z/VM
7.4

OpenExtensions Advanced Application Programming Tools

SC24-6295-74

Note:

Before you use this information and the product it supports, read the information in “Notices” on page 135.

This edition applies to version 7, release 4 of IBM® z/VM® (product number 5741-A09) and to all subsequent releases and modifications until otherwise indicated in new editions.

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About this Document

This document provides information on using the IBM® z/VM® OpenExtensions™ `lex`, `yacc`, and `make` utilities to help you write OpenExtensions applications. This document also describes debugging services associated with OpenExtensions.

Before using these utilities, you should have some knowledge of OpenExtensions concepts and services. Some knowledge of the open systems standards or a UNIX® operating system is also assumed.

Intended Audience

This information is for application programmers who need to:

- Port to OpenExtensions their POSIX-conforming applications that use `lex` and `yacc`
- Develop POSIX-conforming applications for OpenExtensions that use `lex` and `yacc`
- Manage application development using `make`
- Debug applications

Conventions Used in This Document

The following conventions are used in this document.

Case-Sensitivity

The OpenExtensions shell commands and utilities are case-sensitive and distinguish characters as either uppercase or lowercase. Therefore, `FILE1` is not the same as `file1`.

Typography

The following typographic conventions are used:

`bold`
Bold lowercase is used for shell commands (`make`).

variable
Lowercase italics is used to indicate a variable.

VARIABLE
Uppercase italics is used to indicate a shell environment variable.

`example font`
Example font is used to indicate file specifications (`.profile`, `XEDIT PROFILE`), directory names (`/usr/lib/nls/charmap`), and verbatim user input.

Where to Find More Information

For information about OpenExtensions concepts and services, see *z/VM: OpenExtensions User's Guide*.

For information on how OpenExtensions adheres to the POSIX standards, see *z/VM: OpenExtensions POSIX Conformance Document*.

For a list of other z/VM publications, see "Bibliography" on page 139.

Links to Other Documents and Websites

The PDF version of this document contains links to other documents and websites. A link from this document to another document works only when both documents are in the same directory or database, and a link to a website works only if you have access to the Internet. A document link is to a specific

edition. If a new edition of a linked document has been published since the publication of this document, the linked document might not be the latest edition.

How to provide feedback to IBM

We welcome any feedback that you have, including comments on the clarity, accuracy, or completeness of the information. See How to send feedback to IBM for additional information.

Summary of Changes for z/VM: OpenExtensions Advanced Application Programming Tools

This information includes terminology, maintenance, and editorial changes. Technical changes or additions to the text and illustrations for the current edition are indicated by a vertical line (**|**) to the left of the change.

SC24-6295-74, z/VM 7.4 (September 2024)

This edition supports the general availability of z/VM 7.4. Note that the publication number suffix (-74) indicates the z/VM release to which this edition applies.

SC24-6295-73, z/VM 7.3 (December 2023)

This edition includes terminology, maintenance, and editorial changes.

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This edition supports the general availability of z/VM 7.3. Note that the publication number suffix (-73) indicates the z/VM release to which this edition applies.

SC24-6295-01, z/VM 7.2 (September 2020)

This edition supports the general availability of z/VM 7.2.

Chapter 1. Tutorial Using OpenExtensions lex and yacc

This tutorial introduces the basic concepts of `lex` and `yacc` and describes how you can use the programs to produce a simple desk calculator. New users should work through the tutorial to get a feel for how to use `lex` and `yacc`.

Those who are already familiar with the concepts of input analysis and interpretation may decide to skip this chapter and go directly to Chapter 2, "Generating a Lexical Analyzer Using OpenExtensions lex," on page 29 and Chapter 3, "Generating a Parser Using OpenExtensions yacc," on page 49. These chapters give full details of all aspects of the programs.

All documentation for `lex` and `yacc` assumes that you are familiar with the C programming language. To use the two programs, you need to be able to write C code.

Uses for the lex and yacc Utilities

The `lex` and `yacc` utilities of the OpenExtensions Shell and Utilities are a pair of programs that help write other programs. Input to `lex` and `yacc` describes how you want your final program to work. The output is source code in the C programming language; you can compile this source code to get a program that works the way that you originally described.

You use `lex` and `yacc` to produce software that analyzes and interprets input. For example, suppose you want to write a simple desk calculator program. Such a desk calculator is easy to create using `lex` and `yacc`, and this tutorial shows how one can be put together.

The C code produced by `lex` analyzes input and breaks it into *tokens*. In the case of a simple desk calculator, math expressions must be divided into tokens. For example:

```
178 + 85
```

would be treated as **178**, **+**, and **85**.

The C code produced by `yacc` *interprets* the tokens that the `lex` code has obtained. For example, the `yacc` code figures out that a number followed by a **+** followed by another number means that you want to add the two numbers together.

`lex` and `yacc` take care of most of the technical details involved in analyzing and interpreting input. You just describe what the input looks like; the code produced by `lex` and `yacc` then worries about recognizing the input and matching it to your description. Also, the two programs use a format for describing input that is simple and intuitive; `lex` and `yacc` input is much easier to understand than a C program written to do the same work.

You can use the two programs separately if you want. For example, you can use `lex` to break input into tokens and then write your own routines to work with those tokens. Similarly, you can write your own software to break input into tokens and then use `yacc` to analyze the tokens you have obtained. However, the programs work very well together and are often most effective when combined.

Code Produced by lex and yacc

The C code that is directly produced by `lex` and `yacc` is intended to be POSIX-conforming. When user-written code is added, the portability of the resulting program depends on whether the added code conforms to the POSIX standards.

To make it easy for you to add your own code, all identifiers and functions created by `lex` and `yacc` begin with `yy` or `YY`. If you avoid using such identifiers in your own code, your code will not conflict with code generated by the two programs.

lex Output

The goal of `lex` is to generate the code for a C function named `yylex()`. This function is called with no operands. It returns an `int` value. A value of 0 is returned when end-of-file is reached; otherwise, `yylex()` returns a value indicating what kind of token was found.

`lex` also creates two important external data objects:

1. A string named `yytext`. This string contains a sequence of characters making up a single input token. The token is read from the stream `yyin`, which, by default, is the standard input (**stdin**).
2. An integer variable named `yyleng`. This gives the number of characters in the `yytext` string.

In most `lex` programs, a token in `yytext` has an associated *value* that must be calculated and passed on to the supporting program. By convention, `yacc` names this data object `yylval`. For example, if `yylex()` reads a token which is an integer, `yytext` contains the string of digits that made up the integer, while `yylval` typically contains the actual value of the integer. By default, `yylval` is declared to be an `int`, but there are ways to change this default.

Usually, a call to `yylex()` obtains a single token from the standard input; however, it is possible to have `yylex()` process the entire input, applying transformations and writing new output.

yacc Output

The goal of `yacc` is to generate the code for a C function named `yyparse()`. The `yyparse()` function calls `yylex()` to read a token from the standard input until end of file. `yyparse()` uses the return values from `yylex()` to figure out the types of each token obtained, and it uses `yylval` in each case as the actual value of that token.

The `yyparse()` function is called without any operands. The result of the function is 0 if the input that was parsed was valid (that is, if the form of the input matched the descriptions given to `lex` and `yacc`). The result is 1 if the input contained errors of any kind.

Defining Tokens

As noted previously, `yylex()` returns a code value indicating what kind of token has been found, and `yyparse()` bases its actions on this value. Obviously then, the two functions must agree on the values that they assign to different tokens.

One way to do this is by using C *header files*. For example, consider a simple desk calculator program. Its input consists of expressions with simple forms such as:

```
789 + 45
3 * 24
9045 - 723
```

Thus there are two types of tokens: integer operands and mathematical operators.

If `yylex()` reads an operator like **+** or **-**, it can just return the operator itself to indicate the type of token obtained. If it reads an integer operand, it should store the value of the operand in `yylval`, and return a code indicating that an integer has been found. To make sure that both `yylex()` and `yyparse()` agree on this code, you might create a file that contains the C definition:

```
#define INTEGER 257
```

The values of the tokens are started at 257 to distinguish them from characters, and because `yacc` uses 256 internally. After this has been defined, you can include this file, with a C `#include` statement, and then use the **INTEGER** definition any time you want to refer to an integer token.

Suppose now that our desk calculator expands so that it recognizes variables as well as integer operands. Then change our header file to show that there are now two types of operands:

```
#define INTEGER 257
#define VARIABLE 258
```

Again, by using these definitions, it insures that `yylex()` and `yyparse()` agree on what stands for what.

`yacc` has facilities that can automatically generate such definition files; therefore, early chapters speak in terms of header files created by hand; later chapters use header files created by `yacc`.

Calling the Code

The code produced by `lex` and `yacc` only constitutes part of a program. For example, it does not include a **main** routine. At the very minimum, therefore, you need to create a **main** routine of the form:

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

This calls `yyparse()`, which then goes on to read and process the input, calling on `yylex()` to break the input into tokens. `yyparse()` terminates when it reaches end-of-file, when it encounters some construct that marks the logical end of input, or when it finds an error that it is not prepared to handle. The value returned by `yyparse()` is returned as the status of the whole program. This **main** routine is available in a `yacc` library, as shown later.

Obviously, the **main** routine may have to be much more complex It may also be necessary to write a number of functions that are called by `yylex()` to help analyze the input, or by `yyparse()` to help process it.

Using the lex and yacc Commands

Suppose that `file.l` contains `lex` input. Then the command

```
lex file.l
```

uses that input to produce a file named **lex.yy.c**. This file can then be compiled using c89 to produce the object code for `yylex()`.

Suppose that **file.y** contains `yacc` input. Then the command:

```
yacc file.y
```

uses that input to produce a file named **y.tab.c**. You can then compile this file using c89 to produce the object code for `yyparse()`.

To produce a complete program, you must link the object code for `yyparse()` and `yylex()` together, along with any other necessary functions.

The OpenExtensions Shell and Utilities provides a library of useful `lex` routines. It also provides a `yacc` library that contains the entry point for the simple **main** entry point described earlier. These libraries should have been installed or created as part of your installation. When you use any library, be sure to add the library name to the linker commands that you use to build the final program. Chapter 2, “Generating a Lexical Analyzer Using OpenExtensions lex,” on page 29 and Chapter 3, “Generating a Parser Using OpenExtensions yacc,” on page 49 describe these routines.

Tokenizing with lex

As mentioned earlier, the code produced by `lex` breaks its input into *tokens*, the basic logical pieces of the input. This section discusses how you describe input tokens to `lex` and what `lex` does with your description.

Characters and Regular Expressions

`lex` assumes that the input is a sequence of characters. The most important of these characters are usually the printable ones: the letters, digits, and assorted punctuation marks.

The input to `lex` indicates the *patterns* of characters that make up various types of tokens. For example, suppose you are using `lex` to help make a desk calculator program. Such a program performs various calculations with numbers, so you must tell `lex` what pattern of characters makes up a number. Of course, a typical number is made up of a sequence of one or more digit characters, so you need a way to describe such a sequence.

In `lex`, patterns of characters are described using *regular expressions*. The sections that follow describe several kinds of regular expressions you can use to describe character patterns.

Character Strings

The simplest way to describe a character pattern is just to list the characters. In `lex` input, enclose the characters in quotation marks:

```
"if"
"while"
"goto"
```

These are called *character strings*. A character string matches the sequence of characters enclosed in the string.

Inside character strings, the standard C escape sequences are recognized:

```
\n — newline
\b — backspace
\t — tab
```

and so on. See Chapter 2, “Generating a Lexical Analyzer Using OpenExtensions lex,” on page 29 for the complete list. These can be used in regular expressions to stand for otherwise unprintable characters.

Anchoring Patterns

A pattern can be anchored to the start or end of a line. You can use **^** at the start of a regular expression to force a match to the start of a line, and **$** at the end of an expression to match the end of a line. For example,

```
^"We"
```

matches the string `We` only when it appears at the beginning of a line. The pattern:

```
"end"$
```

matches the string `end` only when it appears at end of a line, whereas the pattern:

```
^"name"$
```

matches the string `name` only when it appears alone on a line.

Character Classes

A *character class* is written as a number of characters inside square brackets, as in:

```
[0123456789]
```

This is a regular expression that stands for any one of the characters inside the brackets. This character class stands for any digit character.

```
[0123456789][0123456789][0123456789]
```

stands for any three digits in a row.

The digit character class can be written more simply as:

```
[0-9]
```

The **-** stands for all the characters that come between the two characters on either side. Thus:

```
[a-z]
```

stands for all characters between *a* and *z,* whereas:

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

stands for all characters in both the range *a* to *z* and the range *A* to *Z*.

Note: - is *not* treated as a range indicator when it appears at the beginning or end of a character class.

If the first character after the **[** is a circumflex (**^**), the character class stands for all characters that are *not* listed in the brackets. For example:

```
[^0-9]
```

stands for all characters that are *not* digits. Similarly:

```
[^a-zA-Z0-9]
```

stands for all characters that are not alphabetic or numeric.

There is a special character class—written as **.** —that matches *any* character except newline. The pattern:

```
“p.x”
```

matches any 3-character sequence starting with *p* and ending with *x*.

Note: A newline is never matched except when explicitly specified as **\n**, or in a range. In particular, a **.** never matches newline.

New character class symbols have been introduced by POSIX. These are provided as special sequences that are valid only within character class definitions. The sequences are:

```
[.coll.]"        collation of character coll
[=equiv=]        collation of the character class equiv
[:char-class:]    any of the characters from char-class
```

`lex` accepts only the POSIX locale for these definitions. In particular, multicharacter collation symbols are not supported. You can still use, for example, the character class:

```
[[.a.]-[.z.]]
```

which is equivalent to:

```
[a-z]
```

for the POSIX locale.

`lex` accepts the following POSIX-defined character classes:

```
[:alnum:]  [:cntrl:]  [:lower:]  [:space:]
[:alpha:]  [:digit:]  [:print:]  [:upper:]
[:blank:]  [:graph:]  [:punct:]  [:xdigit:]
```

It is more portable (and more obvious) to use the new expressions.

Repetitions

Any regular expression followed by an asterisk (*****) stands for zero or more repetitions of the character pattern that matches the regular expression. For example, consider:

```
[[:digit:]][[:digit:]]*
```

This stands for a pattern of characters beginning with a digit, followed by zero or more additional digits. In other words, this regular expression stands for the pattern of characters that form a typical number. As another example, consider:

```
[[:upper:]][[:lower:]]*
```

This stands for an uppercase letter followed by zero or more lowercase letters.

Take a moment to consider the regular expression that matches any legal variable name in the C programming language. The answer is:

```
[[:alpha:]_][[:alnum:]_]*
```

which stands for a letter or underscore, followed by any number of letters, digits, or underscores.

The ***** stands for zero or more repetitions. You can use the **+** character in the same way to stand for one or more repetitions. For example:

```
[[:digit:]]+
```

stands for a sequence of one or more digit characters. This is another way to represent the pattern of a typical number. It is equivalent to:

```
[[:digit:]][[:digit:]]*
```

You can indicate a specific number of repetitions by putting a number inside brace brackets. For example:

```
[[:digit:]]{3}
```

stands for a sequence of three digits. You can also indicate a possible range of repetitions with a form such as:

```
[[:digit:]]{1,10}
```

This indicates a pattern of one to ten digits. You might use this kind of regular expression if you want to avoid numbers that are too large to handle. As another example:

```
[[:alpha:]_][[:alnum:]_]{0,31}
```

describes a pattern of 1 to 32 characters. You might use this to describe C variable names that can be up to 32 characters long. (Just remember that you must provide an action to discard the extra characters in a longer name.)

Optional Expressions

A regular expression followed by a question mark (**?**) makes that expression optional. For example:

```
A?
```

matches 0 or 1 occurrence of the character *A*.

Alternatives

Two regular expressions separated by an "or" bar (**|**) produces a regular expression that matches either one of the expressions. For example:

```
[[:lower:]]|[[:upper:]]
```

matches either a lowercase letter or an uppercase one.

Grouping

You may use parentheses to group together regular expressions. For example,

```
("high"|"low"|"medium")
```

matches one occurrence of any of the three strings `high`, `low`, or `medium`.

Note: Quotation marks do *not* group; a common mistake is to write:

```
"is"?
```

This pattern matches the letter *i*, followed by an optional *s*. To make the entire string optional, use parentheses:

```
("is")?
```

Definitions

A `lex` definition associates a name with a character pattern. The format of a definition is:

```
name regular-expression
```

where the *regular-expression* describes the pattern that gets the name. For example:

```
digit [[:digit:]]
lower [[:lower:]]
upper [[:upper:]]
```

are three definitions that give names to various character patterns.

A `lex` definition can refer to a name that has already been defined by putting that name in brace brackets. For example,

```
letter {lower}|{upper}
```

defines the `letter` pattern as one that matches the previously defined `lower` or `upper` patterns. Similarly,

```
variable {letter}({letter}|{digit})*
```

defines a `variable` pattern as a letter followed by zero or more letters or digits.

For POSIX conformance, `lex` now treats the definition, when expanded, as a group. Essentially, the expression is treated as if you had enclosed it in parentheses. Older `lex` processors did not always do this.

Definitions are always the first things that appear in the input to `lex`. They make the rest of the `lex` input more readable, because names are more easily understood than regular expressions. In `lex` input, the last definition is followed by a line containing only:

```
%%
```

This serves to mark the end of the definitions.

Translations

After the **%%** that marks the end of definitions, `lex` input contains a number of *translations*. The translations describe the actual tokens that you expect to see in input, and what is to be done with each token when it is received.

The format of a translation is:

```
token-pattern { actions }
```

The *token-pattern* is given by a regular expression that may contain definitions from the previous section. The *actions* are a set of zero or more C source code statements indicating what is to be done when such a pattern is recognized. Actions are written with the usual C formatting rules, so they can be split over a number of lines.

Also allowed as an action is a single "or" bar (**|**) which indicates that the action to be used is that of the next translation rule; for example:

```
"if"|
"while"{
        /* handle keywords */
    }
```

This could have been written as:

```
("if")|("while") { …. }
```

but you will find that using the alteration operator (**|**) makes your scanner larger and slower. It is always better to have many simple expressions that share one action separated with a single "or" bar.

In general, the actions associated with a token should determine the value to be returned by `yylex()` to indicate the token type. The actions may also assign a value to `yylval` to indicate the *value* of the token.

As a simple example, let's go back to the desk calculator. This might have the translation rule:

```
[[:digit:]]+    {
    yylval = atoi(yytext);
    return INTEGER;
    }
```

Recall that `yytext` holds the text of the token that was found, and `yylval` is supposed to hold the actual value of that token. Thus:

```
yylval = atoi(yytext);
```

uses the C `atoi()` library function to convert this text into an integer value and assigns that integer to `yylval`. After this conversion has taken place, the action returns the defined value **INTEGER** to indicate that an integer has been obtained. (“Defining Tokens” on page 2 talks about this kind of definition.)

As another example of a translation, consider this:

```
[-+*/]    {
    return *yytext;
    }
```

This says each of the four operator characters inside the parentheses is also a separate token. If one of these is found, the action returns the first character of `yytext`, which is the operator character itself; therefore if `yylex()` finds an operator, it returns the operator itself, which is the first character in `yytext`. (Remember that **-** is *not* treated as a range indicator when it appears at the beginning or end of a character class.) If the action in a translation consists of a single C statement, you can omit the brace brackets. For example, you could have written:

```
[-+*/]    return *yytext;
```

Declarations

The definition or translation sections of `lex` input may contain *declarations*. These are usual C declarations for any data objects that the actions in translations may need.

If a translation section contains declarations, they must appear at the beginning of the section. The special construct **%{** begins the declarations, and **%}** ends them. These constructs must appear alone at the beginning of a line.

As an example, consider the following:

```
%%

%{
    int wordcount = 0;
%}

[^ \t\n]+    { wordcount++; }
[ \t]+    ;
[\n]    {
        printf("%d\n",wordcount);
        wordcount = 0;
    }
```

This generates a simple program that counts the words on each line of input. If `yylex()` finds a token consisting of one or more characters that are not spaces, tabs, or newlines, it increments **wordcount**. For sequences of one or more tabs or spaces, it does nothing (the action is just **;**—a null statement). When it encounters a newline, it displays the current value of **wordcount** and resets the count to zero.

Declarations given in the translations section are local to the `yylex()` function that `lex` produces. Declarations may also appear at the beginning of the definition section; in this case, they are external to the `yylex()` function. As an example, consider the following `lex` input, provided as the file **wc.l** in the **/etc/samples** directory:

```
%{
        int characters = 0;
        int words = 0;
        int lines = 0;
%}
%%
\n      {
                ++lines;
                ++characters;
        }
[ \t]+          characters += yyleng;
[^ \t\n]+ {
                ++words;
                characters += yyleng;
        }

%%
```

The definition section ends at the **%%**, which means that it consists only of the given declarations. These declare external data objects. After the **%%** come three translations. If a newline character is found, `yylex()` increments the count of lines and characters. If a sequence of spaces or tabs is found, the character count is incremented by the length of the sequence (specified by `yyleng`, which gives the length of a token). If a sequence of one or more other characters is found, `yylex()` increments the word count and again increments the character count by the value of `yyleng`.

You can use the `yylex()` generated by this example with a **main** routine of the form:

```
#include <stdio.h>

int yylex(void);

int main(void)
{
        extern int characters, words, lines;

        yylex();
        printf("%d characters, ", characters);
        printf("%d words, ", words);
        printf("%d lines\n", lines);
        return 0;
}
```

This example is provided as **wc.c** in the **/etc/samples** directory. It calls `yylex()` to tokenize the standard input. Because none of the translation actions tell `yylex()` to return, it keeps reading token after token until it reaches end-of-file. At this point, it returns and the **main** function proceeds to display the accumulated counts of characters, words, and lines in the input.

lex Input for Simple Desk Calculator

This chapter has been discussing the `lex` input for a simple desk calculator. To finish things off, here's the complete input file. (This example, with minor changes, is provided as the file **dc1.l** in the **/etc/samples** directory of the distribution.) Assume that the file **defines.h** contains the C definition for **INTEGER**, as given earlier.

```
%{
#include "y.tab.h"
extern int yylval;
%}

%%

[[:digit:]]+    {
                yylval = atoi(yytext);
                return INTEGER;
        }

[-+/*\n]        return *yytext;

[ \t]+          ;
```

This is almost the same as the previous presentation, except that it includes the newline as one of the operator characters. Each line of input is a separate calculation, so you have to pay attention to where lines end.

This input creates a `yylex()` that recognizes all the tokens required for the desk calculator. The next section, "yacc Grammars" on page 10, discusses how to use `yacc` to create a `yyparse()` that can use this `yylex()`.

yacc Grammars

By tradition, the input for `yacc` is called a *grammar*. `yacc` was invented to create parsers for compilers of computing languages; the `yacc` input was used to describe the grammar of such a language.

The primary output of `yacc` is a file named **y.tab.c**. This file contains the source code for a function named `yyparse()`. `yacc` can also produce a number of other kinds of output, as later sections describe.

`yacc` input is divided into three sections: the *declarations* section, the *rule* section, and the *function* section.

The Declarations Section

The declarations section of a `yacc` grammar describes the tokens that make up the grammar.

The simplest way to describe a token is with a line of the form:

```
%token name
```

where *name* is a name that stands for some kind of token. For example, you might have:

```
%token INTEGER
```

to state that **INTEGER** represents an integer token.

Creating Token Definition Files

When you run a grammar through `yacc` using the `-d` option, `yacc` produces a C definition file containing C definitions for all the names declared with `%token` lines in the declarations section of the grammar. The name of this file is **y.tab.h**. Each definition created in this way is given a unique number.

You can use a definition file created by `yacc` to provide definitions for `lex`, or other parts of the program. For example, suppose that **file.l** contains `lex` input for a program and that **file.y** contains `yacc` input:

```
yacc -d file.y
```

creates a **y.tab.h** file as well as a **y.tab.c** file containing `yyparse()`. In the declarations part of the definitions section of the `lex` input in **file.l**, you can have:

```
%{
#include "y.tab.h"
%}
```

to get the C definitions from the generated file. The rest of **file.l** can make use of these definitions.

Precedence Rules

The declarations section of `yacc` input can also contain *precedence rules*. These describe the *precedence* and *binding* of operator tokens.

To understand precedence and binding, it is best to start with an example. In conventional mathematics, multiplication and division are supposed to take place before addition and subtraction (unless parentheses change the order of operation). Multiplication has the *same precedence* as division, but multiplication and division have *higher precedence* than addition and subtraction have.

To understand binding, consider the C expressions:

```
A - B - C
A = B + 8 * 9
```

To evaluate the first expression, you usually picture the operation proceeding from left to right:

```
(A - B) - C
```

To evaluate the second however, you perform the multiplication first, because it has higher precedence than addition:

```
A = ( B + (8 * 9) )
```

The multiplication takes place first, the value is added to **B**, and then the result is assigned to **A**.

Operations that operate from left to right are called *left associative*; operations that operate from right to left are called *right associative*. For example:

```
a/b/c
```

can be parsed as the *left associative*:

```
(a/b)/c
```

or as the *right associative*:

```
a/(b/c)
```

Inside the declarations section of a `yacc` grammar, you can specify the precedence and binding of operators with lines of the form:

```
%left operator operator …
%right operator operator …
```

Operators listed on the same line have the same precedence. For example, you might say:

```
%left '+' '-'
```

to indicate that the **+** and **-** operations have the same precedence and left associativity. The operators are expressed as single characters inside apostrophes. Literal characters in `yacc` input are always shown in this format.

When you are listing precedence classes in this way, list them in order of precedence, from lowest to highest. For example:

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

says that addition and subtraction have a lower precedence than multiplication and division have.

As an example, C generally evaluates expressions from left to right (that is, left associative) while FORTRAN evaluates them from right to left (that is, right associative).

Code Declarations

The declarations section of a `yacc` grammar can contain explicit C source code declarations. These are external to the `yyparse()` function that `yacc` produces. As in `lex`, explicit source code is introduced with the **%{** construct and ends with **%}**; thus:

```
%{
    /* source code */
%}
```

The Grammar Rules Section

The end of the declarations section is marked by a line consisting only of:

```
%%
```

After this comes the rules section, the heart of the grammar.

A rule describes a valid *grammatical construct,* which can be made out of the recognized input tokens and other grammatical constructs. To understand this, here are some sample rules that make sense for a desk calculator program:

```
expression : INTEGER;
expression : expression '+' expression;
expression : expression '-' expression;
expression : expression '*' expression;
expression : expression '/' expression;
```

These rules describe various forms of a grammatical construct called an *expression*. The simplest expression is just an integer token. More complex expressions may be created by adding, subtracting, multiplying, or dividing simpler expressions. In a rule like:

```
expression : expression '+' expression
```

the definition has three *components*: an expression, a **+** token, and another expression.

If a program uses this grammar to analyze the input:

```
1 + 2 + 3
```

what does it do? First, it sees the number 1. This is an **INTEGER** token, so it can be interpreted as an expression. The input thus has the form:

```
expression + 2 + 3
```

Of course, the 2 is also an **INTEGER** and therefore an expression. This gives the form:

```
expression + expression + 3
```

But the program recognizes the first part of this input as one valid form of an expression. Thus, it boils down to:

```
expression + 3
```

In a similar way, this is interpreted as a valid form for an expression.

Actions

The rules section of a yacc grammar does not just describe grammatical constructs; it also tells what to do when each construct is recognized. In other words, it lets you associate *action*s with rules. The general form of a rule is:

```
name : definition { action } ;
```

where *name* is the name of the construct being defined, *definition* is the definition of the construct in terms of tokens and other nonterminal symbols, and *action* is a sequence of zero or more instructions that are to be carried out when the program finds input of a form that matches the given *definition*. For compatibility with older yacc processors, a single **=** can be placed before the opening **{** of the action.

The instructions in the *action* part of the rule can be thought of as C source code; however, they can also contain notations that are not valid in C. The notation **$1** stands for the *value* of the first component of the definition; if the component is a token, this is the yylval value associated with the token. Similarly, **$2** stands for the value of the second component, **$3** stands for the value of the third component, and so on. The notation **$$** represents the value of the construct being defined.

As an example, consider the following rule:

```
expression: expression '+' expression { $$ = $1 + $3; } ;
```

This action adds the value of the first component (the first subexpression) to the value of the third component (the second subexpression) and uses this as the *result* of the whole expression. Similarly, you can write:

```
expression: expression '-' expression { $$ = $1 - $3; };
expression: expression '*' expression { $$ = $1 * $3; };
expression: expression '/' expression { $$ = $1 / $3; };
expression: INTEGER { $$ = $1; };
```

The last rule says that if the form of an expression is just an integer token, the value of the expression is just the value of the token.

If no action is specified in a rule, the default action is:

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

This says that the default value of a construct is the value of its first component. Thus you can just write:

```
expression: INTEGER ;
```

Compressing Rules

If several rules give different forms of the same grammatical construct, they can be compressed into the form:

```
name : definition1 { action1}
     | definition2 { action2 }
     | definition3 { action3 }
     ...
     ;
```

There must be a semicolon to mark the end of the rule. Also, each definition has its own associated action. If a particular definition does not have an explicit action, the default action **$$=$1** is assumed.

Using this form, you can write:

```
expression:
      INTEGER
     | expression '+' expression { $$ = $1 + $3;}
     | expression '-' expression { $$ = $1 - $3; }
     | expression '*' expression { $$ = $1 * $3; }
```

```
    | expression '/' expression { $$ = $1 / $3; }
    ;
```

Start Symbols

The first grammatical construct defined in the rules section must be the most *all-inclusive* construct in the grammar. For example, if `yacc` input describes the grammar of a programming language, the first rule defined should be a complete program. The name of this first rule is called the *start symbol*.

The goal of the `yyparse()` routine is to gather input that fits the description of the start symbol. If your grammar defines a programming language and the start symbol represents a complete program, `yyparse()` stops when it finds a complete program according to this rule.

Obviously, you should define the starting symbol in such a way that it takes in all the valid streams of input that you expect. For example, consider our desk calculator. You might define a program with the rule:

```
program :
      /* nothing */
    | program expression '\n'
    ;
```

This gives two definitions for a program: it can consist of an expression followed by a newline character (a line to be calculated) followed by more such lines; or it can be nothing at all. The nothing definition comes into play at the start of input.

Interior Actions

Associate an action with the program rule of the previous section. The action should display the result of the expression on the input line as soon as the entire line has been read; therefore, write:

```
program:
      expression '\n' { printf("%d\n&",$1); } program
    | /* NOTHING */
    ;
```

This rule contains an *interior action*. The instruction in the brace brackets is run as soon as `yyparse()` reaches the part of the rule where the instruction appears (that is, as soon as it has read the newline token). This call to the `printf()` function of the C library immediately displays the value of the first component `$1` as a decimal integer. Then `yyparse()` goes on to gather the rest of the definition of **program** (more input lines).

Explicit Internal Source Code Declarations

The rules section of a `yacc` grammar can contain explicit source code declarations. As before, these begin with `%{` and end with `%}`. They are internal to the `yyparse()` function that `yacc` produces.

The Functions Section

The functions section of a `yacc` grammar does not always appear. When it does, it must begin with another `%%` construct (thus there is one `%%` between the declarations and the rules section, and another between the rules and the functions).

The functions section consists entirely of C source code. This source code typically contains definitions of functions that actions in the rules section call.

It is usually better to compile all such functions separately, rather than include them as part of the `yacc` input.

The Simple Desk Calculator

Now present the yacc input for our simple desk calculator program. This input corresponds to the lex input given in the previous section. (This example is provided as the file **dc1.y**.)

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

%token INTEGER
%left '+' '-'
%left '*' '/'

%%

program:
                program expression '\n'         = { printf("%d\n", $2); }
|               /* NULL */
;

expression:
                INTEGER
|               expression '+' expression       = { $$ = $1 + $3; }
|               expression '-' expression       = { $$ = $1 - $3; }
|               expression '*' expression       = { $$ = $1 * $3; }
|               expression '/' expression       = { $$ = $1 / $3; }
;
```

When this is run through yacc, the result is source code for a function named yyparse() that reads and interprets line after line of input. Linking this program with the yacc and lex libraries, you get a simple **main** function that calls yyparse() and exits. The exit status is 1 if the input was not in the correct format (for example, if you mistyped a calculation); it is 0 if the input was correct. (Be sure to link the yacc library before the lex library, to get the **main** routine in the yacc library that calls yyparse().)

Error Handling

Errors are possible in any input. Dealing with errors always tends to be difficult, because there is no way to predict the forms that errors may take. Dealing with errors in highly structured forms of input (for example, program source code) is especially difficult, because you want to get back on track as soon as possible. Usually, you want to discard erroneous input and then resume processing good input as usual. The trick lies in figuring out where erroneous input ends and where good input begins.

This section looks at some of the error handling abilities of lex and yacc. To make things more concrete, the examples give the simple desk calculator program the ability to handle errors. They also give it a few more sophisticated features:

- Users can store integer values in variables (using assignment statements). Variables have names that are only one letter long. Uppercase letters are equivalent to lowercase ones, so there are a maximum of 26 possible variables.
- You can use parentheses in the usual way, to change the order of arithmetic evaluation.
- You can express integers in octal or hexadecimal as well as decimal forms, using the C conventions for octal numbers (leading zero) and hexadecimal numbers (leading 0x).

It may be useful to think about how you might go about writing lex and yacc descriptions of these new features before you read the rest of this chapter.

Error Handling in lex

From the point of view of lex, the most common sort of error is an input that does not have the form of any of the recognized tokens. A translation rule of the form:

```
.    { action }
```

(a dot followed by an *action*) can be placed at the end of all the other translation rules to take care of unrecognized input. For example, you can write:

```
.    { printf("Incorrect input: %s\n",yytext); }
```

to issue an error message for any input that is not one of the recognized tokens. Because the *action* is a single C statement, you can omit the brace brackets, as in:

```
.    printf("Incorrect input: %s\n",yytext);
```

Instead of using `printf()`, you can make use of a `lex` library function named `yyerror()`. You call the `yyerror()` function just like `printf()`: its operands are a `printf()`-style format string followed by any appropriate operand values. It is better to use `yyerror()` than making your own call to `printf()`, because `lex` also uses `yyerror()` for issuing error messages. If your code uses `yyerror()`, all the error messages are issued in the same way. Thus, you might write:

```
.  { yyerror("Unrecognized input: %s\n",yytext); }
```

You can replace the standard `yyerror()` function with a version of your own if there is some standard error message format that you want to use.

Other Errors in lex

It is possible for other errors to be detected in the `yylex()` function that `lex` produces, but these have to be *expected* errors. In other words, you must write a translation rule that says, ‘‘If you see a token with *this* format, it is an error and here is how it is to be handled.’’ This sort of behavior is different for each application;however, trying to detect such errors is a useful exercise if there are some types of erroneous input that you can predict and handle in some special useful way.

lex Input for the Improved Desk Calculator

The following is the `lex` input to produce our improved version of the desk calculator program. (This example is provided as **dc2.l**.)

