 --[e]--> s3

```

## 合并

将上述各个 NFA 合并为一个总的 NFA，通过添加一个新的起始状态，并从该状态出发通过  $\epsilon$  转移到各个子 NFA 的起始状态。最终接受状态为各子 NFA 的接受状态集合。

```

1 LEXER_NFA:
2   states:
3     - S0
4     - all states from each sub-NFA (renamed to avoid collision)
5   start: S0
6   accept:
7     - all accept states from each sub-NFA
8   transitions:
9     # epsilon transitions from global start
10    S0 --[ε]--> ID_S0
11    S0 --[ε]--> NUM_S0
12    S0 --[ε]--> COMMENT_S0
13    S0 --[ε]--> POW2_S0
14    S0 --[ε]--> POW1_S0
15    S0 --[ε]--> EQ_S0
16    S0 --[ε]--> NEQ_S0
17    S0 --[ε]--> GE_S0
18    S0 --[ε]--> LE_S0
19    S0 --[ε]--> ASSIGN_S0
20    S0 --[ε]--> PLUS_S0
21    S0 --[ε]--> MINUS_S0
22    S0 --[ε]--> MUL_S0
23    S0 --[ε]--> DIV_S0

```

```

24 S0 --[ε]--> GT_s0
25 S0 --[ε]--> LT_s0
26 S0 --[ε]--> SEP_s0
27 S0 --[ε]--> WS_s0
28 S0 --[ε]--> KEY_s0
29
30 ID_s0 --[A-Zabcdefghijklmnopqrstuvwxyz_]--> ID_s1
31 ID_s1 --[A-Za-z0-9_]--> ID_s1
32
33 NUM_s0 --[0-9]--> NUM_s1
34 NUM_s1 --[0-9]--> NUM_s1
35 NUM_s1 --[.]--> NUM_s2
36 NUM_s2 --[0-9]--> NUM_s3
37 NUM_s3 --[0-9]--> NUM_s3
38
39 COMMENT_s0 --[/]--> COMMENT_s1
40 COMMENT_s1 --[/]--> COMMENT_s2
41 COMMENT_s2 --[^n]--> COMMENT_s2
42
43 POW2_s0 --[\^]--> POW2_s1
44 POW2_s1 --[\^]--> POW2_s2
45
46 POW1_s0 --[\^]--> POW1_s1
47
48 EQ_s0 --[=]--> EQ_s1
49 EQ_s1 --[=]--> EQ_s2
50
51 NEQ_s0 --[!]--> NEQ_s1
52 NEQ_s1 --[=]--> NEQ_s2
53
54 GE_s0 --[>]--> GE_s1
55 GE_s1 --[=]--> GE_s2
56
57 LE_s0 --[<]--> LE_s1
58 LE_s1 --[=]--> LE_s2
59
60 ASSIGN_s0 --[=]--> ASSIGN_s1
61
62 PLUS_s0 --[+]--> PLUS_s1
63 MINUS_s0 --[-]--> MINUS_s1
64 MUL_s0 --[*]--> MUL_s1
65 DIV_s0 --[/]--> DIV_s1
66 GT_s0 --[>]--> GT_s1
67 LT_s0 --[<]--> LT_s1
68
69 SEP_s0 --[()--> SEP_s1
70 SEP_s0 --[()])--> SEP_s1
71 SEP_s0 --[{]--> SEP_s1
72 SEP_s0 --[}]--> SEP_s1
73 SEP_s0 --[;]--> SEP_s1
74 SEP_s0 --[,]--> SEP_s1
75
76 WS_s0 --[ \t\n\r]--> WS_s1
77 WS_s1 --[ \t\n\r]--> WS_s1
78
79 KEY_s3 --[A-Za-z0-9_]--> KEY_ID
80 KEY_ID --[A-Za-z0-9_]--> KEY_ID
81 # "let"

```

```

82   KEY_s0 --[1]--> KEY_s1
83   KEY_s1 --[A-Za-df-z0-9_]--> KEY_ID
84   KEY_s1 --[e]--> KEY_s2
85   KEY_s2 --[A-Za-su-z0-9_]--> KEY_ID
86   KEY_s2 --[t]--> KEY_s3
87
88   # "print"
89   KEY_s0 --[p]--> KEY_s4
90   KEY_s4 --[A-Za-qs-z0-9_]--> KEY_ID
91   KEY_s4 --[r]--> KEY_s5
92   KEY_s5 --[A-Za-hj-z0-9_]--> KEY_ID
93   KEY_s5 --[i]--> KEY_s6
94   KEY_s6 --[A-Za-mo-z0-9_]--> KEY_ID
95   KEY_s6 --[n]--> KEY_s7
96   KEY_s7 --[A-Za-su-z0-9_]--> KEY_ID
97   KEY_s7 --[t]--> KEY_s3
98
99   # "read"
100  KEY_s0 --[r]--> KEY_s9
101  KEY_s9 --[A-Za-qst-z0-9_]--> KEY_ID
102  KEY_s9 --[e]--> KEY_s10
103  KEY_s10 --[A-Zb-z0-9_]--> KEY_ID
104  KEY_s10 --[a]--> KEY_s11
105  KEY_s10 --[A-Za-ce-z0-9_]--> KEY_ID
106  KEY_s11 --[d]--> KEY_s3
107
108  # "if"
109  KEY_s0 --[i]--> KEY_s13
110  KEY_s13 --[A-Za-eg-z0-9_]--> KEY_ID
111  KEY_s13 --[f]--> KEY_s3
112
113  # "else"
114  KEY_s0 --[e]--> KEY_s15
115  KEY_s15 --[A-Za-km-z0-9_]--> KEY_ID
116  KEY_s15 --[l]--> KEY_s16
117  KEY_s16 --[A-Za-rt-z0-9_]--> KEY_ID
118  KEY_s16 --[s]--> KEY_s17
119  KEY_s17 --[A-Za-df-z0-9_]--> KEY_ID
120  KEY_s17 --[e]--> KEY_s3

```

## 最小化

通过状态合并和消除不可达状态，对上述 NFA 进行最小化处理，得到一个等价的最小化 DFA，用于实际的词法分析过程。表示为 json 格式以便于程序读取和处理。

```

1  {
2      "states": [
3          "START",
4          "ID",
5          "NUM_INT",
6          "NUM_MIDDLE",
7          "NUM_FLOAT",
8          "OP1",
9          "OP2",
10         "REPEAT",

```

