DOCUMENTS FOR USE WITH THE UNIX TIME-SHARING SYSTEM

Sixth Edition

CONTENTS

SETTING UP UNIX − Sixth Edition

Enclosed are:

1. 'UNIX Programmer's Manual,' Sixth Edition.
2. Documents with the following titles:

   Setting Up UNIX − Sixth Edition
   The UNIX Time-Sharing System
   C Reference Manual
   Programming in C − A Tutorial
   UNIX Assembler Reference Manual
   A Tutorial Introduction to the ED Text Editor
   UNIX for Beginners
   RATFOR − A Preprocessor for a Rational Fortran
   YACC − Yet Another Compiler-Compiler
   NROFF Users' Manual
   The UNIX I/O System
   A Manual for the Tmg Compiler-writing Language
   On the Security of UNIX
   The M6 Macro Processor
   A System for Typesetting Mathematics
   DC − An Interactive Desk Calculator
   BC − An Arbitrary Precision Desk-Calculator Language
   The Portable C Library (on UNIX)
   UNIX Summary

3. The UNIX software on magtape or disk pack.

If you are set up to do it, it might be a good idea immediately to make a copy of the disk or tape to guard against disaster. The tape contains 12100 512-byte records followed by a single file mark; only the first 4000 512-byte blocks on the disk are significant.

The system as distributed corresponds to three fairly full RK packs. The first contains the binary version of all programs, and the source for the operating system itself; the second contains all remaining source programs; the third contains manuals intended to be printed using the formatting programs roff or nroff. The 'binary' disk is enough to run the system, but you will almost certainly want to modify some source programs.

Making a Disk From Tape

If your system is on magtape, perform the following bootstrap procedure to obtain a disk with the binaries.

1. Mount magtape on drive 0 at load point.
2. Mount formatted disk pack on drive 0.
3. Key in and execute at 100000

TU10	TU16
012700	(to be added)
172526	
010040	
012740	
060003	
000777	

The tape should move and the CPU loop. (The TU10 code is *not* the DEC bulk ROM for tape; it reads block 0, not block 1.)

4. Halt and restart the CPU at 0. The tape should rewind. The console should type '='.

5. Copy the magtape to disk by the following. This assumes TU10 and RK05; see 6 below for other devices. The machine's printouts are shown in italic (the '=' signs should be considered italic). Terminate each line you type by carriage return or line-feed.

```
= tmrk
disk offset
0
tape offset
100          (See 6 below)
count
1            (The tape should move)
= tmrk
disk offset
1
tape offset
101          (See 7 below)
count
3999         (The tape moves lots more)
=
```

To explain: the *tmrk* program copies tape to disk with the given offsets and counts. Its first use copies a bootstrap program to disk block 0; the second use copies the file system itself onto the disk. You may get back to '=' level by starting at 137000.

6. If you have TU16 tape say 'htrk' instead of 'tmrk' in the above example. If you have an RP03 disk, say 'tmrp' or 'htrp', and use a 99 instead of 100 tape offset. If you have an RP04 disk, use 'tmhp' or 'hthp' instead or 'tmrk', and use a 98 instead of 100 tape offset. The different offsets load bootstrap programs appropriate to the disk they will live on.

7. This procedure generates the 'binary' disk; the 'source' disk may be generated on another RK pack by using a tape offset of 4101 instead of 101. The 'document' disk is at offset 8101 instead of 101. Unless you have only a single RK drive, it is probably wise to wait on generating these disks. Better tools are available using UNIX itself.

Booting UNIX

Once the UNIX 'binary' disk is obtained, the system is booted by keying in and executing one of the following programs at 100000. These programs correspond to the DEC bulk ROMs for disks, since they read in and execute block 0 at location 0.

RK05	RP03	RP04
012700	012700	(to be added)
177414	176726	
005040	005040	
005040	005040	
010040	005040	
012740	010040	
000005	012740	
105710	000005	
002376	105710	
005007	002376	
	005007	

Now follow the indicated dialog, where '@' and '#' are prompts:

```
@ rkunix        (or 'rpunix' or 'hpunix')
mem = xxx
login: root
#
```

The *mem* message gives the memory available to user programs in .1K units. Most of the UNIX software will run with 120 (for 12K words), but some things require much more.

UNIX is now running, and the 'UNIX Programmer's manual' applies; references below of the form X-Y mean the subsection named X in section Y of the manual. The '#' is the prompt from the UNIX Shell, and indicates you are logged in as the super-user. The only valid user names are 'root' and 'bin'. The root is the super-user and bin is the owner of nearly every file in the file system.

Before UNIX is turned up completely, a few configuration dependent exercises must be performed. At this point, it would be wise to read all of the manuals and to augment this reading with hand to hand combat. It might be instructive to examine the Shell run files mentioned below.

Reconfiguration

The UNIX system running is configured to run on an 11/40 with the given disk, TU10 magtape and TU56 DECtape. This is almost certainly not the correct configuration. Print (cat-I) the file /usr/sys/run. This file is a set of Shell commands that will completely recompile the system source, install it in the correct libraries and build the three configurations for rk, rp and hp.

Using the Shell file as a guide, compile (cc-I) and rename (mv-I) the configuration program 'mkconf'. Run the configuration program and type into it a list of the controllers on your system. Choose from:

pc (PC11)
lp (LP11)
rf (RS11)
hs (RS03/RS04)
tc (TU56)
rk (RK03/RK05)
tm (TU10)
rp (RP03)
hp (RP04)
ht (TU16)
dc* (DC11)
kl* (KL11/DL11-ABC)
dl* (DL11-E)
dp (DP11)
dn (DN11)
dh (DH11)
dhdm (DM11-BB)

The devices marked with * should be preceded by a number specifying how many. (The console typewriter is automatically included; don't count it in the kl specification.) Mkconf will generate the two files l.s (trap vectors) and c.c (configuration table). Take a careful look at l.s to make sure that all the devices that you have are assembled in the correct interrupt vectors. If your configuration is non-standard, you will have to modify l.s to fit your configuration.

In the run Shell file, the 11/45 code is commented out. If you have an 11/45 you must also edit (ed-I) the file /usr/sys/conf/m45.s to set the assembly flag fpp to reflect if you have the FP11-B floating point unit. The main difference between an 11/40 and an 11/45 (or 11/70) system is that in the former instruction restart after a segmentation violation caused by overflowing a user stack must be handled by software, while in the latter machines there is hardware help. As mentioned above, the 11/45 and 11/70 systems include conditionally-enabled code to save the status of the floating point unit when switching users. The source for such things is in one of the two files m40.s and m45.s.

Another difference is that in 11/45 and 11/70 systems the instruction and data spaces are separated inside UNIX itself. Since the layout of addresses in the system is somewhat peculiar, and not directly supported by the link-editor *ld,* the *sysfix* program has to be run before the loaded output file can be booted.

There are certain magic numbers and configuration parameters imbedded in various device drivers that you may want to change. The device addresses of each device are defined in each driver. In case you have any non-standard device addresses, just change the address and recompile. (The device drivers are in the directory /usr/sys/dmr.)

The DC11 driver is set to run 14 lines. This can be changed in dc.c.

The DH11 driver will only handle a single DH with a full complement of 16 lines. If you have less, you may want to edit dh.c.

The DN11 driver will handle 3 DN's. Edit dn.c.

The DP11 driver can only handle a single DP. This cannot be easily changed.

The KL/DL driver is set up to run a single DL11-A, -B, or -C (the console) and no DL11-E's. To change this, edit kl.c to have NKL11 reflect the total number of DL11-ABC's and NDL11 to reflect the number of DL11-E's. So far as the driver is concerned, the difference between the devices is their addresses.

The line printer driver is set up to print the 96 character set on 80 column paper (LP11-H) with indenting. Edit lp.c.

All of the disk and tape drivers (rf.c, rk.c, rp.c, tm.c, tc.c, hs.c, hp.c, ht.c) are set up to run 8 drives and should not need to be changed. The big disk drivers (rp.c and hp.c) have partition tables in them which you may want to experiment with.

After all the corrections have been made, use /usr/sys/run as a guide to recompile the changed drivers, install them in /usr/sys/lib2 and to assemble the trap vectors (l.s), configuration table (c.c) and machine language assist (m40.s or m45.s). After all this, link edit the objects (ld-I) and if you have an 11/45, sysfix the result. The final object file (a.out) should be renamed /unix and booted. See Boot Procedures-VIII for a discussion of booting. (Note: remember, before booting, always perform a sync-VIII to force delayed output to the disk.)

Special Files

Next you must put in all of the special files in the directory /dev using mknod-VIII. Print the configuration file c.c created above. This is the major device switch of each device class (block and character). There is one line for each device configured in your system and a null line for place holding for those devices not configured. The block special devices are put in first by executing the following generic command for each disk or tape drive. (Note that some of these files already exist in the directory /dev. Examine each file with ls-I with −l flag to see if the file should be removed.)

/etc/mknod /dev/NAME b MAJOR MINOR

The NAME is selected from the following list:

c.c	NAME	device
rf	rf0	RS fixed head disk
tc	tap0	TU56 DECtape
rk	rk0	RK03 RK05 moving head disk
tm	mt0	TU10 TU16 magtape
rp	rp0	RP moving head disk
hs	hs0	RS03 RS04 fixed head disk
hp	hp0	RP04 moving head disk

The major device number is selected by counting the line number (from zero) of the device's entry in the block configuration table. Thus the first entry in the table bdevsw would be major device zero.

The minor device is the drive number, unit number or partition as described under each device in section IV. The last digit of the name (all given as 0 in the table above) should reflect the minor device number. For tapes where the unit is dial selectable, a special file may be made for each possible selection.

The same goes for the character devices. Here the names are arbitrary except that devices meant to be used for teletype access should be named /dev/ttyX, where X is any character. The files tty8 (console), mem, kmem, null are already correctly configured.

The disk and magtape drivers provide a 'raw' interface to the device which provides direct transmission between the user's core and the device and allows reading or writing large records. The raw device counts as a character device, and should have the name of the corresponding standard block special file with 'r' prepended. Thus the raw magtape files would be called /dev/rmtX.

When all the special files have been created, care should be taken to change the access modes (chmod-I) on these files to appropriate values.

The Source Disk

You should now extract the source disk. This can be done as described above or the UNIX command dd-I may be used. The disk image begins at block 4100 on the tape, so the command

dd if=/dev/mt0 of=/dev/rk1 count=4000 skip=4100

might be used to extract the disk to RK drive 1.

This disk should be mounted (mount-VIII) on /usr/source; it contains directories of source code. In each directory is a Shell file run that will recompile all the source in the directory. These run files should be consulted whenever you need to recompile.

Floating Point

UNIX only supports the 11/45 FP11-B floating point unit. For machines without this hardware, there is a user subroutine available that will catch illegal instruction traps and interpret floating point operations. (See fptrap-III.) The system as delivered has this code included in all commands that have floating point. This code is never used if the FP hardware is available and therefore does not need to be changed. The penalty is a little bit of disk space and loading time for the few floating commands.

The C compiler in /usr/source/c probably should be changed if floating point is available. The fpp flag in c0t.s should be set and C should be recompiled and reloaded and installed. This allows floating point C programs to be compiled without the −f flag and prevents the floating point interpreter from getting into new floating programs. (See /usr/source/c/run.)

Time Conversion

If your machine is not in the Eastern time zone, you must edit (ed-I) the subroutine /usr/source/s4/ctime.c to reflect your local time. The variable 'timezone' should be changed to reflect the time difference between local time and GMT. For EST, this is 5*60*60; for PST it would be 8*60*60. This routine also contains the names of the standard and Daylight Savings time zone; so 'EST' and 'EDT' might be changed to 'PST' and 'PDT' respectively. Notice that these two names are in upper case and escapes may be needed (tty-IV). Finally, there is a 'daylight' flag; when it is 1 it causes the time to shift to Daylight Savings automatically between the last Sundays in April and October (or other algorithms in 1974 and 1975). Normally this will not have to be reset. After ctime.c has been edited it should be compiled and installed in its library. (See /usr/source/s4/run.) Then you should (at your leisure) recompile and reinstall all programs performing time conversion. These include: (in s1) date, dump, ls, cron, (in s2) mail, pr, restor, who, sa and tp.

Disk Layout

If there are to be more file systems mounted than just the root, use mkfs-VIII to create the new file system and put its mounting in the file /etc/rc (see init-VIII and mount-VIII). (You might look at /etc/rc anyway to see what has been provided for you.)

There are two considerations in deciding how to adjust the arrangement of things on your disks: the most important is making sure there is adequate space for what is required; secondarily, throughput should be maximized. The RK disk (or its image) as distributed has 4000 blocks for file storage, and the remainder of the disk (872 blocks) is set aside for swap space. In our own system, which allows 14 simultaneous users, this amount of swap space is not quite enough, so we use 1872 blocks for this purpose; it is large enough so running out of swap space never occurs.

Many common system programs (C, the editor, the assembler etc.) create intermediate files in the /tmp directory, so the file system where this is stored also should be made large enough to accommodate most high-water marks. In an idle state, we have about 900 free blocks on the file system where /tmp resides, and hit the bottom every few days or so. (This causes a momentary disruption, but not a crash, as swap-space runout does.) All the programs that create files in /tmp try to take care to delete them, but most are not immune to events like being hung up upon, and can leave dregs. The directory should be examined every so often and the old files deleted.

Exhaustion of user-file space is certain to occur now and then; the only mechanisms for controlling this phenomenon are occasional use of du-I and threatening messages of the day and personal letters.

The efficiency with which UNIX is able to use the CPU is largely dictated by the configuration of disk controllers. For general time-sharing applications, the best strategy is to try to split user files, the root directory (including the /tmp directory) and the swap area among three controllers. In our own system, for example, we have user files on an RP, the root on an RF fixed-head disk, and swap on an RK. This is best for us since the RK has a faster transfer rate than the rather slow RF, and in swapping the transfer rate rather than access time is the dominant influence on throughput.

Once you have decided how to make best use of your hardware, the question is how to initialize it. If you have the equipment, the best way to move a file system is to dump it (dump-VIII) to magtape, use mkfs-VIII to create the new file system, and restore the tape. If you don't have magtape, dump accepts an

argument telling where to put the dump; you might use another disk or DECtape. Sometimes a file system has to be increased in logical size without copying. The super-block of the device has a word giving the highest address which can be allocated. For relatively small increases, this word can be patched using the debugger (db-I) and the free list reconstructed using icheck-VIII. The size should not be increased very greatly by this technique, however, since although the allocatable space will increase the maximum number of files will not (that is, the i-list size can't be changed). Read and understand the description given in file system-VI before playing around in this way.

