Chapter 8

PROGRAM DEVELOPMENT

in the Unix Programming Environment

The UNIX system was originally meant as a program development environment. In this chapter we'll talk about some of the tools that are particularly suited for developing programs. Our vehicle is a substantial program, an interpreter for a programming language comparable in power to BASIC. We chose to implement a language because it's representative of problems encountered in large programs. Furthermore, many programs can profitably be viewed as languages that convert a systematic input into a sequence of actions and outputs, so we want to illustrate the language development tools.

In this chapter, we will cover specific lessons about

– `yacc`, a parser generator, a program that generates a parser from a grammatical description of a language;
– `make`, a program for specifying and controlling the process by which a complicated program is compiled;
– `lex`, a program analogous to `yacc`, for making lexical analyzers.

We also want to convey some notions of how to go about such a project—the importance of starting with something small and letting it grow; language evolution; and the use of tools.

We will describe the implementation of the language in six stages, each of which would be useful even if the development went no further. These stages closely parallel the way that we actually wrote the program.

(1) A four-function calculator, providing `+ - * /` and parentheses, that operates on floating point numbers. One expression is typed on each line; its value is printed immediately.

(2) Variables with names `a` through `z`. This version also has unary minus and some defenses against errors.

(3) Arbitrarily-long variable names, built-in functions for `sin`, `exp`, etc., useful constants like π (spelled `PI` because of typographic limitations), and an exponentiation operator.

(4) A change in internals: code is generated for each statement and subsequently interpreted, rather than being evaluated on the fly. No new features are added, but it leads to (5).

(5) Control flow: `if-else` and `while`, statement grouping with `{` and `}`, and relational operators like `>`, `<=`, etc.

(6) Recursive functions and procedures, with arguments. We also added statements for input and for output of strings as well as numbers.

The resulting language is described in Chapter 9, where it serves as the main example in our presentation of the UNIX document preparation software. Appendix 2 is the reference manual.

This is a very long chapter, because there's a lot of detail involved in getting a non-trivial program written correctly, let alone presented. We are assuming that you understand C, and that you have a copy of the *Unix Programmer's Manual*, Volume 2, close at hand, since we simply don't have space to explain every nuance. Hang in, and be prepared to read the chapter a couple of times. We have also included all of the code for the final version in Appendix 3, so you can see more easily how the pieces fit together.

By the way, we wasted a lot of time debating names for this language but never came up with anything satisfactory. We settled on `hoc`, which stands for "high-order calculator." The versions are thus `hoc1`, `hoc2`, etc.

Stage 1: A four-function calculator

This section describes the implementation of `hoc1`, a program that provides about the same capabilities as a minimal pocket calculator. It has only four functions: `+`, `-`, `*`, and `/`, but it does have parentheses that can be nested arbitrarily deeply, which few pocket calculators provide. If you type an expression followed by RETURN, the anwer will be printed on the next line:

```
$ hoc1
4*3*2
        24
(1+2) * (3+4)
        21
1/2
        0.5
355/113
        3.1415929
-3-4
hoc1: syntax error near line 4    It doesn't have unary minus yet
$
```

Grammars. Ever since Backus-Naur Form was developed for Algol, languages have been described by formal grammars. The grammar for `hoc1` is small and simple in its abstract representation:

```
list:  expr \n
       list expr \n
expr:  NUMBER
       expr + expr
       expr - expr
       expr * expr
       expr / expr
       ( expr )
```

In other words, a `list` is a sequence of expressions, each followed by a newline. An expression is a number, or a pair of expressions joined by an operator, or a parenthesized expression.

This is not complete. Among other things, it does not specify the normal precedence and associativity of the operators, nor does it attach a meaning to any construct. And although `list` is defined in terms of `expr`, and `expr` is defined in terms of `NUMBER`, `NUMBER` itself is nowhere defined. These details have to be filled in to go from a sketch of the language to a working program.

Overview of yacc. `yacc` is a *parser generator*,† that is, a program for converting a grammatical specification of a language like the one above into a parser that will parse statements in the language. `yacc` provides a way to associate meanings with the components of the grammar in such a way that as the parsing takes place, the meaning can be "evaluated" as well. The stages in using `yacc` are the following.

First, a grammar is written, like the one above, but more precise. This specifies the syntax of the language. `yacc` can be used at this stage to warn of errors and ambiguities in the grammar.

Second, each rule or *production* of the grammar can be augmented with an *action*—a statement of what to do when an instance of that grammatical form is found in a program being parsed. The "what to do" part is written in C, with conventions for connecting the grammar to the C code. This defines the semantics of the language.

Third, a *lexical scanner* is needed, which will read the input being parsed and break it up into meaningful chunks for the parser. A `NUMBER` is an example of a lexical chunk that is several characters long; single-character operators like `+` and `*` are also chunks. A lexical chunk is called a *token*.

Finally, a controlling routine is needed, to call the parser that `yacc` built.

`yacc` proceses the grammar and the semantic actions into a parsing function, named `yyparse`, and writes it out as a file of C code. If `yacc` finds no errors, the parser, the lexical analyzer, and the control routines can be compiled, perhaps linked with other C routines, and executed. The operation of this program is to call repeatedly upon the lexical analyzer for tokens, recognize the grammatical (syntactic) structure in the input, and perform the semantic actions as each grammatical rule is recognized. The entry to the lexical analyzer must be named

† `yacc` stands for "yet another compiler-compiler," a comment by its creator, Steve Johnson, on the number of such programs extant at the time it was being developed (around 1972). `yacc` is one of a handful that have flourished.

`yylex`, since that is the function that `yyparse` calls each time it wants another token. (All names used by `yacc` start with `y`.)

To be somewhat more precise, the input to `yacc` takes this form:

```
%{
C statements like #include, declarations, etc. This section is optional
%}
yacc declarations: lexical tokens, grammar variables,
   precedence and associativity information
%%
grammar rules and actions
%%
more C statements (optional):
main() { ...; yyparse(); ... }
yylex() { ... }
...
```

This is processed by `yacc` and the result is written into a file called `y.tab.c`, whose layout is like this:

```
C statements from between %{ and %}, if any
C statements from after second %%, if any:
main() { ...; yyparse(); ...  }
yylex() { ...  }
...
yyparse() { parser, which calls yylex() }
```

It is typical of the UNIX approach that `yacc` produces C instead of a compiled object (`.o`) file. This is the most flexible arrangement—the generated code is portable and amenable to other processing whenever someone has a good idea.

`yacc` itself is a powerful tool. It takes some effort to learn, but the effort is repaid many times over. `yacc`-generated parsers are small, efficient, and correct (though the semantic actions are your own responsibility); many nasty parsing problems are taken care of automatically. Language-recognizing programs are easy to build, and (probably more important) can be modified repeatedly as the language definition evolves.

Stage 1 program. The source code for `hoc1` consists of a grammar with actions, a lexical routine `yylex`, and a `main`, all in one file `hoc.y`. (`yacc` filenames traditionally end in `.y`, but this convention is not enforced by `yacc` itself, unlike `cc` with `.c` files) The grammar part is the first half of `hoc.y`:

```
%{
#include <stdio.h>        includes needed for code later on
#include <ctype.h>

#define YYSTYPE double    /* data type of yacc stack */
%}
```

```
%token  NUMBER
%left   '+' '-'   /* left associative, same precedence */
%left   '*' '/'   /* left associative, higher precedence */
%%
list:     /* nothing */
        | list '\n'
        | list expr '\n'  { printf("\t%.8g\n", $2); }
        ;
expr:     NUMBER          { $$ = $1; }
        | expr '+' expr   { $$ = $1 + $3; }
        | expr '-' expr   { $$ = $1 - $3; }
        | expr '*' expr   { $$ = $1 * $3; }
        | expr '/' expr   { $$ = $1 / $3; }
        | '(' expr ')'    { $$ = $2; }
        ;
%%
        /* end of grammar */
...
```

There's a lot of new information packed into these few lines. We are not going to explain all of it, and certainly not how the parser works—for that, you will have to read the `yacc` manual.

Alternate rules are separated by '`|`'. Any grammar rule can have an associated action, which will be performed when an instance of that rule is recognized in the input. An action is a sequence of C statements enclosed in braces `{` and `}`. Within an action, `$`*n* (that is, `$1`, `$2`, etc.) refers to the value returned by the *n*th component of the rule, and `$$` is the value to be returned as the value of the whole rule. So for example, in the rule

```
expr:  NUMBER  { $$ = $1; }
```

`$1` is the value returned by recognizing `NUMBER`; that value is to be returned as the value of the `expr`. The particular assignment `$$=$1` can be omitted—`$$` is always set to `$1` unless you explicitly set it to something else.

At the next level, when the rule is

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

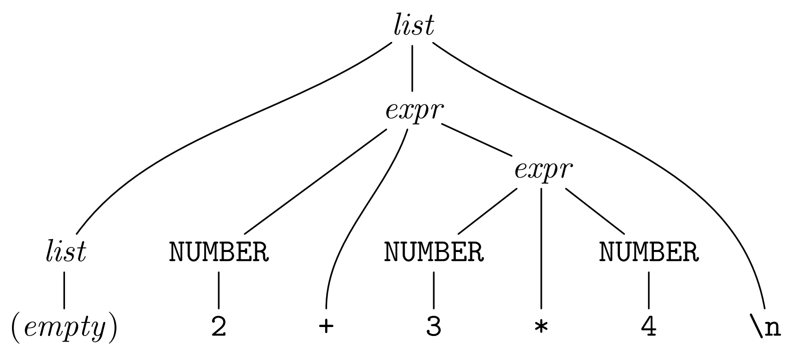
the value of the result `expr` is the sum of the values from the two component `expr`'s. Notice that `'+'` is `$2`; every component is numbered.

At the level above this, an expression followed by a newline `'\n'` is recognized as a list and its value is printed. If the end of the input follows such a construction, the parsing process terminates cleanly. A `list` can be an empty string; this is how blank input lines are handled.

`yacc` input is free form; our format is the recommended standard.

In this implementation, the act of recognizing or parsing the input also causes immediate evaluation of the expression. In more complicated situations (including `hoc4` and its successors), the parsing process generates code for later execution.

You may find it helpful to visualize parsing as drawing a *parse tree* like the one in the figure, and to imagine values being computed and propagated up the tree from the leaves towards the root. Here is the parse tree for `2 + 3 * 4`:



The values of incompletely-recognized rules are actually kept on a stack; this is how the values are passed from one rule to the next. The data type of this stack is normally an `int`, but since we are processing floating point numbers, we have to override the default. The definition

```
#define YYSTYPE double
```

sets the stack type to `double`.

Syntactic classes that will be recognized by the lexical analyzer have to be declared unless they are single character literals like `+` and `-`. The declaration `%token` declares one or more such objects. Left or right associativity can be specified if appropriate by using `%left` or `%right` instead of `%token`. (Left associativity means that `a-b-c` will be parsed as `(a-b)-c` instead of `a-(b-c)`.) Precedence is determined by order of appearance: tokens in the same declaration are at the same level of precedence; tokens declared later are of higher precedence. In this way the grammar proper is ambiguous (that is, there are multiple ways to parse some inputs), but the extra information in the declarations resolves the ambiguity.

The rest of the code is the routines in the second half of the file `hoc.y`:

```
char    *progname;       /* for error messages */
int     lineno = 1;

int main(int argc, char *argv[])  /* hoc1 */
{
        progname = argv[0];
        yyparse();
        return 0;
}
```

`main` calls `yyparse` to parse the input. Looping from one expression to the next is done entirely within the grammar, by the sequence of productions for `list`. It would have been equally acceptable to put a loop around the call to `yyparse` in `main` and have the action for `list` print the value and return immediately.

