Scanners and parsers

A *scanner* or *lexer* transforms a string of characters into a string of tokens:
- uses a combination of *deterministic finite automata* (DFA);
- plus some glue code to make it work;
- can be generated by tools like `flex` (or `lex`), JFlex, ...

A *parser* transforms a string of tokens into a parse tree, according to some grammar:
- it corresponds to a *deterministic push-down automaton*;
- plus some glue code to make it work;
- can be generated by `bison` (or `yacc`), CUP, ANTLR, SableCC, Beaver, JavaCC, ...

Tokens are defined by *regular expressions*:
- \( \emptyset \), the empty set: a language with no strings
- \( \varepsilon \), the empty string
- \( a \), where \( a \in \Sigma \) and \( \Sigma \) is our alphabet
- \( M \mid N \), alternation: either \( M \) or \( N \)
- \( M \cdot N \), concatenation: \( M \) followed by \( N \)
- \( M^* \), zero or more occurrences of \( M \)

where \( M \) and \( N \) are both regular expressions. What are \( M^? \) and \( M^{+?} \)?

We can write regular expressions for the tokens in our source language using standard POSIX notation:
- simple operators: "*", "/", "+", "-"
- parentheses: "(", ")"
- integer constants: \( 0 \mid (1-9) \mid 0-9 \)
- identifiers: \[ a-zA-Z_][a-zA-Z0-9_]* \]
- white space: \[ \s\]
flex accepts a list of regular expressions (regex), converts each regex internally to an NFA (Thompson construction), and then converts each NFA to a DFA (see Appel, Ch. 2):

Each DFA has an associated action.

Why the “longest match” principle?
Example: keywords

[ \t]+ /* ignore */;
...
import
   return tIMPORT;
...
[a-zA-Z_][a-zA-Z0-9_]*{
   yyval.stringconst = (char *)malloc(strlen(yytext)+1);
   printf(yyval.stringconst,"%s",yytext);
   return tIDENTIFIER;
}

Want to match ‘importedFiles’ as tIDENTIFIER(importedFiles) and not as tIMPORT tIDENTIFIER(edFiles).
Because we prefer longer matches, we get the right result.

Why the “first match” principle?
Again — Example: keywords

[ \t]+ /* ignore */;
...
continue
   return tCONTINUE;
...
[a-zA-Z_][a-zA-Z0-9_]*{
   yyval.stringconst = (char *)malloc(strlen(yytext)+1);
   printf(yyval.stringconst,"%s",yytext);
   return tIDENTIFIER;
}

Want to match ‘continue foo’ as tCONTINUE tIDENTIFIER(foo) and not as tIDENTIFIER(continue) tIDENTIFIER(foo).
“First match” rule gives us the right answer:
When both tCONTINUE and tIDENTIFIER match, prefer the first.
When “first longest match” (flm) is not enough, look-ahead may help.

FORTRAN allows for the following tokens:

- .EQ., .363, 363., .363

flm analysis of 363. EQ. 363 gives us:

tFLOAT(363) E Q tFLOAT(0.363)

What we actually want is:

tINTEGER(363) tEQ tINTEGER(363)

flex allows us to use look-ahead, using '/':

363/.EQ. return tINTEGER;

Another example taken from FORTRAN:

Fortran ignores whitespace

1. DO5I = 1.25 363 = 1.25
   in C: do5i = 1.25;

2. DO 5 I = 1,25 + 5 I = 1,25
   in C: for(i=1;i<25;++i){...}
   (5 is interpreted as a line number here)

Case 1: flm analysis correct:

tID(DO5I) tEQ tREAL(1.25)

Case 2: want:

tDO tINT(5) tID(I) tEQ tINT(1) tCOMMA tINT(25)

Cannot make decision on tDO until we see the comma!

Look-ahead comes to the rescue:

DO/({letter}|{digit})*=({letter}|{digit})*, return tDO;

Using flex to create a scanner is really simple:

$ emacs print_tokens.l
$ flex print_tokens.l
$ gcc -o print_tokens lex.yy.c -lfl

When input a*(b-17) + 5/c:

our print_tokens scanner outputs:

identifier: a
times
left parenthesis
identifier: b
minus
integer constant: 17
right parenthesis
white space, length 1
plus
white space, length 1
integer constant: 5
div
identifier: c
white space, length 1