If you have only an RP disk, see section rp-IV for some suggestions on how to lay out the information on it. The file systems distributed on tape, containing the binary, the source, and the manuals, are each only 4000 blocks long. Perhaps the simplest way to integrate the latter two into a large file system is to extract the tape into the upper part of the RP, dump it, and restore it into an empty, non-overlapping file system structure. If you have to merge a file system into another, existing one, the best bet is to use ncheck-VIII to get a list of names, then edit this list into a sequence of mkdir and cp commands which will serve as input to the Shell. (But notice that owner information is lost.)

New Users

Install new users by editing the password file /etc/passwd (passwd-V). You'll have to make current directories for the new users and change their owners to the newly installed name. Login as each user to make sure the password file is correctly edited. For example:

```
ed /etc/passwd
$a
joe::10:1::/usr/joe:
.
w
q
mkdir /usr/joe
chown joe /usr/joe
login joe
ls −la
login root
```

This will make a new login entry for joe. His default current directory is /usr/joe which has been created. The delivered password file has the user *ken* in it to be used as a prototype.

Multiple Users

If UNIX is to support simultaneous access from more than just the console teletype, the file /etc/ttys (ttys-V) has to be edited. For some historical reason tty8 is the name of the console typewriter. To add new typewriters be sure the device is configured and the special file exists, then set the first character of the appropriate line of /etc/ttys to 1 (or add a new line). Note that init.c will have to be recompiled if there are to be more than 20 typewriters. Also note that if the special file is inaccessible when init tries to create a process for it, the system will thrash trying and retrying to open it.

File System Health

Periodically (say every day or so) and always after a crash, you should check all the file systems for consistency (icheck, dcheck-VIII). It is quite important to execute sync (VIII) before rebooting or taking the machine down. This is done automatically every 30 seconds by the update program (VIII) when a multiple-user system is running, but you should do it anyway to make sure.

Dumping of the file system should be done regularly, since once the system is going it is very easy to become complacent. Just remember that our RP controller has failed three times, each time in such a way that all information on the disk was wiped out without any error status from the controller. Complete and incremental dumps are easily done with the dump command (VIII) but restoration of individual files is painful. Dumping of files by name is best done by tp (I) but the number of files is limited. Finally if there are enough drives entire disks can be copied using cp-I, or preferably with dd-I using the raw special files

and an appropriate block size. Note that there is no stand-alone program with UNIX that will restore any of these formats. Unless some action has been taken to prevent destruction of a running version of UNIX, you can find yourself stranded even though you have backup.

Odds and Ends

The programs dump, icheck, dcheck, ncheck, and df (source in /usr/source/s1 and /usr/source/s2) should be changed to reflect your default mounted file system devices. Print the first few lines of these programs and the changes will be obvious.

If you would like to share any UNIX compatible software with others, please let us know about it. If you find bugs in the software or the documentation, again let us know.

Lastly, there is a UNIX users' group forming. To get on their mailing list, send your name(s) and address to:

Prof. Melvin Ferentz
Physics Dept.
Brooklyn College of CUNY
Brooklyn, N.Y. 11210

Good luck.
Ken Thompson
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The UNIX Time-Sharing System

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ABSTRACT

UNIX is a general-purpose, multi-user, interactive operating system for the Digital Equipment Corporation PDP-11/40, 11/45 and 11/70 computers. It offers a number of features seldom found even in larger operating systems, including

1. A hierarchical file system incorporating demountable volumes,
2. Compatible file, device, and inter-process I/O,
3. The ability to initiate asynchronous processes,
4. System command language selectable on a per-user basis,
5. Over 100 subsystems including a dozen languages.

This paper discusses the nature and implementation of the file system and of the user command interface.

1. Introduction

There have been three versions of UNIX. The earliest version (circa 1969-70) ran on the Digital Equipment Corporation PDP-7 and -9 computers. The second version ran on the unprotected PDP-11/20 computer. This paper describes only the PDP-11/40, /45 and /70[1] system, since it is more modern and many of the differences between it and older UNIX systems result from redesign of features found to be deficient or lacking.

Since PDP-11 UNIX became operational in February, 1971, about 100 installations have been put into service; they are generally smaller than the system described here. Most of them are engaged in applications such as the preparation and formatting of patent applications and other textual material, the collection and processing of trouble data from various switching machines within the Bell System, and recording and checking telephone service orders. Our own installation is used mainly for research in operating systems, languages, computer networks, and other topics in computer science, and also for document preparation.

This is a revised version of an article appearing in the Communications of the ACM, Volume 17, Number 7 (July 1974) pp. 365-375. That article is a revised version of a paper presented at the Fourth ACM Symposium on Operating Systems Principles, IBM Thomas J. Watson Research Center, Yorktown Heights, New York, October 15-17, 1973.

Perhaps the most important achievement of UNIX is to demonstrate that a powerful operating system for interactive use need not be expensive either in equipment or in human effort: UNIX can run on hardware costing as little as $40,000, and less than two man-years were spent on the main system software. Yet UNIX contains a number of features seldom offered even in much larger systems. Hopefully, however, the users of UNIX will find that the most important characteristics of the system are its simplicity, elegance, and ease of use.

Besides the system proper, the major programs available under UNIX are

assembler,
text editor based on QED[2],
linking loader,
symbolic debugger,
compiler for a language resembling BCPL[3] with types and structures (C),
interpreter for a dialect of BASIC,
phototypesetting and equation setting programs
Fortran compiler,
Snobol interpreter,
top-down compiler-compiler (TMG[4]),
bottom-up compiler-compiler (YACC),
form letter generator,
macro processor (M6[5]),
permuted index program.

There is also a host of maintenance, utility, recreation and novelty programs. All of these programs were written locally. It is worth noting that the system is totally self-supporting. All UNIX software is maintained under UNIX; likewise, this paper and all other UNIX documents were generated and formatted by the UNIX editor and text formatting program.

2. Hardware and software environment

The PDP-11/45 on which our UNIX installation is implemented is a 16-bit word (8-bit byte) computer with 112K bytes of core memory; UNIX occupies 53K bytes. This system, however, includes a very large number of device drivers and enjoys a generous allotment of space for I/O buffers and system tables; a minimal system capable of running the software mentioned above can require as little as 64K bytes of core altogether.

Our PDP-11 has a 1M byte fixed-head disk, used for file system storage and swapping, four moving-head disk drives which each provide 2.5M bytes on removable disk cartridges, and a single moving-head disk drive which uses removable 40M byte disk packs. There are also a high-speed paper tape reader-punch, nine-track magnetic tape, and DECtape (a variety of magnetic tape facility in which individual records may be addressed and rewritten). Besides the console typewriter, there are 30 variable-speed communications interfaces attached to 100-series datasets and a 201 dataset interface used primarily for spooling printout to a communal line printer. There are also several one-of-a-kind devices including a Picturephone® interface, a voice response unit, a voice synthesizer, a phototypesetter, a digital switching network, and a satellite PDP-11/20 which generates vectors, curves, and characters on a Tektronix 611 storage-tube display.

The greater part of UNIX software is written in the above-mentioned C language[6]. Early versions of the operating system were written in assembly language, but during the summer of 1973, it was rewritten in C. The size of the new system is about one third greater than the old. Since the new system is not only much easier to understand and to modify but also includes many functional improvements, including multiprogramming and the ability to share reentrant code among several user programs, we considered this increase in size quite acceptable.

3. The File system

The most important role of UNIX is to provide a file system. From the point of view of the user, there are three kinds of files: ordinary disk files, directories, and special files.

3.1 Ordinary files

A file contains whatever information the user places on it, for example symbolic or binary (object) programs. No particular structuring is expected by the system. Files of text consist simply of a string of characters, with lines demarcated by the new-line character. Binary programs are sequences of words as they will appear in core memory when the program starts executing. A few user programs manipulate files with more structure; for example, the assembler generates, and the loader expects, an object file in a particular format. However, the structure of files is controlled by the programs which use them, not by the system.

3.2 Directories

Directories provide the mapping between the names of files and the files themselves, and thus induce a structure on the file system as a whole. Each user has a directory of his own files; he may also create subdirectories to contain groups of files conveniently treated together. A directory behaves exactly like an ordinary file except that it cannot be written on by unprivileged programs, so that the system controls the contents of directories. However, anyone with appropriate permission may read a directory just like any other file.

The system maintains several directories for its own use. One of these is the *root* directory. All files in the system can be found by tracing a path through a chain of directories until the desired file is reached. The starting point for such searches is often the root. Another system directory contains all the programs provided for general use; that is, all the *commands*. As will be seen, however, it is by no means necessary that a program reside in this directory for it to be executed.

Files are named by sequences of 14 or fewer characters. When the name of a file is specified to the system, it may be in the form of a *path name,* which is a sequence of directory names separated by slashes "/" and ending in a file name. If the sequence begins with a slash, the search begins in the root directory. The name */alpha/beta/gamma* causes the system to search the root for directory *alpha,* then to search *alpha* for *beta,* finally to find *gamma* in *beta*. *Gamma* may be an ordinary file, a directory, or a special file. As a limiting case, the name "/" refers to the root itself.

A path name not starting with "/" causes the system to begin the search in the user's current directory. Thus, the name *alpha/beta* specifies the file named *beta* in subdirectory *alpha* of the current directory. The simplest kind of name, for example *alpha*, refers to a file which itself is found in the current directory. As another limiting case, the null file name refers to the current directory.

The same non-directory file may appear in several directories under possibly different names. This feature is called *linking;* a directory entry for a file is sometimes called a link. UNIX differs from other systems in which linking is permitted in that all links to a file have equal status. That is, a file does not exist within a particular directory; the directory entry for a file consists merely of its name and a pointer to the information actually describing the file. Thus a file exists independently of any directory entry, although in practice a file is made to disappear along with the last link to it.

Each directory always has at least two entries. The name "**.**" in each directory refers to the directory itself. Thus a program may read the current directory under the name "**.**" without knowing its complete path name. The name "**..**" by convention refers to the parent of the directory in which it appears, that is, to the directory in which it was created.

The directory structure is constrained to have the form of a rooted tree. Except for the special entries "**.**" and "**..**", each directory must appear as an entry in exactly one other, which is its parent. The reason for this is to simplify the writing of programs which visit subtrees of the directory structure, and more important, to avoid the separation of portions of the hierarchy. If arbitrary links to directories were permitted, it would be quite difficult to detect when the last connection from the root to a directory was severed.

3.3 Special files

Special files constitute the most unusual feature of the UNIX file system. Each I/O device supported by UNIX is associated with at least one such file. Special files are read and written just like ordinary disk files, but requests to read or write result in activation of the associated device. An entry for each special file resides in directory */dev,* although a link may be made to one of these files just like an ordinary file. Thus, for example, to punch paper tape, one may write on the file */dev/ppt*. Special files exist for each communication line, each disk, each tape drive, and for physical core memory. Of course, the active disks and the core special file are protected from indiscriminate access.

There is a threefold advantage in treating I/O devices this way: file and device I/O are as similar as possible; file and device names have the same syntax and meaning, so that a program expecting a file name as a parameter can be passed a device name; finally, special files are subject to the same protection mechanism as regular files.

3.4 Removable file systems

Although the root of the file system is always stored on the same device, it is not necessary that the entire file system hierarchy reside on this device. There is a *mount* system request which has two arguments: the name of an existing ordinary file, and the name of a special file whose associated storage volume (e. g. disk pack) should have the structure of an independent file system containing its own directory hierarchy. The effect of *mount* is to cause references to the heretofore ordinary file to refer instead to the root directory of the file system on the removable volume. In effect, *mount* replaces a leaf of the hierarchy tree (the ordinary file) by a whole new subtree (the hierarchy stored on the removable volume). After the *mount*, there is virtually no distinction between files on the removable volume and those in the permanent file system. In our installation, for example, the root directory resides on the fixed-head disk, and the large disk drive, which contains user's files, is mounted by the system initialization program; the four smaller disk drives are available to users for mounting their own disk packs. A mountable file system is generated by writing on its corresponding special file. A utility program is available to create an empty file system, or one may simply copy an existing file system.

There is only one exception to the rule of identical treatment of files on different devices: no link may exist between one file system hierarchy and another. This restriction is enforced so as to avoid the elaborate bookkeeping which would otherwise be required to assure removal of the links when the removable volume is finally dismounted. In particular, in the root directories of all file systems, removable or not, the name "**..**" refers to the directory itself instead of to its parent.

3.5 Protection

Although the access control scheme in UNIX is quite simple, it has some unusual features. Each user of the system is assigned a unique user identification number. When a file is created, it is marked with the user ID of its owner. Also given for new files is a set of seven protection bits. Six of these specify independently read, write, and execute permission for the owner of the file and for all other users.

If the seventh bit is on, the system will temporarily change the user identification of the current user to that of the creator of the file whenever the file is executed as a program. This change in user ID is effective only during the execution of the program which calls for it. The set-user-ID feature provides for privileged programs which may use files inaccessible to other users. For example, a program may keep an accounting file which should neither be read nor changed except by the program itself. If the set-user-identification bit is on for the program, it may access the file although this access might be forbidden to other programs invoked by the given program's user. Since the actual user ID of the invoker of any program is always available, set-user-ID programs may take any measures desired to satisfy themselves as to their invoker's credentials. This mechanism is used to allow users to execute the carefully-written commands which call privileged system entries. For example, there is a system entry invokable only by the "super-user" (below) which creates an empty directory. As indicated above, directories are expected to have entries for "**.**" and "**..**". The command which creates a directory is owned by the super-user and has the set-user-ID bit set. After it checks its invoker's authorization to create the specified directory, it creates it and makes the entries for "**.**" and "**..**".

Since anyone may set the set-user-ID bit on one of his own files, this mechanism is generally available without administrative intervention. For example, this protection scheme easily solves the MOO accounting problem posed in

[7].

The system recognizes one particular user ID (that of the ‘‘super-user’’) as exempt from the usual constraints on file access; thus (for example) programs may be written to dump and reload the file system without unwanted interference from the protection system.

3.6 I/O calls

The system calls to do I/O are designed to eliminate the differences between the various devices and styles of access. There is no distinction between ‘‘random’’ and ‘‘sequential’’ I/O, nor is any logical record size imposed by the system. The size of an ordinary file is determined by the highest byte written on it; no predetermination of the size of a file is necessary or possible.

To illustrate the essentials of I/O in UNIX, some of the basic calls are summarized below in an anonymous language which will indicate the required parameters without getting into the complexities of machine language programming. Each call to the system may potentially result in an error return, which for simplicity is not represented in the calling sequence.

To read or write a file assumed to exist already, it must be opened by the following call:

filep = open (name, flag)

Name indicates the name of the file. An arbitrary path name may be given. The *flag* argument indicates whether the file is to be read, written, or ‘‘updated,’’ that is read and written simultaneously.

The returned value *filep* is called a *file descriptor.* It is a small integer used to identify the file in subsequent calls to read, write or otherwise manipulate the file.

To create a new file or completely rewrite an old one, there is a *create* system call which creates the given file if it does not exist, or truncates it to zero length if it does exist. *Create* also opens the new file for writing and, like *open,* returns a file descriptor.

