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Chapter 9

make: A Program for Maintaining Programs

9.1 Introduction

It is common practice to divide large programs into smaller, more manageable pieces. The pieces may require quite different treatments: some may need to be run through a macro processor, some may need to be processed by a sophisticated program generator such as yacc or lex. The outputs of these generators may then have to be compiled with special options and with certain definitions and declarations. The code resulting from these transformations may then need to be loaded together with certain libraries under the control of special options. Related maintenance activities involve running complicated test scripts and installing validated modules.

Unfortunately, it is very easy to forget which files depend on which others, which files have been modified recently, and the exact sequence of operations needed to make or exercise a new version of the program. After a long editing session, you may easily lose track of which files have been changed and which object modules are still valid, since a change to a declaration can render obsolete a dozen other files. Forgetting to compile a routine that you've changed or one that uses changed declarations result in a program that does not work, and a bug that can be very hard to track down. On the other hand, recompiling everything in sight just to be safe is very wasteful.

make is a program that mechanizes many of the activities of program development and maintenance. If the information on inter-file dependencies and command sequences is stored in a file, the simple command

```
$ make
```

is frequently sufficient to update the relevant files, regardless of the number that have been edited since the last "make". In most cases, the description file is easy to write and changes infrequently. It is usually easier to type the make command than to issue even one of the needed operations, so the typical cycle of program development operations becomes

think — edit — make — test . . .

make is most useful for medium-sized programming projects; it does not solve the problems of maintaining multiple source versions or of describing huge programs. This chapter is a guide for users of make.

> NOTE: The Domain Software Engineering Environment (DSEE) is an optional product that provides users with an integrated programming environment. Some of the features of make are similar to those of DSEE, although DSEE provides additional features as well. For more information about DSEE, see *Getting Started with the Domain Software Engineering Environment* (008788).

9.2 Basic Features

The basic operation of make is to update a target file by ensuring that all of the files on which it depends exist and are current, then creating the target if it has not been modified since its dependents were. make does a depth-first search of the graph of dependences. The operation of the command depends on the ability to find the date and time that a file was last modified.

To illustrate, let us consider a simple example. A program named prog is made by compiling and loading three C language files x.c, y.c, and z.c with the lS library. By convention, the output of the C compilations are found in files named x.o, y.o, and z.o. Assume that the files x.c and y.x share some declarations in a file named defs, but that z.c does not. That is, x.c and y.c have the line

```
#include "defs"
```

The following text describes the relationships and operations:

```
prog : x.o y.o z.o
        cc x.o y.o z.o -lS -o prog

x.o y.o : defs
```

If this information is stored in a file named makefile, the command

```
$ make
```

performs the operations needed to recreate prog after any changes had been made to any of the four source files x.c, y.c, z.c, or defs.

make operates by using three sources of information: a user-supplied description file (as above), filenames and "last-modified" times from the file system, and built-in rules to bridge some of the gaps.

In our example, the first line says that prog depends on three .o files. Once these object files are current, the second line describes how to load them to create prog. The third line says that x.o and y.o depend on the file defs.

From the file system, make discovers that there are three .c files corresponding to the needed .o files. It then uses built-in information about how to generate an object from a source file (i.e., issue a cc command with the -c option).

If make did not have the ability to determine automatically what needs to be done, this longer description file would be necessary:

```
prog : x.o y.o z.o
        cc x.o y.o z.o -lS -o prog

x.o : x.c defs
        cc -c x.c

y.o : y.c defs
        cc -c y.c

z.o : z.c
        cc -c z.c
```

If none of the source or object files had changed since the last time prog was made, all of the files would be current, and the command

```
$ make
```

simply announces this fact and stops. If, however, the defs file had been edited, x.c and y.c (but not z.c) are recompiled, and then prog is created from the new .o files. If only the file y.c had changed, only it is recompiled, but prog must still be reloaded.

If no target name is given on the make command line, the first target mentioned in the description is created; otherwise, the specified targets are made. The command

```
$ make x.o
```

recompiles x.o if x.c or defs had changed.

If the file exists after the commands are executed, its time of last modification is used in further decisions; otherwise, the current time is used. It is often useful for programs to include rules with mnemonic names and commands that don't actually produce a file with that name. These entries can take advantage of make's ability to generate files and substitute macros. Thus, an entry "save" might be included to copy a certain set of files, or an entry "cleanup" might be used to throw away unneeded intermediate files.

You can also maintain a zero-length file purely to keep track of the time at which certain actions were performed. This technique is useful for maintaining remote archives and listings.

make has a simple macro mechanism for substituting in dependency lines and command strings. Macros are defined by command arguments or description file lines with embedded equal signs. A macro is invoked by preceding the macro name with a dollar sign; macro names longer than one character must be enclosed in parentheses. The name of the macro is either the single character after the dollar sign or a name inside parentheses. The following are valid macro invocations:

```
$(CFLAGS)
$2
$(xy)
$Z
$(Z)
```

The last two invocations are identical.

> **NOTE:** To get a dollar sign, escape it with another dollar sign. The sequence $$ is escaped to $.

All of these macros are assigned values during input, as shown below. Four special macros change values during the execution of the command:

- $*
- $@
- $?
- $<

They are discussed later. The following fragment shows the use of some macros:

```
OBJECTS = x.o y.o z.o
LIBES = -lS
prog: $(OBJECTS)
        cc $(OBJECTS) $(LIBES) -o prog
```

The command

```
$ make
```

loads the three object files with the lS library. The command

```
$ make "LIBES= -ll -lS"
```

loads them with both the lex (-ll) and the standard (-lS) libraries, because macro definitions on the command line override definitions in the description. (The shell requires that you quote arguments that include embedded blanks.)

The following sections detail the form of description files and the command line, and discuss options and built-in rules in more detail.

9.3 Description Files and Substitutions

A description file contains three types of information:

- Macro definitions
- Dependency information
- Executable commands

A comment convention is also supplied: all characters after a pound sign (#) are ignored, as is the pound sign itself. Blank lines and lines beginning with this character are totally ignored. If a non-comment line is too long, it can be continued using a backslash. If the last character of a line is a backslash, the backslash, newline, and following blanks and tabs are replaced by a single blank.

A macro definition is an identifier followed by an equal sign (=); the identifier must not be preceded by a colon or a tab. The name (string of letters and digits) to the left of the equal sign (trailing blanks and tabs are stripped) is assigned the string of characters following the equal sign (leading blanks and tabs are stripped.) The following are valid macro definitions:

```
2 = xyz
abc = -ll -ly -lS
LIBES =
```

The last definition assigns LIBES the null string. A macro that is never explicitly defined has the null string as value. Macro definitions may also appear on the make command line.

The general form of an entry in a description file is:

target1 [*target2* . . .] :[:] [*dependent1* . . .] [; *commands*] [# . . .]
[(tab) *commands*] [# . . .]

Items inside brackets may be omitted. Targets and dependents are strings of letters, digits, periods, and slashes. (Shell metacharacters * and ? are expanded when the line is evaluated.) A command is any string of characters not including a pound sign (except when the pound sign is in quotes) or newline. Commands may appear either

- After a semicolon on a dependency line
- On lines beginning with a tab immediately following a dependency line

A dependency line may have either a single or a double colon. A target name may appear on more than one dependency line, but all of those lines must be of the same (single or double colon) type.

For the more common single-colon case, a command sequence may be associated with at most one of these dependency lines. If the target is out-of-date with any of the dependents on any of the lines, and a command sequence is specified (even a null one following a semicolon or tab), it is executed; otherwise, a default creation rule may be invoked.

In the double-colon case, a command sequence may be associated with each dependency line; if the target is out of date with any of the files on a particular line, the associated commands are executed. A built-in rule may also be executed. The double-colon form is particularly useful in updating archive-type files.

If a target must be created, the sequence of commands is executed. Normally, each command line is printed and then passed to a separate invocation of the shell after substituting for macros. (The printing is suppressed in silent mode or if the command line begins with an @ sign). make normally stops if any command signals an error by returning a non-zero error code. (Errors are ignored if the -i option is specified on the make command line, if the fake target name ".IGNORE" appears in the description file, or if the command string in the description file begins with a hyphen. Some Domain commands return meaningless status). Because each command line is passed to a separate invocation of the shell, care must be taken with certain commands (e.g., cd and shell control commands) that have meaning only within a single shell process; the results are forgotten before the next line is executed.

Before issuing any command, certain macros are set:

- $@ is set to the name of the file to be "made"
- $? is set to the string of names that were found to be younger than the target. If the command was generated by an implicit rule (see below)

- $< is the name of the related file that caused the action
- $* is the prefix shared by the current and the dependent filenames.

If a file must be made but there are no explicit commands or relevant built-in rules, the commands associated with the name ".DEFAULT" are used. If no such name exists, make prints a message and stops.

9.4 Using make

The make command takes four kinds of arguments: macro definitions, flags, description filenames, and target filenames. The prototypical make command line is:

```
$ make [ flags ] [ macro definitions ] [ targets ]
```

The following summary of the operation of the command explains how these arguments are interpreted.

First, all macro definition arguments (arguments with embedded equal signs) are analyzed and the assignments are made. Command-line macros override corresponding definitions found in the description files.

Next, the flag arguments are examined. The permissible flags are as follows:

-i	Ignore error codes returned by invoked commands. This mode is entered if the fake target name ".IGNORE" appears in the description file.
-s	Silent mode. Do not print command lines before executing. This mode is also entered if the fake target name ".SILENT" appears in the description file.
-r	Do not use the built-in rules.
-n	No execute mode. Print commands, but do not execute them. Even lines beginning with an at-sign (@) are printed.
-t	Touch the target files (causing them to be up-to-date) rather than issue the usual commands.
-q	Question. The make command returns a zero or non-zero status code depending on whether the target file is or is not up-to-date.
-p	Print out the complete set of macro definitions and target descriptions.
-d	Debug mode. Print out detailed information on files and times examined.
-f	Description filename. The next argument is assumed to be the name of a description file. A filename of "-" denotes the standard input. If no -f arguments appear, the file named makefile in the current directory is read.

NOTE: The contents of the description files override any built-in rules present.

Finally, the remaining arguments are assumed to be the names of targets to be made; they are done in left to right order. If there are no such arguments, the first name in the description files that does not begin with a period is "made".

9.4.1 Implicit Rules

make uses a table of suffixes and a set of transformation rules to supply default dependency information and implied commands. The default suffix list is as follows:

.o	Object file
.c	C source file
.e	Efl source file
.r	Ratfor source file
.f	FORTRAN source file
.s	Assembler source file
.y	Yacc-C source grammar
.yr	Yacc-Ratfor source grammar
.ye	Yacc-Efl source grammar
.l	Lex source grammar

The following diagram summarizes the default transformation paths. If there are two paths connecting a pair of suffixes, the longer one is used only if the intermediate file exists or is named in the description.

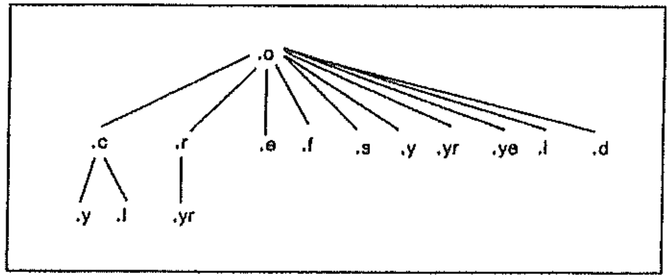


Figure 9-1. make Dependency Tree

If the file x.o is needed and there is an x.c in the description or directory, the x.o is compiled. If there is also an x.l, that grammar is run through lex before compiling the result. However, if there is no x.c but there is an x.l, then make discards the intermediate C-language file and uses the direct link shown in Figure 9-1.

It is possible to change the names of some of the compilers used in the default, or the flag arguments with which they are invoked by knowing the macro names used. The compiler names are the macros **AS**, **CC**, **RC**, **EC**, **YACC**, **YACCR**, **YACCE**, and **LEX**. The command

```
$ make CC=newcc
```

causes the newcc command to be used instead of the usual C compiler. The macros **CFLAGS**, **RFLAGS**, **EFLAGS**, **YFLAGS**, and **LFLAGS** may be set to cause these commands to be issued with optional flags. Thus,

```
$ make "CFLAGS=-O"
```

causes the optimizing C compiler to be used.

9.4.2 An Example

To illustrate the use of make, here's the description file used to maintain the make command itself. The code for make is spread over many C source files and a yacc grammar. The description file contains:

```
# Description file for the make command

P = und -3 | opr -r2 # send to GCOS to be printed
FILES = makefile version.c defs main.c doname.c misc.c files.c
dosys.cgram.y lex.c gcos.c
OBJECTS = version.o main.o doname.o misc.o files.o dosys.o gram.o
LIBES= -lS
LINT = lint -p
CFLAGS = -O

make: $(OBJECTS)
          cc $(CFLAGS) $(OBJECTS) $(LIBES) -o make
          size make

$(OBJECTS): defs
gram.o: lex.c

cleanup:
          -rm *.o gram.c
          -du
```

```
install:
        @size make /usr/bin/make
        cp make /usr/bin/make ; rm make

print: $(FILES)     # print recently changed files
        pr $? | $P
        touch print

test:
        make -dp | grep -v TIME >1zap
        /usr/bin/make -dp | grep -v TIME >2zap
        diff 1zap 2zap
        rm 1zap 2zap

lint : dosys.c doname.c files.c main.c misc.c version.c gram.c
        $(LINT) dosys.c doname.c files.c main.c misc.c version.c gram.c
        rm gram.c

arch:
        ar uv /sys/source/s2/make.a $(FILES)
```

make usually prints each command before issuing it. Typing make with no arguments in a directory containing only the source and description file outputs the following:

```
cc -c version.c
cc -c main.c
cc -c doname.c
cc -c misc.c
cc -c files.c
cc -c dosys.c
yacc gram.y
mv y.tab.c gram.c
cc -c gram.c
cc version.o main.o doname.o misc.o files.o dosys.o gram.o -lS -o make
13188+3348+3044 = 19580b = 046174b
```

Although none of the source files or grammars are mentioned by name in the description file, make found them using its suffix rules and issued the needed commands. The string of digits results from the "size make" command; the printing of the command line itself was suppressed by an @ sign. The @ sign on the size command in the description file suppressed the printing of the command, so only the sizes are written.

The last few entries in the description file are useful maintenance sequences. The "print" entry prints only the files that have been changed since the last "make print" command. A zero-length file **print** is maintained to keep track of the time of the printing; the $? macro in the command line then picks up only the names of the files changed since **print** was touched. The printed output can be sent to a different printer or to a file by changing the definition of the P macro:

```
$ make print "P = opr -sp"
```

or

```
$ make print "P= cat >zap"
```

9.5 Suggestions and Warnings

The most common difficulties arise from make's specific understanding of what constitutes a dependency. If file x.c has a `#include "defs"` line, then the object file x.o depends on *defs*; the source file x.c does not. (If defs is changed, it is not necessary to do anything to the file x.c, while it is necessary to recreate x.o.)

To discover what make would do, the -n option is very useful. The command

```
$ make -n
```

orders make to print out the commands it would issue without actually taking the time to execute them. If a change to a file is absolutely certain to be benign (e.g., adding a new definition to an include file), the -t (touch) option can save a lot of time, instead of issuing a large number of superfluous recompilations, make updates the modification times on the affected file. Thus, the command

```
$ make -ts
```

("touch silently") causes the relevant files to appear up-to-date. Be careful, though, because this mode of operation subverts the intention of make and destroys all memory of the previous relationships.