```
11     "ASSIGN",
12     "WS",
13     "SEP",
14     "COMMENT",
15     "KEY"
16 ],
17 "start": "START",
18 "accept": [
19     "ID",
20     "NUM_INT",
21     "NUM_FLOAT",
22     "OP1",
23     "OP2",
24     "REPEAT",
25     "ASSIGN",
26     "WS",
27     "SEP",
28     "COMMENT",
29     "KEY"
30 ],
31 "trans": [
32     {
33         "from": "START",
34         "to": "ID",
35         "pattern": "[A-Zabcdefghijklmnopqrstuvwxyz_]"
36     },
37     {
38         "from": "ID",
39         "to": "ID",
40         "pattern": "[A-Za-z0-9_]"
41     },
42     {
43         "from": "START",
44         "to": "NUM_INT",
45         "pattern": "[0-9]"
46     },
47     {
48         "from": "NUM_INT",
49         "to": "NUM_INT",
50         "pattern": "[0-9]"
51     },
52     {
53         "from": "NUM_INT",
54         "to": "NUM_MIDDLE",
55         "pattern": "[.]"
56     },
57     {
58         "from": "NUM_MIDDLE",
59         "to": "NUM_FLOAT",
60         "pattern": "[0-9]"
61     },
62     {
63         "from": "NUM_FLOAT",
64         "to": "NUM_FLOAT",
65         "pattern": "[0-9]"
66     },
67     {
68         "from": "START",
```

```
69         "to": "OP1",
70         "pattern": "[\\^]"
71     },
72     {
73         "from": "OP1",
74         "to": "REPEAT",
75         "pattern": "[\\^]"
76     },
77     {
78         "from": "START",
79         "to": "ASSIGN",
80         "pattern": "[=]"
81     },
82     {
83         "from": "ASSIGN",
84         "to": "OP2",
85         "pattern": "[=]"
86     },
87     {
88         "from": "START",
89         "to": "OP1",
90         "pattern": "[<]"
91     },
92     {
93         "from": "OP1",
94         "to": "OP2",
95         "pattern": "[=]"
96     },
97     {
98         "from": "START",
99         "to": "OP1",
100        "pattern": "[/]"
101    },
102    {
103        "from": "START",
104        "to": "OP1",
105        "pattern": "[>]"
106    },
107    {
108        "from": "OP1",
109        "to": "OP2",
110        "pattern": "[=]"
111    },
112    {
113        "from": "START",
114        "to": "OP1",
115        "pattern": "[ -]"
116    },
117    {
118        "from": "START",
119        "to": "OP1",
120        "pattern": "[+]"
121    },
122    {
123        "from": "START",
124        "to": "OP1",
125        "pattern": "[ *]"
126    },
```

```
127      {
128          "from": "START",
129          "to": "WS",
130          "pattern": "[ \\\t\\\n\\\r]"
131      },
132      {
133          "from": "WS",
134          "to": "WS",
135          "pattern": "[ \\\t\\\n\\\r]"
136      },
137      {
138          "from": "START",
139          "to": "OP1",
140          "pattern": "[!]"
141      },
142      {
143          "from": "OP1",
144          "to": "OP2",
145          "pattern": "[=]"
146      },
147      {
148          "from": "START",
149          "to": "SEP",
150          "pattern": "[(){};,]"
151      },
152      {
153          "from": "OP1",
154          "to": "COMMENT",
155          "pattern": "[/]"
156      },
157      {
158          "from": "COMMENT",
159          "to": "COMMENT",
160          "pattern": "[^\\\n]"
161      },
162      {
163          "from": "KEY",
164          "to": "ID",
165          "pattern": "[A-Za-z0-9_]"
166      },
167      {
168          "from": "START",
169          "to": "LET:L",
170          "pattern": "[1]"
171      },
172      {
173          "from": "LET:L",
174          "to": "ID",
175          "pattern": "[A-Za-df-z0-9_]"
176      },
177      {
178          "from": "LET:L",
179          "to": "LET:E",
180          "pattern": "[e]"
181      },
182      {
183          "from": "LET:E",
184          "to": "ID",
```

```
185         "pattern": "[A-Za-su-z0-9_]"
186     },
187     {
188         "from": "LET:E",
189         "to": "KEY",
190         "pattern": "[t]"
191     },
192     {
193         "from": "START",
194         "to": "PRINT:P",
195         "pattern": "[p]"
196     },
197     {
198         "from": "PRINT:P",
199         "to": "ID",
200         "pattern": "[A-Za-qs-z0-9_]"
201     },
202     {
203         "from": "PRINT:P",
204         "to": "PRINT:R",
205         "pattern": "[r]"
206     },
207     {
208         "from": "PRINT:R",
209         "to": "ID",
210         "pattern": "[A-Za-hj-z0-9_]"
211     },
212     {
213         "from": "PRINT:R",
214         "to": "PRINT:I",
215         "pattern": "[i]"
216     },
217     {
218         "from": "PRINT:I",
219         "to": "ID",
220         "pattern": "[A-Za-mo-z0-9_]"
221     },
222     {
223         "from": "PRINT:I",
224         "to": "PRINT:N",
225         "pattern": "[n]"
226     },
227     {
228         "from": "PRINT:N",
229         "to": "ID",
230         "pattern": "[A-Za-su-z0-9_]"
231     },
232     {
233         "from": "PRINT:N",
234         "to": "KEY",
235         "pattern": "[t]"
236     },
237     {
238         "from": "START",
239         "to": "READ:R",
240         "pattern": "[r]"
241     },
242     {
```

```
243         "from": "READ:R",
244         "to": "ID",
245         "pattern": "[A-Za-df-z0-9_]"
246     },
247     {
248         "from": "READ:R",
249         "to": "READ:E",
250         "pattern": "[e]"
251     },
252     {
253         "from": "READ:E",
254         "to": "ID",
255         "pattern": "[A-Zb-z0-9_]"
256     },
257     {
258         "from": "READ:E",
259         "to": "READ:A",
260         "pattern": "[a]"
261     },
262     {
263         "from": "READ:A",
264         "to": "ID",
265         "pattern": "[A-Za-ce-z0-9_]"
266     },
267     {
268         "from": "READ:A",
269         "to": "KEY",
270         "pattern": "[d]"
271     },
272     {
273         "from": "START",
274         "to": "IF:I",
275         "pattern": "[i]"
276     },
277     {
278         "from": "IF:I",
279         "to": "ID",
280         "pattern": "[A-Za-eg-z0-9_]"
281     },
282     {
283         "from": "IF:I",
284         "to": "KEY",
285         "pattern": "[f]"
286     },
287     {
288         "from": "START",
289         "to": "ELSE:E",
290         "pattern": "[e]"
291     },
292     {
293         "from": "ELSE:E",
294         "to": "ID",
295         "pattern": "[A-Za-km-z0-9_]"
296     },
297     {
298         "from": "ELSE:E",
299         "to": "ELSE:L",
300         "pattern": "[1]"
```