There are no user-visible locks in the file system, nor is there any restriction on the number of users who may have a file open for reading or writing. Although it is possible for the contents of a file to become scrambled when two users write on it simultaneously, in practice difficulties do not arise. We take the view that locks are neither necessary nor sufficient, in our environment, to prevent interference between users of the same file. They are unnecessary because we are not faced with large, single-file data bases maintained by independent processes. They are insufficient because locks in the ordinary sense, whereby one user is prevented from writing on a file which another user is reading, cannot prevent confusion when, for example, both users are editing a file with an editor which makes a copy of the file being edited.

It should be said that the system has sufficient internal interlocks to maintain the logical consistency of the file system when two users engage simultaneously in such inconvenient activities as writing on the same file, creating files in the same directory, or deleting each other’s open files.

Except as indicated below, reading and writing are sequential. This means that if a particular byte in the file was the last byte written (or read), the next I/O call implicitly refers to the first following byte. For each open file there is a pointer, maintained by the system, which indicates the next byte to be read or written. If *n* bytes are read or written, the pointer advances by *n* bytes.

Once a file is open, the following calls may be used.

n = read (filep, buffer, count)

n = write (filep, buffer, count)

Up to *count* bytes are transmitted between the file specified by *filep* and the byte array specified by *buffer.* The returned value *n* is the number of bytes actually transmitted. In the *write* case, *n* is the same as *count* except under exceptional conditions like I/O errors or end of physical medium on special files; in a *read,* however, *n* may without error be less than *count.* If the read pointer is so near the end of the file that reading *count* characters would cause reading beyond the end, only sufficient bytes are transmitted to reach the end of the file; also, typewriter-like devices

never return more than one line of input. When a *read* call returns with *n* equal to zero, it indicates the end of the file. For disk files this occurs when the read pointer becomes equal to the current size of the file. It is possible to generate an end-of-file from a typewriter by use of an escape sequence which depends on the device used.

Bytes written on a file affect only those implied by the position of the write pointer and the count; no other part of the file is changed. If the last byte lies beyond the end of the file, the file is grown as needed.

To do random (direct access) I/O it is only necessary to move the read or write pointer to the appropriate location in the file.

location = seek (filep, offset, base)

The pointer associated with *filep* is moved to a position *offset* bytes from the beginning of the file, from the current position of the pointer, or from the end of the file, depending on *base. Offset* may be negative. For some devices (e.g. paper tape and typewriters) seek calls are ignored. The actual offset from the beginning of the file to which the pointer was moved is returned in *location.*

3.6.1 Other I/O calls

There are several additional system entries having to do with I/O and with the file system which will not be discussed. For example: close a file, get the status of a file, change the protection mode or the owner of a file, create a directory, make a link to an existing file, delete a file.

4. Implementation of the file system

As mentioned in §3.2 above, a directory entry contains only a name for the associated file and a pointer to the file itself. This pointer is an integer called the *i-number* (for index number) of the file. When the file is accessed, its i-number is used as an index into a system table (the *i-list*) stored in a known part of the device on which the directory resides. The entry thereby found (the file's *i-node*) contains the description of the file:

1. its owner;
2. its protection bits;
3. the physical disk or tape addresses for the file contents;
4. its size;
5. time of last modification;
6. the number of links to the file; that is, the number of times it appears in a directory;
7. a bit indicating whether the file is a directory;
8. a bit indicating whether the file is a special file;
9. a bit indicating whether the file is "large" or "small."

The purpose of an *open* or *create* system call is to turn the path name given by the user into an i-number by searching the explicitly or implicitly named directories. Once a file is open, its device, i-number, and read/write pointer are stored in a system table indexed by the file descriptor returned by the *open* or *create.* Thus the file descriptor supplied during a subsequent call to read or write the file may be easily related to the information necessary to access the file.

When a new file is created, an i-node is allocated for it and a directory entry is made which contains the name of the file and the i-node number. Making a link to an existing file involves creating a directory entry with the new name, copying the i-number from the original file entry, and incrementing the link-count field of the i-node. Removing (deleting) a file is done by decrementing the link-count of the i-node specified by its directory entry and erasing the directory entry. If the link-count drops to 0, any disk blocks in the file are freed and the i-node is deallocated.

The space on all fixed or removable disks which contain a file system is divided into a number of 512-byte blocks logically addressed from 0 up to a limit which depends on the device. There is space in the i-node of each file for eight device addresses. A *small* (non-special) file fits into eight or fewer blocks; in this case the addresses of the blocks themselves are stored. For *large* (non-special) files, seven of the eight device addresses may point to indirect blocks each containing 256 addresses for the data blocks of the file. If required, the eighth word is the address of a

double-indirect block containing 256 more addresses of indirect blocks. Thus files may conceptually grow to (7+256)·256·512 bytes; actually they are restricted to 16,777,216 (2^{24}) bytes. Once opened, a small file (size 1 to 8 blocks) can be accessed directly. A large file (size 9 to 32768 blocks) requires one additional access to read below logical block 1792 (7·256) and two additional references above 1792.

The foregoing discussion applies to ordinary files. When an I/O request is made to a file whose i-node indicates that it is special, the last seven device address words are immaterial, and the first is interpreted as a pair of bytes which constitute an internal *device name.* These bytes specify respectively a device type and subdevice number. The device type indicates which system routine will deal with I/O on that device; the subdevice number selects, for example, a disk drive attached to a particular controller or one of several similar typewriter interfaces.

In this environment, the implementation of the *mount* system call (§3.4) is quite straightforward. *Mount* maintains a system table whose argument is the i-number and device name of the ordinary file specified during the *mount,* and whose corresponding value is the device name of the indicated special file. This table is searched for each (i-number, device)-pair which turns up while a path name is being scanned during an *open* or *create;* if a match is found, the i-number is replaced by 1 (which is the i-number of the root directory on all file systems), and the device name is replaced by the table value.

To the user, both reading and writing of files appear to be synchronous and unbuffered. That is, immediately after return from a *read* call the data are available, and conversely after a *write* the user's workspace may be reused. In fact the system maintains a rather complicated buffering mechanism which reduces greatly the number of I/O operations required to access a file. Suppose a *write* call is made specifying transmission of a single byte. UNIX will search its buffers to see whether the affected disk block currently resides in core memory; if not, it will be read in from the device. Then the affected byte is replaced in the buffer and an entry is made in a list of blocks to be written. The return from the *write* call may then take place, although the actual I/O may not be completed until a later time. Conversely, if a single byte is read, the system determines whether the secondary storage block in which the byte is located is already in one of the system's buffers; if so, the byte can be returned immediately. If not, the block is read into a buffer and the byte picked out.

The system recognizes when a program has made accesses to sequential blocks of a file, and asynchronously pre-reads the next block. This significantly reduces the running time of most programs while adding little to system overhead.

A program which reads or writes files in units of 512 bytes has an advantage over a program which reads or writes a single byte at a time, but the gain is not immense; it comes mainly from the avoidance of system overhead. A program which is used rarely or which does no great volume of I/O may quite reasonably read and write in units as small as it wishes.

The notion of the i-list is an unusual feature of UNIX. In practice, this method of organizing the file system has proved quite reliable and easy to deal with. To the system itself, one of its strengths is the fact that each file has a short, unambiguous name which is related in a simple way to the protection, addressing, and other information needed to access the file. It also permits a quite simple and rapid algorithm for checking the consistency of a file system, for example verification that the portions of each device containing useful information and those free to be allocated are disjoint and together exhaust the space on the device. This algorithm is independent of the directory hierarchy, since it need only scan the linearly-organized i-list. At the same time the notion of the i-list induces certain peculiarities not found in other file system organizations. For example, there is the question of who is to be charged for the space a file occupies, since all directory entries for a file have equal status. Charging the owner of a file is unfair in general, since one user may create a file, another may link to it, and the first user may delete the file. The first user is still the owner of the file, but it should be charged to the second user. The simplest reasonably fair algorithm seems to be to spread the charges equally among users who have links to a file. The current version of UNIX avoids the issue by not charging any fees at all.

4.1 Efficiency of the file system

To provide an indication of the overall efficiency of UNIX and of the file system in particular, timings were made of the assembly of a 8848-line program. The assembly was run alone on the machine; the total clock time was 32 seconds, for a rate of 276 lines per second. The time was divided as follows: 66% assembler execution time, 21% system overhead, 13% disk wait time. We will not attempt any interpretation of these figures nor any comparison with other systems, but merely note that we are generally satisfied with the overall performance of the system.

5. Processes and images

An *image* is a computer execution environment. It includes a core image, general register values, status of open files, current directory and the like. An image is the current state of a pseudo-computer.

A *process* is the execution of an image. While the processor is executing on behalf of a process, the image must reside in core; during the execution of other processes it remains in core unless the appearance of an active, higher-priority process forces it to be swapped out to the fixed-head disk.

The user-core part of an image is divided into three logical segments. The program text segment begins at location 0 in the virtual address space. During execution, this segment is write-protected and a single copy of it is shared among all processes executing the same program. At the first 8K byte boundary above the program text segment in the virtual address space begins a non-shared, writable data segment, the size of which may be extended by a system call. Starting at the highest address in the virtual address space is a stack segment, which automatically grows downward as the hardware's stack pointer fluctuates.

5.1 Processes

Except while UNIX is bootstrapping itself into operation, a new process can come into existence only by use of the *fork* system call:

processid = fork (label)

When *fork* is executed by a process, it splits into two independently executing processes. The two processes have independent copies of the original core image, and share any open files. The new processes differ only in that one is considered the parent process: in the parent, control returns directly from the *fork*, while in the child, control is passed to location *label.* The *processid* returned by the *fork* call is the identification of the other process.

Because the return points in the parent and child process are not the same, each image existing after a *fork* may determine whether it is the parent or child process.

5.2 Pipes

Processes may communicate with related processes using the same system *read* and *write* calls that are used for file system I/O. The call

filep = pipe ( )

returns a file descriptor *filep* and creates an inter-process channel called a *pipe*. This channel, like other open files, is passed from parent to child process in the image by the *fork* call. A *read* using a pipe file descriptor waits until another process writes using the file descriptor for the same pipe. At this point, data are passed between the images of the two processes. Neither process need know that a pipe, rather than an ordinary file, is involved.

Although inter-process communication via pipes is a quite valuable tool (see §6.2), it is not a completely general mechanism, since the pipe must be set up by a common ancestor of the processes involved.

5.3 Execution of programs

Another major system primitive is invoked by

execute (file, arg_1, arg_2, . . . , arg_n)

which requests the system to read in and execute the program named by *file*, passing it string arguments arg_1, arg_2,

. . . , arg_n. All the code and data in the process using *execute* is replaced from the *file*, but open files, current directory, and inter-process relationships are unaltered. Only if the call fails, for example because *file* could not be found or because its execute-permission bit was not set, does a return take place from the *execute* primitive; it resembles a "jump" machine instruction rather than a subroutine call.

5.4 Process synchronization

Another process control system call

processid = wait ( )

causes its caller to suspend execution until one of its children has completed execution. Then *wait* returns the *processid* of the terminated process. An error return is taken if the calling process has no descendants. Certain status from the child process is also available.

5.5 Termination

Lastly,

exit (status)

terminates a process, destroys its image, closes its open files, and generally obliterates it. When the parent is notified through the *wait* primitive, the indicated *status* is available to the parent. Processes may also terminate as a result of various illegal actions or user-generated signals (§7 below).

6. The Shell

For most users, communication with UNIX is carried on with the aid of a program called the Shell. The Shell is a command line interpreter: it reads lines typed by the user and interprets them as requests to execute other programs. In simplest form, a command line consists of the command name followed by arguments to the command, all separated by spaces:

command arg_1 arg_2 . . . arg_n

The Shell splits up the command name and the arguments into separate strings. Then a file with name *command* is sought; *command* may be a path name including the "/" character to specify any file in the system. If *command* is found, it is brought into core and executed. The arguments collected by the Shell are accessible to the command. When the command is finished, the Shell resumes its own execution, and indicates its readiness to accept another command by typing a prompt character.

If file *command* cannot be found, the Shell prefixes the string */bin/* to *command* and attempts again to find the file. Directory */bin* contains all the commands intended to be generally used.

6.1 Standard I/O

The discussion of I/O in §3 above seems to imply that every file used by a program must be opened or created by the program in order to get a file descriptor for the file. Programs executed by the Shell, however, start off with two open files which have file descriptors 0 and 1. As such a program begins execution, file 1 is open for writing, and is best understood as the standard output file. Except under circumstances indicated below, this file is the user's typewriter. Thus programs which wish to write informative or diagnostic information ordinarily use file descriptor 1. Conversely, file 0 starts off open for reading, and programs which wish to read messages typed by the user usually read this file.

The Shell is able to change the standard assignments of these file descriptors from the user's typewriter printer and keyboard. If one of the arguments to a command is prefixed by ">", file descriptor 1 will, for the duration of the command, refer to the file named after the ">". For example,

ls

ordinarily lists, on the typewriter, the names of the files in the current directory. The command

```
ls >there
```

creates a file called *there* and places the listing there. Thus the argument ‘‘>there’’ means, ‘‘place output on *there*.’’ On the other hand,

```
ed
```

ordinarily enters the editor, which takes requests from the user via his typewriter. The command

```
ed <script
```

interprets *script* as a file of editor commands; thus ‘‘<script’’ means, ‘‘take input from *script*.’’

Although the file name following ‘‘<’’ or ‘‘>’’ appears to be an argument to the command, in fact it is interpreted completely by the Shell and is not passed to the command at all. Thus no special coding to handle I/O redirection is needed within each command; the command need merely use the standard file descriptors 0 and 1 where appropriate.

6.2 Filters

An extension of the standard I/O notion is used to direct output from one command to the input of another. A sequence of commands separated by vertical bars causes the Shell to execute all the commands simultaneously and to arrange that the standard output of each command be delivered to the standard input of the next command in the sequence. Thus in the command line

```
ls | pr −2 | opr
```

ls lists the names of the files in the current directory; its output is passed to *pr*, which paginates its input with dated headings. The argument ‘‘−2’’ means double column. Likewise the output from *pr* is input to *opr*. This command spools its input onto a file for off-line printing.

This procedure could have been carried out more clumsily by

```
ls >temp1
pr −2 <temp1 >temp2
opr <temp2
```

followed by removal of the temporary files. In the absence of the ability to redirect output and input, a still clumsier method would have been to require the *ls* command to accept user requests to paginate its output, to print in multi-column format, and to arrange that its output be delivered off-line. Actually it would be surprising, and in fact unwise for efficiency reasons, to expect authors of commands such as *ls* to provide such a wide variety of output options.

A program such as *pr* which copies its standard input to its standard output (with processing) is called a *filter*. Some filters which we have found useful perform character transliteration, sorting of the input, and encryption and decryption.