You should confirm this for yourself!
Count lines and characters:

```c
%{
  int lines = 0, chars = 0;
%
  lines++; chars++;
  . chars++;
%x
main () {
  yylex ();
  printf (#lines = %i, #chars = %i\n", lines, chars);
}
```

Remove vowels and increment integers:

```c
%(#include <stdlib.h> /* for atoi */
#include <stdio.h> /* for printf */
%)

%(\[aeiouy\] /* ignore */
[0-9]+ printf (%i, atoi (yytext) + 1);

%x
main () {
  yylex ();
}
```

A context-free grammar is a 4-tuple \((V, \Sigma, R, S)\), where we have:

- \(V\), a set of variables (or non-terminals)
- \(\Sigma\), a set of terminals such that \(V \cap \Sigma = \emptyset\)
- \(R\), a set of rules, where the LHS is a variable in \(V\) and the RHS is a string of variables in \(V\) and terminals in \(\Sigma\)
- \(S \in V\), the start variable

CFGs are stronger than regular expressions, and able to express recursively-defined constructs.

Example: we cannot write a regular expression for any number of matched parentheses:

\((\), (\)), ((\))\), ...

Using a CFG:

\[E \rightarrow ( E ) \mid \epsilon\]

Automatic parser generators use CFGs as input and generate parsers using the machinery of a deterministic pushdown automaton.

Example:

- Simple CFG example:
  - Alternatively:
    - \(A \rightarrow a B\)
    - \(A \rightarrow a B \mid \epsilon\)
    - \(A \rightarrow \epsilon\)
    - \(B \rightarrow b B\)
    - \(B \rightarrow c\)

In both cases we specify \(S = A\). Can you write this grammar as a regular expression?

We can perform a rightmost derivation by repeatedly replacing variables with their RHS until only terminals remain:

\[A\]
\[a B\]
\[a b B\]
\[a b b B\]
\[a b b c\]
There are several different grammar formalisms. First, consider BNF (Backus-Naur Form):

\[
\text{stmt} ::= \text{stmt_expr } ; \mid \\
\quad \quad \text{while_stmt} \mid \\
\quad \quad \text{block} \mid \\
\quad \quad \text{if_stmt} \\
\text{while_stmt} ::= \text{WHILE } "(\text{ expr })" \text{ stmt} \\
\text{block} ::= "\{\text{ stmt_list }\}" \\
\text{if_stmt} ::= \text{IF } "(\text{ expr })" \text{ stmt} \mid \\
\quad \quad \text{IF } "(\text{ expr })" \text{ stmt ELSE stmt}
\]

We have four options for stmt_list:
1. stmt_list ::= stmt stmt_list stmt | ϵ → 0 or more, left-recursive
2. stmt_list ::= stmt stmt_list stmt | ϵ → 0 or more, right-recursive
3. stmt_list ::= stmt stmt_list stmt | stmt → 1 or more, left-recursive
4. stmt_list ::= stmt stmt_list stmt | stmt → 1 or more, right-recursive

Second, consider EBNF (Extended BNF):

<table>
<thead>
<tr>
<th>BNF</th>
<th>derivations</th>
<th>EBNF</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A \rightarrow A \mid b )</td>
<td>( A \rightarrow a \mid A a b )</td>
<td>( A \rightarrow a \mid b { a } )</td>
</tr>
<tr>
<td>(left-recursive)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( A \rightarrow A \mid b )</td>
<td>( A \rightarrow a A \mid a a )</td>
<td>( A \rightarrow { a } b )</td>
</tr>
<tr>
<td>(right-recursive)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where '{' and '}' are like Kleene *'s in regular expressions. Using EBNF repetition, our four choices for stmt_list become:
1. stmt_list ::= { stmt }
2. stmt_list ::= { stmt }
3. stmt_list ::= { stmt } stmt
4. stmt_list ::= stmt { stmt }

EBNF also has an optional-construct. For example:

\[
\text{stmt_list} ::= \text{stmt} \; \text{stmt_list} \mid \text{stmt}
\]

could be written as:

\[
\text{stmt_list} ::= \text{stmt } [ \text{ stmt_list } ]
\]

And similarly:

\[
\text{if_stmt} ::= \text{IF } "(\text{ expr })" \text{ stmt} \mid \\
\quad \quad \text{IF } "(\text{ expr })" \text{ stmt ELSE stmt}
\]

could be written as:

\[
\text{if_stmt} ::= \\
\quad \quad \text{IF } "(\text{ expr })" \text{ stmt } [ \text{ ELSE stmt } ]
\]

where '{' and '}' are like '?' in regular expressions.