```

301     },
302     {
303         "from": "ELSE:L",
304         "to": "ID",
305         "pattern": "[A-Za-z0-9_]"
306     },
307     {
308         "from": "ELSE:L",
309         "to": "ELSE:S",
310         "pattern": "[s]"
311     },
312     {
313         "from": "ELSE:S",
314         "to": "ID",
315         "pattern": "[A-Za-df-z0-9_]"
316     },
317     {
318         "from": "ELSE:S",
319         "to": "KEY",
320         "pattern": "[e]"
321     }
322 ]
323 }
```

## CFG

---

- Program -> StmtList
- StmtList -> Stmt StmtList | ε
- Stmt -> DeclStmt | AssignStmt | BlockMaybeRepeat | FuncCallStmt | IfStmt
- DeclStmt -> KEY(let) ID SEP(;) | ε
- AssignStmt -> ID ASSIGN Expr SEP(;) | ε
- BlockMaybeRepeat -> Block | RepeatTail
- Block -> SEP({} StmtList SEP{}) | ε
- FuncCallStmt -> FuncCall SEP(;) | ε
- FuncCall -> KEY(print) SEP() Expr SEP() | KEY(read) SEP() ID SEP() | ε
- IfStmt -> KEY(if) SEP() Expr SEP() Block ElsePart | ε
- ElsePart -> KEY(else) Block | ε
- RepeatTail -> REPEAT Expr SEP(;) | ε
- Expr -> EqualityExpr
- EqualityExpr -> RelationExpr EqualityExpr'
- EqualityExpr' -> OP2(==) RelationExpr EqualityExpr' | OP2(!=) RelationExpr EqualityExpr' | ε
- RelationExpr -> AddExpr RelationExpr'
- RelationExpr' -> OP2(>=) AddExpr RelationExpr' | OP2(<=) AddExpr RelationExpr' | OP1(>) AddExpr RelationExpr' | OP1(<) AddExpr RelationExpr' | ε
- AddExpr -> MulExpr AddExpr'
- AddExpr' -> OP1(+) MulExpr AddExpr' | OP1(-) MulExpr AddExpr' | ε

- $\text{MulExpr} \rightarrow \text{UnaryExpr MulExpr}'$
- $\text{MulExpr}' \rightarrow \text{OP1(*) UnaryExpr MulExpr}' \mid \text{OP1(/) UnaryExpr MulExpr}' \mid \epsilon$
- $\text{UnaryExpr} \rightarrow \text{OP1(+)} \mid \text{OP1(-)} \mid \text{OP1(!)}$
- $\text{PowerExpr} \rightarrow \text{PrimaryExpr PowerExpr}'$
- $\text{PowerExpr}' \rightarrow \text{OP1(^)} \mid \epsilon$
- $\text{PrimaryExpr} \rightarrow \text{SEP(()) Expr SEP(())} \mid \text{NUM\_INT} \mid \text{NUM\_FLOAT} \mid \text{ID}$

## First and Follow Sets

- First Sets
  - $\text{First(Program)} = \text{First(StmtList)} = \{\text{KEY(let)}, \text{ID}, \text{SEP(())}, \text{KEY(print)}, \text{KEY(read)}, \text{KEY(if)}, \epsilon\}$
  - $\text{First(Stmt)} = \{\text{KEY(let)}, \text{ID}, \text{SEP(())}, \text{KEY(print)}, \text{KEY(read)}, \text{KEY(if)}\}$
  - $\text{First(DeclStmt)} = \{\text{KEY(let)}\}$
  - $\text{First(AssignStmt)} = \{\text{ID}\}$
  - $\text{First(BlockMaybeRepeat)} = \text{First(Block)} = \{\text{SEP(())}\}$
  - $\text{First(FuncCallStmt)} = \text{First(FuncCall)} = \{\text{KEY(print)}, \text{KEY(read)}\}$
  - $\text{First(IfStmt)} = \{\text{KEY(if)}\}$
  - $\text{First(ElsePart)} = \{\text{KEY(else)}, \epsilon\}$
  - $\text{First(RepeatTail)} = \{\text{REPEAT}, \epsilon\}$
  - $\text{First(Expr)} = \text{First(EqualityExpr)} = \text{First(RelationExpr)} = \text{First(AddExpr)} = \text{First(MulExpr)} = \{\text{SEP(())}, \text{NUM\_INT}, \text{NUM\_FLOAT}, \text{ID}, \text{OP1(+), OP1(-), OP1(!)}\}$
  - $\text{First(UnaryExpr)} = \{\text{OP1(+), OP1(-), OP1(!), SEP(())}, \text{NUM\_INT}, \text{NUM\_FLOAT}, \text{ID}\}$
  - $\text{First(EqualityExpr')} = \{\text{OP2(==), OP2(!=)}, \epsilon\}$
  - $\text{First(RelationExpr')} = \{\text{OP2(>=), OP2(<=), OP1(>), OP1(<)}, \epsilon\}$
  - $\text{First(AddExpr')} = \{\text{OP1(+), OP1(-)}, \epsilon\}$
  - $\text{First(MulExpr')} = \{\text{OP1(*)}, \text{OP1(/)}, \epsilon\}$
  - $\text{First(PowerExpr)} = \{\text{SEP(())}, \text{NUM\_INT}, \text{NUM\_FLOAT}, \text{ID}\}$
  - $\text{First(PowerExpr')} = \{\text{OP1(^)}, \epsilon\}$
  - $\text{First(PrimaryExpr)} = \{\text{SEP(())}, \text{NUM\_INT}, \text{NUM\_FLOAT}, \text{ID}\}$
- Follow Sets
  - $\text{Follow(Program)} = \{\#\}$
  - $\text{Follow(StmtList)} = \{\#, \text{SEP(())}\}$
  - $\text{Follow(Stmt)} = \text{Follow(DeclStmt)} = \text{Follow(AssignStmt)} = \text{Follow(IfStmt)} = \text{Follow(ElsePart)} = \text{Follow(Block)} = \{\text{KEY(let)}, \text{ID}, \text{SEP(())}, \text{KEY(print)}, \text{KEY(read)}, \text{KEY(if)}, \text{SEP(())}, \#\}$
  - $\text{Follow(BlockMaybeRepeat)} = \{\text{KEY(let)}, \text{ID}, \text{SEP(())}, \text{KEY(print)}, \text{KEY(read)}, \text{KEY(if)}, \text{SEP(())}, \#, \text{KEY(else)}, \text{REPEAT}\}$
  - $\text{Follow(RepeatTail)} = \{\text{KEY(let)}, \text{ID}, \text{SEP(())}, \text{KEY(print)}, \text{KEY(read)}, \text{KEY(if)}, \text{SEP(())}, \#\}$
  - $\text{Follow(FuncCallStmt)} = \text{Follow(FuncCall)} = \{\text{SEP(())}\}$
  - $\text{Follow(Expr)} = \text{Follow(EqualityExpr)} = \text{Follow(EqualityExpr')} = \{\text{SEP(())}, \text{SEP(())}\}$
  - $\text{Follow(RelationExpr)} = \text{Follow(RelationExpr')} = \{\text{OP2(==), OP2(!=), SEP(())}, \text{SEP(())}\}$

- Follow(AddExpr) = Follow(AddExpr') = {OP2(>=), OP2(<=), OP1(>), OP1(<), OP2(==), OP2(!=), SEP(), SEP(;)}
- Follow(MulExpr) = Follow(MulExpr') = {OP1(+), OP1(-), OP2(>=), OP2(<=), OP1(>), OP1(<), OP2(==), OP2(!=), SEP(), SEP(;)}
- Follow(UnaryExpr) = {OP1(\*), OP1(/), OP1(+), OP1(-), OP2(>=), OP2(<=), OP1(>), OP1(<), OP2(==), OP2(!=), SEP(), SEP(;)}
- Follow(PowerExpr) = Follow(PowerExpr') = {OP1(^), OP1(\*), OP1(/), OP1(+), OP1(-), OP2(>=), OP2(<=), OP1(>), OP1(<), OP2(==), OP2(!=), SEP(), SEP(;)}
- Follow(PrimaryExpr) = {OP1(^), OP1(\*), OP1(/), OP1(+), OP1(-), OP2(>=), OP2(<=), OP1(>), OP1(<), OP2(==), OP2(!=), SEP(), SEP(;)}

## LL(1) Parsing Table

注：此文档由markdown编写，转化为pdf后此表可能展示不全，如需所有详细信息，请阅读report.md文件源码

Non-Terminal	KEY(let)	ID	SEP();	KEY(print)	KEY(read)	KEY(if)	SEP()	NUM_INT	NUM_FLOAT	OPI(+)	OPI(-)	OPI(^)	SEP();	KEY(else)	REPEAT	SEP();	#
Program	StmtList	StmtList	StmtList	StmtList	StmtList	StmtList	StmtList										StmtList
StmtList	Stmt	Stmt StmtList	Stmt StmtList	Stmt StmtList	Stmt StmtList	Stmt StmtList	Stmt StmtList								ε	ε	ε
Stmt	DeclStmt	AssignStmt	BlockMaybeRepeat	FuncCallStmt	FuncCallStmt	IfStmt											
DeclStmt	KEY(let) ID SEP();)																
AssignStmt		ID ASSIGN Expr SEP();)															
BlockMaybeRepeat		Block RepeatTail															
RepeatTail															REPEAT Expr SEP();)	ε	ε
Block		SEP(); StmtList SEP();)															
FuncCallStmt			FuncCall SEP();	FuncCall SEP();													
FuncCall			KEY(prnt) SEP(); Expr SEP();)	KEY(read) SEP();)	KEY(); ID SEP();)												
IfStmt				KEY(if) SEP(); Expr SEP();)	Block	ElsePart											
ElsePart														ε	KEY(else) Block		
Expr				SEP(); Expr	NUM_INT Expr	NUM_FLOAT Expr	OPI(+); Expr	OPI(-); Expr	OPI(^); Expr								
EqualityExpr				SEP();	NUM_INT	NUM_FLOAT	OPI(+)	OPI(-)	OPI(^)								
RelationExpr				RelationExpr	RelationExpr	RelationExpr	OPI(+)	OPI(-)	OPI(^)								
EqualityExpr'				EqualityExpr'	EqualityExpr'	EqualityExpr'	OPI(+)	OPI(-)	OPI(^)					ε	ε	ε	
RelationExpr'							OPI(+)	OPI(-)	OPI(^)								
AddExpr				SEP(); MulExpr AddExpr'	NUM_INT MulExpr AddExpr'	NUM_FLOAT MulExpr AddExpr'	OPI(+); MulExpr AddExpr'	OPI(-); MulExpr AddExpr'	OPI(^); MulExpr AddExpr'								
AddExpr'							OPI(+); MulExpr AddExpr'	OPI(-); MulExpr AddExpr'	OPI(^); MulExpr AddExpr'					ε	ε	ε	
MulExpr				SEP(); UnaryExpr MulExpr'	NUM_INT UnaryExpr MulExpr'	NUM_FLOAT UnaryExpr MulExpr'	OPI(+); UnaryExpr MulExpr'	OPI(-); UnaryExpr MulExpr'	OPI(^); UnaryExpr MulExpr'								
MulExpr'							OPI(+); UnaryExpr MulExpr'	OPI(-); UnaryExpr MulExpr'	OPI(^); UnaryExpr MulExpr'					ε	ε	ε	
UnaryExpr				SEP(); PowerExpr	NUM_INT PowerExpr	NUM_FLOAT PowerExpr	OPI(+); UnaryExpr	OPI(-); UnaryExpr	OPI(^); UnaryExpr								
PowerExpr				SEP();	NUM_INT PrimaryExpr PowerExpr'	NUM_FLOAT PrimaryExpr PowerExpr'											
PowerExpr'															ε	ε	ε
PrimaryExpr				SEP(); Expr SEP();)	NUM_INT	NUM_FLOAT											

## f. 重要数据结构描述

### Token