6.3 Command Separators; Multitasking

Another feature provided by the Shell is relatively straightforward. Commands need not be on different lines; instead they may be separated by semicolons.

```
ls; ed
```

will first list the contents of the current directory, then enter the editor.

A related feature is more interesting. If a command is followed by ‘‘&’’, the Shell will not wait for the command to finish before prompting again; instead, it is ready immediately to accept a new command. For example,

```
as source >output &
```

causes *source* to be assembled, with diagnostic output going to *output;* no matter how long the assembly takes, the Shell returns immediately. When the Shell does not wait for the completion of a command, the identification of the

process running that command is printed. This identification may be used to wait for the completion of the command or to terminate it. The "&" may be used several times in a line:

```
as source >output & ls >files &
```

does both the assembly and the listing in the background. In the examples above using "&", an output file other than the typewriter was provided; if this had not been done, the outputs of the various commands would have been intermingled.

The Shell also allows parentheses in the above operations. For example

```
( date; ls ) >x &
```

prints the current date and time followed by a list of the current directory onto the file *x*. The Shell also returns immediately for another request.

6.4 The Shell as a Command; Command Files

The Shell is itself a command, and may be called recursively. Suppose file *tryout* contains the lines

```
as source
mv a.out testprog
testprog
```

The *mv* command causes the file *a.out* to be renamed *testprog*. *A.out* is the (binary) output of the assembler, ready to be executed. Thus if the three lines above were typed on the console, *source* would be assembled, the resulting program renamed *testprog*, and *testprog* executed. When the lines are in *tryout*, the command

```
sh <tryout
```

would cause the Shell *sh* to execute the commands sequentially.

The Shell has further capabilities, including the ability to substitute parameters and to construct argument lists from a specified subset of the file names in a directory. It is also possible to execute commands conditionally on character string comparisons or on existence of given files and to perform transfers of control within filed command sequences.

6.5 Implementation of the Shell

The outline of the operation of the Shell can now be understood. Most of the time, the Shell is waiting for the user to type a command. When the new-line character ending the line is typed, the Shell's *read* call returns. The Shell analyzes the command line, putting the arguments in a form appropriate for *execute*. Then *fork* is called. The child process, whose code of course is still that of the Shell, attempts to perform an *execute* with the appropriate arguments. If successful, this will bring in and start execution of the program whose name was given. Meanwhile, the other process resulting from the *fork*, which is the parent process, *wait* s for the child process to die. When this happens, the Shell knows the command is finished, so it types its prompt and reads the typewriter to obtain another command.

Given this framework, the implementation of background processes is trivial; whenever a command line contains "&", the Shell merely refrains from waiting for the process which it created to execute the command.

Happily, all of this mechanism meshes very nicely with the notion of standard input and output files. When a process is created by the *fork* primitive, it inherits not only the core image of its parent but also all the files currently open in its parent, including those with file descriptors 0 and 1. The Shell, of course, uses these files to read command lines and to write its prompts and diagnostics, and in the ordinary case its children_the command programs_inherit them automatically. When an argument with "<" or ">" is given however, the offspring process, just before it performs *execute,* makes the standard I/O file descriptor 0 or 1 respectively refer to the named file. This is easy because, by agreement, the smallest unused file descriptor is assigned when a new file is *open* ed (or *create* d); it is only necessary to close file 0 (or 1) and open the named file. Because the process in which the command program runs simply terminates when it is through, the association between a file specified after "<" or ">" and file descriptor 0 or 1 is ended automatically when the process dies. Therefore the Shell need not know the actual names of the

files which are its own standard input and output, since it need never reopen them.

Filters are straightforward extensions of standard I/O redirection with pipes used instead of files.

In ordinary circumstances, the main loop of the Shell never terminates. (The main loop includes that branch of the return from *fork* belonging to the parent process; that is, the branch which does a *wait*, then reads another command line.) The one thing which causes the Shell to terminate is discovering an end-of-file condition on its input file. Thus, when the Shell is executed as a command with a given input file, as in

```
sh <comfile
```

the commands in *comfile* will be executed until the end of *comfile* is reached; then the instance of the Shell invoked by *sh* will terminate. Since this Shell process is the child of another instance of the Shell, the *wait* executed in the latter will return, and another command may be processed.

6.6 Initialization

The instances of the Shell to which users type commands are themselves children of another process. The last step in the initialization of UNIX is the creation of a single process and the invocation (via *execute*) of a program called *init*. The role of *init* is to create one process for each typewriter channel which may be dialed up by a user. The various subinstances of *init* open the appropriate typewriters for input and output. Since when *init* was invoked there were no files open, in each process the typewriter keyboard will receive file descriptor 0 and the printer file descriptor 1. Each process types out a message requesting that the user log in and waits, reading the typewriter, for a reply. At the outset, no one is logged in, so each process simply hangs. Finally someone types his name or other identification. The appropriate instance of *init* wakes up, receives the log-in line, and reads a password file. If the user name is found, and if he is able to supply the correct password, *init* changes to the user's default current directory, sets the process's user ID to that of the person logging in, and performs an *execute* of the Shell. At this point the Shell is ready to receive commands and the logging-in protocol is complete.

Meanwhile, the mainstream path of *init* (the parent of all the subinstances of itself which will later become Shells) does a *wait*. If one of the child processes terminates, either because a Shell found an end of file or because a user typed an incorrect name or password, this path of *init* simply recreates the defunct process, which in turn reopens the appropriate input and output files and types another login message. Thus a user may log out simply by typing the end-of-file sequence in place of a command to the Shell.

6.7 Other programs as Shell

The Shell as described above is designed to allow users full access to the facilities of the system, since it will invoke the execution of any program with appropriate protection mode. Sometimes, however, a different interface to the system is desirable, and this feature is easily arranged.

Recall that after a user has successfully logged in by supplying his name and password, *init* ordinarily invokes the Shell to interpret command lines. The user's entry in the password file may contain the name of a program to be invoked after login instead of the Shell. This program is free to interpret the user's messages in any way it wishes.

For example, the password file entries for users of a secretarial editing system specify that the editor *ed* is to be used instead of the Shell. Thus when editing system users log in, they are inside the editor and can begin work immediately; also, they can be prevented from invoking UNIX programs not intended for their use. In practice, it has proved desirable to allow a temporary escape from the editor to execute the formatting program and other utilities.

Several of the games (e.g., chess, blackjack, 3D tic-tac-toe) available on UNIX illustrate a much more severely restricted environment. For each of these an entry exists in the password file specifying that the appropriate game-playing program is to be invoked instead of the Shell. People who log in as a player of one of the games find themselves limited to the game and unable to investigate the presumably more interesting offerings of UNIX as a whole.

7. Traps

The PDP-11 hardware detects a number of program faults, such as references to non-existent memory, unimplemented instructions, and odd addresses used where an even address is required. Such faults cause the processor to trap to a system routine. When an illegal action is caught, unless other arrangements have been made, the system terminates the process and writes the user's image on file *core* in the current directory. A debugger can be used to determine the state of the program at the time of the fault.

Programs which are looping, which produce unwanted output, or about which the user has second thoughts may be halted by the use of the *interrupt* signal, which is generated by typing the ''delete'' character. Unless special action has been taken, this signal simply causes the program to cease execution without producing a core image file.

There is also a *quit* signal which is used to force a core image to be produced. Thus programs which loop unexpectedly may be halted and the core image examined without prearrangement.

The hardware-generated faults and the interrupt and quit signals can, by request, be either ignored or caught by the process. For example, the Shell ignores quits to prevent a quit from logging the user out. The editor catches interrupts and returns to its command level. This is useful for stopping long printouts without losing work in progress (the editor manipulates a copy of the file it is editing). In systems without floating point hardware, unimplemented instructions are caught and floating point instructions are interpreted.

8. Perspective

Perhaps paradoxically, the success of UNIX is largely due to the fact that it was not designed to meet any predefined objectives. The first version was written when one of us (Thompson), dissatisfied with the available computer facilities, discovered a little-used PDP-7 and set out to create a more hospitable environment. This essentially personal effort was sufficiently successful to gain the interest of the remaining author and others, and later to justify the acquisition of the PDP-11/20, specifically to support a text editing and formatting system. When in turn the 11/20 was outgrown, UNIX had proved useful enough to persuade management to invest in the PDP-11/45. Our goals throughout the effort, when articulated at all, have always concerned themselves with building a comfortable relationship with the machine and with exploring ideas and inventions in operating systems. We have not been faced with the need to satisfy someone else's requirements, and for this freedom we are grateful.

Three considerations which influenced the design of UNIX are visible in retrospect.

First: since we are programmers, we naturally designed the system to make it easy to write, test, and run programs. The most important expression of our desire for programming convenience was that the system was arranged for interactive use, even though the original version only supported one user. We believe that a properly-designed interactive system is much more productive and satisfying to use than a ''batch'' system. Moreover such a system is rather easily adaptable to non-interactive use, while the converse is not true.

Second: there have always been fairly severe size constraints on the system and its software. Given the partially antagonistic desires for reasonable efficiency and expressive power, the size constraint has encouraged not only economy but a certain elegance of design. This may be a thinly disguised version of the ''salvation through suffering'' philosophy, but in our case it worked.

Third: nearly from the start, the system was able to, and did, maintain itself. This fact is more important than it might seem. If designers of a system are forced to use that system they quickly become aware of its functional and superficial deficiencies and are strongly motivated to correct them before it is too late. Since all source programs were always available and easily modified on-line, we were willing to revise and rewrite the system and its software when new ideas were invented, discovered, or suggested by others.

The aspects of UNIX discussed in this paper exhibit clearly at least the first two of these design considerations. The interface to the file system, for example, is extremely convenient from a programming standpoint. The lowest possible interface level is designed to eliminate distinctions between the various devices and files and between direct and sequential access. No large ''access method'' routines are required to insulate the programmer from the system calls; in fact all user programs either call the system directly or use a small library program, only tens of instructions long, which buffers a number of characters and reads or writes them all at once.

Another important aspect of programming convenience is that there are no ‘‘control blocks’’ with a complicated structure partially maintained by and depended on by the file system or other system calls. Generally speaking, the contents of a program's address space are the property of the program, and we have tried to avoid placing restrictions on the data structures within that address space.

Given the requirement that all programs should be usable with any file or device as input or output, it is also desirable from a space-efficiency standpoint to push device-dependent considerations into the operating system itself. The only alternatives seem to be to load routines for dealing with each device with all programs, which is expensive in space, or to depend on some means of dynamically linking to the routine appropriate to each device when it is actually needed, which is expensive either in overhead or in hardware.

Likewise, the process control scheme and command interface have proved both convenient and efficient. Since the Shell operates as an ordinary, swappable user program, it consumes no wired-down space in the system proper, and it may be made as powerful as desired at little cost. In particular, given the framework in which the Shell executes as a process which spawns other processes to perform commands, the notions of I/O redirection, background processes, command files, and user-selectable system interfaces all become essentially trivial to implement.

8.1 Influences

The success of UNIX lies not so much in new inventions but rather in the full exploitation of a carefully selected set of fertile ideas, and especially in showing that they can be keys to the implementation of a small yet powerful operating system.

The *fork* operation, essentially as we implemented it, was present in the Berkeley time sharing system[8]. On a number of points we were influenced by Multics, which suggested the particular form of the I/O system calls[9] and both the name of the Shell and its general functions. The notion that the Shell should create a process for each command was also suggested to us by the early design of Multics, although in that system it was later dropped for efficiency reasons. A similar scheme is used by TENEX[10].

9. Statistics

The following numbers are presented to suggest the scale of our operation. Those of our users not involved in document preparation tend to use the system for program development, especially language work. There are few important ‘‘applications’’ programs.

Overall, we have

100	user population
14	maximum simultaneous users
380	directories
4800	files
66300	512-byte secondary storage blocks used

There is a ‘‘background’’ process that runs at the lowest possible priority; it is used to soak up any idle CPU time. It has been used to produce a million-digit approximation to the constant $e-2$, and is now solving all rook-and-pawn vs. rook chess endgames. Not counting this background work, we average daily

2400	commands
5.5	CPU hours
100	connect hours
32	different users
100	logins

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References

1. Digital Equipment Corporation. *PDP-11/40 Processor Handbook* (1972), *PDP-11/45 Processor Handbook* (1971), and *PDP-11/70 Processor Handbook* (1975).
2. Deutsch, L.P., and Lampson, B.W. An online editor. *Comm. ACM 10,* 12 (Dec. 1967), 793-799, 803.
3. Richards, M. BCPL: A tool for compiler writing and system programming. Proc. AFIPS 1969 SJCC, Vol. 34, AFIPS Press, Montvale, N.J., pp. 557-566.
4. McClure, R.M. TMG—A syntax directed compiler. Proc. ACM 20th Nat. Conf., ACM, 1965, New York, pp. 262-274.
5. Hall, A.D. The M6 macroprocessor. Computing Science Tech. Rep. #2, Bell Telephone Laboratories, 1969.
6. Ritchie, D.M. C reference manual. Unpublished memorandum, Bell Telephone Laboratories (1973).
7. Aleph-null. Computer Recreations. *Software Practice and Experience 1,* 2 (Apr.-June 1971), 201-204.
8. Deutch, L.P. and Lampson, B.W. SDS 930 time-sharing system preliminary reference manual. Doc. 30.10.10, Project GENIE, Univ. Cal. at Berkeley (Apr. 1965).
9. Feiertag, R.J., and Organick, E.I. The Multics input-output system. Proc. Third Symposium on Operating Systems Principles. Oct. 18-20, 1971, ACM, New York, pp. 35-41.
10. Bobrow, D.G., Burchfiel, J.D., Murphy, D.L., and Tomlinson, R.S. TENEX, a paged time sharing system for the PDP-10. *Comm. ACM 15.,* 3 (March 1972) 135-143.

C Reference Manual

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1. Introduction

C is a computer language based on the earlier language B [1]. The languages and their compilers differ in two major ways: C introduces the notion of types, and defines appropriate extra syntax and semantics; also, C on the PDP-11 is a true compiler, producing machine code where B produced interpretive code.

Most of the software for the UNIX time-sharing system [2] is written in C, as is the operating system itself. C is also available on the HIS 6070 computer at Murray Hill and and on the IBM System/370 at Holmdel [3]. This paper is a manual only for the C language itself as implemented on the PDP-11. However, hints are given occasionally in the text of implementation-dependent features.

The UNIX Programmer's Manual [4] describes the library routines available to C programs under UNIX, and also the procedures for compiling programs under that system. ''The GCOS C Library'' by Lesk and Barres [5] describes routines available under that system as well as compilation procedures. Many of these routines, particularly the ones having to do with I/O, are also provided under UNIX. Finally, ''Programming in C– A Tutorial,'' by B. W. Kernighan [6], is as useful as promised by its title and the author's previous introductions to allegedly impenetrable subjects.