Third, consider “railroad” syntax diagrams:

(thanks rail.sty!)

\[\text{stmt}\]

\[\text{stmt_expr} \rightarrow ; \]

\[\text{while_stmt}\]

\[\text{block}\]

\[\{\text{ stmt_list }\} \]

\[\text{while} \rightarrow \{ \text{ expr } \rightarrow \} \rightarrow \text{stmt} \]
A grammar is **ambiguous** if a sentence has different parse trees:

\[
\begin{align*}
S & \rightarrow S \mid S \\
S & \rightarrow \text{id} := E \\
S & \rightarrow \text{print} ( L ) \\
E & \rightarrow \text{id} \\
E & \rightarrow \text{num} \\
L & \rightarrow L , E \\
L & \rightarrow E \\
E & \rightarrow E + E \\
E & \rightarrow ( S , E ) \\
\end{align*}
\]

a := 7;

b := c + (d := 5 + 6, d)

The above is harmless, but consider:

\[
\begin{align*}
\text{id} & := \text{id} - \text{id} - \text{id} \\
\text{id} & := \text{id} + \text{id} \ast \text{id} \\
\end{align*}
\]

Clearly, we need to consider associativity and precedence when designing grammars.
An ambiguous grammar:

\[ E \rightarrow \text{id} \]
\[ E \rightarrow E / E \]
\[ E \rightarrow \text{num} \]
\[ E \rightarrow E + E \]
\[ E \rightarrow E - E \]
\[ E \rightarrow E \ast E \]
\[ E \rightarrow (E) \]

may be rewritten to become unambiguous:

\[ E \rightarrow E + T \]
\[ T \rightarrow T \ast F \]
\[ E \rightarrow E - T \]
\[ T \rightarrow T / F \]
\[ E \rightarrow T \]
\[ T \rightarrow F \]
\[ F \rightarrow \text{id} \]
\[ F \rightarrow \text{num} \]
\[ F \rightarrow (E) \]

There are fundamentally two kinds of parser:

1) Top-down, *predictive* or *recursive descent* parsers. Used in all languages designed by Wirth, e.g. Pascal, Modula, and Oberon.

![Diagram of a parse tree](image)

Algorithm: look at beginning of input (up to \( k \) characters) and unambiguously expand leftmost non-terminal.

2) Bottom-up parsers.

Algorithm: look for a sequence matching RHS and reduce to LHS. Postpone any decision until entire RHS is seen, plus \( k \) tokens lookahead.

Can write a bottom-up parser by hand (tricky), or generate one from an LR(\( k \)) grammar (easy):

- *Left-to-right parse*;
- *Rightmost-derivation*; and
- \( k \) symbol lookahead.

The *shift-reduce* bottom-up parsing technique.

1) Extend the grammar with an end-of-file $, introduce fresh start symbol \( S' \):

\[ S' \rightarrow S $ \]
\[ S \rightarrow S ; S \]
\[ E \rightarrow \text{id} \]
\[ L \rightarrow E \]
\[ S \rightarrow \text{id} := E \]
\[ E \rightarrow \text{num} \]
\[ L \rightarrow L , E \]
\[ S \rightarrow \text{print (L)} \]
\[ E \rightarrow E + E \]
\[ E \rightarrow (S,E) \]

2) Choose between the following actions:

- *shift*: move first input token to top of stack
- *reduce*: replace \( \alpha \) on top of stack by \( X \) for some rule \( X \rightarrow \alpha \)
- *accept*: when \( S' \) is on the stack
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```
<table>
<thead>
<tr>
<th>state</th>
<th>terminals</th>
<th>non-terminals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>s4 s7</td>
<td>S E L</td>
</tr>
<tr>
<td>2</td>
<td>s3</td>
<td>a</td>
</tr>
<tr>
<td>3</td>
<td>s4 s7</td>
<td>g5</td>
</tr>
<tr>
<td>4</td>
<td>s6</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>r1 r1 r1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>s20 s10</td>
<td>s8</td>
</tr>
<tr>
<td>7</td>
<td>s4 s7</td>
<td>g11</td>
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<tr>
<td>8</td>
<td>s9</td>
<td></td>
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<tr>
<td>9</td>
<td></td>
<td>g15 g14</td>
</tr>
<tr>
<td>10</td>
<td>r5 r5 r5</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>r2 r2 s16</td>
<td>r2</td>
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<tr>
<td>12</td>
<td>s3 s18</td>
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<tr>
<td>13</td>
<td>r3 r3</td>
<td>r3</td>
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<tr>
<td>14</td>
<td>s19 s13</td>
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<td>15</td>
<td>r8 r8</td>
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<td>16</td>
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<td>s6 s10</td>
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<td>18</td>
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<td>s8</td>
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<tr>
<td>20</td>
<td>r4 r4 r4</td>
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<td>21</td>
<td>s22</td>
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<td>22</td>
<td>r7 r7 r7</td>
<td>r7 r7</td>
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<tr>
<td>23</td>
<td>r9 s16 r9</td>
<td></td>
</tr>
</tbody>
</table>
```

Error transitions omitted.

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Use a DFA to choose the action; the stack only contains DFA states now.

Start with the initial state (s1) on the stack.

Lookup (stack top, next input symbol):

- shift(n): skip next input symbol and push state n
- reduce(k): rule k is X→α; pop |α| times; lookup (stack top, X) in table
- goto(n): push state n
- accept: report success
- error: report failure

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LR(1) is an algorithm that attempts to construct a parsing table:

- **Left-to-right parse**;
- **Rightmost-derivation**; and
- 1 symbol lookahead.

If no conflicts (shift/reduce, reduce/reduce) arise, then we are happy; otherwise, fix grammar.

An LR(1) item \((A \rightarrow \alpha . \beta \gamma, x)\) consists of:

1. A grammar production, \(A \rightarrow \alpha \beta \gamma\)
2. The RHS position, represented by ‘.’
3. A lookahead symbol, \(x\)

An LR(1) state is a set of LR(1) items.

The sequence \(\alpha\) is on top of the stack, and the head of the input is derivable from \(\beta \gamma x\). There are two cases for \(\beta\), terminal or non-terminal.

We first compute a set of LR(1) states from our grammar, and then use them to build a parse table. There are four kinds of entry to make:

1. **goto**: when \(\beta\) is non-terminal
2. **shift**: when \(\beta\) is terminal
3. **reduce**: when \(\beta\) is empty (the next state is the number of the production used)
4. **accept**: when we have \(A \rightarrow B . \$\)

Follow construction on the tiny grammar:

\[
egin{align*}
0 & \quad S \rightarrow E \$
1 & \quad E \rightarrow T + E
2 & \quad E \rightarrow T
3 & \quad E \rightarrow T \cdot E
4 & \quad T \rightarrow x +
5 & \quad T \rightarrow x
6 & \quad E \rightarrow T + E
\end{align*}
\]

Constructing the LR(1) NFA:

- **start with state** \(S \rightarrow . E \$
- **state** \(A \rightarrow \alpha . B \beta \ 1\) has:
  - \(\epsilon\)-successor \(B \rightarrow . \gamma \ x\), if:
    * exists rule \(B \rightarrow \gamma\), and
    * \(x \in\) lookahead(\(\beta\))
  - \(B\)-successor \(A \rightarrow \alpha B . \beta \ 1\)
- **state** \(A \rightarrow \alpha . x \beta \ 1\) has:
  - \(x\)-successor \(A \rightarrow \alpha x . \beta \ 1\)

Constructing the LR(1) DFA:

Standard power-set construction, “inlining” \(\epsilon\)-transitions.
Conflicts

\[
\begin{align*}
A & \rightarrow B \quad x \\
A & \rightarrow C, \quad y
\end{align*}
\]
no conflict (lookahead decides)

\[
\begin{align*}
A & \rightarrow B \quad x \\
A & \rightarrow C \\
\end{align*}
\]
shift/reduce conflict

\[
\begin{align*}
A & \rightarrow x \\
A & \rightarrow C \\
\end{align*}
\]
shift/reduce conflict

\[
\begin{align*}
A & \rightarrow B \quad x \\
A & \rightarrow C \\
\end{align*}
\]
reduce/reduce conflict

\[
\begin{align*}
A & \rightarrow B \\
A & \rightarrow C \\
\end{align*}
\]
shift/shift conflict?

\[
\Rightarrow \text{ by construction of the DFA}
\]
we have \( s_i = s_j \)

**bison** (yacc) is a parser generator:

- it inputs a grammar;
- it computes an LALR(1) parser table;
- it reports conflicts;
- it resolves conflicts using defaults (!); and
- it creates a C program.

Nobody writes (simple) parsers by hand anymore.

**LR(1) tables may become very large.**

Parser generators use LALR(1), which merges states that are identical except for lookaheads.

The grammar:

\[
\begin{align*}
1 & \quad E \rightarrow \text{id} \\
4 & \quad E \rightarrow E / E \\
7 & \quad E \rightarrow ( E ) \\
2 & \quad E \rightarrow \text{num} \\
5 & \quad E \rightarrow E + E \\
3 & \quad E \rightarrow E * E \\
6 & \quad E \rightarrow E - E
\end{align*}
\]

is expressed in **bison** as:

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The grammar is ambiguous:

```bash
$ bison --verbose exp.y # --verbose produces exp.output
exp.y contains 16 shift/reduce conflicts.
$ cat exp.output
State 11 contains 4 shift/reduce conflicts.
State 12 contains 4 shift/reduce conflicts.
State 13 contains 4 shift/reduce conflicts.
State 14 contains 4 shift/reduce conflicts.
[...]
state 11
```

```latex
\begin{verbatim}
exp -> exp . '*' exp (rule 3)
exp -> exp . '/' exp . (rule 3) <-- problem is here
exp -> exp . '+' exp (rule 5)
exp -> exp . '-' exp (rule 4)

'*' shift, and go to state 6
'/,' shift, and go to state 7
'+' shift, and go to state 8
'-' shift, and go to state 9

'+' [reduce using rule 3 (exp)]
'/' [reduce using rule 3 (exp)]
'+' [reduce using rule 3 (exp)]
'-' [reduce using rule 3 (exp)]
$default reduce using rule 3 (exp)
\end{verbatim}
```

Rewrite the grammar to force reductions:

```latex
E \rightarrow E + T
E \rightarrow E - T
T \rightarrow T \ast F
T \rightarrow T / F
F \rightarrow \text{id}
F \rightarrow \text{num}
```

```
\%token tIDENTIFIER tINTCONST
\%start exp
\%
exp : exp + term
| exp - term
| term
|
| term \ast factor
| term \slash factor
| factor
|
factor : tIDENTIFIER
| tINTCONST
| '(' exp ')' 
\%
```

which resolve shift/reduce conflicts:

```
Conflict in state 11 between rule 5 and token '+'
resolved as reduce.  \text{\texttt{--- Reduce exp + exp . +}}
Conflict in state 11 between rule 5 and token '-'
resolved as reduce.  \text{\texttt{--- Reduce exp + exp . -}}
Conflict in state 11 between rule 5 and token '*'
resolved as shift.  \text{\texttt{--- Shift exp + exp . *}}
Conflict in state 11 between rule 5 and token '/'
resolved as shift.  \text{\texttt{--- Shift exp + exp . /}}
```

Note that this is not the same state 11 as before.

The precedence directives are:

- \%left (left-associative)
- \%right (right-associative)
- \%nonassoc (non-associative)

When constructing a parse table, an action is chosen based on the precedence of the last symbol on the right-hand side of the rule.

Precendences are ordered from lowest to highest on a linewise basis.

If precedences are equal, then:

- \%left favors reducing
- \%right favors shifting
- \%nonassoc yields an error

This usually ends up working.
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```
state 0
  tIDENTIFIER shift, and go to state 1
  tINTCONST shift, and go to state 2
  '(' shift, and go to state 3
  exp go to state 4

state 1
  exp -> tIDENTIFIER . (rule 1)
  $default reduce using rule 1 (exp)

state 2
  exp -> tINTCONST . (rule 2)
  $default reduce using rule 2 (exp)

state 14
  exp -> exp . '*' exp (rule 3)
  exp -> exp . '/' exp (rule 4)
  exp -> exp '/' exp . (rule 4)
  exp -> exp . '+' exp (rule 5)
  exp -> exp '-' exp (rule 6)
  $default reduce using rule 4 (exp)

state 15
  $ go to state 16

state 16
  $default accept
```

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```
$ cat exp.y

#include <stdio.h> /* for printf */
extern char *yytext; /* string from scanner */
void yyerror() {
    printf("syntax error before %s\n", yytext);
}
%

%union {
    int intconst;
    char *stringconst;
}
%
%token <intconst> tINTCONST
%token <stringconst> tIDENTIFIER
%
%start exp
%
%left '+' '-'
%left '*' '/'
%
exp :
    tIDENTIFIER { printf("load %s\n", $1); }
  | tINTCONST { printf("push %i\n", $1); }
  | exp '*' exp { printf("mult\n"); }
  | exp '/' exp { printf("div\n"); }
  | exp '+' exp { printf("plus\n"); }
  | exp '-' exp { printf("minus\n"); }
  | '(' exp ')' {};