```

1 #[derive(Debug, Clone, PartialEq, Eq, Hash, Serialize)]
2 pub struct Token {
3     pub kind: String,
4     pub lexeme: String,

```

Token 是词法分析阶段的产物，也是语法分析阶段的最小输入单位。

成员：

kind: 类别标识（如 "ID", "NUM", "IF"），在语法分析中作为终结符匹配。

lexeme: 源代码中的原始文本内容（如变量名 x 或数字 3.14）。

关键逻辑：

to\_key() 方法：这是一个映射逻辑，用于在 LL(1) 查表时将具体的 lexeme 归类。例如，所有的标识符在查表时都统一视为 "ID"。

## DFA

```

1 #[derive(Debug, Deserialize)]
2 struct DFA {
3     states: Vec<String>,
4     start: String,
5     accept: Vec<String>,
6     trans: Vec<Transition>,
7 }

```

该结构用于描述如何从字符串流中切割出 Token。

成员：

states: 状态集合。

start: 起始状态。

accept: 接受状态列表。这里的关键设计是：lex\_code 函数将到达的接受状态名称直接作为生成的 Token 的 kind。

trans: 转移函数集合，定义了在当前状态下遇到特定字符（pattern）时应跳转到哪个状态。

## L11Table

```

1 #[derive(Debug)]
2 struct L11Table {
3     terminals: Vec<Token>,
4     non_terminals: Vec<Token>,
5     table: HashMap<Token, HashMap<Token, Vec<Token>>>,
6 }

```

这是语法分析器的“大脑”，决定了给定当前的非终结符和输入符号，应该推导出哪条产生式。

结构：HashMap<Token, HashMap<Token, Vec>>

外层 Key: 当前栈顶的非终结符（Non-terminal）。

内层 Key: 当前输入的终结符（Terminal/Lookahead）。

Value: 对应的产生式右部（由 Token 组成的向量）。

特殊符号：支持  $\epsilon$ （空产生式）和 #（输入结束标记）。

## ASTNode (抽象语法树节点)