The -d (debugging) option causes make to print a very detailed description of its activities, including file times. The output is verbose, and recommended only as a last resort.

9.6 Summary of Suffixes and Rules

The make program itself does not know what file name suffixes are interesting or how to transform a file with one suffix into a file with another suffix. This information is stored in an internal table that has the form of a description file. If the -r option is used, this table is not used.

The list of suffixes is actually the dependency list for the name ".SUFFIXES"; make looks for a file with any of the suffixes on the list. If such a file exists, and if there is a transformation rule for that combination, make acts as described earlier. The transformation rule names are the concatenation of the two suffixes.

The name of the rule to transform a .r file to a .o file is thus r.o. If the rule is present and no explicit command sequence has been given in your description files, the command sequence for the rule r.o is used. If a command is generated by using one of these suffixing rules, the macro $* is given the value of the stem (everything but the suffix) of the name of the file to be made, and the macro $< is the name of the dependent that caused the action.

The order of the suffix list is significant, since it is scanned from left to right, and the first name that is formed that has both a file and a rule associated with it is used. If new names are to be appended, you can just add an entry for ".SUFFIXES" in its own description file; the dependents are added to the usual list. A ".SUFFIXES" line without any dependents deletes the current list. (It is necessary to clear the current list if the order of names is to be changed.)

The following is an excerpt from the default rules file:

```
.SUFFIXES: .o .c .e .r .f .y .yr .ye .l .s
YACC=yacc
YACCR=yacc -r
YACCE=yacc -e
YFLAGS=

LEX=lex
LFLAGS=
CC=cc
AS=as -
CFLAGS=
RC=ec
RFLAGS=
EC=ec
EFLAGS=
FFLAGS=

.c.o:
        $(CC) $(CFLAGS) -c $<
.e.o .r.o .f.o:
        $(EC) $(RFLAGS) $(EFLAGS) $(FFLAGS) -c $<
.s.o:
        $(AS) -o $@ $<
```

```
.y.o:
        $(YACC) $(YFLAGS) $<
        $(CC) $(CFLAGS) -c y.tab.c
        rm y.tab.c
        mv y.tab.o $@
.y.c:
        $(YACC) $(YFLAGS) $<
        mv y.tab.c $@
```

9.7 Extensions to make

NOTE: The following sections describe extensions to make that were added after the preceeding documentation was written.

While make is an excellent program administration tool, it had a number of limitations that hindered its use for large-scale software development:

- Handling of libraries was tedious.
- Handling of the Source Code Control System (SCCS) filename format was difficult or impossible.
- Environment variables were completely ignored.
- Ability to maintain files in a remote directory was inadequate.

The augmented version of make eliminates these problems. The additional features are within the original syntactic framework of make and few, if any, new syntactical entities are introduced. A notable exception is the include file capability.

9.8 Environment Variables

Environment variables are read and added to the macro definitions each time make executes. Precedence is a prime consideration in doing this properly. The following describes make's interaction with the environment. A new macro, MAKEFLAGS, is maintained by make and defined as the collection of all input flag arguments into a string (without minus signs). The new macro is exported and thus accessible to further invocations of make. Command line flags and assignments in the makefile update MAKEFLAGS. Thus, to describe how the environment interacts with make, consider the MAKEFLAGS macro (environment variable).

9

`lex` — a Lexical Analyzer Generator

`lex` is a program generator designed for lexical processing of character input streams. `lex` accepts a high-level, problem-oriented specification for character string matching, and produces a program in a general-purpose language which recognizes regular expressions. The regular expressions are specified by the programmer in the source specifications given to `lex`. The `lex` written code recognizes these expressions in an input stream and partitions the input stream into strings matching the expressions. At the boundaries between strings, program sections provided by the programmer are executed. The `lex` source file associates the regular expressions and the program fragments. As each expression appears in the input to the program written by `lex`, the corresponding fragment is executed.

The programmer supplies the additional code beyond expression matching needed to complete his tasks, possibly including code written by other generators. The program that recognizes the expressions is generated in the general-purpose programming language employed for the programmer's program fragments. Thus, a high-level expression language is provided to write the string expressions to be matched while the programmer's freedom to write actions is unimpaired. This avoids forcing the programmer who wishes to use a string manipulation language for input analysis to write processing programs in the same and often inappropriate string handling language.

`lex` source is a table of regular expressions and corresponding program fragments. The table is translated to a program which reads an input stream, copying it to an output stream and partitioning the input into strings which match the given expressions. As each such string is recognized the corresponding program fragment is executed. The recognition of the expressions is performed by a deterministic finite automaton generated by `lex`. The program fragments written by the programmer are executed in the order in which the corresponding regular expressions occur in the input stream.

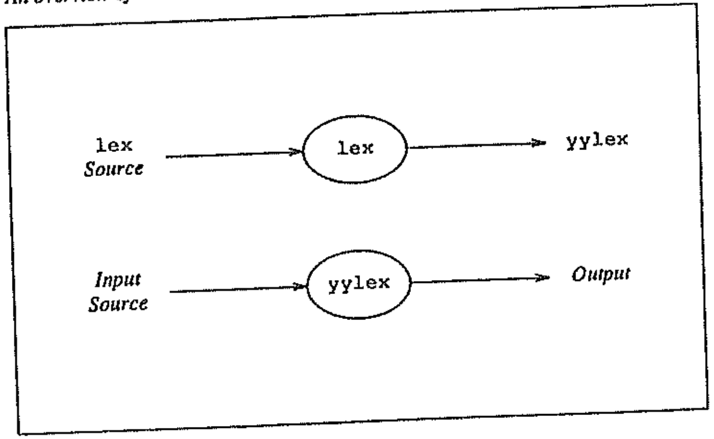
The lexical analysis programs written with `lex` accept ambiguous specifications and choose the longest match possible at each input point. If necessary, substantial lookahead is performed on the input, but the input stream is then backed up to the end of the current partition, so that the programmer has general freedom to manipulate it.

`lex` is designed to simplify interfacing with `yacc`, which is described in the next chapter.

`lex` is not a complete language, but rather a generator representing a new language feature which can be added to different programming languages, called 'host languages.' Just as general-purpose languages can produce code to run on different computer hardware, `lex` can write code in different host languages. The host language is used for the output code generated by `lex` and also for the program fragments added by the programmer. Compatible run-time libraries for the different host languages are also provided. This makes `lex` adaptable to different environments and different programmer. Each application may be directed to the combination of hardware and host language appropriate to the task, the programmer's background, and the properties of local implementations.

`lex` turns the programmer's expressions and actions (called `source` in this document) into the host general-purpose language; the generated program is named `yylex`. The `yylex` program recognizes expressions in a stream (called `input` in this document) and performs the specified actions for each expression as it is detected — see Figure 9-1 below.

Figure 9-1 *An overview of* `lex`



For a trivial example, consider a program to delete from the input all blanks or tabs at the ends of lines(followed by newlines.

```
%%
[ \t]+$ ;
```

is all that is required. The program contains a %% delimiter to mark the beginning of the rules, and one rule. This rule contains a regular expression which matches one or more instances of the characters blank or tab (written \t for visibility, in accordance with the C convention) just prior to the end of a line. The brackets indicate the character class made of blank and tab; the + indicates 'one or more ...'; and the $ indicates 'end-of-line'.* No action is specified, so the program generated by `lex` (`yylex`) ignores these characters. Everything else is copied to the output stream. To change any remaining string of blanks or tabs to a single blank, add another rule:

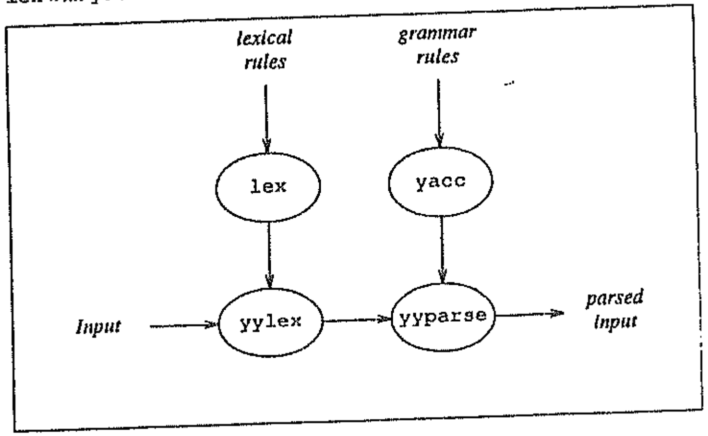
```
%%
[ \t]+$ ;
[ \t]+  printf(" ");
```

The finite automaton generated for this source scans for both rules at once, observing at the termination of the string of blanks or tabs whether or not there is a newline character, and executing the desired rule action. The first rule matches all strings of blanks or tabs at the ends of lines, and the second rule all remaining strings of blanks or tabs.

`lex` can also be used with a parser generator to perform the lexical analysis phase.

`lex` can be used alone for simple transformations, or for analysis and statistics gathering on a lexical level. `lex` can also be used with a parser generator to perform the lexical analysis phase; it is particularly easy to interface `lex` and `yacc`. `lex` programs recognize only regular expressions; `yacc` writes parsers that accept a large class of context-free grammars, but require a lower-level analyzer to recognize input tokens. Thus, a combination of `lex` and `yacc` is often appropriate. When used as a preprocessor for a later parser generator, `lex` is used to partition the input stream, and the parser generator assigns structure to the resulting pieces. The flow of control in such a case (which might be the first half of a compiler, for example) is shown in Figure 9-2. Additional programs, written by other generators or by hand, can be added easily to programs written by `lex`.

Figure 9-2 `lex` *with* `yacc`



`yacc` programmers will realize that the name `yylex` is what `yacc` expects its lexical analyzer to be named, so that the use of this name by `lex` simplifies interfacing.

---

* followed by newlines

`lex` generates a deterministic finite automaton from the regular expressions in the source. The automaton is interpreted, rather than compiled, in order to save space. The result is still a fast analyzer. In particular, the time taken by a `lex` program to recognize and partition an input stream is proportional to the length of the input. The number of `lex` rules or the complexity of the rules is not important in determining speed, unless rules which include forward context require a significant amount of rescanning. What does increase with the number and complexity of rules is the size of the finite automaton, and therefore the size of the program generated by `lex`.

In the program written by `lex`, the programmer's fragments (representing the *actions* to be performed as each regular expression is found) are gathered as cases of a switch. The automaton interpreter directs the control flow. Opportunity is provided for the programmer to insert either declarations or additional statements in the routine containing the actions, or to add subroutines outside this action routine.

`lex` is not limited to source which can be interpreted on the basis of one character lookahead. For example, if there are two rules, one looking for `ab` and another for `abcdefg`, and the input stream is `abcdefh`, `lex` recognizes `ab` and leave the input pointer just before `"cd..."` Such backup is more costly than processing simpler languages.

9.1. `lex` Source

The general format of `lex` source is:

```
{definitions }
%%
{rules}
%%
{programmer subroutines }
```

where the definitions and the programmer subroutines are often omitted. The second `%%` is optional, but the first is required to mark the beginning of the rules. The absolute minimum `lex` program is thus

```
%%
```

(no definitions, no rules) which translates into a program which copies the input to the output unchanged.

In the outline of `lex` programs shown above, the *rules* represent the programmer's control decisions; they are a table, in which the left column contains *regular expressions* (see section 9.2) and the right column contains *actions*, program fragments to be executed when the expressions

```
integer printf("found keyword INT");
```

to look for the string `integer` in the input stream and print the message 'found keyword INT' whenever it appears. In this example the host procedural language is C and the C library function `printf()` is used to print the string. The end of the expression is indicated by the first blank or tab character. If the action is merely a single C expression, it can just be given on the right side of the line; if it is compound, or takes more than a line, it should be enclosed in braces. As a slightly more useful example, suppose it is desired to change a number of words from British to American spelling. `lex` rules such as

```
colour  printf("color");
mechanise       printf("mechanize");
petrol  printf("gas");
```

would be a start. These rules are not quite enough, since the word `petroleum` would become `gaseum`; a way of dealing with this is described later.

9.2. `lex` Regular Expressions

The definitions of regular expressions are very similar to those in the editors *ex*(1) and *vi*(1). A regular expression specifies a set of strings to be matched. It contains text characters (which match the corresponding characters in the strings being compared) and operator characters (which specify repetitions, choices, and other features). The letters of the alphabet and the digits are always text characters; thus the regular expression

```
integer
```

matches the string `integer` wherever it appears and the expression

```
a57D
```

looks for the string `a57D`.

Operators

The operator characters are

```
" \ [ ] ^ - ? . * + | ( ) $ / { } % < >
```

and if they are to be used as text characters, an escape must be used. The quotation mark operator (") indicates that whatever is contained between a pair of quotes is to be taken as text characters. Thus

```
xyz"++"
```

matches the string `xyz++` when it appears. Note that a part of a string may be quoted. It is harmless but unnecessary to quote an ordinary text character; the expression

```
"xyz++"
```

is the same as the one above. Thus by quoting every non-alphanumeric character being used as a text character, the programmer can avoid remembering the list above of current operator characters, and is safe should further extensions to `lex` lengthen the list.

An operator character may also be turned into a text character by preceding it with `\` as in

```
xyz\+\+
```

which is another, less readable, equivalent of the above expressions. Another use of the quoting mechanism is to get a blank into an expression; normally, as explained above, blanks or tabs end a rule. Any blank character not contained within [ ] (see below) must be quoted. Several normal C escapes with `\` are recognized: `\n` is newline, `\t` is tab, and `\b` is backspace. To enter `\` itself, use `\\`. Since newline is illegal in an expression, `\n` must be used; it is not required to escape tab and backspace. Every character but blank, tab, newline and the list above is always a text character.

Character Classes

Classes of characters can be specified using the operator pair [ ]. The construction `[abc]` matches a single character, which may be a, b, or c. Within square brackets, most operator meanings are ignored. Only three characters are special: `\`, `-`, and `^`. The `-` character indicates ranges. For example,

```
[a-z0-9<>_]
```

indicates the character class containing all the lower case letters, the digits, the angle brackets, and underline. Ranges may be given in either order. Using `-` between any pair of characters which are not both upper case letters, both lower case letters, or both digits is implementation-dependent and generates a warning message. For example, `[0-z]` in ASCII is many more characters than it is in EBCDIC. If it is desired to include the character `-` in a character class, it should be first or last, thus:

```
[-+0-9]
```

matches all the digits and the two signs.

In character classes, the `^` operator must appear as the first character after the left bracket; it indicates that the resulting string is to be complemented with respect to the system's character set. Thus

```
[^abc]
```

matches all characters except a, b, or c, including all special or control characters; and

```
[^a-zA-Z]
```

is any character which is not a letter. The `\` character provides the usual escapes within character class brackets.

Arbitrary Character

To match almost any character, the operator character

```
.
```

(period) is the class of all characters except newline. Escaping into octal is possible although non-portable:

```
[\40-\176]
```

matches all printable characters in the ASCII character set, from octal 40 (blank) to octal 176 (tilde).

Optional Expressions

The operator `?` indicates an optional element of an expression. Thus

```
ab?c
```

matches either `ac` or `abc`.

