Lex & Yacc

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A compiler or an interpreter performs its task in 3 stages:

1) Lexical Analysis:

Lexical analyzer: scans the input stream and converts sequences of characters into tokens.

Token: a classification of groups of characters.

Examples:

Lexeme	Token
`Sum`	`ID`
`for`	`FOR`
`=`	`ASSIGN_OP`
`==`	`EQUAL_OP`
`57`	`INTEGER_CONST`
`"Abcd"`	`STRING_CONST`
`*`	`MULT_OP`
`,`	`COMMA`
`:`	`SEMICOLUMN`
`(`	`LEFT_PAREN`

Lex is a tool for writing lexical analyzers.

2) Syntactic Analysis (Parsing):

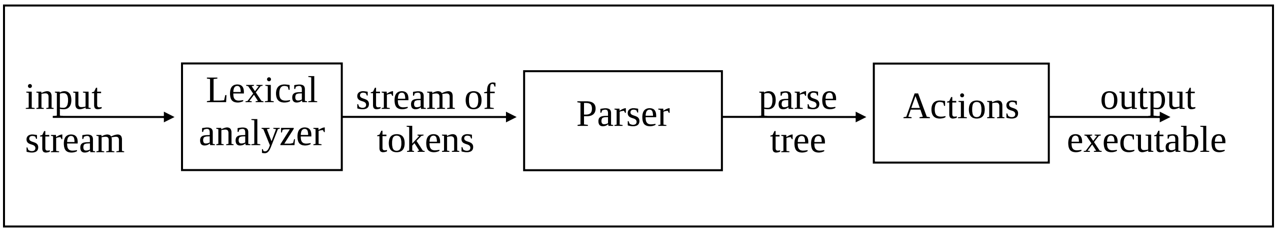
Parser: reads tokens and assembles them into language constructs using the grammar rules of the language.

Yacc (Yet Another Compiler Compiler) is a tool for constructing parsers.

3) Actions:

Acting upon input is done by code supplied by the compiler writer.

Basic model of parsing for interpreters and compilers:

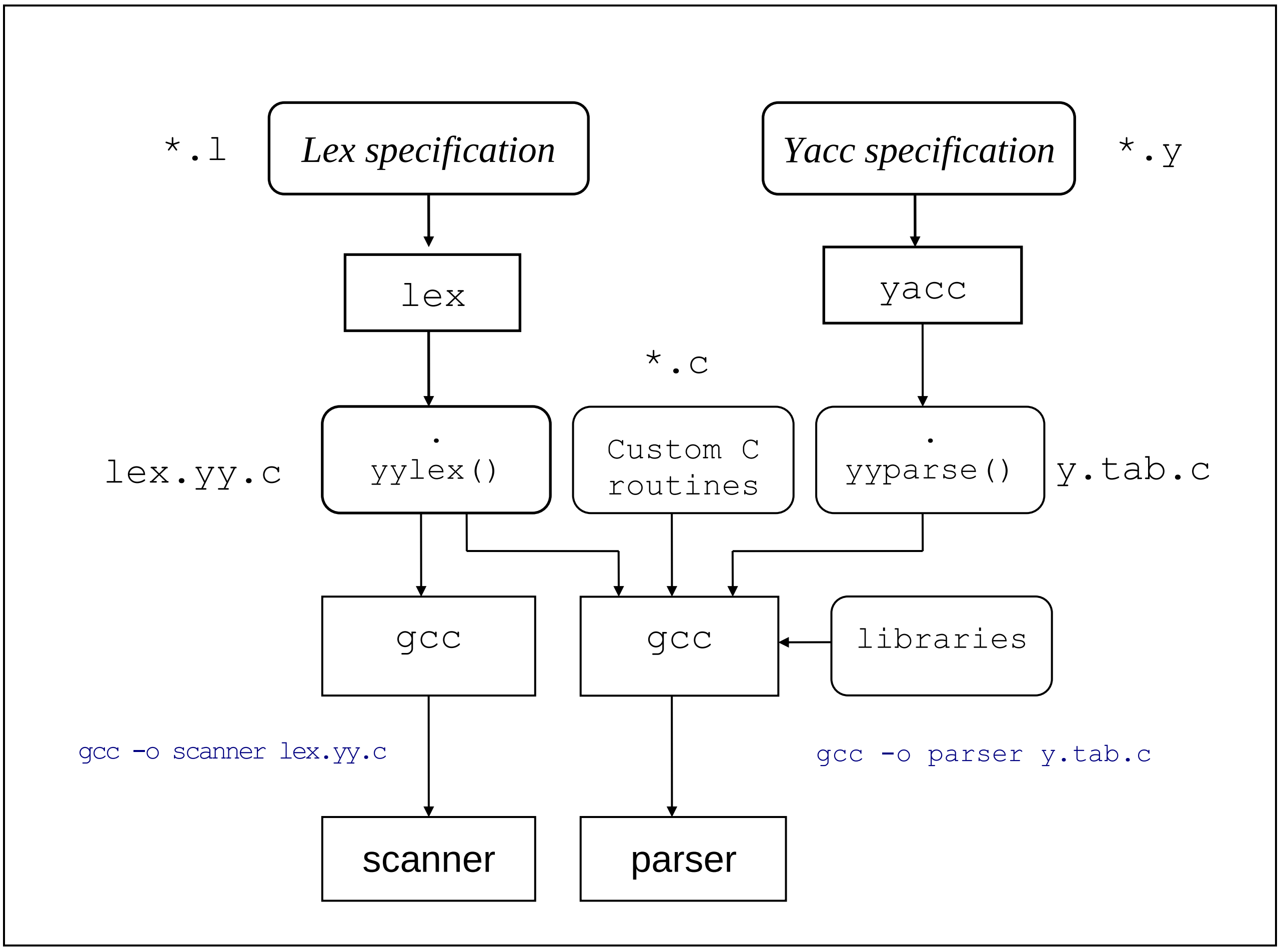


Lex: reads a specification file containing regular expressions and generates a C routine that performs lexical analysis.

Matches sequences that identify tokens.

Yacc: reads a specification file that codifies the grammar of a language and generates a parsing routine.

Using lex and yacc tools:



Lex

Regular Expressions in lex:

`a`	matches `a`
`abc`	matches `abc`
`[abc]`	matches `a`, `b` or `c`
`[a-f]`	matches `a`, `b`, `c`, `d`, `e`, or `f`
`[0-9]`	matches any digit
`X+`	mathces one or more of X
`X*`	mathces zero or more of X
`[0-9]+`	matches any integer
`(…)`	grouping an expression into a single unit
`|`	alternation (or)
`(a|b|c)*`	is equivalent to `[a-c]*`
`X?`	X is optional (0 or 1 occurrence)
`if(def)?`	matches `if` or `ifdef` (equivalent to `if|ifdef`)
`[A-Za-z]`	matches any alphabetical character
`.`	matches any character except newline character
`\.`	matches the . character
`\n`	matches the newline character
`\t`	matches the tab character
`\\`	matches the `\` character
`[ \t]`	matches either a space or tab character
`[^a-d]`	matches any character other than a,b,c and d

Examples:

Real numbers, e.g., 0, 27, 2.10, .17

`[0-9]+|[0-9]+\.[0-9]+|\.[0-9]+`

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

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

To include an optional preceding sign: `[+-]?[0-9]*(\.)?[0-9]+`

Contents of a lex specification file:

```
definitions
%%
regular expressions and associated actions (rules)
%%
user routines
```

Example ($ is the unix prompt):

```
$emacs ex1.l
$ls
ex1.l
$cat ex1.l
%option main
%%
zippy  printf("I recognized ZIPPY");
$lex ex1.l
$ls
ex1.l   lex.yy.c
$gcc -o ex1 lex.yy.c
$ls
ex1 ex1.l   lex.yy.c
$emacs test1
$cat test1
tom
zippy
ali zip
and zippy here
$cat test1 | ./ex1                or $./ex1 < test1
tom
I recognized ZIPPY
ali zip
and I recognized ZIPPY here
```

During pattern matching, lex searches the set of patterns for the single longest possible match.

```
$cat ex2.l
%option main
%%
zip     printf("ZIP");
zippy   printf("ZIPPY");
```

```
$cat test2
Azip and zippyr zipzippy
$cat test2 | ex2
AZIP and ZIPPYr ZIPZIPPY
```

Lex declares an external variable called `yytext` which contains the matched string

```
$cat ex3.l
%option main
%%
tom|jerry   printf(">%s<", yytext);
$cat test3
Did tom chase jerry?
$cat test3 | ex3
Did >tom< chase >jerry<?
```