`yyparse` in turn calls `yylex` repeatedly for input tokens. Our `yylex` is easy: it skips blanks and tabs, converts strings of digits into a numeric value, counts input lines for error reporting, and returns any other character as itself. Since the grammar expects to see only `+`, `-`, `*`, `/`, `(`, `)`, and `\n`, any other character will cause `yyparse` to report an error. Returning a `0` signals "end of file" to `yyparse`.

```
int yylex(void)  /* hoc1 */
{
        int c;
        while ((c=getchar()) == ' ' || c == '\t')
                ;
        if (c == EOF)
                return 0;
        if (c == '.' || isdigit(c)) {   /* number */
                ungetc(c, stdin);
                scanf("%lf", &yylval);
                return NUMBER;
        }
        if (c == '\n')
                lineno++;
        return c;
}
```

The variable `yylval` is used for communication between the parser and the lexical analyzer; it is defined by `yyparse`, and has the same type as the `yacc` stack. `yylex` returns the *type* of a token as its function value, and sets `yylval` to the *value* of the token (if there is one). For instance, a floating point number has the type `NUMBER` and a value like 12.34. For some tokens, especially single characters like `'+'` and `'\n'`, the grammar does not use the value, only the type. In that case, `yylval` need not be set.

The `yacc` declaration `%token NUMBER` is converted into a `#define` statement in the `yacc` output file `y.tab.c`, so `NUMBER` can be used as a constant anywhere in the C program. `yacc` chooses values that won't collide with ASCII characters.

If there is a syntax error, `yyparse` calls `yyerror` with a string containing the cryptic message "`syntax error`." The `yacc` user is expected to provide a `yyerror`; ours just passes the string on to another function, `warning`, which prints somewhat more information. Later versions of `hoc` will make direct use of `warning`.

```
void yyerror(char *s)  /* called for yacc syntax error */
{
        warning(s, 0);
}

void warning(char *s, char *t)  /* print warning message */
{
        fprintf(stderr, "%s: %s", progname, s);
        if (t) fprintf(stderr, " %s", t);
        fprintf(stderr, " near line %d\n", lineno);
}
```

This marks the end of the routines in `hoc.y`.

Compilation of a `yacc` program is a two-step process:

```
$ yacc hoc.y              Leaves output in  y.tab.c
$ cc y.tab.c -o hoc1      Leaves executable program in  hoc1
$ hoc1
2/3
        0.66666667
-3-4
hoc1: syntax error near line 1
$
```

Exercise 8-1. Examine the structure of the `y.tab.c` file. □

Making changes—unary minus. We claimed earlier that using `yacc` makes it easy to change a language. As an illustration, let's add unary minus to `hoc1`, so that expressions like `-3-4` are evaluated, not rejected as syntax errors.

Exactly two lines have to be added to `hoc.y`. A new token `UNARYMINUS` is added to the end of the precedence section, to make unary minus have highest precedence:

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

The grammar is augmented with one more production for `expr`:

```
expr:    NUMBER                         { $$ = $1; }
       | '-' expr  %prec UNARYMINUS  { $$ = -$2; }  /* new */
```

The `%prec` says that a unary minus sign (that is, a minus sign before an expression) has the precedence of `UNARYMINUS` (high); the action is to change the sign. A minus sign between two expressions takes the default precedence.

Exercise 8-2. Add the operators `%` (modulus or remainder) and unary `+` to `hoc1`. Suggestion: look at `frexp`(3) [or rather `fmod`(3)]. □

A digression on `make`. It's a nuisance to have to type two commands to compile a new version of `hoc1`. Although it's certainly easy to make a shell file that does the job, there's a better way, one that will generalize nicely later on when there is more than one source file in the program. The program `make` reads a specification of how the components of a program depend on each other, and how to process them to create an up-to-date version of the program. It checks the times at which the various components were last modified, figures out the minimum amount of recompilation that has to be done to make a consistent new version, then runs the processes. `make` also understands the intricacies of multi-step processes like `yacc`, so these tasks can be put into a `make` specification without spelling out the individual steps.

`make` is most useful when the program being created is large enough to be spread over several source files, but it's handy even for something as small as `hoc1`. Here is the `make` specification for `hoc1`, which `make` expects in a file called `makefile` [or `Makefile`].

```
hoc1: hoc.o
        $(CC) $(CFLAGS) hoc.o -o hoc1
```

The second line is indented with a tab, not with blanks! This makefile says that `hoc1` depends on `hoc.o`, and that `hoc.o` is converted into `hoc1` by running the C compiler and putting the output in `hoc1`. `make` already knows how to convert the `yacc` source file in `hoc.y` to an object file `hoc.o`:

```
$ make                    Make the first thing in Makefile, hoc1
yacc hoc.y
cc -c y.tab.c
rm y.tab.c
mv y.tab.o hoc.o
cc hoc.o -o hoc1
$ make                    Do it again
‘hoc1’ is up to date.     make realizes it’s unnecessary
$
```

Stage 2: Variables and error recovery

The next step (a small one) is to add “memory” to `hoc1`, to make `hoc2`. The memory has 26 variables, named `a` to `z`. This isn’t very elegant, but it’s an easy and useful intermediate step. We’ll also add some error handling. If you try `hoc1`, you’ll recognize that its approach to syntax errors is to print a message and die, and its treatment of arithmetic errors like division by zero is reprehensible:

```
$ hoc1
1/0
Floating exception - core dumped
$
```

The changes needed for these new features are modest, about 35 lines of code. The lexical analyzer `yylex` has to recognize letters as variables; the grammar has to include productions of the form

```
expr:   VAR
      | VAR ’=’ expr
```

An expression can contain an assignment, which permits multiple assignments like

```
x = y = z = 0
```

The easiest way to store the values of the variables is in a 26-element array; the single-letter variable name can be used to index the array. But if the grammar is to process both variable names and values in the same stack, `yacc` has to be told that its stack contains a union of a `double` and an `int`, not just a `double`. This is done with the `%union` declaration near the top. A `#define` or a `typedef` is fine for setting the stack to a basic type like `double`, but the `%union` mechanism is required for union types because `yacc` checks for consistency in expressions like `$$=$2`.

Here is the grammar part of `hoc.y` for `hoc2`:

```
%{
double mem[26];          /* memory for variables 'a' to 'z' */
%}
%union {
        double  val;     /* actual value */
        int     index;   /* index into mem[] */
}
%token  <val>   NUMBER
%token  <index> VAR      /* VAR is index member of union */
%type   <val>   expr     /* expr is val member of union */
%right  '='
%left   '+' '-'
%left   '*' '/'
%left   UNARYPM
%%
list:     /* nothing */
        | list '\n'
        | list expr '\n'      { printf("\t%.8g\n", $2); }
        | list error '\n'     { yyerrok; }
        ;
expr:     NUMBER
        | VAR            { $$ = mem[$1]; }
        | VAR '=' expr   { $$ = mem[$1] = $3; }
        | expr '+' expr  { $$ = $1 + $3; }
        | expr '-' expr  { $$ = $1 - $3; }
        | expr '*' expr  { $$ = $1 * $3; }
        | expr '/' expr  { if ($3 == 0.0)
                              execerror("division by zero", "");
                            $$ = $1 / $3; }
        | '(' expr ')'   { $$ = $2; }
        | '-' expr  %prec UNARYPM  { $$ = -$2; }
        ;
%%
        /* end of grammar */
...
```

The `%union` says that stack elements hold either a `double` (a number, the usual case), or an `int`, which is an index into the array `mem`. The `%token` declarations have been augmented with a type indicator. The `%type` declaration specifies that `expr` is the `<val>` member of the union, i.e., a `double`. The type information makes it possible for `yacc` to generate references to the corect members of the union. Notice also that `=` is right-associative, while the other operators are left-associative.

Error handling comes in several pieces. The obvious one is a test for a zero divisor; if one occurs, an error routine `execerror` is called.

A second test is to catch the "floating point exception" signal that occurs when a floating point number overflows. The signal is set in `main`.

The final part of error recovery is the addition of a production for `error`. "`error`" is a reserved word in a `yacc` grammar; it provides a way to anticipate and recover from a syntax error. If an error occurs, `yacc` will eventually try to use this production, recognize the error as grammatically "correct," and thus recover. The action `yyerrok` sets a flag in the parser that permits it to get back into a sensible parsing state. Error recovery is difficult in any parser; you should be aware that we have taken only the most elementary steps here, and have skipped rapidly over `yacc`'s capabilities as well.

The actions in the `hoc2` grammar are not much changed. Here is `main`, to which we have added `setjmp` to save a clean state suitable for resuming after an error. `execerror` does the matching `longjmp`.

```
...
#include <signal.h>
#include <setjmp.h>
jmp_buf begin;

int main(int argc, char *argv[])  /* hoc2 */
{
        void fpecatch(int);

        progname = argv[0];
        setjmp(begin);
        signal(SIGFPE, fpecatch);
        yyparse();
        return 0;
}

void execerror(char *s, char *t)  /* run-time error recovery */
{
        warning(s, t);
        longjmp(begin, 0);
}

void fpecatch(int signum)  /* catch floating point exceptions */
{
        execerror("floating point exception", (char *) 0);
}
```

For debugging, we found it convenient to have `execerror` call `abort`(3), which causes a core dump that can be perused with `adb` or `sdb` [or `gdb`]. Once the program is fairly robust, `abort` is replaced by `longjmp`.

The lexical analyzer is a little different in `hoc2`. There is an extra test for a lower-case letter, and since `yylval` is now a union, the proper member has to be set before `yylex` returns. Here are the parts that have changed:

```
int yylex(void)  /* hoc2 */
...
```

```
        if (c == '.' || isdigit(c)) {  /* number */
                ungetc(c, stdin);
                scanf("%lf", &yylval.val);
                return NUMBER;
        }
        if (islower(c)) {
                yylval.index = c - 'a';  /* ASCII only */
                return VAR;
        }
...
```

Again, notice how the token type (e.g., `NUMBER`) is distinct from its value (e.g., 3.1416);

Let us illustrate variables and error recovery, the new things in `hoc2`:

```
$ hoc2
x = 355
        355
y = 113
        113
p = x/z                              z is undefined and thus zero
hoc2: division by zero near line 4        Error recovery
x/y
        3.1415929
1e30 * 1e30                               Overflow
hoc2: floating point exception near line 5
...
```

Actually, the PDP-11 requires special arrangements to detect floating point overflow, but on most other machines `hoc2` behaves as shown.

Exercise 8-3. Add a facility for remembering the most recent value computed, so that it does not have to be retyped in a sequence of related computations. One solution is to make it one of the variables, for instance '`p`' for 'previous.' □

Exercise 8-4. Modify `hoc` so that a semicolon can be used as an expression terminator equivalent to a newline. □

Stage 3: Arbitrary variable names; built-in functions

This version, `hoc3`, adds several major new capabilities, and a corresponding amount of extra code. The main feature is access to built-in functions:

```
sin   cos   atan   exp   log   log10   sqrt   int   abs
```

We have also added an exponentiation operator '`^`'; it has the highest precendence, and is right-associative.