```
%{
#include "y.tab.h"
extern int yylval;
char upper[] = "ABCDEFGHIJKLMNOPQRSTUVWXYZ";
char lower[] = "abcdefghijklmnopqrstuvwxyz";
%}

%%

[[:upper:]]    {
          int i;
          for (i = 0; *yytext != upper[i]; ++i)
               ;
          yylval = i;
          return VARIABLE;
     }

[[:lower:]]    {
          int i;
          for (i = 0; *yytext != lower[i]; ++i)
               ;
          yylval = i;
          return VARIABLE;
     }

[[:digit:]]+   {
          yylval = strtol(yytext, (char **)NULL, 0);
          return INTEGER;
     }

0x[[:xdigit:]]+     {
          yylval = strtol(yytext, (char **)NULL, 16);
          return INTEGER;
     }

[-()=+/*\n]     return *yytext;
```

```
[ \t]+    ;

.         yyerror("Unknown character");
```

Note: This code looks complex because it handles character sets where characters are not continuous. If you're familiar with ASCII, it's tempting to get the value of `yylval` with a statement like `yylval = *yytext - 'A';` but this depends upon character ordering in ASCII. The loops in the example are slower but portable. If an input token is a single letter (uppercase or lowercase), the program returns a token value named **VARIABLE**. This is defined in the `yacc` input; it is obtained with the `#include` directive that gets the **y.tab.h** file that `yacc` generates.

To indicate which **VARIABLE** is being referred to, the `yylval` variable is set to an integer that indicates the letter: 0 for **A**, 1 for **B**, and so on. The same integer is used for both the uppercase and lowercase version of the letter. This corresponds to the 26 different variables that the desk calculator recognizes.

There are two types of integer tokens. Ones that begin with **0x** are interpreted as hexadecimal integers using the C `strtol()` function (which takes an integer string and produces the corresponding integer). Other integer tokens are also interpreted by `strtol()`, which determines the correct base to use (base 8 or base 10).

All the operators that the desk calculator recognizes are simply returned directly from `yylex()`. Blanks and horizontal tabs are skipped.

Any other character produces the error message associated with the translation rule. The `yylex()` function then tries to get another token; if this also finds erroneous input, `yylex()` keeps looping until it finds something it recognizes. The result is that erroneous input is skipped—`yylex()` never returns any indication that it found such input.

Error Handling in yacc

Error handling in `yacc` must be much more sophisticated than in `lex`. The `yylex()` function that `lex` produces only has to detect erroneous input that can *never* have a recognized meaning; the `yyparse()` function that `yacc` produces has to figure out what to do with tokens that can be valid in some contexts but are not valid in the current context. For example, `yyparse()` has to figure out what to do with:

```
A = + * 5
```

All the tokens in this input are valid tokens, but put together in this way, they have no meaning. `yyparse()` has to figure out what to do when things do not make sense.

The Error Construct

To handle errors, `yacc` introduces a symbol named **error**. This stands for any *ungrammatical* construct: any sequence of one or more tokens that do not fit into the grammar anywhere else.

The `yacc` input for the new desk calculator shows how this is used. This example is provided as **dc2.y**.

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

%token INTEGER VARIABLE
%left '+' '-'
%left '*' '/'

%{
static int variables[26];
%}

%%

program:
    program statement '\n'
|    program error '\n'        = { yyerrok; }
|    /* NULL */
;
```

```
statement:
    expression               = { printf("%d\n", $1); }
|    VARIABLE '=' expression     = { variables[$1] = $3; }
;

expression:
    INTEGER
|    VARIABLE                = { $$ = variables[$1]; }
|    expression '+' expression     = { $$ = $1 + $3; }
|    expression '-' expression     = { $$ = $1 - $3; }
|    expression '*' expression     = { $$ = $1 * $3; }
|    expression '/' expression     = { $$ = $1 / $3; }
|    '(' expression ')'        = { $$ = $2; }
;
```

The rules for **expression** are almost the same as before. To evaluate an operand that consists of a variable, you obtain the value of the variable from the **variables** array. To evaluate a parenthesized expression, just take the value of the expression inside the parentheses.

The rules for **statement** are new, but simple. If a statement just consists of an expression, it displays the value of the expression; otherwise, it assigns the result of an expression to a variable, so you can store the value of the expression in the array element associated with the variable.

A program is either a null input, a valid program followed by a statement, or a valid program followed by an error. You do not have to do anything for null inputs. You do not have to do anything for valid programs followed by statements either, because the definition of **statement** does the work associated with each statement.

Now, consider what `yyparse()` does when it reads a line that contains an error.

1. Up to the point when it begins reading the line, it has collected a valid program construct.
2. It begins reading the erroneous line. Because it has already gathered a valid program construct, there are two rules that can apply to the situation:

   ```
   program : program statement '\n'
   program : program error '\n'
   ```

3. Part way through the line, it comes across an erroneous construct. This rules out the possibility that the input has the form:

   ```
   program statement '\n'
   ```

   Therefore the form of the input must be:

   ```
   program error '\n'
   ```

4. `yyparse()` keeps reading. Any sequence of tokens matches the **error** construct, so `yyparse()` is happy.
5. When it finally gets to the end of the line, `yyparse()` has successfully read the sequence:

   ```
   program error '\n'
   ```

This is one definition for a *valid* **program** construct. It performs the action associated with this rule; a later section discusses the action.

When `yyparse()` finishes performing the action, it has successfully dealt with the rule:

```
program : program error '\n'
```

In essence, `yyparse()` has found one of the expected forms of a valid **program** construct. `yyparse()` therefore proceeds to process the next line as if it has just finished reading a valid **program**.

Using yyerror()

As soon as `yyparse()` encounters input that does not match any known grammatical construction, it calls the `yyerror()` function. In this case, the operand that it passes to `yyerror()` is:

```
"Syntax error"
```

If you are using the default version of `yyerror()`, it simply displays this message; however, you can supply your own `yyerror()` function if you want to do other processing. See Chapter 3, "Generating a Parser Using OpenExtensions yacc," on page 49 for more details.

The yyerrok Function

When `yyparse()` discovers ungrammatical input, it calls `yyerror()`. It also sets a flag saying that it is now in an *error state*. `yyparse()` stays in this error state until it sees three consecutive tokens that make sense (that is, are not part of the error).

It is possible for `yyparse()` to leave the error state as soon as it finds one or two tokens that make sense; however, experience has shown that this is not enough to be sure that the error has really passed; one or two tokens being correct may just be a coincidence. If `yyparse()` leaves its error state quickly and then finds more erroneous input, it raises another error, calls `yyerror()` again to issue a new error message, and so on. In other words, it behaves as if it had found a brand new error, even though it is likely just a continuation of the old error. Waiting for three good tokens prevents a lot of error messages arising from a single error.

There are, however, times when you want `yyparse()` to leave the error state before it finds the three good tokens. To do this, call the macro `yyerrok`, as in:

```
yyerrok;
```

In effect, `yyerrok` says, ''The old error is finished. If something else goes wrong, it is to be regarded as a new error.''

This should help you understand the rule:

```
program : program error '\n' { yyerrok; }
```

in the desk calculator program. After `yyparse()` has found the newline that ends an erroneous input line, you want to leave the error state. Any errors on the line should be regarded as *closed*. If the next line also contains errors, you want to see a new error message produced.

Other Error Handling Facilities

The error handling facilities in `yacc` offer a much greater level of sophistication than the simple features discussed here. For further details, see Chapter 3, "Generating a Parser Using OpenExtensions yacc," on page 49.

A Sophisticated Example

This section examines a sophisticated desk calculator program. This is similar to the example in the previous section, but has several new features:

- `while` loops (similar to C `while` loops).
- `if` and `if-else` constructs.
- The introduction of C comparison operations (**>**, **>=**, **<**, **<=**, **==**, **!=**) to support condition testing.
- An explicit `print` command that displays the result of an expression.
- Statements can now extend over more than one line, using a semicolon to mark the end of a statement.
- Blocks of statements can now be enclosed in brace brackets, as in C.

Here is an example of the sort of input that the new program accepts:

```
a = 100;
while (a > 0) {
    print a;
    b = 50;
    while (b > 0) {
        print b;
        b = b - 10;
    }
    a = a - 20;
}
```

These new features introduce an interesting amount of complexity to the problem. For example, with the introduction of loops and `if-else` statements, you can no longer evaluate a statement as soon as you come to the end of the statement; you must save the input and run it when you reach the end of each construct. Because you can nest constructs, you need a way to record a lot of information.

Multiple Values for yylval

By default, the `yylval` variable has the `int` type. Up until now, this has been satisfactory; however, `yylval` should be able to represent the value of any token you find, which means that in some programs it should be able to represent more than just the `int` type. This means giving `yylval` a `union` type, the different interpretations of which match the various types of value that tokens may have. This is done in the `yacc` input using a construct of the form:

```
%union {
    /* union declaration */
};
```

For example, suppose that you want the `yylex` routine to be able to return either integers or floating point numbers. Then you write:

```
%union {
    int i;
    float f;
};
```

to show that `yylval` can have either type.

In the case of the desk calculator, you want to represent variables and integers. You can therefore define:

```
%union {
    char variable;
    int ivalue;
};
```

lex Input

Here is the `lex` input for the new desk calculator program. This example is provided as **dc3.l**.

```
%{
#include "header.h"
#include "y.tab.h"
char upper[] = "ABCDEFGHIJKLMNOPQRSTUVWXYZ";
char lower[] = "abcdefghijklmnopqrstuvwxyz";
%}

%%

[[:upper:]]     {
                int i;
                for (i = 0; *yytext != upper[i]; ++i)
                        ;
                yylval.variable = i;
                return VARIABLE;
        }

[[:lower:]]     {
                int i;
```

```
                for (i = 0; *yytext != lower[i]; ++i)
                        ;
                yylval.variable = i;
                return VARIABLE;
        }

[[:digit:]]+    {
                yylval.ivalue = strtol(yytext, (char **)NULL, 0);
                return INTEGER;
        }

0x[[:xdigit:]]+ {
                yylval.ivalue = strtol(yytext, (char **)NULL, 16);
                return INTEGER;
        }

[-{}()<>=+/*;]  return yylval.ivalue = *yytext;

">="            return yylval.ivalue = GE;
"<="            return yylval.ivalue = LE;
"=="            return yylval.ivalue = EQ;
"!="            return yylval.ivalue = NE;

"while"         return WHILE;
"if"            return IF;
"else"          return ELSE;
"print"         return PRINT;

[ \t\n]         ;

.       yyerror("Unknown character");
```

The new definitions are:

```
">="       return GE;
"<="       return LE;
"=="       return EQ;
"!="       return NE;
"while"    return WHILE;
"if"       return IF;
"else"     return ELSE;
"print"    return PRINT;
```

The symbols **GE**, **LE**, and so on are all C definitions. They represent new kinds of tokens that can be found in the input. If `yylex()` finds one of these new tokens, it returns the corresponding defined value.

These definitions, as given, recognize only lowercase keywords. The translation rule:

```
"while"|"WHILE"   return WHILE;
```

recognizes either all uppercase or all lowercase. To accept mixed case, you can write:

```
[wW][hH][iI][lL][eE]  return WHILE;
```

The yacc Bare Grammar

The following is the `yacc` bare grammar without actions attached to the rules in the rules section. It also leaves out a bit of explicit code in the declarations section.

```
%union {
         int ivalue;
         char variable;
         struct nnode *np;  /* discussed later */
};
%token <variable>  VARIABLE
%token <ivalue>    INTEGER '+' '-' '*' '/' '<' '>' GE LE NE EQ

%token WHILE IF PRINT ELSE
%left GE LE EQ NE '>' '<'
%left '+' '-'
%left '*' '/'

%type <np> statement expression statementlist simplestatement

%%
```

```
program: program statement
       | error ';'
       | /* NOTHING */
       ;

statement:  simplestatement ';'
         |  WHILE '(' expression ')' statement
         |  IF '(' expression ')' statement ELSE statement
         |  IF '(' expression ')' statement
         |  '{' statementlist '}'
         ;

statementlist:   statement
             |   statementlist statement
             ;

simplestatement: expression
               | PRINT expression
               | VARIABLE '=' expression
               ;

expression: INTEGER
          | VARIABLE
          | expression '+' expression
          | expression '-' expression
          | expression '*' expression
          | expression '/' expression
          | expression '<' expression
          | expression '>' expression
          | expression GE expression
          | expression LE expression
          | expression EQ expression
          | expression NE expression
          | '(' expression ')'
          ;
```

As you can see, the definition of the grammar is quite straightforward. You may notice that the format of the %token lines have changed.

```
%token <ivalue>  INTEGER
```

states that when the return value of yylex() is **INTEGER**, the yyparse() routine is to use the ivalue interpretation of yylval. The same sort of thing applies to:

```
%token <variable> VARIABLE
```

You may also notice that this example introduces:

```
%type <np> statement expression statementlist simplestatement
```

as a new statement. This tells how to interpret the $$ construct in definitions of **statement**, **expression**, **statementlist**, and **simplestatement**. In those constructs, $$ (the *value* of the constructs) should have the np type. Because **program** does not have an assignment to $$, it is not given a type.

np is given as another possible interpretation in the %union directive. The %union gives possible interpretations of both yylval and $$, so add the extra interpretation to the %union.

In general, %type lines can indicate the type of $$ in any construct. The form of the directive is:

```
%type <interp> construct construct …
```

where *interp* is one of the interpretation names given in the %union directive.

The next section discusses what the np type does.

Expression Trees

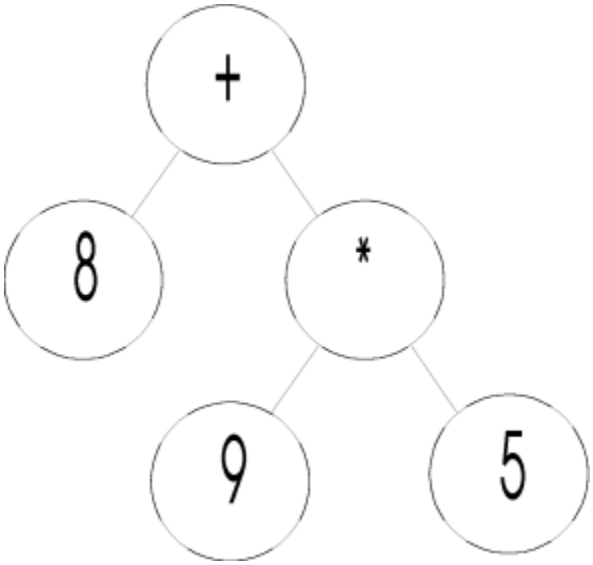
Earlier this chapter discussed the need to *record* expression while reading them for future evaluation. The best way to do this is by using a *tree*. To understand how a tree works, consider an expression such as:

```
8 + 9 * 5
```

which is evaluated as:

```
8 + (9 * 5)
```

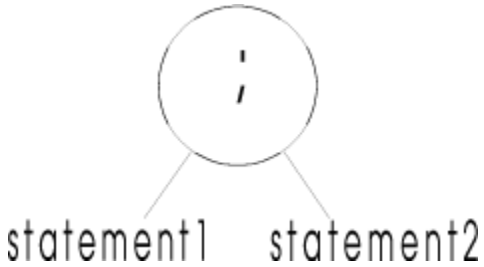
Each operation has three components: the operator, and the two operands.



The operators are called the *nodes* of the tree. At each node, there are two *branches*, representing the two operands of the operator. The end of each branch is a simple operand that is not an expression; such an operand is called a *leaf*.

Tree structures are a good way to represent expressions. They record all the information needed to evaluate the expression.

Tree structures can also represent a list of statements. In this case, think of the operator as the semicolon that separates the two.



A `while` loop is represented similarly, with one branch giving the condition expression and the other giving the statement list. Finally, an `if-else` statement can be represented as a tree with *three* branches: one for the condition expression, one for the `if` statements, and one for the `else` statements. An `if` without an `else` is just a special case where the third branch is empty.

To represent these trees, the desk calculator example creates the following data types. These are defined in the header file **header.h**, which you include (with the `#include` directive) into the appropriate C source code files.

```
typedef union {
        int     value;
        struct nnode *np;
} ITEM;
typedef struct nnode {
        int     operator;
        ITEM    left, right, third;
} NODE;
#define LEFT    left.np
#define RIGHT   right.np

#define NNULL           ((NODE *) 0)
#define node(a,b,c)     triple(a, b, c, NNULL)
```

```
extern int variables[26];

int execute(NODE *np);
```

To record an expression, use `malloc()` to allocate an **nnode** structure. The operator is set to the operator of the expression; the tokens **INTEGER**, **VARIABLE**, **WHILE**, and **IF** are also used as appropriate. For leaves of the tree (simple operands), call a function named `leaf()` to fill in the left field and put null pointers in the other two. For operations that have two operands, call a function named `node()` to fill in the left and right fields with pointers to trees for the operands; the third field is given a null pointer value. For operations with three operands, call a function named `triple()` to fill in all three pointers.

As input is collected, tree structures are allocated and organized. When a complete statement has been collected, you can then call a function named `execute()` to *walk* through the tree and run the statement appropriately.

When the statement has been run, the tree is no longer needed. At that point, call a function named `freeall()` to free the memory used for all the structures that make up the tree.

Putting all this together produces the following grammar for the desk calculator program. Note that the functions part of the input contains everything you need except the `execute()` function. This example is provided in **dc3.y**.

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

#include "header.h"

static NODE *nalloc(void);
static NODE *leaf(int type, int value);
static NODE *triple(int op, NODE *left, NODE *right, NODE *third);
static void freeall(NODE *np);

int variables[26];
%}

%union {
        int ivalue;
        char variable;
        NODE *np;
};

%token <variable>  VARIABLE
%token <ivalue>    INTEGER '+' '-' '*' '/' '<' '>' GE LE NE EQ

%token WHILE IF PRINT ELSE
%left GE LE EQ NE '>' '<'
%left '+' '-'
%left '*' '/'

%type <np>      statement expression statementlist simplestatement

%%

program:
          program statement     { execute($2); freeall($2); }
        | program error ';'     { yyerrok; }
        | /* NULL */
        ;

statement:
          simplestatement ';'
        | WHILE '(' expression ')' statement
                { $$ = node(WHILE, $3, $5); }
        | IF '(' expression ')' statement ELSE statement
                { $$ = triple(IF,$3,$5,$7); }
        | IF '(' expression ')' statement
                { $$ = triple(IF,$3,$5,NNULL); }
        | '{' statementlist '}'
                { $$ = $2; }
        ;

statementlist:
          statement
        | statementlist statement       { $$ = node(';', $1, $2); }
```

```
        ;

simplestatement:
          expression
        | PRINT expression              { $$ = node(PRINT,$2,NNULL); }
        | VARIABLE '=' expression
                        { $$ = node('=', leaf(VARIABLE, $1), $3); }
        ;

expression:
          INTEGER               { $$ = leaf(INTEGER, $1); }
        | VARIABLE              { $$ = leaf(VARIABLE, $1); }
        | expression '+' expression
                { binary: $$ = node($2, $1, $3); }
        | expression '-' expression     { goto binary; }
        | expression '*' expression     { goto binary; }
        | expression '/' expression     { goto binary; }
        | expression '<' expression     { goto binary; }
        | expression '>' expression     { goto binary; }
        | expression GE expression      { goto binary; }
        | expression LE expression      { goto binary; }
        | expression NE expression      { goto binary; }
        | expression EQ expression      { goto binary; }
        | '(' expression ')'            { $$ = $2; }
        ;

%%

static NODE *
nalloc()
{
        NODE *np;

        np = (NODE *) malloc(sizeof(NODE));
        if (np == NNULL) {
                printf("Out of Memory\n");
                exit(1);
        }
        return np;
}

static NODE *
leaf(type, value)
int type, value;
{
        NODE *np = nalloc();

        np->operator = type;
        np->left.value = value;
        return np;
}

static NODE *
triple(op, left, right, third)
int op;
NODE *left, *right, *third;
{
        NODE *np = nalloc();

        np->operator = op;
        np->left.np = left;
        np->right.np = right;
        np->third.np = third;
        return np;
}

static void
freeall(np)
NODE *np;
{
        if (np == NNULL)
                return;
        switch(np->operator) {
        case IF:                /* Triple */
                freeall(np->third.np);
        /* FALLTHROUGH */
                                /* Binary */
        case '+': case '-': case '*': case '/':
        case ';': case '<': case '>':
        case GE: case LE: case NE: case EQ:
        case WHILE:
        case '=':
```

```
                freeall(np->RIGHT);
        /* FALLTHROUGH */
        case PRINT:             /* Unary */
                freeall(np->LEFT);
                break;
        }
        free(np);
}
```

Note that there is a shift-reduce conflict in this grammar. This is because the rules:

```
statement: IF '(' expression ')' statement ELSE statement ;
statement: IF '(' expression ')' statement ;
```

The default rules for resolving this conflict favor the shift action, which is what is desired in this case. An `else` that follows an `if` statement matches with the closest preceding `if`. (See Chapter 3, "Generating a Parser Using OpenExtensions yacc," on page 49 for more details.)

The source code for the `execute()` function can be compiled separately. It walks through the tree node by node, calling itself recursively to run the branches at each node. The `execute()` function is basically a big `switch` statement, which looks at the node operator and takes appropriate action. It is quite straightforward. In the examples provided, this is file **execute.c**.

```
#include <stdio.h>
#include <stdlib.h>

#include "header.h"
#include "y.tab.h"

int
execute(np)
struct nnode *np;
{
        switch(np->operator) {
        case INTEGER:   return np->left.value;
        case VARIABLE:  return variables[np->left.value];
        case '+':       return execute(np->LEFT) + execute(np->RIGHT);
        case '-':       return execute(np->LEFT) - execute(np->RIGHT);
        case '*':       return execute(np->LEFT) * execute(np->RIGHT);
        case '/':       return execute(np->LEFT) / execute(np->RIGHT);
        case '<':       return execute(np->LEFT) < execute(np->RIGHT);
        case '>':       return execute(np->LEFT) > execute(np->RIGHT);
        case GE:        return execute(np->LEFT) >= execute(np->RIGHT);
        case LE:        return execute(np->LEFT) <= execute(np->RIGHT);
        case NE:        return execute(np->LEFT) != execute(np->RIGHT);
        case EQ:        return execute(np->LEFT) == execute(np->RIGHT);
        case PRINT:     printf("%d\n", execute(np->LEFT)); return 0;
        case ';':       execute(np->LEFT); return execute(np->RIGHT);
        case '=':
                        return
                          variables[np->LEFT->left.value] = execute(np->RIGHT);
        case WHILE:
                        while (execute(np->LEFT))
                                execute(np->RIGHT);
                        return 0;
        case IF:
                        if (execute(np->LEFT))
                                execute(np->RIGHT);
                        else if (np->third.np != NNULL)
                                execute(np->third.np);
                        return 0;
        }
        printf("Internal error! Bad node type!");
        exit(1);
}
```

Note that `execute()` calls the `yyerror()` function to issue error messages.

Compilation

By changing the `execute` function, you can *compile* the input program instead of just running it. The output of the function is the sequence of hardware commands required to run the program. Doing this for a real machine is too complicated for the purposes of this tutorial; however, this section shows how to do it for a simple hypothetical machine.

Note: This section assumes that you have a basic knowledge of computer architecture.

Consider a hypothetical machine with the following characteristics:

- The machine works with a hardware stack.
- It has 26 registers, numbered 0 through 25.
- It has a *push register* command that pushes the value of a register onto the stack.
- It has a *push constant* command (`push`) that pushes the value of a constant onto the stack.
- It has a *pop register* command (`pop`) that pops the top value off the stack and stores it in a specified register.
- It has the following binary operators:

```
add   sub   /*  + and -  */
mul   div   /*  * and /  */
cmpl  cmpg  /*  < and >  */
cmple cmpge /* <= and >= */
cmpeq cmpne /* == and != */
```

  Each of these instructions pops the top two values from the stack, performs the indicated operation, and then pushes the result. The result of a comparison is 1 if true, and 0 if false.
- There is a `print` operation that pops the top value from the stack and displays it.
- There is a `jmp` command that transfers control to a different location.
- There is a `jfalse` command that pops a value off the stack and transfers to a different location if the value is zero.

Given this setup, here is the *compiling* version of `execute`. Store this in a file so that you can run the compiled program anytime. In the examples, this is the file **compile.c**.

```
#include <stdio.h>
#include <stdlib.h>

#include "header.h"
#include "y.tab.h"

int
execute(np)
struct nnode *np;
{
        int toplab, botlab, falselab;
        static int labno;

        switch(np->operator) {
        case INTEGER:
                printf("\tpush\t$%d\n", np->left.value);
                break;
        case VARIABLE:
                printf("\tpush\tr%d\n", np->left.value);
                break;
        case '=':
                execute(np->RIGHT);
                printf("\tpop\tr%d\n", np->LEFT->left.value);
                return 0;
        case '+': case '*': case '-': case '/':
        case '<': case '>': case GE: case LE: case NE&co
                execute(np->LEFT); execute(np->RIGHT);
                switch(np->operator) {
                case '+':       printf("\tadd\n"); break;
                case '-':       printf("\tsub\n"); break;
                case '*':       printf("\tmul\n"); break;
                case '/':       printf("\tdiv\n"); break;
                case '<':       printf("\tcmpl\n"); break;
                case '>':       printf("\tcmpg\n"); break;
                case GE:        printf("\tcmpge\n"); break;
                case LE:        printf("\tcmple\n"); break;
                case NE:        printf("\tcmpne\n"); break;
                case EQ:        printf("\tcmpeq\n"); break;
                }
                break;
        case PRINT:
                execute(np->LEFT);
                printf("\tprint\n");
```

```
                break;
        case ';':
                execute(np->LEFT); execute(np->RIGHT);
                break;
        case WHILE:
                printf("L%d:", toplab = labno++);
                execute(np->LEFT);
                printf("\tjfalse\tL%d\n", botlab = labno++);
                execute(np->RIGHT);
                printf("\tjmp\tL%d\n", toplab);
                printf("L%d:", botlab);
                break;
        case IF:
                execute(np->LEFT);
                printf("\tjz\tL%d\n", falselab = labno++);
                execute(np->RIGHT);
                printf("\tjmp\tL%d\n", botlab = labno++);
                printf("L%d:", falselab);
                if(np->third.np != NNULL)
                        execute(np->third.np);
                printf("L%d:", botlab);
                break;
        default:
                printf("Internal error! Bad node type!");
                exit(1);
        }
}
```

Chapter 2. Generating a Lexical Analyzer Using OpenExtensions lex

A computer program often has an input stream of characters, which are easier to process as larger elements, such as tokens or names. A compiler is a common example of such a program: It reads a stream of characters forming a program, and it must convert this stream into a sequence of items (for example, identifiers and operators) for parsing. In a compiler, the procedures that do this are collectively called the *lexical analyzer*, or *scanner*.

Expressing the scanning task in a general-purpose procedural programming language is usually difficult. The scanning transformations are usually easy enough to describe; however, it is hard to express them concisely in these languages.

Introduction to the lex Utility

The `lex` utility of the OpenExtensions Shell and Utilities is a program that writes large parts of a lexical analyzer automatically, based on a description supplied by the programmer. The items or tokens to be recognized are described as regular expressions, in a special-purpose language for writing lexical analyzers. `lex` translates this language, which is easy to write, into an analyzer that is both fast and compact.

The purpose of a `lex` program is to read an input stream, and recognize *tokens.* As the lexical analyzer usually exists as a subroutine in a larger set of programs, it is usually written to return a *token number*, indicating the token that was found, and possibly a *token value*, providing more detailed information about the token (for example, a copy of the token itself, or an index into a symbol table). This need not be the only possibility; by itself, a `lex` program is often a good description of the structure of a computation.

`lex` is based on a similar program written by Charles Forsyth at the University of Waterloo (Ontario, Canada) and described in an unpublished paper entitled “A Lexical Analyzer Generator” (1978). The implementation is loosely based on the description and suggestions in the book *Compilers, Principles, Techniques, and Tools*, by A. V. Aho, Ravi Sethi, and J. D. Ullman (Addison-Wesley, 1986).

This `lex` was inspired by a processor of the same name at Bell Labs, which also runs under UNIX systems, and, more distantly, on AED-0. UNIX `lex` is described in the paper “Lex — A Lexical Analyser Generator,” by M. E. Lesk, *Computer Science Technical Report* 39 (Bell Labs, October 1975). AED-0 is described in “Automatic Generation of Efficient Lexical Analysers Using Finite State Techniques,” by W. L. Johnson, appearing in *Communications of the ACM* 11 (no. 12, 1968): 805-13.

The lex Input Language

In this section the `lex` input language is discussed. This includes the following topics.

- Fundamentals of the language, including characters, strings, and character classes
- Putting together the fundamentals to form regular expressions
- `lex` programs and their basic form
- Using definitions for regular expressions
- Translations, which associate regular expressions with actions
- C declarations that can be included in `lex` programs

Language Fundamentals

`lex` expressions (also known as *regular expressions,* or *patterns*) are basic to its operation. The nature and construction of these expressions is described first.

Characters, strings, and sets of characters called character classes are the fundamental elements of `lex` expressions. These stand for, or match, characters in the input stream; characters and character classes match single characters of the input, whereas strings match a fixed-length sequence of input characters.

Characters

A *character* is any character. The letters *a* through *z, A* through *Z,* the underscore _, and the digits `0` to `9` stand for single occurrences of themselves in the input. Most other characters are treated specially by `lex`. The escape character (****) written in front of a special character has no special significance; it can match an occurrence of itself in the input stream.

The escape can also be used to create an escape sequence standing for a different character. `lex` understands the following C language escape sequences. The value in parentheses is the EBCDIC value for that escape sequence. With these, you can represent any 8-bit character, including the escape character, quotation marks, and newlines:

```
\a    BEL    (0X2F)
\b    BS    (0X16)
\f    FF    (0X0C)
\n    NL    (0X15)
\r    CR    (0X0D)
\t    TAB    (0X05)
\v    VTAB    (0X0B)
\nnn    (nnn)
\xhh    (hh)
\"    "
\'    '
\c    c
\\     \
```

where *nnn* is a number in octal, *hh* is a number in hexadecimal, and *c* is any printable character.

Strings

A *string* is a sequence of characters, not including newline, enclosed in double quotation marks. For example, "+" is a *string* that matches a single **+** in the input. Within a string, only the escape character (****) has any special significance. The escape sequences given earlier are recognized within a string. You can continue long strings across a line by placing an escape before the end of the line. The escape and the newline are not incorporated into the string.

Character Classes

A sequence of characters enclosed by brackets—[and]—forms a character class, which matches a single instance of any character within the brackets. If a circumflex (**^**) follows the opening bracket, the class matches any characters except those inside the brackets.

Within a character class the character **-** is treated specially, unless it occurs at the start (after any **^**) or end of the character class. If two characters are written separated by **-** the sequence is taken to include all characters in the character set from the first to the second (using the numeric values of characters in the character set).

Thus [a-z] stands for all characters between *a* and *z*. You can use the escapes used in strings in character classes as well.

The POSIX locale is supported in `lex`. These are provided as special sequences that are valid only within character class definitions. The sequences are:

```
[.coll.]        collation of character coll
[=equiv=]       collation of the character class equiv
[:char-class:]   any of the characters from char-class
```

`lex` accepts the POSIX locale only for these definitions. In particular, multicharacter collation symbols are not supported. You can still use, for example, the character class:

```
[[.a.]-[.z.]]
```

which is equivalent to:

```
[a-z]
```

for the POSIX locale.

`lex` accepts the POSIX-defined character classes shown in Table 1 on page 31.

It is more portable (and more obvious) to use the new expressions; for example, the character class:

```
[[:alnum:]]
```

is the same as:

```
[a-zA-Z0-9]
```

in the POSIX locale, but is portable to other locales.

There is a special character class, written as—which matches *any* character but newline. Newline must always be matched explicitly.

Table 1. POSIX-Defined Character Classes in lex

Name	**Definition**
[:alpha:]	Any letter
[:lower:]	A lowercase letter
[:upper:]	A uppercase letter
[:digit:]	Any digit
[:xdigit:]	Any digit, or the letters *a–f A–F*
[:alnum:]	Any letter or digit
[:cntrl:]	Any control (nonprinting) character
[:space:]	Any spacing character, including blank, tab, and carriage return
[:print:]	Any printable character
[:blank:]	A blank or tab character
[:graph:]	Any printable character other than space
[:punct:]	A punctuation mark

Putting Things Together

Various operators are available to construct regular expressions or patterns from strings, characters, and character classes. A reference to an *occurrence* of a regular expression is generally taken to mean an occurrence of any string matched by that regular expression.

The operators are presented in order of decreasing priority. In all cases, operators work on characters, character classes, strings, or regular expressions.

1. Any character, string, or character class forms a regular expression that matches whatever the character, string, or character class stands for (as described earlier).
2. The operator ***** following a regular expression forms a new regular expression, which matches an arbitrary number of (that is, zero or more) adjacent occurrences of the first regular expression. The operation is often referred to as (Kleene) *closure*. For example, the expression:

   ```
   ab*
   ```

   matches a followed by zero or more b's; that is a, ab, abb, and so on.

3. The operator **+** is used like ***** but forms a regular expression that matches one or more adjacent occurrences of a given regular expression. For example:

   ```
   ab+
   ```

   matches a followed by one or more b's. This is equivalent to abb*.
4. A repetition count can follow a regular expression, enclosed in **{}**. This is analogous to simply writing the same regular expression as many times as indicated. A range of repetitions can be provided, separated by a comma. For example:

   ```
   ab{4}
   ```

   matches a followed by exactly four b's. That is, abbbb.

   ```
   ab{2,4}
   ```

   matches a followed by from 2 to 4 b's.
5. The operator ? written after a regular expression indicates that the expression is optional: the resulting regular expression matches either the first regular expression, or the empty string. For example:

   ```
   [[:lower:]]?
   ```

   matches a lowercase letter or nothing (an optional letter).
6. The operation of *concatenation* of two regular expressions is expressed simply by writing the regular expressions adjacent to each other. The resulting regular expression matches any occurrence of the first regular expression followed directly by an occurrence of the second regular expression. For example:

   ```
   a*b*
   ```

   matches any number of a's followed immediately by any number of b's.
7. The operator **|**, *alternation,* written between two regular expressions forms a regular expression that matches an occurrence of the first regular expression *or* an occurrence of the second regular expression. For example:

   ```
   [[:lower:]]|[[:digit:]]
   ```

   matches a lowercase letter or a digit. This is equivalent to:

   ```
   [[:lower:][:digit:]]
   ```
8. You can enclose any regular expression in parentheses to cause the priority of operators to be overridden. For example, the expression:

   ```
   [[:lower:]]([[:digit:]]|[[:lower:]])*
   ```

   matches a name starting with a lowercase letter, followed by any number of lowercase letters or digits.
9. Operators lose special meaning when escaped by **** or quoted as in a string "...". The characters also stand for themselves within brackets.

lex Programs

A `lex` program consists of three sections: a section containing *definitions*, a section containing *translations*, and a section containing *functions*. The style of this layout is similar to that of `yacc`.

Throughout a `lex` program, you can freely use newlines and C-style comments; they are treated as white space. Lines starting with a blank or tab are copied through to the `lex` output file. Blanks and tabs are usually ignored, except when you use them to separate names from definitions, or expressions from actions.

The definition section is separated from the following section by a line consisting only of **%%**. In this section, named regular expressions can be defined, which means you can use names of regular expressions in the translation section, in place of common subexpressions, to make that section more readable. The definition section can be empty, but the **%%** separator is required.

The translation section follows the definition section, and contains regular expressions paired with *action*s, which describe what the lexical analyzer is to do when a match of a given regular expression is found. The first nonescaped space or tab on a line in the translation section signals the start of the action. Actions are further described in later sections of this chapter.

You can omit the function section; if it is present, it is separated from the translation section by a line containing only **%%**. This section can contain anything, because it is simply attached to the end of the `lex` output file.

Definitions

You can define regular expressions once, and then refer to them by name in any subsequent regular expression. Definition must precede use. A definition has the form:

```
name expression
```

where a *name* is composed of a letter or underscore, followed by a sequence of letters, underscores, or digits. Within an expression, you can refer to another defined name by enclosing that name in braces, as in {*name*}. For example:

```
digit   [[:digit:]]
letter  [[:alpha:]]
name    {letter}({letter}|{digit})
```

which defines an expression called *name* that matches a variable name. A definition must completely fit onto one line.

As well as definitions, the definition section can also contain declarations and directives. Declarations are described in “Declarations” on page 35. Directives define *start conditions* and to change the size of internal `lex` tables.

New directives are provided to define the type of `yytext`. The `%array` directive causes `yytext` to be defined as an array of `char`; this is also the default. The `%pointer` directive causes `yytext` to be defined as a pointer to an array of **char**.

Internal `lex` tables include NFA and DFA tables, and a move table.

Note: A deterministic finite automata (DFA) is a type of graph used to recognize patterns. In a DFA, there is only one path from a given node (state) for any given input, there is a fixed and known number of nodes and branches, and the transition from node to node (state to state) is completely determined by the input. A non-deterministic finite automata (NFA) is the same as a DFA, except that there may be more than one possible next state.

The default sizes of these tables may not be sufficient for large scanners. You can change table sizes by the following directives, with the number *size* giving the number of entries to use:

Table 2. lex Table Size Specifications

Line	Table Size Affected	Default Size
%e *size*	Number of NFA entries	1000
%n *size*	Number of DFA entries	500
%p *size*	Number of move entries	2500

Often, you can reduce the NFA and DFA space to make room for more move entries. UNIX `lex` allows additional table size specifications, as follows:

Table 3. Additional UNIX lex Table Size Specifications	
Line	**Table Size Affected**
%a*size*	Number of transitions
%k*size*	Packed character classes
%o*size*	Output array size

As these sizes are unnecessary in `lex`, a warning is issued, and the specification is ignored.

Translations

An action can be associated with a regular expression in the translation section. The resulting translation has the following form:

```
expression action
```

or

```
expression  {
    action
}
```

The action is given as either a single C statement on the rest of the line, or a C statement within braces, possibly spread out over a number of lines, and starting after the first blank or tab on the line. (Remember not to use blanks or tabs inside an expression unless they are escaped with **** or within strings.)

A compiler typically enters an identifier into a symbol table, reads and remembers a string, or returns a particular token to the parser. In text processing, you might want to reproduce most of the input stream on an output stream unchanged, but make substitutions when a particular sequence of characters is found.

Allowing a translation action to be in C provides a great deal of power to the scanner, as shown in later sections. A library of C functions and macros is provided to allow controlled access to some of the data structures used by the scanner.

Token String and Length

A `lex` expression typically matches a number of input strings. For example:

```
%%
[[:alpha:]_][[:alnum:]_]*
```

matches any C identifiers in the input. It is useful to be able to obtain the portion of the input matched by such expressions, for use by the action code.

In `lex`, the current token is found in the character array `yytext`. The end of the token is marked by a null byte, so that it has the usual form of a string in C. The following `lex` program displays all the identifiers in a C program (including keywords), one per line.