Repeated Expressions

Repetitions of classes are indicated by the operators `*` and `+`.

```
a*
```

is any number of consecutive a characters, including zero; while

```
a+
```

is one or more instances of a. For example,

```
[a-z]+
```

is all strings of lower case letters. And

```
[A-Za-z][A-Za-z0-9]*
```

indicates all alphanumeric strings with a leading alphabetic character. This is a typical expression for recognizing identifiers in computer languages.

Alternation and Grouping

The operator `|` indicates alternation:

```
(ab | cd)
```

matches either `ab` or `cd`. Note that parentheses are used for grouping, although they are not necessary on the outside level;

```
ab | cd
```

would have sufficed. Parentheses can be used for more complex expressions:

```
(ab | cd+)?(ef)*
```

matches such strings as `abefef`, `efefef`, `cdef`, or `cddd`; but not `abc`, `abcd`, or `abcdef`.

Context Sensitivity

`lex` recognizes a small amount of surrounding context. The two simplest operators for this are `^` and `$`. If the first character of an expression is `^`, the expression is only be matched at the beginning of a line This can never conflict with the other meaning of `^`, complementation of character classes, since that only applies within the `[ ]` operators. If the very last character is `$`, the expression is only be matched at the end of a line (when immediately followed by newline).

The latter operator is a special case of the / operator character, which indicates trailing context. The expression

```
ab/cd
```

matches the string `ab`, but only if it is followed by `cd`. Thus

```
ab$
```

is the same as

```
ab/\n.
```

Left context is handled in `lex` by *start conditions* as explained in section 9.9 — *Left Context-Sensitivity*. If a rule is only to be executed when the `lex` automaton interpreter is in start condition `x`, the rule should be prefixed by

```
<x>
```

using the angle bracket operator characters. If we considered 'being at the beginning of a line' to be start condition `ONE`, then the ^ operator would be equivalent to

```
<ONE>.
```

Start conditions are explained more fully below.

Repetitions and Definitions

The operators { } specify either repetitions (if they enclose numbers) or definition expansion (if they enclose a name). For example

```
{digit}
```

looks for a predefined string named `digit` and inserts it at that point in the expression. The definitions are given in the first part of the `lex` input, before the rules. In contrast,

```
a{1,5}
```

looks for 1 to 5 occurrences of a.

Finally, initial `%` is special, being the separator for `lex` source segments.

9.3. `lex` Actions

When an expression written as above is matched, `lex` executes the corresponding action. This section describes some features of `lex` which aid in writing actions. Note that there is a default action, which consists of copying the input to the output. This is performed on all strings not otherwise matched. Thus the `lex` programmer who wishes to absorb the entire input, without producing any output, must provide rules to match everything. When `lex` is being used with `yacc`, this is the normal situation. One may consider that actions are what is done instead of copying the input to the output; thus, in general, a rule which merely copies can be omitted. Also, a character combination which is omitted from the rules and which appears as input is likely to be printed on the output, thus calling attention to the gap in the rules.

One of the simplest things that can be done is to ignore the input. Specifying a C null statement, `;` as an action does this. A frequent rule is

```
[ \t\n] ;
```

which ignores the three spacing characters (blank, tab, and newline).

Another easy way to avoid writing actions is the action character |, which indicates that the action to be used for this rule is the action given for the next rule. The previous example could also have been written

```
" "             |
"\t"            |
"\n"            ;
```

with the same result. The quotes around \n and \t are not required.

Actual Text that Matched

In more complex actions, the programmer often wants to know the actual text that matched some expression like `[a-z]+`. `lex` leaves this text in an external character array named `yytext`.
Thus, to print the name found, a rule like

```
[a-z]+ printf("%s", yytext);
```

prints the string in `yytext`. The C function `printf` accepts a format argument and data to be printed; in this case, the format is 'print string' (% indicating data conversion, and `s` indicating string type), and the data are the characters in `yytext`. So this just places the matched string on the output. This action is so common that it may be written as ECHO:

```
[a-z]+ ECHO;
```

is the same as the above. Since the default action is just to print the characters found, one might ask why give a rule, like this one, which merely specifies the default action? Such rules are often required to avoid matching some other rule which is not desired. For example, if there is a rule which matches `read()` it normally matches the instances of `read` contained in `bread` or `readjust`; to avoid this, a rule of the form `[a-z]+` is needed. This is explained further below.

Length of Matched Text

Sometimes it is more convenient to know the end of what has been found; hence `lex` also provides a count `yyleng` of the number of characters matched. To count both the number of words and the number of characters in words in the input, the programmer might write

```
[a-zA-Z]+      {words++; chars += yyleng;}
```

which accumulates in `chars` the number of characters in the words recognized. The last character in the string matched can be accessed by

```
yytext[yyleng-1].
```

`yymore` *and* `yyless`

Occasionally, a `lex` action may decide that a rule has not recognized the correct span of characters. Two routines are provided to aid with this situation. First, `yymore()` can be called to indicate that the next input expression recognized is to be tacked on to the end of this input. Normally, the next input string would overwrite the current entry in `yytext`. Second, `yyless(n)` may be called to indicate that not all the characters matched by the currently successful expression are wanted right now. The argument n indicates the number of characters to be retained in `yytext`. Further characters previously matched are returned to the input. This provides the same sort of lookahead offered by the / operator, but in a different form.

Example: Consider a language which defines a string as a set of characters between quotation (") marks, and provides that to include a " in a string it must be preceded by a \. The regular expression which matches that is somewhat confusing, so that it might be preferable to write:

```
\"[^"]*  {
         if (yytext[yyleng-1] == '\\')
              yymore();
         else
              ... normal programmer processing
         }
```

which, when faced with a string such as `"abc\"def"` first matches the five characters `"abc\`; then the call to `yymore()` tacks the next part of the string, `"def`, onto the end. Note that the final quote terminating the string should be picked up in the code labeled 'normal processing'.

The function `yyless()` might be used to reprocess text in various circumstances. Consider the problem of resolving (in old-style C) the ambiguity of '=-a'. Suppose it is desired to treat this as '=- a' but print a message. A rule might be

```
=-[a-zA-Z]        {
        printf("Operator (=-) ambiguous\n");
        yyless(yyleng-1);
        ... action for =- ...
        }
```

which prints a message, returns the letter after the operator to the input stream, and treats the operator as '=-'. Alternatively it might be desired to treat this as '= -a'. To do this, just return the minus sign as well as the letter to the input:

```
=-[a-zA-Z]        {
        printf("Operator (=-) ambiguous\n");
        yyless(yyleng-2);
        ... action for = ...
        }
```

performs the other interpretation. Note that the expressions for the two cases might more easily be written:

```
=-/[A-Za-z]
```

in the first case and

```
=/-[A-Za-z]
```

in the second; no backup would be required in the rule action. It is not necessary to recognize the whole identifier to observe the ambiguity. The possibility of '=-3', however, makes

```
=-/[^ \t\n]
```

a still better rule.

In addition to these routines, `lex` also permits access to the I/O routines it uses. They are:

1. `input()` which returns the next input character;
2. `output(c)` which writes the character c on the output; and
3. `unput(c)` pushes the character c back onto the input stream to be read later by `input()`.

By default these routines are provided as macro definitions, but the programmer can override them and supply private versions. These routines define the relationship between external files and internal characters, and must all be retained or modified consistently. They may be redefined, to transmit input or output to or from strange places, including other programs or internal memory; but the character set used must be consistent in all routines; a value of zero returned by `input` must mean end of file; and the relationship between `unput` and `input` must be retained or the `lex` lookahead will not work. `lex` does not look ahead at all if it does not have to, but every rule ending in + * ? or $ or containing / implies lookahead. Lookahead is also necessary to match an expression that is a prefix of another expression. See section 9.10 for a discussion of the character set used by `lex`. The standard `lex` library imposes a 100-character limit on backup.

Another `lex` library routine that the programmer will sometimes want to redefine is `yywrap()` which is called whenever `lex` reaches an end-of-file. If `yywrap` returns a 1, `lex` continues with the normal wrapup on end of input. Sometimes, however, it is convenient to arrange for more input to arrive from a new source. In this case, the programmer should provide a `yywrap` which arranges for new input and returns 0. This instructs `lex` to continue processing. The default `yywrap` always returns 1.

This routine is also a convenient place to print tables, summaries, etc. at the end of a program. Note that it is not possible to write a normal rule which recognizes end-of-file; the only access to this condition is through `yywrap`. In fact, unless a private version of `input()` is supplied a file containing nulls cannot be handled, since a value of 0 returned by `input` is taken to be end-of-file.

9.4. Ambiguous Source Rules

`lex` can handle ambiguous specifications. When more than one expression can match the current input, `lex` chooses as follows:

1. The longest match is preferred.
2. Among rules which matched the same number of characters, the rule given first is preferred.

Thus, suppose the rules

```
integer keyword action ... ;
[a-z]+  identifier action ... ;
```

to be given in that order. If the input is `integers`, it is taken as an identifier, because `[a-z]+` matches 8 characters, while `integer` matches only 7. If the input is `integer`, both rules match 7 characters, and the keyword rule is selected because it was given *first*. Anything shorter (for example, `int`) will not match the expression `integer`, and so the identifier interpretation is used.

The principle of preferring the longest match makes rules containing expressions like `.*` dangerous. For example,

```
'.*'
```

might seem a good way of recognizing a string in single quotes. But it is an invitation for the program to read far ahead, looking for a distant single quote. Presented with the input

```
'first' quoted string here, 'second' here
```

the above expression matches

```
'first' quoted string here, 'second'
```

which is probably not what was wanted. A better rule is of the form

```
'[^'\n]*'
```

which, on the above input, stops after `'first'`. The consequences of errors like this are mitigated by the fact that the `.` operator does not match newline. Thus expressions like `.*` stop on the current line. Don't try to defeat this with expressions like `[.\n]+` or equivalents; the `lex` generated program will try to read the entire input file, causing internal buffer overflows.

Note that `lex` is normally partitioning the input stream, not searching for all possible matches of each expression. This means that each character is accounted for once and only once. For example, suppose it is desired to count occurrences of both `she` and `he` in an input text. Some `lex` rules to do this might be

```
she     s++;
he      h++;
\n      |
.       ;
```

where the last two rules ignore everything besides `he` and `she`. Remember that '.' does not include newline. Since `she` includes `he`, `lex` will normally not recognize the instances of `he` included in `she`, since once it has passed a `she` those characters are gone.

Sometimes the programmer would like to override this choice. The action `REJECT` means 'go do the next alternative.' It executes whatever rule was second choice after the current rule. The position of the input pointer is adjusted accordingly. Suppose the programmer really wants to count the included instances of `he`:

```
she     {s++; REJECT;}
he      {h++; REJECT;}
\n      |
.       ;
```

these rules are one way of changing the previous example to do just that. After counting each expression, it is rejected; whenever appropriate, the other expression is then counted. In this example, of course, the programmer could note that `she` includes `he` but not vice versa, and omit the `REJECT` action on `he`; in other cases, however, it would not be possible *a priori* to tell which input characters were in both classes.

Consider the two rules

```
a[bc]+   { ... ; REJECT;}
a[cd]+   { ... ; REJECT;}
```

If the input is `ab`, only the first rule matches, and on `ad` only the second matches. The input string `accb` matches the first rule for four characters and then the second rule for three characters. In contrast, the input `accd` agrees with the second rule for four characters and the first rule for three.

In general, `REJECT` is useful whenever the purpose of `lex` is not to partition the input stream but to detect all examples of some items in the input, and the instances of these items may overlap or include each other. Suppose a digram table of the input is desired; normally the digrams overlap, that is the word `the` is considered to contain both `th` and `he`. Assuming a two-dimensional array named `digram` to be incremented, the appropriate source is shown below.

```
%%
[a-z][a-z]   {digram[yytext[0]][yytext[1]]++; REJECT;}
.           ;
\n          ;
```

where the `REJECT` is necessary to pick up a letter pair beginning at every character, rather than at every other character.

9.5. `lex` Source Definitions

Remember the format of the `lex` source:

```
{definitions}
%%
{rules}
%%
{programmer routines}
```

So far only the rules have been described. The programmer needs additional options, though, to define variables for use in his program and for use by `lex`. These can go either in the definitions section or in the rules section.

Remember that `lex` is turning the rules into a program. Any source not intercepted by `lex` is copied into the generated program. There are three classes of such things.

1. Any line which is not part of a `lex` rule or action which begins with a blank or tab is copied into the `lex`-generated program. Such source input prior to the first %% delimiter is external to any function in the code; if it appears immediately after the first %%, it appears in an appropriate place for declarations in the function written by `lex` which contains the actions. This material must look like program fragments, and should precede the first `lex` rule.

   As a side effect of the above, lines which begin with a blank or tab, and which contain a comment, are passed through to the generated program. This can be used to include comments in either the `lex` source or the generated code. The comments should follow the host language convention.

2. Anything included between lines containing only the delimiters `%{` and `%}` is copied out as above. The delimiters are discarded. This format permits entering text like preprocessor statements that must begin in column 1, or copying lines that do not look like programs.

3. Anything after the third %% delimiter, regardless of formats, etc., is copied out after the `lex` output.

Definitions intended for `lex` are given before the first %% delimiter. Any line in this section not contained between %{ and %}, and beginning in column 1, is assumed to define `lex` substitution strings. The format of such lines is

```
name translation
```

and it associates the string given as a translation with the name. The name and translation must be separated by at least one blank or tab, and the name must begin with a letter. The translation can then be invoked by the {name} syntax in a rule. Using {D} for the digits and {E} for an exponent field, for example, might abbreviate rules to recognize numbers:

```
D        [0-9]
E        [DEde][-+]?{D}+
%%
{D}+    printf("integer");
{D}+"."{D}*({E})?          |
{D}*"."{D}+({E})?          |
{D}+{E}            printf("real");
```

Note the first two rules for real numbers; both require a decimal point and contain an optional exponent field, but the first requires at least one digit before the decimal point and the second requires at least one digit after the decimal point. To correctly handle the problem posed by a FORTRAN expression such as `35.EQ.I`, which does not contain a real number, a context-sensitive rule such as

```
[0-9]+/"."EQ    printf("integer");
```

could be used in addition to the normal rule for integers.

The definitions section may also contain other commands, including the selection of a host language, a character set table, a list of start conditions, or adjustments to the default size of arrays within `lex` itself for larger source programs. These possibilities are discussed below under section 9.11 — *Summary of Source Format.*

9.6. Using `lex`

There are two steps in compiling a `lex` source program. First, the `lex` source must be turned into a generated program in the host general-purpose language. Then this program must be compiled and loaded, usually with a library of `lex` subroutines. The generated program is on a file named `lex.yy.c`. The I/O library is defined in terms of the C standard library in section 3 of the *SunOS Reference Manual.*

The `lex` library is accessed by the loader flag `-ll`.
So an appropriate set of commands is:

```
tutorial% lex source
tutorial% cc lex.yy.c -ll
```

The resulting program is placed on the usual file `a.out` for later execution. To use `lex` with `yacc` see below. Although the default `lex` I/O routines use the C standard library, the `lex` automata themselves do not do so; if private versions of `input`, `output`, and `unput` are given, the library can be avoided. `lex` has several options which are described in the `lex`(1) manual page.

9.7. `lex` and `yacc`

If you want to use `lex` with `yacc`, note that what `lex` writes is a program named `yylex()`, the name required by `yacc` for its analyzer. Normally, the default main program in the `lex` library calls this routine, but if `yacc` is loaded, and its main program is used, `yacc` calls `yylex()`.