Definitions:

```
/* float0.l */
%%
[+-]?[0-9]*(\.)?[0-9]+     printf("FLOAT");
```

input: `ab7.3c--5.4.3+d++5-`
output: `abFLOATc-FLOATFLOAT+d+FLOAT-`

The same lex specification can be written as:

```
/* float1.l */
%option main
digit    [0-9]
%%
[+-]?{digit}*(\.)?{digit}+    printf("FLOAT");
```

Local variables can be defined:

```
/* float2.l */
%option main
digit    [0-9]
sign     [+-]
%%
   float val;
{sign}?{digit}*(\.)?{digit}+  {sscanf(yytext, "%f", &val);
                                printf(">%f<", val);}
```

Input	Output
`ali-7.8veli`	`ali>-7.800000<veli`
`ali--07.8veli`	`ali->-7.800000<veli`
`+3.7.5`	`>3.700000<>0.500000<`

Other examples

```
/* echo-upcase-wrods.l */
%option main
%%
[A-Z]+[ \t\n\.\,]  printf("%s",yytext);
.    ;    /* no action specified */
```

The scanner with the specification above echoes all strings of capital letters, followed by a space tab (`\t`)or newline (`\n`) dot (`\.`) or comma (`\,`) to stdout, and all other characters will be ignored.

Input	Output
`Ali  VELI → A7, X. 12`	`VELI → X.`
`HAMI  BEY a`	`HAMI BEY`

Definitions can be used in definitions

```
/* def-in-def.l */
%option main
alphabetic     [A-Za-z_$]
digit          [0-9]
alphanumeric   ({alphabetic}|{digit})
%%
{alphabetic}{alphanumeric}*  printf("Java identifier");
\,                           printf("Comma");
\{                           printf("Left brace");
\=                           printf("Assignment op");
\=\=                         printf("Equality op");
```

Among rules that match the same number of characters, the rule given first will be chosen.

Example,

```
/* rule-order.l */
%option main
%%
for     printf("FOR");
[a-z]+  printf("IDENTIFIER");
```

for input

```
for count = 1 to 10
```

the output would be

```
FOR IDENTIFIER = 1 IDENTIFIER 10
```

However, if we swap the two lines in the specification file:

```
%option main
%%
[a-z]+  printf("IDENTIFIER");
for     printf("FOR");
```

for the same input

the output would be

```
IDENTIFIER IDENTIFIER = 1 IDENTIFIER 10
```

Important note:

Do not leave extra spaces and/or empty lines at the end of a lex specification file.

Yacc

Yacc specification describes a CFG, that can be used to generate a parser.

Elements of a CFG:

1. Terminals: tokens and literal characters,
2. Variables (nonterminals): syntactical elements,
3. Production rules, and
4. Start rule.

Format of a production rule:

```
symbol:    definition
           {action}
           ;
```

Example:

`<a> → <b>c` in BNF is written as `a: b 'c';` in yacc

Format of a yacc specification file:

```
declarations
%%
grammar rules and associated actions
%%
C programs
```

Declarations: To define tokens and their characteristics

`%token:`	declare names of tokens
`%left:`	define left-associative operators
`%right:`	define right-associative operators
`%nonassoc:`	define operators that may not associate with themselves
`%type:`	declare the type of variables
`%union:`	declare multiple data types for semantic values
`%start:`	declare the start symbol (default is the first variable in rules)
`%prec:`	assign precedence to a rule

```
%{
   C declarations
%}
```

directly copied to the resulting C program (E.g., variables, types, macros…)

Example: A yacc specification to accept $L = \{a^n b^n \mid n > 0\}$.

```
/* anbn0.l */
%%
a   return (A);
b   return (B);
.   return (yytext[0]);
\n  return ('\n');
%%
int yywrap() { return 1; }
```

Function **`yywrap()`** is called by lex when input is exhausted.

Return 1 if you are done or 0 if more processing is required.

```
/*anbn0.y */
%token A B
%%
start:   anbn '\n' {return 0;}
anbn:    A B
        | A anbn B
        ;
%%
#include "lex.yy.c"
main() {
  return yyparse();
}
int yyerror( char *s ) { fprintf(stderr, "%s\n", s); }
```

If the input stream does not match `start`, the default message of "`syntax error`" is printed and program terminates.