```
%%
[[:alpha:]_][[:alnum:]_]*    printf("%s\n", yytext);
\n|.                ;    /* discard other input */
```

In some applications, the null byte might itself be a valid input character, and it may be useful to know the true length of the token. The value `yyleng` holds the length of the token in `yytext` and also may save a call to `strlen()` to determine the length of a token.

Numbers and Values

Typically, a lexical analyzer returns a value to its caller indicating which token has been found. Within an action, this is done by writing a C `return` statement, which returns the appropriate value:

```
digit    [[:digit:]]
letter    [[:lower:]]
integer    {digit}+
name        {letter}({letter}|{digit})*
%%
"goto"    { return GOTO; }
{integer} { return INTEGER; }
{name}    { lookup(yytext); return NAME; }
```

In many cases, the lexical analyzer must supply other information to its caller. Within a compiler, for example, when an identifier is recognized, both a pointer to a symbol table entry, and the token number **NAME** must be returned; however, the C `return` statement can return only a single value. `yacc` solves this problem by having the lexical analyzer set an external `yylval` to the *token value*, and return the *token number*. This mechanism can be used by `lex` programs when used with `yacc`; otherwise, you can define another interface. For example:

```
{name} { yylval = lookup(yytext); return(NAME); }
```

In the absence of a `return` statement, the lexical analyzer does not return to its caller but looks instead for another token. This is typically used when a comment sequence has been discovered, and discarded, or when the purpose of the `lex` program is to change some set of tokens into some other set of strings.

To summarize, the token number is set by the action with a `return` statement, and the token value is set by assigning this value to the external value `yylval`. An action need not return.

Declarations

C declarations can be included in both the definition and translation sections. C code in the declarations section should be bracketed by the sequence `%{` and `%}` on lines by themselves, as in `yacc`. Such declarations are external to the function `yylex()`. The characters within these brackets are copied unchanged into the appropriate spots in the lexical analyzer program that `lex` writes.

An action enclosed in braces forms a local block, and declarations therein are local to the particular action, as determined by C scope rules.

To declare variables that are local within `yylex()`, you can use the same `%{ .. %}` syntax at the beginning of the translation section. Names declared in this way do not conflict with other external variables.

Using lex

This section discusses how to use `lex` in practice, with attention to the following aspects:

- Using the lexical analyzer, `yylex()`, in conjunction with `yacc`
- Generating a table file from the `lex` program
- Compiling the table file
- An overview of the `lex` library routines fully usable with `yylex()`

Using yylex()

The structure of `lex` programs is influenced by what `yacc` requires of its lexical analyzer.

To begin with, the lexical analyzer is named `yylex()` and has no parameters. It is expected to return a token number (of type `int`), where that number is determined by `yacc`. The token number for a character is its value as a C character constant. `yacc` can also be used to define token names, using the `token` statement, where C definitions of these tokens can be written on the file **y.tab.h** with the `-d` option to `yacc`. This file defines each token name as its token number.

yacc also allows yylex() to pass a value to the yacc action routines, by assigning that value to the external yylval. The type of yylval is by default int, but this may be changed by the use of the yacc %union statement. lex assumes that the programmer defines yylval correctly; yacc writes a definition for yylval to the file **y.tab.h** if the %union statement is used.

For compatibility with yacc, lex provides a lexical analyzer named yylex(), which interprets tables formed from the lex program, and which returns token numbers from the actions it performs. The actions may include assignments to yylval (or its components, if it is a union of types), so that use with yacc is straightforward.

In the absence of a return statement in an action, yylex() does not return but continues to look for further matches. If some computation is performed entirely by the lexical analyzer with no usual return from any action, a suitable main program is:

```
#include <stdio.h>

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

The value 0 (zero) is returned by yylex() at end-of-file; this program allows for an error return to the program's caller. You can find such a main program in the lex library.

Generating a Table File

In the absence of instructions to the contrary, lex reads a given lex language file, and produces a C program file **lex.yy.c**, which contains a set of tables, and a yylex() program to interpret them. The actions you supply in each translation are combined with a switch statement into a single function, which the table interpreter calls when a particular token is found. The contents of the program section of the lex file are added at the end of the C program file. Declarations and macro definitions required by lex are inserted at the top of the file. You can modify some of these, as described in the following sections. lex uses the standard I/O library, and automatically generates the directive:

```
#include <stdio.h>
```

required to use that library.

A set of C macros is provided that allows the user to access values maintained by lex, or to control the operation of the lexical analyzer in various ways.

The values maintained by lex are:

yytext
The characters forming the current token, terminated by a null byte.

yyleng
The length of the token; this is useful if the token may contain a null byte.

yylineno
The current line number of the input.

Some other defined constants are also special to lex:

YYLEX
Provides the name of the lexical analyzer function. By default, this is yylex, but a user may use #undef and then redefine **YYLEX** to obtain another name.

YYLMAX
Specifies the maximum length of the token buffer yytext. The default length is 100 characters. This value is checked when pushing characters back into the input (see unput in "The lex Library Routines" on page 37). During the scan, an error message is produced if insufficient space remains.

Compiling the Table File

lex is called by the command line:

```
lex source.l
```

where **source.l** is the name of a file containing a lex source program. lex reads the given file, and (in the absence of any irrecoverable errors) produces the file **lex.yy.c**, described earlier.

Compile this file in the usual way. Using the c89 command, you can type something like this:

```
c89 -c lex.yy.c
```

When linking, the lex library is usually required. This library, described in "The lex Library Routines" on page 37, can be in a number of different places. The usual library is:

```
/usr/lib/libl.a
```

which can be abbreviated on the c89 command line to -ll.

As lex writes its output, it prepends the contents of the **/etc/yylex.c** file. The **yylex.c** file contains the prototype scanner.

The following example shows the use of a program with lex and yacc, with the lex source in **scanner.l** and the yacc source in **grammar.y**. The user code is in the file **code.c**, and the code uses components of the lex library and the main() routine from the yacc library.

Note: The yacc library is specified first. (There is a main() routine in the lex library as well; if the lex library is specified first, that main() is used, calling the lexical analyzer one time and exiting.) The user code and the scanner make use of tokens defined by yacc; so the -D option is given to yacc to create the **gram.h** file:

```
lex scanner.l
yacc -D gram.h grammar.y
c89 code.c lex.yy.c y.tab.c -ly -ll
```

The **gram.h** file has to be included by the **scanner.l** file, with:

```
%{
#include "gram.h"
%}
```

in the definition section of the **scanner** lex file.

The lex Library Routines

The lex library contains routines that are either essential or generally useful to lex programs. These routines have an intimate knowledge of yylex(), and can correctly manipulate the input stream.

Those functions that produce diagnostics do so by calling yyerror() , which is called as:

```
yyerror(const char * format, …)
```

and is expected to write its arguments using vfprintf, followed by a newline, on some output stream, typically **stderr**. A yyerror() function is included in the lex library but can be redefined by the programmer.

A description of the typedefs, constants, variables, macros, functions, and library routines currently available follows:

Typedefs

YY_SAVED
A typedef that is an internal data structure used to save the current state of the scanner. See the description of yySaveScan in the functions subsection.

yy_state_t
A typedef defined by lex to be the appropriate unsigned integral for indexing state tables. It will be either "**unsigned\ char**" or "**unsigned\ int**", depending on the size of your scanner.

Constants

YYLMAX
A constant that defines the maximum length of tokens the lex scanner can recognize. Its default value is 100 characters, and can be changed with the C preprocessor #undef and #define directives in the input declarations section.

Variables

yyleng
A variable that defines the length of the input token in yytext.

yylineno
A variable that defines the current input line number, maintained by input and yycomment.

yyin
A variable that determines the input stream for the yylex() and input functions.

yyout
A variable that determines the output stream for the output macro, which processes input that does not match any rules. The values of yyin and yyout can be changed by assignment.

yytext
A variable that defines the current input token recognized by the lex scanner. It is accessible both within a lex action and on return of the yylex() function. It is terminated with a null (zero) byte. If %pointer is specified in the definitions section, yytext is defined as a pointer to a preallocated array of char.

Macros

BEGIN
A macro that can be used as an action to cause lex to enter a new start condition.

ECHO
A macro that can be used as an action to copy the matched input token yytext to the lex output stream yyout.

NLSTATE
A macro that resets yylex() as though a newline had been seen on the input.

REJECT
A macro that causes yylex() to discard the current match and examine the next possible match, if any.

YY_FATAL
A macro that can be called with a string message upon an error. The message is printed to **stderr**, and yylex() exits with an error code of 1

yygetc()
A macro that is called by yylex() to obtain characters. Currently, this is defined as:

```
#define yygetc() getc(yyin)
```

A new version can be defined for special purposes, by first using #undef to remove the current macro definition.

YY_INIT
A macro that reinitializes yylex() from an unknown state. This macro can be used only in a lex action; otherwise, use the function yy_reset.

YY_INTERACTIVE
A macro that is usually defined in the code as being equal to 1. If defined as 1, `yylex()` attempts to satisfy its input requirements without looking ahead past newlines, which is useful for interactive input. If YY_INTERACTIVE is defined as 0, `yylex()` does look past newlines; it is also slightly faster

YY_PRESERVE
A macro that is usually not defined. If defined, when an expression is matched, `lex` saves any pushback in `yytext` before calling any user action and restores this pushback after the action. This may be needed for older `lex` programs that change `yytext`. It's not recommended, because the state saves are fairly expensive.

Functions

input
A function that returns the next character from the `lex` input stream. (This means that `lex` does not see it.) This function properly accounts for any lookahead that `lex` may require.

unput(int *c*)
A function that may be called by a translation when `lex` recognizes the sequence of characters that mark the start of a comment in the given syntax.

yycomment
A function that takes a sequence of characters marking the end of a comment, and skips over characters in the input stream until this sequence is found. Newlines found while skipping characters increment the external `yylineno`. An unexpected end-of-file produces a suitable diagnostic (using `yyerror`). The following `lex` rules match C and shell-style comments:

```
"/*"        yycomment("*/");
#.*\n   ;
```

A `lex` pattern is more efficient at recognizing a newline-terminated comment, whereas the function can handle comments longer than **YYLMAX**.

yyerror
A function that is used by routines that generate diagnostics. A version of `yyerror()` is provided in the library, which simply passes its arguments to `vfprintf` with output to the error stream **stderr**. A newline is written following the message. You can provide a replacement.

yylex
The scanner that `lex` produces. It returns a token if it has located in the input. A negative or zero value indicates error or end of input.

yymapch(int*delim*,int*esc*)
A function that can be used to process C-style character constants or strings. It returns the next string character from the input, or -1 when the character *delim* is reached. The usual C escapes are recognized: *esc* is the escape character to use; for C it is backslash.

yymore
A function that causes the next token to be concatenated to the current token in `yytext`. The current token is not rescanned.

yy_reset
A function that can be called from outside a `lex` action to reset the `lex` scanner. This is useful when starting a scan of new input.

yyRestoreScan
A function that restores the state of scanner after a `yySaveScan` call, and frees the allocated save block. The `yySaveScan` and `yyRestoreScan` functions allow an `include` facility to be safely defined for `lex`. Here is how the save functions can be used:

```
include(FILE * newfp)
{
    void * saved;
    saved = (void *) yySaveScan(newfp);
    /*
     * scan new file
     * using yylex() or yyparse()
```

```
     */
    yyRestoreScan(saved);
}
```

yySaveScan
A function that can be called to save the current state of `yylex()` and initialize the scanner to read from the given file pointer. The scanner state is saved in a newly allocated YY_SAVED record; this record is then returned. The contents of the save block are not of interest to the caller. Instead, the save block is intended to be passed to `yyRestoreScan` to reset the scanner.

Library Routines

yywrap
A library routine called by `yylex()` when it gets EOF from `yygetc`. The default version of `yywrap` returns `1`, which indicates no more input is available. `yylex()` then returns `0`, indicating end of file. If the user wishes to supply more input, a `yywrap` should be provided, which sets up the new input (possibly by assigning a new file stream to `yyin`), then returns `0` to indicate that more input is available.

Error Detection and Recovery

A character that is detected in the input stream that cannot be added to the last-matched string, and that cannot start a string, is considered not allowed by `lex`. `lex` might be instructed to write the character to an output stream, write a diagnostic and discard the character, ignore the character, or return an `error` token. The default action is to write the character to the output stream `yyout`. `lex` does this by invoking the macro:

```
#define output(c) putc((c),yyout)
```

By replacing the `output` macro, the user may change the default action to any C statement. Some possible definitions are:

```
/* type a diagnostic */
#define output(x) \
    error("Not Allowed character %c (%o)", (x),(x))

/* ignore the character */
#define output(c)
```

The file `yyout` is the standard output, by default.

When `lex` encounters input that cannot be handled, such as an overflow of the buffer, it calls the macro YY_FATAL:

```
YY_FATAL("message");
```

This macro displays the indicated message on **stderr** and then exits the program.

To change this behavior, you can redefine YY_FATAL in the definition section. For example, if `lex` is scanning an input file, but error recovery requires that other operations be carried out, you can redefine YY_FATAL to simply return a special value to flag that error.

For debugging a complex scanner, you can call `lex` called with the `-T` option. This causes a description of the various states of the scanner to be left in the text file **l.output**. You can then compile the scanner in **lex.yy.c** with the preprocessor flag YY_DEBUG defined, to get a scanner that displays, on **stderr**, the intermediate transitions and states of the scanner as it reads input. With the **l.output** information as a guide, these states can be related back to the input scanner description.

Ambiguity and Lookahead

A `lex` program may be ambiguous, in the sense that a particular input string may match more than one translation expression. Consider this example:

```
%%
[[:lower:]] { putchar(*yytext); }
aaa*  { printf("abc"); }
```

in which the string `aa` matches by both regular expressions (twice by the first, and one time by the second). Also, the string `aaaaaa` may be matched in many different ways.

If the input matches more than one expression, `lex` uses the following rules to determine which action to take:

1. The rule that matches the longest possible input stream is preferred.
2. If more than one rule matches an input of the same length, the rule that appears first in the translations section is preferred.

In the previous example, rule 1 causes both `aa` and `aaaaaa` to match the second action, while a single `a` matches the first action.

As another example, the following program works as expected:

```
"<"  { return(LESS); }
"=&" { return(EQUAL); }
"<=" { return(LESSEQ); }
```

Here, the sequence **<=** is taken to be an instance of a less-than-or-equal symbol, rather than an instance of a less-than symbol followed by an equals symbol.

Consider yet another example:

```
letter [[:lower:]]
%%
a({letter})* { return('A'); }
ab({letter})* { return('B'); }
```

which attempts to distinguish sequences of letters that begin with `a` from similar sequences that begin with `ab`. In this example, rule 1 is not sufficient, as, for example, the string `abb9` applies to either action; therefore, by rule 2, the first matching action should apply.

As written, the second action is never performed. To achieve the effect indicated, reverse the rules as follows:

```
letter [[:lower:]]
%%
ab{letter}* { return('B'); }
a{letter}* { return('A'); }
```

There is a danger in the lookahead that is done in trying to find the longest match. For example, an expression such as:

```
[.\n]+
```

causes the entire input to be read for a match! Another example is reading a quoted expression; for example:

```
'.*'
```

matches the string:

```
'quote one' followed by 'quote two'
```

because `lex` attempts to read too much of the input. The correct definition of this string is:

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

which stops after reading `'quote one'`.

Lookahead

A facility for looking ahead in the input stream is sometimes required. You can also use this facility to control the default ambiguity resolution process.

A traditional example is from FORTRAN, which does not have reserved words. Further scanning is required to determine whether the sequence `if(` is in fact an `if` statement, and not the subscripting of an array named `if`. In this case, a rather large amount of lookahead is required, to see what character follows the closing `)`; if the character is a letter, or a digit, then an `if` statement has indeed been found; otherwise, the array reference (or a syntax error) is indicated.

Another example is from C, where a name followed by `(` is to be contextually declared as an external function if it is otherwise undefined. In Pascal, lookahead is required to determine that:

```
123..1234
```

is an integer 123, followed by the subrange symbol **..**—which is followed by the integer 1234, and not simply two real numbers run together.

In all these cases, the desire is to look ahead in the input stream far enough to be able to make a decision, but without losing tokens in the process.

A special form of regular expression indicates lookahead:

```
re1 / re2
```

where *re1* and *re2* are regular expressions that do not themselves contain lookahead. The slash is treated as concatenation for the purposes of matching incoming characters: Both *re1* and *re2* must match adjacently for an action to be performed. *re1* indicates that part of the input string which is the token to be returned in `yytext`, whereas *re2* indicates the context. The characters matched by *re2* are reread at the next call to `yylex()` and broken into tokens.

For the C external function example, the lookahead operator is used in the following manner:

```
digit    [[:digit:]]
letter    [[:lower:]]\
name        {letter}({digit}|{letter})*

%%

{name}/"("    {
    if (name undefined)
        declare name a global function;
    }
{name}    { usual processing for identifiers }
```

To handle the (not reserved) `if` identifier in FORTRAN, the following is used:

```
space    [ \t]*
digit    [[:digit:]]
letter    [[:lower:]]

%%

if/{space]"(".*")"{space}({letter}|{digit}) {
                                    /* if statement */
                                }
{name}    { /* any other use of if */ }
```

If a `lex` expression is a prefix of some other expression, it has a hidden 1-character lookahead at the end, whether the lookahead operator is used or not. This enables `lex` to implement the longest-string rule correctly.

Left Context Sensitivity and Start Conditions

Even a fairly simple syntax may be difficult or impossible to describe with a single set of translations. For example, in the C programming language, literal strings have a different structure, and must be read and parsed separately from the rest of the input.

`lex` provides a facility called *start conditions*, which allow the input to be processed by different sets of rules. Start conditions are declared in the definitions section, with lines of the form:

```
%Start    name1 name2 ….
```

(You can abbreviate `%Start` to %S or %s). When a start condition name is placed at the beginning of a rule within **<>**, that rule can match only when `lex` is in that start condition. To enter a start condition, you can code the action:

```
BEGIN name
```

To revert to the usual state, use:

```
BEGIN 0
```

To make a rule active in several start conditions, use the prefix:

```
<name1,name2,…>
```

at the beginning of the expression. All rules without a start condition prefix are always active.

Here is a simple example of the use of start conditions. When `lex` sees a line containing only a 1, it switches to the **OTHER** start condition, until a line containing only a 0 is seen. While in the **OTHER** start condition, input is echoed with the text **OTHER** prefix to each line.

```
%s OTHER
%%

"0"\n         BEGIN 0;
"1"\n         BEGIN OTHER;
<OTHER>.*     printf("OTHER %s",yytext);
```

A more realistic example follows. This parses a C string.

```
%{
#include <stdio.h>
      static char buf[200];
      char *s;
      char *strchr();
      long strtol();
      char *yylval;
#define     STRING      1
%}

%s string

%%

<0>\"                 { BEGIN string; s = buf; }
<string>\\[0-7]{1,3}  {
                            *s++ = strtol(yytext+1,
                                                (char **)0, 8);
                      }
<string>\\\"         *s++ = '"';
<string>\\[rbfntv]    {
                            *s++ = *(strchr("\rr\bb\ff\nn\tt\vv",
                                   yytext[1])-1);
                      }
<string>\\\n         /* Escaped newline ignored */;
<string>\n            {
                             yyerror("Unterminated string");
                             BEGIN 0;
                      }
<string>\"            {
                             *s = '\0';
                             BEGIN 0;
```

```
                              yylval = buf;
                              return STRING;
                        }
<string>.               *s++ = *yytext;

%%

main()
{
     while(yylex( == STRING)  {
           printf(">>>"),
           fputs(yylval, stdout),
           printf("<<<\n);
     }
}
```

Sometimes the input is so structured that you require several completely different and conflicting sets of rules. You need a mechanism for defining *minianalyzers* that are enabled for some specific task.

To handle this need, you can define *exclusive* start conditions. When an exclusive start condition is active, no other rules are active; thus, a set of rules with the same (prefix) exclusive start condition effectively describe a minianalyzer that is independent of the usual rules. Exclusive start conditions are entered and left in the usual way, with the BEGIN action. To define exclusive start conditions, use %x instead of %s in the definition section.

The main feature of exclusive start conditions is that rules without a start condition prefix are *not* automatically applied to all start conditions. This allows a better structuring of the rules in some situations.

Tracing a lex Program

With the -T option, lex produces a description of the scanner that it is generating in the file **l.output**. This description consists of two parts: a description of the initial state table, specified as an NFA, followed by description of the minimized DFA for the final scanner. Usually only the latter is of interest. Here is the complete output for the previous example using start conditions. The actions are *not* represented.

```
NFA for complete syntax

state 0
  3: rule 0, start set 0 1 2 3
        epsilon 1
  4: rule 1, start set 0 1 2 3
        epsilon 5
  5: rule 2, start set 2 3
        epsilon 11
  6: rule 3, start set 0 1 2 3
        epsilon 15

state 1
        0  2

state 2
        \n  4

state 4
        final state

state 5
        1  6

state 6
        \n  8

state 8
        final state

state 11
        epsilon  9
        epsilon  12

state 9
        [\0-\t\13-\177]  10

state 10
        epsilon  9
```

```
        epsilon  12

state 12
        final state

state 15
        epsilon  13
        epsilon  16

state 13
        [\0-\t\13-\177]  14

state 14
        epsilon  13
        epsilon  16

state 16
        final state


Minimized DFA for complete syntax

state 0, rule 3, lookahead
        [\0-\t]       4
        [\13-/]       4
        0       7
        1       5
        [2-\177]      4

state 1, rule 3, lookahead
        .       same as 0

state 2, rule 2, rule 3, lookahead
        [\0-\t]       9
        [\13-/]       9
        0       11
        1       10
        [2-\177]      9

state 3, rule 2, rule 3, lookahead
        .       same as 2

state 4, rule 3, lookahead
        [01]  4
        .       same as 0


state 5, rule 3, lookahead
        \n      6
        [01]  4
        .       same as 0

state 6, rule 1, lookahead

state 7, rule 3, lookahead
        \n      8
        [01]  4
        .       same as 0

state 8, rule 0, lookahead

state 9, rule 2, rule 3, lookahead
        [01]  9
        .       same as 2

state 10, rule 2, rule 3, lookahead
        \n      6
        [01]  9
        .       same as 2

state 11, rule 2, rule 3, lookahead
        \n      8
        [01]  9
        .       same as 2
```

Looking at the minimal DFA reported, the table transitions are easy to trace. Starting at state 0, the rules are:

```
state 0, rule 3, lookahead
        [\0-\t]       4
```

```
        [\13-/]       4
        0       7
        1       5
        [2-\177]      4
```

The meaning of this description is: while in state 0 (which is based on rule 3), on reading the letter **0**, switch to state 7; for the letter **1**, switch to state 5; and on any other letter, switch to state 4.

Assume that the letter **1** is read. The scanner checks the rules for state 0, and transfers to state 5. In states 5 and 6, the following rules apply:

```
state 5, rule 3, lookahead
        \n      6
        [01]  4
        .       same as 0

state 6, rule 1, lookahead
```

The rules in state 5 describe a transition to state 6 upon reading a newline (\n), and a return to state 4 if anything else is read. (An optimization in the state tables allows state 5 to reuse state 0's transitions.) State 6 has no rules; it corresponds to the action that triggers the **OTHER** start condition.

The REJECT Action

To remember results of a previous scan for purposes of finding another possible match, the action **REJECT** can be used in the translation section. This action causes `lex` to do the next alternative. For example, the following program counts instances of the words **he** and **she**:

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

Anything not matching **he** or **she** is ignored, because of the bottom two rules.

This program, however, does not count instances of **he** embedded inside instances of **she**. To obtain this behavior, a **REJECT** action is required to force `lex` to consider any other rules that might match, adjusting the input accordingly. The program then becomes:

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

After counting each **he** or **she**, the expression is rejected and the other expression is examined. As **he** cannot include **she**, the second **REJECT** is actually not required in this case.

Character Set

`lex` handles characters internally as small integer values, as given by the bit pattern on the host computer's character set. To change the interpretation of input characters, you can provide a translation table in the definition section that associates an integer value with a character or group of characters. The translation table should be bracketed by lines containing %T.

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

This table maps lowercase and uppercase letters together into the range 1–26, newline into 27, **+** into 28, **-** into 29, and the digits into 30–39. The character values range from `0` to the highest possible value in the host computer's character set. Every possible input character must be enumerated in the table.

To work properly, the user must then redefine `yygetc` to translate input characters, so that **A** or **a** are given to `lex` as 1, **B** or **b** are given as 2, and so on.

Chapter 3. Generating a Parser Using OpenExtensions yacc

The yacc utility of the OpenExtensions Shell and Utilities is a tool for writing compilers and other programs that parse input according to strict *grammar* rules. The OpenExtensions yacc utility can produce anything from a simple parser for a desk calculator program to a very elaborate parser for a programming language. Those who are using yacc for complex tasks have to know all the idiosyncrasies of the program, including a good deal about the internal workings of yacc. On the other hand, the internal workings are mostly irrelevant to someone who is making an easy straightforward parser.

For this reason, novices may want to concentrate on the information in Chapter 1, "Tutorial Using OpenExtensions lex and yacc," on page 1 for an overview of how to use yacc. This tutorial also shows how you can use lex. and yacc together in the construction of a simple desk calculator.

How yacc Works

The input to yacc describes the rules of a grammar. yacc uses these rules to produce the source code for a program that parses the grammar. You can then compile this source code to obtain a program that reads input, parses it according to the grammar, and takes action based on the result.

The source code produced by yacc is written in the C programming language. It consists of a number of data tables that represent the grammar, plus a C function named yyparse(). By default, yacc symbol names used begin with yy. This is an historical convention, dating back to yacc's predecessor, UNIX yacc. You can avoid conflicts with yacc names by avoiding symbols that start with yy.

If you want to use a different prefix, indicate this with a line of the form:

```
%prefix prefix
```

at the beginning of the yacc input. For example:

```
%prefix ww
```

asks for a prefix of ww instead of yy. Alternatively, you could specify -p ww on the lex command line. The prefix chosen should be 1 or 2 characters long; longer prefixes lead to name conflicts on systems that truncate external names to 6 characters during the loading process. In addition, at least 1 of the characters in the prefix should be a lowercase letter (because yacc uses an all-uppercase version of the prefix for some special names, and this has to be different from the specified prefix).

Note: Different prefixes are useful when two yacc-produced parsers are to be merged into a single program. For the sake of convenience, however, the yy convention is used throughout this manual.

yyparse() and yylex()

yyparse() returns a value of 0 if the input it parses is valid according to the given grammar rules. It returns a 1 if the input is incorrect and error recovery is impossible.

yyparse() does not do its own lexical analysis. In other words, it does not pull the input apart into tokens ready for parsing. Instead, it calls a routine called yylex() every time it wants to obtain a token from the input.

yylex() returns a value indicating the *type* of token that has been obtained. If the token has an actual *value*, this value (or some representation of the value, for example, a pointer to a string containing the value) is returned in an external variable named yylval.

It is up to the user to write a yylex() routine that breaks the input into tokens and returns the tokens one by one to yyparse(). See "Function Section" on page 58 for more information on the lexical analyzer.

Grammar Rules

The grammar rules given to yacc not only describe what inputs are valid according to the grammar but also specify what action is to be taken when a given input is encountered. For example, if the parser recognizes a statement that assigns a value to a variable, the parser should either perform the assignment itself or take some action to ensure that the assignment eventually takes place.

If the parser is part of an interactive desk calculator, it can carry out arithmetic calculations as soon as the instructions are recognized; however, if the parser is the first pass in a compiler, it may simply encode the input in a way that is used in a later code-generation pass.

In summary, you must provide a number of things when using yacc to produce a parser:

- Grammar rules indicating what input is and is not valid.
- A lexical analyzer—yylex()— that breaks raw input into tokens for the parsing routine yyparse().
- Any source code or functions that may be needed to perform appropriate actions after particular inputs are recognized.
- A mainline routine that performs any necessary initializations, calls yyparse(), and then performs possible cleanup actions. The simplest kind of mainline is just a function **main** that calls yyparse() and then returns.

Input to yacc

This section describes the input to yacc when you are defining an LALR(1) grammar.

The input to yacc is broken into three sections:

- Declarations section
- Grammar rules section
- Functions section

The contents of each section are described shortly, but first, here are some overall rules for yacc input.

Sections of yacc input are separated by the symbol %%.

The general layout of yacc input is therefore:

```
declarations
%%
grammar rules
%%
functions
```

You can omit the declarations section if no declarations are necessary. In this case, the input starts with the first %%. You can also omit the function section, from the second %% on. The simplest input for yacc is therefore:

```
%%
grammar rules
```

Blanks, tabs, and newlines separate items in yacc input. These are called *white-space* characters. Wherever a white-space character is valid, any number of blanks, tabs, or newlines can be used. This means, for example, that the %% to separate sections does not have to be on a line all by itself; however, giving it a line of its own makes the yacc input easier to read.

Comments may appear anywhere a blank is valid. As in C, comments begin with **/*** and end with ***/**.

Identifiers used in yacc input can be of arbitrary length, and can consist of all letters (uppercase and lowercase), all digits, and the characters dot (**.**) and underscore (**_**). The first character of an identifier cannot be a digit. yacc distinguishes between uppercase and lowercase letters; **this**, **THIS**, and **This** are all different identifiers.

Literals in yacc input consist of a single character enclosed in single quotation marks—for example, 'c'. The standard C escape sequences are recognized:

```
\b    — backspace
\n    — newline
\r    — carriage return
\t    — tab
\v    — vertical tab
\'    — single quotation mark
\\    — backslash
\nnn    — any character
    (nnn is octal representation)
```

For technical reasons, the null character (\000) should never appear in yacc input.

Declarations Section

The declarations section describes many of the identifiers that are used in the rest of the yacc input. There are two types of declarations:

- Token declarations
- Declarations of functions and variables used in the actions that the parser takes when a particular input is recognized

The declarations section can also specify rules for the precedence and binding of operators used in the grammar. For example, you usually define the standard order of arithmetic operations in the declarations section.

Token Declarations

All characters are automatically recognized as tokens. For example, 'a' stands for a token that is the literal character *a*.

Other tokens are declared with statements of the form:

```
%token name1 name2 name3 …
```

This tells yacc that the given names refer to tokens. For example:

```
%token INTEGER
```

indicates that the identifier **INTEGER** refers to a particular type of token returned by the lexical analyzer yylex(). If **INTEGER** stands for any integer number token, you might have the following code in a handcoded yylex():

```
c = getchar();
if ((c >= '0') && (c <= '9')) {
      yylval = 0;
      do {
          yylval = (yylval * 10) + (c - '0');
          c = getchar();
      } while (c >= '0' && c <= '9');
      ungetc(c, stdin);
      return(INTEGER);
}
```

yylex() returns **INTEGER** to indicate that a certain kind of token (an integer number) has been returned. The actual value of this number is returned in yylval. The grammar rules in the yacc input dictate where an **INTEGER** token is valid.

In the C source code produced by yacc, the identifiers named in a %token statement appear as constants set up with #define. The first named token has a defined value of 257, the next is defined as 258, and so on. Token values start at 257, so they do not conflict with characters that have values in the 0-to-255 range or with character 256, which is used internally by yacc.

Because token identifiers are set up as defined constants, they must not conflict with reserved words or other identifiers that are used by the parser. For example:

```
%token if yyparse …
```

almost certainly leads to errors when you try to compile the source code output of `yacc`. To avoid this, this manual uses the convention of creating token names in uppercase, and you should follow the same practice.

Precedence and Associativity

Parsers that evaluate expressions usually have to establish the order in which various operations are carried out. For example, parsers for arithmetic expressions usually carry out multiplications before additions. Two factors affect order of operation: precedence and associativity.