In this case each `lex` rule should end with

```
return(token);
```

to return the appropriate token value.

An easy way to get access to `yacc`'s names for tokens is to compile the `lex` output file as part of the `yacc` output file by placing the line

```
# include "lex.yy.c"
```

in the last section of `yacc` input. Supposing the grammar to be named 'good' and the lexical rules to be named 'better' the command sequence can just be:

```
tutorial% yacc good
tutorial% lex better
tutorial% cc y.tab.c -ll
tutorial%
```

The `lex` and `yacc` programs can be generated in either order.

9.8. Examples

As a trivial problem, consider copying an input file while adding 3 to every non-negative number divisible by 7. Here is a suitable `lex` source program

```
%%
        int k;
[0-9]+  {
        k = atoi(yytext);
        if (k%7 == 0)
             printf("%d", k+3);
        else
             printf("%d",k);
        }
```

to do just that. The rule `[0-9]+` recognizes strings of digits; `atoi()` converts the digits to binary and stores the result in k. The operator `%` (remainder) is used to check whether k is divisible by 7; if it is, it is incremented by 3 as it is written out. It may be objected that this program will alter such input items as `49.63` or `X7`. Furthermore, it increments the absolute value of all negative numbers divisible by 7. To avoid this, just add a few more rules after the active one, as shown below.

```
%%
        int k;
-?[0-9]+{
        k = atoi(yytext);
        printf("%d", k%7 == 0 ? k+3 : k);
        }
-?[0-9.]+       ECHO;
[A-Za-z][A-Za-z0-9]+    ECHO;
```

Numerical strings containing a '.' or preceded by a letter are picked up by one of the last two rules, and not changed. The `if-else` has been replaced by a C conditional expression to save space; the form `a?b:c` means 'if a then b else c'.

For an example of statistics gathering, here is a program which constructs a histogram of the lengths of words, where a word is defined as a string of letters.

```
        int lengs[100];
%%
[a-z]+  lengs[yyleng]++;
.       |
\n      ;
%%
1 s.
yywrap()
{
int i;
printf("Length  No. words\n");
for(i=0; i<100; i++)
     if (lengs[i] > 0)
          printf("%5d%10d\n",i,lengs[i]);
return(1);
}
```

This program accumulates the histogram, while producing no output. At the end of the input it prints the table. The final statement `return(1);` indicates that `lex` is to perform wrapup. If `yywrap` returns zero (false) it implies that further input is available and the program is to continue reading and processing. To provide a `yywrap` that never returns true causes an infinite loop.

As a larger example, here are some parts of a program written by N. L. Schryer to convert double-precision FORTRAN to single-precision FORTRAN. Because FORTRAN does not distinguish upper and lower case letters, this routine begins by defining a set of classes including both cases of each letter:

```
a       [aA]
b       [bB]
c       [cC]
...
z       [zZ]
```

An additional class recognizes white space:

```
W       [ \t]*
```

The first rule changes `double precision` to `real`, or `DOUBLE PRECISION` to `REAL`.

```
{d}{o}{u}{b}{l}{e}{W}{p}{r}{e}{c}{i}{s}{i}{o}{n} {
     printf(yytext[0]=='d'? "real" : "REAL");
     }
```

Care is taken throughout this program to preserve the case (upper or lower) of the original program. The conditional operator is used to select the proper form of the keyword. The next rule copies continuation card indications to avoid confusing them with constants:

```
^"      "[^ 0]    ECHO;
```

In the regular expression, the quotes surround the blanks. It is interpreted as 'beginning of line, then five blanks, then anything but blank or zero.' Note the two different meanings of `^`. There follow some rules to change double-precision constants to ordinary floating constants.

```
[0-9]+{W}{d}{W}[+-]?{W}[0-9]+      |
[0-9]+{W}"."{W}{d}{W}[+-]?{W}[0-9]+      |
"."{W}[0-9]+{W}{d}{W}[+-]?{W}[0-9]+      {
     /* convert constants */
     for(p=yytext; *p != 0; p++)
          {
          if (*p == 'd' || *p == 'D')
               *p=+ 'e'- 'd';
          ECHO;
          }
```

After the floating point constant is recognized, it is scanned by the `for` loop to find the letter `d` or `D`. The program then adds `'e'-'d'`, which converts it to the next letter of the alphabet. The modified constant, now single-precision, is written out again. There follow a series of names which must be respelled to remove their initial `d`. By using the array `yytext` the same action suffices for all the names (only a sample of a rather long list is given here).

```
{d}{s}{i}{n}      |
{d}{c}{o}{s}      |
{d}{s}{q}{r}{t}   |
{d}{a}{t}{a}{n}   |
...
{d}{f}{l}{o}{a}{t}       printf("%s",yytext+1);
```

Another list of names must have initial `d` changed to initial `a`:

```
{d}{l}{o}{g}      |
{d}{l}{o}{g}10    |
{d}{m}{i}{n}1     |
{d}{m}{a}{x}1     {
          yytext[0] =+ 'a' - 'd';
          ECHO;
          }
```

And one routine must have initial `d` changed to initial `r`:

```
{d}1{m}{a}{c}{h}          {yytext[0] =+ 'r'  - 'd';
                    ECHO;
                    }
```

To avoid such names as `dsinx` being detected as instances of `dsin`, some final rules pick up longer words as identifiers and copy some surviving characters:

```
[A-Za-z][A-Za-z0-9]*      |
[0-9]+    |
\n        |
.         ECHO;
```

Note that this program is not complete; it does not deal with the spacing problems in FORTRAN or with the use of keywords as identifiers.

9.9. Left Context-Sensitivity

Sometimes it is desirable to have several sets of lexical rules to be applied at different times in the input. For example, a compiler preprocessor might distinguish preprocessor statements and analyze them differently from ordinary statements. This requires sensitivity to prior context, and there are several ways of handling such problems. The `^` operator, for example, is a prior context operator, recognizing immediately preceding left context just as `$` recognizes immediately following right context. Adjacent left context could be extended, to produce a facility similar to that for adjacent right context, but it is unlikely to be as useful, since often the relevant left context appeared some time earlier, such as at the beginning of a line.

This section describes three means of dealing with different environments: a simple use of flags, when only a few rules change from one environment to another, the use of *start conditions* on rules, and the possibility of making multiple lexical analyzers all run together. In each case, there are rules which recognize the need to change the environment in which the following input text is analyzed, and set some parameter to reflect the change. This may be a flag explicitly tested by the programmer's action code; such a flag is the simplest way of dealing with the problem, since `lex` is not involved at all. It may be more convenient, however, to have `lex` remember the flags as initial conditions on the rules. Any rule may be associated with a start condition. It is only be recognized when `lex` is in that start condition. The current start condition may be changed at any time. Finally, if the sets of rules for the different environments are very dissimilar, clarity may be best achieved by writing several distinct lexical analyzers, and switching from one to another as desired.

Consider the following problem: copy the input to the output, changing the word `magic` to `first` on every line which begins with the letter `a`, changing `magic` to `second` on every line which begins with the letter `b`, and changing `magic` to `third` on every line which begins with the letter `c`. All other words and all other lines are left unchanged.

These rules are so simple that the easiest way to do this job is with a flag:

```
        int flag;
%%
^a      {flag = 'a'; ECHO;}
^b      {flag = 'b'; ECHO;}
^c      {flag = 'c'; ECHO;}
\n      {flag =  0 ; ECHO;}
magic   {
        switch (flag)
        {
        case 'a': printf("first"); break;
        case 'b': printf("second"); break;
        case 'c': printf("third"); break;
        default: ECHO; break;
        }
        }
```

should be adequate.

To handle the same problem with start conditions, each start condition must be introduced to `lex` in the definitions section with a line reading

```
%Start  name1 name2 ...
```

where the conditions may be named in any order. The word `Start` may be abbreviated to `s` or `S`. The conditions may be referenced at the head of a rule with the <> brackets:

```
<name1>expression
```

is a rule which is only recognized when `lex` is in the start condition `name1`. To enter a start condition, execute the action statement

```
BEGIN name1;
```

which changes the start condition to `name1`. To resume the normal state,

```
BEGIN 0;
```

which resets to the initial condition of the `lex` automaton interpreter. A rule may be active in several start conditions:

```
<name1,name2,name3>
```

is a legal prefix. Any rule not beginning with the <> prefix operator is always active.

The same example as before can be written:

```
%START AA BB CC
%%
^a      {ECHO; BEGIN AA;}
^b      {ECHO; BEGIN BB;}
^c      {ECHO; BEGIN CC;}
\n      {ECHO; BEGIN 0;}
<AA>magic       printf("first");
<BB>magic       printf("second");
<CC>magic       printf("third");
```

where the logic is exactly the same as in the previous method of handling the problem, but `lex` does the work rather than the programmer's code.

9.10. Character Set

The programs generated by `lex` handle character I/O only through the routines `input, output,` and `unput`. Thus the character representation provided in these routines is accepted by `lex` and employed to return values in `yytext`. For internal use a character is represented as a small integer which, if the standard library is used, has a value equal to the integer value of the bit pattern representing the character on the host computer. Normally, the letter `a` is represented in the same form as the character constant `'a'`. If this interpretation is changed, by providing I/O routines which translate the characters, `lex` must be told about it, by giving a translation table. This table must be in the definitions section, and must be bracketed by two lines containing only '%T'. The table contains lines of the form

```
{integer} {character string}
```

which indicate the value associated with each character. Thus the next example maps the lower and upper case letters together into the integers 1 through 26, newline into 27, + and – into 28 and 29, and the digits into 30 through 39. Note the escape for newline. If a table is supplied, every character that is to appear

Figure 9-3 *Sample character table.*

```
%T
 1      Aa
 2      Bb
...
26      Zz
27      \n
28      +
29      -
30      0
31      1
...
39      9
%T
```

either in the rules or in any valid input must be included in the table. No character may be assigned the number 0, and no character may be assigned a bigger number than the size of the hardware character set.

9.11. Summary of Source Format

The general form of a `lex` source file is:

```
{definitions}
%%
{rules}
%%
{programmer subroutines}
```

The definitions section contains a combination of

1. Definitions, in the form 'name space translation'.
2. Included code, in the form 'space code'.
3. Included code, in the form

```
%{
code
%}
```

4. Start condition declarations, given in the form

```
%S name1 name2 ...
```

5. Character set tables, in the form

```
%T
number space character-string
...
%T
```

6. Changes to internal array sizes, in the form

```
%x nnn
```

where *nnn* is a decimal integer representing an array size and *x* selects the parameter as follows:

Table 9-1 *Changing Internal Array Sizes in lex*

Letter	*Parameter*
p	positions
n	states
e	tree nodes
a	transitions
k	packed character classes
o	output array size

Lines in the rules section have the form 'expression action' where the action may be continued on succeeding lines by using braces to delimit it.

Regular expressions in `lex` use the following operators:

Table 9-2 *Regular Expression Operators in lex*

Operator	*Meaning*
x	the character "x"
"x"	an "x", even if x is an operator
\x	an "x", even if x is an operator
[xy]	the character x or y
[x-z]	the characters x, y or z
[^x]	any character but x
.	any character but newline
^x	an x at the beginning of a line
<y>x	an x when lex is in start condition y
x$	an x at the end of a line followed by newline
x?	an optional x
x*	0,1,2, ... instances of x
x+	1,2,3, ... instances of x
x|y	an x or a y
(x)	an x
x/y	an x but only if followed by y
{xx}	the translation of xx from the definitions section
x{m,n}	*m* through *n* occurrences of x

9.12. Caveats and Bugs

There are pathological expressions which produce exponential growth of the tables when converted to deterministic automata; fortunately, they are rare.

`REJECT` does not rescan the input; instead it remembers the results of the previous scan. This means that if a rule with trailing context is found, and `REJECT` is executed, the programmer must not have used `unput` to change the characters forthcoming from the input stream. This is the only restriction on the programmer's ability to manipulate the not-yet-processed input.

10

`yacc` — Yet Another Compiler-Compiler

Computer program input generally has some structure; in fact, every computer program that does input can be thought of as defining an 'input language' which it accepts. An input language may be as complex as a programming language, or as simple as a sequence of numbers. Unfortunately, usual input facilities are limited, difficult to use, and often are lax about checking their inputs for validity.

`yacc` provides a general tool for describing the input to a computer program. The `yacc` programmer specifies the structure of the input, together with code to be invoked as each item is recognized. `yacc` turns such a specification into a subroutine that handles the input process; frequently, it is convenient and appropriate to have most of the flow of control in the programmer's application handled by this subroutine.

The input subroutine produced by `yacc` calls a programmer-supplied routine to return the next basic input item. Thus, the programmer can specify his input in terms of individual input characters, or in terms of higher-level constructs such as names and numbers. The programmer-supplied routine may also handle idiomatic features such as comment and continuation conventions, which typically defy easy grammatical specification.

The class of specifications that `yacc` accepts is a very general one: LALR(1) grammars with disambiguating rules.

In addition to compilers for C, FORTRAN, APL, Pascal, Ratfor, etc., `yacc` has also been used for less conventional languages, including a phototypesetter language, several desk calculator languages, a document retrieval system, and a FORTRAN debugging system.

`yacc` provides a general tool for imposing structure on the input to a computer program. The `yacc` programmer prepares a specification of the input process; this includes rules describing the input structure, code to be invoked when these rules are recognized, and a low-level routine to do the basic input. `yacc` then generates a function to control the input process. This function, called a *parser*, calls the programmer-supplied low-level input routine (the *lexical analyzer*) to pick up the basic items (called *tokens*) from the input stream. These tokens are organized according to the input structure rules, called *grammar rules*; when one of these rules has been recognized, then programmer code supplied for this rule, an *action*, is invoked; actions have the ability to return values and make use of the values of other actions.

yacc generates its actions and output subroutines in C. Moreover, many of the syntactic conventions of yacc follow C.

The heart of the yacc input specification is a collection of grammar rules. Each rule describes an allowable structure and gives it a name. For example, one grammar rule might be:

```
date  :  month_name  day  ','  year   ;
```

Here, *date*, *month_name*, *day*, and *year* represent structures of interest in the input process; presumably, *month_name*, *day*, and *year* are defined elsewhere. The comma ',' is enclosed in single quotes — implying that the comma is to appear literally in the input. The colon and semicolon merely serve as punctuation in the rule, and have no significance in controlling the input. Thus, with proper definitions, the input

```
July  4, 1776
```

might be matched by the above rule.

An important part of the input process is carried out by the lexical analyzer. This routine reads the input stream, recognizing the lower-level structures, and communicates these tokens to the parser. For historical reasons, a structure recognized by the lexical analyzer is called a *terminal symbol*, while the structure recognized by the parser is called a *nonterminal symbol*. To avoid confusion, terminal symbols are referred to as *tokens*.

There is considerable leeway in deciding whether to recognize structures using the lexical analyzer or grammar rules. For example, the rules

```
month_name  :  'J'  'a'  'n'    ;
month_name  :  'F'  'e'  'b'    ;

...

month_name  :  'D'  'e'  'c'    ;
```

might be used in the above example. The lexical analyzer would only need to recognize individual letters, and *month_name* would be a nonterminal symbol. Such low-level rules tend to waste time and space, and may complicate the specification beyond yacc's ability to deal with it. Usually, the lexical analyzer would recognize the month names, and return an indication that a *month_name* was seen; in this case, *month_name* would be a token.