```
1 #[derive(Debug, Clone)]
2 pub enum ASTNode {
3     Terminal {
4         token: Token,
5     },
6     NonTerminal {
7         kind: String,
8         children: Vec<Rc<RefCell<ASTNode>>,
9     },
10 }
```

这是一个递归的枚举类型，代表了源代码的树形结构化表示。

变体：

Terminal: 叶子节点，存储具体的 Token。

NonTerminal: 中间节点，包含一个类别名 (kind) 和一组子节点 (children)。

设计细节：

使用了 `Rc<RefCell>`。这是为了在 LL(1) 解析这种自顶向下的过程中，能够方便地在父节点创建后动态地追加子节点，解决 Rust 的所有权和可变性限制。

## g. 核心算法描述

### 词法分析：基于 DFA 的最大匹配逻辑

`lex_code` 函数是程序的第一道工序，它负责将源代码切割成一个个 Token。

状态转移与贪婪匹配：程序从 `pos` 位置开始，模拟 DFA 的状态跳转。它不仅记录当前是否到达了 `accept`（接受）状态，还会尽可能向后多读字符 (`last_accept_pos`)。

回溯机制：如果读到某个字符发现无法继续跳转，它会“回退”到最后一个记录的接受状态。

Token 产出：一旦确定了最长匹配，就将该段文本截取，并以 DFA 状态名作为 Token 的 kind。

### 语法分析：基于栈的 LL(1) 驱动算法

`parse_111` 函数是程序最复杂的逻辑所在。它实现了一个非递归的预测分析器，核心逻辑是一个 while 循环：

符号匹配 (Match)：

如果栈顶是终结符 (Terminal) , 且与当前输入的 Token 种类一致, 则匹配成功, 同步弹出栈顶和输入流头部的符号。

展开产生式 (Expand) :

如果栈顶是非终结符 (Non-Terminal) , 程序会去 LlTable 中查表: table[栈顶符号][当前输入符号]。

查到的结果是一条产生式 (如 A -> B C) 。程序会将栈顶的 A 弹出, 然后将右部的符号 C 和 B 逆序压入栈中 (这样 B 就在栈顶, 能够先被处理) 。

空产生式处理: 如果查到的是  $\epsilon$  (epsilon) , 表示该非终结符可以推导为空, 此时只需弹出栈顶, 不压入新符号。

## AST 的动态构建逻辑

由于使用的是非递归分析, 如何在“展开”产生式的同时构建树状结构是一个难点。代码通过以下方式解决:

同步对象: 在将符号压入栈时, 不仅压入了符号名, 还压入了一个 Rc<RefCell>。

父子绑定:

当一个非终结符被展开时, 它会先创建好所有子节点的“空壳”。

这些子节点被存入父节点的 children 向量中。

同时, 这些子节点被压入栈。当后续逻辑处理到这些栈元素时, 会直接填充这些“空壳”的内容 (如填充 Terminal 的 lexeme) 。

引用计数管理: 通过 Rc<RefCell<...>>, 父节点和栈同时拥有指向子节点的指针, 确保了在复杂的压栈/弹栈过程中, 树形结构能被正确连接。

## h. 运行用例

测试源代码(./test\_code.txt)为

```
1 let x;
2 x = 42;
3 let y;
4 read(y);
5 let abc;
6 abc = x + y + 23.3;
7 {
8     abc = abc * 23.3;
9 } ^^ 66;
10 if (x >= y + x == y + x != y) {print(x);} else {print(y);}
```

运行程序后, 输出的 Token 序列(./dfa\_lexer/token.txt)为:

1	AcceptState: KEY	Lexeme: 'let'
2	AcceptState: WS	Lexeme: ' '
3	AcceptState: ID	Lexeme: 'x'
4	AcceptState: SEP	Lexeme: ';'

5	AcceptState: WS	Lexeme: '\n'
6	AcceptState: ID	Lexeme: 'x'
7	AcceptState: WS	Lexeme: ' '
8	AcceptState: ASSIGN	Lexeme: '='
9	AcceptState: WS	Lexeme: ' '
10	AcceptState: NUM_INT	Lexeme: '42'
11	AcceptState: SEP	Lexeme: ';'
12	AcceptState: WS	Lexeme: '\n'
13	AcceptState: KEY	Lexeme: 'let'
14	AcceptState: WS	Lexeme: ' '
15	AcceptState: ID	Lexeme: 'y'
16	AcceptState: SEP	Lexeme: ';'
17	AcceptState: WS	Lexeme: '\n'
18	AcceptState: KEY	Lexeme: 'read'
19	AcceptState: SEP	Lexeme: '('
20	AcceptState: ID	Lexeme: 'y'
21	AcceptState: SEP	Lexeme: ')'
22	AcceptState: SEP	Lexeme: ';'
23	AcceptState: WS	Lexeme: '\n'
24	AcceptState: KEY	Lexeme: 'let'
25	AcceptState: WS	Lexeme: ' '
26	AcceptState: ID	Lexeme: 'abc'
27	AcceptState: SEP	Lexeme: ';'
28	AcceptState: WS	Lexeme: '\n'
29	AcceptState: ID	Lexeme: 'abc'
30	AcceptState: WS	Lexeme: ' '
31	AcceptState: ASSIGN	Lexeme: '='
32	AcceptState: WS	Lexeme: ' '
33	AcceptState: ID	Lexeme: 'x'
34	AcceptState: WS	Lexeme: ' '
35	AcceptState: OP1	Lexeme: '+'
36	AcceptState: WS	Lexeme: ' '
37	AcceptState: ID	Lexeme: 'y'
38	AcceptState: WS	Lexeme: ' '
39	AcceptState: OP1	Lexeme: '+'
40	AcceptState: WS	Lexeme: ' '
41	AcceptState: NUM_FLOAT	Lexeme: '23.3'
42	AcceptState: SEP	Lexeme: ';'
43	AcceptState: WS	Lexeme: '\n'
44	AcceptState: SEP	Lexeme: '{'
45	AcceptState: WS	Lexeme: '\n' '
46	AcceptState: ID	Lexeme: 'abc'
47	AcceptState: WS	Lexeme: ' '
48	AcceptState: ASSIGN	Lexeme: '='
49	AcceptState: WS	Lexeme: ' '
50	AcceptState: ID	Lexeme: 'abc'
51	AcceptState: WS	Lexeme: ' '
52	AcceptState: OP1	Lexeme: '*'
53	AcceptState: WS	Lexeme: ' '
54	AcceptState: NUM_FLOAT	Lexeme: '23.3'
55	AcceptState: SEP	Lexeme: ';'
56	AcceptState: WS	Lexeme: '\n'
57	AcceptState: SEP	Lexeme: '}'
58	AcceptState: WS	Lexeme: ' '
59	AcceptState: REPEAT	Lexeme: '^~'
60	AcceptState: WS	Lexeme: ' '
61	AcceptState: NUM_INT	Lexeme: '66'
62	AcceptState: SEP	Lexeme: ';'