2. Lexical conventions

There are six kinds of tokens: identifiers, keywords, constants, strings, expression operators, and other separators. In general blanks, tabs, newlines, and comments as described below are ignored except as they serve to separate tokens. At least one of these characters is required to separate otherwise adjacent identifiers, constants, and certain operator-pairs.

If the input stream has been parsed into tokens up to a given character, the next token is taken to include the longest string of characters which could possibly constitute a token.

2.1 Comments

The characters `/*` introduce a comment, which terminates with the characters `*/`.

2.2 Identifiers (Names)

An identifier is a sequence of letters and digits; the first character must be alphabetic. The underscore ''_'' counts as alphabetic. Upper and lower case letters are considered different. No more than the first eight characters are significant, and only the first seven for external identifiers.

2.3 Keywords

The following identifiers are reserved for use as keywords, and may not be used otherwise:

```
int                     break
char                    continue
float                   if
double                  else
struct                  for
auto                    do
extern                  while
register                switch
static                  case
goto                    default
return                  entry
sizeof
```

The `entry` keyword is not currently implemented by any compiler but is reserved for future use.

2.3 Constants

There are several kinds of constants, as follows:

2.3.1 Integer constants

An integer constant is a sequence of digits. An integer is taken to be octal if it begins with `0`, decimal otherwise. The digits `8` and `9` have octal value 10 and 11 respectively.

2.3.2 Character constants

A character constant is 1 or 2 characters enclosed in single quotes " ´ ". Within a character constant a single quote must be preceded by a back-slash "\". Certain non-graphic characters, and "\" itself, may be escaped according to the following table:

BS	\b
NL	\n
CR	\r
HT	\t
ddd	*ddd*
\	\\

The escape "*ddd*" consists of the backslash followed by 1, 2, or 3 octal digits which are taken to specify the value of the desired character. A special case of this construction is "\0" (not followed by a digit) which indicates a null character.

Character constants behave exactly like integers (not, in particular, like objects of character type). In conformity with the addressing structure of the PDP-11, a character constant of length 1 has the code for the given character in the low-order byte and 0 in the high-order byte; a character constant of length 2 has the code for the first character in the low byte and that for the second character in the high-order byte. Character constants with more than one character are inherently machine-dependent and should be avoided.

2.3.3 Floating constants

A floating constant consists of an integer part, a decimal point, a fraction part, an `e`, and an optionally signed integer exponent. The integer and fraction parts both consist of a sequence of digits. Either the integer part or the fraction part (not both) may be missing; either the decimal point or the `e` and the exponent (not both) may be missing. Every floating constant is taken to be double-precision.

2.4 Strings

A string is a sequence of characters surrounded by double quotes " **"** ". A string has the type array-of-characters (see below) and refers to an area of storage initialized with the given characters. The compiler places a null byte (\0) at the end of each string so that programs which scan the string can find its end. In a string, the character " **"** " must be preceded by a "\" ; in addition, the same escapes as described for character constants may be used.

3. Syntax notation

In the syntax notation used in this manual, syntactic categories are indicated by *italic* type, and literal words and characters in `gothic`. Alternatives are listed on separate lines. An optional terminal or non-terminal symbol is indicated by the subscript "opt," so that

{ expression$_{opt}$ *}*

would indicate an optional expression in braces.

4. What's in a Name?

C bases the interpretation of an identifier upon two attributes of the identifier: its *storage class* and its *type.* The storage class determines the location and lifetime of the storage associated with an identifier; the type determines the meaning of the values found in the identifier's storage.

There are four declarable storage classes: automatic, static, external, and register. Automatic variables are local to each invocation of a function, and are discarded on return; static variables are local to a function, but retain their values independently of invocations of the function; external variables are independent of any function. Register variables are stored in the fast registers of the machine; like automatic variables they are local to each function and disappear on return.

C supports four fundamental types of objects: characters, integers, single-, and double-precision floating-point numbers.

Characters (declared, and hereinafter called, `char`) are chosen from the ASCII set; they occupy the rightmost seven bits of an 8-bit byte. It is also possible to interpret `char`s as signed, 2's complement 8-bit numbers.

Integers (`int`) are represented in 16-bit 2's complement notation.

Single precision floating point (`float`) quantities have magnitude in the range approximately $10^{\pm 38}$ or 0; their precision is 24 bits or about seven decimal digits.

Double-precision floating-point (`double`) quantities have the same range as `float`s and a precision of 56 bits or about 17 decimal digits.

Besides the four fundamental types there is a conceptually infinite class of derived types constructed from the fundamental types in the following ways:

arrays of objects of most types;

functions which return objects of a given type;

pointers to objects of a given type;

structures containing objects of various types.

In general these methods of constructing objects can be applied recursively.

5. Objects and lvalues

An object is a manipulatable region of storage; an lvalue is an expression referring to an object. An obvious example of an lvalue expression is an identifier. There are operators which yield lvalues: for example, if E is an expression of pointer type, then ∗E is an lvalue expression referring to the object to which E points. The name "lvalue" comes from the assignment expression "E1 = E2" in which the left operand E1 must be an lvalue expression. The discussion of each operator below indicates whether it expects lvalue operands and whether it yields an lvalue.

6. Conversions

A number of operators may, depending on their operands, cause conversion of the value of an operand from one type to another. This section explains the result to be expected from such conversions.

6.1 Characters and integers

A `char` object may be used anywhere an `int` may be. In all cases the `char` is converted to an `int` by propagating its sign through the upper 8 bits of the resultant integer. This is consistent with the two's complement representation used for both characters and integers. (However, the sign-propagation feature disappears in other implementations.)

6.2 Float and double

All floating arithmetic in C is carried out in double-precision; whenever a `float` appears in an expression it is lengthened to `double` by zero-padding its fraction. When a `double` must be converted to `float`, for example by an assignment, the `double` is rounded before truncation to `float` length.

6.3 Float and double; integer and character

All `int`s and `char`s may be converted without loss of significance to `float` or `double`. Conversion of `float` or `double` to `int` or `char` takes place with truncation towards 0. Erroneous results can be expected if the magnitude of the result exceeds 32,767 (for `int`) or 127 (for `char`).

6.4 Pointers and integers

Integers and pointers may be added and compared; in such a case the `int` is converted as specified in the discussion of the addition operator.

Two pointers to objects of the same type may be subtracted; in this case the result is converted to an integer as specified in the discussion of the subtraction operator.

7. Expressions

The precedence of expression operators is the same as the order of the major subsections of this section (highest precedence first). Thus the expressions referred to as the operands of + (§7.4) are those expressions defined in §§7.1—7.3. Within each subsection, the operators have the same precedence. Left- or right-associativity is specified in each subsection for the operators discussed therein. The precedence and associativity of all the expression operators is summarized in an appendix.

Otherwise the order of evaluation of expressions is undefined. In particular the compiler considers itself free to compute subexpressions in the order it believes most efficient, even if the subexpressions involve side effects.

7.1 Primary expressions

Primary expressions involving `.`, `->`, subscripting, and function calls group left to right.

7.1.1 *identifier*

An identifier is a primary expression, provided it has been suitably declared as discussed below. Its type is specified by its declaration. However, if the type of the identifier is "array of ...", then the value of the identifier-expression is a pointer to the first object in the array, and the type of the expression is "pointer to ...". Moreover, an array identifier is not an lvalue expression.

Likewise, an identifier which is declared "function returning ...", when used except in the function-name position of a call, is converted to "pointer to function returning ...".

7.1.2 *constant*

A decimal, octal, character, or floating constant is a primary expression. Its type is `int` in the first three cases, `double` in the last.

7.1.3 *string*

A string is a primary expression. Its type is originally "array of `char`"; but following the same rule as in §7.1.1 for identifiers, this is modified to "pointer to `char`" and the result is a pointer to the first character in the string.

7.1.4 (*expression*)

A parenthesized expression is a primary expression whose type and value are identical to those of the unadorned expression. The presence of parentheses does not affect whether the expression is an lvalue.

7.1.5 *primary-expression* `[` *expression* `]`

A primary expression followed by an expression in square brackets is a primary expression. The intuitive meaning is that of a subscript. Usually, the primary expression has type "pointer to ...", the subscript expression is `int`, and the type of the result is "...". The expression "E1[E2]" is identical (by definition) to "*((E1)+(E2))". All the clues needed to understand this notation are contained in this section together with the discussions in §§ 7.1.1, 7.2.1, and 7.4.1 on identifiers, *, and + respectively; §14.3 below summarizes the implications.

7.1.6 *primary-expression* `(` $expression\text{-}list_{opt}$ `)`

A function call is a primary expression followed by parentheses containing a possibly empty, comma-separated list of expressions which constitute the actual arguments to the function. The primary expression must be of type "function returning ...", and the result of the function call is of type "...". As indicated below, a hitherto unseen identifier followed immediately by a left parenthesis is contextually declared to represent a function returning an integer; thus in the most common case, integer-valued functions need not be declared.

Any actual arguments of type `float` are converted to `double` before the call; any of type `char` are converted to `int`.

In preparing for the call to a function, a copy is made of each actual parameter; thus, all argument-passing in C is strictly by value. A function may change the values of its formal parameters, but these changes cannot possibly affect the values of the actual parameters. On the other hand, it is perfectly possible to pass a pointer on the understanding that the function may change the value of the object to which the pointer points.

Recursive calls to any function are permissible.

7.1.7 *primary-lvalue* `.` *member-of-structure*

An lvalue expression followed by a dot followed by the name of a member of a structure is a primary expression. The object referred to by the lvalue is assumed to have the same form as the structure containing the structure member. The result of the expression is an lvalue appropriately offset from the origin of the given lvalue whose type is that of the named structure member. The given lvalue is not required to have any particular type.

Structures are discussed in §8.5.

7.1.8 *primary-expression* `->` *member-of-structure*

The primary-expression is assumed to be a pointer which points to an object of the same form as the structure of which the member-of-structure is a part. The result is an lvalue appropriately offset from the origin of the pointed-to structure whose type is that of the named structure member. The type of the primary-expression need not in fact be pointer; it is sufficient that it be a pointer, character, or integer.

Except for the relaxation of the requirement that E1 be of pointer type, the expression "E1->MOS" is exactly equivalent to "(*E1).MOS".

7.2 Unary operators

Expressions with unary operators group right-to-left.

7.2.1 `*` *expression*

The unary * operator means *indirection:* the expression must be a pointer, and the result is an lvalue referring to the object to which the expression points. If the type of the expression is "pointer to ...", the type of the result is "...".

7.2.2 `&` *lvalue-expression*

The result of the unary `&` operator is a pointer to the object referred to by the lvalue-expression. If the type of the lvalue-expression is "...", the type of the result is "pointer to ...".

7.2.3 `-` *expression*

The result is the negative of the expression, and has the same type. The type of the expression must be `char`, `int`, `float`, or `double`.

7.2.4 `!` *expression*

The result of the logical negation operator `!` is 1 if the value of the expression is 0, 0 if the value of the expression is non-zero. The type of the result is `int`. This operator is applicable only to `int`s or `char`s.

7.2.5 `~` *expression*

The ~ operator yields the one's complement of its operand. The type of the expression must be `int` or `char`, and the result is `int`.

7.2.6 ++ *lvalue-expression*

The object referred to by the lvalue expression is incremented. The value is the new value of the lvalue expression and the type is the type of the lvalue. If the expression is `int` or `char`, it is incremented by 1; if it is a pointer to an object, it is incremented by the length of the object. ++ is applicable only to these types. (Not, for example, to `float` or `double`.)

7.2.7 –– *lvalue-expression*

The object referred to by the lvalue expression is decremented analogously to the ++ operator.

7.2.8 *lvalue-expression* ++

The result is the value of the object referred to by the lvalue expression. After the result is noted, the object referred to by the lvalue is incremented in the same manner as for the prefix ++ operator: by 1 for an `int` or `char`, by the length of the pointed-to object for a pointer. The type of the result is the same as the type of the lvalue-expression.

7.2.9 *lvalue-expression* ––

The result of the expression is the value of the object referred to by the the lvalue expression. After the result is noted, the object referred to by the lvalue expression is decremented in a way analogous to the postfix ++ operator.

7.2.10 `sizeof` *expression*

The `sizeof` operator yields the size, in bytes, of its operand. When applied to an array, the result is the total number of bytes in the array. The size is determined from the declarations of the objects in the expression. This expression is semantically an integer constant and may be used anywhere a constant is required. Its major use is in communication with routines like storage allocators and I/O systems.

7.3 Multiplicative operators

The multiplicative operators `*`, `/`, and `%` group left-to-right.

7.3.1 *expression* `*` *expression*

The binary `*` operator indicates multiplication. If both operands are `int` or `char`, the result is `int`; if one is `int` or `char` and one `float` or `double`, the former is converted to `double`, and the result is `double`; if both are `float` or `double`, the result is `double`. No other combinations are allowed.

7.3.2 *expression* / *expression*

The binary / operator indicates division. The same type considerations as for multiplication apply.

7.3.3 *expression* `%` *expression*

The binary `%` operator yields the remainder from the division of the first expression by the second. Both operands must be `int` or `char`, and the result is `int`. In the current implementation, the remainder has the same sign as the dividend.

7.4 Additive operators

The additive operators + and – group left-to-right.

7.4.1 *expression* + *expression*

The result is the sum of the expressions. If both operands are `int` or `char`, the result is `int`. If both are `float` or `double`, the result is `double`. If one is `char` or `int` and one is `float` or `double`, the former is converted to `double` and the result is `double`. If an `int` or `char` is added to a pointer, the former is converted by multiplying it by the length of the object to which the pointer points and the result is a pointer of the same type as the original pointer. Thus if P is a pointer to an object, the expression "P+1" is a pointer to another object of the same type as the first and immediately following it in storage.

No other type combinations are allowed.

7.4.2 *expression* − *expression*

The result is the difference of the operands. If both operands are `int`, `char`, `float`, or `double`, the same type considerations as for + apply. If an `int` or `char` is subtracted from a pointer, the former is converted in the same way as explained under + above.

If two pointers to objects of the same type are subtracted, the result is converted (by division by the length of the object) to an `int` representing the number of objects separating the pointed-to objects. This conversion will in general give unexpected results unless the pointers point to objects in the same array, since pointers, even to objects of the same type, do not necessarily differ by a multiple of the object-length.

7.5 Shift operators

The shift operators << and >> group left-to-right.

7.5.1 *expression* << *expression*
7.5.2 *expression* >> *expression*

Both operands must be `int` or `char`, and the result is `int`. The second operand should be non-negative. The value of "E1<<E2" is E1 (interpreted as a bit pattern 16 bits long) left-shifted E2 bits; vacated bits are 0-filled. The value of "E1>>E2" is E1 (interpreted as a two's complement, 16-bit quantity) arithmetically right-shifted E2 bit positions. Vacated bits are filled by a copy of the sign bit of E1. [Note: the use of arithmetic rather than logical shift does not survive transportation between machines.]

7.6 Relational operators

The relational operators group left-to-right, but this fact is not very useful; "a<b<c" does not mean what it seems to.