Literal characters such as ',' must also be passed through the lexical analyzer, and are also considered tokens.

Specification files are very flexible. It is realively easy to add to the above example the rule

```
date  :  month  '/'  day  '/'  year   ;
```

allowing

```
7 / 4 / 1776
```

as a synonym for

```
July 4, 1776
```

In most cases, this new rule could be 'slipped in' to a working system with minimal effort and little danger of disrupting existing input.

The input being read may not conform to the specifications. These input errors are detected as early as is theoretically possible with a left-to-right scan; thus, not only is the chance of reading and computing with bad input data substantially reduced, but the bad data can usually be quickly found. Error handling, provided as part of the input specifications, permits the reentry of bad data, or the continuation of the input process after skipping over the bad data.

In some cases, yacc fails to produce a parser when given a set of specifications. For example, the specifications may be self-contradictory, or they may require a more powerful recognition mechanism than that available to yacc. The former cases represent design errors; the latter cases can often be corrected by making the lexical analyzer more powerful, or by rewriting some of the grammar rules. While yacc cannot handle all possible specifications, its power compares favorably with similar systems; moreover, the constructions which are difficult for yacc to handle are also frequently difficult for human beings to handle. Some users have reported that the discipline of formulating valid yacc specifications for their input revealed errors of conception or design early in the program development.

The next several sections describe the basic process of preparing a yacc specification; Section 10.1 describes the preparation of grammar rules, Section 10.2 the preparation of the programmer-supplied actions associated with these rules, and Section 10.3 the preparation of lexical analyzers. Section 10.4 describes the operation of the parser. Section 10.5 discusses various reasons why yacc may be unable to produce a parser from a specification, and what to do about it. Section 10.6 describes a simple mechanism for handling operator precedences in arithmetic expressions. Section 10.7 discusses error detection and recovery. Section 10.8 discusses the operating environment and special features of the parsers yacc produces. Section 10.9 gives some suggestions which should improve the style and efficiency of the specifications. Section 10.10 discusses some advanced topics. Section 10.11 has a brief example, and section 10.12 gives a summary of the yacc input syntax. Section 10.13 gives an example using some of the more advanced features of yacc, and, finally, section 10.14 describes mechanisms and syntax no longer actively supported, but provided for historical continuity with older versions of yacc.

10.1. Basic Specifications

Names refer to either tokens or nonterminal symbols. `yacc` requires token names to be declared as such. In addition, for reasons discussed in Section 10.3, it is often desirable to include the lexical analyzer as part of the specification file; it may be useful to include other programs as well. Thus, every specification file consists of three sections: the *declarations*, *(grammar) rules*, and *programs*. The sections are separated by double percent `%%` marks. The percent `%` is generally used in `yacc` specifications as an escape character.

In other words, a full specification file looks like

```
declarations
%%
rules
%%
programs
```

The declaration section may be empty. Moreover, if the programs section is omitted, the second `%%` mark may be omitted also; thus, the smallest legal `yacc` specification is

```
%%
rules
```

Spaces (also called blanks), tabs, and newlines are ignored except that they may not appear in names or multi-character reserved symbols. Comments may appear wherever a name is legal — they are enclosed in `/* . . . */`, as in C and PL/I.

The rules section is made up of one or more grammar rules. A grammar rule has the form:

```
A  :  BODY  ;
```

A represents a nonterminal name, and *BODY* represents a sequence of zero or more names and literals. The colon and the semicolon are `yacc` punctuation.

Names may be of arbitrary length, and may be made up of letters, dot '.', underscore '_', and non-initial digits. Upper and lower case letters are distinct. The names used in the body of a grammar rule may represent tokens or nonterminal symbols.

A literal consists of a character enclosed in single quotes '''. As in C, the backslash '\' is an escape character within literals, and all the C escapes are recognized:

```
'\n'    newline
'\r'    return
'\''    single quote '
'\\'    backslash '\'
'\t'    tab
'\b'    backspace
'\f'    form feed
'\xxx'  'xxx' in octal
```

For a number of technical reasons, the NUL character ('\0' or 0) should never be used in grammar rules.

If there are several grammar rules with the same left hand side, the vertical bar '|' can be used to avoid rewriting the left hand side. In addition, the semicolon at the end of a rule can be dropped before a vertical bar. Thus the grammar rules

```
A       :       B  C  D   ;
A       :       E  F   ;
A       :       G   ;
```

can be given to `yacc` as

```
A       :       B  C  D
        |       E  F
        |       G
        ;
```

It is not necessary that all grammar rules with the same left side appear together in the grammar rules section, although it makes the input much more readable, and easier to change.

If a nonterminal symbol matches the empty string, this can be indicated in the obvious way:

```
empty :   ;
```

Names representing tokens must be declared; this is most simply done by writing

```
%token   name1  name2 . . .
```

in the declarations section. See Sections 3 , 5, and 6 for much more discussion. Every name not defined in the declarations section is assumed to represent a nonterminal symbol. Every nonterminal symbol must appear on the left side of at least one rule.

Of all the nonterminal symbols, one, called the *start symbol*, has particular importance. The parser is designed to recognize the start symbol; thus, this symbol represents the largest, most general structure described by the grammar rules. By default, the start symbol is taken to be the left hand side of the first grammar rule in the rules section. It is possible, and in fact desirable, to declare the start symbol explicitly in the declarations section using the %start keyword:

```
%start   symbol
```

The end of the input to the parser is signaled by a special token, called the *endmarker*. If the tokens up to, but not including, the endmarker form a structure which matches the start symbol, the parser function returns to its caller after the endmarker is seen; it *accepts* the input. If the endmarker is seen in any other context, it is an error.

It is the job of the programmer-supplied lexical analyzer to return the endmarker when appropriate — see Section 10.3, below. Usually the endmarker represents some reasonably obvious I/O status, such as 'end-of-file' or 'end-of-record'.

10.2. Actions

With each grammar rule, the programmer may associate actions to be performed each time the rule is recognized in the input process. These actions may return values, and may obtain the values returned by previous actions. Moreover, the lexical analyzer can return values for tokens, if desired.

An action is an arbitrary C statement, and as such can do input and output, call subprograms, and alter external vectors and variables. An action is specified by one or more statements, enclosed in curly braces '{' and '}'. For example,

```
A       :       '('  B  ')'
                      {      hello( 1, "abc" );   }
```

and

```
XXX     :       YYY  ZZZ
                      {      printf("a message\n");
                             flag = 25;    }
```

are grammar rules with actions.

To facilitate easy communication between the actions and the parser, the action statements are altered slightly. The dollar sign symbol '$' is used as a signal to `yacc` in this context.

To return a value, the action normally sets the pseudo-variable '$$' to some value. For example, an action that does nothing but return the value 1 is

```
{   $$ = 1;   }
```

To obtain the values returned by previous actions and the lexical analyzer, the action may use the pseudo-variables $1, $2, . . ., which refer to the values returned by the components of the right side of a rule, reading from left to right. Thus, if the rule is

```
A       :       B  C  D   ;
```


for example, then `$2` has the value returned by `C`, and `$3` the value returned by `D`.

As a more concrete example, consider the rule

```
expr     :        '('  expr  ')'    ;
```

The value returned by this rule is usually the value of the *expr* in parentheses. This can be indicated by

```
expr     :        '('  expr  ')'          {  $$ = $2 ;  }
```

By default, the value of a rule is the value of $1 (the first element in it). Thus, grammar rules of the form

```
A        :        B    ;
```

frequently need not have an explicit action.

In the examples above, all the actions came at the end of their rules. Sometimes, it is desirable to get control before a rule is fully parsed. `yacc` permits an action to be written in the middle of a rule as well as at the end. This rule is assumed to return a value, accessible through the usual $ mechanism by the actions to the right of it. In turn, it may access the values returned by the symbols to its left. Thus, in the rule

```
A        :        B
                            {  $$ = 1;   }
                  C
                            {   x = $2;    y = $3;   }
         ;
```

the effect is to set *x* to 1, and *y* to the value returned by C.

Actions that do not terminate a rule are actually handled by `yacc` by manufacturing a new nonterminal symbol name, and a new rule matching this name to the empty string. The interior action is the action triggered off by recognizing this added rule. `yacc` actually treats the above example as if it had been written:

```
$ACT     :        /* empty */
                            {  $$ = 1;   }
         ;
A        :        B  $ACT  C
                            {   x = $2;    y = $3;   }
         ;
```

In many applications, output is not done directly by the actions; rather, a data structure, such as a parse tree, is constructed in memory, and transformations are applied to it before output is generated. Parse trees are particularly easy to construct, given routines to build and maintain the tree structure desired. For example, suppose there is a C function `node`, written so that the call

```
node( L, n1, n2 )
```

creates a node with label L, and descendants n1 and n2, and returns the index of the newly created node. The parse tree can be built by supplying actions such as:

```
expr    :       expr  '+'  expr
                      {  $$ = node( '+', $1, $3 );  }
```

in the specification.

The programmer may define other variables to be used by the actions. Declarations and definitions can appear in the declarations section, enclosed in the marks '`%{`' and '`%}`'. These declarations and definitions have global scope, so they are known to the action statements and the lexical analyzer. For example,

```
%{   int variable = 0;   %}
```

could be placed in the declarations section, making `variable` accessible to all of the actions. The `yacc` parser uses only names beginning in 'yy'; the programmer should avoid such names.

In these examples, all the values are integers: a discussion of values of other types will be found in Section 10.10.

10.3. Lexical Analysis

The programmer must supply a lexical analyzer to read the input stream and communicate tokens (with values, if desired) to the parser. The lexical analyzer is an integer-valued function called `yylex()`. The function returns an integer, the *token number*, representing the kind of token read. If there is a value associated with that token, it should be assigned to the external variable `yylval()`.

The parser and the lexical analyzer must agree on these token numbers in order for communication between them to take place. The numbers may be chosen by `yacc`, or chosen by the programmer. In either case, the '# define' mechanism of C is used to allow the lexical analyzer to return these numbers symbolically. For example, suppose that the token name `DIGIT` has been defined in the declarations section of the `yacc` specification file. The relevant portion of the lexical analyzer might look like:

```
yylex(){
        extern int yylval;
        int c;
        ...
        c = getchar();
        ...
        switch( c ) {
        ...
        case '0':
        case '1':
        ...
        case '9':
                yylval = c-'0';
                return( DIGIT );
                ...
                }
        ...
```

The intent is to return the token number of `DIGIT`, and a value equal to the numerical value of the digit. Provided that the lexical analyzer code is placed in the programs section of the specification file, the identifier `DIGIT` will be defined as the token number associated with the token `DIGIT`.

This mechanism leads to clear, easily modified lexical analyzers; the only pitfall is the need to avoid using any token names in the grammar that are reserved or significant in C or the parser; for example, the use of `if` or `while` as token names will almost certainly cause severe difficulties when the lexical analyzer is compiled. The token name `error` is reserved for error handling, and should not be used naively (see Section 10.7).

As mentioned above, the token numbers may be chosen by `yacc` or by the programmer. In the default situation, the numbers are chosen by `yacc`. The default token number for a literal character is the numerical value of the character in the local character set. Other names are assigned token numbers starting at 257.

To assign a token number to a token (including literals), the first appearance of the token name or literal *in the declarations section* can be immediately followed by a nonnegative integer. This integer is taken to be the token number of the name or literal. Names and literals not defined by this mechanism retain their default definition. It is important that all token numbers be distinct.

For historical reasons, the endmarker must have token number 0 or negative. This token number cannot be redefined by the programmer; thus, all lexical analyzers should be prepared to return 0 or negative as a token number upon reaching the end of their input.

A very useful tool for constructing lexical analyzers is the *lex* program developed by Mike Lesk[8] and described in the previous chapter on `lex`. These lexical analyzers are designed to work in close harmony with `yacc` parsers. The specifications use regular expressions instead of grammar rules. `lex` can be easily used to produce quite complicated lexical analyzers, but there remain some languages (such as FORTRAN) which do not fit any theoretical framework, and whose lexical analyzers must be crafted by hand.

10.4. How the Parser Works

`yacc` turns the specification file into a C program, which parses the input according to the specification given. The algorithm used to go from the specification to the parser is complex, and will not be discussed here (see the references for more information). The parser itself, however, is relatively simple, and understanding how it works, while not strictly necessary, will nevertheless make treatment of error recovery and ambiguities much more comprehensible.

The parser produced by `yacc` consists of a finite-state machine with a stack. The parser can read and remember the next input token (called the *lookahead* token). The *current state* is always the one on the top of the stack. The states of the finite-state machine are given small integer labels; initially, the machine is in state 0, the stack contains only state 0, and no lookahead token has been read.

The machine has only four actions available to it, called *shift*, *reduce*, *accept*, and *error*. A move of the parser is done as follows:

1. Based on its current state, the parser decides whether it needs a lookahead token to decide what action should be done; if it needs one, and does not have one, it calls `yylex()` to obtain the next token.
2. Using the current state, and the lookahead token if needed, the parser decides on its next action, and carries it out. This may result in states being pushed onto the stack, or popped off the stack, and in the lookahead token being processed or left alone.

`shift` Action

The *shift* action is the most common action the parser takes. Whenever a shift action is taken, there is always a lookahead token. For example, in state 56 there may be an action:

```
        IF      shift 34
```

which says, in state 56, if the lookahead token is `IF`, the current state (56) is pushed down on the stack, and state 34 becomes the current state (on the top of the stack). The lookahead token is cleared.

`reduce` Action

The *reduce* action keeps the stack from growing without bound. Reduce actions are appropriate when the parser has seen the right hand side of a grammar rule, and is prepared to announce that it has seen an instance of the rule, replacing the right hand side by the left hand side. It may be necessary to consult the lookahead token to decide whether to reduce, but usually it is not; in fact, the default action (represented by a '.') is often a reduce action.

Reduce actions are associated with individual grammar rules. Grammar rules are also given small integer numbers, leading to some confusion. The action

```
        .  reduce 18
```

refers to *grammar rule* 18, while the action

```
        IF      shift 34
```

refers to *state* 34.

Suppose the rule being reduced is

```
  A       : x  y  z    ;
```

The reduce action depends on the left hand symbol (A in this case), and the number of symbols on the right hand side (three in this case). To reduce, first pop off the top three states from the stack (In general, the number of states popped equals the number of symbols on the right side of the rule). In effect, these states were the ones put on the stack while recognizing *x*, *y*, and *z*, and no longer serve any useful purpose. After popping these states, a state is uncovered which was the state the parser was in before beginning to process the rule. Using this uncovered state, and the symbol on the left side of the rule, perform what is in effect a shift of A. A new state is obtained, pushed onto the stack, and parsing continues. There are significant differences between the processing of the left hand symbol and an ordinary shift of a token, however, so this action is called a *goto* action. In particular, the lookahead token is cleared by a shift, and is not affected by a goto. In any case, the uncovered state contains an entry such as:

```
        A       goto 20
```

which pushes state 20 onto the stack, and becomes the current state.

In effect, the reduce action 'turns back the clock' in the parse, popping the states off the stack to go back to the state where the right hand side of the rule was first seen. The parser then behaves as if it had seen the left side at that time. If the right hand side of the rule is empty, no states are popped off the stack: the uncovered state is in fact the current state.