Precedence dictates which of two *different* operations is to be carried out first. For example, in:

```
A + B * C
```

the standard arithmetic rules of precedence dictate that the multiplication is to take place before the addition. Operations that are to be carried out first are said to have a *higher* precedence than operations that are to be performed later.

Different operators can sometimes have the same precedence. In C, for example, addition and subtraction are similar enough to share the same precedence.

Associativity indicates which of two *similar* operations is to be carried out first. By *similar*, this means operations with the same precedence (for example, addition and subtraction in C). For example, C chooses to parse

```
A - B - C
```

as

```
(A - B) - C
```

whereas such languages as APL or FORTRAN use:

```
A - (B - C)
```

If the first operation is evaluated before the second (as C does), the operation is *left associative*. If the second operation is evaluated before the first (as APL does), the operation is *right associative*.

Occasionally, a compiler may have operations that are not associative. For example, FORTRAN regards:

```
A .GT. B .GT. C
```

as incorrect. In this case, the operation is *nonassociative*.

You can declare the precedence and associativity of operator tokens in the declarations section by using the keywords:

```
%left
%right
%nonassoc
```

For example:

```
%left '+' '-'
```

indicates that the **+** and **-** operations have the same precedence and are left associative.

Associativity declarations should be given in order of precedence. Operations with lowest precedence are listed first, and those with highest precedence are listed last. Operations with equal precedence are listed on the same line. For example,

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

says that **=** has a lower precedence than **+** and **-**, which in turn have a lower precedence than *****, **/**, and **%**. **=** is also right associative, so that

```
A = B = C
```

is parsed as

```
A = (B = C)
```

Because of the way yacc specifies precedence and associativity, operators with equal precedence always have the same associativity. For example, if **A** and **B** have equal precedence, their precedence must have been set with one of

```
%left A B
%right A B
%nonassoc A B
```

which means **A** and **B** must have the same associativity.

The names supplied with %right, %left, and %nonassoc can be literals or yacc identifiers. If they are identifiers, they are regarded as token names. yacc generates a %token directive for such names if they have not already been declared. For example, in:

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

UMINUS is taken to be a token identifier. There is no need to define **UMINUS** as a token identifier; a %token directive is generated automatically if necessary. It is perfectly valid to have an explicit:

```
%token UMINUS
```

if you want; however, it must precede the %left declaration.

For a more technical discussion of how precedence and associativity rules affect a parser, see “Ambiguities” on page 72.

Variable and Function Declarations

The declarations section may contain standard C declarations for variables or functions used in the actions specified in the grammar rules section. All such declarations should be included in a block that begins with **%{** and ends with **%}**. For example:

```
%{
    int i, j, k;
    static float x = 1.0;
%}
```

gives a few variable declarations. These declarations are essentially transferred *as is* to the *beginning* of the source code that yacc produces. This means that they are *external* to yyparse() and therefore global definitions.

Summary

The source code produced by yacc contains the following:

- Code from the declarations section
- Parsing tables produced by yacc to represent the grammar
- The yyparse() routine
- Code specified in the function section

Grammar Rules Section

A yacc grammar rule has the general form

```
identifier : definition ;
```

A colon separates the definition from the identifier being defined. A semicolon ends the definition.

The identifiers defined in the grammar rule section are known as *nonterminal symbols*. *Nonterminal* suggests that these symbols are not final; instead, they are made up of smaller things: tokens or other nonterminal symbols.

Here is a simple example of the definition of a nonterminal symbol:

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

This says that a paren_expr consists of a left parenthesis, followed by an expr, followed by a right parenthesis. The expr is either a token or a nonterminal symbol defined in another grammar rule. This grammar rule can be interpreted to say that a parenthesized expression consists of a usual expression inside parentheses.

A nonterminal symbol can have more than one definition. For example, you might define if statements with:

```
if_stat : IF '(' expr ')' stat ;
if_stat : IF '(' expr ')' stat ELSE stat ;
```

This definition assumes that IF and ELSE are tokens recognized by the lexical analyzer (which means that this parser's yylex() can recognize keywords). The definition also assumes that expr and stat are nonterminal symbols defined elsewhere.

When a single symbol has more than one meaning, yacc lets you join the various possibilities into a single definition. Different meanings are separated by "or" bars (**|**). Thus you can write:

```
if_stat : IF '(' expr ')' stat
        | IF '(' expr ')' stat ELSE stat
        ;
```

This technique is highly recommended, because it makes yacc input more readable.

Definitions in a grammar can be recursive. For example:

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

defines list to be one or more items separated by commas.

```
intexp : '(' intexp ')'
       | intexp '+' intexp
       | intexp '-' intexp
       | intexp '*' intexp
       | intexp '/' intexp
       | INTEGER
       ;
```

says that an integer expression can be another integer expression in parentheses, the sum of integer expressions, the difference of integer expressions, the product of integer expressions, the quotient of integer expressions, or an integer number standing on its own (where **INTEGER** is a token recognized by the lexical analyzer).

In recursive symbol definitions, it is often useful to have the empty string as one of the possible definitions. For example:

```
program :
        /* the empty string */
      | statement ';' program
      ;
```

defines a program as zero or more statements separated by semicolons.

This definition of `list` was an example of *left recursion* because `list` was on the left in the recursive definition. The definition of `program` was an example of *right recursion*, which is seldom recommended. For a discussion of the pros and cons of the two types of recursion, see "Input to yacc" on page 50.

Recognition Actions

In addition to defining what a nonterminal symbol *is*, a grammar rule usually describes what to do if the nonterminal symbol is encountered in parser input. This is called a *recognition action*.

Recognition actions are specified as part of the grammar rule. They are enclosed in brace brackets in the definition:

```
break_stat : BREAK ';'    { breakfn(); };
```

In this definition, `break_stat` is a nonterminal symbol made up of the token known as BREAK, followed by a semicolon. If this symbol is recognized, the parser calls a function named `breakfn`. Presumably this is a user-defined function that handles a `break;` statement.

Note: A semicolon is needed to mark the end of the definition, even though the recognition action ends in a brace bracket. Programmers who use C should bear this in mind.

For compatibility with some versions of UNIX `yacc`, OpenExtensions `yacc` lets you put an equals sign (**=**) before the opening brace that begins a recognition action:

```
break_stat : BREAK ';'    = { breakfn(); };
```

When a symbol has more than a single definition, a different recognition action may be associated with each definition. The next section shows an example of this.

Token and Symbol Values

One of the most common recognition actions is to return a value. For example, if an input is recognized as an expression to be evaluated, the parser may want to return the resulting value of the expression. To return a value, the recognition action merely assigns the value to a special variable named $$. For example:

```
hexdigit : '0' { $$ = 0; }
         | '1' { $$ = 1; }
                …
         | 'A' { $$ = 10; }
         | 'B' { $$ = 11; }
         | 'C' { $$ = 12; }
         | 'D' { $$ = 13; }
         | 'E' { $$ = 14; }
         | 'F' { $$ = 15; }
         ;
```

is one way to convert hexadecimal digits into numeric values. In this case, `yylex()` just returns the digits it finds, and `yyparse()` performs the actual conversion.

Another common recognition action is to return a value based on one or more of the items that make up the nonterminal symbol. Inside the recognition action, $1 stands for the value of the first item in the symbol, $2 stands for the value of the second item, and so on. If the item is a token, its value is the `yylval` value returned by `yylex()` when the token was read. If the item is a nonterminal symbol, its value is the $$ value set by the recognition action associated with the symbol. Thus you might write:

```
intexp : '(' intexp ')'         { $$ = $2; }
          /* value of parenthesized expression
             is expression inside parentheses */
       | intexp '+' intexp      { $$ = $1 + $3 ; }
          /* value of addition is sum of two
             expressions */
       | intexp '-' intexp      { $$ = $1 - $3 ; }
          /* value of subtraction is difference
             of two expressions */
```

```
        |  /* and so on */
        ;
```

This particular definition shows that each part of a multiple definition may have a different recognition action.

In the source code for `yyparse()`, this set of actions is turned into a large `switch` statement. The cases of the `switch` are the various possible recognition actions.

If no recognition action is specified for a definition, the default is:

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

This action just returns the value of the first item (if the item has a value).

Precedence in the Grammar Rules

The discussion of the declarations section showed how precedence can be assigned to *operators*. Precedence can also be assigned to *grammar rules*, and this is done in the grammar rules section.

One way to give a grammar rule a precedence uses the `%prec` construct:

```
%prec TOKEN
```

in a grammar rule indicates that the rule has the same precedence as the specified token.

For example, consider the unary minus operator. Suppose your declaration section contains:

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

In the grammar rules section, you can write:

```
exp : exp '+' exp
    | exp '-' exp
    | exp '*' exp
    | exp '/' exp
    | '-' exp %prec UMINUS
    | /* and so on */
    ;
```

You cannot directly set up a precedence for the unary minus, because you had already set up a precedence for the "`-`" token. Instead, you created a token named `UMINUS` and gave it the precedence you wanted to assign the unary minus. The grammar rule for the unary minus added:

```
%prec UMINUS
```

to show that this rule has the precedence of `UMINUS`.

As another example, you might set up precedence rules for the right shift and left shift operations of C with:

```
%left RS LS
    ...
exp :
    | exp '<' '<' exp %prec LS
    | exp '>' '>' exp %prec RS
    ...
```

In this way you give the shift operations the proper precedence and avoid confusing them with the comparison operations > and <. Of course, another way to resolve this problem is to make the lexical analyzer clever enough to recognize >> and << and to return the RS or LS tokens directly.

Although symbols like `UMINUS`, `LS`, and `RS` are treated as tokens, they do not have to correspond to actual input. They may just be placeholders for operator tokens that have two different meanings.

Note: The use of %prec is relatively rare in yacc. People do not usually think of %prec in their first draft of a grammar. %prec is added only in later drafts, when it is needed to resolve conflicts that appear when the rules are run through yacc.

If a grammar rule is not assigned a precedence using %prec, the precedence of the rule is taken from the last *token* in the rule. For example, if the rule is:

```
expr : expr '+' expr
```

the last token in the rule is "+" (because expr is a nonterminal symbol, not a token). Thus the precedence of the rule is the same as the precedence of +.

If the last token in a rule has no assigned precedence, the rule does not have a precedence. This can result in some surprises if you are not careful. For example, if you define:

```
expr : expr '+' expr ';'
```

the last token in the rule is ";"— so the rule probably does not have a precedence even if + does.

Start Symbol

The first nonterminal symbol defined in the rules section is called the *start symbol*. This symbol is taken to be the largest, most general structure described by the grammar rules. For example, if you are generating the parser for a compiler, the start symbol should describe what a complete program looks like in the language to be parsed.

If you do not want the first grammar rule to be taken as the start symbol, you can use the directive:

```
%start name
```

in your rules section. This indicates that the nonterminal symbol *name* is the start symbol. *name* must be defined somewhere in the rules section.

The start symbol must be all-encompassing: Every other rule in the grammar must be related to it. In a sense, the grammar rules form a *tree*: The root is the start symbol, the first set of branches are the symbols that make up the start symbol, the next set of branches are the symbols that make up the first set, and so on. Any symbol that is *outside* this tree is reported as a *useless variable* in yacc output. The parser ignores useless variables; it is looking for a complete start symbol, and nothing else.

End Marker

The end of parser input is marked by a special token called the *end marker*. This token is often written as $end; the value of the token is zero.

It is the job of the lexical analyzer yylex() to return a zero to indicate $end when the end of input is reached (for example, at end of file, or at a keyword that indicates end of input).

yyparse() terminates when it has parsed a start symbol followed by the end marker.

Declarations in yyparse()

You can specify C declarations that are local to yyparse() in much the same way that you specify external declarations in the Declarations Section. Enclose the declarations in %{ and %} symbols, as in

```
%{
    /* External declarations */
%}
%%
/* Grammar Rules start here */
%{
    /* Declarations here are
       local to yyparse() */
%}
/* Rules */
%%
/* Function section */
```

You can also put declarations at the start of recognition action code, which is local to that action.

Function Section

The function section of `yacc` input may contain functions that should be linked in with the `yyparse()` routine. `yacc` itself does nothing with these functions; it simply adds the source code on the end of the source code produced from the grammar rules. In this way, the functions can be compiled at the same time that the `yacc`-produced code is compiled.

Of course, these additional functions can be compiled separately and linked with the `yacc`-produced code later on (after everything is in object code format). Separate compilation of modules is strongly recommended for large parsers; however, functions that are compiled separately need a special mechanism if they want to use any definitions that are defined in the `yacc`-produced code, and it is sometimes simpler to make the program part of the `yacc` input.

For example, consider the case of `yylex()`. Every time `yylex()` obtains a token from the input, it returns to `yyparse()` with a value that indicates the type of token found. Obviously, then, `yylex()` and `yyparse()` must agree on which return values indicate which kind of tokens. Because `yyparse()` already refers to tokens using compile-time constants (created in the declarations section with the `%token` directive), it makes sense for `yylex()` to use the same constants. The lexical analyzer can do this very easily if it is compiled along with `yyparse()`.

Size might be the determining factor. With very simple parsers, it is easier to put `yylex()` in the function section. With larger parsers, the advantages of separate compilation are well worth the extra effort.

If you are going to compile `yylex()` or other routines separately from `yyparse()`, use the:

```
-D file.h
```

option on the `yacc` command line. `yacc` writes out the compiler constant definitions to the file of your choice. This file can then be included (with the `#include` directive) to obtain these definitions for `yylex()` or any other routine that needs them. The constants are already included in the generated parser code, so you need them only for separately compiled modules.

Lexical Analyzer

The lexical analyzer `yylex()` reads input and breaks it into tokens; in fact, it determines what constitutes a token. For example, some lexical analyzers may return numbers one digit at a time, whereas others collect numbers in their entirety before passing them to the parser.

Similarly, some lexical analyzers may recognize such keywords as `if` or `while` and tell the parser that an `if` token or `while` token has been found. Others may not be designed to recognize keywords, so it is up to the parser itself to distinguish between keywords and other things, such as variable names.

Each token named in the declarations section of the `yacc` input is set up as a defined C constant. The value of the first token named is 257, the value of the next is 258, and so on. You can also set your own values for tokens by placing a positive integer after the first appearance of any token in the declarations section. For example:

```
%token AA 56
```

assigns a value of 56 to the definition of the token symbol AA. This mechanism is very seldom needed, and you should avoid it whenever possible.

There is little else to say about requirements for `yylex()`. If the function is to return the value of a token as well as an indication of its type, the value is assigned to the external variable `yylval`. By default, `yylval` is defined as an `int` value, but it can also be used to hold other types of values. For more information, see the description of `%union` in “Types” on page 70.

Internal Structures

To use yacc effectively, it is helpful to understand some of the internal workings of the parser that yacc produces. This section looks at some of these workings.

As a point of reference, consider a parser with the following grammar:

```
%token NUM
%left '+' '-'
%left '*' '/'
%%
expr : NUM
     | expr '+' expr
     | expr '-' expr
     | expr '*' expr
     | expr '/' expr
     | '(' expr ')'
     ;
```

States

As the parser reads in token after token, it switches between various *states*. You can think of a state as a point where the parser says, ‘‘I have read *this* particular sequence of input tokens and now I am looking for one of *these* tokens.''

For example, a parser for the C language might be in a state where it has finished reading a complete statement and is ready for the start of a new statement. It therefore expects some token that can legitimately start a statement (for example, a keyword such as `if` or `while`, or the name of a variable for an assignment). In this state, it reads a token. Say it finds the token corresponding to the keyword `if`. It then switches to a new state, where it says, ‘‘I have seen an `if` and now I want to see the `(` that begins the `if` condition.'' When it finds the `(`, it switches again to a state that says, ‘‘I have found `if(` and now I want the start of a condition expression.''

States break the parsing process into simple steps. At each step, the parser knows what it has seen and what it is looking for next.

yacc assigns numbers to every possible state the parser can enter. The `0`th state is always the one that describes the parser's condition before it has read any input. Other states are numbered arbitrarily.

Sometimes a particular input be the start of only one construct. For example, the `for` keyword in C can be the start of only a `for` statement, and the `for` statement has only one form.

On the other hand, a grammar can have several nonterminal symbols that start the same way. In the sample grammar, all of:

```
expr '+' expr
expr '-' expr
expr '*' expr
expr '/' expr
```

start with `expr`. If the parser finds that the input begins with `expr`, the parser has no idea which rule matches the input until it has read the operator following the first `expr`.

The parser chooses which state it enters next by looking at the next input token. This token is called the *lookahead symbol* for that state.

Diagramming States

yacc uses simple diagrams to describe the various states of the parser. These diagrams show what the parser has seen and what it is looking for next. The diagrams are given in the parser description report produced by yacc. See “yacc Output” on page 66 for more information.

For example, consider the state where the parser has just read a complete `expr` at the beginning of a larger expression. It is now in a state where it expects to see one of the operators `+`, `-`, `*`, or `/`, or perhaps the `$end` marker (indicating the end of input). `yacc` diagrams this state as:

```
$accept:  expr.$end
expr:     expr.'+' expr
expr:     expr.'-' expr
expr:     expr.'*' expr
expr:     expr.'/' expr
```

This lists the possible grammar constructs that the parser may be working on. (In the first line, `$accept` stands for the start symbol.) The dot (`.`) indicates how much the parser has read so far.

If the lookahead symbol is `*`, the parser switches to a state diagrammed by:

```
expr:     expr '*'.expr
```

In this state, the parser knows that the next thing to come is another `expr`. This means that the only valid tokens that can be read next are "`(`" or `NUM`, because those are the only things that start a valid `expr`.

State Actions

There are several possible actions that the parser can take in a state:

- *Accept* the input
- *Shift* to a new state
- *Reduce* one or more input tokens to a single nonterminal symbol, according to a grammar rule
- *Go to* a new state
- Raise an *error* condition

To decide which action to take, the parser checks the lookahead symbol (except in states where the parser can take only one possible action, so that the lookahead symbol is irrelevant).

This means that a typical state has a series of possible actions based upon the possible values of the lookahead symbol. In `yacc` output, you might see:

```
'+'   shift 8
'-'   shift 7
'*'   shift 6
'/'   shift 5
')'   shift 9
.     error
```

This says that if the parser is in this state and the lookahead symbol is "+", the parser shifts to state 8. If the lookahead symbol is "-", the parser shifts to state 7, and so on.

The dot (`.`) in the final line stands for any other token not mentioned in the preceding list. If the parser finds any unexpected tokens in this particular state, it takes the **Error** action.

The sections that follow explain precisely what each state action means and what the parser does to handle these actions.

Accept

The **Accept** action happens only when the parser is in a state that indicates it has seen a complete input and the lookahead symbol is the end marker `$end`. When the parser takes the **Accept** action, `yyparse()` terminates and returns a zero to indicate that the input was correct.

Shift

The **Shift** action happens when the parser is partway through a grammar construct and a new token is read in. As an example, state 4 in the sample parser is diagrammed with:

```
expr:     expr.'+' expr
expr:     expr.'-' expr
expr:     expr.'*' expr
expr:     expr.'/' expr
expr:     '(' expr.')'

'+'   shift 8
'-'   shift 7
'*'   shift 6
'/'   shift 5
')'   shift 9
 .    error
```

This shows that the parser shifts to various other states depending on the value of the lookahead symbol. For example, if the lookahead symbol is "*"—the parser shifts to state 6, which has the diagram:

```
expr:     expr '*'.expr

NUM   shift 2
'('   shift 1
 .    error

expr  goto 11
```

In this new state, the parser has further shifts it can make, depending on the next lookahead symbol.

When the parser shifts to a new state, it saves the previous state on a stack called the *state stack*. The stack provides a history of the states that the parser has passed through while it was reading input. It is also a control mechanism, as described in “yacc Output” on page 66.

Paralleling the state stack is a *value* stack, which records the values of tokens and nonterminal symbols encountered while parsing. The value of a token is the `yylval` value returned by `yylex()` at the time the token was read. The value of a nonterminal symbol is the $$ value set by the recognition action associated with that symbol's definition. If the definition did not have an associate recognition action, the value of the symbol is the value of the first item in the symbol's definition.

At the same time that the **Shift** action pushes the current state onto the state stack, it also pushes the `yylval` value of the lookahead symbol (token) onto the value stack.

Reduce

The **Reduce** action takes place in states where the parser has recognized all the items that make up a nonterminal symbol. For example, the diagram of state 9 in the sample grammar is:

```
expr:     '(' expr ')'.

 .    reduce (6)
```

At this point, the parser has seen all three components that make up the nonterminal symbol `expr`. As the line:

```
 .    reduce (6)
```

shows, it does not matter what the lookahead symbol is at this point. The nonterminal symbol has been recognized, and the parser is ready for a **Reduce** action.

Note: The `(6)` just means that the parser has recognized the nonterminal symbol defined in rule `(6)` of the grammar. See “yacc Output” on page 66 for more information.

The **Reduce** action performs a number of operations. First, it pops states off the state stack. If the recognized nonterminal symbol had *N* components, a reduction pops *N*-1 states off the 1 stack. In other words, the parser goes back to the state it was in when it first began to gather the recognized construct.

Next, the **Reduce** action pops values off the value stack. If the definition that is being reduced consisted of *N* items, the **Reduce** action conceptually pops *N* values off the stack. The topmost value on the stack is assigned to $N, the next to $N-1, and so on down to $1.

After the **Reduce** action has gathered all the $X values, the parser calls the recognition action that was associated with the grammar rule being reduced. This recognition action uses the $1-$N values to come up with a $$ value for the nonterminal symbol. This value is pushed onto the value stack, thereby replacing the *N* values that were previously on the stack.

If the nonterminal symbol had no recognition action, or if the recognition action did not set $$, the parser puts the value of $1 back on the stack. (In reality, the value is never popped off.)

Lastly, the **Reduce** action sets things up so that the lookahead symbol seems to be the nonterminal symbol that was just recognized. For example, it may say that the lookahead symbol is now an `expr` instead of a token.

Goto

The **Goto** action is a continuation of the **Reduce** process. **Goto** is almost the same as **Shift**; the only difference is that the **Goto** action takes place when the lookahead symbol is a nonterminal symbol while a **Shift** takes place when the lookahead symbol is a token.

For example, state 6 in the sample grammar reads:

```
expr:    expr '*'.expr

NUM   shift 2
'('   shift 1
 .    error

expr  goto 12
```

The first time the parser enters this state, the lookahead symbol is a token and the parser shifts into some state where it begins to gather an `expr` . When it has a complete `expr`, it performs a **Reduce** action that returns to this state and set the lookahead symbol to `expr`. Now when the parser has to decide what to do next, it sees that it has an `expr` for the lookahead symbol and therefore takes the **Goto** action and moves to state 12.

The **Shift** action pushes the current state onto the state stack. The **Goto** does not have to do this: The state was on the stack already. Similarly, **Shift** pushes a value onto the value stack, but **Goto** does not, because the value corresponding to the nonterminal symbol was already put on the value stack by the **Reduce** action. **Goto** replaces the top of the state stack with the target stack.

When the parser reaches the new state, the lookahead symbol is restored to whatever it was at the time of the **Reduce** action.

Essentially then, a **Goto** is like a **Shift**, except that it takes place when you come *back* to a state with the **Reduce** action. Also, a **Shift** is based on the value of a single input token, whereas a **Goto** is based on a nonterminal symbol.

Error

The parser takes the **Error** action when it encounters any input token that cannot legally appear in a particular input location. When this happens, the parser raises the `error` condition. Because error handling can be quite complicated, the whole of the next section is devoted to the subject.

Error Handling

If a piece of input is incorrect, the parser can do nothing with it. Except in extreme cases, however, it is inappropriate for the parser to stop all processing as soon as an error is found. Instead, the parser should skip over the incorrect input and resume parsing as soon after the error as possible. In this way, the parser can find many syntax errors in a single pass through the input, saving time and trouble for the user.

yacc therefore tries to generate a parser that can *restart* as soon as possible after an error occurs. yacc does this by letting you specify points at where the parser can pick up after errors. You can also dictate what special processing is to take place if an error is encountered at one of these points.

The error Symbol

yacc's error handling facilities use the identifier `error` to stand for erroneous input. Therefore, you should not use `error` as the name of a user-defined token or nonterminal symbol.

You should put `error` in your grammar rules where error recovery might take place. For example, you might write:

```
statement: error
    | /* other definitions of a statement */;
```

This tells yacc that errors may occur in statements, and that after an error, the parser is free to restart parsing at the end of a complete statement.

The Error Condition

As noted in "Internal Structures" on page 59, yacc takes the **Error** action if it finds an input that is not valid in a particular location. The **Error** action has the following steps:

1. See if the current state has a **Shift** action associated with the `error` symbol. If it does, shift on this action.
2. If the current state has no such action, pop the state off the stack and check the next state. Also pop off the top value on the value stack, so that the state stack and value stack stay in synch.
3. Repeat the second step until the parser finds a state that can shift on the `error` symbol.
4. Take the **Shift** action associated with the `error` symbol. This pushes the current state on the stack—that is, the state that can handle errors. No new value is pushed onto the value stack; the parser keeps whatever value was already associated with the state that can handle errors.

When the parser shifts out of the state that can handle errors, the lookahead symbol is whatever token caused the error condition in the first place. The parser then tries to proceed with usual processing.

Of course, it is quite possible that the original lookahead symbol is incorrect in the new context. If the lookahead symbol causes an error again, it is discarded and the error condition stays in effect. The parser continues to read new tokens and discard them until it finds a token that can validly follow the error. The parser then takes whatever action is associated with the valid token.

In a typical grammar, the state that has been handling errors is eventually popped off the stack in a **Reduce** operation.

Notice that the parser always shifts (through the **Shift** action) on the `error` token. It never reduces on `error`, even if the grammar has a state where `error` is associated with a **Reduce** action.

In some situations, an error condition is raised and the parser pops all the way to the bottom of the state stack without finding a state that can handle the `error` symbol. For example, the grammar may have no provisions for error recovery. In this case, `yyparse()` simply terminates and returns a 1 to its caller.

Examples

As a simple example, consider a parser for a simple desk calculator. All statements end in a semicolon. Thus you might see the rule:

```
statement : var '=' expr ';'
          | expr ';'
          | error ';'
          ;
```

When an error occurs in input, the parser pops back through the state stack until it comes to a state where the `error` symbol is recognized. For example, the state might be diagrammed as:

```
$accept:   .statement $end

error  shift 2
NUM    shift 4
.      error

var       goto 7
expr      goto 3
statement goto 5
```

If an error occurs anywhere in an input statement, the parser pops back to this state, and then shifts to state 2. State 2 looks like this:

```
statement:   error.';'

';'   shift 6
 .    error
```

In other words, the next token must be a semicolon. If it is not, another error occurs. The parser pops back to the previous state and takes the `error` shift again. Input is discarded token by token until a semicolon is found. When the semicolon is found, the parser is able to shift from state 2 to state 6, which is:

```
statement:  error ';'.

.    reduce (3)
```

The erroneous line is reduced to a `statement` nonterminal symbol.

Now this example is simple, but it has its drawbacks. It gets you into trouble if the grammar has any concept of block structure or parenthesization. Why? After an error occurs, the rule:

```
statement : error ';'
```

effectively tells the parser to discard absolutely everything until it finds a `';'` character. If you have a parser for C, for example, it would skip over important characters such as) or } until it found a semicolon. Your parentheses and braces would be out of balance for the rest of the input, and the whole parsing process would be a waste of time. The same principle applies to any rule that shows the `error` token followed by some other nonnull symbol: It can lead to hopeless confusion in a lot of grammars.

It is safer to write the rule in a form like this:

```
statement : error
          | ';'
          | /* other stuff */
```

In this case, the `error` token matches material only until the parser finds something else it recognizes (for example, the semicolon). After this happens, the `error` state is reduced to a `statement` symbol and popped off the stack. Parsing can then proceed as usual.

Error Recognition Actions

The easiest way to generate an error message is to associate a recognition action with the grammar rule that recognizes the error. You can do something simple:

```
statement: error
    {
        printf("You made an error!\n");
    }
```

or you can be fancier:

```
line: error '\n' prompt line
    { $$ = $4; };
```

```
prompt: /* null token */
    { printf("Please reenter line.\n"); };
```

If an error occurs, the parser skips until it finds a newline character. After the newline, it always finds a null token matching `prompt`, and the recognition action for `prompt` displays the message:

```
Please reenter line.
```

The final symbol in the rule is another `line`, and the action after the `error` rule shows that the result of the rule ($$) should be the material associated with the second input line.

All this means that if the user makes a mistake entering an input line, the parser displays an error message and accepts a second input line in place of the first. This allows for an interactive user to correct an input line that was incorrectly typed the first time.

Of course, this setup works only if the user does not make an error the second time the line is typed too. If the next token he or she types is also incorrect, the parser discards the token and decides that it is still gobbling up the original error.

The yyclearin Macro

After an **Error** action, the parser restores the lookahead symbol to the value it had at the time the error was detected; however, this is sometimes undesirable.

For example, your grammar may have a recognition action associated with the `error` symbol, and this may read through the next lot of input until it finds the next sure-to-be-valid data. If this happens, you certainly do not want the parser to pick up the old lookahead symbol again after error recovery is finished.

If you want the parser to throw away the old lookahead symbol after an error, put:

```
yyclearin ;
```

in the recognition action associated with the `error` symbol. `yyclearin` is a macro that expands into code that discards the lookahead symbol.

The yyerror Function

The first thing the parser does when it performs the **Error** action is to call a function named `yyerror()`. This happens *before* the parser begins going down the state stack in search of a state that can handle the `error` symbol. `yyerror` must be supplied by the user; its name must be in lowercase.

The simplest `yyerror()` functions either end the parsing job or just return so that the parser can perform its standard error handling.

The `yyerror()` function is passed one operand: a character string describing the type of error that just took place. This string is almost always:

```
Syntax error
```

The only other operand strings that might be passed are:

```
Not enough space for parser stacks
Parser stack overflow
```

which are used when the parser runs out of memory for the state stack.

After `yyerror()` returns to `yyparse()`, the parser proceeds popping down the stack in search of a state that can handle errors.

If another error is encountered soon after the first, `yyerror()` is *not* called again. The parser considers itself to be in a *potential error* situation until it finds three correct tokens in a row. This avoids the torrents of error messages that often occur as the parser wades through input in search of some recognizable sequence.

After the parser has found three correct tokens in a row, it leaves the potential error situation. If a new error is found later on, `yyerror()` is called again.

The yyerrok Macro

In some situations, you may want `yyerror()` to be called even if the parser has not seen three correct tokens because the last error.

For example, suppose you have a parser for a line-by-line desk calculator. A line of input contains errors, so `yyerror()` is called. `yyerror()` displays an error message to the user, throws away the rest of the line, and prompts for new input. If the next line contains an error in the first three tokens, the parser usually starts discarding input *without* calling `yyerror()` again. This means that `yyerror()` does not display an error message for the user, even though the input line is wrong.

To avoid this problem, you can explicitly tell the parser to leave its potential error state, even if it has not yet seen three correct tokens. Simply code:

```
yyerrok ;
```

as part of the error recognition action.

For example, you might have the rule:

```
expr : error {
         yyerrok;
         printf("Please re-enter line.\n");
         yyclearin;
     }
```

`yyerrok` expands into code that takes the parser out of its potential error state and lets it start fresh.

Other Error Support Routines

YYABORT
Halts `yyparse()` in midstream and immediately returns a `1`. To the function that called `yyparse()`, this means that `yyparse()` failed for some reason.

YYACCEPT
Halts the parser in midstream and returns a `0`. To the function that called `yyparse()`, this means that `yyparse()` ended successfully, even if the entire input has not yet been scanned.

YYRETURN(*value*)
Halts the parser in midstream and returns whatever *value* is. You should use this rather than simply coding `return(`*value*`)`.

YYERROR
Is a macro that *fakes* an error. (Note that it is uppercase.) When YYERR0R is encountered in the code, the parser reacts as if it just saw an error and goes about recovering from the error. “Advanced yacc Topics” on page 74 gives an example of how YYERR0R can be useful.

yacc Output

`yacc` can produce several output files. Options on the `yacc` command line dictate which files are actually generated.

The most important output file is the one containing source code that can be compiled into the actual parser. The name of this file is specified with the `-o` *file.c* command line option.

Another possible output file contains compile-time definitions. The name of this file is specified with `-D` *file.h* on the command line. This file is a distillation of the declarations section of the `yacc` input. For example, all the `%token` directives are restated in terms of constant definitions.

```
%token IF
```

appears as:

```
#define IF 257
```

in the definition file (assuming that IF is the first token in the declarations section). By including this file with:

```
#include "file.h"
```

separately compiled modules can make use of all the pertinent definitions in the yacc input.

The third output file that yacc can produce is called the parser description. The name of the file is specified with -V *stats* on the command line. The parser description is split into three sections:

- A summary of the grammar rules
- A list of state descriptions
- A list of statistics for the parser generated by yacc

The sections that follow show what the parser description looks like for the following grammar:

```
%token IF ELSE A
%%
stmt : IF stmt ELSE stmt
     | IF stmt
     | A
     ;
```

Rules Summary

The rules summary section of the parser description begins with the command line used to call yacc. This is intended to serve as a heading for the output material.

Next comes a summary of the grammar rules. The example has:

```
Rules:
   (0)  $accept:  stmt $end
   (1)  stmt:     IF stmt ELSE stmt
   (2)  stmt:     IF stmt
   (3)  stmt:     A
```

The 0th rule is always the definition for a symbol named $accept. This describes what a complete input looks like: the **Start** symbol followed by the end marker. Other rules are those given in the grammar.

yacc puts a form-feed character on the line after the last grammar rule, so that the next part of the parser description starts on a new page.

State Descriptions

The parser description output contains complete descriptions of every possible state. For example, here is the description of one state from the sample grammar:

```
State 2
    stmt :  IF.stmt ELSE stmt
    stmt :  IF.stmt

   IF   shift 2
    A    shift 1
    .    error

    stmt     goto 4
```

By now, this sort of diagram should be familiar to you. The numbers after the word shift indicate the state to which the parser shifts if the lookahead symbol happens to be IF or A. If the lookahead symbol is anything else, the parser raises the error condition and starts error recovery.

If the parser pops back to state 2 by means of a **Reduce** action, the lookahead symbol is now stmt and the parser will go to state 4.

As another example of a state, here is state 1:

```
State 1
    (3)   stmt:    A.

          .     reduce (3)
```

This is the state that is entered when an A token has been found. The (3) on the end of the first line is a *rule number*. It indicates that this particular line sums up the whole of the third grammar rule that was specified in the `yacc` input. The line:

```
    .    reduce (3)
```

indicates that no matter what token comes next, you can reduce this particular input using grammar rule (3) and say that you have successfully collected a valid `stmt`. The parser performs a reduction by popping the top state off the stack and setting the lookahead symbol to `stmt`.

It is important to distinguish between:

```
  A  shift 1
```

in state 2 and:

```
  .  reduce (3)
```

in state 1. In the **Shift** instruction, the number that follows is the number of a *state*. In the **Reduce** instruction, the number that follows is the number of a *grammar rule* (using the numbers given to the grammar rules in the first part of the parser description). The parser description always encloses rule numbers in parentheses, and leaves state numbers as they are.