7.6.1 *expression* < *expression*
7.6.2 *expression* > *expression*
7.6.3 *expression* <= *expression*
7.6.4 *expression* >= *expression*

The operators < (less than), > (greater than), <= (less than or equal to) and >= (greater than or equal to) all yield 0 if the specified relation is false and 1 if it is true. Operand conversion is exactly the same as for the + operator except that pointers of any kind may be compared; the result in this case depends on the relative locations in storage of the pointed-to objects. It does not seem to be very meaningful to compare pointers with integers other than 0.

7.7 Equality operators

7.7.1 *expression* == *expression*
7.7.2 *expression* != *expression*

The == (equal to) and the != (not equal to) operators are exactly analogous to the relational operators except for their lower precedence. (Thus "a<b == c<d" is 1 whenever a<b and c<d have the same truth-value).

7.8 *expression* & *expression*

The & operator groups left-to-right. Both operands must be `int` or `char`; the result is an `int` which is the bitwise logical `and` function of the operands.

7.9 *expression* ^ *expression*

The ^ operator groups left-to-right. The operands must be `int` or `char`; the result is an `int` which is the bit-wise exclusive `or` function of its operands.

7.10 *expression* | *expression*

The | operator groups left-to-right. The operands must be `int` or `char`; the result is an `int` which is the bit-wise inclusive `or` of its operands.

7.11 *expression* && *expression*

The && operator returns 1 if both its operands are non-zero, 0 otherwise. Unlike &, && guarantees left-to-right evaluation; moreover the second operand is not evaluated if the first operand is 0.

The operands need not have the same type, but each must have one of the fundamental types or be a pointer.

7.12 *expression* || *expression*

The || operator returns 1 if either of its operands is non-zero, and 0 otherwise. Unlike |, || guarantees left-to-right evaluation; moreover, the second operand is not evaluated if the value of the first operand is non-zero.

The operands need not have the same type, but each must have one of the fundamental types or be a pointer.

7.13 *expression* ? *expression* : *expression*

Conditional expressions group left-to-right. The first expression is evaluated and if it is non-zero, the result is the value of the second expression, otherwise that of third expression. If the types of the second and third operand are the same, the result has their common type; otherwise the same conversion rules as for + apply. Only one of the second and third expressions is evaluated.

7.14 Assignment operators

There are a number of assignment operators, all of which group right-to-left. All require an lvalue as their left operand, and the type of an assignment expression is that of its left operand. The value is the value stored in the left operand after the assignment has taken place.

7.14.1 *lvalue* = *expression*

The value of the expression replaces that of the object referred to by the lvalue. The operands need not have the same type, but both must be `int`, `char`, `float`, `double`, or pointer. If neither operand is a pointer, the assignment takes place as expected, possibly preceded by conversion of the expression on the right.

When both operands are `int` or pointers of any kind, no conversion ever takes place; the value of the expression is simply stored into the object referred to by the lvalue. Thus it is possible to generate pointers which will cause addressing exceptions when used.

7.14.2 *lvalue* =+ *expression*
7.14.3 *lvalue* =− *expression*
7.14.4 *lvalue* =∗ *expression*
7.14.5 *lvalue* =/ *expression*
7.14.6 *lvalue* =% *expression*
7.14.7 *lvalue* =>> *expression*
7.14.8 *lvalue* =<< *expression*
7.14.9 *lvalue* =& *expression*
7.14.10 *lvalue* =^ *expression*
7.14.11 *lvalue* =| *expression*

The behavior of an expression of the form "E1 =op E2" may be inferred by taking it as equivalent to "E1 = E1 op E2"; however, E1 is evaluated only once. Moreover, expressions like "i =+ p" in which a pointer is added to an integer, are forbidden.

7.15 *expression* , *expression*

A pair of expressions separated by a comma is evaluated left-to-right and the value of the left expression is discarded. The type and value of the result are the type and value of the right operand. This operator groups left-to-right. It should be avoided in situations where comma is given a special meaning, for example in actual arguments to function calls (§7.1.6) and lists of initializers (§10.2).

8. Declarations

Declarations are used within function definitions to specify the interpretation which C gives to each identifier; they do not necessarily reserve storage associated with the identifier. Declarations have the form

declaration:
decl-specifiers declarator-list$_{opt}$;

The declarators in the declarator-list contain the identifiers being declared. The decl-specifiers consist of at most one type-specifier and at most one storage class specifier.

decl-specifiers:
type-specifier
sc-specifier
type-specifier sc-specifier
sc-specifier type-specifier

8.1 Storage class specifiers

The sc-specifiers are:

sc-specifier:
`auto`
`static`
`extern`
`register`

The `auto`, `static`, and `register` declarations also serve as definitions in that they cause an appropriate amount of storage to be reserved. In the `extern` case there must be an external definition (see below) for the given identifiers somewhere outside the function in which they are declared.

There are some severe restrictions on `register` identifiers: there can be at most 3 register identifiers in any function, and the type of a register identifier can only be `int`, `char`, or pointer (not `float`, `double`, structure, function, or array). Also the address-of operator `&` cannot be applied to such identifiers. Except for these restrictions (in return for which one is rewarded with faster, smaller code), register identifiers behave as if they were automatic. In fact implementations of C are free to treat `register` as synonymous with `auto`.

If the sc-specifier is missing from a declaration, it is generally taken to be `auto`.

8.2 Type specifiers

The type-specifiers are

type-specifier:
`int`
`char`
`float`
`double`
`struct` *{ type-decl-list }*
`struct` *identifier { type-decl-list }*
`struct` *identifier*

The `struct` specifier is discussed in §8.5. If the type-specifier is missing from a declaration, it is generally taken to be `int`.

8.3 Declarators

The declarator-list appearing in a declaration is a comma-separated sequence of declarators.

declarator-list:
declarator
declarator , *declarator-list*

The specifiers in the declaration indicate the type and storage class of the objects to which the declarators refer. Declarators have the syntax:

declarator:
identifier
∗ *declarator*
declarator ( )
declarator [*constant-expression*$_{opt}$]
(*declarator*)

The grouping in this definition is the same as in expressions.

8.4 Meaning of declarators

Each declarator is taken to be an assertion that when a construction of the same form as the declarator appears in an expression, it yields an object of the indicated type and storage class. Each declarator contains exactly one identifier; it is this identifier that is declared.

If an unadorned identifier appears as a declarator, then it has the type indicated by the specifier heading the declaration.

If a declarator has the form

∗ D

for D a declarator, then the contained identifier has the type "pointer to ...", where "..." is the type which the identifier would have had if the declarator had been simply D.

If a declarator has the form

D ( )

then the contained identifier has the type "function returning ...", where "..." is the type which the identifier would have had if the declarator had been simply D.

A declarator may have the form

D[constant-expression]

or

D[ ]

In the first case the constant expression is an expression whose value is determinable at compile time, and whose type is `int`. in the second the constant 1 is used. (Constant expressions are defined precisely in §15.) Such a declarator makes the contained identifier have type "array." If the unadorned declarator D would specify a non-array of type "...", then the declarator "D[i]" yields a 1-dimensional array with rank i of objects of type "...". If the unadorned declarator D would specify an n-dimensional array with rank $i_1 \times i_2 \times \ldots \times i_n$, then the declarator "D[i_{n+1}]" yields an $(n+1)$-dimensional array with rank $i_1 \times i_2 \times \ldots \times i_n \times i_{n+1}$.

An array may be constructed from one of the basic types, from a pointer, from a structure, or from another array (to generate a multi-dimensional array).

Finally, parentheses in declarators do not alter the type of the contained identifier except insofar as they alter the binding of the components of the declarator.

Not all the possibilities allowed by the syntax above are actually permitted. The restrictions are as follows: functions may not return arrays, structures or functions, although they may return pointers to such things; there are no arrays of functions, although there may be arrays of pointers to functions. Likewise a structure may not contain a function, but it may contain a pointer to a function.

As an example, the declaration

```
int i, *ip, f(), *fip(), (*pfi)();
```

declares an integer *i*, a pointer *ip* to an integer, a function *f* returning an integer, a function *fip* returning a pointer to an integer, and a pointer *pfi* to a function which returns an integer. Also

```
float fa[17], *afp[17];
```

declares an array of `float` numbers and an array of pointers to `float` numbers. Finally,

```
static int x3d[3][5][7];
```

declares a static three-dimensional array of integers, with rank 3×5×7. In complete detail, *x3d* is an array of three items: each item is an array of five arrays; each of the latter arrays is an array of seven integers. Any of the expressions "x3d", "x3d[i]", "x3d[i][j]", "x3d[i][j][k]" may reasonably appear in an expression. The first three have type "array", the last has type `int`.

8.5 Structure declarations

Recall that one of the forms for a structure specifier is

`struct` *{ type-decl-list }*

The *type-decl-list* is a sequence of type declarations for the members of the structure:

type-decl-list:
type-declaration
type-declaration type-decl-list

A type declaration is just a declaration which does not mention a storage class (the storage class "member of structure" here being understood by context).

type-declaration:
type-specifier declarator-list **;**

Within the structure, the objects declared have addresses which increase as their declarations are read left-to-right. Each component of a structure begins on an addressing boundary appropriate to its type. On the PDP-11 the only requirement is that non-characters begin on a word boundary; therefore, there may be 1-byte, unnamed holes in a structure, and all structures have an even length in bytes.

Another form of structure specifier is

`struct` *identifier { type-decl-list }*

This form is the same as the one just discussed, except that the identifier is remembered as the *structure tag* of the structure specified by the list. A subsequent declaration may then be given using the structure tag but without the list, as in the third form of structure specifier:

`struct` *identifier*

Structure tags allow definition of self-referential structures; they also permit the long part of the declaration to be given once and used several times. It is however absurd to declare a structure which contains an instance of itself, as distinct from a pointer to an instance of itself.

A simple example of a structure declaration, taken from §16.2 where its use is illustrated more fully, is

```
struct tnode {
        char tword[20];
        int count;
        struct tnode *left;
        struct tnode *right;
};
```

which contains an array of 20 characters, an integer, and two pointers to similar structures. Once this declaration has

been given, the following declaration makes sense:

```
struct tnode s, *sp;
```

which declares *s* to be a structure of the given sort and *sp* to be a pointer to a structure of the given sort.

The names of structure members and structure tags may be the same as ordinary variables, since a distinction can be made by context. However, names of tags and members must be distinct. The same member name can appear in different structures only if the two members are of the same type and if their origin with respect to their structure is the same; thus separate structures can share a common initial segment.

9. Statements

Except as indicated, statements are executed in sequence.

9.1 Expression statement

Most statements are expression statements, which have the form

expression **;**

Usually expression statements are assignments or function calls.

9.2 Compound statement

So that several statements can be used where one is expected, the compound statement is provided:

compound-statement:
{ statement-list }

statement-list:
statement
statement statement-list

9.3 Conditional statement

The two forms of the conditional statement are

`if (` *expression* `)` *statement*
`if (` *expression* `)` *statement* `else` *statement*

In both cases the expression is evaluated and if it is non-zero, the first substatement is executed. In the second case the second substatement is executed if the expression is 0. As usual the "else" ambiguity is resolved by connecting an `else` with the last encountered elseless `if`.

9.4 While statement

The `while` statement has the form

`while (` *expression* `)` *statement*

The substatement is executed repeatedly so long as the value of the expression remains non-zero. The test takes place before each execution of the statement.

9.5 Do statement

The `do` statement has the form

`do` *statement* `while (` *expression* `) ;`

The substatement is executed repeatedly until the value of the expression becomes zero. The test takes place after each execution of the statement.

9.6 For statement

The `for` statement has the form

`for ( `*expression-1*$_{opt}$`; `*expression-2*$_{opt}$` ; `*expression-3*$_{opt}$` )` *statement*

This statement is equivalent to

expression-1;
`while (`*expression-2*`) {`
statement
expression-3 `;`
`}`

Thus the first expression specifies initialization for the loop; the second specifies a test, made before each iteration, such that the loop is exited when the expression becomes 0; the third expression typically specifies an incrementation which is performed after each iteration.

Any or all of the expressions may be dropped. A missing *expression-2* makes the implied `while` clause equivalent to "while(1)"; other missing expressions are simply dropped from the expansion above.

9.7 Switch statement

The `switch` statement causes control to be transferred to one of several statements depending on the value of an expression. It has the form

`switch (` *expression* `)` *statement*

The expression must be `int` or `char`. The statement is typically compound. Each statement within the statement may be labelled with case prefixes as follows:

`case` *constant-expression* `:`

where the constant expression must be `int` or `char`. No two of the case constants in a switch may have the same value. Constant expressions are precisely defined in §15.

There may also be at most one statement prefix of the form

`default :`

When the `switch` statement is executed, its expression is evaluated and compared with each case constant in an undefined order. If one of the case constants is equal to the value of the expression, control is passed to the statement following the matched case prefix. If no case constant matches the expression, and if there is a `default` prefix, control passes to the prefixed statement. In the absence of a `default` prefix none of the statements in the switch is executed.

Case or default prefixes in themselves do not alter the flow of control.

9.8 Break statement

The statement

`break ;`

causes termination of the smallest enclosing `while`, `do`, `for`, or `switch` statement; control passes to the statement following the terminated statement.

9.9 Continue statement

The statement

`continue ;`

causes control to pass to the loop-continuation portion of the smallest enclosing `while`, `do`, or `for` statement; that is to the end of the loop. More precisely, in each of the statements

```
while ( . . . ) {          do {                    for ( . . . ) {
   . . .                      . . .                   . . .
contin:;                   contin:;                contin:;
}                          } while ( . . . );      }
```

a `continue` is equivalent to ‘‘goto contin’’.

9.10 Return statement

A function returns to its caller by means of the `return` statement, which has one of the forms

```
return ;
return ( expression ) ;
```

In the first case no value is returned. In the second case, the value of the expression is returned to the caller of the function. If required, the expression is converted, as if by assignment, to the type of the function in which it appears. Flowing off the end of a function is equivalent to a return with no returned value.

9.11 Goto statement

Control may be transferred unconditionally by means of the statement

```
goto expression ;
```

The expression should be a label (§§9.12, 14.4) or an expression of type ‘‘pointer to `int`’’ which evaluates to a label. It is illegal to transfer to a label not located in the current function unless some extra-language provision has been made to adjust the stack correctly.

9.12 Labelled statement

Any statement may be preceded by label prefixes of the form

```
identifier :
```

which serve to declare the identifier as a label. More details on the semantics of labels are given in §14.4 below.

9.13 Null statement

The null statement has the form

```
;
```

A null statement is useful to carry a label just before the ‘‘}’’ of a compound statement or to supply a null body to a looping statement such as `while`.

10. External definitions

A C program consists of a sequence of external definitions. External definitions may be given for functions, for simple variables, and for arrays. They are used both to declare and to reserve storage for objects. An external definition declares an identifier to have storage class `extern` and a specified type. The type-specifier (§8.2) may be empty, in which case the type is taken to be `int`.