The reduce action is also important in the treatment of programmer-supplied actions and values. When a rule is reduced, the code supplied with the rule is executed before the stack is adjusted. In addition to the stack holding the states, another stack, running in parallel with it, holds the values returned from the lexical analyzer and the actions. When a shift takes place, the external variable `yylval()` is copied onto the value stack. After the return from the programmer's code, the reduction is carried out. When the *goto* action is done, the external variable `yyval()` is copied onto the value stack. The pseudo-variables $1, $2, etc., refer to the value stack.

`accept` and `error` Actions

The other two parser actions are conceptually much simpler. The *accept* action indicates that the entire input has been seen and that it matches the specification. This action appears only when the lookahead token is the endmarker, and indicates that the parser has successfully done its job. The *error* action, on the other hand, represents a place where the parser can no longer continue parsing according to the specification. The input tokens it has seen, together with the lookahead token, cannot be followed by anything that would result in a legal input. The parser reports an error, and attempts to recover the situation and resume parsing: the error recovery (as opposed to the detection of error) will be covered in Section 10.7.

It is time for an example! Consider the specification

```
%token  DING  DONG  DELL
%%
rhyme    :       sound  place
         ;
sound    :       DING  DONG
         ;
place    :       DELL
         ;
```

When yacc is invoked with the -v option, a file called *y.output* is produced, with a human-readable description of the parser. The *y.output* file corresponding to the above grammar (with some statistics stripped off the end) is:

```
state 0
        $accept  :  _rhyme  $end

        DING  shift 3
        .  error

        rhyme  goto 1
        sound  goto 2

state 1
        $accept  :  rhyme_$end

        $end  accept
        .  error

state 2
        rhyme  :  sound_place

        DELL  shift 5
        .  error

        place   goto 4

state 3
        sound   :  DING_DONG

        DONG  shift 6
        .  error

state 4
        rhyme  :  sound  place_    (1)

        .   reduce  1

state 5
        place  :  DELL_    (3)

        .   reduce  3

state 6
        sound   :  DING  DONG_    (2)

        .   reduce  2
```

Notice that, in addition to the actions for each state, there is a description of the parsing rules being processed in each state. The _ character is used to indicate what has been seen, and what is yet to come, in each rule. Suppose the input is

```
DING  DONG  DELL
```

It is instructive to follow the steps of the parser while processing this input.

Initially, the current state is state 0. The parser needs to refer to the input in order to decide between the actions available in state 0, so the first token, `DING`, is read, becoming the lookahead token. The action in state 0 on `DING` is 'shift 3', so state 3 is pushed onto the stack, and the lookahead token is cleared. State 3 becomes the current state. The next token, `DONG`, is read, becoming the lookahead token. The action in state 3 on the token `DONG` is 'shift 6', so state 6 is pushed onto the stack, and the lookahead is cleared. The stack now contains 0, 3, and 6. In state 6, without even consulting the lookahead, the parser reduces by rule 2.

```
        sound  :  DING  DONG
```

This rule has two symbols on the right hand side, so two states, 6 and 3, are popped off the stack, uncovering state 0. Consulting the description of state 0, looking for a goto on *sound*,

```
        sound   goto 2
```

is obtained; thus state 2 is pushed onto the stack, becoming the current state.

In state 2, the next token, `DELL`, must be read. The action is 'shift 5', so state 5 is pushed onto the stack, which now has 0, 2, and 5 on it, and the lookahead token is cleared. In state 5, the only action is to reduce by rule 3. This has one symbol on the right hand side, so one state, 5, is popped off, and state 2 is uncovered. The goto in state 2 on *place*, the left side of rule 3, is state 4. Now, the stack contains 0, 2, and 4. In state 4, the only action is to reduce by rule 1. There are two symbols on the right, so the top two states are popped off, uncovering state 0 again. In state 0, there is a goto on *rhyme* causing the parser to enter state 1. In state 1, the input is read; the endmarker is obtained, indicated by '$end' in the *y.output* file. The action in state 1 when the endmarker is seen is to accept, successfully ending the parse.

The reader is urged to consider how the parser works when confronted with such incorrect strings as `DING DONG DONG`, `DING DONG`, `DING DONG DELL DELL`, and so on. A few minutes spend with this and other simple examples will probably be repaid when problems arise in more complicated contexts.

10.5. Ambiguity and Conflicts

A set of grammar rules is *ambiguous* if there is some input string that can be structured in two or more different ways. For example, the grammar rule

```
    expr    :       expr  '-'  expr
```

is a natural way of expressing the fact that one way of forming an arithmetic expression is to put two other expressions together with a minus sign between them. Unfortunately, this grammar rule does not unambiguously specify the way that all complex inputs should be structured. For example, if the input is

```
    expr  -  expr  -  expr
```

the rule allows this input to be structured as either

```
    (  expr  -  expr  )  -  expr
```

or as

```
    expr  -  (  expr  -  expr  )
```

The first is called *left association*, the second *right association*.

`yacc` detects such ambiguities when it is attempting to build the parser. It is instructive to consider the problem that confronts the parser when it is given an input such as

```
    expr  -  expr  -  expr
```

When the parser has read the second expr, the input that it has seen:

```
    expr  -  expr
```

matches the right side of the grammar rule above. The parser could *reduce* the input by applying this rule; after applying the rule; the input is reduced to *expr* (the left side of the rule). The parser would then read the final part of the input:

```
    -  expr
```

and again reduce. The effect of this is to take the left-associative interpretation.

Alternatively, when the parser has seen

```
    expr  -  expr
```

it could defer the immediate application of the rule, and continue reading the input until it had seen

```
    expr  -  expr  -  expr
```

It could then apply the rule to the rightmost three symbols, reducing them to *expr* and leaving

```
    expr  -  expr
```

Now the rule can be reduced once more; the effect is to take the right associative interpretation. Thus, having read

```
    expr  -  expr
```

the parser can do two legal things, a shift or a reduction, and has no way of deciding between them. This is called a *shift / reduce conflict*. It may also happen that the parser has a choice of two legal reductions; this is called a *reduce / reduce conflict*. Note that there are never any 'shift/shift' conflicts.

When there are shift/reduce or reduce/reduce conflicts, `yacc` still produces a parser. It does this by selecting one of the valid steps wherever it has a choice. A rule describing which choice to make in a given situation is called a *disambiguating rule*.

`yacc` invokes two disambiguating rules by default:

1. In a shift/reduce conflict, the default is to do the shift.
2. In a reduce/reduce conflict, the default is to reduce by the *earlier* grammar rule (in the input sequence).

Rule 1 implies that reductions are deferred whenever there is a choice, in favor of shifts. Rule 2 gives the programmer rather crude control over the behavior of the parser in this situation, but reduce/reduce conflicts should be avoided whenever possible.

Conflicts may arise because of mistakes in input or logic, or because the grammar rules, while consistent, require a more complex parser than `yacc` can construct. The use of actions within rules can also cause conflicts, if the action must be done before the parser can be sure which rule is being recognized. In these cases, the application of disambiguating rules is inappropriate, and leads to an incorrect parser. For this reason, `yacc` always reports the number of shift/reduce and reduce/reduce conflicts resolved by Rule 1 and Rule 2.

In general, whenever it is possible to apply disambiguating rules to produce a correct parser, it is also possible to rewrite the grammar rules so that the same inputs are read but there are no conflicts. For this reason, most previous parser generators have considered conflicts to be fatal errors. Our experience has suggested that this rewriting is somewhat unnatural, and produces slower parsers; thus, `yacc` will produce parsers even in the presence of conflicts.

As an example of the power of disambiguating rules, consider a fragment from a programming language involving an 'if-then-else' construction:

```
stat    :       IF  '('  cond  ')'  stat
        |       IF  '('  cond  ')'  stat  ELSE  stat
        ;
```

In these rules, `IF` and `ELSE` are tokens, *cond* is a nonterminal symbol describing conditional (logical) expressions, and *stat* is a nonterminal symbol describing statements. The first rule will be called the *simple-if rule*, and the second the *if-else rule*.

These two rules form an ambiguous construction, since input of the form:

```
IF ( condition-1 )  IF ( condition-2 ) statement-1  ELSE statement-2
```

can be structured according to these rules in two ways:

```
IF  (  condition-1  )  {
       IF  (  condition-2  )  statement-1
}
ELSE  statement-2
```

or

```
IF  (  condition-1  )  {
       IF  (  condition-2  )  statement-1
       ELSE  statement-2
}
```

The second interpretation is the one given in most programming languages having this construct. Each `ELSE` is associated with the last preceding 'un-*ELSE*'d' `IF`. In this example, consider the situation where the parser has seen

```
IF  (  condition-1  )  IF  (  condition-2  )  statement-1
```

and is looking at the `ELSE`. It can immediately reduce by the simple-if rule to get

```
IF  (  condition-1  )  stat
```

and then read the remaining input,

```
ELSE  statement-2
```

and reduce

```
IF  (  condition-1  )  stat  ELSE  statement-2
```

by the if-else rule. This leads to the first of the above groupings of the input.

On the other hand, the `ELSE` may be shifted, *statement*-2 read, and then the right hand portion of

```
IF  (  condition-1  )  IF  (  condition-2  )  statement-1  ELSE  statement-2
```

can be reduced by the if-else rule to get

```
IF  (  condition-1  )  stat
```

which can be reduced by the simple-if rule. This leads to the second of the above groupings of the input, which is usually desired.

Once again the parser can do two valid things – there is a shift/reduce conflict. The application of disambiguating rule 1 tells the parser to shift in this case, which leads to the desired grouping.

This shift/reduce conflict arises only when there is a particular current input symbol, `ELSE`, and particular inputs already seen, such as

```
IF  (  condition-1  )  IF  (  condition-2  )  statement-1
```

In general, there may be many conflicts, and each one will be associated with an input symbol and a set of previously read inputs. The previously read inputs are characterized by the state of the parser.

The conflict messages of `yacc` are best understood by examining the verbose (–v) option output file. For example, the output corresponding to the above conflict state might be:

```
23: shift/reduce conflict (shift 45, reduce 18) on ELSE

state 23

         stat  :  IF  (  cond  )  stat_          (18)
         stat  :  IF  (  cond  )  stat_ELSE  stat

        ELSE     shift 45
        .        reduce 18
```

The first line describes the conflict, giving the state and the input symbol. The ordinary state description follows, giving the grammar rules active in the state, and the parser actions. Recall that the underline marks the portion of the grammar rules which has been seen. Thus in the example, in state 23 the parser has seen input corresponding to

```
IF  (  cond  )  stat
```

and the two grammar rules shown are active at this time. The parser can do two possible things. If the input symbol is `ELSE`, it is possible to shift into state 45. State 45 will have, as part of its description, the line

```
stat  :  IF  (  cond  )  stat  ELSE_stat
```

since the `ELSE` will have been shifted in this state. Back in state 23, the alternative action, described by '.', is to be done if the input symbol is not mentioned explicitly in the above actions; thus, in this case, if the input symbol is not `ELSE`, the parser reduces by grammar rule 18:

```
stat  :  IF  '('  cond  ')'  stat
```

Once again, notice that the numbers following 'shift' commands refer to other states, while the numbers following 'reduce' commands refer to grammar rule numbers. In the *y.output* file, the rule numbers are printed after those rules which can be reduced. In most states, there will be at most one reduce action possible in the state, and this will be the default command. Programmers who encounter unexpected shift/reduce conflicts will probably want to look at the verbose output to decide whether the default actions are appropriate. In really tough cases, the programmer might need to know more about the behavior and construction of the parser than can be covered here. In this case, one of the theoretical references cited in Chapter 1 might be consulted.

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10.6. Precedence

There is one common situation where the rules given above for resolving conflicts are not sufficient; this is in the parsing of arithmetic expressions. Most of the commonly used constructions for arithmetic expressions can be naturally described by the notion of *precedence* levels for operators, together with information about left or right associativity. It turns out that ambiguous grammars with appropriate disambiguating rules can be used to create parsers that are faster and easier to write than parsers constructed from unambiguous grammars. The basic notion is to write grammar rules of the form

```
expr  :  expr  OP  expr
```

and

```
expr  :  UNARY  expr
```

for all binary and unary operators desired. This creates a very ambiguous grammar, with many parsing conflicts. As disambiguating rules, the programmer specifies the precedence, or binding strength, of all the operators, and the associativity of the binary operators. This information is sufficient to allow `yacc` to resolve the parsing conflicts in accordance with these rules, and construct a parser that realizes the desired precedences and associativities.

The precedences and associativities are attached to tokens in the declarations section. This is done by a series of lines beginning with a `yacc` keyword: `%left`, `%right`, or `%nonassoc`, followed by a list of tokens. All of the tokens on the same line are assumed to have the same precedence level and associativity; the lines are listed in order of increasing precedence or binding strength. Thus,

```
%left  '+'  '-'
%left  '*'  '/'
```

describes the precedence and associativity of the four arithmetic operators. Plus and minus are left-associative, and have lower precedence than star and slash, which are also left-associative. The keyword `%right` is used to describe right-associative operators, and the keyword `%nonassoc` is used to describe operators, like the `.LT.` operator in FORTRAN, that may not associate with themselves; thus,

```
A  .LT.  B  .LT.  C
```

is illegal in FORTRAN, and such an operator would be described with the keyword `%nonassoc` in `yacc`. As an example of the behavior of these declarations, the description

```
%right  '='
%left   '+'  '-'
%left   '*'  '/'

%%

expr    :       expr  '='  expr
        |       expr  '+'  expr
        |       expr  '-'  expr
        |       expr  '*'  expr
        |       expr  '/'  expr
        |       NAME
        ;
```

might be used to structure the input

```
a  =  b  =  c*d  -  e  -  f*g
```

as follows:

```
a = ( b = ( ((c*d)-e) - (f*g) ) )
```

When this mechanism is used, unary operators must, in general, be given a precedence. Sometimes a unary operator and a binary operator have the same symbolic representation, but different precedences. An example is unary and binary '-'; unary minus may be given the same strength as multiplication, or even higher, while binary minus has a lower strength than multiplication. The keyword `%prec` changes the precedence level associated with a particular grammar rule. `%prec` appears immediately after the body of the grammar rule, before the action or closing semicolon, and is followed by a token name or literal. It changes the precedence of the grammar rule to become that of the following token name or literal. For example, to make unary minus have the same precedence as multiplication the rules might resemble:

```
%left   '+'   '-'
%left   '*'   '/'

%%

expr    :       expr   '+'   expr
        |       expr   '-'   expr
        |       expr   '*'   expr
        |       expr   '/'   expr
        |       '-'   expr      %prec   '*'
        |       NAME
        ;
```

A token declared by `%left`, `%right`, and `%nonassoc` need not be, but may be, declared by `%token` as well.

The precedences and associativities are used by `yacc` to resolve parsing conflicts; they give rise to disambiguating rules. Formally, the rules work as follows:

1. The precedences and associativities are recorded for those tokens and literals that have them.
2. A precedence and associativity is associated with each grammar rule; it is the precedence and associativity of the last token or literal in the body of the rule. If the `%prec` construction is used, it overrides this default. Some grammar rules may have no precedence and associativity associated with them.
3. When there is a reduce/reduce conflict, or there is a shift/reduce conflict and either the input symbol or the grammar rule has no precedence and associativity, then the two disambiguating rules given at the beginning of the section are used, and the conflicts are reported.
4. If there is a shift/reduce conflict, and both the grammar rule and the input character have precedence and associativity associated with them, then the conflict is resolved in favor of the action (shift or reduce) associated with the higher precedence. If the precedences are the same, then the associativity is used; left-associative implies reduce, right-associative implies shift, and nonassociating implies error.