Since the lexical analyzer has to cope with built-in names longer than a single character, it isn't much extra effort to permit variable names to be arbitrarily long as well. We will need a more sophisticated symbol table to keep track of these variables, but once we have it, we can pre-load it with names and values for some useful constants:

`DEG`	57.29577951308232087680	$180/\pi$, degrees per radian
`E`	2.71828182845904523536	e, base of natural logarithms
`GAMMA`	0.57721566490153286060	γ, Euler-Mascheroni constant
`PHI`	1.61803398874989484820	$(\sqrt{5}+1)/2$, the golden ratio
`PI`	3.14159265358979323846	π, circular transcendental number

The result is a useful calculator:

```
$ hoc3
1.5^2.3
        2.5410306
exp(2.3*log(1.5))
        2.5410306
sin(PI/2)
        1
atan(1)*DEG
        45
...
```

We have also cleaned up the behavior a little. In `hoc2`, the assignment `x=`*expr* not only causes the assignment but also prints the value, because all expressions are printed:

```
$ hoc2
x = 2 * 3.14159
        6.28318           Value printed for assignment to variable
```

In `hoc3`, a distinction is made between assignments and expressions; values are printed only for expressions:

```
$ hoc3
x = 2 * 3.14159          Assignment: no value is printed
x                        Expression:
        6.28318            value is printed
```

The program that results from all these changes is big enough (about 250 lines) that it is best split into separate files for easier editing and faster compilation. There are now five files instead of one:

`hoc.y`	Grammar, `main`, `yylex` (as before)
`hoc.h`	Global data structures for inclusion
`symbol.c`	Symbol table routines: `lookup`, `install`
`init.c`	Built-ins and constants: `init`
`math.c`	Interfaces to math routines: `Sqrt`, `Log`, etc.

This requires that we learn more about how to organize a multi-file C program, and more about `make` so it can do some of the work for us.

We'll get back to `make` shortly. First, let us look at the symbol table code. A symbol has a name, a type (it's either a `VAR` or a `BLTIN`), and a value. If the symbol is a `VAR`, the value is a `double`; if the symbol is a built-in, the value is a pointer to a function that returns a `double`. This information is needed in `hoc.y`, `symbol.c`, and `init.c`. We could just make three copies, but it's too easy to make a mistake or forget to update one copy when a change is made. Instead we put the common information into a header file `hoc.h` that will be included by any file that needs it. (The suffix `.h` is conventional but not enforced by any program.) We will also add to the `Makefile` the fact that these files depend on `hoc.h`, so that when it changes, the necessary recompilations are done too. Here is `hoc.h`:

```
typedef struct Symbol {  /* symbol table entry */
        char    *name;
        short   type;           /* VAR, BLTIN, UNDEF */
        union {
                double  val;            /* if VAR */
                double  (*ptr)();       /* if BLTIN */
        } u;
        struct Symbol   *next;  /* to link to another */
} Symbol;

Symbol *install(char *s, int t, double d);
Symbol *lookup(char *s);

void init(void);
void execerror(char *s, char *t);
```

The type `UNDEF` is a `VAR` that has not yet been assigned a value.

The symbols are linked together in a list using the `next` field in `Symbol`. The list itself is local to `symbol.c`; the only access to it is through the functions `lookup` and `install`. This makes it easy to change the symbol table organization if it becomes necessary. (We did that once.) `lookup` searches the list for a particular name and returns a pointer to the `Symbol` with that name if found, and zero otherwise. The symbol table uses linear search, which is entirely adequate for our interactive calculator, since variables are looked up only during parsing, not execution. `install` puts a variable with its associated type and value at the head of the list. `emalloc` calls `malloc`(3), the standard storage allocator, and checks the result. These three routines are the contents of `symbol.c`. The file `y.tab.h` is generated by running `yacc -d`; it contains `#define` statements that `yacc` has generated for tokens like `NUMBER`, `VAR`, `BLTIN`, etc. Here is `symbol.c`:

```
#include "hoc.h"
#include "y.tab.h"
#include <stdlib.h>
#include <string.h>

void *emalloc(unsigned nbytes);

static Symbol *symlist = 0;  /* symbol table: linked list */

Symbol *lookup(char *s)  /* find s in symbol table */
{
        Symbol *sp;
        for (sp = symlist; sp; sp = sp->next)
                if (strcmp(sp->name, s) == 0)
                        return sp;
        return 0;  /* not found */
}

Symbol *install(char *s, int t, double d)  /* add s to symtab */
{
        Symbol *sp = emalloc(sizeof(Symbol));
        sp->name = emalloc(strlen(s)+1);  /* +1 for '\0' */
        strcpy(sp->name, s);
        sp->type = t;
        sp->u.val = d;
        sp->next = symlist;  /* put at front of list */
        symlist = sp;
        return sp;
}

void *emalloc(unsigned nbytes)  /* check return from malloc */
{
        void *p = malloc(nbytes);
        if (!p) execerror("out of memory", 0);
        return p;
}
```

The file `init.c` contains definitions for the constants (`PI`, etc.) and function pointers for built-ins; they are installed in the symbol table by the function `init`, which is called by `main`. Here is `init.c`:

```
#include "hoc.h"
#include "y.tab.h"
#include <math.h>

extern double Log(), Log10(), Exp(), Sqrt(), integer();
```

```
static struct {         /* Constants */
    char    *name;
    double  cval;
} consts[] = {
    { "PI",    3.14159265358979323846 },
    { "E",     2.71828182845904523536 },
    { "GAMMA", 0.57721566490153286060 },  /* Euler */
    { "DEG",  57.29577951308232087680 },  /* deg/radian */
    { "PHI",   1.61803398874989484820 },  /* golden ratio */
    { 0,       0 }
};

static struct {         /* Built-ins */
    char    *name;
    double  (*func)();
} builtins[] = {
    { "sin",    sin     },
    { "cos",    cos     },
    { "atan",   atan    },
    { "log",    Log     },  /* checks argument */
    { "log10",  Log10   },  /* checks argument */
    { "exp",    Exp     },  /* checks argument */
    { "sqrt",   Sqrt    },  /* checks argument */
    { "int",    integer },
    { "abs",    fabs    },
    { 0,        0       }
};

void init(void)  /* install constants and built-ins in symtab */
{
        int i;
        Symbol *sp;

        for (i = 0; consts[i].name; i++)
                install(consts[i].name, VAR, consts[i].cval);
        for (i = 0; builtins[i].name; i++) {
                sp = install(builtins[i].name, BLTIN, 0.0);
                sp->u.ptr = builtins[i].func;
        }
}
```

The data is kept in tables rather than being wired into the code because tables are easier to read and to change. The tables are declared `static` so that they are visible only within this file rather than throughout the program. We'll come back to the math routines like `Log` and `Sqrt` shortly.

With the foundation in place, we can move on to the changes in the grammar that make use of it. Here is `hoc.y`:

```
%{
#include "hoc.h"
#include <stdio.h>
extern double Pow();
%}
%union {
        double  val;    /* actual value */
        Symbol *sym;    /* symbol table pointer */
}
%token  <val>   NUMBER
%token  <sym>   VAR BLTIN UNDEF
%token  <val>   expr asgn
%right  '='
%left   '+' '-'
%left   '*' '/'
%left   UNARYPM
%right  '^'     /* exponentiation */
%%
list:     /* nothing */
        | list       '\n'
        | list asgn  '\n'
        | list expr  '\n'    { printf("\t%.8g\n", $2); }
        | list error '\n'    { yyerrok; }
        ;
asgn:     VAR '=' expr  { $$ = $1->u.val = $3; $1->type = VAR; }
        ;
expr:     NUMBER
        | VAR { if ($1->type == UNDEF)
                    execerror("undefined variable", $1->name);
                $$ = $1->u.val; }
        | asgn
        | BLTIN '(' expr ')'  { $$ = (*($1->u.ptr))($3); }
        | expr '+' expr  { $$ = $1 + $3; }
        | expr '-' expr  { $$ = $1 - $3; }
        | expr '*' expr  { $$ = $1 * $3; }
        | expr '/' expr  { if ($3 == 0.0)
                              execerror("division by zero", "");
                           $$ = $1 / $3; }
        | expr '^' expr  { $$ = Pow($1, $3); }
        | '(' expr ')'   { $$ = $2; }
        | '-' expr  %prec UNARYPM  { $$ = -$2; }
        | '+' expr  %prec UNARYPM  { $$ = $2; }
        ;
%%
        /* end of grammar */
...
```

The grammar now has `asgn`, for assignment, as well as `expr`; an input line that contains just

```
VAR = expr
```

is an assignment, and so no value is printed. Notice, by the way, how easy it was to add exponentiation to the grammar, including its right associativity.

The `yacc` stack has a different `%union`: instead of referring to a variable by its index in a 26-element table, there is a pointer to an object of type `Symbol`. The header file `hoc.h` contains the definition of this type.

The lexical analyzer recognizes variable names, looks them up in the symbol table, and decides whether they are variables (`VAR`) or built-ins (`BLTIN`). The type returned by `yylex` is one of these; both user-defined variables and pre-defined variables like `PI` are `VAR`'s.

One of the properties of a variable is whether or not it has been assigned a value, so the use of an undefined variable can be reported as an error by `yyparse`. The test for whether a variable is defined has to be in the grammar, not in the lexical analyzer. When a `VAR` is recognized lexically, its context isn't yet known; we don't want a complaint that `x` is undefined when the context is a perfectly legal one such as the left side of an assignment like `x=1`.

Here is the revised part of `yylex`:

```
int yylex(void)  /* hoc3 */
...
        if (isalpha(c)) {
                Symbol *sp;
                char sbuf[100], *p = sbuf;
                do {
                        *p++ = c;
                } while ((c=getchar()) != EOF && isalnum(c));
                ungetc(c, stdin);
                *p = '\0';
                if ((sp=lookup(sbuf)) == 0)
                        sp = install(sbuf, UNDEF, 0.0);
                yylval.sym = sp;
                return sp->type == UNDEF ? VAR : sp->type;
        }
...
```

[Required exercise: find the buffer overrun bug and fix it!]

`main` has one extra line, which calls the initialization routine `init` to install built-ins and pre-defined names like `PI` in the symbol table. Here it is:

```
#include <setjmp.h>
#include <signal.h>

int main(int argc, char *argv[])  /* hoc3 */
{
        void fpecatch(int);
        progname = argv[0];
        init();
        setjmp(begin);
        signal(SIGFPE, fpecatch);
        yyparse();
        return 0;
}
```

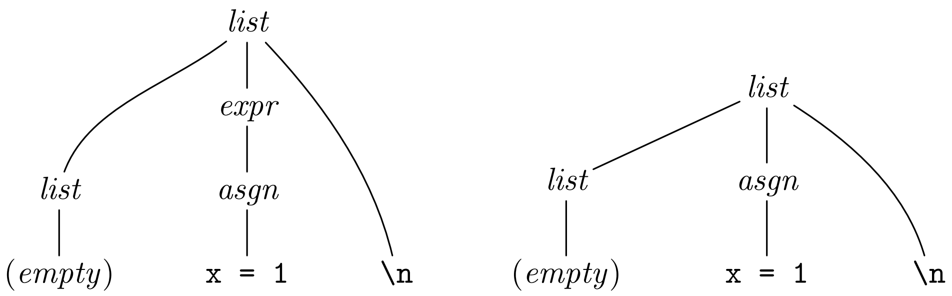
The only remaining file is `math.c`. Some of the standard mathematical functions need an error-checking interface for messages and recovery—for example the standard function `sqrt` silently returns zero if its argument is negative. The code in `math.c` uses the error tests found in Section 2 of the *UNIX Programmer's Manual.* This is more reliable and portable than writing our own tests, since presumably the specific limitations of the routines are best reflected in the "official" code. The header file `<math.h>` contains type declarations for the standard mathematical functions. `<errno.h>` contains names for the errors that can be incurred. Here is `math.c`:

```
#include "hoc.h"
#include <math.h>
#include <errno.h>

double errcheck(double d, char *s);

double Log(double x)   { return errcheck(log(x),   "log");   }
double Log10(double x) { return errcheck(log10(x), "log10"); }
double Exp(double x)   { return errcheck(exp(x),   "exp");   }
double Sqrt(double x)  { return errcheck(sqrt(x),  "sqrt");  }
double Pow(double x, double y) {
                         return errcheck(pow(x,y), "pow");   }

double integer(double x) { return (double)(long) x; }

double errcheck(double d, char *s)
{ /* check result of library call */
        if (errno == EDOM) {
                errno = 0;
                execerror(s, "argument out of domain");
        }
        else if (errno == ERANGE) {
                errno = 0;
                execerror(s, "result out of range");
        }
        return d;
}
```

An interesting (and ungrammatical) diagnostic appears when we run `yacc` on the new grammar:

```
$ yacc hoc.y
conflicts: 1 shift/reduce
$
```

The "shift/reduce" message means that the `hoc3` grammar is ambiguous: the single line of input `x = 1` can be parsed in two ways:



The parser can decide that the *asgn* should be reduced to an *expr* and then to a *list*, as in the parse tree on the left, or it can decide to use the following `\n` immediately ("shift") and convert the whole thing to a *list* without the intermediate rule, as in the tree on the right. Given the ambiguity, `yacc` chooses to shift, since this is almost always the right thing to do with real grammars. You should try to understand such messages, to be sure that `yacc` has made the right decision.† Running `yacc` with the option `-v` produces a voluminous file called `y.output` that hints at the origin of conflicts.