%
```

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Scanners and Parsers (47)

```
$ cat exp.l

#include "y.tab.h" /* for exp.y types */
#include <string.h> /* for strlen */
#include <stdlib.h> /* for malloc and atoi */
%

[ 	
]+ /* ignore */;

"*" return '*';
"/" return '/';
"+" return '+';
"-" return '-';
"(" return '(';
")" return ')';

0|[1-9][0-9]* {
    yylval.intconst = atoi (yytext);
    return tINTCONST;
}

[a-zA-Z_][a-zA-Z0-9]* {
    yylval.stringconst = (char *) malloc (strlen (yytext) + 1);
    sprintf (yylval.stringconst, "%s", yytext);
    return tIDENTIFIER;
}

. /* ignore */
%
```

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Scanners and Parsers (48)

```
$ cat main.c

void yyparse();

int main (void)
{
    yyparse ();
}

Using flex/bison to create a parser is simple:

```bash
$ flex exp.l
$ bison --yacc --defines exp.y # note compatibility options
$ gcc lex.yy.c y.tab.c y.tab.h main.c -o exp -lfl
```

When input `a*(b-17) + 5/c`:

```bash
$ echo "a*(b-17) + 5/c" | ./exp
```

our `exp` parser outputs the correct order of operations:

```
load a
load b
push 17
minus
push 5
load c
div
plus
```

You should confirm this for yourself!
If the input contains syntax errors, then the \texttt{bison}-generated parser calls \texttt{yyerror} and stops. We may ask it to recover from the error:

\begin{verbatim}
exp : tIDENTIFIER { printf ("load %s\n", $1); }
    | '(' exp ')'
    | error { yyerror(); }
;
\end{verbatim}

and on input \texttt{a@(b-17) ++ 5/c} get the output:

\begin{verbatim}
load a
syntax error before ( 
syntax error before ( 
syntax error before ( 
syntax error before b 
push 17 
minus 
syntax error before ) 
syntax error before ) 
syntax error before + 
plus 
push 5 
load c 
div 
plus
\end{verbatim}

Error recovery hardly ever works.

SableCC (by Etienne Gagnon, McGill alumnus) is a \textit{compiler compiler}: it takes a grammatical description of the source language as input, and generates a lexer (scanner) and parser for it.

The SableCC 2 grammar for our Tiny language:

\begin{verbatim}
Package tiny;

Helpers
  tab = 9;
  cr = 13;
  lf = 10;
  digit = ['0'..'9'];
  lowercase = ['a'..'z'];
  uppercase = ['A'..'Z'];
  letter = lowercase | uppercase;
  idletter = letter | '_';
  idchar = letter | '_' | digit;

Tokens
  eol = cr | lf | cr lf;
  blank = ' ' | tab;
  star = '*';
  slash = '/';
  plus = '+';
  minus = '-';
  l_par = '{';
  r_par = '}';
  number = '0' [digit='0'] digit*;
  id = idletter idchar*;

Ignored Tokens
  blank, eol;
\end{verbatim}

Version 2 produces parse trees, a.k.a. concrete syntax trees (CSTs).
The SableCC 3 grammar for our Tiny language:

Productions

cst_exp (-> exp) =
(cst_plus) cst_exp plus factor
    (-> New exp.plus(cst_exp.exp,factor.exp)) |
(cst_minus) cst_exp minus factor
    (-> New exp.minus(cst_exp.exp,factor.exp)) |
(factor) factor (-> factor.exp);

factor (-> exp) =
(cst_mult) factor star term
    (-> New exp.mult(factor.exp,term.exp)) |
(cst_divd) factor slash term
    (-> New exp.divd(factor.exp,term.exp)) |
(term) term (-> term.exp);

term (-> exp) =
(paren) l_par cst_exp r_par (-> cst_exp) |
(cst_id) id (-> New exp.id(id)) |
(cst_number) number (-> New exp.number(number));

Abstract Syntax Tree

exp =
(plus) [l]:exp [r]:exp |
(minus) [l]:exp [r]:exp |
(mult) [l]:exp [r]:exp |
(divd) [l]:exp [r]:exp |
(id) id |
(number) number;

Version 3 generates abstract syntax trees (ASTs).