```

63 AcceptState: WS           Lexeme: '\n'
64 AcceptState: KEY          Lexeme: 'if'
65 AcceptState: WS           Lexeme: ' '
66 AcceptState: SEP          Lexeme: '('
67 AcceptState: ID           Lexeme: 'x'
68 AcceptState: WS           Lexeme: ' '
69 AcceptState: OP2          Lexeme: '>='
70 AcceptState: WS           Lexeme: ' '
71 AcceptState: ID           Lexeme: 'y'
72 AcceptState: WS           Lexeme: ' '
73 AcceptState: OP1          Lexeme: '+'
74 AcceptState: WS           Lexeme: ' '
75 AcceptState: ID           Lexeme: 'x'
76 AcceptState: WS           Lexeme: ' '
77 AcceptState: OP2          Lexeme: '==''
78 AcceptState: WS           Lexeme: ' '
79 AcceptState: ID           Lexeme: 'y'
80 AcceptState: WS           Lexeme: ' '
81 AcceptState: OP1          Lexeme: '+'
82 AcceptState: WS           Lexeme: ' '
83 AcceptState: ID           Lexeme: 'x'
84 AcceptState: WS           Lexeme: ' '
85 AcceptState: OP2          Lexeme: '!='
86 AcceptState: WS           Lexeme: ' '
87 AcceptState: ID           Lexeme: 'y'
88 AcceptState: SEP          Lexeme: ')'
89 AcceptState: WS           Lexeme: ' '
90 AcceptState: SEP          Lexeme: '{'
91 AcceptState: KEY          Lexeme: 'print'
92 AcceptState: SEP          Lexeme: '('
93 AcceptState: ID           Lexeme: 'x'
94 AcceptState: SEP          Lexeme: ')'
95 AcceptState: SEP          Lexeme: ';'
96 AcceptState: SEP          Lexeme: '}'
97 AcceptState: WS           Lexeme: ' '
98 AcceptState: KEY          Lexeme: 'else'
99 AcceptState: WS           Lexeme: ' '
100 AcceptState: SEP          Lexeme: '{'
101 AcceptState: KEY          Lexeme: 'print'
102 AcceptState: SEP          Lexeme: '('
103 AcceptState: ID           Lexeme: 'y'
104 AcceptState: SEP          Lexeme: ')'
105 AcceptState: SEP          Lexeme: ';'
106 AcceptState: SEP          Lexeme: '}'

```

最后，生成的抽象语法树（AST）（./dfa\_lexer/ast.json）如下所示：

```

1  {
2      "type": "NonTerminal",
3      "kind": "Program",
4      "children": [
5          {
6              "type": "NonTerminal",
7              "kind": "StmtList",
8              "children": [
9                  {
10                     "type": "NonTerminal",

```

```
11     "kind": "Stmt",
12     "children": [
13     {
14         "type": "NonTerminal",
15         "kind": "DeclStmt",
16         "children": [
17             {
18                 "kind": "Terminal",
19                 "token": {
20                     "kind": "KEY",
21                     "lexeme": "let"
22                 }
23             },
24             {
25                 "kind": "Terminal",
26                 "token": {
27                     "kind": "ID",
28                     "lexeme": "x"
29                 }
30             },
31             {
32                 "kind": "Terminal",
33                 "token": {
34                     "kind": "SEP",
35                     "lexeme": ";"
36                 }
37             }
38         ]
39     }
40 ],
41 },
42 {
43     "type": "NonTerminal",
44     "kind": "StmtList",
45     "children": [
46     {
47         "type": "NonTerminal",
48         "kind": "Stmt",
49         "children": [
50             {
51                 "type": "NonTerminal",
52                 "kind": "AssignStmt",
53                 "children": [
54                     {
55                         "kind": "Terminal",
56                         "token": {
57                             "kind": "ID",
58                             "lexeme": "x"
59                         }
60                     },
61                     {
62                         "kind": "Terminal",
63                         "token": {
64                             "kind": "ASSIGN",
65                             "lexeme": "="
66                         }
67                     },
68                 ]
69             }
70         ]
71     }
72 ],
73 },
74 {
75     "type": "NonTerminal",
76     "kind": "ExprList",
77     "children": [
78         {
79             "type": "NonTerminal",
80             "kind": "Expr",
81             "children": [
82                 {
83                     "type": "NonTerminal",
84                     "kind": "TermList",
85                     "children": [
86                         {
87                             "type": "NonTerminal",
88                             "kind": "Term",
89                             "children": [
90                                 {
91                                     "type": "NonTerminal",
92                                     "kind": "FactorList",
93                                     "children": [
94                                         {
95                                             "type": "NonTerminal",
96                                             "kind": "Factor",
97                                             "children": [
98                                                 {
99                                                     "type": "NonTerminal",
100                                                    "kind": "PrimaryExpr",
101                                                    "children": [
102                                                        {
103                                                            "type": "NonTerminal",
104                                                            "kind": "Identifier",
105                                                            "children": [
106                                                                {
107                                                                    "type": "NonTerminal",
108                                                                    "kind": "IdentifierToken",
109                                                                    "children": [
110                                                                        {
111                                                                            "type": "Terminal",
112                                                                            "token": {
113                                                                                "kind": "ID",
114                                                                                "lexeme": "y"
115                                                                            }
116                                                                        }
117                                                                    ]
118                                                                }
119                                                            ]
120                                                        }
121                                                    ]
122                                                }
123                                            ]
124                                        }
125                                    ]
126                                }
127                            ]
128                        }
129                    ]
130                }
131            ]
132        }
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1204                         "lexeme": "y"  
1205                     }},  
1206                     "PrimaryExpr",  
1207                     "NonTerminal",  
1208                     "kind":  
1209                     "PowerExpr'",  
1210                     "children": []  
1211                 }],  
1212             "NonTerminal",  
1213             "kind":  
1214             "MulExpr'",  
1215             "children": []  
1216         },  
1217         {  
1218             "type":  
1219             "NonTerminal",  
1220             "kind":  
1221             "AddExpr'",  
1222             "children": []  
1223         }],  
1224     "type":  
1225     "NonTerminal",  
1226     "kind": "AddExpr'",  
1227     "children": []
```





```
1325    {
1326        "type": "NonTerminal",
1327        "kind": "PrimaryExpr",
1328        "children": [
1329            {
1330                "kind": "Terminal",
1331                "token": {
1332                    "kind": "ID",
1333                    "lexeme": "x"
1334                }
1335            }
1336        ]
1337    },
1338    {
1339        "type": "NonTerminal",
1340        "kind": "PowerExpr'",
1341        "children": []
1342    }
1343]
1344}
1345]
1346},
1347{
1348    "type": "NonTerminal",
1349    "kind": "MulExpr'",
1350    "children": []
1351}
1352]
1353},
1354{
1355    "type": "NonTerminal",
1356    "kind": "AddExpr'",
1357    "children": []
```

```
1358 }  
1359 ]  
1360 },  
1361 {  
1362 "type":  
1363 "NonTerminal",  
1364 "kind":  
1365 "RelationExpr'",  
1366 "children":  
1367 []  
1368 }  
1369 ]  
1370 },  
1371 "type":  
1372 "NonTerminal",  
1373 "kind":  
1374 "EqualityExpr'",  
1375 "children": []  
1376 }  
1377 ]  
1378 },  
1379 {  
1380 "kind": "Terminal",  
1381 "token": {  
1382 "kind": "SEP",  
1383 "lexeme": ")"  
1384 }  
1385 }  
1386 {  
1387 "kind": "Terminal",  
1388 "token": {  
1389 "kind": "SEP",  
1390 "lexeme": ";"  
1391 }  
1392 }  
1393 ]  
1394 }  
1395 ]  
1396 },  
1397 {  
1398 "type": "NonTerminal",  
1399 "kind": "StmtList",  
1400 "children": []  
1401 }  
1402 ]  
1403 },  
1404 {  
1405 "kind": "Terminal",  
1406 "token": {  
1407 "kind": "SEP",  
1408 "lexeme": ")"  
1409 }  
1410 }
```