Exercise 8-5. As `hoc3` stands, it's legal to say `PI = 3`. Is this a good idea? How would you change `hoc3` to prohibit assignment to "constants"? □

Exercise 8-6. Add the built-in function `atan2(y,x)`, which returns the angle whose tangent is `y/x`. Add the built-in `rand()`, which returns a floating point random variable uniformly distributed on the interval $(0, 1)$. How do you have to change the grammar to allow for built-ins with different numbers of arguments? □

Exercise 8-7. How would you add a facility to execute commands from within `hoc`, similar to the `!` feature of other UNIX programs? □

Exercise 8-8. Revise the code in `math.c` to use a table instead of the set of essentially identical functions that we presented. □

Another digression on `make`. Since the program for `hoc3` now lives on five files, not one, the `Makefile` is more complicated:

```
YFLAGS = -d                     # force creation of y.tab.h
OBJS = hoc.o init.o math.o symbol.o       # abbreviation

hoc3: $(OBJS)
        $(CC) $(OBJS) -lm -o hoc3
```

† The `yacc` message "reduce/reduce conflict" indicates a serious problem, more often the symptom of an outright error in the grammar than an intentional ambiguity.

```
hoc.o: hoc.h

init.o symbol.o: hoc.h y.tab.h

pr:
        @pr hoc.y hoc.h init.c math.c symbol.c Makefile

clean:
        rm -f $(OBJS) y.tab.[ch]
```

The `YFLAGS = -d` line adds the option `-d` to the `yacc` command line generated by `make`; this tells `yacc` to produce the `y.tab.h` file of `#define` statements. The `OBJS = ...` line defines a shorthand for a construct to be used several times subsequently. The syntax is not the same as for shell variables—the parentheses are mandatory. The flag `-lm` causes the math library to be searched for the mathematical functions.

`hoc3` now depends on four `.o` files; some of the `.o` files depend on `.h` files. Given these dependencies, `make` can deduce what recompilation is needed after changes are made to any of the files involved. If you want to see what `make` will do without actually running the processes, try

```
$ make -n
```

On the other hand, if you want to force the file times into a consistent state, the `-t` ("touch") option will update them without doing any compilation steps.

Notice that we have added not only a set of dependencies for the source files but miscellaneous utility routines as well, all neatly encapsulated in one place. By default, `make` makes the first thing listed in the `Makefile`, but if you name an item that labels a dependency rule, like `symbol.o` or `pr`, that will be made instead. An empty dependency is taken to mean that the item is never "up to date," so that action will always be done when requested. Thus

```
$ make pr | lpr
```

produces the listing you asked for on a line printer. (The leading `@` in "`@pr`" suppresses the echo of the command being executed by `make`.) And

```
$ make clean
```

removes the `yacc` output files and the `.o` files.

This mechanism of empty dependencies in the `Makefile` is often preferable to a shell file as a way to keep all the related computations in a single file. And `make` is not restricted to program development—it is valuable for packaging any set of operations that have time dependencies.

A digression on `lex`. The program `lex` creates lexical analyzers in a manner analogous to the way that `yacc` creates parsers: you write a specification of the lexical rules of your language, using regular expressions and fragments of C to be executed when a matching string is found. `lex` translates that into a recognizer. `lex` and `yacc` cooperate by the same mechanism as the lexical analyzers we have already written. We are not going into great detail on `lex` here; the following discussion is mainly to interest you in learning more.

First, here is the `lex` program, from the file `lex.l`; it replaces the function `yylex` that we have used so far.

```
%{
#include "hoc.h"
#include "y.tab.h"
extern int lineno;
%}
%%
[ \t]   { ; }   /* skip blanks and tabs */
[0-9]+\.?|[0-9]*\.[0-9]+ {
        sscanf(yytext, "%lf", &yylval.val); return NUMBER; }
[a-zA-Z][a-zA-Z0-9]* {
        Symbol *s;
        if ((s = lookup(yytext)) == 0)
                s = install(yytext, UNDEF, 0.0);
        yylval.sym = s;
        return s->type == UNDEF ? VAR : s->type; }
\n      { lineno++; return '\n'; }
.       { return yytext[0]; }   /* everything else */
```

Each "rule" is a regular expression like those in `egrep` or `awk`, except that `lex` recognizes C-style escapes like `\t` and `\n`. The action is enclosed in braces. The rules are attempted in order, and constructs like `*` and `+` match as long a string as possible. If the rule matches the next part of the input, the action is performed. The input string that matched is accessible in a `lex` string called `yytext`.

The `Makefile` has to be changed to use `lex`:

```
YFLAGS = -d
OBJS = hoc.o lex.o init.o math.o symbol.o

hoc3: $(OBJS)
        $(CC) $(OBJS) -lm -ll -o hoc3

hoc.o: hoc.h

lex.o init.o symbol.o: hoc.h y.tab.h
...
```

Again, `make` knows how to get from a `.l` file to the proper `.o`; all it needs from us is the dependency information. (We also have to add the `lex` library `-ll` to the list searched by `cc` since the `lex`-generated recognizer is not self-contained.) The output is spectacular and completely automatic:

```
$ make
yacc -d hoc.y
conflicts: 1 shift/reduce
cc  -c y.tab.c
rm y.tab.c
mv y.tab.o hoc.o
lex  lex.l
```

```
cc  -c lex.yy.c
rm lex.yy.c
mv lex.yy.o lex.o
cc  -c init.c
cc  -c math.c
cc  -c symbol.c
cc hoc.o lex.o init.o math.o symbol.o -lm -ll -o hoc3
$
```

If a signle file is changed, the single command `make` is enough to make an up-to-date version:

```
$ touch lex.l                    Change modified-time of lex.l
$ make
lex  lex.l
cc  -c lex.yy.c
rm lex.yy.c
mv lex.yy.o lex.o
cc hoc.o lex.o init.o math.o symbol.o -lm -ll -o hoc3
$
```

We debated for quite a while whether to treat `lex` as a digression, to be illustrated briefly and then dropped, or as the primary tool for lexical analysis once the language got complicated. There are arguments on both sides. The main problem with `lex` (aside from requiring that the user learn yet another language) is that it tends to be slow to run and to produce bigger and slower recognizers than the equivalent C versions. It is also somewhat harder to adapt its input mechanism if one is doing anything unusual, such as error recovery or even input from files. None of these issues is serious in the context of `hoc`. The main limitation is space: it takes more pages to describe the `lex` version, so (regretfully) we will revert to C for subsequent lexical analysis. It is a good exercise to do the `lex` versions, however.

Exercise 8-9. Compare the sizes of the two versions of `hoc3`. Hint: see `size`(1). □

Stage 4: Compmilation into a machine

We are heading towards `hoc5`, an interpreter for a language with control flow. `hoc4` is an intermediate step, providing the same functions as `hoc3`, but implemented within the interpreter framework of `hoc5`. We actually wrote `hoc4` this way, since it gives us two programs that should behave identically, which is valuable for debugging. As the input is parsed, `hoc4` generates code for a simple computer instead of immediately computing answers. Once the end of a statement is reached, the generated code is executed ("interpreted") to compute the desired result.

The simple computer is a *stack machine*: when an operand is encountered, it is pushed onto a stack (more precisely, code is generated to push it onto a stack); most operators operate on items on the top of the stack. For example, to handle the assignment

```
x = 2 * y
```

the following code is generated:

`constpush`	*Push a constant onto stack*
`  2`	*... the constant* `2`
`varpush`	*Push symbol table pointer onto stack*
`  y`	*... for the variable* `y`
`eval`	*Evaluate: replace pointer by value*
`mul`	*Multiply top two items; product replaces them*
`varpush`	*Push symbol table pointer onto stack*
`  x`	*... for the variable* `x`
`assign`	*Store value in variable, pop pointer*
`pop`	*Clear top value from stack*
`STOP`	*End of instruction sequence*

When this code is executed, the expression is evaluated and the result is stored in `x`, as indicated by the comments. The final `pop` clears the value off the stack because it is not needed any longer.

Stack machines usually result in simple interpreters, and ours is no exception: it's just an array containing operators and operands. The operators are the machine instructions; each is a function call with its arguments, if any, following the instruction. Other operands may already be on the stack, as they were in the example above.

The symbol table code for `hoc4` is identical to that for `hoc3`; the initialization in `init.c` and the mathematical functions in `math.c` are the same as well. The grammar is the same as for `hoc3`, but the actions are quite different. Basically, each action generates machine instructions and any arguments that go with them. For example, three items are generated for a `VAR` in an expression: a `varpush` instruction, the symbol table pointer for the variable, and an `eval` instruction that will replace the symbol table pointer by its value when executed. The code for '`*`' is just `mul`, since the operands for that will already bo on the stack.

```
%{
#include "hoc.h"
#define code2(c1,c2)    code(c1); code(c2)
#define code3(c1,c2,c3) code(c1); code(c2); code(c3)
%}
%union{
        Symbol  *sym;   /* symbol table pointer */
        Inst    *inst;  /* machine instruction */
}
%token  <sym>   NUMBER VAR BLTIN UNDEF
%right  '='
%left   '+' '-'
%left   '*' '-'
%left   UNARYPM
%right  '^'     /* exponentiation */
```

```
%%
list:     /* nothing */
        | list       '\n'
        | list asgn  '\n'  { code2(drop, STOP); return 1; }
        | list expr  '\n'  { code2(print, STOP); return 1; }
        | list error '\n'  { yyerrok; }
        ;
asgn:     VAR '=' expr   { code3(varpush, (Inst)$1, assign); }
        ;
expr:     NUMBER         { code2(constpush, (Inst)$1); }
        | VAR            { code3(varpush, (Inst)$1, eval); }
        | asgn
        | BLTIN '(' expr ')' { code2(bltin, (void*)$1->u.ptr); }
        | expr '+' expr  { code(add); }
        | expr '-' expr  { code(sub); }
        | expr '*' expr  { code(mul); }
        | expr '/' expr  { code(div); }
        | expr '^' expr  { code(power); }
        | '(' expr ')'
        | '-' expr  %prec UNARYPM  { code(negate); }
        | '+' expr  %prec UNARYPM
        ;
%%
        /* end of grammar */
...
```

Inst is the data type of a machine instruction (a pointer to a function returning an void), which we will return to shortly. Notice that the arguments to code are function names, that is, pointers to functions, or other values that are coerced to function pointers.