Here is the complete list of state descriptions for the grammar:

```
State 0
         $accept: .stmt $end

    IF    shift 2
    A     shift 1
    .     error

    stmt    goto 3

State 1
    (3)  stmt:     A.

    .     reduce (3)

State 2
         stmt:     IF.stmt ELSE stmt
         stmt:     IF.stmt

    IF    shift 2
    A     shift 1
    .     error

    stmt    goto 4

State 3
         $accept:  stmt.$end

    $end  accept
    .     error

State 4
         stmt:     IF stmt.ELSE stmt
    (2)  stmt:     IF stmt. [ $end ELSE ]

    ELSE  shift 5
    .     reduce (2)

State 5
         stmt:     IF stmt ELSE.stmt

    IF    shift 2
    A     shift 1
    .     error
```

```
    stmt    goto 6

State 6
    (1)  stmt:     IF stmt ELSE stmt.

    .     reduce (1)
```

The parser always begins in state 0, that is, in a state where no input has been read yet. An acceptable input is a stmt followed by the end marker. When a stmt has been collected, the parser goes to state 3. In state 3, the required end marker, $end, indicates that the input is to be accepted. Anything else found is excess input and means an error.

In state 4, the rule labeled (2) has:

```
[ $end ELSE ]
```

on the end. This just means that the parser expects to see one of these two tokens next.

Parser Statistics

The last section of the parser description is a set of statistics summarizing yacc's work. Here are the statistics you see when you run the sample grammar through yacc:

```
4 rules, 5 tokens, 2 variables, 7 states
Memory:  max = 9K
States: 3 wasted, 4 resets
Items:  18, 0 kernel, (2,0) per state, maxival=16 (1 w/s)
Lalr:  1 call, 2 recurs, (0 trans, 12 epred)
Actions:  0 entries, gotos: 0 entries
Exceptions: 1 states, 4 entries
Simple state elim: 0%, Error default elim: 33%
Optimizer: in 0, out 0
Size of tables:  24 bytes
1 seconds, final mem = 4K
```

Some of these values are machine-independent (for example, the number of rules), others are machine-dependent (for example, the amount of memory used), and some can be different every time you run the job (for example, time elapsed while yacc was running).

Many of these are of no interest to the usual user; yacc generates them only for the use of those maintaining the yacc software. A number of the statistics refer to shift-reduce or reduce-reduce conflicts; for a discussion of these, see “Ambiguities” on page 72. Here is a description of the statistic lines:

4 rules, 5 tokens, 2 variables, 7 states
: The four rules are the grammar rules given in the first part of the parser description. The five tokens are A, IF, ELSE, $endf, and error (which is always defined, even if it is not used in this grammar). The two variables are the nonterminal symbols, stmt and the special $accept. The seven states are states 0 to 6.

Memory: max = 9K
: This gives the maximum amount of dynamic memory that yacc required while producing the parser. This line may also have a *success rate*, which tells how often yacc succeeded in having enough memory to handle a situation and how often it had to ask for more memory.

States: 3 wasted, 4 resets
: The algorithm that constructs states from the grammar rules makes a guess at the number of states it needs, very early in the yacc process. If this guess is too high, the excess states are said to be *wasted*.

  When states from the various grammar rules are being created, a state from one rule sometimes duplicates the state from another (for example, there were two rules that started with IF in the previous example). In the final parsing tables, such duplicate states are merged into a single state. The number of *resets* is the number of duplicate states formed and then merged.

Items: 18, 0 kernel, (2,0) per state, maxival=16 (1 w/s)
A state is made of items, and the kernel items are an important subset of these: The size of the resulting parsing tables and the running time for `yacc` are proportional to the number of items and kernel items. The rest of the statistics in this line are not of interest to usual users.

Lalr: 1 call, 2 recurs, (0 trans, 12 epred)
This gives the number of calls and recursive calls to the conflict resolution routine. The parenthesized figures are related to the same process. In some ways, this is a measure of the complexity of the grammar being parsed. This line does not appear if there are no reduce-reduce or shift-reduce conflicts in your grammar.

Actions: 0 entries, gotos: 0 entries
This gives the number of entries in the tables `yyact` and `yygo`. `yyact` keeps track of the possible *shifts* that a program may make and `yygo` keeps track of the *gotos* that take place at the end of states.

Exceptions: 1 states, 4 entries
This gives the number of entries in the table `yygdef`, yet another table used in `yacc`. `yygdef` keeps track of the possible **Reduce**, **Accept**, and **Error** actions that a program may make.

Simple state elim: 0%, Error default elim: 33%
The percentage figures indicate how much table space can be saved through various optimization processes. The better written your grammar, the greater the percentage of space that can be saved; therefore, high percentages here are an indication of a well-written grammar.

Optimizer: in 0, out 0
These are optimization statistics, not of interest to typical `yacc` users,

Size of tables: 24 bytes
The size of the tables generated to represent the parsing rules. This size is given in bytes on the host machine, so it is inaccurate if a cross-compiler is being used on the eventual source code output. The size does not include stack space used by `yyparse()` or debug tables obtained by defining YYDEBUG.

1 second, final mem = 4K
The total real time that `yacc` used to produce the parser, and the final dynamic memory of the parser (in K bytes).

Types

Earlier sections mentioned that `yylval` is `int` by default, as are $$, $1, $2, and so on. If you want these to have different types, you can redeclare them in the declarations section of the `yacc` input. This is done with a statement of the form:

```
%union {
     /*
      * possible types for yylval and
      * $$, $1, $2, and so on
      */
}
```

For example, suppose `yylval` can be either integer or floating point. You might write:

```
%union {
     int intval;
     float realval;
}
```

in the declarations section of the `yacc` input. `yacc` converts the `%union` statement into the following C source:

```
typedef union {
    int intval;
    float realval;
} YYSTYPE;
```

yylval is always declared to have type YYSTYPE. If no %union statement is given in the yacc input, it uses:

```
#define YYSTYPE int
```

After YYSTYPE has been defined as a union, you may specify a particular interpretation of the union by including a statement of the form:

```
%type <interpretation> symbol
```

in the declarations section of the yacc input. The *interpretation* enclosed in the angle brackets is the name of the union member you want to use. The *symbol* is the name of a nonterminal symbol defined in the grammar rules. For example, you might write:

```
%type <intval> intexp
%type <realval> realexp
```

to indicate that an integer expression has an integer value and a real expression has a floating-point value.

Tokens can also be declared to have types. The %token statement follows the same form as %type. For example:

```
%token <realval> FLOATNUM
```

If you use types in your yacc input, yacc enforces compatibility of types in all expressions. For example, if you write:

```
$$ = $2
```

in an action, yacc demands that the two corresponding tokens have the same type; otherwise, the assignment is marked as incorrect. The reason for this is that yacc must always know what interpretation of the union is being used to generate correct code.

The Default Action

The default action associated with any rule can be written as:

```
$$ = $1
```

which means that the value of associated with $1 on the value stack is assigned $$ on the value stack when the rule is reduced. If, for example, $1 is an integer, then $$ is the same integer after the reduction occurs.

On the other hand, suppose that the recognition action associated with a rule explicitly states:

```
$$ = $1
```

This explicit assignment may not have the same effect as the implicit assignment. For example, suppose that you define:

```
%union {
    float floatval;
    int intval;
}
```

Also suppose that the type associated with $$ is floatval and the type associated with $1 is intval. Then the explicit statement:

```
$$ = $1
```

performs an integer to floating-point conversion when the value of $1 is assigned to $$, whereas the implicit statement did an integer to integer assignment and did *not* perform this conversion. You must therefore be careful and think about the effects of implicit versus explicit assignments.

Ambiguities

Suppose you have a grammar with the rule:

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

and the parser is reading an expression of the form:

```
expr - expr - expr
```

The parser reads this token by token, of course, so after three tokens it has:

```
expr - expr
```

The parser recognizes this form. In fact, the parser can reduce this right away into a single `expr` according to the given grammar rule.

The parser, however, has a problem. At this point, the parser does not know what comes next, and perhaps the entire line is something like:

```
expr - expr * expr
```

If it is, the precedence rules specify that the multiplication is to be performed before the subtraction, so handling the subtraction first is incorrect. The parser must therefore read another token to see if it is really all right to deal with the subtraction now, or if the correct action is to skip the subtraction for the moment and deal with whatever follows the second `expr`.

In terms of parser states, this problem boils down to a choice between *reducing* the expression:

```
expr - expr
```

or *shifting* and acquiring more input before making a reduction. This is known as a *shift-reduce conflict*.

Sometimes a parser must also choose between two possible reductions. This kind of situation is called a *reduce-reduce conflict*.

In case you are curious, there is no such thing as a shift-shift conflict. To see why this is impossible, suppose that you have the following definitions:

```
thing : a b
      | a c
      ;
b : T rest_of_b;
c : T rest_of_c;
```

If the parser is in the state where it has seen a, you have the diagram:

```
thing : a.b
thing : a.c
```

You might think that if the lookahead symbol was the token T, the parser would be confused, because T is the first token of both b and c; however, there is no confusion at all. The parser just shifts to a state diagrammed with:

```
thing : a T.rest_of_b
thing : a T.rest_of_c
```

Resolving Conflicts by Precedence

The precedence directives (`%left`, `%right`, and `%nonassoc`) let `yacc`-produced parsers resolve shift-reduce conflicts in an obvious way:

1. The precedence of a **Shift** operation is defined to be the precedence of the token on which the **Shift** takes place.

2. The precedence of a **Reduce** operation is defined to be the precedence of the grammar rule that the **Reduce** operation uses.

If you have a shift-reduce conflict, and the **Shift** and **Reduce** operations both have a precedence, the parser chooses the operation with the high precedence.

Rules to Help Remove Ambiguities

Precedence cannot resolve conflicts if one or both conflicting operations have no precedence. For example, consider the following:

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

Given this rule, how should the parser interpret the following input?

```
IF ( cond1 ) IF ( cond2 ) statmt1 ELSE statmt2
```

There are two equally valid interpretations of this input:

```
IF ( cond1 ) {
     IF ( cond2 ) statmt1
     ELSE statmt2
}
```

and:

```
IF ( cond1 ) {
     IF ( cond2 ) statmt1
}
ELSE statmt2
```

In a typical grammar, the IF and IF-ELSE statements would not have a precedence, so precedence could not resolve the conflict. Thus consider what happens at the point when the parser has read:

```
IF ( cond1 ) IF ( cond2 ) statmt1
```

and has just picked up ELSE as the look-ahead symbol.

1. It can immediately reduce the:

   ```
   IF ( cond2 ) statmt1
   ```

   using the first definition of `statmt` and obtain:

   ```
   IF ( cond1 ) statmt ELSE ...
   ```

   thereby associating the ELSE with the first IF.
2. It can shift, which means ignoring the first part (the IF with cond1) and going on to handle the second part, thereby associating the ELSE with the second IF.

In this case, most programming languages choose to associate the ELSE with the second IF; that is, they want the parser to shift instead of reduce. Because of this (and other similar situations), yacc-produced parsers are designed to use the following rule to resolve shift-reduce conflicts.

Rule 1
If there is a shift-reduce conflict in situations where no precedence rules have been created to resolve the conflict, the default action is to shift. The conflict is also reported in the yacc output so you can check that shifting is actually what you want. If it is not what you want, the grammar rules have to be rewritten.

The rule is used only in situations where precedence rules cannot resolve the conflict. If both the shift operation and the reduce operation have an assigned precedence, the parser can compare precedences

and decide which operation to perform first. Even if the precedences are equal, the precedences must have originated from either `%left`, `%right`, or `%nonassoc`, so the parser knows how to handle the situation. The only time a rule is needed to remove ambiguity is when one or both of the shift or reduce operations does not have an assigned precedence.

In a similar vein, `yacc`-produced parsers use the following rule to resolve reduce-reduce conflicts.

Rule 2
If there is a reduce-reduce conflict, the parser always reduces by the rule that was given first in the rules section of the yacc input. Again, the conflict is reported in the `yacc` output so that users can ensure that the choice is correct.

Precedence is *not* consulted in reduce-reduce conflicts. `yacc` always reduces by the earliest grammar rule, regardless of precedence.

The rules are simple to state, but they can have complex repercussions if the grammar is nontrivial. If the grammar is sufficiently complicated, these simple rules for resolving conflicts may not be capable of handling all the necessary intricacies in the way you want. Users should pay close attention to all conflicts noted in the parsing table report produced by `yacc` and should ensure that the default actions taken by the parser are the desired ones.

Conflicts in yacc Output

If your grammar has shift-reduce or reduce-reduce conflicts, there is also a table of conflicts in the statistics section of the parser description. For example, if you change the rules section of the sample grammar to:

```
stmt : IF stmt ELSE stmt
     | IF stmt
     | stmt stmt
     | A ;
```

you get the following conflict report:

```
Conflicts:
    State  Token      Action
        5  IF         shift 2
        5  IF         reduce (3)
        5  A          shift 1
        5  A          reduce (3)
```

This shows that state 5 has two shift-reduce conflicts. If the parser is in state 5 and encounters an IF token, it can shift to state 2 or reduce using rule 3. If the parser encounters an A token, it can shift to state 1 or reduce using rule 3. This is summarized in the final statistics with the line:

```
2 shift-reduce conflicts
```

Reading the conflict report shows you what action the parser takes in case of a conflict: The parser always takes the *first* action shown in the report. This action is chosen in accordance with the two rules for removing ambiguities.

Advanced yacc Topics

The following topics are covered in this section:

- Rules with multiple actions
- Selection preferences for rules
- Using nonpositive numbers in $N constructs
- Using lists and handling null strings
- Right recursion versus left recursion

- Using YYDEBUG to generate debugging information
- Important symbols used for debugging
- Using the YYERR0R macro
- Rules controlling the default action
- Errors and shift-reduce conflicts
- Making `yyparse()` reentrant
- Miscellaneous points

Rules with Multiple Actions

A rule can have more than one action. For example, you might have:

```
a : A1 {action1} A2 {action2} A3 {action3};
```

The nonterminal symbol a consists of symbols A1, A2, and A3. When A1 is recognized, `action1` is called; when A2 is recognized, `action2` is called; and when A3 is recognized (and therefore the entire symbol A), `action3` is called. In this case:

```
$1   — is the value of A1
$2   — is the value of $$ in action1
$3   — is the value of A2
$4   — is the value of $$ in action2
$5   — is the value of A3
```

If types are involved, multiple actions become more complicated. If `action1` mentions $$, there is no way for `yacc` to guess what type $$ has, because it is not really associated with a token or nonterminal symbol. You must therefore state it explicitly by specifying the appropriate type name in angle brackets between the two dollar signs. If you had:

```
%union {
    int intval;
    float realval;
}
```

you might code:

```
$<realval>$
```

in place of $$ in the action, to show that the result had type `float`. In the same way, if `action2` refers to $2 (the result of action1), you might code:

```
$<realval>2
```

To deal with multiple actions, `yacc` changes the form of the given grammar rule and creates grammar rules for dummy symbols. The dummy symbols have names made up of a $ followed by the rule number. For example:

```
a : A1 {action1} A2 {action2} A3 {action3};
```

might be changed to the rules:

```
$21 : /* null */ {action1} ;
$22 : /* null */ {action2} ;
a : A1 $21 A2 $22 A3 {action3};
```

These rules are shown in the rules summary of the parser description report.

This technique can introduce conflicts. For example, if you have:

```
a : A1 {action1} A2 X;
b : A1 A2 Y;
```

These are changed to:

```
$50 : /* null */ {action1};
a : A1 $50 A2 X;
b : A1 A2 Y;
```

The definitions of a and b give a shift-reduce conflict because the parser cannot tell whether A1 followed by A2 has the null string for $50 in the middle. It has to decide whether to reduce $50 or to shift to a state diagrammed by:

```
b : A1 A2.Y
```

As a general rule, you can resolve this conflict by moving intermediate actions to just before a disambiguating token.

Selection Preferences for Rules

A *selection preference* can be added to a grammar rule to help resolve conflicts. The following input shows a simple example of how a selection preference can resolve conflicts between two rules:

```
a1 : a b ['+' '-']
     { /* Action 1 */ } ;
a2 : a b
     { /* Action 2 */ } ;
```

The selection preference is indicated by zero or more *tokens* inside square brackets. If the token that follows the b is one of the tokens inside the square brackets, the parser uses the grammar rule for a1. If it is not one of the given tokens, the parser uses the rule for a2. In this way, the conflict between the two rules is resolved; the preference tells which one to select, depending on the value of the lookahead token.

Note: A selection preference states that a rule is to be used when the next token is one of the ones listed in the brackets and is not to be used if it is not in the brackets.

The lookahead token is merely used to determine which rule to select. It is *not* part of the rule itself. For example, suppose you have:

```
a1 : a b ['+' '-'] ;
a2 : a b ;
xx : a1 op expr ;
```

and suppose you have an a, a b, and "+" as the lookahead token. The + indicates that the a and b is to be reduced to a1. The parser does this and finds that the a1 is part of the xx rule. The + lookahead token is associated with the op symbol in the xx rule. In other words, a selection preference does not *use up* an input token; it just looks at the token value to help resolve a conflict.

The square brackets of a selection preference may contain no tokens, as in:

```
x : y z [ ];
```

This says that the parser will never use this rule unless it cannot be avoided.

Selection preferences can also be stated using the construct:

```
[^ T1 T2 T3 …]
```

where the first character is a caret (^) and T1, T2, and so on are tokens. When this is put on the end of a rule, it indicates that the rule is to be used if the lookahead token is *not* one of the listed tokens. For example:

```
a1 : a b
   { /* Action 1 */ } ;
a2 : a b [^ '+' '-']
   { /* Action 2 */ } ;
```

says that rule a2 is to be used if the token after the b is *not* a + or -. If the token is + or -, a2 is not to be used (so a1 is).

Selection preference constructs can be put in the middle of rules as well as on the end. For example, you can write:

```
expr : expr ['+' '-'] op expr
       { /* Action 1 */ }
     | expr op expr
       { /* Action 2 */ } ;
```

This states that if the first `expr` is followed by a + or - you want to use the first rule; otherwise, you want to use the second. The preference does not use up the + or - token; you still need a symbol (op) to represent such tokens.

Selection preferences that appear in the middle of a rule are implemented in the same way as multiple actions, using dummy rules. The previous example results in something like the following:

```
$23 : ['+' '-'] ;
expr : expr $23 op expr
       { /* Action 1 */ }
     | expr op expr
       { /* Action 2 */ } ;
```

(where the *23* in $23 is just a number chosen at random). The dummy rule that is created is a null string with the selection preference on the end. The first token for op is the + or - that was the lookahead token in rule $23.

If a selection preference in the middle of a rule is immediately followed by an action, only one dummy rule is created to handle both the action and the preference.

In most cases, a selection preference counts as a $N symbol, but it has no associated value. For example, in:

```
expr : expr ['+' '-'] op expr
```

there is:

```
$1 — first expr
$2 — no value
$3 — op
$4 — second expr
```

If the preference is followed by an action, the preference and the action count as a single $N symbol, the value of which is equal to the $$ value of the action. For example, in:

```
expr : expr ['+' '-'] {action} op expr
```

there is:

```
$1 — first expr
$2 — $$ of action
$3 — op
$4 — second expr
```

The `%prec` construct is incompatible with rules that contain selection preferences, because the preference is all that is needed to resolve conflicts. For this reason, `yacc` issues an error message if a rule contains both a preference and the `%prec` construct.

Selection preferences can be used to resolve most conflicts. Indeed, there may be cases where the most practical course of action is to write a number of conflicting rules that contain selection preferences to resolve the conflicts, as in:

```
expr : expr ['+' '-'] op expr
     | expr ['*' '/' '%'] op expr
     | expr ['&' '|'] op expr
              ...
```

Note: Selection preferences of the form:

```
[error]
[^ error]
```

are not useful. Selection preferences are implemented through (dummy) **Reduce** actions, but the parser's error-handling routines always look for **Shift** actions and ignore reductions.

Using Nonpositive Numbers in $N Constructs

`yacc` lets you use constructs like `$0`, `$-1`, `$-2`, and so on in recognition actions. These were at one time important, but the techniques for specifying multiple actions have made them obsolete. `yacc` supports the constructs only for compatibility with older grammars.

To understand what these constructs mean, it is important that you think in terms of the state stack. Each `$N` construct is associated with a state on the stack; the value of `$N` is the value of the token or nonterminal symbol associated with the state at the time of a **Reduce** operation. (Recall that recognition actions are performed when the appropriate **Reduce** action takes place.) `$1` is the value associated with the state that found the first component of the grammar rule, `$2` is the value associated with the second state, and so on. `$0` is the value associated with the state that was on top of the stack before the first component of the grammar rule was found. `$-1` is the value associated with the state before that, and so on. All of these states are still on the stack, and their value can be obtained in this way.

As an artificial example, suppose that a grammar has the rules:

```
stmt : IF condition stmt
     | WHILE condition stmt
condition : /* something */
          { /* action */ }
```

The action associated with the condition can use the `$-1` construct to find out if the preceding token was `IF` or `WHILE`. (Of course, this assumes that the only items that can precede a condition are the `IF` and `WHILE` tokens.) There are occasionally times when this sort of information is needed.

Using Lists and Handling Null Strings

Grammars often define lists of items. There are two common ways to do this:

```
list : item
     | list item ;
```

or:

```
list : /* null */
     | list item ;
```

The first definition means that every `list` has at least one item. The second allows zero-length lists.

Using the second definition is sometimes necessary or convenient, but it can lead to difficulties. To understand why, consider a grammar with:

```
list1 : /* null */
      | list1 item1 ;
list2 : /* null */
      | list2 item2 ;
list  : list1
      | list2 ;
```

When the parser is in a position to look for a `list`, it automatically finds a null string and then gets a conflict because it cannot decide if the null string is an instance of `list1` or `list2`. This problem is less likely to happen if you define:

```
list1 : item1
      | list1 item1 ;
list2 : item2
      | list2 item2 ;
list  : /* null */
      | list1
```

```
      | list2
      ;
```

The parser can determine if it has a `list1` or a `list2` by seeing if the list starts with `item1` or `item2`.

A `yacc`-produced parser avoids infinite recursions that result from matching the same null string over and over again. If the parser matches a null string in one state, goes through a few more states, and shifts again into the state where the null string was matched, it does not match the null string again. Without this behavior, infinite recursions on null strings can occur; however, the behavior occasionally gets in the way if you *want* to match more than one null string in a row. For example, consider how you might write the grammar rules for types that may be used in a C cast operation, as in:

```
char_ptr = (char *) float_ptr;
```

The rules for the parenthesized cast expression might be written as:

```
cast : '(' basic_type opt_abstract ')' ;
opt_abstract : /* null */
             | abstract;
abstract : '(' abstract ')'
         | opt_abstract '[' ']'
         | opt_abstract '(' ')'
         | '*' opt_abstract
         ;
```

Consider what happens with a cast such as:

```
(int *[])
```

This is interpreted as a "`*`" followed by a null `opt_abstract` followed by a null `opt_abstract` followed by square brackets; however, the parser does *not* accept two null `opt_abstracts` in a row, and takes some other course of action. To correct this problem, you must rewrite the grammar rules. Rather than using the `opt_abstract` rules, have rules with and without an `abstract`:

```
cast : '(' basic_type abstract ')' ;
abstract : /* null */
         | abstract '[' ']'
         | '[' ']'
         | abstract '(' ')'
         | '(' ')'
         | '*' abstract
         | '*'
         ;
```

Right Recursion versus Left Recursion

“Input to yacc” on page 50 mentioned left and right recursion. For example, if a program consists of a number of statements separated by semicolons, you might define it with right recursion as:

```
program : statement
        | statement ';' program ;
```

or with left recursion as:

```
program : statement
        | program ';' statement ;
```

If you think about the way that the state stack works, you can see that the second way is much to be preferred. Consider, for example, the way something like:

```
S1 ; S2 ; S3 ; S4
```

is handled (where all the S*n*'s are statements).

With right recursion, the parser gathers S1`;` and then go looking for a program. To gather this program, it gathers S2. It then looks at the lookahead symbol ";" and sees that this program has the form:

```
statement ';' program
```

The parser then gathers the program after the semicolon. But after S3, it finds another semicolon, so it begins gathering yet another program. If you work the process through, you find that the state stack grows to seven entries (one for each S*n:* and one for each "`;`") before the first **Reduce** takes place.

On the other hand, if you have the left recursion:

```
program : program ';' statement
```

and the same input, the parser performs a **Reduce** as soon as it sees:

```
S1 ; S2
```

This is reduced to a single state corresponding to the nonterminal symbol `program`. The parser reads `;`S3 and reduces:

```
program ; S3
```

to `program` again. The process repeats for the last statement. If you follow it through, the state stack never grows longer than three states, as compared with the seven that are required for the right recursive rule. With right recursion, no reduction takes place until the entire list of elements has been read; with left recursion, a reduction takes place as each new list element is encountered. Left recursion can therefore save a lot of stack space.

The choice of left or right recursion can also affect the order that recognition actions are performed in. Suppose T is a token. If you define:

```
x : /* null */
  | y ',' x {a1} ;
y : T {a2} ;
```

then the input:

```
T , T , T
```

performs recognition actions in the order:

```
{a2} {a2} {a2} {a1} {a1} {a1}
```

The `{a2}` actions are performed each time a T is reduced to y. The `{a1}` actions do not happen until the entire list has been read, because right recursion reads the entire list before any **Reduce** actions take place.

On the other hand, if you define:

```
x : /* null */
  | x ',' y {a1} ;
y : T {a2};
```

the recognition actions for the same input take place in the order:

```
{a2} {a1} {a2} {a1} {a2} {a1}
```

With left recursion, **Reduce** actions take place every time a new element is read in for the list.

This means that if you want the action order:

```
{a2} {a2} {a2} {a1} {a1} {a1}
```

you must use right recursion even though it takes more stack space.

Using YYDEBUG to Generate Debugging Information

If you define a symbol (with the #define directive) named YYDEBUG in the declarations section and set the variable yydebug to a nonzero value, your parser displays a good deal of debugging information as it parses input. The -t command line option is a convenient shortcut to defining the symbol named YYDEBUG. Your program may set yydebug to a nonzero value before calling yyparse() or while yyparse() is executing. The following describes the output you may see.

Every time yylex() obtains a token, the parser displays:

```
read T (VALUE)
```

T is the name of the token and *VALUE* is the numeric value. Thus if yylex() has read an IF token, you might see:

```
read IF (257)
```

Every time the parser enters a state, it displays:

```
state N (X), char (C)
```

where *N* is the state number as given in the state description report, and *X* and *C* are other integers. *X* is another number for the state; yacc actually renumbers the states and grammar rules after it generates the state description report to improve the parser's efficiency, and *X* gives the state number after renumbering. *C* is the token type of the lookahead symbol if the symbol is a token. If the symbol is not a token, or if there is no lookahead symbol at the moment, *C* is -1. As an example:

```
state 6 (22), char (-1)
```

indicates that the parser has entered state 6 on the state description report (state 22 after renumbering) and that the current lookahead symbol is not a token.

Every time the parser performs a **Shift** action, it displays:

```
shift N (X)
```

where *N* is the number of the state that the parser is shifting to and *X* is the number of the same state after renumbering.

Every time the parser performs a **Reduce** action, it displays:

```
reduce N (X), pops M (Y)
```

This says the parser has reduced by grammar rule *N* (renumbered to *X*). After the reduction, the state on top of the state stack was state *M* (renumbered to *Y*).

Important Symbols Used for Debugging

Debugging a yacc-produced parser is difficult, because only part of the code is produced by user input. The remainder is standard code produced by yacc. This is aggravated by the fact that the state and rule numbers shown in the state description report are not the same as those used when the parser actually runs. For optimization purposes, the states are sorted into a more convenient order. Thus, the *internal* state number used by the program is usually not the same as the *external* state number known to the user.

To help you when examining parser code using a symbolic debugger, the following are a few of the important variables that the parser uses:

yyval
Holds the value $$ at the time of a reduction. This has the type YYSTYPE.

yychar
Holds the most recent token value returned by yylex().

yystate
Is the *internal* number of the current state.

yyps
Points to the current top of the state stack. Thus `yyps[0]` is the internal number of the current state, `yyps[-1]` is the internal number of the previous state, and so on.

yypv
Points to the top of the current value stack. The entries in this stack have the type YYSTYPE. When a **Reduce** operation performs a recognition action, this pointer is moved down the stack to the point where:

```
yypv[1] = $1
yypv[2] = $2
```

and so on.

yyi
Is the internal number of the rule being reduced by a **Reduce** action.

yyrmap
is an array present only when YYDEBUG is defined. It converts internal rule numbers to external ones. For example, `yyrmap[yyi]` is the external number of the rule being reduced by a **Reduce** action.

yysmap
Is an array present only when YYDEBUG is defined. It converts internal state numbers to external ones. For example, `yysmap[yystate]` is the external number of the current state.

Using the YYERROR Macro

The YYERROR macro creates an artificial error condition. To show how this can be useful, suppose you have a line-by-line desk calculator that allows parenthesizing expressions and suppose you have a variable *depth* that keeps track of how deeply parentheses are nested. Every time the parser finds an opening parenthesis, it adds 1 to *depth*. Every time it finds a closing parenthesis, it subtracts 1.

Consider how the following definitions work:

```
expr : lp expr ')'
           {depth--;}
     | lp error
           {depth--;}
     ;
lp : '(' {depth++;};
```

If no error occurs, the *depth* variable is incremented and decremented correctly. If an error does occur, however, what happens? Your `yyerror()` routine is called on to recover from the error in the middle of an expression. Often, it is more reasonable to postpone this recovery until you reach a point where you have a whole expression; therefore, you might use the following alternate definition:

```
expr : lp error
           {depth--; YYERROR;}
     ;
line : error '\n' prompt line
       { $$ = $4; } ;
prompt : /* null token */
       {printf("Please reenter line.\n");};
```

Now, what happens when the grammar is asked to parse a line such as:

```
1 + (( a +
```

When the end of the line is encountered, the parser recognizes an error has occurred. Going up the stack, the first state ready to handle the error is:

```
expr : lp error ;
```

At this point, the parser reduces the input:

```
( a +
```

into an `expr`. The reduction performs the recognition action: it decrements the *depth* variable and then signals that an error has taken place. The **Error** action begins popping the stack again. It finds the previous opening parenthesis, recognize another:

```
lp error
```

construct, and perform another reduction. The parenthesis count is again decremented, and another error condition is generated.

This time, the grammar rule that deals with the error is the definition of `line`. An error message is issued and a new line is requested. In this way, the parser has worked its way back to error-handling code that can deal with the situation. Along the way, the parser correctly decremented the *depth* variable to account for the missing parentheses.

This method of dealing with errors decrements *depth* for every unbalanced opening parenthesis on the line. This corrects the *depth* count properly. Our first definition (without the YYERROR call) would have decremented *depth* only once.

This example is somewhat contrived, of course; you can always just set *depth* to zero whenever you start a new line of input. The usefulness of the technique is more apparent in situations where you obtain memory with `malloc`, whenever you get an opening delimiter and free the memory with `free`, and whenever you get a closing delimiter. In this case, it is obvious that you need to do precisely as many `free` operations as `malloc` operations, so you must raise the error condition for each unbalanced opening delimiter.

You might think that the symbol `lp` is unnecessary, and you can just define:

```
expr : '(' {depth++;} expr ')' {depth--;}
     | '(' error {depth--;} ;
```

However, this does not work in general. There is no guarantee that the action:

```
{depth++;}
```

is performed in all cases, particularly if the token after the "`(`" is one that could not start an expression.

As an interesting example of another way to use YYERROR, consider the following (taken from a parser for the Pascal programming language):

```
program:
    declaration
|    program declaration
;
declaration:
    LABEL label_list
|    CONST const_list
|    VAR var_list
|    PROC proc_header
|    CTION func_header
;
label_list :
    label_list ',' label
|    label
|     error
|     error [LABEL CONST VAR PROC FUNC BEGIN]
                { YYERROR; /*  other code */ }
;
```

This deals with errors in two different ways:

1. If an error is followed by one of the tokens LABEL, CONST, and so on (representing the beginning of new declaration sections in Pascal), the input is reduced to a complete `label_list` and an appropriate action is taken. This action uses YYERROR to raise the error condition, but only *after* the reduction has taken place.

2. The other rule is used when the parser finds an error that is not followed by one of the listed tokens. This corresponds to an error in the middle of a label list and requires a different sort of handling. In this case, error handling is allowed to take place immediately, without reduction, because there may be another `label_list` to come.

This kind of approach can be used to distinguish different kinds of errors that may take place in a particular situation.

Rules Controlling the Default Action

The default action is the one that is taken when the parser finds a token that has no specified effect in the current state. In a state diagram, the default action is marked with a dot (`.`). The default is always a **Reduce** or an **Error** action, chosen according to the following rules:

1. If the state has no **Shift** actions and only one **Reduce**, the default is the **Reduce** action.
2. Apart from rule 1, an empty rule never has **Reduce** as a default.
3. If a state has more than one **Reduce** action, the parser examines the *popularity* of each **Reduce**. For example, if reduction A is used with any of three different input tokens and reduction B is used with only one input token, reduction A is three times as *popular* as B. If one **Reduce** action is more than twice as popular as its closest contender (that is, if it is taken on more than twice as many input tokens), and if that **Reduce** action is associated with a rule that contains at least *five* tokens, the popular **Reduce** action is made the default.
4. In all other cases, the default action is an **Error** action. For example, **Error** is chosen when a rule has more than one **Reduce** action, and there is no **Reduce** that is more than twice as popular as all the other contenders.

Note: OpenExtensions `yacc`'s predecessor UNIX `yacc` always chooses the most popular **Reduce** action as a default (if there is one). It does not use the same requirements as 3. As a result of this difference, OpenExtensions `yacc`'s parser tables are about 20% larger than UNIX `yacc`'s, but an OpenExtensions `yacc`-generated parser usually detects errors much earlier than a parser generated by UNIX `yacc`.

Errors and Shift-Reduce Conflicts

A grammar may contain shift-reduce conflicts that occur when an error is encountered. In this case, the **Shift** action is always taken and no warning message is displayed.

Making yyparse() Reentrant

If you define YYALLOC in the declarations section (with the `#define` directive), the state and value stacks used by `yyparse()` are allocated dynamically through `malloc` and freed before `yyparse()` returns. In other words, `yyparse()` makes itself reentrant by saving a number of externals when it begins execution and restoring them upon completion. The externals involved are:

```
yylval   yyval   yypvt
yynerrs  yychar  yyerrflag
```

If you specify `longjmp` to get out of `yyparse()` (because an action), the externals are *not* restored, and `yyparse()` is not reentrant.

Miscellaneous Points

It is incorrect to code either:

```
%token X 0
```

or:

```
%token X 256
```

The value `0` is reserved for the end marker and `256` is reserved for `error`.

If you define YYSTATIC, both the state and value stacks are static; otherwise, the state stack is *auto* (allocated on the program stack) and the value stack is static. Defining YYALLOC saves both stack space and static space; defining YYSTATIC saves stack space.

If you define YYSYNC, the parser always has a lookahead token when it performs a shift or reduce action. If the symbol is not defined, the parser obtains a lookahead token only if the value of the token is needed.

Chapter 4. Tutorial Using OpenExtensions make

The make utility of the OpenExtensions Shell and Utilities can be a key factor in the successful management of software development projects, as well as any other type of project where you must keep a collection of files in synchronization with one another. make is used in situations where a change in one file necessitates the *updating* of one or more other files that depend on the changed file.