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Conflicts resolved by precedence are not counted in the number of shift/reduce and reduce/reduce conflicts reported by `yacc`. This means that mistakes in the specification of precedences may disguise errors in the input grammar; it is a good idea to be sparing with precedences, and use them in an essentially 'cookbook' fashion, until some experience has been gained. The *y.output* file is very useful in deciding whether the parser is actually doing what was intended.

10.7. Error Handling

Error handling is an extremely difficult area, and many of the problems are semantic ones. When an error is found, for example, it may be necessary to reclaim parse tree storage, delete or alter symbol table entries, and, typically, set switches to avoid generating any further output.

It is seldom acceptable to stop all processing when an error is found; it is more useful to continue scanning the input to find further syntax errors. This leads to the problem of getting the parser 'restarted' after an error. A general class of algorithms to do this involves discarding a number of tokens from the input string, and attempting to adjust the parser so that input can continue.

To allow the programmer some control over this process, `yacc` provides a simple, but reasonably general, feature. The token name 'error' is reserved for error handling. This name can be used in grammar rules; in effect, it suggests places where errors are expected, and recovery might take place. The parser pops its stack until it enters a state where the token 'error' is legal. It then behaves as if the token 'error' were the current lookahead token, and performs the action encountered. The lookahead token is then reset to the token that caused the error. If no special error rules have been specified, the processing halts when an error is detected.

In order to prevent a cascade of error messages, the parser, after detecting an error, remains in error state until three tokens have been successfully read and shifted. If an error is detected when the parser is already in error state, no message is given, and the input token is quietly deleted.

As an example, a rule of the form

```
stat    :       error
```

would, in effect, mean that on a syntax error the parser would attempt to skip over the statement in which the error was seen. More precisely, the parser will scan ahead, looking for three tokens that might legally follow a statement, and start processing at the first of these; if the beginnings of statements are not sufficiently distinctive, it may make a false start in the middle of a statement, and end up reporting a second error where there is in fact no error.

Actions may be used with these special error rules. These actions might attempt to reinitialize tables, reclaim symbol table space, etc.

Error rules such as the above are very general, but difficult to control. Somewhat easier are rules such as

```
stat    :       error  ';'
```

Here, when there is an error, the parser attempts to skip over the statement, but will do so by skipping to the next ';'. All tokens after the error and before the next ';' cannot be shifted, and are discarded. When the ';' is seen, this rule will be reduced, and any 'cleanup' action associated with it performed.

Another form of error rule arises in interactive applications, where it may be desirable to permit a line to be reentered after an error. A possible error rule might be

```
input    :        error  '\n'  {  printf( "Reenter last line: " );   }  input
                               {        $$  =  $4;  }
```

There is one potential difficulty with this approach; the parser must correctly process three input tokens before it admits that it has correctly resynchronized after the error. If the reentered line contains an error in the first two tokens, the parser deletes the offending tokens, and gives no message; this is clearly unacceptable. For this reason, there is a mechanism that can be used to force the parser to believe that an error has been fully recovered from. The statement

```
yyerrok ;
```

in an action resets the parser to its normal mode. The last example is better written

```
input    :        error  '\n'
                         {        yyerrok;
                                  printf( "Reenter last line: " );    }
                  input
                         {        $$  =  $4;  }
         ;
```

As mentioned above, the token seen immediately after the 'error' symbol is the input token at which the error was discovered. Sometimes, this is inappropriate; for example, an error recovery action might take upon itself the job of finding the correct place to resume input. In this case, the previous lookahead token must be cleared. The statement

```
yyclearin ;
```

in an action will have this effect. For example, suppose the action after error were to call some sophisticated resynchronization routine, supplied by the programmer, that attempted to advance the input to the beginning of the next valid statement. After this routine was called, the next token returned by `yylex()` would presumably be the first token in a legal statement; the old, illegal token must be discarded, and the error state reset. This could be done by a rule like

```
stat     :        error
                          {        resynch();
                                   yyerrok ;
                                   yyclearin ;    }
         ;
```

These mechanisms are admittedly crude, but do allow for a simple, fairly effective recovery of the parser from many errors; moreover, the programmer can get control to deal with the error actions required by other portions of the program.

10.8. The `yacc` Environment

When the programmer inputs a specification to `yacc`, the output is a file of C programs, called *y.tab.c* on most systems (due to local file system conventions, the name may differ from installation to installation). `yacc` produces an integer-valued function called `yyparse()`. When `yyparse()` is called, it in turn repeatedly calls `yylex()` — the lexical analyzer supplied by the programmer (see Section 10.3) to obtain input tokens. Eventually, either an error is detected, in which case (if no error recovery is possible) `yyparse()` returns the value 1, or the lexical analyzer returns the endmarker token and the parser accepts. In this case, `yyparse()` returns the value 0.

The programmer must provide a certain amount of environment for this parser in order to obtain a working program. For example, as with every C program, a program called `main` must be defined, that eventually calls `yyparse()`. In addition, a routine called `yyerror()` prints a message when a syntax error is detected.

The programmer must supply these two routines in one form or another. They can be as simple as the following example, or they can be as complex as needed.

```
main(){
        return( yyparse() );
        }
```

and

```
# include <stdio.h>

yyerror(s) char *s; {
        fprintf( stderr, "%s\n", s );
        }
```

The argument to `yyerror()` is a string containing an error message, usually the string 'syntax error'. The average application will want to do better than this. Ordinarily, the program should keep track of the input line number, and print it along with the message when a syntax error is detected. The external integer variable `yychar` contains the lookahead token number at the time the error was detected; this may be of some interest in giving better diagnostics.

The external integer variable `yydebug` is normally set to 0. If it is set to a nonzero value, the parser generates a verbose description of its actions, including a discussion of which input symbols have been read, and what the parser actions are. Depending on the operating environment, it may be possible to set this variable by using a debugging system.

10.9. Hints for Preparing Specifications

This section contains miscellaneous hints on preparing efficient, easy to change, and clear specifications. The individual subsections are more or less independent.

Input Style

It is difficult to provide rules with substantial actions and still have a readable specification file. The following style hints owe much to Brian Kernighan.

1. Use all capital letters for token names, all lower case letters for nonterminal names. This rule comes under the heading of 'knowing who to blame when things go wrong.'
2. Put grammar rules and actions on separate lines. This allows either to be changed without an automatic need to change the other.
3. Put all rules with the same left hand side together. Put the left hand side in only once, and let all following rules begin with a vertical bar.
4. Put a semicolon only after the last rule with a given left hand side, and put the semicolon on a separate line. This allows new rules to be added easily.
5. Indent rule bodies by two tab stops, and action bodies by three tab stops.

The example in section 10.11 is written following this style, as are the examples in the text of this paper (where space permits). The programmer must make up his own mind about these stylistic questions; the central problem, however, is to make the rules visible through the morass of action code.

Left Recursion

The algorithm used by the `yacc` parser encourages so called 'left-recursive' grammar rules: rules of the form

```
name    :       name  rest_of_rule  ;
```

These rules frequently arise when writing specifications of sequences and lists:

```
list    :       item
        |       list  ','  item
        ;
```

and

```
seq     :       item
        |       seq  item
        ;
```

In each of these cases, the first rule will be reduced for the first item only, and the second rule will be reduced for the second and all succeeding items.

With right-recursive rules, such as

```
seq     :       item
        |       item  seq
        ;
```

the parser would be a bit bigger, and the items would be seen, and reduced, from right to left. More seriously, an internal stack in the parser would be in danger of overflowing if a very long sequence were read. Thus, the programmer should use left recursion wherever reasonable.

It is worth considering whether a sequence with zero elements has any meaning, and if so, consider writing the sequence specification with an empty rule:

```
seq     :       /* empty */
        |       seq  item
        ;
```

Once again, the first rule would always be reduced exactly once, before the first item was read, and then the second rule would be reduced once for each item read. Permitting empty sequences often leads to increased generality. However, conflicts might arise if `yacc` is asked to decide which empty sequence it has seen, when it hasn't seen enough to know!

Lexical Tie-ins

Some lexical decisions depend on context. For example, the lexical analyzer might want to delete blanks normally, but not within quoted strings. Or names might be entered into a symbol table in declarations, but not in expressions.

One way of handling this situation is to create a global flag that is examined by the lexical analyzer, and set by actions. For example, suppose a program consists of 0 or more declarations, followed by 0 or more statements. Consider:

```
%{
        int dflag;
%}
        other declarations

%%
prog    :       decls  stats
        ;
decls   :       /* empty */
                        {       dflag = 1;   }
        |       decls  declaration
        ;
stats   :       /* empty */
                        {       dflag = 0;   }
        |       stats  statement
        ;
        other rules
```

The flag *dflag* is now 0 when reading statements, and 1 when reading declarations, *except* for the first token in the first statement. This token must be seen by the parser before it can tell that the declaration section has ended and the statements have begun. In many cases, this single-token exception does not affect the lexical scan.

This kind of 'backdoor' approach can be elaborated to a noxious degree. Nevertheless, it represents a way of doing some things that are difficult, if not impossible, to do otherwise.

Reserved Words

Some programming languages permit the programmer to use words like 'if', which are normally reserved, as label or variable names, provided that such use does not conflict with the legal use of these names in the programming language. This is extremely hard to do in the framework of `yacc`; it is difficult to pass information to the lexical analyzer telling it 'this instance of `if` is a keyword, and that instance is a variable'. The programmer can make a stab at it, using the mechanism described in the last subsection, but it is difficult.

A number of ways of making this easier are under advisement. Until then, it is better that the keywords be *reserved*; that is, be forbidden for use as variable names. There are powerful stylistic reasons for preferring this, anyway.

10.10. Advanced Topics

This section discusses a number of advanced features of `yacc`.

Simulating Error and Accept in Actions

The parsing actions of error and accept can be simulated in an action by use of macros YYACCEPT and YYERROR. YYACCEPT makes `yyparse` return the value 0; YYERROR makes the parser behave as if the current input symbol results in a syntax error; `yyerror()` is called, and error recovery takes place. These mechanisms can be used to simulate parsers with multiple endmarkers or context-sensitive syntax checking.

Accessing Values in Enclosing Rules.

An action may refer to values returned by actions to the left of the current rule. The mechanism is simply the same as with ordinary actions, a dollar sign followed by a digit, but in this case the digit may be 0 or negative. Consider

```
sent     :   adj  noun  verb  adj  noun
             {   look at the sentence  . . .   }
    ;

adj :    THE      {    $$ = THE;   }
    |    YOUNG    {    $$ = YOUNG;   }
    . . .
    ;

noun     :   DOG
             {    $$ = DOG;   }
    |    CRONE
             {    if( $0 == YOUNG ){
                       printf( "what?\n" );
                       }
                  $$ = CRONE;
                  }
    ;
    . . .
```

In the action following the word CRONE, a check is made that the preceding token shifted was not YOUNG. Obviously, this is only possible when a great deal is known about what might precede the symbol *noun* in the input. There is also a distinctly unstructured flavor about this. Nevertheless, at times this mechanism will save a great deal of trouble, especially when a few combinations are to be excluded from an otherwise regular structure.

Support for Arbitrary Value Types

By default, the values returned by actions and the lexical analyzer are integers. `yacc` can also support values of other types, including structures. In addition, `yacc` keeps track of the types, and inserts appropriate union member names so that the resulting parser will be strictly type checked. The `yacc` value stack (see Section 10.4) is declared to be a `union` of the various types of values desired. The programmer declares the union, and associates a union member name to each token and nonterminal symbol having a value. When the value is referenced through a `$$` or `$n` construction, `yacc` automatically inserts the appropriate union name, so that no unwanted conversions will take place. In addition, type-checking commands such as `lint(1)` will be far more silent.

There are three mechanisms used to provide for this typing. First, there is a way of defining the union; this must be done by the programmer since other programs, notably the lexical analyzer, must know about the union member names. Second, there is a way of associating a union member name with tokens and nonterminals. Finally, there is a mechanism for describing the type of those few values where `yacc` cannot easily determine the type.

To declare the union, the programmer includes in the declaration section:

```
%union  {
        body of union ...
        }
```

This declares the `yacc` value stack, and the external variables `yylval` and `yyval`, to have type equal to this union. If `yacc` was invoked with the `-d` option, the union declaration is copied onto the *y.tab.h* file. Alternatively, the union may be declared in a header file, and a typedef used to define the variable `YYSTYPE` to represent this union. Thus, the header file might also have said:

```
typedef union {
        body of union ...
        } YYSTYPE;
```

The header file must be included in the declarations section, by use of `%{` and `%}`.

Once `YYSTYPE` is defined, the union member names must be associated with the various terminal and nonterminal names. The construction

```
< name >
```

is used to indicate a union member name. If this follows one of the keywords `%token`, `%left`, `%right`, and `%nonassoc`, the union member name is associated with the tokens listed. Thus, saying

```
%left  <optype>  '+'  '-'
```

will tag any reference to values returned by these two tokens with the union member name *optype*. Another keyword, `%type`, is used similarly to associate union member names with nonterminals. Thus, one might say

```
%type  <nodetype>  expr  stat
```

There remain a couple of cases where these mechanisms are insufficient. If there is an action within a rule, the value returned by this action has no *a priori* type. Similarly, reference to left-context values (such as $0 — see the previous subsection) leaves `yacc` with no easy way of knowing the type. In this case, a type can be imposed on the reference by inserting a union member name, between < and >, immediately after the first $. An example of this usage is

```
rule    :   aaa  {  $<intval>$  =  3;  } bbb
                 {    fun( $<intval>2, $<other>0 );   }
        ;
```

This syntax has little to recommend it, but the situation arises rarely.

A sample specification is given in 10.13. The facilities in this subsection are not triggered until they are used: in particular, the use of `%type` will turn on these mechanisms. When they are used, there is a fairly strict level of checking. For example, use of $n or $$ to refer to something with no defined type is diagnosed. If these facilities are not triggered, the `yacc` value stack is used to hold `int`'s, as was true historically. This paper is reprinted in this manual.

10.11. A Simple Example

This example gives the complete `yacc` specification for a small desk calculator; the desk calculator has 26 registers, labeled 'a' through 'z', and accepts arithmetic expressions made up of the operators +, –, *, /, % (mod operator), & (bitwise and), | (bitwise or), and assignment. If an expression at the top level is an assignment, the value is not printed; otherwise it is. As in C, an integer that begins with 0 (zero) is assumed to be octal; otherwise, it is assumed to be decimal.