We have changed main somewhat. The parser now returns after each statement or expression; the code that it generated is executed. yyparse returns zero at end of file.

```
#include <ctype.h>
#include <setjmp.h>
#include <signal.h>
#include <stdio.h>

int main(int argc, char *argv[])  /* hoc4 */
{
        void fpecatch(int);

        progname = argv[0];
        init();
        setjmp(begin);
        signal(SIGFPE, fpecatch);

        for (initcode(); yyparse(); initcode())
                execute(prog);
        return 0;
}
```

The lexical analyzer is only a little different. The main change is that numbers have to be preserved, not used immediately. The easiest way to do this is to install them in the symbol table along with the variables. Here is the changed part of `yylex`:

```
int yylex(void)  /* hoc4 */
...
        if (c == '.' || isdigit(c)) {  /* number */
                double d;
                ungetc(c, stdin);
                scanf("%lf", &d);
                yylval.sym = install("", NUMBER, d);
                return NUMBER;
        }
...
```

Each element on the interpreter stack is either a floating point value or a pointer to a symbol table entry; the stack data type is a union of these. The machine itself is an array of pointers that point either to routines like `mul` that perform an operation, or to data in the symbol table. The header file `hoc.h` has to be augmented to include these data structures and function declarations for the interpreter, so they will be known where necessary throughout the program. (By the way, we chose to put all this information in one file instead of two. In a larger program, it might be better to divide the header information into several files so that each is included only where really needed.) Here is `hoc.h`:

```
typedef struct Symbol {  /* symbol table entry */
        char   *name;
        short  type;    /* VAR, BLTIN, UNDEF */
        union {
                double  val;         /* if VAR */
                double  (*ptr)();    /* if BLTIN */
        } u;
        struct Symbol   *next;  /* to link to another */
} Symbol;

Symbol *install(char *s, int t, double d);
Symbol *lookup(char *s);

void init(void);
void execerror(char *s, char *t);

typedef union Datum {    /* interpreter stack type */
        double  val;     /* for literal numbers */
        Symbol *sym;     /* for variables */
} Datum;
```

```
typedef void (*Inst)();  /* machine instruction */
#define STOP (Inst) 0

extern  Inst prog[];
extern  void constpush(), varpush(), drop();
extern  void add(), sub(), mul(), divide(), power(), negate();
extern  void eval(), assign(), bltin(), print();

extern  void initcode(void);
extern  Inst *code(Inst f);
extern  void execute(Inst *p);
```

[Renamed `div` to `divide` to avoid collision with `div`(3) from the standard library.]

The routines that execute the machine instructions and manipulate the stack are kept in a new file called `code.c`. Since it is about 150 lines long, we will show it in pieces.

```
#include "hoc.h"
#include "y.tab.h"
#include <stdio.h>

#define NSTACK  256
static  Datum   stack[NSTACK];  /* the stack */
static  Datum  *stackp;         /* next free spot on stack */

#define NPROG   2000
        Inst    prog[NPROG];    /* the machine */
static  Inst   *progp;          /* next free spot (code gen) */
static  Inst   *pc;             /* program counter (runtime) */

void initcode(void)  /* initialize for code generation */
{
        stackp = stack;
        progp = prog;
}
```

The stack is manipulated by calls to `push` and `pop`:

```
static void push(Datum d)  /* push d onto stack */
{
        if (stackp >= &stack[NSTACK])
                execerror("stack overflow", 0);
        *stackp++ = d;
}

static Datum pop(void)  /* pop and return top from stack */
{
        if (stackp <= stack)
                execerror("stack underflow", 0);
        return *--stackp;
}
```

The machine is generated during parsing by calls to the function `code`, which simply puts an instruction into the next free spot in the array `prog`. It returns the location of the instruction (which is not used in `hoc4`).

```
Inst *code(Inst f)  /* install one instruction or operand */
{
        Inst *oprogp = progp;
        if (progp >= &prog[NPROG])
                execerror("program too big", 0);
        *progp++ = f;
        return oprogp;
}
```

Execution of the machine is simple; in fact, it's rather neat how small the routine is that "runs" the machine once it's set up:

```
void execute(Inst *p)  /* run the machine */
{
        for (pc = p; *pc != STOP; )
                (*(*pc++))();
}
```

Each cycle executes the function pointed to by the instruction pointed to by the program counter `pc`, and increments `pc` so it's ready for the next instruction. An instruction with opcode `STOP` terminates the loop. Some instructions, such as `constpush` and `varpush`, also increment `pc` to step over any arguments that follow the instruction.

```
void constpush(void)  /* push constant onto stack */
{
        Datum d;
        d.val = ((Symbol *) *pc++)->u.val;
        push(d);
}

void varpush(void)  /* push variable onto stack */
{
        Datum d;
        d.sym = (Symbol *) (*pc++);
        push(d);
}

void drop(void)  /* pop and discard top item from stack */
{
        (void) pop();
}
```

[`drop` is the instruction form of `pop`; in the book, `pop` is used as an instruction, but this fails with recent C compilers because it has a different signature.]

The rest of the machine is easy. For instance, the arithmetic operations are all basically the same, and were created by editing a single prototype. Here is `add`:

```
    void add(void)  /* add top two elems on stack */
    {
            Datum d2 = pop();
            Datum d1 = pop();
            d1.val += d2.val;
            push(d1);
    }
```

The remaining routines are equally simple.

```
    void eval(void)  /* evaluate variable on stack */
    {
            Datum d = pop();
            if (d.sym->type == UNDEF)
                    execerror("undefined variable", d.sym->name);
            d.val = d.sym->u.val;
            push(d);
    }

    void assign(void)  /* assign to top var next value */
    {
            Datum v = pop();
            Datum x = pop();
            if (v.sym->type != VAR && v.sym->type != UNDEF)
                    execerror("assignment to non-variable",
                              v.sym->name);
            v.sym->u.val = x.val;
            v.sym->type = VAR;
            push(x);  /* push back value because asgn is an expr */
    }

    void print(void)  /* pop top value from stack, print it */
    {
            Datum d = pop();
            printf("\t%.8g\n", d.val);
    }

    void bltin(void)  /* evaluate built-in on top of stack */
    {
            Datum d = pop();
            d.val = (*(double (*)())(void*)(*pc++))(d.val);
            push(d);
    }
```

The hardest part is the cast in `bltin`, which says that `*pc` should be cast to "pointer to function returning a `double`," and that function executed with `d.val` as argument. [The intermediate `(void*)` cast silences a compiler warning because an `Inst` returns `void`, not `double`.]

The diagnostics in `eval` and `assign` should never occur if everything is working properly; we left them in in case some program error causes the stack to be curdled. The overhead in time and space is small compared to the benefit of detecting the error if we make a careless change in the program. (We did, several times).

C's ability to manipulate pointers to functions leads to compact and efficient code. An alternative, to make the operators constants and combine the semantic functions into a big `switch` statement in `execute`, is straightforward and is left as an exercise.

A third digression on `make`. As the source code for `hoc` grows, it becomes more and more valuable to keep track mechanically of what has changed and what depends on that. The beauty of `make` is that it automates jobs that we would otherwise do by hand (and get wrong sometimes) or by creating a specialized shell file.

We have made two improvements to the `Makefile`. The first is based on the observation that although several files depend on the `yacc`-defined constants in `y.tab.h`, there's no need to recompile them unless the constants change—changes to the C code in `hoc.y` don't affect anything else. In the new `Makefile` the `.o` files depend on a new file `x.tab.h` that is updated only when the *contents* of `y.tab.h` change. The second improvement is to make the rule for `pr` (printing the source files) depend on the source files, so that only changed files are printed.

The first of these changes is a great time-saver for larger programs when the grammar is static but the semantics are not (the usual situation). The second change is a great paper-saver.

Here is the new `Makefile` for `hoc4`:

```
YFLAGS = -d
OBJS = hoc.o code.o init.o math.o symbol.o

hoc4: $(OBJS)
        $(CC) $(OBJS) -o hoc4 -lm

hoc.o code.o init.o symbol.o: hoc.h
code.o init.o symbol.o: x.tab.h

x.tab.h: y.tab.h
        -cmp -s x.tab.h y.tab.h || cp y.tab.h x.tab.h

pr: hoc.y hoc.h code.c init.c math.c symbol.c
        @pr $?
        @touch pr

clean:
        rm -f $(OBJS) [xy].tab.[ch]
```

The '`-`' before `cmp` tells `make` to carry on even if the `cmp` fails; this permits the process to work even if `x.tab.h` doesn't exist. (The `-s` option causes `cmp` to produce no output but set the exit status.) The symbol `$?` expands into the list of items from the rule that are not up to date. Regrettably, `make`'s notational conventions are at best loosely related to those of the shell.

To illustrate how these operate, suppose that everything is up to date. Then:

```
$ touch hoc.y                       Change date of hoc.y
$ make
yacc -d hoc.y
conflicts: 1 shift/reduce
cc  -c y.tab.c
rm y.tab.c
mv y.tab.o hoc.o
cmp -s x.tab.h y.tab.h || cp y.tab.h x.tab.h
cc hoc.o code.o init.o math.o symbol.o -o hoc4 -lm
$ make -n pr                        Print changed files
pr hoc.y
touch pr
$
```

Notice that nothing was recompiled except `hoc.y`, because the `y.tab.h` file was the same as the previous one.

Exercise 8-10. Make the sizes of `stack` and `prog` dynamic, so that `hoc4` never runs out of space if memory can be obtained by calling `malloc`. □

Exercise 8-11. Modify `hoc4` to use a `switch` on the type of operation in `execute` instead of calling functions. How do the versions compare in lines of source code and execution spead? How are they likely to compare in case of maintenance and growth? □

Stage 5: Control flow and relational operators

This version, `hoc5`, derives the benefit of the effort we put into making an interpreter. It provides `if-else` and `while` statements like those in C, statement grouping with `{` and `}`, and a `print` statement. A full set of relational operators is included (`>`, `>=`, etc.), as are the AND and OR operators `&&` and `||`. (These last two do not guarantee the left-to-right evaluation that is such an asset in C; they evaluate both conditions even if it is not necessary.)