For example, suppose a program is built from several separate object files, each of which depends on its own source file. If you change a source file and then run make, make can automatically determine which object files are out of date (older than their corresponding source files). make can then recompile the changed source files to get new object modules, and then link all the component object files to get an updated version of the program.

Basic Concepts

This section discusses the major concepts that underlie the make command and gives some simple examples of how to use make.

The Makefile

To use make, you usually require a *makefile*, a text file that describes the interdependencies of the files that you want make to supervise, as well as the *recipes* for remaking files whenever necessary.

An example makes this easier to understand. (You will find this example a lot more verbose than a typical makefile, but there is no need to confuse things by taking a lot of shortcuts right now.) The following example shows the contents of a sample makefile for a small program using the c89 compiler interface:

```
program : main.o func.o
    c89 -o program main.o func.o
main.o : main.c
    c89 -c main.c
func.o : func.c
    c89 -c func.c
```

This makefile consists of three *rules*. The first rule is:

```
program : main.o func.o
    c89 -o program main.o func.o
```

The first line in this rule states that the file **program** depends upon the two **.o** files that follow the colon (**:**). If any or all of the **.o** files have changed since the last time **program** was made, make attempts to remake **program**. It does this using the recipe on the next line. This recipe consists of a c89 command that links **program** from the two object files.

Before make remakes **program**, it checks to see if any of the **.o** files need remaking. To do this, it checks the other rules in the makefile to determine the dependencies of the **.o** files. If any of the **.o** files need remaking (because they have become *out of date* with their associated **.c** files), make remakes the **.o** files first. and then makes **program**. make updates each object file by processing the recipe that follows the appropriate file.

Writing a Rule

The previous example showed a collection of simple rules. All the rules follow a consistent format:

```
target target … : prerequisite prerequisite …
<tab>    recipe
```

make accepts rules with more complicated formats, but this tutorial restricts itself to this simple form for the time being.

The term *target* usually refers to a file made from other files. For example, a target could consist of an object file built by compiling a source file. make also recognizes a number of *special targets*, which are not files.

A rule may have several targets:

```
func1.o func2.o : includes.h
    c89 -c func1.c
    c89 -c func2.c
```

This says that if you change **includes.h**, you must update both **func1.o** and **func2.o**.

The *prerequisite* part of a rule consists of a list of files. The targets depend directly or indirectly on these files: if any of the files change, the targets require remaking. The prerequisite list appears on the same line as the targets, separated from the targets by a colon (**:**).

The *recipe* part of a rule consists of one or more commands that remake the target when necessary. The recipe usually begins on the line following the target and prerequisite list. A recipe can consist of any number of lines, but each line in the recipe must begin with a tab character.

Typing a Tab Character

If you are using the OpenExtensions ed editor, you can type a tab character as a <Esc-i> sequence. After you press <Enter>, the tab character is displayed as the correct number of blanks.

If you are using the XEDIT editor, you cannot type a tab character (XEDIT handles only displayable characters). Instead, you can:

1. Select a character that you will not be using in the file—for example, the character @.
2. At the beginning of each line of the recipe, type an @ instead of a tab character.
3. When you have finished editing the file, on the XEDIT command line enter the following commands:

   ```
   top
   alter @ 05 * *
   ```

You can insert any number of blank lines between lines in a recipe, provided that each line begins with a tab character. A line that does not begin with a tab ends the recipe.

In the interests of efficiency, make processes most recipe lines itself. However, a recipe line may contain a character special to your command interpreter or shell (for example, the **>** and **<** redirection constructs). In these cases, make calls the command interpreter to process the line, so that the special characters are handled properly.

File names Containing a Colon

Occasionally, target names may contain a colon:

```
a:file
```

Usually, make interprets a colon as the mark separating the target names from the prerequisite list. To avoid confusion, use quotation marks to enclose any file name that contains a colon:

```
“a:program” : “a:main.o” func1.o …
    recipe
```

White Space

White space separates items in a target or prerequisite list. White space consists of one or more blanks or tab characters. You can also surround the colon between the target list and the prerequisite list with white space; however, you do not have to.

Continuation Lines

A backslash (****) as the last character of a line indicates that the line is not finished; it continues on to the next line of the file. For example:

```
target list :\
prerequisite list
```

is equivalent to:

```
target list :  prerequisite list
```

You will find this useful if the length of a list makes it impossible to fit everything on one line. You can do this several times; a single line can be broken into any number of continuation lines.

Targets with More Than One Recipe

A file may appear as the target in more than one rule. If several of these rules have associated recipes, use a double colon (**::**) to separate the target and prerequisites. As an example, consider the file **A** that depends on three other files; **B**, **C**, and **D**:

```
A :: B C
          first recipe
A :: C D
          second recipe
```

If **A** is up to date with **C**, and **D**, but not **B**, make processes only the first recipe. If **A** is out of date with **C**, make processes both recipes.

When a target has different recipes for different prerequisites, you must use the double colon in each of the rules associated with the target. You can use a single colon in several rules for the same target, provided that only one of those rules contains a recipe. Metarules do not follow this general rule. For more information on metarules, see “Metarules” on page 97.

Comments

A makefile may contain comments. A comment begins with a number sign character (**#**), and extends to the end of the line. Consider the following example:

```
#  This is a comment line
target : prerequisite # This is another comment
    recipe # One more comment
```

make ignores the contents of all comments; they simply allow the creator of the makefile to explain its contents.

Running make

To run make in its most basic form, type the following command:

```
make
```

When you use make in this way, it expects to find your makefile in the working directory with the name **makefile**. After it finds your makefile, make checks to see if the first target has become out of date with its prerequisites. Part of this process requires checking that the prerequisites *themselves* do not require remaking. make remakes all the files it requires to properly remake the first target.

Because of this, many users often put an *artificial* rule at the beginning of a makefile, naming all the targets they remake most frequently. The following example could serve as the first rule of a makefile:

```
all : target1  target2 …
```

The file named **all** does not exist, but when make tries to remake **all**, it automatically checks **all**'s specified prerequisites to ensure they do not require remaking. make looks through the makefile for any rules that have **all**'s prerequisites as targets. make remakes any that have become out of date with their own specific prerequisites. When make remakes the files, it displays the recipe lines as it runs them.

You can also specify *targetnames* on the command line:

```
make target1  target2
```

make attempts to remake only the given targets, plus any prerequisites of those targets that need remaking. For example, you could type the following command:

```
make func1.o func2.o
```

make then remakes the given **.o** files, if they require it.

If you give your makefile a name other than **makefile**, or place it in a separate directory, you have to specify the name of the file you want make to use. You do this with the **-f** option:

```
make -f file name
```

In this case, you indicate a makefile called *file name*. You can combine these two options; you can specify particular targets *and* a different name for the makefile:

```
make -f file name  target1  target2 …
```

One other interesting option is -n. When you specify this option (before any target names), make displays the commands it must process to bring the targets up to date, but does not actually process the commands. Consider the following example:

```
make -n program
```

make displays the commands needed to bring **program** up to date. You will find this option useful if you have just created a makefile and you want to check it to see if it behaves the way you expect. In effect, it gives you a dry run of the updating process.

There are a large number of other options for the make command. This tutorial discusses a few of these options. The full list of options is provided with the make command description in *z/VM: OpenExtensions Commands Reference*.

Macros

Suppose you are using make to maintain a C program that you are compiling with the c89 command. The c89 command features a -L option that allows you to specify a directory to add to the search path when c89 searches for libraries.

All the modules that make up this C program should be compiled with libraries from the same directory. This means that you can set up your makefile as follows:

```
module1.o : module1.c
    c89 -L libdir -c module1.c
module2.o : module2.c
    c89 -L libdir -c module2.c
# And so on
```

These commands all use libraries from the directory **libdir**. (They also use the -c option, which compiles the source code but does not link it.)

Now suppose that you want to use the libraries stored in the directory **libdir2** instead of those stored in **libdir**. You need to go back to your makefile and change all the:

```
-L libdir
```

references into:

```
-L libdir2
```

This task is time consuming and error-prone. You may easily miss one of the recipes that have to be changed, or make a typing mistake while you are editing the file.

Macros simplify this kind of situation. The term *macro* refers to a symbol that stands for a string of text. The following example demonstrates the form used to create a macro:

```
macro_name = string
```

When make encounters the construction:

```
$(macro_name)
```

it expands it to the *string* associated with *macro_name*.

For example, consider the following:

```
CC = c89
CFLAGS = -L libdir
module1.o : module1.c
    $(CC) -c $(CFLAGS) module1.c
module2.o : module2.c
    $(CC) -c $(CFLAGS) module2.c
# And so on
```

The first line creates a macro named CC. The makefile assigns the string c89 (the command that calls your compiler) to the macro. The second line creates a macro named CFLAGS, which contains the options you want to specify to the compiler. Throughout the makefile, the example uses $(CC) and $(CFLAGS) in place of the compilation command and its options.

This makefile works exactly the same as the previous one; however, it is much easier to change. If you decide that you want to compile with libraries from the directory **libdir2** instead of **libdir**, you just have to change the CFLAGS definition to:

```
CFLAGS = -L libdir2
```

By changing the one line, you can change all the appropriate recipes in the file. In the same way, you can add more standard options to your definition of CFLAGS.

By changing the definition of CC, you can switch to an entirely different C compiler. The following example shows the same makefile in terms of a hypothetical C compiler called by ccomp.

```
CC = ccomp
CFLAGS = -L libdir
module1.o : module1.c
    $(CC) -c $(CFLAGS) module1.c
module2.o : module2.c
    $(CC) -c $(CFLAGS) module2.c
# And so on
```

You did not need to modify the rules and recipes, just the two macro definitions.

Naming Macros

Any sequence of uppercase or lowercase letters, digits, or underscores (_) may form the name of a macro. The first character cannot be a digit. Traditionally, macros are given uppercase names to stand out more clearly in your makefile.

Because make assumes the **$** represents the beginning of a macro expansion when it appears in a makefile, you must type two **$** characters to represent an actual (literal) **$** character. The following example creates a macro named DOLLAR containing the single character **$**.

```
DOLLAR = $$
```

Macro Examples

For example, if you are using c89, you might have a makefile with these definitions:

```
USER = /usr/jsmith
# directory where object modules are kept
DIROBJ = $(USER)/project/obj
# directory where src modules are kept
DIRSRC = $(USER)/project/src
$(DIROBJ)/module.o : $(DIRSRC)/module.c
   # compile the file
   $(CC) -c $(DIRSRC)/module.c
   # and move the object file to the specified directory
   mv $(DIRSRC)/module.o $(DIROBJ)/module.o
```

This makefile defines macros for the directories that contain source files and object modules. These macros can be changed easily. For example, if you want to store all the object files in a different directory, just change the definition of DIROBJ.

The next example comes from a difference between various C compilers. Some compilers put compiled object code into files ending with **.obj** and executable code into files ending with **.exe**, whereas others put the object code into files ending with **.o** and executable code into files with no suffix. If you plan to switch from one system to another, you might use the following macro definitions:

```
O = .obj
E = .exe
program$(E) : module1$(O) module2$(O) …
    recipe
module1$(O) : …
```

If you change to a compiler that uses the **.o** suffix for object files, you can just change the definition of **O** to change all the suffixes in the file. Similarly, if you change to a system that does not use suffixes with executable programs, you can define:

```
E =
```

so that $(**E**) expands to an empty (null) string.

When a macro name consists of a single character, make lets you omit the parentheses, so that, for example, you can write the macro $(E) as $E. You will find this useful if you use common suffix macros:

```
program$E : module1$O module2$O …
    recipe
module1$O : …
```

Command-Line Macros

The command line that you use to call make may contain macro definitions. You place these after any options and before any targets:

```
make -f makefile DIROBJ=/usr/rhood program
```

The macro definition:

```
DIROBJ=/usr/rhood
```

assigning DIROBJ the value of **/usr/rhood** follows the make **-f** option and precedes the target **program**.

Definitions for macros in the prerequisite portion of a dependency line cannot be replaced by macro definitions from the command line. Prerequisite macros are expanded as they are read, but command line macro definitions are not applied macros in the make file until the entire file has been read. Therefore, with the exception of macros in the prerequisite of a dependency line, if a macro is already defined when make encounters a new definition for it, the new definition replaces the old one.

If a command-line macro definition contains white space, you must enclose it in quotation marks or apostrophes, as in the following example:

```
make 'FILES = a.c b.c' target target…
```

Variations

You can contain a macro name within braces (**{}**) as well as parentheses. The following two forms are equivalent:

```
$(macro)
```

and:

```
${macro}
```

A `$(name)` construct can contain other `$(name)` constructs. For example, suppose you have a program suitable with either the c89 compiler interface and the hypothetical `ccomp` compiler. You might write the following in your makefile:

```
CFLAGS_C89 = -L libdir
CFLAGS_CCOMP = -l libdir
CC_C89 = c89
CC_CCOMP = ccomp
module1.o : module1.c
    $(CC_$(COMP)) -c $(CFLAGS_$(COMP)) module1.c
```

You can then call `make` with the following command line:

```
make “COMP=C89”
```

Inside the construct `$(CC_$(COMP))` the `$(COMP)` is replaced with `C89` . The original construct becomes:

```
$(CC_C89)
```

which then expands to c89. Similarly, the following transformations occur, in order:

```
$(CFLAGS_$(COMP))    expands to    $(CFLAGS_C89)
$(CFLAGS_C89)        expands to    -L libdir
```

On the other hand, if you call `make` with:

```
make “COMP=CCOMP”
```

the macro expansions produce `CC_CCOMP` and `CFLAGS_CCOMP`. These, in turn, produce `ccomp` and `-l libdir`.

Special Run-time Macros

In addition to the macros already discussed, `make` lets you use a number of *special run-time macros* that `make` expands as it carries out a recipe. These macros yield meaningful results only when they appear in the recipe part of a rule, except for the dynamic prerequisite macros (which are useful outside recipe lines).

The most straightforward of the special macros is **$@**. When this appears in a recipe, it expands to the name of the target currently being updated. For example, suppose the rule is:

```
file1.o file2.o : includes.h
    cp $@ /backup
    rm $@
    # commands to remake file
```

This rule has two targets. When either target needs remaking, the recipe uses the `cp` command to copy the current target file to the **/backup** directory and then uses the `rm` command to delete the current file. `make` then goes on to remake the file. In this instance, the **$@** conveniently stands for whichever file is being remade. You do not want to delete one of the targets if it was not being remade.

The special macro $* stands for the name of the target, with its suffix omitted. For example, if the target is:

```
/dir1/dir2/file.o
```

then $* is:

```
/dir1/dir2/file
```

Consider this example of using $* in a makefile:

```
file1.o file2.o : include.h
    $(CC) -c $(CFLAGS) $*.c
```

If **include.h** changes, make updates **file1.o** by compiling **file1.c**, and updates **file2.o** by compiling **file2.c**. Remember that this form can appear only in the recipe part of a rule, not in the prerequisite list.

The special construct $& stands for all the prerequisites of a target in all the rules that apply to that target. $^ stands for all the prerequisites of a target in the single rule the recipe of which is being used to remake the target. For example, consider:

```
A : B C
    recipe …
A : D
```

Inside the recipe, $^ stands for B C, whereas $& stands for B C D.

Note: The $^ symbol is an extension not found in traditional implementations of make.

The **$<** macro is similar to **$^**, but it only gives the names of the prerequisites that prompt the processing of the associated rule (for usual rules, those newer than the target). In the previous example, if **B** is newer than **A**, but **C** is older, **$<** stands for **B** inside the recipe.

Several other macros of this kind exist. For more detail on run-time macros, see "Run-time Macros" on page 125.

Dynamic Prerequisites

The special macros discussed in the previous section become useful only when used in the recipe part of a rule. There are similar constructs that you can use in the prerequisite part of a rule, written as $$@, and $$*. You can use these constructs to create *dynamic prerequisites*.

When **$$@** appears in the prerequisite list, it stands for the target name. If you are building a library, it stands for the name of the *archive library*. For example, the two following rules are equivalent:

```
file1 : $$@.c
file1 : file1.c
```

Similarly, the following rule uses the dynamic prerequisite symbol as well as one of the special run-time macros discussed in the previous section:

```
file1 file2 file3 : $$@.c
    $(CC) -c $(CFLAGS) $@.c
```

When $$* appears in the prerequisite list, it stands for the name of the target, but without the *suffix*.

See "Modified Expansions" on page 94 for examples that make use of the **$$@** dynamic prerequisite. There are other dynamic prerequisite macros. For more detail see "Dynamic Prerequisites" on page 126 and the make command description in *z/VM: OpenExtensions Commands Reference*.

Modified Expansions

You can modify the way in which make expands macros. This section describes extensions not found in traditional implementations of make.

The following example shows you how macro modification works. If the macro **FILE** represents the full pathname of a file, then `$(FILE:d)` expands to the name of the directory that contains the file.

For example, if you define:

```
FILE = /usr/george/program.c
```

then `$(FILE:d)` expands to **/usr/george**. The macro modifier `d.` stands for *directories only*. To modify a macro, put a colon followed by one or more modifiers after the macro name.

If a file name has no explicit directory, the `:d` modifier produces dot (**.**), standing for the working directory.

Consider these two other macro modifiers:

```
b (base)  – file portion of name, not including suffix
f (file)  – file portion of name, with suffix
```

Using the previous definition of **$(FILE)**, the two other macro modifiers produce these results:

```
$(FILE:b) expands to   program
$(FILE:f) expands to   program.c
```

You can combine modifiers. For example:

```
$(FILE:db) expands to   /usr/george/program
```

If a macro consists of several pathnames, modifiers apply to each appropriate pathname in the expansion. For example, suppose you define:

```
LIST = /d1/d2/d3/file.ext x.ext d4/y.ext
```

Then you have the following sample macro expansions:

```
$(LIST:d)  →  /d1/d2/d3 . d4
${LIST:b}  →  file x y
${LIST:f}  →  file.ext x.ext y.ext
$(LIST:db) →  /d1/d2/d3/file x d4/y
```

You can apply modifiers to special run-time macros and to the dynamic prerequisite symbol. or example, consider:

```
file1.o file2.o : $$(@:b).c
    $(CC) -c $(CFLAGS) $(@:b).c
```

This is equivalent to the following two rules:

```
file1.o : file1.c
    $(CC) -c $(CFLAGS) file1.c
file2.o : file2.c
    $(CC) -c $(CFLAGS) file2.c
```

Substitution Modifiers

The substitution modifier is another extension not found in traditional implementations of `make`. It is similar to the modifiers discussed in the previous section but somewhat more complicated.

The substitution modifier has the following form:

```
s/original/replacement/
```

The *original* string usually appears in the macro expansion, and the substitution modifier will replace *original* with the *replacement* string.

As an example, using the previous definition for **$(LIST)**:

```
$(LIST:s/ext/abc/) expands to /d1/d2/d3/file.abc x.abc d4/y.abc
```

Every occurrence of ext is replaced with abc. As another example:

```
FILE = /usr/jsmith/file.c
$(FILE) : $(FILE:s/jsmith/mjones/)
    cp $(FILE:s/jsmith/mjones/) $(FILE)
```

is equivalent to:

```
/usr/jsmith/file.c : /usr/mjones/file.c
    cp /usr/mjones/file.c /usr/jsmith/file.c
```

You can combine the substitution modifier with other modifiers, and make applies the modifiers in order from left to right. For example:

```
$(LIST:s/ext/abc/:f)  expands to  file.abc x.abc y.abc
```

Tokenization

The tokenization modifier is another extension not found in traditional implementations of make. For make's purposes, a *token* represents a sequence of characters lacking any blanks or tab characters. make interprets a string enclosed in quotation marks as a single token, even if the quoted string includes blanks or tabs.

The construct:

```
$(macro:t"string")
```

expands the given macro and puts the given *string* between each token in the expanded macro. This process is called *tokenization*. For example, if you define:

```
LIST = a b c
```

the tokenization construct

```
$(LIST:t"+")
```

produces:

```
a+b+c
```

make places the **+** *between* each pair of tokens; however, it does not add it after the last token. This more useful example puts a **+** and a newline character (\n) between pairs of tokens:

```
$(LIST:t"+\n")    expands to a+
                    b+
                    c
```

“Additional Tips on Using make” on page 104 tells how to use this kind of expansion with linkers.

Prefix and Suffix Operations

The prefix and suffix modifiers:

```
:‸"prefix"
:+"suffix"
```

add a prefix or suffix to each space separated token in the expanded macro. Consider the following macro definition:

```
test = main func1 func2
```

This definition of **test** produces the following expansions:

```
$(test:‸"/src/")
```

expands to:

```
/src/main /src/func1 /src/func
```

and:

```
$(test:+".c")
```

expands to:

```
main.c func1.c func2.c
```

You can combine these modifiers:

```
$(test:^"/src/":+".c")
```

expands to:

```
/src/main.c /src/func1.c /src/func2.c
```

If the prefix and suffix strings themselves consist of a blank separated list of tokens, the expansion produces the cross-product of both lists. For example, given the following macro assignment:

```
test = a b c
```

the following expansions occur:

```
$(test:^"1 2 3")    expands to    1a 1b 1c 2a 2b 2c 3a 3b 3c
$(test:+"1 2 3")    expands to    a1 b1 c1 a2 b2 c2 a3 b3 c3
```

In combination, make produces this expansion:

```
$(test:^"1 2 3":+"1 2 3")

expands to 1a1 1b1 1c1 2a1 2b1 2c1 3a1 3b1 3c1
           1a2 1b2 1c2 2a2 2b2 2c2 3a2 3b2 3c2
           1a3 1b3 1c3 2a3 2b3 2c3 3a3 3b3 3c3
```

Inference Rules

So far, you have had to create explicit recipes for remaking every target. You would find it useful, however, if make offered a way to state general guidelines, like this: ‘‘If you want to remake an object file, compile the source file with the same basename.’’

Metarules create such guidelines. Metarules employ a form similar to usual rules; however, they describe general guidelines not specific recipes for specific rules. This section examines the ways you create and use metarules.

Note: The new metarule format, discussed in this chapter, may not be recognized by older versions of make. Older versions of make need the less general *suffix rules*. For compatibility, make also supports suffix rules; see “Suffix Rules” on page 98 for more information.

Metarules

Consider this simple example of a metarule:

```
%.o : %.c
     $(CC) -c $(CFLAGS) $<
```

The first line says ‘‘If the name of a target ends with the suffix **.o** and you do not have an explicit rule, the prerequisite of the target has the same base name but with the suffix **.c**.’’ After that comes the recipe line, which uses the special **$<** macro to refer to the single prerequisite in this rule (that is, the **.c** file).

As an example of a makefile that uses metarules, consider the following:

```
CC = c89
CFLAGS = -O
FILES=main func
program : $(FILES:+".o")
    $(CC) $(CFLAGS) $& -o program
%.o : %.c
    $(CC) -c $(CFLAGS) $*.c
```

When make tries to remake **program**, it checks the two specified object files to see if either needs *remaking*. make notes that these files end in the **.o** suffix. Because there is no explicit rule for these files, make uses the metarule for targets ending in **.o**:

```
%.o : %.c
    $(CC) -c $(CFLAGS) $*.c
```

make therefore checks on the **.c** files that correspond to the **.o** files. If any of the **.o** files are out of date with respect to their corresponding **.c** files, make uses the metarule recipe to remake the **.o** files from the **.c** source.

Note: There is no need for specific rules for any of the **.o** files; the general metarule covers them all.

If a rule is given without a recipe, and a metarule applies, the metarule and the prerequisites in the explicit rule are combined. For example:

```
file.o : includes.h
%.o : %.c
    $(CC) -c $(CFLAGS) $*.c
```

states that **file.o** depends on **includes.h** as well as **file.c**. The metarule remakes **file.o** if it is out of date with respect to either **includes.h** or **file.c**.

Suffix Rules

Suffix rules are an older form of inference rule. They have the form:

```
.suf1.suf2:
recipe…
```

make matches the suffixes against the suffixes of targets with no explicit rules. Unfortunately, they don't work quite the way you would expect. The rule

```
.c.o :
recipe…
```

says that **.o** files depend on **.c** files. Compare this with the usual rules

```
    file.o : file.c # compile file.c to get file.o
```

and you will see that suffix rule syntax seems backward! This, by itself, serves as good reason to avoid suffix rules.

You can also specify single-suffix rules such as:

```
.c:
        recipe…
```

which match files ending in **.c**.

For a suffix rule to work, the component suffixes must appear in the prerequisite list of the .SUFFIXES special target. You turn off suffix rules by placing:

```
.SUFFIXES:
```

in your makefile. This clears the prerequisites of the .SUFFIXES target, which prevents the enaction of any suffix rules. The order in which the suffixes appear in the .SUFFIXES rule determines the order in which make checks the suffix rules.

The following steps describe the search algorithm for suffix rules:

1. Extract the suffix from the target.
2. Is it in the .SUFFIXES list? If not, quit the search.
3. If it is in the .SUFFIXES list, look for a double suffix rule that matches the target suffix.
4. If you find one, extract the basename of the file, add on the second suffix, and see if the resulting file exists. If it does not, keep searching the double suffix rules. If it does exist, use the recipe for this rule.
5. If no successful match is made, the inference has failed.
6. If the target did not have a suffix, check the single suffix rules in the order that the suffixes are specified in the .SUFFIXES target.
7. For each single suffix rule, add the suffix to the target name and see if the resulting file name exists.
8. If the file exists, process the recipe associated with that suffix rule. If the file does not exist, continue trying the rest of the single suffix rules. If no successful match is made, the inference has failed.

Try some experiments with the -v option specified to see how this works.

make also provides a special feature in the suffix rule mechanism for archive library handling. If you specify a suffix rule of the form:

```
.suf.a:
     recipe
```

the rule matches any target having the LIBRARYM attribute set, regardless of what the actual suffix was. For example, if your makefile contains the rules:

```
    SUFFIXES: .a .o
.o.a:
        echo adding $< to library $@
```

then if **mem.o** exists,

```
make "mylib(mem.o)"
```

causes:

```
adding mem.o to library mylib
```

to be printed.

See “Making Libraries” on page 131 for more information about libraries and the .LIBRARY and .LIBRARYM attributes.

The Default Rules File

When you run make, it usually begins by examining the startup file that contains the default rules. (“Command-Line Options” on page 109 explains how to use the -r option to prevent make from using the default rules in the startup file.)

The startup file is created at the time that you install make on your system. The name of the file is **/etc/startup.mk**.

The startup file contains a number of macro definitions and option settings, as well as various metarules. make processes the information in the startup file before your makefile, so you can think of the default information as *predefined*.

Consider the metarules in the startup file. For example, this file contains:

```
O = .o
%$O : %.c
     $(CC) -c $(CFLAGS) $<
```

The definition of the O macro gives the standard suffix for object files. The metarule that follows the definition tells how object files can be obtained from **.c** files.

The metarule makes several assumptions:

- The macro CC gives the name of the command to call the compiler. When you install make, you tell the installation procedure which C compiler you are using. The installation procedure then sets things up so that the CC macro refers to your choice of C compiler.
- The CFLAGS macro specifies any compiler arguments that appear before the name of the source file. You can redefine your own CFLAGS macro to specify any standard flags. Again, the installation procedure sets up a default value for CFLAGS based on the compiler you use.
- A -c option is specified. This option indicates that the source file is only to be compiled, not linked.
- The rule ends with **$<**. Recall that, in usual rules, this special run-time macro stands for the list of prerequisites in the rule that prompt the rule's processing; in this metarule, it stands for the **.c** file associated with the object file being remade.

If some of these assumptions are not useful to you, you may consider changing the startup file. For example, you might change the default definition of CFLAGS to a set of compilation options that you intend to use frequently. You can edit the startup file with any text editor.

Controlling the Behavior of make

There are several methods for controlling the way that make does its work. This discussion of make touches on *attributes*, *special targets*, and *control macros*.

Some Important Attributes

Attributes are qualities which you may attach to targets. When make finds it necessary to update a target that has one or more attributes, the attributes cause make to take special actions. This section covers only a few of the attributes available; see “Using Attributes to Control Updates” on page 119 for a complete list.

The first attribute is .IGNORE. If make encounters an error when trying to remake a target with this attribute, it ignores the error, and goes on trying to remake other targets. (Usually, if make encounters an error, it just issues an error message and stops all processing.)

You can assign attributes to targets in two different ways. First, your makefile can contain a separate line of the following form:

```
attribute attribute … : target target…
```

For example:

```
.IGNORE : file.o
```

indicates that **file.o** has the .IGNORE attribute. Errors that arise while making **file.o** are ignored.

You can also specify attributes inside a rule. The rule would then have the following form:

```
targets attribute attribute … : prerequisites
    recipe
```

This assigns attributes to the given targets as well as stating the prerequisites and recipes for the targets. Consider the following example:

```
file.o .IGNORE : file.c
    $(CC) -c $(CFLAGS) file.c
```

indicates that make may ignore errors when remaking **file.o**.

When make remakes a target, it usually displays the recipe lines that are being used in the operation; however, if a target has the .SILENT attribute, make does not display these lines. In addition, make does not issue any warnings that might usually result.

The .PRECIOUS attribute may be used in a rule. .PRECIOUS tells make that it must not remove the associated target. For example, you can use the following rule to protect object files employed in making a program:

```
.PRECIOUS : main.o func1.o func2.o
```

You will find .PRECIOUS useful because make usually removes intermediate targets that did not exist before make started processing. For example, if you have a target with dependencies on **main.o**, **func1.o**, and **func2.o**, make compiles **main.c**, **func1.c**, and **func2.c** to produce them. These **.o** files are intermediate targets. If they did not exist before make is called, they are deleted after the target is created. Marking these object files as .PRECIOUS avoids this deletion.

Some Important Special Targets

The *special targets* of make are not really targets at all; they are keywords that control the behavior of make. These keywords are called *targets* because they appear as targets in lines that have the same format as usual rules.

A rule with a special target may not have any other targets (usual or special); however, some special targets *may* be given attributes.

The sections that follow discuss some useful special targets. “Special Target Directives” on page 121 provides complete details on all the recognized special targets.

The .ERROR Target

A rule of the form

```
.ERROR : prerequisites
     recipe
```

tells make to process the given recipe if it encounters an error in other processing.

For example, you might code:

```
.ERROR :
     echo “Error! Removing tempfile."
    rm tempfile
```

to issue an error message. Usually, this is not necessary, because make displays error messages of its own; however, you can use the .ERROR rule to perform extra *cleanup* actions after errors.

If a special .ERROR rule has prerequisites, all the prerequisites are brought up to date if an error occurs.

Including Other Makefiles

You use the .INCLUDE special target in a rule of the form:

```
.INCLUDE : file1 file2 …
```

When make encounters a rule like this in a makefile, it reads in the contents of the given files (in order from left to right) and uses their contents as if they had appeared in the current makefile. For example, suppose the file **macrodef** contains a set of macro definitions. Then:

```
.INCLUDE : macrodef
```

obtains those macro definitions and processes them as if they actually appeared at this point in the makefile.

It is possible to store *includable* files under other directories. To do this, you use another special target:

```
.INCLUDEDIRS : dir1 dir2 …
```

specifies a list of directories to be searched if make cannot find a relative name in an .INCLUDE rule in the working directory. For example, with:

```
.INCLUDEDIRS : /usr/dir1
.INCLUDE : file1
```

make searches for **file1** in the working directory first, and then in **/usr/dir1**.

If you enclose the file names in an .INCLUDE rule in angle brackets:

```
.INCLUDE : <file1> <dir/file2>
```

make does not look for these files in the working directory. It goes straight to the directories named in any preceding .INCLUDEDIRS rule. This lets you obtain input for make from other directories without worrying about conflicts with files in the working directory.

If a file name given in an .INCLUDE rule is an absolute name (for example, **/usr/jsmith/file**), make uses the name as is. In the case of a relative name , make looks for the file in the include directories as described earlier.

An included file may contain .INCLUDE rules of its own. This process is called *nesting* include files.

If make cannot find a file you want to .INCLUDE , make usually issues an error message and quits. However, you can give the .IGNORE attribute to the .INCLUDE target:

```
.INCLUDE .IGNORE : file
```

If make cannot find the given file, it simply continues processing the current makefile. .IGNORE is the only attribute that can be given to .INCLUDE.

Environment Variables

The .IMPORT special target imports environment variables and defines them as macros. For example:

```
.IMPORT : SHELL
```

obtains the value of the **SHELL** environment variable. It creates a macro named SHELL containing the current value of the **SHELL** environment variable.

If you try to import a currently undefined environment variable, make issues an error message and quits. However, you can use the .IGNORE attribute to tell make to ignore this error:

```
.IMPORT .IGNORE: HOME
```

The special rule:

```
.IMPORT : .EVERYTHING
```

imports all the currently defined environment variables, and sets up appropriate macros.

You use the .EXPORT special target to export variables to the environment of subsequently run commands. The following line exports environment variables that have the same names as the given macros:

```
.EXPORT : macro1 macro2 …
```

make assigns the current values of the macros to the environment variables. make ignores any attributes attached to this special target. Environment changes do not affect the environment of the process that called make (usually your command interpreter).

Some Important Control Macros

Control macros are special macros that give information to make and obtain information in return. For example, the PWD control macro contains the name of the working directory. Thus you can use $(PWD) to refer to the working directory in a makefile.

Some control macros let you control how make behaves. For example, you can use the SHELL macro to indicate the command interpreter that make uses to process certain recipe command lines.

The sections that follow describe some useful control macros. "Control Macros" on page 123 provides complete descriptions of all the recognized control macros.

Information Macros

You can obtain certain types of information with *information macros* while using make.

DIRSEPSTR
Gives the characters that you can use to separate parts of a file name. This is usually just the slash (**/**) character.

MAKEDIR
Gives the full pathname of the working directory from which make was called.

NULL
Contains the null string (that is, a string with no characters). This section describes one use of this, later on.

OS
Contains the name of the operating system you are using.

PWD
Gives the full pathname of the working directory.

make automatically sets all these information macros.

Attribute Macros

You can set attributes for make using *attribute macros*. These macros all follow the same pattern. If the macro has a NULL value, make turns off the associated attribute. If the macro has a non-NULL value, make turns on the associated attribute for all subsequent targets.

As an example, the .IGNORE attribute macro lets you assign the .IGNORE attribute to all the targets named in the makefile.

```
.IGNORE = yes
```

turns on the option. make gives the .IGNORE attribute to every target and ignores all errors. The following macro assignment assigns the null string to the .IGNORE control macro.

```
.IGNORE = $(NULL)
```

After this, make only ignores errors in targets that explicitly have the .IGNORE attribute. Note the use of the NULL macro in turning off the option.

Similarly, the macros .PRECIOUS and .SILENT give all targets the associated attributes.

Other Control Macros

Consider this list of some other useful control macros.

MAKESTARTUP
Contains the full pathname of the startup file. A built-in rule sets this to **/etc/startup.mk**, but you can change it on the command line or in the environment.

SHELL
Names a file that contains a shell. Usually, make tries to process recipe lines without calling a shell; however, some recipe lines require processing by a shell to work properly. For example, lines that employ the redirection constructs **>** or **<** require processing by a shell. The SHELL macro tells make where to find the appropriate shell. The startup file specifies this macro's value.