However, customized error messages can be generated.

```
/*anbn1.y */
%token A B
%%
start:   anbn '\n' {printf("  is in anbn\n");
                    return 0;}
anbn:    A B
    |    A anbn B
    ;
%%
#include "lex.yy.c"
yyerror(char *s) { printf("%s, it is not in anbn\n", s); }
main() {
  return yyparse();
}
```

```
$./anbn
aabb
  is in anbn
$./anbn
acadbefbg
Syntax error, it is not in anbn
$
```

A grammar to accept L = {$a^n b^n$ | $n \geq 0$}.

```
/*anbn_0.y */
%token A B
%%
start:   anbn '\n' {printf("  is in anbn_0\n");
                    return 0;}
anbn:   empty
    |   A anbn B
    ;
empty: ;
%%
#include "lex.yy.c"
yyerror(char *s) { printf("%s, it is not in anbn_0\n", s); }
main() {
  return yyparse();
}
```

Positional assignment of values for items.

$$: left-hand side
$1: first item in the right-hand side
$*n*: *n*th item in the right-hand side

Example: Simple adder

```
/* add.l */
digit   [0-9]
%%
{digit}+ {sscanf(yytext, "%d", &yylval);
          return(INT);
         }
\+       return(PLUS);
\n       return(NL);
.        ;
%%
int yywrap() { return 1; }
```

```
/* add.y */
/* L = {INT PLUS INT NL} */
%token INT PLUS NL
%%
add: INT PLUS INT NL { printf("%d\n", $1 + $3);}
%%
#include "lex.yy.c"
yyerror(char *s) { printf("%s\n", s); }
main() {
  return yyparse();
}
```

```
$ ./add
003+05
8
```

Example: printing integers in a loop

```
/* print-int.l */
%%
[0-9]+    {sscanf(yytext, "%d", &yylval);
           return(INTEGER);
          }
\n        return(NEWLINE);
.         return(yytext[0]);
%%
int yywrap() { return 1; }
```

```
/* print-int.y */
%token INTEGER NEWLINE
%%
lines: /* empty */
     | lines NEWLINE
     | lines line NEWLINE {printf("=%d\n", $2);}
     | error NEWLINE {yyerror("Reenter:"); yyerrok;}
     ;
line:  INTEGER {$$ = $1;}
    ;
%%
#include "lex.yy.c"
yyerror(char *s) { printf("%s, it is not an integer\n", s); }
main() {
  return yyparse();
}
```

Execution:

```
$./print-int
7
=7
007
=7
zippy
syntax error
Reenter:
_
```

Although right-recursive rules can be used in yacc, left-recursive rules are preferred, and, in general, generate more efficient parsers.

The type of `yylval` is `int` by default. To change the type of `yylval` use macro `YYSTYPE` in the declarations section of a yacc specifications file.

```
%{
#define YYSTYPE double
%}
```

If there are more than one data types for token values, `yylval` is declared as a `union`.

Example with three possible types for yylval:

```
%union{
    double  real;    /* real value */
    int     integer; /* integer value */
    char    str[30]; /* string value */
}
```

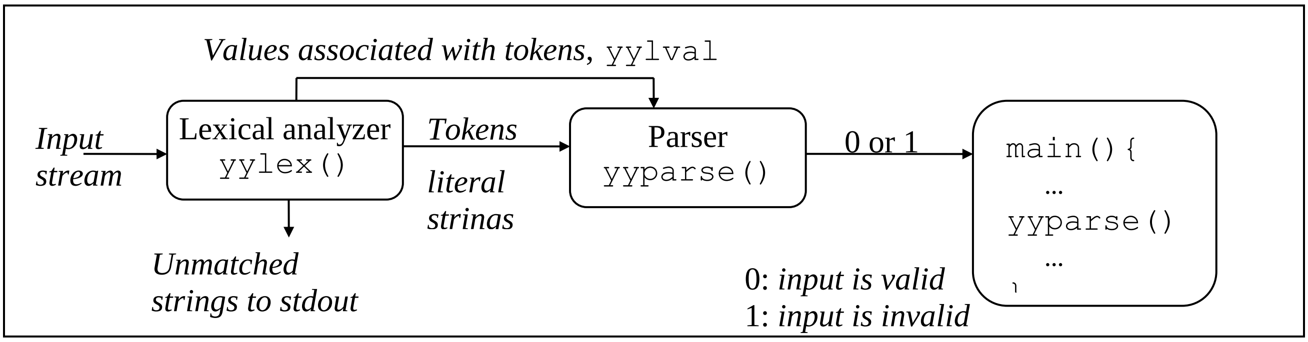
Example:

`yytext = "0012",` type of `yylval: int`, value of `yylval: 12`

`yytext = "+1.70",` type of `yylval: float`, value of `yylval: 1.7`

The type of associated values of tokens can be specified by `%token` as

```
%token <real> REAL
%token <integer> INTEGER
%token <str> IDENTIFIER STRING
```



Type of variables can be defined by `%type` as

```
%type <real> real-expr
%type <integer> integer-expr
```

To return values for tokens from a lexical analyzer:

```
/* types.l */
alphabetic    [A-Za-z]
digit         [0-9]
alphanumeric  ({alphabetic}|{digit})

[+-]?{digit}*(\.)?{digit}+      {sscanf(yytext, "%lf", &yylval.real);
                                 return REAL;
                                }
{alphabetic}{alphanumeric}*     {strcpy(yylval.str, yytext);
                                 return IDENTIFIER;
                                }
\<\-                            return ASSIGNOP;
\n                              return NL;
%%
int yywrap() { return 1; }
```

```
/* types.y */
%union{
  double  real;    /* real value */
  int     integer; /* integer value */
  char    str[30]; /* string value */
 }
%token <real> REAL
%token <str>  IDENTIFIER
%token ASSIGNOP NL
%type <real> assignment_stmt
%%
assignment_stmt: IDENTIFIER ASSIGNOP REAL NL {
                           $$ = $3;
                           printf("%s is assigned to %g\n", $1, $$);
                 }
%%
#include "lex.yy.c"
yyerror(char *s) { printf("%s, it is not an assignment!\n", s); }
main() {
  return yyparse();
}
```

```
[guvenir@dijkstra types]$ ./types
total <- 5.7
total is assigned to 5.7
^D
```

Example: yacc specification of a calculator is given the web page of the course.

Actions between rule elements:

```
/* lex specification */
%%
a return A;
b return B;
\n return NL;
. ;
%%
int yywrap() { return 1; }
```

```
/* yacc specification */
%{
#include <stdio.h>
%}
%token A B NL
%%
s: {printf("1");}
   a
   {printf("2");}
   b
   {printf("3");}
   NL
   {return 0;}
   ;
a: {printf("4");}
   A
   {printf("5");}
   ;
b: {printf("6");}
   B
   {printf("7");}
   ;
%%
#include "lex.yy.c"
int yyerror(char *s) {
  printf ("%s\n", s);
}
int main(void){ yyparse(); }
```

input: `ab`
output: `1452673`

input: `aa`
output: `14 syntax error`
`526`

input: `ba`
output: `14 syntax error`

Conflicts

Pointer model: A pointer moves (right) on the RHS of a rule while input tokens and variables are processed.

```
%token A B C
%%
start: A B C     /* after reading A: start: A B C */
```

When all elements on the right-hand side are processed (pointer reaches the end of a rule), the rule is ***reduced***.

If a rule reduces, the pointer then returns to the rule it was called.

Conflict: There is a *conflict* if a rule is reduced when there is more than one pointer. yacc looks one-token-ahead to see if the number of tokens reduces to one before declaring a conflict.

Example:

```
%token A B C D E F
%%
start: x | y;
x: A B C D;
y: A B E F;
```

After tokens A and B, either one of the tokens, or both will disappear. For example, if the next token is E, the first, if the next token is C the second token will disappear. If the next token is anything other than C or E both pointers will disappear. Therefore there is no conflict.

The other way for pointers to disappear is to merge in a common subrule.

Example:

```
%token A B C D E F
%%
start: x | y;
x: A B z D E;
y: A B z D F;
z: C;
```

Initially there are two pointers, one in, the other in y rules. After reading tokens A, and B, these two pointers shift. Then these two pointers merge in the z rule. The state after reading token C is shown below.

```
%token A B C D E F
%%
start: x | y ;
x: A B z D E ;
y: A B z D F ;
z: C ;
```

However, after reading A B C, the `z` rule reduces. There is only one pointer when `z` reduces. Then this pointer splits again into two pointers in `x` and `y` rules.

```
%token A B C D E F
%%
start: x | y ;
x: A B z D E ;
y: A B z D F ;
z: C;                              No conflicts
```

Conflict example:

```
%token A B
%%
start: x B | y B ;
x: A ;        reduce
y: A ;        reduce               reduce/reduce conflict on B.
```

After `A`, there are two pointers. Both rules (`x` and `y`) want to reduce at the same time. If the next token is `B`, there will be still two pointers. Such conflicts are called **reduce/reduce** conflict.