```
1411     ]
1412 },
1413 {
1414     "type": "NonTerminal",
1415     "kind": "ElsePart",
1416     "children": [
1417         {
1418             "kind": "Terminal",
1419             "token": {
1420                 "kind": "KEY",
1421                 "lexeme": "else"
1422             }
1423         },
1424         {
1425             "type": "NonTerminal",
1426             "kind": "Block",
1427             "children": [
1428                 {
1429                     "kind": "Terminal",
1430                     "token": {
1431                         "kind": "SEP",
1432                         "lexeme": "{"
1433                     }
1434                 },
1435                 {
1436                     "type": "NonTerminal",
1437                     "kind": "StmtList",
1438                     "children": [
1439                         {
1440                             "type": "NonTerminal",
1441                             "kind": "Stmt",
1442                             "children": [
1443                                 {
1444                                     "type": "NonTerminal",
1445                                     "kind": "FuncCallStmt",
1446                                     "children": [
1447                                         {
1448                                             "type": "NonTerminal",
1449                                             "kind": "FuncCall",
1450                                             "children": [
1451                                                 {
1452                                                     "kind": "Terminal",
1453                                                     "token": {
1454                                                         "kind": "KEY",
1455                                                         "lexeme": "print"
1456                                                     }
1457                                                 },
1458                                                 {
1459                                                     "kind": "Terminal",
1460                                                     "token": {
1461                                                         "kind": "SEP",
1462                                                         "lexeme": "("
1463                                                     }
1464                                                 },
1465                                                 {
1466                                                     "type": "NonTerminal",
1467                                                     "kind": "Expr",
1468                                                 }
1469                                             ]
1470                                         ]
1471                                     ]
1472                                 ]
1473                             ]
1474                         ]
1475                     ]
1476                 ]
1477             ]
1478         ]
1479     ]
1480 }
```

```
1468
1469
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1471
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1478
1479
1480
1481
1482
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1485
1486
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1489
1490
1491
1492
1493
1494
1495
1496
1497
1498
1499
    "children": [
      {
        "type": "NonTerminal",
        "kind": "EqualityExpr",
        "children": [
          {
            "type": "NonTerminal",
            "kind": "RelationExpr",
            "children": [
              [
                {
                  "type": "NonTerminal",
                  "kind": "AddExpr",
                  "children": [
                    {
                      "type": "NonTerminal",
                      "kind": "MulExpr",
                      "children": [
                        {
                          "type": "NonTerminal",
                          "kind": "UnaryExpr",
                          "children": [
                            {
                              "type": "NonTerminal",
                              "kind": "PowerExpr",
                              "children": [
                                {
                                  "type": "NonTerminal",
                                  "kind": "PrimaryExpr",
                                  "children": [
                                    {
                                      "type": "Terminal",
                                      "token": {

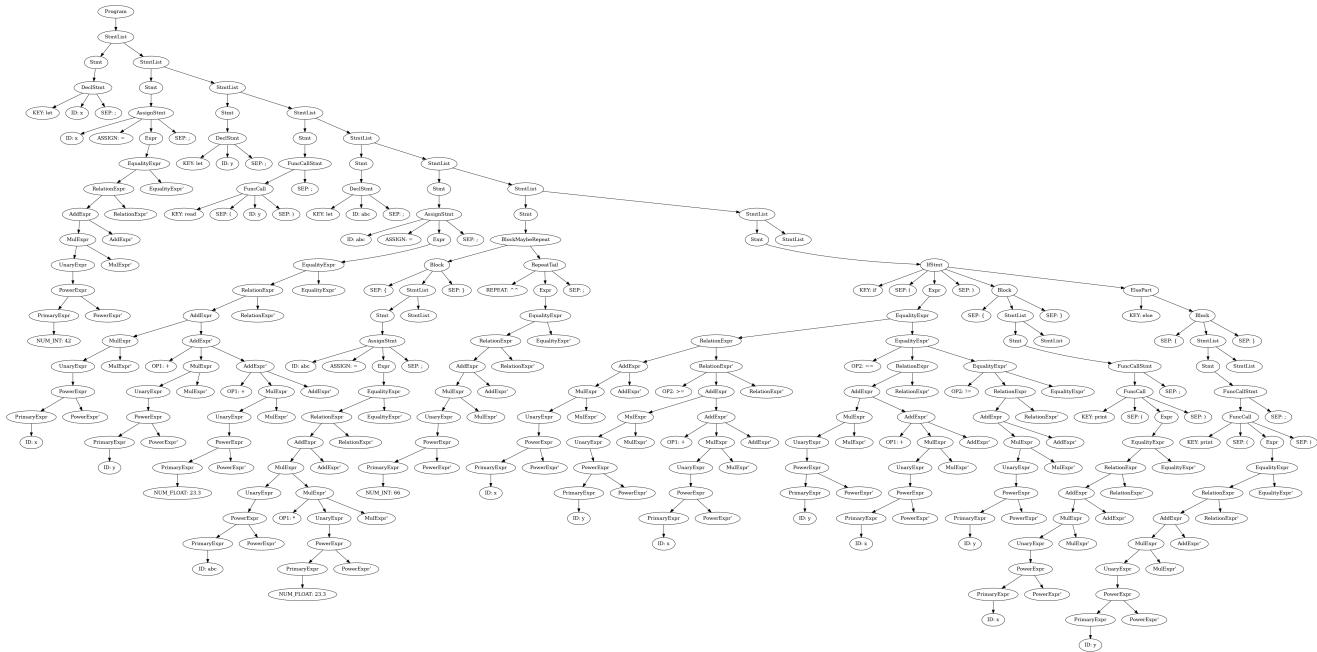
```

```
1500             "kind": "ID",
1501             "lexeme": "y"
1502         }
1503     }
1504 ]
1505 },
1506 {
1507     "type": "NonTerminal",
1508     "kind": "PowerExpr",
1509     "children": []
1510 }
1511 ]
1512 }
1513 ]
1514 },
1515 {
1516     "type": "NonTerminal",
1517     "kind": "MulExpr",
1518     "children": []
1519 }
1520 ]
1521 },
1522 {
1523     "type": "NonTerminal",
1524     "kind": "AddExpr",
1525     "children": []
1526 }
1527 ]
1528 },
1529 {
1530     "type": "NonTerminal",
1531     "kind": "RelationExpr",
1532     "children": []
1533 }
```