SHELLFLAGS
Gives a collection of flags to pass to the shell if and when make calls it to process a recipe command line. The startup file specifies the default value for SHELLFLAGS, based on the value of SHELL.

SHELLMETAS
Contains a string of characters for which make keeps watch when examining recipe command lines. If a command line contains any of the characters in the string line, make passes the command line to the shell specified by the SHELL macro. If a command line does not contain any of these characters, make processes it directly.

As an example, you want the SHELLMETAS macro to contain the redirection symbols **<** and **>** as part of its value. Command recipes commonly employ redirection, but make must perform redirection through a shell; make cannot directly perform redirection. The startup file specifies a default value for SHELLMETAS, based on the value of SHELL.

Additional Tips on Using make

Recipe Lines

Until now, examples have placed all recipe lines after the first line of a rule, starting every recipe line with a tab. In fact, you can put a recipe on the same line as the prerequisite list if you put a semicolon (**;**) after the list. For example, you can write:

```
 %.o : %.c ; $(CC) -c $(CFLAGS) $<
```

The recipe comes immediately after the semicolon.

As another feature, make lets you designate special processing for particular recipe lines. If the tab at the beginning of a recipe line is immediately followed by an at character (**@**), make does *not* echo the line when it is processed. Using the **@** this way affects make like .SILENT, but for one line only:

```
file1.o : file1.c
    @cp file1.o /backup
    $(CC) -c $(CFLAGS) file1.c
```

make does not show the cp command when processing it, but does display the compilation command.

A minus sign (**\-**) immediately following the initial tab of a recipe line, affects make like .IGNORE , but for one line only:

```
file1.o : file1.c
    -cp file1.o /backup
    $(CC) -c $(CFLAGS) file1.c
```

make does not stop if the cp command gets an error (for example, because the device with the directory **/backup** is full). More technically, when minus sign precedes a command line, make ignores any nonzero return value the command produces.

A plus sign (**+**) immediately following the initial tab of a recipe line, forces make to process the recipe line even when you specify the -n, \-q, or \-t options. You will find this particularly useful when doing a recursive make. For example, suppose you have the following rule in your recipe:

```
dir :
    +make -c subdir
```

and you call make in the following way:

```
make -n
```

make simply prints most commands. However, make processes this recipe line allowing you to see what make will build in **subdir**. Because make will place -n in the MAKEFLAGS inherited by the child process, it also will print rather than process. This lets you to see all of the commands that would be processed, not just the ones in the working directory.

You can combine these markers in any order:

```
file1.o : file1.c
    -@+cp file1.o /backup
    $(CC) -c $(CFLAGS) file1.c
```

Libraries

It is often good programming practice to save compiled object code in an *object library*, a collection of object modules stored in a single file. When a library is linked with your code, only the object modules referred to in the library are actually linked into the final program.

If object code is stored in a library, your makefile must have access to the code from that library. This means you have to tell make when a target is a library, because make requires special handling to check whether library members are up to date.

make employs the .LIBRARY attribute to determine if a particular target is a library:

```
LIBOBJS = mod1 mod2 mod3
userlib$(LIBSUFFIX) .LIBRARY : $(LIBOBJS:+"$O")
```

This example tells make that **userlib$(LIBSUFFIX)** has the .LIBRARY attribute and is therefore a library. The prerequisites for this target are the object files

```
mod1$O mod2$O mod3$O
```

This example makes use of the **LIBSUFFIX** macro defined in the startup file. **LIBSUFFIX** specifies the usual suffix for libraries, just as **O** specifies the usual suffix for object files. (For brevity, the default rules also define the **A** macro equal in value to **LIBSUFFIX**.)

In any rule, you may use a construct of the form:

```
libname$(LIBSUFFIX)(member)
```

to refer to an object file contained in a library. This kind of construct may appear as a target or prerequisite. For example, you might have:

```
 prog$E : prog$O mylib$(LIBSUFFIX)(module$O)
     # recipe for linking object and library
```

make infers the following information from this:

- The file **mylib$(LIBSUFFIX)** is a library.
- The module **module$O** is a member of that library; and therefore, it is a prerequisite for the library.
- The **module$O** module inside the library is a prerequisite of **prog$E** (that is, the program links in that module).

The recipe in this rule should tell make how to link the object file with the library module. The library metarules in the standard startup file specify the means for updating libraries.

Library Metarules

The standard startup file contains the following metarule for libraries:

```
%$(LIBSUFFIX) .PRECIOUS:
    $(AR) $(ARFLAGS) $@ $?
```

This indicates that make may update any library (that is, a file ending in the appropriate library suffix) with the $(AR) command, given the list of out of date member files.

The default rules define the AR macro with the following macro assignment:

```
AR = ar
```

ar updates libraries stored in the standard library format. You can assign the ARFLAGS macro any option flags used in the library updating process; the default rules set the flags to update an existing library, or create a new library, as appropriate.

With this metarule, it is not usually necessary to call ar from a user written makefile. You can accomplish your library handling simply by specifying the names of the object members of the library:

```
LIBOBJS= mod1 mod2 mod3
userlib$(LIBSUFFIX) .LIBRARY: $(LIBOBJS:+"$O")
```

For further information on the ar command, see the command description in *z/VM: OpenExtensions Commands Reference*.

Group Recipes

OpenExtensions make supports *group recipes*, but traditional implementations of make do not. A group recipe signifies a collection of command lines fed as a unit to the command interpreter. By contrast, make processes commands in a usual recipe one by one.

You enclose a group recipe's command lines in square brackets. The opening square bracket ([) must appear as the first non-white-space character in a line. The closing square bracket (]) must also appear as the first non-white-space character in a line. The square brackets can enclose as many command lines as you want.

A typical group recipe might involve special command constructs, such as the looping constructs of the KornShell. Consider the following example:

```
book : chap1.tr chap2.tr chap3.tr
[
    >book
    for i in $&
    do
        fmt -j -l 66 $$i >>book
    done
]
```

This creates an OpenExtensions shell for loop that uses the fmt application to format each file under the **dir** directory and append the formatted material to the **book** file. A usual rule cannot be written in this way, because the recipe command lines in a usual rule are processed one by one.

Note: make expands the group recipe; therefore, you must write the **$i** OpenExtensions shell variable as **$$i**; otherwise, make attempts to expand the **$i** make variable.

The command lines inside a group recipe do not require an initial tab character. Also, an **@** character, a **+** character, or a **-** character immediately after the opening bracket ([) has the same effect as in a usual recipe, for the entire group recipe:

- **@** silences the group recipe processing

- **+** causes the recipe always to be processed regardless of the option flags set
- **-** ignores error returns

Special Group Recipe Constructs

You can set the GROUPSHELL control macro to indicate which command interpreter will receive your group recipes. For example, you might set:

```
SHELL = rsh
GROUPSHELL = sh
```

so that you pass usual recipes to the restricted shell and group recipes to the full OpenExtensions shell. The default rules specify the same value for the GROUPSHELL as for SHELL.

When make encounters group recipes, it creates a temporary file to hold the command lines and then submits this temporary file to the shell.

The GROUPFLAGS control macro lets you specify any option flags make uses when invoking a group recipe. This is similar to the SHELLFLAGS control macro used for usual recipe lines.

Chapter 5. More Information on OpenExtensions make

The following example describes the general form of the make command line:

```
make [ options ] [ macro definitions ] [  target … ]
```

You can omit items shown between [and] brackets. The brackets are part of the standard documentation style; they enclose optional items and are not used on make's actual command line.

The *target*s specified on the command line are usually file names. make attempts to update these *target*s, if necessary, using the rules defined in a startup file and rules taken from a user makefile.

If you do not specify any *target* names on the command line, make attempts to find a makefile. It also updates the first nonspecial target specified in the makefile. (“Special Target Directives” on page 121 describes special targets.)

The *macro definitions* specified on the command line have the same form as macro definitions in a makefile. Command-line *macro definitions* take effect after any definitions in the startup file and the user makefile. See “Macros” on page 115 for more information.

Command-Line Options

You can specify a number of options on the make command line. Most take the form of a minus sign (**-**) followed by a single letter. The case of the letter is significant; for example, -e and -E are different *options* and have different effects.

If a command line has several such *options*, they can be *bundled* together. For example, the following two command lines are equivalent:

```
make -i -e
make -ie
```

The following list explains all the command line options of make. Many of these match options in other versions of make.

-c *dir*
Attempts to change into the specified directory when make starts up. If make can't change the directory, an error message is printed. This is useful for recursive makefiles when building in a different directory.

-E
Suppresses reading of the environment. Usually when make starts up, it reads all strings defined in the environment into the corresponding macros. For example, if you have an environment variable named **PATH** defined, make creates a macro with the same name and value. If you specify neither -E nor -e, make reads the environment *before* reading the makefile.

-e
Reads the environment *after* reading the makefile. If you specify neither -e nor -E, make reads the environment *before* reading the makefile.

-f *file*
Tells make to use *file* as the makefile. If you specify a minus sign (**-**) in place of *file*, make reads the standard input. (In other words, make expects you to enter the makefile from the terminal or redirect it from a file.)

-i
Tells make to ignore all errors and continue making targets. This is equivalent to the .IGNORE attribute or macro.

-k
Makes all independent targets, even if an error occurs. Ordinarily, make stops after a command returns a nonzero status. Specifying -k tells make to ignore the error and continue to make other targets, as long as they are unrelated to the target that received the error. make does not attempt to update anything that depends on the target that was being made when the error occurred.

-n
Displays the commands that need to be run to update the chosen targets, but does not actually run the commands. This feature works with group recipes, but in this case, make will run the commands. If make finds the string $(MAKE) in a recipe line, that line is run with $(MAKE) replaced by:

```
make -n $(MAKEFLAGS)
```

(MAKEFLAGS is described in "Special Macros" on page 123). This lets you see what recursive calls to make do. ("Makefile Input" on page 111 explains group recipes.)

-p
Prints the digested makefile. This display is in a human-readable form useful for debugging, but you cannot use it as input to make.

-q
Checks whether the target is up to date. If it is up to date, make exits with a status of 0; otherwise, it exits with a status of 1 (typically interpreted as an error by other software). No commands are run when -q is specified.

-r
Tells make not to read the startup file. "Finding the Makefile" on page 111 explains the startup file.

-S
Ends make if an error occurs during operations to bring a target up to date (opposite of -k). This is the default.

-s
Tells make to do all its work silently. make does not display the commands it is running or any warning messages. This is equivalent to setting the .SILENT attribute, or assigning a nonnull value to the .SILENT macro.

-t
Touches the targets to mark them as up to date, without actually running any commands to change the targets. Use the -t option with caution: Careless use may cause make to consider files as recently changed (because they have been touched), even though you have not changed them. This can result in a target that isn't brought up to date when required.

-u
Forces an unconditional update: make behaves as if all the prerequisites of the given target are out of date.

-V
Prints the version number of make. It also prints the *built-in rules* of this version of make. For more about built-in rules, see "Finding the Makefile" on page 111.

-v
Causes make to display a detailed account of its progress. This includes:

- What files it reads
- The definition and redefinition of each macro
- Metarule and suffix rule searches
- Other information

-x
Exports all macro definitions to the environment. This happens just before making any targets, but after the entire makefile has been read.

Finding the Makefile

make works with information from several different sources:

Built-in rules
The make program itself contains built-in rules. They may change from one release to the next, but you cannot change them yourself. The command make -V displays the built-in rules for your version of make.

Default rules
The standard startup file contains a group of default rules used by make. You can specify the name of this startup file by setting the value of the **MAKESTARTUP** environment variable. If **MAKESTARTUP** contains a *null* value (the default), then make uses **/etc/startup.mk**. You can use a different file by assigning a file name to **MAKESTARTUP** on the make command line as if it were a macro. You can edit the contents of the startup file with a usual text editor. When make is installed, the startup file is set up according to your specifications. You should not customize this file until you are familiar with make and have decided how you want to control its behavior. This file defines various control macros and default rules; if you lose this file or put incorrect material into it, make will not work as documented here. The standard startup file specifies default values for all required control macros and default metarules.

A local default rules file
As distributed, the last line of the startup file prompts make to read the local **startup.mk** file, if such a file exists.

The makefile
A makefile is just a usual text file that you create with any text editor. It provides specific rules for remaking your targets. (If you use a word processor or editor that inserts embedded control characters, you have to save the file as a usual text file, without those control characters.)

When you call make, it first tries to find a startup file and then tries to find a user makefile. make follows these steps to find the startup file:

- If the command line contains a macro definition for **MAKESTARTUP**, make uses that value as the name of a different startup file. If the file can be read, make uses it as the startup file.
- If the command line does not have a **MAKESTARTUP** macro, or if make cannot read the file it names, make checks the environment for a variable named **MAKESTARTUP**. If this variable exists, make attempts to read its value as the startup file.
- If neither of these is successful, make looks for the file named **startup.mk** as defined in the built-in rules.

You can therefore use a **MAKESTARTUP** macro definition on the command line or in the environment to obtain a different startup file.

The special target .MAKEFILES determines the location of your makefile. This is discussed in "Special Target Directives" on page 121. The built-in rules version of .MAKEFILES tells make to look for **makefile** or **Makefile** in the working directory. **makefile** is tried first; **Makefile** is used only if **makefile** cannot be found. You can also use the -f *file* option to give the name of the user makefile explicitly.

If you specify the -r option on the command line, make does not attempt to read a startup file. Instead, it uses the built-in rules and attempts to find a user makefile directly.

Makefile Input

A makefile can contain any or all of the following:

- Macro definition lines
- Target definition lines
- Recipe lines
- Comments

The ordering of these within a makefile is very flexible. There are only two restrictions:

- The recipe lines for a target must immediately follow the target definition line.
- The recipe describing how to make a target cannot span more than one makefile.

For a discussion of how to use more than one makefile, see the explanation of .INCLUDE in "Special Target Directives" on page 121.

If a makefile line cannot fit on a single text line, you can break it over several text lines by putting a backslash (****) at the end of each partial line. For example:

```
macro = abc\
def
```

is the same as:

```
macro = abcdef
```

If you are using the `-n` option to display what `make` would process, `make` puts backslash and line-feed characters at the end of each partial line so that the output resembles the makefile input.

Comments

Comments begin with the **#** character and extend to the end of line, as in:

```
# This is a comment
```

`make` itself ignores all comment text. If you need to put a **#** in your makefile without creating a comment, put a backslash (****) in front of it, or enclose it in double quotation marks.

Rules

A makefile contains a series of *rules* that specify targets, dependencies, and recipes. For example, a rule might state that an object file depends on a source file; if you change the source file, you want `make` to remake the object file using the changed source.

Files that depend on other files are called *targets*. The files that a target depends on are called *prerequisites*.

This is the general format of a rule:

```
targets [attributes] ruleop [prerequisites] [; recipe ]
{<tab> recipe}
```

You need include items enclosed by [ ]; items within { } can appear zero or more times. In a rule:

targets
Represents a list of one or more dependent files.

attributes
Represents a list, possibly empty, of attributes to apply to the list of targets. See "Using Attributes to Control Updates" on page 119 for more details.

ruleop
Represents an operator that separates the target names from the prerequisite names, and optionally affects the processing of the specified targets. All rule operators begin with a colon (**:**). For more information about rule operators, see "Rule Operators" on page 113.

prerequisites
Represents a list of file names on which the specified targets depend.

recipe
May follow on the same line as the prerequisites, separated from them by a semicolon. If such a recipe exists, `make` uses it as the first in a list of recipe lines defining a method for remaking the named targets. Additional recipe lines may follow the first line of the rule. Each such recipe line must begin with a tab character. For more about recipes, see "Recipes" on page 114.

As an example of a simple rule, consider the following:

```
main.o : include.h
```

This rule contains a single target, **main.o**, and a single prerequisite, **include.h**. The rule states that if **include.h** changes, **main.o** will require remaking. A typical makefile does not specify a recipe for making **main.o** from **main.c**; instead, the default rules provide the recipe using a metarule or suffix rule. These rules are discussed in "Using Inference Rules" on page 128.

When make parses rules, it treats the targets and prerequisites as tokens separated by white space (one or more blank or tab characters). In addition, make treats the rule operator (*ruleop*) as a token, but does not require white space around it.

Makefiles can contain special rules that control the behavior of make instead of stating a dependency between targets and prerequisites. For more information about such rules, see "Special Target Directives" on page 121.

Rule Operators

The *rule operator* in a rule separates the targets from the prerequisites. Rule operators also let you modify the way in which make handles the making of the associated targets. make recognizes the following rule operators:

:
Separates targets and prerequisites. The same target may have many **:** rules stating different prerequisites for the target, but only one such rule can specify a recipe for making the target—except with metarules. Within metarules, you can specify more than one recipe for making the target. If the target has more than one associated metarule, make uses the first metarule that matches.

::
Indicates that this rule may not be the only rule with a recipe for the target. There may be other **::** rules that specify a different set of prerequisites, with different recipes for updating the target. make builds any such target if any of the rules find the target out of date with any related prerequisites. make then uses the corresponding recipe to perform the update. You can find an example later in this section.

:!
Tells make to process the recipe for the associated targets one at a time for each recently changed prerequisite. Ordinarily, make processes the recipe only one time for all recently changed prerequisites at the same time.

:^
Tells make to insert the specified prerequisites before any other prerequisites already associated with the specified targets.

:-
Forces make to clear the previous list of prerequisites before adding the new prerequisites. Thus, you can replace:

```
.SOURCE
.SOURCE: dir1 dir2
```

with the following:

```
.SOURCE :- dir1 dir2
```

However, the old form still works as expected. See "Special Target Directives" on page 121.

:|
Used only in metarules, tells make to treat each metadependency as an independent metarule; for example:

```
    %.o :| archive/%.c rcs/%.c /srcarc/rcs/%.c
        recipe…
```

is equivalent to:

```
%.o : archive/%.c
    recipe…
%.o : rcs/%.c
    recipe…
%.o : /srcarc/rcs/%.c
    recipe…
```

You will find this operator particularly useful for searching for **rcs** file archives. If the **RCSPATH** variable used by **rcs** contains the following value:

```
archive/%f;rcs/%f;/srcarc/rcs/%f
```

then the metarule:

```
% :| $(RCSPATH:s/%f/%/:s/;/ /)
co -l $<
```

searches the path looking for an **rcs** file and checks it. See "Pattern Substitution" on page 116 for an explanation of macro expansion.

It is meaningless to specify **:!**, **:-**, or **:^** with an empty list of prerequisites (although this is not considered an error).

The following example shows how **::** works. Suppose a makefile contains:

```
a.o :: a.c b.h
# first recipe for making a.o
a.o :: a.y b.h
# second recipe for making a.o
```

If make finds **a.o** out of date with respect to **a.c**, it uses the first recipe to make **a.o**. If **a.o** is found out of date with respect to **a.y**, make uses the second recipe. If make finds **a.o** out of date with respect to **b.h**, it calls both recipes to make **a.o**. In the last case, the order of invocation matches the order of the rule definitions in the makefile.

Remember that you should use the **::** operator if a target has more than one associated recipe—unless you form metarules. For more information on metarules see "Metarules" on page 128.

The following example is an error:

```
joe : fred … ; recipe
joe : more … ; recipe  #error
```

Recipes

The recipe consists of a list (possibly empty) of lines defining the actions make carries out to update a target. make defines recipe lines as arbitrary strings that may contain macro expansions. These follow a target-prerequisite line, and you can space them apart by comment or blank lines. You end a recipe by a new target description, a macro definition, or end of file.

Each recipe line *must* begin with a tab character. Optionally, you can place **-**, **@**, **+** (or any combination) directly after the tab.

- **-** instructs make to ignore nonzero exit values when it processes this recipe line; otherwise, make stops processing after an error.
- **@** instructs make *not* to echo the recipe line to the standard output prior to its processing; otherwise, make prints each line as it processes the line.
- **+** instructs make to always process the recipe line, even when you have specified the -n, -q, or -t options.

See "Special Target Directives" on page 121 for other ways to obtain this behavior.

make also accepts *group recipes*. A group recipe begins with an opening bracket ([) in the first non-white-space position of a line, and ends with a closing bracket (]) in the first non-white-space position of a line. In this format, recipe lines do not require a leading tab character.

make passes group recipes, as a single unit, to a command interpreter for processing whenever the corresponding target requires updating. If the [that starts the group immediately precedes one or more of **-**, **+**, or **@**, they apply to the entire group in the same way that **-**, **+**, and **@** apply to single recipe lines.

As noted earlier, rules can have *;recipe* on the same line as the target definition line. If additional lines with a leading tab character follow the rule definition, *;recipe* is used as the first recipe line, and the additional lines follow it. Otherwise, the text after the **;** is used as the entire recipe. If the semicolon is present but the rest of the recipe line is empty, make interprets this as an empty recipe.

Missing Recipes

If make cannot find a recipe for a particular target, it usually displays a message on the standard error stream, in the form:

```
Don't know how to make target
```

make does *not* generate this message if a rule has an explicitly empty recipe.

Macros

A *macro* fulfills a function similar to a programming language's variable: You can assign a value to a macro, and can then use this value in subsequent operations by referring to the macro. You can define make macros within the makefile or on the command line, or by importing them from the environment. For instructions on importing environment variables as macros, see “Special Target Directives” on page 121.

On the command line and inside a makefile, you have three ways to create a macro. make recognizes the first form (most other versions of make do as well):

```
macro = string
```

This example gives the value of *string* to *macro*.

The other two forms are not found in traditional implementations of make:

```
macro := string
```

expands *string* (including any macros it contains) and then assigns the expanded string to *macro*.

```
macro += string
```

changes the current value of *macro* by adding a single space and then the value of *string*. In this case, make does *not* expand *string*.

When make defines a macro other than definitions read from the environment, it strips any leading and trailing white space from the macro value. White space consists of any combination of blanks or tabs.

After you have defined a macro, you can use it in any makefile line. Whenever make finds one of the following constructs in a makefile:

```
$(macro)
${macro}
```

it replaces *macro* with its associated, predefined string. Thus, $(TEST) causes an expansion of the macro variable named **TEST**. If you have defined **TEST**, make expands any reference to $(TEST) to your associated string. If you haven't defined **TEST** at that time, $(TEST) expands to the **NULL** string (a string containing no characters). This is equivalent to the following macro definition:

```
TEST=
```

If the name of a macro consists of a single character, you can omit the parentheses or braces. Thus, $X is equivalent to $(X).

make processes macro definitions on the command line last; they will override definitions for macros of the same name found within the makefile. Therefore, definitions found inside the makefile cannot redefine macros defined on the command line.

Modified Macro Expansions

make supports several new macro expansion expressions, of the form:

```
$(macro_name:modifier_list:modifier_list:…)
```

Each *modifier_list* consists of one or more characters that tell make to extract only part of the string associated with the given macro. A list of characters and their meanings follows:

```
b or B    — File portion of all pathnames, without suffix
d or D    — Directory portion of all pathnames
f or F    — File portion of all pathnames, including suffix
s or S    — Simple pattern substitution (see "Pattern Substitution" on page 116)
t or T    — Tokenization (see "Tokenization" on page 117)
u or U    — All characters in the expansion are mapped into uppercase
l or L    — All characters in the expansion are mapped into lowercase
^         — token prefixing (see "Prefix and Suffix Operations" on page 117)
+         — token suffixing (see "Prefix and Suffix Operations" on page 117)
```

You can use either uppercase or lowercase for modifier letters. Suppose, for example, you define a macro with:

```
test = D1/D2/d3/a.out f.out d1/k.out
```

Then the following macro expansions take on the values shown.

```
$(test:d)            → D1/D2/d3 . d1
$(test:b)            → a f k
$(test:F)            → a.out f.out k.out
${test:DB}           → D1/D2/d3/a f d1/k
${test:s/out/in/}    → D1/D2/D3/a.in f.in d1/k.in
$(test:t"+")         → D1/D2/D3/a.out+f.out+d1/k.out
$(test:u)            → D1/D2/D3/A.OUT F.OUT D1/K.OUT
$(test:l)            → d1/d2/d3/a.out f.out d1/k.out
$(test:^"/rd/")      → /rd/D1/D2/d3/a.out /rd/f.out /rd/d1/k.out
$(test:+".Z")        → D1/D2/d3/a.out.Z f.out.Z d1/k.out.Z
```

The :d modifier gives a **.** for names that do not have explicit directories.

Pattern Substitution

You use the substitution modifier to substitute strings in a macro definition:

```
:s/pattern/replace/
```

You can use any printing character in place of the **/** character to delimit the pattern and replacement text, as long as you use it consistently within the command.

For compatibility with UNIX System V, make also supports the suffix replacement modifier:

```
$(name:oldsuffix=newsuffix)
```

This expands $(name) usually, and then replaces any occurrences of the suffix *oldsuffix* with *newsuffix* make replaces the **o** string only when it appears in the position of a suffix:

```
LIST = apple.o orange.o object.o
$(LIST:o=c) → apple.c orange.c object.c
```

Tokenization

The tokenization modifier:

```
:t"string"
```

expands the macro value into tokens (strings of characters separated by white space) separated by the quoted *string* that follows the `t` modifier. `make` does not append the separator string to the last token. The following list shows the special escape sequences that may appear in the separator string and their meanings:

```
\"    →    "
\\    →    \
\a    →    alert (bel)
\b    →    backspace
\f    →    formfeed
\n    →    newline
\r    →    carriage return
\t    →    horizontal tab
\v    →    vertical tab
\ooo →    EBCDIC character octalooo>
```

Thus, using the previous definition of `$test`, the following expansion occurs:

```
$(test:f:t"+\n")    expands to    a.out+
          ;                 f.out+
                               k.out
```

Prefix and Suffix Operations

You use prefix and suffix modifiers:

```
:^"prefix"
:+"suffix"
```

to add a prefix or suffix to each space separated token in the expanded macro.

For example, suppose you specify the following macro definition:

```
test = main func1 func2
```

Then the following expansions occur:

```
$(test:^"/src/")expands to /src/main /src/func1 /src/func2
$(test:+".c") expands to main.c func1.c func2.c
```

You can combine these two macro references:

```
$(test:^"/src/":+".c")
```

expands to:

```
/src/main.c /src/func1.c/src/func2.c
```

If the prefix and suffix strings themselves consist of a list of tokens separated by blanks, the resulting expansion is the cross-product of both lists.

For example, if you specify the following definition of `test`:

```
test = a b c
```

Then the following expansions occur:

```
$(test:^"1 2 3")    expands to    1a 1b 1c 2a 2b 2c 3a 3b 3c
$(test:+"1 2 3")    expands to    a1 b1 c1 a2 b2 c2 a3 b3 c3
```

You can combine these two references:

```
$(test:␣"1 2 3":+"1 2 3")

expands to              1a1 1b1 1c1 2a1 2b1 2c1 3a1 3b1 3c1
                        1a2 1b2 1c2 2a2 2b2 2c2 3a2 3b2 3c2
                        1a3 1b3 1c3 2a3 2b3 2c3 3a3 3b3 3c3
```

Nested Macros

make also allows the values of macros to control the expansion of other macros. You can include such nested macros in the following ways:

```
$(string)
```

or

```
${string}
```

where *string* contains additional **$(...)** or **${...}** macro expansions. Consider the following example:

```
$(CFLAGS$(_HOST)$(_COMPILER))
```

make first expands $(_HOST) and $(_COMPILER) to get results and then uses those results as the name of the macro to expand. This is useful when you write a makefile for more than one target environment. Suppose you import $(_HOST) and $(_COMPILER) from the environment and they represent the host machine type and the host compiler, respectively. If the makefile contains the following macro definition, CFLAGS takes on a value that corresponds to the environment in which make is being called:

```
CFLAGS_VM_CC = -c -O
  # for _HOST == "_VM", _COMPILER == "_C89"
CFLAGS_PC_MSC = -c -ML
  # for _HOST == "_PC",  _COMPILER == "_MSC"
CFLAGS := $(CFLAGS$(_HOST)$(_COMPILER))
```

Text Diversion

With text diversion you can directly create files from within a recipe. This feature is an extension to traditional make systems and probably absent from other implementations.

In a recipe, you can use a construct of the form:

```
<+ text +>
```

where the given *text* can stand for anything; several lines long if desired. When make encounters this construct, it creates a temporary file with a unique name, and copies the given *text* to that file. Then, make processes the recipe with the name of the temporary file inserted in place of the diversion. When make finishes processing, it removes all the temporary files. (You can use the -v option to have make show the names of these temporary files, and leave them around to be examined.)

make places temporary files in the /tmp directory unless the **TMPDIR** environment variable is set.

make expands macro references inside the text in the usual way, so that the file contains the text with all macro references replaced by the associated strings. Newline characters are copied as they appear in the diversion.

Usually, make does *not* copy white space at the beginning of each line of the *text* into the temporary file, unless you put a backslash at the front of a white space character, the white space from that point on is copied into the temporary file:

```
<+
    This line does not begin with white space
\   This one does.
+>
```

As a simple example of text diversion, suppose that the **CC** macro currently contains c89 (the c89 compiler interface). If make encounters the recipe line with your written application copy:

```
copy <+ Using $(CC) as compiler
     +> hifile
```

it creates a temporary file containing:

```
Using c89 as compiler
```

After make strips white space from the beginning of the second line, the contents of the temporary file end at the newline character at the end of the first line.

The temporary file that the text diversion process creates has a unique name. Suppose that the name is **temp**. make changes the original recipe line to:

```
copy temp hifile
```

with the result that the line:

```
Using c89 as compiler
```

is copied into **hifile**.

Consider a more realistic example of how you can use this feature with your written application link:

```
OBJECTS=program$O module1$O module2$O
program: $(OBJECTS)
        link @<+ $(OBJECTS:t"+\n")
                 $@/noignorecase
         $(NULL)
         $(LDLIBS)
              +>
```

The tokenizing expression:

```
$(OBJECTS:t"+\n")
```

adds a **+** and a newline after each token in the OBJECTS macro. The run-time macro $@ stands for the name of the target being made (as explained in “Special Macros” on page 123). As a result, the temporary file created by the text diversion contains:

```
program.o+
module1.o+
module2.o
program/noignorecase
```

which is the sort of input file that the link command can handle. The recipe therefore consists of the following command:

```
link @tempfile
```

tempfile stands for the name of the temporary file holding the text diversion.

Creating a text diversion in this way is complicated, but it may be the only way to handle some situations.

Using Attributes to Control Updates

make defines several target attributes. You can assign attributes to a single target, a group of targets, or to all targets in the makefile. Attributes affect what make does when it needs to update a target. make recognizes the following attributes:

.EPILOG
Inserts shell epilog code when processing a group recipe associated with any target having this attribute set. (See also .PROLOG).

.IGNORE
Ignores any errors encountered when trying to make a target with this attribute set.

.LIBRARY
Indicates that target is a library. If make finds a target of the form *lib(member)* or *lib((entry))*, make automatically gives the .LIBRARY attribute to the target named *lib*. For further information, see "Making Libraries" on page 131.

.PRECIOUS
Tells make not to remove this target under any circumstances. Any automatically inferred prerequisite inherits this attribute. For an explanation of why this is provided, see the discussion of .REMOVE in "Special Target Directives" on page 121.

.PROLOG
Inserts shell prolog code when processing a group recipe associated with any target having this attribute set.

.SETDIR
Changes the working directory to a specified directory when making associated targets. The syntax of this attribute is:

```
.SETDIR=path
```

where *path* represents the pathname of desired working directory.

.SILENT
Does not echo the recipe lines when making any target with this attribute set, and does not issue any warnings.

You can set any of the previous attributes. make recognizes two more attributes which you cannot set; the .LIBRARYM and .SYMBOL attributes.

.LIBRARYM
Indicates that the target is a library member. You cannot explicitly set this attribute; make automatically gives it to targets or prerequisites of the form *lib(entry)*; that is, *lib* sets the .LIBRARY attribute, and *entry* gets the .LIBRARYM attribute.

.SYMBOL
Indicates that target is the library member with a given entry point. You cannot explicitly set this attribute; make automatically gives it to targets or prerequisites of the form *lib((entry))*.

You can use attributes in several ways:

```
targets attribute_list : prerequisites
attribute_list : targets
```

Both of these examples assign the attributes specified by *attribute_list* to each of the *targets*.

A line of the form:

```
attribute_list :
```

(with no *targets*) applies the list of attributes to all targets in the makefile. Traditional versions of make may let you do this with the .IGNORE attribute, but not with any others attributes.

You can use any attribute with any target (including special targets). Some combinations are useless (for example, .INCLUDE .PRECIOUS: ...). Other combinations are quite useful:

```
.INCLUDE .IGNORE : "startup.mk"
```

This example tells make not to complain if it cannot find **startup.mk** using the include file search rules. If you do not use a specified attribute with the special target, make issues a warning and ignores the attribute.

Special Target Directives

Special targets are called *targets* because they appear in the target position of rules; however, they really function as keywords, not targets; and the rules in which they appear serve as *directives*, which control the behavior of make.

The special target must be the only target in a special target rule; you cannot list other usual or special targets.

Some attributes do not affect special targets. You can give any attribute to any special target, but often the combination is meaningless and the attribute has no effect.

.BRACEEXPAND
Cannot have prerequisites or recipes associated with it. If set, the .BRACEEXPAND special target allows use of the brace expansion feature from previous versions of make. If you have old makefiles that use the now-outdated brace expansion feature, you can use this special target to continue using them without modification. For more information about brace expansion, see *z/VM: OpenExtensions Commands Reference*.

.DEFAULT
Takes no prerequisites, but does have a recipe associated with it. If make cannot find a mechanism to build a target, it uses the recipe from the .DEFAULT rule. If your makefile contains:

```
.DEFAULT:
    echo no other rule found
    echo so doing default rule for $<
```

and no other rule for **file.c**, then:

```
    make file.c
```

displays:

```
no other rule found
so doing default rule for file.c
```

.ERROR
If defined, prompts the processing of the recipe associated with this target whenever make detects an error condition. You can use any attribute with this target. make brings any prerequisites of this target up to date during its processing.

Note: make ignores any errors while making this target.

.EXPORT
Prompts make to determine which prerequisites associated with this target correspond to macro names. make exports these to the environment, with the values they hold, at the point in the makefile at which make reads this rule. make ignores any attributes specified with this target. Although make exports the value specified to the environment at the point at which it reads the rule, no actual processing of commands takes place until the entire makefile is read. Only the final exported value of a given variable affects processed commands.

.GROUPEPILOG
Prompts make to add recipe associated with this target after any group recipe for a target that has the .EPILOG attribute. See “Processing Recipes” on page 130 for further information.

.GROUPPROLOG
Puts the recipe associated with this target in before any group recipe for a target that has the .PROLOG attribute. See “Processing Recipes” on page 130 for further information.

.IMPORT
Prompts make to search for the associated prerequisite names in the environment. make defines the names it finds as macros with the value of the macro taken from the environment. If it cannot find a name, it issues an error message; however, if you specify the .IGNORE attribute, make does not generate an error message and does not change the macro value.

If you give the prerequisite .EVERYTHING to .IMPORT, make reads in the entire environment. (Requiring this special prerequisite instead of an empty string helps to avoid accidentally importing the entire environment by expanding a null macro as the prerequisite of .IMPORT).

Note: Usually make imports the entire environment unless suppressed by the -E option.