As an example of a `yacc` specification, the desk calculator does a reasonable job of showing how precedences and ambiguities are used, and demonstrating simple error recovery. The major oversimplifications are that the lexical analysis phase is much simpler than for most applications, and the output is produced immediately, line-by-line. Note the way that decimal and octal integers are read in by the grammar rules; This job is probably better done by the lexical analyzer.

```
%{
#  include  <stdio.h>
#  include  <ctype.h>

int  regs[26];
int  base;

%}

%start  list

%token  DIGIT  LETTER

%left  '|'
%left  '&'
```



```
%left  '+'  '-'
%left  '*'  '/'  '%'
%left UMINUS   /* supplies precedence for unary minus */

%%   /* beginning of rules section */

list    :       /* empty */
        |       list  stat  '\n'
        |       list  error  '\n'
                        {       yyerrok;  }
        ;

stat    :       expr
                        {       printf( "%d\n", $1 );  }
        |       LETTER  '='  expr
                        {       regs[$1]  =  $3;  }
        ;

expr    :       '('  expr  ')'
                        {       $$  =  $2;  }
        |       expr  '+'  expr
                        {       $$  =  $1  +  $3;  }
        |       expr  '-'  expr
                        {       $$  =  $1  -  $3;  }
        |       expr  '*'  expr
                        {       $$  =  $1  *  $3;  }
        |       expr  '/'  expr
                        {       $$  =  $1  /  $3;  }
        |       expr  '%'  expr
                        {       $$  =  $1  %  $3;  }
        |       expr  '&'  expr
                        {       $$  =  $1  &  $3;  }
        |       expr  '|'  expr
                        {       $$  =  $1  |  $3;  }
        |       '-'  expr        %prec  UMINUS
                        {       $$  =  -  $2;  }
        |       LETTER
                        {       $$  =  regs[$1];  }
        |       number
        ;

number  :       DIGIT
                        {       $$ = $1;    base  =  ($1==0)  ?  8  :  10;  }
        |       number  DIGIT
                        {       $$  =  base * $1  +  $2;  }
        ;

%%   /* start of programs */

yylex()          /* lexical analysis routine */
{
/* returns LETTER for lower case letter, yylval=0 thru 25 */
/* return DIGIT for digit, yylval=0 thru 9 */
/* all other characters are returned immediately */

        int     c;

        while((c = getchar()) == ' ') { /* skip blanks */ }
```

```
                                                    /* c is now nonblank */

        if(islower(c))   {
                yylval = c - 'a';
                return(LETTER);
        }
        if(isdigit(c))   {
                yylval = c - '0';
                return(DIGIT);
        }
        return(c);
}
```

10.12. yacc Input Syntax

This section describes the `yacc` input syntax, as a `yacc` specification. Context dependencies, etc., are not considered. Ironically, the `yacc` input specification language is most naturally specified as an LR(2) grammar; the sticky part comes when an identifier is seen in a rule, immediately following an action. If this identifier is followed by a colon, it is the start of the next rule; otherwise it is a continuation of the current rule, which just happens to have an action embedded in it. As implemented, the lexical analyzer looks ahead after seeing an identifier, and decide whether the next token (skipping blanks, newlines, comments, etc.) is a colon. If so, it returns the token `C_IDENTIFIER`. Otherwise, it returns `IDENTIFIER`. Literals (quoted strings) are also returned as `IDENTIFIERs`, but never as part of `C_IDENTIFIERs`.

```
        /* grammar for the input to yacc */

        /* basic entities */
%token  IDENTIFIER       /* includes identifiers and literals */
%token  C_IDENTIFIER     /* identifier (not literal) followed by : */
%token  NUMBER           /* [0-9]+ */

        /* reserved words:  %type => TYPE, %left => LEFT, etc. */

%token  LEFT  RIGHT  NONASSOC  TOKEN  PREC  TYPE  START  UNION

%token  MARK    /* the %% mark */
%token  LCURL   /* the %{ mark */
%token  RCURL   /* the %} mark */

        /* ascii character literals stand for themselves */

%start  spec

%%

spec    :       defs  MARK  rules  tail
        ;

tail    :       MARK    {     In this action, eat up the rest of the file     }
        |       /* empty: the second MARK is optional */
        ;

defs    :       /* empty */
        |       defs  def
        ;
```

```
def     :       START  IDENTIFIER
        |       UNION  {  Copy union definition to output   }
        |       LCURL  {  Copy C code to output file    }  RCURL
        |       defs  rword  tag  nlist
        ;

rword   :       TOKEN
        |       LEFT
        |       RIGHT
        |       NONASSOC
        |       TYPE
        ;

tag     :       /* empty: union tag is optional */
        |       '<'  IDENTIFIER  '>'
        ;

nlist   :       nmno
        |       nlist  nmno
        |       nlist  ','  nmno
        ;

nmno    :       IDENTIFIER       /* NOTE: literal illegal with %type */
        |       IDENTIFIER NUMBER   /* NOTE: illegal with %type */
        ;

        /* rules section */

rules   :       C_IDENTIFIER  rbody  prec
        |       rules  rule
        ;

rule    :       C_IDENTIFIER  rbody  prec
        |       '|'  rbody  prec
        ;

rbody   :       /* empty */
        |       rbody  IDENTIFIER
        |       rbody  act
        ;

act     :       '{'  {  Copy action, translate $$, etc.   }   '}'
        ;

prec    :       /* empty */
        |       PREC  IDENTIFIER
        |       PREC  IDENTIFIER  act
        |       prec  ';'
        ;
```

10.13. An Advanced Example

This section gives an example of a grammar using some of the advanced features discussed in Section 10.10. The desk calculator example in section 10.11 is modified to provide a desk calculator that does floating point interval arithmetic. The calculator understands floating point constants, the arithmetic operations +, −, *, /, unary −, and = (assignment), and has 26 floating point variables, 'a' through 'z'. Moreover, it also understands *intervals*, written

```
( x , y )
```

where *x* is less than or equal to *y*. There are 26 interval-valued variables 'A' through 'Z' that may also be used. The usage is similar to that in section 10.11 — assignments return no value, and print nothing, while expressions print the (floating or interval) value.

This example explores a number of interesting features of `yacc` and C. Intervals are represented by a structure, consisting of the left and right endpoint values, stored as *double*'s. This structure is given a type name, `INTERVAL`, by using `typedef`.
The `yacc` value stack can also contain floating point scalars, and integers (used to index into the arrays holding the variable values). Notice that this entire strategy depends strongly on being able to assign structures and unions in C. In fact, many of the actions call functions that return structures as well.

It is also worth noting the use of `YYERROR` to handle error conditions: division by an interval containing 0, and an interval presented in the wrong order. In effect, the error recovery mechanism of `yacc` is used to throw away the rest of the offending line.

In addition to the mixing of types on the value stack, this grammar also demonstrates an interesting use of syntax to keep track of the type (for example, scalar or interval) of intermediate expressions. Note that a scalar can be automatically promoted to an interval if the context demands an interval-value. This causes a large number of conflicts when the grammar is run through `yacc`: 18 Shift/Reduce and 26 Reduce/Reduce. The problem can be seen by looking at the two input lines:

```
2.5 + ( 3.5 - 4. )
```

and

```
2.5 + ( 3.5 , 4. )
```

Notice that the 2.5 is to be used in an interval-valued expression in the second example, but this fact is not known until the ',' is read; by this time, 2.5 is finished, and the parser cannot go back and change its mind. More generally, it might be necessary to look ahead an arbitrary number of tokens to decide whether to convert a scalar to an interval. This problem is evaded by having two rules for each binary interval-valued operator: one when the left operand is a scalar, and one when the left operand is an interval. In the second case, the right operand must be an interval, so the conversion will be applied automatically. Despite this evasion, there are still many cases where the conversion may be applied or not, leading to the above conflicts. They are resolved by listing the rules that yield scalars first in the specification file; in this way, the conflicts will be resolved in the direction of keeping scalar-valued expressions scalar-valued until they are forced to become intervals.

This way of handling multiple types is very instructive, but not very general. If there were many kinds of expression types, instead of just two, the number of rules needed would increase dramatically, and the conflicts even more dramatically. Thus, while this example is instructive, it is better practice in a more

normal programming language environment to keep the type information as part of the value, and not as part of the grammar.

Finally, a word about the lexical analysis. The only unusual feature is the treatment of floating point constants. The C library routine *atof* is used to do the actual conversion from a character string to a double-precision value. If the lexical analyzer detects an error, it responds by returning a token that is illegal in the grammar, provoking a syntax error in the parser, and thence error recovery.

```
%{

#  include  <stdio.h>
#  include  <ctype.h>

typedef  struct  interval  {
         double  lo,  hi;
         }  INTERVAL;

INTERVAL  vmul(),  vdiv();

double  atof();

double  dreg[ 26 ];
INTERVAL  vreg[ 26 ];

%}

%start    lines

%union    {
         int  ival;
         double  dval;
         INTERVAL  vval;
         }

%token <ival> DREG VREG    /* indices into dreg, vreg arrays */

%token <dval> CONST                /* floating point constant */

%type <dval> dexp          /* expression */

%type <vval> vexp          /* interval expression */

         /* precedence information about the operators */

%left    '+'  '-'
%left    '*'  '/'
%left    UMINUS    /* precedence for unary minus */

%%

lines    :        /* empty */
         |        lines  line
         ;

line     :        dexp  '\n'
                       {          printf(  "%15.8f\n",  $1  );  }
         |        vexp  '\n'
                       {          printf(  "(%15.8f  ,  %15.8f  )\n",  $1.lo,  $1.hi  );  }
         |        DREG  '='  dexp  '\n'
                       {          dreg[$1]  =  $3;  }
         |        VREG  '='  vexp  '\n'
                       {          vreg[$1]  =  $3;  }
         |        error  '\n'
                       {          yyerrok;  }
```

```
          ;

dexp      :         CONST
          |         DREG
                          {          $$  =  dreg[$1];  }
          |         dexp  '+'  dexp
                          {          $$  =  $1  +  $3;  }
          |         dexp  '-'  dexp
                          {          $$  =  $1  -  $3;  }
          |         dexp  '*'  dexp
                          {          $$  =  $1  *  $3;  }
          |         dexp  '/'  dexp
                          {          $$  =  $1  /  $3;  }
          |         '-'  dexp            %prec  UMINUS
                          {          $$  =  - $2;  }
          |         '('  dexp  ')'
                          {          $$  =  $2;  }

          ;

vexp      :         dexp
                          {          $$.hi  =  $$.lo  =  $1;  }
          |         '('  dexp  ','  dexp  ')'
                          {
                          $$.lo  =  $2;
                          $$.hi  =  $4;
                          if(  $$.lo  >  $$.hi  ){
                                     printf(  "interval  out  of  order\n"  );
                                     YYERROR;
                                     }
                          }
          |         VREG
                          {          $$  =  vreg[$1];    }
          |         vexp  '+'  vexp
                          {          $$.hi  =  $1.hi  +  $3.hi;
                                     $$.lo  =  $1.lo  +  $3.lo;    }
          |         dexp  '+'  vexp
                          {          $$.hi  =  $1  +  $3.hi;
                                     $$.lo  =  $1  +  $3.lo;    }
          |         vexp  '-'  vexp
                          {          $$.hi  =  $1.hi  -  $3.lo;
                                     $$.lo  =  $1.lo  -  $3.hi;    }
          |         dexp  '-'  vexp
                          {          $$.hi  =  $1  -  $3.lo;
                                     $$.lo  =  $1  -  $3.hi;    }
          |         vexp  '*'  vexp
                          {          $$  =  vmul(  $1.lo,  $1.hi,  $3  );  }
          |         dexp  '*'  vexp
                          {          $$  =  vmul(  $1,  $1,  $3  );  }
          |         vexp  '/'  vexp
                          {          if(  dcheck(  $3  )  )  YYERROR;
                                     $$  =  vdiv(  $1.lo,  $1.hi,  $3  );  }
          |         dexp  '/'  vexp
                          {          if(  dcheck(  $3  )  )  YYERROR;
                                     $$  =  vdiv(  $1,  $1,  $3  );  }
          |         '-'  vexp            %prec  UMINUS
                          {          $$.hi  =  -$2.lo;    $$.lo  =  -$2.hi;    }
          |         '('  vexp  ')'
                          {          $$  =  $2;  }
          ;
```

```
%%
# define BSZ 50  /* buffer size for floating point numbers */

        /* lexical analysis */

yylex(){
        register  c;

        while( (c=getchar()) == ' ' ){ /* skip over blanks */ }

        if(  isupper(  c  )  ){
                yylval.ival  =  c  -  'A';
                return(  VREG  );
                }
        if(  islower(  c  )  ){
                yylval.ival  =  c  -  'a';
                return(  DREG  );
                }

        if(  isdigit(  c  )  ||  c=='.'  ){
                /* gobble up digits, points, exponents */

                char  buf[BSZ+1],  *cp  =  buf;
                int  dot  =  0,  exp  =  0;

                for(  ;  (cp-buf)<BSZ  ;  ++cp,c=getchar()  ){

                        *cp  =  c;
                        if(  isdigit(  c  )  )  continue;
                        if(  c  ==  '.'  ){
                                if( dot++ || exp ) return( '.' );
                                        /* will cause syntax error */
                                continue;
                                }

                        if(  c  ==  'e'  ){
                                if( exp++ ) return( 'e' );
                                        /* will cause syntax error */
                                continue;
                                }

                        /* end of number */
                        break;
                        }
                *cp  =  '\0';
                if(  (cp-buf)  >=  BSZ  )
                        printf(  "constant  too  long:  truncated\n"  );
                else ungetc( c, stdin );  /* push back last char read */
                yylval.dval  =  atof(  buf  );
                return(  CONST  );
                }
        return(  c  );
        }

INTERVAL  hilo(  a,  b,  c,  d  )  double  a,  b,  c,  d;  {
        /* returns the smallest interval containing a, b, c, and d */
        /* used by *, / routines */
        INTERVAL  v;

        if(  a>b  )  {  v.hi  =  a;    v.lo  =  b;  }
        else  {  v.hi  =  b;    v.lo  =  a;  }

        if(  c>d  )  {
                if(  c>v.hi  )  v.hi  =  c;
```

```
                if(  d<v.lo  )  v.lo  =  d;
                }
        else  {
                if(  d>v.hi  )  v.hi  =  d;
                if(  c<v.lo  )  v.lo  =  c;
                }
        return(  v  );
        }

INTERVAL  vmul(  a,  b,  v  )  double  a,  b;    INTERVAL  v;  {
        return(  hilo(  a*v.hi,  a*v.lo,  b*v.hi,  b*v.lo  )  );
        }

dcheck(  v  )  INTERVAL  v;  {
        if(  v.hi  >=  0.  &&  v.lo  <=  0.  ){
                printf(  "divisor  interval  contains  0.\n"  );
                return(  1  );
                }
        return(  0  );
        }

INTERVAL  vdiv(  a,  b,  v  )  double  a,  b;    INTERVAL  v;  {
        return(  hilo(  a/v.hi,  a/v.lo,  b/v.hi,  b/v.lo  )  );
        }
```

10.14. Old Features Supported but not Encouraged

This section mentions synonyms and features which are supported for historical continuity, but, for various reasons, are not encouraged.

1. Literals may also be delimited by double quotes "".

2. Literals may be more than one character long. If all the characters are alphabetic, numeric, or _, the type number of the literal is defined, just as if the literal did not have the quotes around it. Otherwise, it is difficult to find the value for such literals.

   The use of multi-character literals is likely to mislead those unfamiliar with `yacc`, since it suggests that `yacc` is doing a job which must be actually done by the lexical analyzer.

3. Most places where % is legal, backslash '\' may be used. In particular, \\ is the same as %%, \left the same as %left, etc.

4. There are a number of other synonyms:

```
        %< is the same as %left
        %> is the same as %right
        %binary and %2 are the same as %nonassoc
        %0 and %term are the same as %token
        %= is the same as %prec
```

5. Actions may also have the form

```
        ={ . . . }
```

   and the curly braces can be dropped if the action is a single C statement.

---

6. C code between %{ and %} used to be permitted at the head of the rules section, as well as in the declaration section.