The grammar has been augmented with tokens, non-terminals, and productions for `if`, `while`, braces, and the relational operators. This makes it quite a bit longer, but (except possibly for the `if` and `while`) not much more complicated:

```
%{
#include "hoc.h"
#define code2(c1,c2)    code(c1); code(c2)
#define code3(c1,c2,c3) code(c1); code(c2); code(c3)
%}
%union {
        Symbol  *sym;   /* symbol table pointer */
        Inst    *inst;  /* machine instruction */
}
```

```
%token  <sym>   NUMBER PRINT VAR BLTIN UNDEF WHILE IF ELSE
%type   <inst>  stmt asgn expr stmtlist cond while if end
%right  '='
%left   OR
%left   AND
%left   GT GE LT LE EQ NE
%left   '+' '-'
%left   '*' '/'
%left   UNARYPM NOT
%right  '^'
%%
list:     /* nothing */
        | list       '\n'
        | list asgn  '\n'  { code2(pop, STOP);   return 1; }
        | list stmt  '\n'  { code(STOP);         return 1; }
        | list expr  '\n'  { code2(print, STOP); return 1; }
        | list error '\n'  { yyerrok; }
        ;
asgn:     VAR '=' expr  {$$=$3; code3(varpush,(Inst)$1,assign);}
        ;
stmt:     expr          { code(drop); }
        | PRINT expr    { code(prexpr); $$ = $2; }
        | while cond stmt end {
                ($1)[1] = (Inst)$3;    /* body of loop */
                ($1)[2] = (Inst)$4; }  /* end, if cond fails */
        | if cond stmt end {           /* else-less if */
                ($1)[1] = (Inst)$3;    /* thenpart */
                ($1)[3] = (Inst)$4; }  /* end, if cond fails */
        | if cond stmt end ELSE stmt end { /* if with else */
                ($1)[1] = (Inst)$3;    /* thenpart */
                ($1)[2] = (Inst)$6;    /* elsepart */
                ($1)[3] = (Inst)$7; }  /* end, if cond fails */
        | '{' stmtlist '}'    { $$ = $2; }
        ;
cond:     '(' expr ')'  { code(STOP); $$ = $2; }
        ;
while:    WHILE  { $$ = code3(whilecode, STOP, STOP); }
        ;
if:      IF    { $$ = code(ifcode); code3(STOP, STOP, STOP); }
        ;
end:      /* nothing */     { code(STOP); $$ = progp; }
        ;
stmtlist: /* nothing */     { $$ = progp; }
        | stmtlist '\n'
        | stmtlist stmt
        ;
```

```
expr:     NUMBER    { $$ = code2(constpush, (Inst)$1); }
        | VAR       { $$ = code3(varpush, (Inst)$1, eval); }
        | asgn
        | BLTIN '(' expr ')'
                    { $$ = $3; code2(bltin, (void*)$1->u.ptr); }
        | '(' expr ')'   { $$ = $2; }
        | expr '+' expr  { code(add); }
        | expr '-' expr  { code(sub); }
        | expr '*' expr  { code(mul); }
        | expr '/' expr  { code(divide); }
        | expr '^' expr  { code(power); }
        | '-' expr %prec UNARYPM { $$=$2; code(negate); }
        | '+' expr %prec UNARYPM { $$=$2; }
        | expr GT expr   { code(gt); }
        | expr GE expr   { code(ge); }
        | expr LT expr   { code(lt); }
        | expr LE expr   { code(le); }
        | expr EQ expr   { code(eq); }
        | expr NE expr   { code(ne); }
        | expr AND expr  { code(land); }
        | expr OR expr   { code(lor); }
        | NOT expr       { $$ = $2; code(lnot); }
        ;
%%
```

The grammar has five shift/reduce conflicts, all like the one mentioned in hoc3.

Notice that STOP instructions are now generated in several places to terminate a sequence; as before, progp is the location of the next instruction that will be generated. When executed these STOP instructions will terminate the loop in execute. The production for end is in effect a subroutine, called from several places, that generates a STOP and returns the location of the instruction that follows it.

The code generated for while and if needs particular study. When the keyword while is encountered, the operation whilecode is generated, and its position in the machine is returned as the value of the production

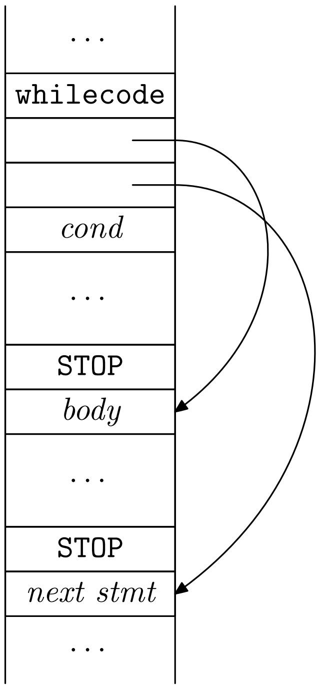
```
while:  WHILE
```

At the same time, however, the two following positions in the machine are also reserved, to be filled in later. The next code generated is the expression that makes up the condition part of the while. The value returned by cond is the beginning of the code for the condition. After the whole while statement has been recognized, the two extra positions reserved after the whilecode instruction are filled with the locations of the loop body and the statement that follows the loop. (Code for that statement will be generated next.)

```
        | while cond stmt end {
                ($1)[1] = (Inst)$3;      body of loop
                ($1)[2] = (Inst)$4; }    end, if cond fails
```

`$1` is the location in the machine at which `whilecode` is stored; therefore, `($1)[1]` and `($1)[2]` are the next two positions.

The situation for an `if` is similar, except that three spots are reserved, for the `then` and `else` parts and the statement that follows the `if`. We will return shortly to how this operates.



Lexical analysis is somewhat longer this time, mainly to pick up the additional operators:

```
int yylex(void)  /* hoc5 */
...
        switch (c) {
        case '>':   return follow('=', GE, GT);
        case '<':   return follow('=', LE, LT);
        case '=':   return follow('=', EQ, '=');
        case '!':   return follow('=', NE, NOT);
        case '|':   return follow('|', OR, '|');
        case '&':   return follow('&', AND, '&');
        case '\n':  lineno++; return '\n';
        default:    return c;
        }
}
```

`follow` looks ahead one character, and puts it back on the input with `ungetc` if it was not what was expected.

```
int follow(int expect, int ifyes, int ifno)  /* look ahead */
{
        int c = getchar();
        if (c == expect)  return ifyes;
        ungetc(c, stdin); return ifno;
}
```

There are more function declarations in `hoc.h`—all of the relationals, for instance—but it's otherwise the same idea as in `hoc4`. Here are the last few lines:

```
...
typedef void (*Inst)();  /* machine instruction */
#define STOP (Inst) 0

extern  Inst prog[];
extern  void constpush(), varpush(), drop();
extern  void add(), sub(), mul(), divide(), power(), negate();
extern  void eval(), assign(), bltin(), print();
extern  void prexpr(), ifcode(), whilecode();
extern  void eq(), ne(), gt(), ge(), lt(), le();
extern  void land(), lor(), lnot();  /* logical and/or/not */
```

Most of `code.c` is the same too, although there are a lot of obvious new routines to handle the relational operators. The function `le` ("less than or equal to") is a typical example:

```
void le(void)
{
        Datum d2 = pop();
        Datum d1 = pop();
        d1.val = (double) (d1.val <= d2.val);
        push(d1);
}
```

The two routines that are not obvious are `whilecode` and `ifcode`. The critical point for understanding them is to realize that `execute` marches along a sequence of instructions until it finds a `STOP`, whereupon it returns. Code generation during parsing has carefully arranged that a `STOP` terminates each sequence of instructions that should be handled by a single call of `execute`. The body of a `while`, and the condition, `then` and `else` parts of an `if` are all handled by recursive calls to `execute` that return to the parent level when they have finished their task. The control of these recursive tasks is done by code in `whilecode` and `ifcode` that corresponds directly to `while` and `if` statements.

```
void whilecode(void)
{
        Datum d;
        Inst *savepc = pc;      /* loop body */
        execute(savepc+2);     /* condition */
        d = pop();
        while (d.val) {
                execute(*((Inst **)(savepc)));  /* body */
                execute(savepc+2);
                d = pop();
        }
        pc = *((Inst **)(savepc+1));  /* next statement */
}
```

Recall from our discussion earlier that the `whilecode` operation is followed by a pointer to the body of the loop, a pointer to the next statement, and then the beginning of the condition part. When `whilecode` is called, `pc` has already been incremented, so it points to the loop body pointer. Thus `pc+1` points to the following statement, and `pc+2` points to the condition. [Indeed `pc` points to a pointer to the body code and thus is dereferenced before being passed to `execute`; similarly, the pointer at `pc+1` is dereferenced before being assigned to `pc`.]

`ifcode` is very similar; in this case, upon entry `pc` points to then `then` part, `pc+1` to the `else`, `pc+2` to the next statement, and `pc+3` is the condition.

```
void ifcode(void)
{
        Datum d;
        Inst *savepc = pc;     /* then part */
        execute(savepc+3);     /* condition */
        d = pop();
        if (d.val)
                execute(*((Inst **)(savepc)));
        else if (*((Inst **)(savepc+1)))  /* else part? */
                execute(*((Inst **)(savepc+1)));
        pc = *((Inst **)(savepc+2));      /* next stmt */
}
```

The initialization code in `init.c` is augmented a little as well, with a table of keywords that are stored in the symbol table along with everything else:

```
...
static struct {  /* Keywords */
        char *name;
        int   kval;
} keywords[] = {
        "if",      IF,
        "else",    ELSE,
        "while",   WHILE,
        "print",   PRINT,
        0,         0
};
...
```

We also need one more loop in `init`, to install keywords.

```
    for (i = 0; keywords[i].name; i++)
            install(keywords[i].name, keywords[i].kval, 0.0);
```

No changes are needed in any of the symbol table management; `code.c` contains the routine `prexpr`, which is called when a statement of the form `print` *expr* is executed.

```
void prexpr(void)  /* print numeric value */
{
        Datum d = pop();
        printf("%.8g\n", d.val);
}
```

This is not the `print` function that is called automatically to print the final result of an evaluation; that one pops the stack and adds a tab to the output.

`hoc5` is by now quite a serviceable calculator, although for serious programming, more facilities are needed. The following exercises suggest some possibilities.

Exercise 8-12. Modify `hoc5` to print the machine it generates in a readable form for debugging. □

Exercise 8-13. Add the assignment operators of C, such as `+=`, `*=`, etc., and the increment and decrement operators `++` and `--`. Modify `&&` and `||` so they guarantee left-to-right evaluation and early termination, as in C. □

Exercise 8-14. Add a `for` statement like that of C to `hoc5`. Add `break` and `continue`. □

Exercise 8-15. How would you modify the grammar or the lexical analyzer (or both) of `hoc5` to make it more forgiving about the placement of newlines? How would you add semicolon as a synonym for newline? How would you add a comment convention? What syntax would you use? □

Exercise 8-16. Add interrupt handling to `hoc5`, so that a runaway computation can be stopped without losing the state of variables already computed. □

Exercise 8-17. It is a nuisance to have to create a program in a file, run it, then edit the file to make a trivial change. How would you modify `hoc5` to provide an edit command that would cause you to be placed in an editor with a copy of your `hoc` program already read in? Hint: consider a `text` opcode. □

Stage 6: Functions and procedures; input/output

The final stage in the evolution of `hoc`, at least for this book, is a major increase in functionality: the addition of functions and procedures. We have also added the ability to print character strings as well as numbers, and to read values from the standard input. `hoc6` also accepts filename arguments, including the name "`-`" for the standard input. Together, these changes add 235 lines of code, bringing the total to about 810, but in effect convert `hoc` from a calculator into a programming language. We won't show every line here; Appendix 3 is a listing of the entire program so you can see how the pieces fit together.

In the grammar, function calls are expressions; procedure calls are statements. Both are explained in detail in Appendix 2 [the `hoc` manual], which also has some more examples. For instance, the definition and use of a procedure for printing all the Fibonacci numbers less than its argument looks like this:

```
$ cat fib
proc fib() {
        a = 0
        b = 1
        while (b < $1) {
                print b
                c = b
                b = a+b
                a = c
        }
        print "\n"
}
$ hoc6 fib -
fib(1000)
1 1 2 3 5 8 13 21 34 55 89 144 233 377 610 987
...
```

This also illustrates the use of files: the filename "`-`" is the standard input.