10.1 External function definitions

Function definitions have the form

function-definition:
    type-specifier$_{opt}$ *function-declarator function-body*

A function declarator is similar to a declarator for a ‘‘function returning ...’’ except that it lists the formal parameters of the function being defined.

function-declarator:
    declarator `(` *parameter-list*$_{opt}$ `)`

parameter-list:

identifier
identifier , *parameter-list*

The function-body has the form

function-body:
type-decl-list function-statement

The purpose of the type-decl-list is to give the types of the formal parameters. No other identifiers should be declared in this list, and formal parameters should be declared only here.

The function-statement is just a compound statement which may have declarations at the start.

function-statement:
{ declaration-list$_{opt}$ *statement-list }*

A simple example of a complete function definition is

```
int max(a, b, c)
int a, b, c;
{
        int m;
        m = (a>b)? a:b;
        return(m>c? m:c);
}
```

Here "int" is the type-specifier; "max(a, b, c)" is the function-declarator; "int a, b, c;" is the type-decl-list for the formal parameters; "{ ... }" is the function-statement.

C converts all `float` actual parameters to `double`, so formal parameters declared `float` have their declaration adjusted to read `double`. Also, since a reference to an array in any context (in particular as an actual parameter) is taken to mean a pointer to the first element of the array, declarations of formal parameters declared "array of ..." are adjusted to read "pointer to ...". Finally, because neither structures nor functions can be passed to a function, it is useless to declare a formal parameter to be a structure or function (pointers to structures or functions are of course permitted).

A free `return` statement is supplied at the end of each function definition, so running off the end causes control, but no value, to be returned to the caller.

10.2 External data definitions

An external data definition has the form

data-definition:
`extern`$_{opt}$ *type-specifier*$_{opt}$ *init-declarator-list*$_{opt}$;

The optional `extern` specifier is discussed in § 11.2. If given, the init-declarator-list is a comma-separated list of declarators each of which may be followed by an initializer for the declarator.

init-declarator-list:
init-declarator
init-declarator , *init-declarator-list*

init-declarator:
declarator initializer$_{opt}$

Each initializer represents the initial value for the corresponding object being defined (and declared).

initializer:
constant
{ constant-expression-list }

constant-expression-list:
constant-expression
constant-expression , *constant-expression-list*

Thus an initializer consists of a constant-valued expression, or comma-separated list of expressions, inside braces. The braces may be dropped when the expression is just a plain constant. The exact meaning of a constant expression is discussed in §15. The expression list is used to initialize arrays; see below.

The type of the identifier being defined should be compatible with the type of the initializer: a `double` constant may initialize a `float` or `double` identifier; a non-floating-point expression may initialize an `int`, `char`, or pointer.

An initializer for an array may contain a comma-separated list of compile-time expressions. The length of the array is taken to be the maximum of the number of expressions in the list and the square-bracketed constant in the array's declarator. This constant may be missing, in which case 1 is used. The expressions initialize successive members of the array starting at the origin (subscript 0) of the array. The acceptable expressions for an array of type "array of ..." are the same as those for type "...". As a special case, a single string may be given as the initializer for an array of `char`s; in this case, the characters in the string are taken as the initializing values.

Structures can be initialized, but this operation is incompletely implemented and machine-dependent. Basically the structure is regarded as a sequence of words and the initializers are placed into those words. Structure initialization, using a comma-separated list in braces, is safe if all the members of the structure are integers or pointers but is otherwise ill-advised.

The initial value of any externally-defined object not explicitly initialized is guaranteed to be 0.

11. Scope rules

A complete C program need not all be compiled at the same time: the source text of the program may be kept in several files, and precompiled routines may be loaded from libraries. Communication among the functions of a program may be carried out both through explicit calls and through manipulation of external data.

Therefore, there are two kinds of scope to consider: first, what may be called the *lexical scope* of an identifier, which is essentially the region of a program during which it may be used without drawing "undefined identifier" diagnostics; and second, the scope associated with external identifiers, which is characterized by the rule that references to the same external identifier are references to the same object.

11.1 Lexical scope

C is not a block-structured language; this may fairly be considered a defect. The lexical scope of names declared in external definitions extends from their definition through the end of the file in which they appear. The lexical scope of names declared at the head of functions (either as formal parameters or in the declarations heading the statements constituting the function itself) is the body of the function.

It is an error to redeclare identifiers already declared in the current context, unless the new declaration specifies the same type and storage class as already possessed by the identifiers.

11.2 Scope of externals

If a function declares an identifier to be `extern`, then somewhere among the files or libraries constituting the complete program there must be an external definition for the identifier. All functions in a given program which refer to the same external identifier refer to the same object, so care must be taken that the type and extent specified in the definition are compatible with those specified by each function which references the data.

In PDP-11 C, it is explicitly permitted for (compatible) external definitions of the same identifier to be present in several of the separately-compiled pieces of a complete program, or even twice within the same program file, with the important limitation that the identifier may be initialized in at most one of the definitions. In other operating systems, however, the compiler must know in just which file the storage for the identifier is allocated, and in which file the identifier is merely being referred to. In the implementations of C for such systems, the appearance of the `extern` keyword before an external definition indicates that storage for the identifiers being declared will be allocated in another file. Thus in a multi-file program, an external data definition without the `extern` specifier must appear in exactly one of the files. Any other files which wish to give an external definition for the identifier must include the `extern` in the definition. The identifier can be initialized only in the file where storage is allocated.

In PDP-11 C none of this nonsense is necessary and the `extern` specifier is ignored in external definitions.

12. Compiler control lines

When a line of a C program begins with the character `#`, it is interpreted not by the compiler itself, but by a preprocessor which is capable of replacing instances of given identifiers with arbitrary token-strings and of inserting named files into the source program. In order to cause this preprocessor to be invoked, it is necessary that the very first line of the program begin with `#`. Since null lines are ignored by the preprocessor, this line need contain no other information.

12.1 Token replacement

A compiler-control line of the form

`# define` *identifier token-string*

(note: no trailing semicolon) causes the preprocessor to replace subsequent instances of the identifier with the given string of tokens (except within compiler control lines). The replacement token-string has comments removed from it, and it is surrounded with blanks. No rescanning of the replacement string is attempted. This facility is most valuable for definition of ''manifest constants'', as in

```
# define tabsize 100
...
int table[tabsize];
```

12.2 File inclusion

Large C programs often contain many external data definitions. Since the lexical scope of external definitions extends to the end of the program file, it is good practice to put all the external definitions for data at the start of the program file, so that the functions defined within the file need not repeat tedious and error-prone declarations for each external identifier they use. It is also useful to put a heavily used structure definition at the start and use its structure tag to declare the `auto` pointers to the structure used within functions. To further exploit this technique when a large C program consists of several files, a compiler control line of the form

`# include "`*filename*`"`

results in the replacement of that line by the entire contents of the file *filename*.

13. Implicit declarations

It is not always necessary to specify both the storage class and the type of identifiers in a declaration. Sometimes the storage class is supplied by the context: in external definitions, and in declarations of formal parameters and structure members. In a declaration inside a function, if a storage class but no type is given, the identifier is assumed to be `int`; if a type but no storage class is indicated, the identifier is assumed to be `auto`. An exception to the latter rule is made for functions, since `auto` functions are meaningless (C being incapable of compiling code into the stack). If the type of an identifier is ''function returning ...'', it is implicitly declared to be `extern`.

In an expression, an identifier followed by `(` and not currently declared is contextually declared to be ''function returning `int`''.

Undefined identifiers not followed by `(` are assumed to be labels which will be defined later in the function. (Since a label is not an lvalue, this accounts for the ''Lvalue required'' error message sometimes noticed when an undeclared identifier is used.) Naturally, appearance of an identifier as a label declares it as such.

For some purposes it is best to consider formal parameters as belonging to their own storage class. In practice, C treats parameters as if they were automatic (except that, as mentioned above, formal parameter arrays and `floats` are treated specially).

14. Types revisited

This section summarizes the operations which can be performed on objects of certain types.

14.1 Structures

There are only two things that can be done with a structure: pick out one of its members (by means of the `.` or `->` operators); or take its address (by unary `&`). Other operations, such as assigning from or to it or passing it as a parameter, draw an error message. In the future, it is expected that these operations, but not necessarily others, will be allowed.

14.2 Functions

There are only two things that can be done with a function: call it, or take its address. If the name of a function appears in an expression not in the function-name position of a call, a pointer to the function is generated. Thus, to pass one function to another, one might say

```
int f();
...
g(f);
```

Then the definition of *g* might read

```
g(funcp)
int (*funcp)();
{
        ...
        (*funcp)();
        ...
}
```

Notice that *f* was declared explicitly in the calling routine since its first appearance was not followed by `(`.

14.3 Arrays, pointers, and subscripting

Every time an identifier of array type appears in an expression, it is converted into a pointer to the first member of the array. Because of this conversion, arrays are not lvalues. By definition, the subscript operator `[]` is interpreted in such a way that "E1[E2]" is identical to "$*((E1)+(E2))$". Because of the conversion rules which apply to +, if E1 is an array and E2 an integer, then E1[E2] refers to the E2-th member of E1. Therefore, despite its asymmetric appearance, subscripting is a commutative operation.

A consistent rule is followed in the case of multi-dimensional arrays. If E is an n-dimensional array of rank $i \times j \times \ldots \times k$, then E appearing in an expression is converted to a pointer to an $(n-1)$-dimensional array with rank $j \times \ldots \times k$. If the $*$ operator, either explicitly or implicitly as a result of subscripting, is applied to this pointer, the result is the pointed-to $(n-1)$-dimensional array, which itself is immediately converted into a pointer.

For example, consider

```
int x[3][5];
```

Here *x* is a 3×5 array of integers. When *x* appears in an expression, it is converted to a pointer to (the first of three) 5-membered arrays of integers. In the expression "x[i]", which is equivalent to "$*(x+i)$", *x* is first converted to a pointer as described; then *i* is converted to the type of *x*, which involves multiplying *i* by the length the object to which the pointer points, namely 5 integer objects. The results are added and indirection applied to yield an array (of 5 integers) which in turn is converted to a pointer to the first of the integers. If there is another subscript the same argument applies again; this time the result is an integer.

It follows from all this that arrays in C are stored row-wise (last subscript varies fastest) and that the first subscript in the declaration helps determine the amount of storage consumed by an array but plays no other part in subscript calculations.

14.4 Labels

Labels do not have a type of their own; they are treated as having type "array of `int`". Label variables should be declared "pointer to `int`"; before execution of a `goto` referring to the variable, a label (or an expression deriving from a label) should be assigned to the variable.

Label variables are a bad idea in general; the `switch` statement makes them almost always unnecessary.

15. Constant expressions

In several places C requires expressions which evaluate to a constant: after `case`, as array bounds, and in initializers. In the first two cases, the expression can involve only integer constants, character constants, and `sizeof` expressions, possibly connected by the binary operators

```
+ - * / % & | ^ << >>
```

or by the unary operators

```
- ~
```

Parentheses can be used for grouping, but not for function calls.

A bit more latitude is permitted for initializers; besides constant expressions as discussed above, one can also apply the unary `&` operator to external scalars, and to external arrays subscripted with a constant expression. The unary `&` can also be applied implicitly by appearance of unsubscripted external arrays. The rule here is that initializers must evaluate either to a constant or to the address of an external identifier plus or minus a constant.

16. Examples.

These examples are intended to illustrate some typical C constructions as well as a serviceable style of writing C programs.

16.1 Inner product

This function returns the inner product of its array arguments.

```
double inner(v1, v2, n)
double v1[], v2[];
{
        double sum;
        int i;
        sum = 0.0;
        for (i=0; i<n; i++)
                sum =+ v1[i] * v2[i];
        return(sum);
}
```

The following version is somewhat more efficient, but perhaps a little less clear. It uses the facts that parameter arrays are really pointers, and that all parameters are passed by value.

```
double inner(v1, v2, n)
double *v1, *v2;
{
        double sum;
        sum = 0.0;
        while(n--)
                sum =+ *v1++ * *v2++;
        return(sum);
}
```

The declarations for the parameters are really exactly the same as in the last example. In the first case array declarations "`[]`" were given to emphasize that the parameters would be referred to as arrays; in the second, pointer declarations were given because the indirection operator and ++ were used.

16.2 Tree and character processing

Here is a complete C program (courtesy of R. Haight) which reads a document and produces an alphabetized list of words found therein together with the number of occurrences of each word. The method keeps a binary tree of words such that the left descendant tree for each word has all the words lexicographically smaller than the given word, and the right descendant has all the larger words. Both the insertion and the printing routine are recursive.

The program calls the library routines *getchar* to pick up characters and *exit* to terminate execution. *Printf* is

called to print the results according to a format string. A version of *printf* is given below (§16.3).

Because all the external definitions for data are given at the top, no `extern` declarations are necessary within the functions. To stay within the rules, a type declaration is given for each non-integer function when the function is used before it is defined. However, since all such functions return pointers which are simply assigned to other pointers, no actual harm would result from leaving out the declarations; the supposedly `int` function values would be assigned without error or complaint.

```
# define nwords 100                    /* number of different words */
# define wsize 20                      /* max chars per word */
struct tnode {                         /* the basic structure */
      char tword[wsize];
      int count;
      struct tnode *left;
      struct tnode *right;
};

struct tnode space[nwords];            /* the words themselves */
int nnodes nwords;                     /* number of remaining slots */
struct tnode *spacep space;            /* next available slot */
struct tnode *freep;                   /* free list */
/*
* The main routine reads words until end-of-file ('\0' returned from "getchar")
* "tree" is called to sort each word into the tree.
*/
main()
{
      struct tnode *top, *tree();
      char c, word[wsize];
      int i;

      i = top = 0;
      while (c=getchar())
            if ('a'<=c && c<='z' || 'A'<=c && c <='Z') {
                  if (i<wsize-1)
                        word[i++] = c;
            } else
                  if (i) {
                        word[i++] = '\0';
                        top = tree(top, word);
                        i = 0;
                  }
      tprint(top);
}
/*
* The central routine.  If the subtree pointer is null, allocate a new node for it.
* If the new word and the node's word are the same, increase the node's count.
* Otherwise, recursively sort the word into the left or right subtree according
* as the argument word is less or greater than the node's word.
*/
struct tnode *tree(p, word)
struct tnode *p;
char word[];
{
      struct tnode *alloc();
      int cond;

      /* Is pointer null? */
      if (p==0) {
            p = alloc();
```

```
            copy(word, p->tword);
            p->count = 1;
            p->right = p->left = 0;
            return(p);
      }
      /* Is word repeated? */
      if ((cond=compar(p->tword, word)) == 0) {
            p->count++;
            return(p);
      }
      /* Sort into left or right */
      if (cond<0)
            p->left = tree(p->left, word);
      else
            p->right = tree(p->right, word);
      return(p);
}
/*
* Print the tree by printing the left subtree, the given node, and the right subtree
*/
tprint(p)
struct tnode *p;
{
      while (p) {
            tprint(p->left);
            printf("%d:  %s\n", p->count, p->tword);
            p = p->right;
      }
}
/*
* String comparison: return number (>, =, <) 0
* according as s1 (>, =, <) s2.
*/
compar(s1, s2)
char *s1, *s2;
{
      int c1, c2;

      while((c1 = *s1++) == (c2 = *s2++))
            if (c1=='\0')
                  return(0);
      return(c2-c1);
}
/*
* String copy: copy s1 into s2 until the null
* character appears.
*/
copy(s1, s2)
char *s1, *s2;
{
      while(*s2++ = *s1++);
}
/*
* Node allocation: return pointer to a free node.
* Bomb out when all are gone.  Just for fun, there
* is a mechanism for using nodes that have been
* freed, even though no one here calls "free."
*/
struct tnode *alloc()
```

```
{
        struct tnode *t;

        if (freep) {
                t = freep;
                freep = freep->left;
                return(t);
        }
        if (--nnodes < 0) {
                printf("Out of space\n");
                exit();
        }
        return(spacep++);
}
/*
* The uncalled routine which puts a node on the free list.
*/
free(p)
struct tnode *p;
{
        p->left = freep;
        freep = p;
}
```

To illustrate a slightly different technique of handling the same problem, we will repeat fragments of this example with the tree nodes treated explicitly as members of an array. The fundamental change is to deal with the subscript of the array member under discussion, instead of a pointer to it. The `struct` declaration becomes

```
struct tnode {
        char tword[wsize];
        int count;
        int left;
        int right;
};
```

and *alloc* becomes

```
alloc()
{
        int t;

        t = --nnodes;
        if (t<=0) {
                printf("Out of space\n");
                exit();
        }
        return(t);
}
```

The *free* stuff has disappeared because if we deal with exclusively with subscripts some sort of map has to be kept, which is too much trouble.