.INCLUDE
Tells make to process one or more additional makefiles, as if their contents had been inserted at the line where make found the .INCLUDE in the current makefile. You specify the makefiles to be read as the prerequisites for .INCLUDE. If the list contains more than one makefile, make reads them in order from left to right.

make uses the following search rules when trying to find the makefile:

- If a relative file name is enclosed in quotation marks (") or is not enclosed, make begins its search in the working directory. If the file is not found, make then searches for it in each directory specified by the .INCLUDEDIRS special target.
- If a relative file name is enclosed with **<** and **>**, (as in <file>), make searches only in the directories specified by the .INCLUDEDIRS special target.
- If an absolute (fully qualified) file name is given, make looks for that file, and ignores the .INCLUDEDIRS list.

If make cannot find a file, it usually issues an error message and ends; however, if the .IGNORE attribute is specified, make just ignores missing files. The .IGNORE attribute is the only attribute that can be specified with .INCLUDE.

For compatibility with make on UNIX System V:

```
include file
```

at the beginning of a line has the same meaning as:

```
.INCLUDE: file
```

.INCLUDEDIRS
Contains a list of specified prerequisites that define the set of directories to search when trying to include a makefile.

.MAKEFILES
Contains a list of prerequisites that name a set of files to try to read as the user makefile. make processes these files in the order specified (from left to right) until it finds one up to date. The built-in rules specify:

```
.MAKEFILES : makefile Makefile
```

.POSIX
Causes make to process the makefile as specified in the POSIX.2 standard. This special target must appear before the first noncomment line in the makefile. This target may have no prerequisites and no recipes associated with it. The .POSIX target does the following:

- It causes make to use the shell when running all recipe lines (one per shell).
- It disables any brace expansion (set with the .BRACEEXPAND special target).
- It disables metarule inferencing.
- It disables conditionals.
- It disables make's use of dynamic prerequisites.
- It disables make's use of group recipes.
- make will *not* check for the string $(MAKE) when run with the -n option specified.

.REMOVE
Causes make to remove intermediate targets. In the course of making some targets, make may create new files as intermediate targets. For example, if make creates a processable file, it may have to create some object files if they don't currently exist. make tries to remove any such intermediate targets that did not exist initially. It does this by using the recipe associated with the .REMOVE special target. The startup file set up an appropriate rm command to serve as a default for .REMOVE. If you want to avoid this automatic removal for certain targets, give those targets the .PRECIOUS attribute. (.PRECIOUS is especially useful for marking libraries, because you usually want them to remain.)

.SOURCE
Contains a prerequisite list that defines a set of directories to check when trying to locate a target file name. For more information, see "Binding Targets" on page 127.

.SOURCE.x
Is similar to .SOURCE, except that make searches the .SOURCE.x list first when trying to locate a file with a name ending in the suffix **.x**.

.SUFFIXES
Contains a prerequisite list of this target, which defines a set of suffixes to use when trying to infer a prerequisite for making a target. There is no need to declare suffixes. If the .SUFFIXES rule has no prerequisites, the list of suffixes is cleared, and make does not use suffix rules when inferring targets.

Special Macros

make defines two classes of special macros: control macros and run-time macros.

The *control macros* control make's behavior. If you have several ways of doing the same thing, using the control macros is preferable. A control macro having the same function as a special target or attribute also has the same name.

make defines the *run-time macros* when making targets, and they are usually useful only within recipes. The exceptions to this are the dynamic prerequisite macros, discussed later in this chapter.

Control Macros

There are two groups of control macros:

- String-valued macros
- Attribute macros

make automatically creates internally defined macros. You can use these macros with the usual $(*name*) construct. For example, you can use $(PWD) to obtain the working directory name.

String-Valued Macros

DIRSEPSTR
Is defined internally. It gives the characters that you can use to separate components in a pathname. This is usually just /. If make finds it necessary to make a pathname, it uses the first character of DIRSEPSTR to separate pathname components.

GROUPFLAGS
Is set by the startup file and can be changed by you. This macro contains the set of flags to pass to the command interpreter when make calls it to process a group recipe. See the discussion of MFLAGS for more about switch characters.

GROUPSHELL
Is set by the startup file and can be changed by you. It defines the full path to the processable image used as the shell (command interpreter) when processing group recipes. This macro must be defined if you use group recipes. It is assigned the default value in the standard startup file.

GROUPSUFFIX
Is set by the startup file and can be changed by you. If defined, this macro gives the string used as a suffix when make creates group recipe files to be handed to the command interpreter. For example, if it is defined as **.sh**, all group recipe files created by make end in the suffix **.sh**.

INCDEPTH
Is defined internally. It gives the current depth of makefile inclusion. This macro contains a string of digits. In your original makefile, this value is 0. If you include another makefile, the value of INCDEPTH is 1 while make processes the included makefile, and goes back to 0 when make returns to the original makefile.

MAKE
Is set by the startup file and can be changed by you. The standard startup file defines it as:

```
$(MAKECMD) $(MFLAGS)
```

make itself does not use the MAKE macro, but it recognizes the string $(MAKE) when using the -n option for single-line recipes.

MAKECMD
Is defined internally. It gives the name you used to call make.

MAKEDIR
Is defined internally. It contains the full path to the directory from which you called make.

MAKEFLAGS
Contains all the flags specified in the **MAKEFLAGS** environment variable plus all the flags specified on the command line, with the following exceptions. It is an error to specify -c, -f, or -p in the environment variable, and any specified on the command line do not appear in the MAKEFLAGS macro. Flags in the **MAKEFLAGS** environment variable can optionally have leading dashes and spaces separating the flags. make strips these out when the MAKEFLAGS macro is constructed.

MAKESTARTUP
May be set by you, but only on the command line or in the environment. This macro defines the full path to the startup file. The built-in rules assign a default value to this macro.

MFLAGS
Is defined internally. It gives the list of flags given to make including a leading dash. That is, $(MFLAGS) is the same as -$(MAKEFLAGS).

NULL
Is defined internally. It is permanently defined to be the NULL string. This is useful when comparing a conditional expression to a NULL value and in constructing metarules without ambiguity. See “Metarules” on page 97 for more information.

OS
Is defined internally. It contains the name of the operating system you are running.

PWD
Is defined internally. It represents the full path to the working directory in which make runs.

SHELL
Is set by the default rules and can be changed by you. It defines the full path to the processable image used as the shell (command interpreter) when processing single-line recipes. This macro must be defined if you use recipes that require processing by a shell. The default rules assign a default value to this macro by inspecting the value of the **SHELL** environment variable.

Note: The startup file must explicitly import the **SHELL** environment variable. The default importation of the environment does not apply to **SHELL**.

SHELLFLAGS
Is set by the startup file and can be changed by you. This macro specifies the list of options (flags) to pass to the shell when calling it to process a single-line recipe. The flags listed in the macro do not possess a leading dash.

SHELLMETAS
Is set by the startup file and can be changed by you. This macro defines a list of characters that you want make to search for in a single recipe line. If make finds any of these characters in the recipe line, make uses the shell to call the recipe; otherwise, make calls the recipe without using the shell.

Attribute Macros

The attribute macros let you turn global attributes on or off. You use the macros by assigning them a value. If the value does not contain a NULL string, make sets the attribute *on* and gives all targets the associated attribute. If the macro *does* contain a NULL string, make sets the attribute *off*.

The following macros correspond to attributes of the same name:

```
.EPILOG
.IGNORE
.PRECIOUS
.PROLOG
.SILENT
```

See "Using Attributes to Control Updates" on page 119 for more information.

Run-time Macros

Run-time macros receive values as make is making targets. They take on different values for each target. These are the recognized run-time macros:

$@
Evaluates to the full name of the target, when building a usual target. When building a library, it expands to the name of the archive library. For example, if the target is **mylib(member)**, $@ expands to **mylib**.

$%
Also evaluates to the full name of the target, when building a usual target. When building a library, it expands to the name of the archive member. In the previous example, $% expands to **member**.

$&
Evaluates to the list of all prerequisites, in all rules that apply to the target.

$?
Evaluates to the list of all prerequisites that are newer than the target. In (CW:: rules, however, this macro evaluates to the same value as the $^ macro.

$>
Evaluates to the name of the library if the current target is a library member. For example, if the target is **mylib(member)**, $> expands to **mylib**.

$^
Evaluates to the list of prerequisites given in the rule that contains the recipe make is processing.

$<
Is similar to $^ , except that it represents only those prerequisites that prompt the processing of the rule. In usual rules, this contains the list of all recently changed prerequisites. In inference rules, however, it always contains the single prerequisite of the processing rule.

$*
Is equivalent to $(%:db). This expands to the target name with no suffix.

$$
Expands to $.

The following example illustrates difference between **$?** and **$<**:

```
a.o : a.c
a.o : b.h c.h
      recipe for making a.o
```

Assume **a.c** and **c.h** are newer than **a.o**, whereas **b.h** is not. When make processes the recipe for **a.o**, the macros expand to the following values:

```
$@  →  a.o
$*  →  a
$&  →  a.c b.h c.h
$?  →  a.c c.h
$^  →  b.h c.h
$<  →  c.h
```

Consider this example of a library target:

```
mylib(mem1.o):
    recipe…
```

For this target, the internal macros then expand to:

```
$@  →  mylib
$*  →  mem1
$>  →  mylib
```

Dynamic Prerequisites

You can use the symbols $$@, $$%, $$*, and $$> to create dynamic prerequisites (that is, prerequisites calculated at the time that make tries to update a target). Only these run-time macros yield meaningful results outside of recipe lines.

When make finds $$@ in the prerequisite list, the macro expands to the target name. If you are building a library, it expands to the name of the *archive library*. With the line:

```
fred : $$@.c
```

make expands $$@ when making **fred**, so the target name **fred** replaces the macro.

You can modify the value of $$@ with any of the macro modifiers. For example, in:

```
a.c : $$(@:b).c
```

the $$(@:b) expands to **a**.

Consider the following example of the $$@ in use:

```
file1 file2 : $$@.c
    $(CC) -c $(CFLAGS) $@.c
```

This has the same effect as:

```
file1 : file1.c
    $(CC) -c $(CFLAGS) file1.c
file2 : file2.c
    $(CC) -c $(CFLAGS) file2.c
```

When make finds $$% in the prerequisite list, it also stands for the name of the target, but when building a library, it stands for the name of the *archive member*.

When make finds $$* in the prerequisite list, it stands for the name of the target, but without the *suffix*.

You can use the $$> macro in the prerequisite list only if you are building a library. In this case, it stands for the name of the *archive library*. Otherwise, its use is invalid.

For more information on dynamic prerequisites and their use, see *z/VM: OpenExtensions Commands Reference*.

Binding Targets

Makefiles often specify target names in the shortest manner possible, relative to the directory that contains the target files. make possesses relatively sophisticated techniques of searching for the file that corresponds to a target name in a makefile.

Assume that you try to bind a target with a name of the form **pathname.ext**, where **.ext** is the suffix and **pathname** is the stem portion (that is, that part which contains the directory and the basename). make performs all search operations relative to the working directory except when the given name is a full pathname starting at the root of a file system.

1. Look for **pathname.ext** relative to the working directory, and use it if found.
2. Otherwise; if the .SOURCE.ext special target is defined, search each directory given in its list of prerequisites for **pathname.ext**. If **.ext** is a NULL suffix (that is, **pathname.ext** is really just **pathname**) use .SOURCE.NULL instead. If found, use that file. If still not found, try this step again using the directories specified by .SOURCE .
3. If still not found, and the target has the library member attribute (.LIBRARYM) set, try to find the target in the library of which the target is a member (see "Making Libraries" on page 131).

   Note: This same set of rules bind a file to the library target at an earlier stage of the makefile processing.
4. If still not found, the search fails. make returns the original name **pathname.ext**.

If at any point the search succeeds, make replaces the name **X.a** of the target with the new bound name and then refers to it by that name internally.

There is potential here for a lot of search operations. The trick is to define .SOURCE.x special targets with short search lists and leave .SOURCE undefined, or as short as possible. Initially, make simply defines .SOURCE as:

```
.SOURCE : .NULL
```

In this context, .NULL tells make to search the working directory by default.

The search algorithm has the following useful side effect. When make searches for a target that has the .LIBRARYM (library member) attribute, make first searches for the target as an ordinary file. When a number of library members require updating, it is desirable to compile all of them first and to update the library at the end in a single operation. If one of the members does not compile and make stops, you can fix the error and run make again. make does not remake any of the targets with object files that have already been generated as long as none of their prerequisite files have been modified.

If a target has the .SYMBOL attribute set (see "Making Libraries" on page 131), make begins its search for the target in the library. If make finds the target, it searches for the member using the search rules. Thus, make first binds library entry point specifications to a member file, and then checks that member file to see if it is out of date.

When defining .SOURCE or .SOURCE.x targets, the construct:

```
.SOURCE :
.SOURCE : fred gerry
```

is equivalent to:

```
.SOURCE :- fred gerry
```

More generally, the processing of the .SOURCE special targets is identical to the processing of the .SUFFIXES special targets.

Using Inference Rules

Specifying recipes for each and every target becomes tedious and error-prone. For this reason, make provides a number of mechanisms allowing you to specify generic rules for a particular type of target. These mechanisms are called *inference rules*. There are two major types: suffix rules and metarules.

Suffix rules are a historical mechanism that matches the suffix of a target against a list of special suffixes and rules to find a recipe to use. For more information, see "Suffix Rules" on page 98.

The second mechanism is called *metarules*. These *pattern rules* are a more recent invention provided by a number of modern versions of make. They are much more flexible and general than the older suffix rules. You should use the metarules rather than the suffix rules. make provides the suffix rules primarily for compatibility reasons. A final way to specify a recipe to a target that does not have any other rule is through the .DEFAULT special target. See "Special Target Directives" on page 121.

Here is the search order for the various mechanisms:

1. Search explicit rules in the makefile.
2. Check to see if an appropriate metarule exists.
3. Check to see if an appropriate suffix rule exists.
4. Check to see if the .DEFAULT target was defined; otherwise, display an error and stop.

Metarules

A metarule states, in general, that targets with names of a particular form depend on prerequisites with names of a related form. The most common example is that targets with a name ending in **.o** depend on prerequisites with the same basename, but with the suffix **.c**. The process of deriving a specific rule from a metarule is called *making an inference*.

Consider this example, which explains the general metarule format:

```
%.o : %.c
    $(CC) -c $(CFLAGS) $<
```

This rule states that any target file that has the suffix **.o**, and does not have an explicit rule, depends on a prerequisite with the suffix **.c** and the same basename. For example, **file.o** depends on **file.c**. The recipe that follows the command tells how to compile the **.c** file to get a corresponding **.o** file.

As another example, consider the following metarule:

```
%.c .PRECIOUS : RCS/%.c,v
    -co -q $<
```

Anyone who uses the public-domain application **rcs** to manage C source files will find this useful. The metarule says that any target with the suffix **.c** depends on a prerequisite that has the same file name, but is found in the subdirectory **RCS** under the same directory that contains the target. For example, **dir/file.c** is checked out of **dir/RCS/file.c,v**. The recipe line uses the special $< macro to stand for the prerequisite (in the **RCS** directory).

The general metarule format is:

```
pre%suf : prerequisite prerequisite…
    recipes
```

where *pre* and *suf* are arbitrary (possibly empty) strings. If the % character appears in the prerequisite list, it stands for whatever the % matched in the target.

Here is an inference rule that omits both the *suf* and *pre* strings:

```
% .PRECIOUS: RCS/%,v
    -co -q $<
```

This rule matches any target and tries to check it out from the **rcs** archive.

A number of technical considerations dictate the order in which make tries to make inferences. If several metarules can apply to the same target, there is no way to control the one that make actually uses. You can use the -v and -n options to find out what make chooses. A well-designed set of metarules yields only one rule for a particular target.

A metarule may specify attributes for a target. If make attempts to make a target that has a particular attribute, it first checks for a metarule that applies to the target and specifies the given attribute. If no such metarule exists, make looks for a metarule that does not specify the attribute. This lets you specify different metarules for targets with different attributes. make performs this test for all attributes except .SILENT, .IGNORE, and .SYMBOL.

Suffix Rules

Suffix rules are an older form of inference rule. They have the form:

```
        recipe…
```

make matches the suffixes against the suffixes of targets with no explicit rules. Unfortunately, they don't work quite the way you would expect.

The rule:

```
.c.o :
        recipe…
```

says that **.o** files depend on **.c** files. Compare this with the usual rules:

```
    file.o : file.c
        compile file.c to get file.o
```

and you will see that suffix rule syntax is backward! This, by itself, gives good reason to avoid suffix rules.

You can also specify single-suffix rules similar to the following, which match files ending in **.c**:

```
.c:
        recipe…
```

For a suffix rule to work, the component suffixes must appear in the prerequisite list of the **.SUFFIXES** special target. The way to turn off suffix rules is simply to place:

```
.SUFFIXES:
```

in your makefile with no prerequisites. This clears the prerequisites of the **.SUFFIXES** targets and prevents any suffix rules from firing. The order in which suffixes appear in the **.SUFFIXES** rule determines the order in which make checks the suffix rules.

Here is the search algorithm for suffix rules:

1. Extract the suffix from the target.
2. If it does not appear in the **.SUFFIXES** list, quit the search.
3. If it is in the **.SUFFIXES** list, look for a double suffix rule that matches the target suffix.
4. If you find one; extract the basename of the file, add on the second suffix, and see if the resulting file exists. If it does not, keep searching the double suffix rules. If it does exist, use the recipe for this rule.
5. If no successful match is made, the inference has failed.
6. If the target did not have a suffix, check the single suffix rules in the order that the suffixes are specified in the **.SUFFIXES** target.
7. For each single suffix rule, add the suffix to the target name and see if the resulting file name exists.
8. If the file exists, process the recipe associated with that suffix rule. If the file does not exist, continue trying the rest of the single suffix rules. If no successful match is made, the inference has failed.

Try some experiments with the -v option specified to see how this works.

There is a "special" feature in the suffix rule mechanism that was not described earlier. It is for archive library handling. If you specify a suffix rule of the form:

```
.suf.a:
        recipe
```

the rule matches any target having the **LIBRARYM** attribute set, regardless of the target's actual suffix.

For example, suppose your makefile contains the rules, and **mem.o** exists:

```
.SUFFIXES: .a .o
.o.a:
        echo adding $< to library $@
```

Then, the following command:

```
make "mylib(mem.o)"
```

causes make to print the following line:

```
adding mem.o to library mylib
```

Refer to “Making Libraries” on page 131 for more information about libraries and the .LIBRARY and .LIBRARYM attributes.

Processing Recipes

To update a target, make *expands* and processes a recipe. The expansion process replaces all macros and text diversions within the recipe. Then, make either processes the commands directly, or passes them to a shell.

Regular Recipes

When make calls a regular recipe, it processes each line of the recipe separately (using a new shell for each, if a shell is required). This means that the effect of some commands does not persist across recipe lines. For example, a change directory (cd) request in a recipe line changes only the current working directory for that recipe line. The next recipe line reverts to the previous working directory.

The value of the macro SHELLMETAS determines whether make uses a shell to process a command. If make finds any character in the value of SHELLMETAS in the expanded recipe line, it passes the command to a shell for processing; otherwise, it processes the command directly. Also, if the makefile contains the .POSIX target, make always uses the shell to process recipe lines.

To force make to use a shell, you can add characters from SHELLMETAS to the recipe line.

The value of the macro SHELL determines the shell that make uses for processing. The value of the macro SHELLFLAGS provides the options that make passes to the shell. Therefore, the command that make uses to run the expanded recipe line is:

```
$(SHELL) -$(SHELLFLAGS) expanded_recipe_line
```

When make is about to call a recipe line, it usually writes the line to the standard output. If the .SILENT attribute is set for the target or the recipe line (using **@**), make does not echo the line.

group recipes

Group recipe processing is similar to that of regular recipes, except that make always calls a shell. make writes the entire group recipe to a temporary file, with a suffix provided by the GROUPSUFFIX macro. make then submits this temporary file to a command interpreter for processing. The value of GROUPSHELL provides the appropriate command interpreter, and make provides the flags from the value of GROUPFLAGS.

If you have set the .PROLOG attribute for the target being made, make adds the recipe associated with the special target .GROUPPROLOG at the beginning of the group recipe. If you have also set the .EPILOG attribute, make adds the recipe associated with the special target .GROUPEPILOG onto the end of the group recipe. You can use this facility to append a common header or trailer to group recipes.

make echoes group recipes to standard output just like standard recipes. You indicate group recipes by enclosing them with lines beginning with [and].

Making Libraries

A library is a file containing a collection of object files. To make a library, specify the library as a target with the .LIBRARY attribute, and give as prerequisites the object files that you want to make members. If you specify the prerequisites in the form:

```
name (member)
```

then make automatically sets the .LIBRARY attribute for the target, and interprets the *member* inside the parentheses as a prerequisite of the library target.

make gives the prerequisites of a .LIBRARY target the .LIBRARYM attribute. The library name is also internally associated with the prerequisites. This lets the file binding mechanism look for the member in an appropriate library if an object file cannot be found.

Using these features, you can write:

```
mylib$A : mylib$A(mem1$O) mylib$A(mem2$O)
    recipe for making library
```

Note that make gives the **A** macro the same value as the LIBSUFFIX macro in the startup file.

If a target or prerequisite has the form:

```
name((entry))
```

make gives the *entry* the .SYMBOL attribute, and gives the target *name* the .LIBRARY attribute. make then searches the library for the entry point, and returns not only the modification time of the member which defines the entry, but also the name of the member file. This name then replaces *entry*, and make uses it for making the member file. After being bound to a library member, make removes the .SYMBOL attribute from the target.

Metarules for Library Support

The startup file defines several macros and metarules that are useful in manipulating libraries. LIBSUFFIX and A both give the standard suffix for a library, and O gives the standard suffix for an object file. The AR macro specifies the librarian program. By default, the macro contains the ar program provided with make. By default, ARFLAGS contains the string -ruv. These flags cause ar to update the library with all the specified members that have changed after the library was last updated. (For further information on ar, see *z/VM: OpenExtensions Commands Reference*.)

The startup file contains the following metarule:

```
%$(LIBSUFFIX) .LIBRARY .PRECIOUS :
    $(AR) $(ARFLAGS) $@ $?
```

With this metarule, you need not directly use the ar command in your makefile. make automatically rebuilds a library with the appropriate suffix when any of the prerequisite object modules are out of date.

As an example of the effect of this metarule, suppose that a makefile contains:

```
lib$A .LIBRARY : mod1$O mod2$O mod3$O
```

make gives the .LIBRARY attribute to the lib$A target, so the metarule applies:

```
make lib.a
```

The startup file contains a metarule for making processable files from object files. This metarule adds the value of the macro LDLIBS as a list of libraries to be linked with the object files. If you have several programs, all of which depend on the same library, you can add the name of your library to the definition of LDLIBS, and automatically get it linked when using the metarule. For example, assume this metarule for your compiler:

```
%$E : %$O
    $(LD) $(LDFLAGS) -o $@ $< $(LDLIBS)
```

You can add the following lines to your makefile:

```
LDLIBS += mylib$A
program1$E : mylib$A
program2$E : mylib$A
```

The first line adds mylib$A to the current definition of LDLIBS. Subsequent lines describe the programs you want to build using this library; because a recipe is not given, make uses the metarule from the startup file to relink the programs. Thus, the command:

```
make program1
```

remakes the library **mylib.a** if required, and then relinks **program1** from **program1.o** using the libraries specified in LDLIBS.

Compatibility Considerations

make attempts to remain compatible with versions of make found on UNIX and POSIX-conforming systems, while meeting the needs of differing environments. This section examines ways in which make may differ from traditional versions.

Conditionals let you selectively include or exclude parts of a makefile. This lets you write rules that have different formats for different systems.

Note: Traditional implementations of make do not recognize conditionals. They are extensions to the POSIX standard.

A conditional has the following format:

```
.IF expression
input1
.ELSIF expression
input2
.ELSE
input3
.END
```

The *expression* has one of the following forms:

```
text
text == text
text != text
```

The value of the first form is *true* if the given text is not null; otherwise, it is *false*. The value of the second form is *true* if the two pieces of text are equal, and the value of the last form is *true* if the two pieces of text are not equal.

When make encounters a conditional construct, it begins by evaluating the *expression* after the .IF. If the value of the expression is *true,* make processes the first piece of input (*input1*) and ignores the second; if the value is *false,* make processes the second (*input2*) and ignores the first. Otherwise, it processes the third input.

The .IF , .ELSE , .ELSIF, and .END keywords must begin in the first column of an input line (no preceding white space).

You may be used to indenting material inside `if-else` constructs; however, you should *not* use tabs to indent text inside conditionals (except, of course, for recipe lines, which are always indented with tabs). The text inside the conditional should have the same form that you would use outside the conditional.

You can omit the .ELSE part of a conditional.

BSD UNIX make

The following is a list of the notable differences between OpenExtensions `make` and the 4.2 or 4.3 BSD UNIX version of `make`.

- BSD UNIX `make` supports wildcard file name expansion for prerequisite names. Thus, if a directory contains **a.h**, **b.h**, and **c.h**, BSD UNIX `make` performs the following expansion:

  ```
  target: *.h    expands to    target: a.h b.h c.h
  ```

  OpenExtensions `make` does not support this type of file name expansion.
- Unlike BSD UNIX `make`, *touching* library members causes `make` to search the library for the member name and to update the time stamp if the member is found.
- OpenExtensions `make` does not support the BSD **VPATH** variable. A similar and more powerful facility is provided through the .SOURCE special target.

System V AUGMAKE

The following special features have been implemented for `make` to be more compatible with System V AUGMAKE:

- You can use the word `include` at the start of a line instead of the .INCLUDE: construct that is usually understood by `make`.
- `make` supports the macro modifier expression `$(macro:str=sub)` for suffix changes.
- When defining special targets for the suffix rules, the special target **.X** is equivalent to **.X.NULL**.
- `make` supports both the:

  ```
  lib(member)
  ```

  and:

  ```
  lib((entry))
  ```

  library handling features of AUGMAKE.
- The startup file contains the following definitions for AUGMAKE compatibility:

  ```
  @B = $(@:b)
  @D = $(@:d)
  @F = $(@:f)
  ?B = $(?:b)
  ?D = $(?:d)
  ?F = $(?:f)
  *B = $(*:b)
  *D = $(*:d)
  *F = $(*:f)
  <B = $(<:b)
  <D = $(<:d)
  <F = $(<:f)
  ```

  This means that AUGMAKE constructs such as `$(@F)` work as expected.

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Acknowledgements

The `lex`, `yacc`, and `make` utilities of the OpenExtensions Shell and Utilities are InterOpen source code products licensed from Mortice Kern Systems (MKS) Inc. of Waterloo, Ontario, Canada. These utilities complement the InterOpen/POSIX Shell and Utilities source code product providing POSIX.2 functionality to the OpenExtensions services offered with z/VM.

The OpenExtensions `lex` utility is based on a similar program written by Charles Forsyth at the University of Waterloo (in Ontario, Canada) and described in an unpublished paper, "A Lexical Analyzer Generator" (1978). The implementation is loosely based on the description and suggestions in the book *Compilers, Principles, Techniques, and Tools*, by A. V. Aho, Ravi Sethi, and J. D. Ullman (Addison-Wesley, 1986).

Information in this document has been adapted from the *InterOpen/POSIX Shell and Utilities User Manual*, supplied by Mortice Kern Systems (MKS) Inc. for use by licensees of their InterOpen/POSIX Shell and Utilities source code product.

Bibliography

This topic lists the publications in the z/VM library. For abstracts of the z/VM publications, see *z/VM: General Information*.

Where to Get z/VM Information

The current z/VM product documentation is available in IBM Documentation - z/VM (https://www.ibm.com/docs/en/zvm).

z/VM Base Library

Overview

- *z/VM: License Information*, GI13-4377
- *z/VM: General Information*, GC24-6286

Installation, Migration, and Service

- *z/VM: Installation Guide*, GC24-6292
- *z/VM: Migration Guide*, GC24-6294
- *z/VM: Service Guide*, GC24-6325
- *z/VM: VMSES/E Introduction and Reference*, GC24-6336

Planning and Administration

- *z/VM: CMS File Pool Planning, Administration, and Operation*, SC24-6261
- *z/VM: CMS Planning and Administration*, SC24-6264
- *z/VM: Connectivity*, SC24-6267
- *z/VM: CP Planning and Administration*, SC24-6271
- *z/VM: Getting Started with Linux on IBM Z*, SC24-6287
- *z/VM: Group Control System*, SC24-6289
- *z/VM: I/O Configuration*, SC24-6291
- *z/VM: Running Guest Operating Systems*, SC24-6321
- *z/VM: Saved Segments Planning and Administration*, SC24-6322
- *z/VM: Secure Configuration Guide*, SC24-6323

Customization and Tuning

- *z/VM: CP Exit Customization*, SC24-6269
- *z/VM: Performance*, SC24-6301

Operation and Use

- *z/VM: CMS Commands and Utilities Reference*, SC24-6260
- *z/VM: CMS Primer*, SC24-6265
- *z/VM: CMS User's Guide*, SC24-6266
- *z/VM: CP Commands and Utilities Reference*, SC24-6268

- *z/VM: System Operation*, SC24-6326
- *z/VM: Virtual Machine Operation*, SC24-6334
- *z/VM: XEDIT Commands and Macros Reference*, SC24-6337
- *z/VM: XEDIT User's Guide*, SC24-6338

Application Programming

- *z/VM: CMS Application Development Guide*, SC24-6256
- *z/VM: CMS Application Development Guide for Assembler*, SC24-6257
- *z/VM: CMS Application Multitasking*, SC24-6258
- *z/VM: CMS Callable Services Reference*, SC24-6259
- *z/VM: CMS Macros and Functions Reference*, SC24-6262
- *z/VM: CMS Pipelines User's Guide and Reference*, SC24-6252
- *z/VM: CP Programming Services*, SC24-6272
- *z/VM: CPI Communications User's Guide*, SC24-6273
- *z/VM: ESA/XC Principles of Operation*, SC24-6285
- *z/VM: Language Environment User's Guide*, SC24-6293
- *z/VM: OpenExtensions Advanced Application Programming Tools*, SC24-6295
- *z/VM: OpenExtensions Callable Services Reference*, SC24-6296
- *z/VM: OpenExtensions Commands Reference*, SC24-6297
- *z/VM: OpenExtensions POSIX Conformance Document*, GC24-6298
- *z/VM: OpenExtensions User's Guide*, SC24-6299
- *z/VM: Program Management Binder for CMS*, SC24-6304
- *z/VM: Reusable Server Kernel Programmer's Guide and Reference*, SC24-6313
- *z/VM: REXX/VM Reference*, SC24-6314
- *z/VM: REXX/VM User's Guide*, SC24-6315
- *z/VM: Systems Management Application Programming*, SC24-6327
- *z/VM: z/Architecture Extended Configuration (z/XC) Principles of Operation*, SC27-4940

Diagnosis

- *z/VM: CMS and REXX/VM Messages and Codes*, GC24-6255
- *z/VM: CP Messages and Codes*, GC24-6270
- *z/VM: Diagnosis Guide*, GC24-6280
- *z/VM: Dump Viewing Facility*, GC24-6284
- *z/VM: Other Components Messages and Codes*, GC24-6300
- *z/VM: VM Dump Tool*, GC24-6335

z/VM Facilities and Features

Data Facility Storage Management Subsystem for z/VM

- *z/VM: DFSMS/VM Customization*, SC24-6274
- *z/VM: DFSMS/VM Diagnosis Guide*, GC24-6275
- *z/VM: DFSMS/VM Messages and Codes*, GC24-6276
- *z/VM: DFSMS/VM Planning Guide*, SC24-6277

- *z/VM: DFSMS/VM Removable Media Services*, SC24-6278
- *z/VM: DFSMS/VM Storage Administration*, SC24-6279

Directory Maintenance Facility for z/VM

- *z/VM: Directory Maintenance Facility Commands Reference*, SC24-6281
- *z/VM: Directory Maintenance Facility Messages*, GC24-6282
- *z/VM: Directory Maintenance Facility Tailoring and Administration Guide*, SC24-6283

Open Systems Adapter

- Open Systems Adapter/Support Facility on the Hardware Management Console (https://www.ibm.com/docs/en/SSLTBW_2.3.0/pdf/SC14-7580-02.pdf), SC14-7580
- Open Systems Adapter-Express ICC 3215 Support (https://www.ibm.com/docs/en/zos/2.3.0?topic=osa-icc-3215-support), SA23-2247
- Open Systems Adapter Integrated Console Controller User's Guide (https://www.ibm.com/docs/en/SSLTBW_2.3.0/pdf/SC27-9003-02.pdf), SC27-9003
- Open Systems Adapter-Express Customer's Guide and Reference (https://www.ibm.com/docs/en/SSLTBW_2.3.0/pdf/ioa2z1f0.pdf), SA22-7935

Performance Toolkit for z/VM

- *z/VM: Performance Toolkit Guide*, SC24-6302
- *z/VM: Performance Toolkit Reference*, SC24-6303

The following publications contain sections that provide information about z/VM Performance Data Pump, which is licensed with Performance Toolkit for z/VM.

- *z/VM: Performance*, SC24-6301. See z/VM Performance Data Pump.
- *z/VM: Other Components Messages and Codes*, GC24-6300. See Data Pump Messages.

RACF® Security Server for z/VM

- *z/VM: RACF Security Server Auditor's Guide*, SC24-6305
- *z/VM: RACF Security Server Command Language Reference*, SC24-6306
- *z/VM: RACF Security Server Diagnosis Guide*, GC24-6307
- *z/VM: RACF Security Server General User's Guide*, SC24-6308
- *z/VM: RACF Security Server Macros and Interfaces*, SC24-6309
- *z/VM: RACF Security Server Messages and Codes*, GC24-6310
- *z/VM: RACF Security Server Security Administrator's Guide*, SC24-6311
- *z/VM: RACF Security Server System Programmer's Guide*, SC24-6312
- *z/VM: Security Server RACROUTE Macro Reference*, SC24-6324

Remote Spooling Communications Subsystem Networking for z/VM

- *z/VM: RSCS Networking Diagnosis*, GC24-6316
- *z/VM: RSCS Networking Exit Customization*, SC24-6317
- *z/VM: RSCS Networking Messages and Codes*, GC24-6318
- *z/VM: RSCS Networking Operation and Use*, SC24-6319
- *z/VM: RSCS Networking Planning and Configuration*, SC24-6320

TCP/IP for z/VM

- *z/VM: TCP/IP Diagnosis Guide*, GC24-6328
- *z/VM: TCP/IP LDAP Administration Guide*, SC24-6329
- *z/VM: TCP/IP Messages and Codes*, GC24-6330
- *z/VM: TCP/IP Planning and Customization*, SC24-6331
- *z/VM: TCP/IP Programmer's Reference*, SC24-6332
- *z/VM: TCP/IP User's Guide*, SC24-6333

Prerequisite Products

Device Support Facilities

- Device Support Facilities (ICKDSF): User's Guide and Reference (https://www.ibm.com/docs/en/SSLTBW_2.5.0/pdf/ickug00_v2r5.pdf), GC35-0033

Related Products

XL C++ for z/VM

- *XL C/C++ for z/VM: Runtime Library Reference*, SC09-7624
- *XL C/C++ for z/VM: User's Guide*, SC09-7625

z/OS

IBM Documentation - z/OS (https://www.ibm.com/docs/en/zos)

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