Here is a factorial function:

```
$ cat fac
func fac() {
        if ($1 <= 0) return 1 else return $1 + fac($1-1)
}
$ hoc6 fac -
fac(0)
        1
fac(7)
        5040
fac(10)
        3628800
...
```

Arguments are referenced within a function or procedure as `$1`, etc., as in the shell, but it is legal to assign to them as well. Functions and procedures are recursive, but only the arguments are local variables; all other variables are global, that is, accessible throughout the program.

hoc distinguishes functions from procedures because doing so gives a level of checking that is valuable in a stack implementation. It is too easy to forget a return or add an extra expression and foul up the stack.

There are a fair number of changes to the grammar to convert hoc5 into hoc6, but they are localized. New tokens and non-terminals are needed, and the %union declaration has a new member to hold argument counts:

```
...
%union {
        Symbol  *sym;   /* symbol table pointer */
        Inst    *inst;  /* machine instruction */
        int     narg;   /* number of arguments */
}
%token  <sym>  NUMBER STRING PRINT VAR BLTIN UNDEF WHILE IF ELSE
%token  <sym>   FUNCTION PROCEDURE RETURN FUNC PROC READ
%token  <narg>  ARG
%type   <inst>  expr stmt asgn prlist stmtlist
%type   <inst>  cond while if begin end
%type   <sym>   procname
%type   <narg>  arglist
...
list:     /* nothing */
        | list       '\n'
        | list defn  '\n'
        | list asgn  '\n'  { code2(pop, STOP); return 1; }
        | list stmt  '\n'  { code(STOP); return 1; }
        | list expr  '\n'  { code2(print, STOP); return 1; }
        | list error '\n'  { yyerrok; }
        ;
asgn:     VAR '=' expr
                   { code3(varpush, (Inst)$1, assign); $$=$3; }
        | ARG '=' expr
                   { defnonly("$"); code2(argassign, (Inst)$1);
                     $$=$3; }
        ;
stmt:     expr     { code(pop); }
        | RETURN   { defnonly("return"); code(procret); }
        | RETURN expr
                   { defnonly("return"); $$=$2; code(funcret); }
        | PROCEDURE begin '(' arglist ')'
                   { $$ = $2; code3(call, (Inst)$1, (Inst)$4); }
        | PRINT prlist  { $$ = $2; }
...
```

```
expr:     NUMBER  { $$ = code2(constpush, (Inst)$1); }
        | VAR     { $$ = code3(varpush, (Inst)$1, eval); }
        | ARG     { defnonly("$"); $$ = code2(arg, (Inst)$1); }
        | asgn
        | FUNCTION begin '(' arglist ')'
                  { $$ = $2; code3(call, (Inst)$1, (Inst)$4); }
        | READ '(' VAR ')'   { $$ = code2(varread, (Inst)$3); }
...
begin:    /* nothing */      { $$ = progp; }
        ;
prlist:   expr               { code(prexpr); }
        | STRING             { $$ = code2(prstr, (Inst)$1); }
        | prlist ',' expr    { code(prexpr); }
        | prlist ',' STRING  { code2(prstr, (Inst)$3); }
        ;
defn:     FUNC procname { $2->type=FUNCTION; indef=1; }
            '(' ')' stmt { code(procret); define($2); indef=0; }
        | PROC procname { $2->type = PROCEDURE; indef=1; }
            '(' ')' stmt { code(procret); define($2); indef=0; }
        ;
procname: VAR
        | FUNCTION
        | PROCEDURE
        ;
arglist:  /* nothing */      { $$ = 0; }
        | expr               { $$ = 1; }
        | arglist ',' expr   { $$ = $1 + 1; }
        ;
%%
...
```

The productions for `arglist` count the arguments. At first sight it might seem necessary to collect arguments in some way, but it's not, because each `expr` in an argument list leaves its value on the stack exactly where it's wanted. Knowing how many are on the stack is all that's needed.

The rules for `defn` introduce a new `yacc` feature, an embedded action. It is possible to put an action in the middle of a rule so that it will be executed during the recognition of the rule. We use that feature here to record the fact that we are in a function or procedure definition. (The alternative is to create a new symbol analogous to `begin`, to be recognized at the proper time.) The function `defnonly` prints a warning message if a construct occurs outside of the definition of a function or procedure when it shouldn't. There is often a choice of whether to detect errors syntactically or semantically; we faced one earlier in handling undefined variables. The `defnonly` function is a good example of a place where the semantic check is easier than the syntactic one.

```
void defnonly(char *s)  /* warn if illegal definition */
{
        if (!indef) execerror(s, "used outside definition");
}
```

The variable `indef` is declared in `hoc.y`, and set by the actions for `defn`.

The lexical analyzer is augmented by tests for arguments—a `$` followed by a number—and for quoted strings. Backslash sequences like `\n` are interpreted in strings by a function `backslash`.

```
int yylex(void)  /* hoc6 */
...
      if (c == '$') {  /* argument? */
            int n = 0;
            while (isdigit(c = getc(fin)))
                  n = 10 * n + c - '0';
            ungetc(c, fin);
            if (n == 0)
                  execerror("strange $...", 0);
            yylval.narg = n;
            return ARG;
      }
      if (c == '"') {  /* quoted string */
            char sbuf[100], *p;
            for (p = sbuf; (c = getc(fin)) != '"'; p++) {
                  if (c == '\n' || c == EOF)
                        execerror("missing quote", "");
                  if (p >= sbuf + sizeof(sbuf) - 1) {
                        *p = '\0';
                        execerror("string too long", sbuf);
                  }
                  *p = backslash(c);
            }
            *p = 0;
            yylval.sym = emalloc(strlen(sbuf)+1);
            strcpy((char*)(void*) yylval.sym, sbuf);
            return STRING;
      }
...
int backslash(int c)  /* get next char with \'s interpreted */
{
        static char transtab[] = "b\bf\fn\nr\rt\t";
        if (c != '\\') return c;
        c = getc(fin);
        if (islower(c) && strchr(transtab, c))
              return strchr(transtab, c)[1];
        return c;
}
```

A lexical analyzer is an example of a *finite state machine*, whether written in C or with a program generator like lex. Our *ad hoc* C version has grown fairly complicated; for anything beyond this, lex is probably better, both in size of source code and ease of change.

Most of the other changes are in code.c, with some additions of function names to hoc.h. The machine is the same as before, except that it has been augmented with a second stack to keep track of nested function and procedure calls. (A second stack is easier than piling more things into the existing one.) Here is the beginning of code.c:

```
#define NPROG   2000
Inst    prog[NPROG];    /* the machine */
Inst    *progp;        /* next free spot for code generation */
Inst    *pc;            /* program counter during execution */
Inst    *progbase = prog;  /* start of current subprogram */
int     returning;      /* 1 if return stmt seen */

typedef struct Frame {  /* proc/func call stack frame */
        Symbol  *sp;    /* symbol table entry */
        Inst    *retpc; /* where to resume after return */
        Datum   *argn;  /* n-th argument on stack */
        int     nargs;  /* number of arguments */
} Frame;

#define NFRAME  100
Frame   frame[NFRAME];
Frame   *fp;            /* frame pointer */

void initcode(void) {
        progp = progbase;
        stackp = stack;
        fp = frame;
        returning = 0;
}
...
```

Since the symbol table now holds pointers to procedures and functions, and to strings for printing, an addition is made to the union type in hoc.h:

```
typedef struct Symbol {  /* symbol table entry */
        char    *name;
        short   type;
        union {
                double  val;         /* VAR */
                double  (*ptr)();    /* BLTIN */
                void    (**defn)();  /* FUNCTION, PROCEDURE */
                char    *str;        /* STRING */
        } u;
        struct Symbol *next;  /* to link to another */
} Symbol;
```

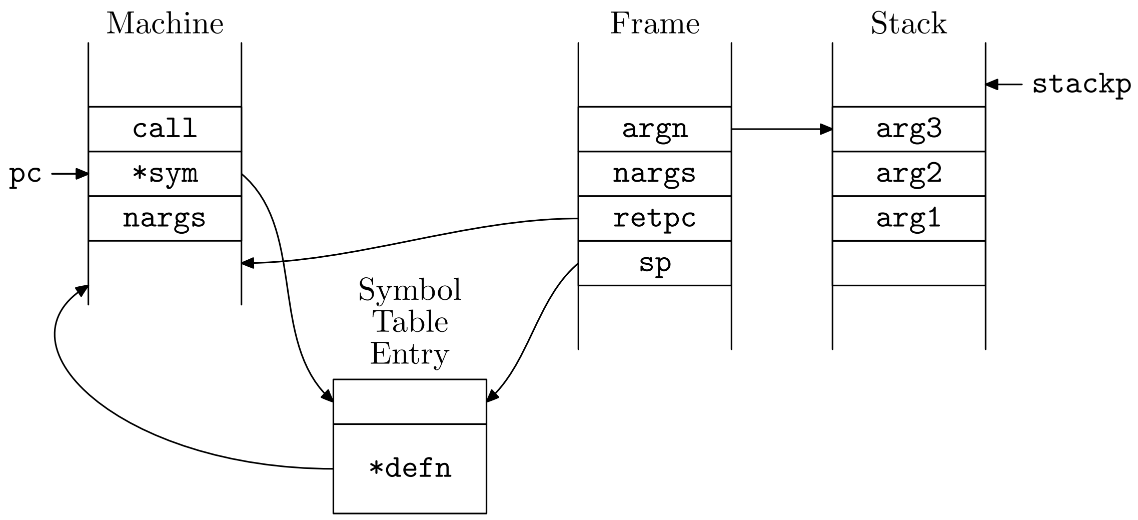
During compilation, a function is entered into the symbol table by `define`, which stores its origin in the table and updates the next free location after the generated code if the compilation is successful.

```
void define(Symbol *sp)  /* put func/proc in symbol table */
{
        sp->u.defn = progbase;  /* start of code */
        progbase = progp;       /* next code starts here */
}
```

When a function or procedure is called during execution, any arguments have already been computed and pushed onto the stack (the first argument is the deepest). The opcode for `call` is followed by the symbol table pointer and the number of arguments. A `Frame` is stacked that contains all the interesting information about the routine—its entry in the symbol table, where to return after the call, where the arguments are on the expression stack, and the number of arguments that it was called with. The frame is created by `call`, which then executes the code of the routine.

```
void call(void)  /* call a function */
{
        Symbol *sp = (Symbol *) pc[0];  /* symbol table entry */
                                        /* for function */
        if (fp++ >= &frame[NFRAME-1])
                execerror(sp->name, "call nested too deeply");
        fp->sp = sp;
        fp->nargs = (int) pc[1];
        fp->retpc = pc + 2;
        fp->argn = stackp - 1;  /* last argument */
        execute(sp->u.defn);
        returning = 0;
}
```

This structure is illustrated in the figure:



Eventually the called routine will return by executing either a `procret` or a `funcret`:

```
void funcret(void)  /* return from a function */
{
        Datum d;
        if (fp->sp->type == PROCEDURE)
            execerror(fp->sp->name, "(proc) returns value");
        d = pop();  /* preserve function return value */
        ret();
        push(d);
}

void procret(void)  /* return from a procedure */
{
        if (fp->sp->type == FUNCTION)
            execerror(fp->sp->name, "(func) returns no value");
        ret();
}
```

The function `ret` pops the arguments off the stack, restores the frame pointer `fp`, and sets the program counter.

```
void ret(void)  /* common return from func or proc */
{
        int i;
        for (i = 0; i < fp->nargs; i++)
                pop();  /* pop arguments */
        pc = (Inst *) fp->retpc;
        --fp;
        returning = 1;
}
```