```
1534 ]  
1535 },  
1536 {  
1537     "type":  
1538     "NonTerminal",  
1539     "kind":  
1540     "EqualityExpr'",  
1541     "children":  
1542     []  
1543     }  
1544   ]  
1545   },  
1546   {  
1547     "kind": "Terminal",  
1548     "token": {  
1549       "kind": "SEP",  
1550       "lexeme": ")"  
1551     }  
1552   }  
1553   },  
1554   {  
1555     "kind": "Terminal",  
1556     "token": {  
1557       "kind": "SEP",  
1558       "lexeme": ";"  
1559     }  
1560   }  
1561   ]  
1562   }  
1563   ]  
1564   },  
1565   {  
1566     "type": "NonTerminal",  
1567     "kind": "StmtList",  
1568     "children": []  
1569   }  
1570 ]  
1571 },  
1572 {  
1573   "kind": "Terminal",  
1574   "token": {  
1575     "kind": "SEP",  
1576     "lexeme": "}"  
1577   }  
1578   }  
1579   ]  
1580   }  
1581   ]  
1582   }  
1583   ]  
1584   }  
1585   ]  
1586 },  
1587 {  
1588   "type": "NonTerminal",
```

```
1589 }  
1590 "children": []  
1591 }  
1592 ]  
1593 }  
1594 ]  
1595 }  
1596 ]  
1597 }  
1598 ]  
1599 }  
1600 ]  
1601 }  
1602 ]  
1603 }  
1604 ]  
1605 }  
1606 ]  
1607 }  
1608 ]  
1609 }
```

对AST进行可视化后得到如下图([./dfa\\_lexer/ast\\_tree.png](#))所示：



### i. 遇到的问题及解决方案

词法分析器的“贪婪匹配”失效

现象：输入的运算符 == 被错误地识别为两个 ASSIGN (=) Token，导致后续语法分析报错。原因：在 lex\_code 的早期实现中，可能一旦匹配到 accept 状态就立即返回了，没有继续尝试匹配更长的字符串。解决方法：

逻辑优化：代码中引入了 last\_accept\_state 和 last\_accept\_pos 变量。

具体做法：即使当前进入了接受状态，循环也不会停止，而是继续读下一个字符，直到无法转移为止。只有当彻底无法匹配时，才回退到“最后一次成功的接受状态”。这就是最大匹配原则（Longest Match）。

## LL(1) 递归构造中的“悬挂子节点”

现象：生成的 AST 结构是扁平的，或者子节点没有正确连接到父节点，导致 JSON 输出只有根节点。原因：在非递归解析中，由于产生式是不断弹栈、压栈的，很难在符号弹出时找到它属于哪个父节点。解决方法：

同步对象设计：在代码中，stack 存储的不只是 Token，而是 (Token, Rc<RefCell>)。

预先绑定：当非终结符展开产生式时，立即创建所有子节点的 Rc 引用，并将其放入父节点的 children 列表中。随后将这些子节点连同符号名一起压入栈。

指针共享：通过 Rc 指针，栈中的任务和树中的节点指向同一个内存地址。当栈处理完终结符并填充 lexeme 时，树结构中的对应节点也同步更新了。

## LL(1) 查表时的“种类失配”

现象：程序报错 No row for non-terminal 'ID'，但 ID 本身应该是终结符。原因：在 parse\_ll1 中，程序有时混淆了“Token 的具体内容”和“Token 的类型”。例如，输入是 NUM(3.14)，但预测表（Table）的列名是 NUM。解决方法：

Key 规范化：引入 Token::to\_key() 方法。

具体实现：

```
1 | match self.kind.as_str() {
2 |     "ID" | "NUM_INT" | "NUM_FLOAT" => Token::from(self.kind.as_str()),
3 |     _ => self.clone(),
4 | }
```

在查表前强制转换，确保对于所有具体的数字，都使用通用的 "NUM" 作为索引去查表。

## JSON 序列化时的“循环引用”或“递归过深”

现象：使用 serde\_json 序列化 AST 时程序崩溃，或生成的 JSON 包含大量重复数据。原因：ASTNode 使用了 Rc<RefCell<...>>，如果处理不当，可能会导致序列化器陷入无限死循环。解决方法：

手动实现 Serialize：代码中通过 impl Serialize for ASTNode 手动控制了序列化行为。

克隆解构：在序列化 NonTerminal 时，通过 .map(|child| child.borrow().clone()) 将引用转换为独立副本，打破了引用计数的复杂链路，确保生成的是标准的树状 JSON。

# j. 心得体会与建议

## 对“数据驱动”编程范式的深刻理解

在实验初期，我倾向于用大量的 if-else 或 match 语句去手写逻辑，但很快发现这种方式在面对复杂语法时难以维护。

感悟：本实验最核心的价值在于通用性。通过加载 min\_dfa.json 和 LL1table.json，程序逻辑与具体的语言语法脱钩了。

收获：我学会了如何设计一个“引擎”，让它能够根据不同的规则配置自动处理不同的编程语言，这种高度抽象的设计思想比单纯的代码实现更为重要。

## Rust 所有权机制与树形结构的博弈

在构建 AST（抽象语法树）时，Rust 的严格所有权系统曾让我感到非常棘手，特别是在非递归的 LL(1) 算法中。

技术突破：为了在栈（Stack）和树（Tree）之间共享节点，我被迫深入学习了 Rc<RefCell> 组合。

心得：理解了如何利用“内部可变性”在保证内存安全的前提下，构建动态增长的复杂数据结构。这不仅解决了 AST 的构建问题，也让我对 Rust 内存管理的底层逻辑有了更真实的体感。

## 理论与实践的“破壁”

以前在书本上学习编译原理时，LL(1) 预测分析表和 DFA 状态转移图只是纸上的推演。

感悟：

词法阶段：亲手实现了“最大匹配原则”后，才真正理解为什么 == 不会被识别为两个 =。

语法阶段：当看到一串扁平的 Token 序列，通过栈的压入弹出，最终神奇地变成一棵层次分明的 JSON 语法树时，那种“将混乱转化为秩序”的成就感是无可比拟的。

反馈：这种“实现一个小型编译器前端”的实验设计非常优秀，它将抽象的代数理论转化为了看得见、摸得着的工程实践。

## 对程序严谨性的敬畏

在实验中，哪怕是正则表达式中少了一个边界符 \b，或者是 LL(1) 表中漏掉了一个 ε 产生式，整个解析器都会瞬间崩塌。

收获：这培养了我极其严谨的思维习惯。在处理边界情况（如文件末尾 EOF、空行、非法字符）时，必须做到逻辑闭环。这种对细节的把控力是作为一名高级软件工程师必备的素质。

## 课程反馈与建议

如果能在后续加入 错误恢复的内容会更好。目前的程序在遇到语法错误时会直接报错退出，如果能学习如何跳过错误 Token 继续解析，将更贴近真实的生产环境。

## k. 附录

- 输入文件路径：
  - 词法分析器配置文件：./min\_dfa.json
  - 语法分析器预测表：./LL1table.json
  - 测试源代码：./test\_code.txt
- 输出文件路径：
  - 词法分析器输出 Token 序列：./dfa\_lexer/token.txt
  - 语法分析器输出 AST JSON：./dfa\_lexer/ast.json
  - 程序源代码路径：./dfa\_lexer/src/
- 实验报告路径：./report.md
- 其他相关文件：
  - AST可视化脚本：./draw\_tree.py
  - AST可视化结果：./dfa\_lexer/ast\_tree.png