Note that yacc looks **one-token-ahead** before declaring any conflict.

```
%token A B C D E
%%
start: A x C D | A y C E ;
x: B ;
y: B ;                             reduce/reduce conflict on C.
```

The pointers in `x` and `y` rules will reduce on `C`, resulting on reduce/reduce conflict on `C`, although the grammar is not ambiguous. If yacc has looked two tokens ahead, it would have realized that only one pointer would remain on tokens `D` or `E`, and no pointer otherwise, so it would not declare any conflict.

Another type of conflict occurs when one rule reduces while the other shifts. Such conflicts are called **shift/reduce** conflicts.

Example:

```
%token A R
%%
start: x | y R;
x: A R ;      shift
y: A ;        reduce          shift/reduce conflict on R
```

After A, y rule reduces, x rule shifts. The next token for both cases is R.

Example:

```
%token A
%%
start: x | y;
x: A;         reduce
y: A;         reduce          reduce/reduce conflict on $end.
```

At the end of each string there is a $end token. Therefore, yacc declares reduce/reduce conflict on $end for the grammar above.

If the RHS of a rule start with an action, yacc inserts an empty variable and its rule into the grammar.

Example:

```
%token A B
%%
start: {printf("Starting…\n");} A A
     | A B;
empty: ;
```

Converted into the following

```
%token A B
%%
start: empty {printf("Starting…\n");} A A
     | A B;
empty: ;                      shift/reduce conflict on A
```

If the next token is A, the empty rule will reduce and second rule (of start) will shift. Therefore yacc declares shift/reduce conflict on A for this grammar.

Debugging:

```
$yacc -v filename.y
```

produces a file named y.output for debugging purposes.

Example:

```
%token A P
%%
s: x | y P;
x: A P; /* shifts on P */
y: A;    /* reduces on P */
```

The `y.output` file for the grammar above is shown below:

```
  0  $accept : s $end
```

`s: x` is called rule number 1

```
  1  s : x
  2    | y P
  3  x : A P
  4  y : A


state 0
        $accept : . s $end
        A  shift 1
        .  error
```

İf A is seen, shift the pointer, goto state 1

Otherwise call yyerror()

Each state corresponds to a unique combination of possible pointers in the yacc specifications file.

```
        s  goto 2
        x  goto 3
        y  goto 4
```

Shift and goto state 5

Reduce rule 4

Shift/reduce conflict on P

```
1: shift/reduce conflict (shift 5, reduce 4) on P
state 1
        x : A . P   (3)
        y : A .   (4)
```

If the next token is P, pointer in rule 3 will shift

If the next token is P, this rule (4) will reduce.

```
        P  shift 5
```

Default action: The sistem will choose to shift and goto state 5.

```
state 2
        $accept : s . $end  (0)
```

State2: input matched the start variable s, if this is the end of string, accpet it.

```
        $end  accept


state 3
        s : x .   (1)
```

State 3: rule (1) s: x is to reduce on any text token

Any character or token

```
        .  reduce 1
```

```
state 4                         State 4: pointer is in rule 2. After y rule is processed

        s : y . P  (2)          If the next token is P, shift the pointer, go to state 6

        P  shift 6              If the next token is anything else, call yyerror()
        .  error


state 5

        x : A P .  (3)


        .  reduce 3

state 6

        s : y P .  (2)


        .  reduce 2


Rules never reduced:

        y : A  (4)



State 1 contains 1 shift/reduce conflict.

   $end, A, P, .         $accept, s, x, y

4 terminals, 4 nonterminals

5 grammar rules, 7 states
```

Using the make utility on linux systems:
Contents of the file named `Makefile`:

```
parser: y.tab.c
    gcc -o parser y.tab.c
y.tab.c: parser.y lex.yy.c
    yacc parser.y
lex.yy.c: scanner.l
    lex scanner.l
```

Just type
`make`

It automatically determines which source files (in this example, `y.tab.c`, `parser.y`, `lex.yy.c`, `scanner.l`) of a program (`parser` in this example) need to be recompiled and/or linked