Several of the interpreter routines need minor fiddling to handle the situation when a `return` occurs in a nested statement. This is done inelegantly but adequately by a flag `returning`, which is true when a `return` statement has been seen. `ifcode`, `whilecode` and `execute` terminate early if `returning` is set; `call` resets it to zero.

```
void ifcode(void)
{
        Datum d;
        Inst *savepc = pc;      /* then part */
        execute(savepc+3);      /* condition */
        d = pop();
        if (d.val)
                execute(*((Inst **)(savepc)));
        else if (*((Inst **)(savepc+1))) /* else part? */
                execute(*((Inst **)(savepc+1)));
        if (!returning)
                pc = *((Inst **)(savepc+2)); /* next stmt */
}
void whilecode(void)
{
        Datum d;
        Inst *savepc = pc;
        execute(savepc+2);     /* condition */
        d = pop();
        while (d.val) {
                execute(*((Inst **)(savepc)));  /* body */
                if (returning) break;
                execute(savepc+2);  /* condition */
                d = pop();
        }
        if (!returning)
                pc = *((Inst **)(savepc+1)); /* next stmt */
}
void execute(Inst *p)
{
        for (pc = p; *pc != STOP && !returning; )
                (*(*pc++))();
}
```

Arguments are fetched for use or assignment by getarg, which does the correct arithmetic on the stack:

```
double *getarg(void)  /* return pointer to argument */
{
        int nargs = (int) *pc++;
        if (nargs > fp->nargs)
               execerror(fp->sp->name, "not enough arguments");
        return &fp->argn[nargs - fp->nargs].val;
}
void arg(void)  /* push argument onto stack */
{
        Datum d;
        d.val = *getarg();
        push(d);
}
void argassign(void)  /* store top of stack in argument */
{
        Datum d = pop();
        push(d);            /* leave value on stack */
        *getarg() = d.val;
}
```

Printing of strings and numbers is done by prstr and prexpr.

```
void prstr(void)  /* print string value */
{
        printf("%s", (char *) *pc++);
}

void prexpr(void)  /* print numeric value */
{
        Datum d = pop();
        printf("%.8g ", d.val);
}
```

Variables are read by a function called `varread`. It returns `0` if end of file occurs; otherwise it returns `1` and sets the specified variable.

```
void varread(void)  /* read into variable */
{
        Datum d;
        extern FILE *fin;
        Symbol *var = (Symbol *) *pc++;
Again:
        switch (fscanf(fin, "%lf", &var->u.val)) {
        case EOF:
                if (moreinput())
                        goto Again;
                d.val = var->u.val = 0.0;
                break;
        case 0:
                execerror("non-number read into", var->name);
                break;
        default:
                d.val = 1.0;
                break;
        }
        var->type = VAR;
        push(d);
}
```

If end of file occurs on the current input file, `varread` calls `moreinput`, which opens the next argument file if there is one. `moreinput` reveals more about input processing than is appropriate here; full details are given in Appendix 3.

This brings us to the end of our development of `hoc`. For comparison purposes, here is the number of non-blank lines in each version:

`hoc1`	59	
`hoc2`	94	
`hoc3`	248	(`lex` version 229)
`hoc4`	396	
`hoc5`	574	
`hoc6`	809	

Of course the counts were computed by programs:

```
$ sed '/^$/d' `pick *.[chyl]` | wc -l
```

The language is by no means finished, at least in the sense that it's still easy to think of useful extensions, but we will go no further here. The following exercises suggest some of the enhancements that are likely to be of value.

Exercise 8-18. Modify `hoc6` to permit named formal parameters in subroutines as an alternative to `$1`, etc. □

Exercise 8-19. As it stands, all variables are global except for parameters. Most of the mechanism for adding local variables maintained on the stack is already present. One approach is to have an `auto` declaration that makes space on the stack for variables listed; variables not so named are assumed to be global. The symbol table will also have to be extended, so that a search is made first for locals, then for globals. How does this interact with named arguments? □

Exercise 8-20. How would you add arrays to `hoc`? How should they be passed to functions and procedures? How are they returned? □

Exercise 8-21. Generalize string handling, so that variables can hold strings instead of numbers. What operators are needed? The hard part of this is storage management: making sure that strings are stored in such a way that they are freed when they are not needed, so that storage does not leak away. As an interim step, add better facilities for output formatting, for example, access to some form of the C `printf` statement. □

Performance evaluation

We compared `hoc` to some of the other UNIX calculator programs, to get a rough idea of how well it works. The table below should be taken with a grain of salt, but it does indicate that our implementation is reasonable. All times are in seconds of user time on a PDP-11/70. There were two tasks. The first is computing Ackermann's function `ack(3,3)`. This is a good test of the function-call mechanism; it requires 2432 calls, some nested quite deeply.

```
func ack() {
        if ($1 == 0) return $2+1
        if ($2 == 0) return ack($1-1, 1)
        return ack($1-1, ack($1, $2-1))
}
ack(3,3)
```

The second test is computing the Fibonacci numbers with values less than 1000 a total of one hundred times; this involves mostly arithmetic with an occasional function call.

Table 8.1: Seconds of user time (PDP-11/70)

program	`ack(3,3)`	100 × `fib(1000)`
`hoc`	5.5	5.0
`bas`	1.3	0.7
`bc`	39.7	14.9
C	<0.1	<0.1

```
proc fib() {
        a = 0
        b = 1
        while (b < $1) {
                c = b
                b = a+b
                a = c
        }
}
i = 1
while (i < 100) {
        fib(1000)
        i = i + 1
}
```

The four languages were `hoc`, `bc`(1), `bas` (an ancient BASIC dialect that only runs on the PDP-11), and C (using `double`'s for all variables).

The nubmers in Table 8.1 are the sum of the user and system CPU time as measured by `time`(1). It is also possible to instrument a C program to determine how much of that time each function uses. The program must be recompiled with profiling turned on, by adding the option `-p` to each C compilation and load. If we modify the `Makefile` to read

```
hoc6: $(OBJS)
        cc $(CFLAGS) $(OBJS) -lm -o hoc6
```

so that the `cc` command uses the variable `CFLAGS`, and then say

```
$ make clean; make CFLAGS=-p
```

the resulting program will contain the profiling code. When the program runs, it will leave a file called `mon.out` of data that is interpreted by the program `prof`.

To illustrate these notions briefly, we made a test on `hoc6` with the Fibonacci program above.

```
$ hoc6 < fibtest                          Run the test
$ prof hoc6 | sed 15q                Analyze
     name  %time  cumsecs  #call  ms/call
     _pop   15.6     0.85  32182     0.03
    _push   14.3     1.63  32182     0.02
   mcount   11.3     2.25
      csv   10.1     2.80
     cret    8.8     3.28
  _assign    8.2     3.73   5050     0.09
    _eval    8.2     4.18   8218     0.05
 _execute    6.0     4.51   3567     0.09
 _varpush    5.9     4.83  13268     0.02
      _lt    2.7     4.98   1783     0.08
 _constpu    2.0     5.09    497     0.22
     _add    1.7     5.18   1683     0.05
  _getarg    1.5     5.26   1683     0.05
 _yyparse    0.6     5.30      3    11.11
$
```

The measurements obtained from profiling are just as subject to chance fluctuations as are those from `time`, so they should be treated as indicators, not absolute truth. The numbers here do suggest how to make `hoc` faster, however, *if it needs to be.* About one third of the run time is going into pushing and popping the stack. The overhead is larger if we include the times for the C subroutine linkage functions `csv` and `cret`. (`mcount` is a piece of the profiling code compiled in by `cc -p`.) Replacing the function calls by macros should make a noticeable difference.

To test this expectation, we modified `code.c`, replacing calls to `push` and `pop` with macros for stack manipulation:

```
#define push(d) *stackp++ = (d)
#define popm()  *--stackp        /* function still needed */
```

(The function `pop` is still needed as an opcode in the machine, so we can't just replace all `pop`'s.) The new version runs about 35 percent faster; the times in Table 8.1 shrink form 5.5 to 3.7 seconds, and from 5.0 to 3.1.

Exercise 8-22. The `push` and `popm` macros do no error checking. Comment on the wisdom of this design. How can you combine the error-checking provided by the function versions with the speed of macros? □

A look back

There are some important lessons to learn from this chapter. First, the language development tools are a boon. They make it possible to concentrate on the interesting part of the job—language design—because it is so easy to experiment. The use of a grammar also provides an organizing structure for the implementation—routines are linked together by the grammar, and called at the right times as parsing proceeds.

A second, more philosophical point, is the value of thinking of the job at hand more as language development than as "writing a program." Organizing a program as a language processor encourages regularity of syntax (which is the user interface), and structures the implementation. It also helps to ensure that new features will mesh smoothly with existing ones. "Languages" are certainly not limited to conventional programming languages—examples from our own experience include `eqn` and `pic`, and `yacc`, `lex` and `make` themselves.

There are also some lessons about how tools are used. For instance, `make` is invaluable. It essentially eliminates the class of error that arises from forgetting to recompile some routine. It helps to ensure that no excess work is done. And it provides a convenient way to package a group of related and perhaps dependent operations in a single file.

Header files are a good way to manage data declarations that must be visible in more than one file. By centralizing the information, they eliminate errors caused by inconsistent versions, especially when coupled with `make`. It is also important to organize the data and the routines into files in such a way that they are not made visible when they don't have to be.

There are a couple of topics that, for lack of space, we did not stress. One is simply the degree to which we used all the *other* UNIX tools during development of the `hoc` family. Each version of the program is in a separate directory, with identical files linked together; `ls` and `du` are used repeatedly to keep track of what is where. Many other questions are answered by programs. For example, where is that variable declared? Use `grep`. What did we change in this version? Use `diff`. How did we integrate the changes into that version? Use `idiff`. How big is the file? Use `wc`. Time to make a backup copy? Use `cp`. How can we back up only the files changed since the last backup? Use `make`. This general style is absolutely typical of day-to-day program development on a UNIX system: a host of small tools, used separately or combined as necessary, help to mechanize work that would otherwise have to be done by hand.

History and bibliographic notes

`yacc` was developed by Steven Johnson. Technically, the class of languages for which `yacc` can generate parsers is called LALR(1): left to right parsing, looking ahead at most one token in the input. The notion of a separate description to resolve precedence and ambiguity in the grammar is new with `yacc`. See "Deterministic parsing of ambiguous grammars," by A. V. Aho, S. C. Johnson, and J. D. Ullman, *CACM*, August, 1975. There are also some innovative algorithms and data structures for creating and storing the parsing tables.

A good description of the basic theory underlying `yacc` and other parser generators may be found in *Principles of Compiler Design*, by A. V. Aho and J. D. Ullmann (Addison-Wesley, 1977). `yacc` itself is described in Volume 2B of *The UNIX Programmer's Manual.* That section also presents a calculator comparable to `hoc2`; you might find it instructive to make the comparison.

`lex` was originally written by Mike Lesk. Again, the theory is described by Aho and Ullman, and the `lex` language itself is documented in *The UNIX Programmer's Manual.*

`yacc`, and to a lesser degree `lex`, have been used to implement many language processors, including the portable C compiler, Pascal, FORTRAN 77, Ratfor, `awk`, `bc`, `eqn`, and `pic`.

`make` was written by Stu Feldman. See "MAKE—a program for maintaining computer programs," *Software—Practice & Experience*, April, 1979.

Writing Efficient Programs by Jon Bently (Prentice-Hall, 1982) describes techniques for making programs faster. The emphasis is on first finding the right algorithm, then refining the code if necessary.