Now the *tree* routine returns a subscript also, and it becomes:

```
tree(p, word)
char word[];
{
        int cond;

        if (p==0) {
                p = alloc();
                copy(word, space[p].tword);
```

```
                space[p].count = 1;
                space[p].right = space[p].left = 0;
                return(p);
        }
        if ((cond=compar(space[p].tword, word)) == 0) {
                space[p].count++;
                return(p);
        }
        if (cond<0)
                space[p].left = tree(space[p].left, word);
        else
                space[p].right = tree(space[p].right, word);
        return(p);
}
```

The other routines are changed similarly. It must be pointed out that this version is noticeably less efficient than the first because of the multiplications which must be done to compute an offset in *space* corresponding to the subscripts.

The observation that subscripts (like "a[i]") are less efficient than pointer indirection (like "*ap") holds true independently of whether or not structures are involved. There are of course many situations where subscripts are indispensable, and others where the loss in efficiency is worth a gain in clarity.

16.3 Formatted output

Here is a simplified version of the *printf* routine, which is available in the C library. It accepts a string (character array) as first argument, and prints subsequent arguments according to specifications contained in this format string. Most characters in the string are simply copied to the output; two-character sequences beginning with "%" specify that the next argument should be printed in a style as follows:

%d	decimal number
%o	octal number
%c	ASCII character, or 2 characters if upper character is not null
%s	string (null-terminated array of characters)
%f	floating-point number

The actual parameters for each function call are laid out contiguously in increasing storage locations; therefore, a function with a variable number of arguments may take the address of (say) its first argument, and access the remaining arguments by use of subscripting (regarding the arguments as an array) or by indirection combined with pointer incrementation.

If in such a situation the arguments have mixed types, or if in general one wishes to insist that an lvalue should be treated as having a given type, then `struct` declarations like those illustrated below will be useful. It should be evident, though, that such techniques are implementation dependent.

Printf depends as well on the fact that `char` and `float` arguments are widened respectively to `int` and `double`, so there are effectively only two sizes of arguments to deal with. *Printf* calls the library routines *putchar* to write out single characters and *ftoa* to dispose of floating-point numbers.

```
printf(fmt, args)
char fmt[];
{
        char *s;
        struct { char **charpp; };
        struct { double *doublep; };
        int *ap, x, c;

        ap = &args;             /* argument pointer */
        for (;;) {
                while((c = *fmt++) != '%') {
                        if(c == '\0')
                                return;
```

```
                        putchar(c);
                }
                switch (c = *fmt++) {
                /* decimal */
                case 'd':
                        x = *ap++;
                        if(x < 0) {
                                x = -x;
                                if(x<0) {  /* is - infinity */
                                        printf("-32768");
                                        continue;
                                }
                                putchar('-');
                        }
                        printd(x);
                        continue;
                /* octal */
                case 'o':
                        printo(*ap++);
                        continue;
                /* float, double */
                case 'f':
                        /* let ftoa do the real work */
                        ftoa(*ap.doublep++);
                        continue;
                /* character */
                case 'c':
                        putchar(*ap++);
                        continue;
                /* string */
                case 's':
                        s = *ap.charpp++;
                        while(c = *s++)
                                putchar(c);
                        continue;
                }
                putchar(c);
        }
}
/*
* Print n in decimal; n must be non-negative
*/
printd(n)
{
        int a;
        if (a=n/10)
                printd(a);
        putchar(n%10 + '0');
}
/*
* Print n in octal, with exactly 1 leading 0
*/
printo(n)
{
        if (n)
                printo( (n>>3)&017777);
        putchar( (n&07)+'0');
}
```

REFERENCES

1. Johnson, S. C., and Kernighan, B. W. ''The Programming Language B.'' Comp. Sci. Tech. Rep. #8., Bell Laboratories, 1972.

2. Ritchie, D. M., and Thompson, K. L. ''The UNIX Time-sharing System.'' C. ACM 7, 17, July, 1974, pp. 365-375.

3. Peterson, T. G., and Lesk, M. E. ''A User's Guide to the C Language on the IBM 370.'' Internal Memorandum, Bell Laboratories, 1974.

4. Thompson, K. L., and Ritchie, D. M. *UNIX Programmer's Manual.* Bell Laboratories, 1973.

5. Lesk, M. E., and Barres, B. A. ''The GCOS C Library.'' Internal memorandum, Bell Laboratories, 1974.

6. Kernighan, B. W. ''Programming in C– A Tutorial.'' Unpublished internal memorandum, Bell Laboratories, 1974.

APPENDIX 1
Syntax Summary

1. Expressions.

expression:
primary
`*` *expression*
`&` *expression*
`-` *expression*
`!` *expression*
`~`*expression*
`++` *lvalue*
`--` *lvalue*
lvalue `++`
lvalue `--`
`sizeof` *expression*
expression binop expression
expression `?` *expression* `:` *expression*
lvalue asgnop expression
expression `,` *expression*

primary:
identifier
constant
string
`(` *expression* `)`
primary `(` *expression-list*$_{opt}$ `)`
primary `[` *expression* `]`
lvalue `.` *identifier*
primary `->` *identifier*

lvalue:
identifier
primary `[` *expression* `]`
lvalue `.` *identifier*
primary `->` *identifier*
`*` *expression*
`(` *lvalue* `)`

The primary-expression operators

```
()   []   .   ->
```

have highest priority and group left-to-right. The unary operators

```
**   &   -   !   ~   ++ -- sizeof
```

have priority below the primary operators but higher than any binary operator, and group right-to-left. Binary operators and the conditional operator all group left-to-right, and have priority decreasing as indicated:

binop:

```
*      /      %
+      -
>>       <<
<      >      <=      >=
==       !=
&
```

```
^
|
&&
||
?  :
```

Assignment operators all have the same priority, and all group right-to-left.

asgnop:

```
=   =+   =-   =*   =/   =%   =>>   =<<   =&   =^   =|
```

The comma operator has the lowest priority, and groups left-to-right.

2. Declarations.

declaration:
decl-specifiers declarator-list$_{opt}$ **;**

decl-specifiers:
type-specifier
sc-specifier
type-specifier sc-specifier
sc-specifier type-specifier

sc-specifier:
`auto`
`static`
`extern`
`register`

type-specifier:
`int`
`char`
`float`
`double`
`struct { ` *type-decl-list* ` }`
`struct` *identifier* `{` *type-decl-list* `}`
`struct` *identifier*

declarator-list:
declarator
declarator **,** *declarator-list*

declarator:
identifier
`*` *declarator*
declarator `( )`
declarator `[` *constant-expression*$_{opt}$ `]`
`(` *declarator* `)`

type-decl-list:
type-declaration
type-declaration type-decl-list

type-declaration:
type-specifier declarator-list **;**

3. Statements.

statement:
expression **;**
{ statement-list }

`if` (*expression*) *statement*
`if` (*expression*) *statement* `else` *statement*
`while` (*expression*) *statement*
`for` ($expression_{opt}$ `;` $expression_{opt}$ `;` $expression_{opt}$) `statement`
`switch` (*expression*) *statement*
`case` *constant-expression* `:` *statement*
`default` `:` *statement*
`break` `;`
`continue` `;`
`return` `;`
`return` (*expression*) `;`
`goto` *expression* `;`
identifier `:` *statement*
`;`

statement-list:
statement
statement statement-list

4. External definitions.

program:
external-definition
external-definition program

external-definition:
function-definition
data-definition

function-definition:
$type\text{-}specifier_{opt}$ *function-declarator function-body*

function-declarator:
declarator ($parameter\text{-}list_{opt}$)

parameter-list:
identifier
identifier `,` *parameter-list*

function-body:
type-decl-list function-statement

function-statement:
`{` $declaration\text{-}list_{opt}$ *statement-list* `}`

data-definition:
`extern`$_{opt}$ $type\text{-}specifier_{opt}$ $init\text{-}declarator\text{-}list_{opt}$ `;`

init-declarator-list:
init-declarator
init-declarator `,` *init-declarator-list*

init-declarator:
declarator $initializer_{opt}$

initializer:
constant
`{` *constant-expression-list* `}`

constant-expression-list:
constant-expression
constant-expression , *constant-expression-list*

constant-expression:
expression

5. Preprocessor

`# define` *identifier token-string*

`# include` "*filename*"

APPENDIX 2
Implementation Peculiarities

This Appendix briefly summarizes the differences between the implementations of C on the PDP-11 under UNIX and on the HIS 6070 under GCOS; it includes some known bugs in each implementation. Each entry is keyed by an indicator as follows:

h	hard to fix
g	GCOS version should probably be changed
u	UNIX version should probably be changed
d	Inherent difference likely to remain

This list was prepared by M. E. Lesk, S. C. Johnson, E. N. Pinson, and the author.

A. Bugs or differences from C language specifications

hg	A.1)	GCOS does not do type conversions in "?:".
hg	A.2)	GCOS has a bug in `int` and `real` comparisons; the numbers are compared by subtraction, and the difference must not overflow.
g	A.3)	When *x* is a `float`, the construction "test ? –x : x" is illegal on GCOS.
hg	A.4)	"p1–>p2 =+ 2" causes a compiler error, where p1 and p2 are pointers.
u	A.5)	On UNIX, the expression in a `return` statement is *not* converted to the type of the function, as promised.
hug	A.6)	`entry` statement is not implemented at all.

B. Implementation differences

d	B.1)	Sizes of character constants differ; UNIX: 2, GCOS: 4.
d	B.2)	Table sizes in compilers differ.
d	B.3)	`char`s and `int`s have different sizes; `char`s are 8 bits on UNIX, 9 on GCOS; words are 16 bits on UNIX and 36 on GCOS. There are corresponding differences in representations of `float`s and `double`s.
d	B.4)	Character arrays stored left to right in a word in GCOS, right to left in UNIX.
g	B.5)	Passing of floats and doubles differs; UNIX passes on stack, GCOS passes pointer (hidden to normal user).
g	B.6)	Structures and strings are aligned on a word boundary in UNIX, not aligned in GCOS.
g	B.7)	GCOS preprocessor supports #rename, #escape; UNIX has only #define, #include.
u	B.8)	Preprocessor is not invoked on UNIX unless first character of file is "#".
u	B.9)	The external definition "static int ..." is legal on GCOS, but gets a diagnostic on UNIX. (On GCOS it means an identifier global to the routines in the file but invisible to routines compiled separately.)
g	B.10)	A compound statement on GCOS must contain one ";" but on UNIX may be empty.
g	B.11)	On GCOS case distinctions in identifiers and keywords are ignored; on UNIX case is significant everywhere, with keywords in lower case.

C. Syntax Differences

g	C.1)	UNIX allows broader classes of initialization; on GCOS an initializer must be a constant, name, or string. Similarly, GCOS is much stickier about wanting braces around initializers and in particular they must be present for array initialization.
g	C.2)	"int extern" illegal on GCOS; must have "extern int" (storage class before type).
g	C.3)	Externals on GCOS must have a type (not defaulted to `int`).
u	C.4)	GCOS allows initialization of internal `static` (same syntax as for external definitions).
g	C.5)	integer–>... is not allowed on GCOS.
g	C.6)	Some operators on pointers are illegal on GCOS (<, >).

g	C.7)	`register` storage class means something on UNIX, but is not accepted on GCOS.
g	C.8)	Scope holes: ''int x; f( ) {int x;}'' is illegal on UNIX but defines two variables on GCOS.
g	C.9)	When function names are used as arguments on UNIX, either ''fname'' or ''&fname'' may be used to get a pointer to the function; on GCOS ''&fname'' generates a doubly-indirect pointer. (Note that both are wrong since the ''&'' is supposed to be supplied for free.)

D. Operating System Dependencies

d	D.1)	GCOS allocates external scalars by SYMREF; UNIX allocates external scalars as labelled common; as a result there may be many uninitialized external definitions of the same variable on UNIX but only one on GCOS.
d	D.2)	External names differ in allowable length and character set; on UNIX, 7 characters and both cases; on GCOS 6 characters and only one case.

E. Semantic Differences

hg	E.1)	''int i, *p; p=i; i=p;'' does nothing on UNIX, does something on GCOS (destroys right half of i) .
d	E.2)	''>>'' means arithmetic shift on UNIX, logical on GCOS.
d	E.3)	When a `char` is converted to integer, the result is always positive on GCOS but can be negative on UNIX.
d	E.4)	Arguments of subroutines are evaluated left-to-right on GCOS, right-to-left on UNIX.

Programming in C — A Tutorial

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1. Introduction

C is a computer language available on the GCOS and UNIX operating systems at Murray Hill and (in preliminary form) on OS/360 at Holmdel. C lets you write your programs clearly and simply — it has decent control flow facilities so your code can be read straight down the page, without labels or GOTO's; it lets you write code that is compact without being too cryptic; it encourages modularity and good program organization; and it provides good data-structuring facilities.

This memorandum is a tutorial to make learning C as painless as possible. The first part concentrates on the central features of C; the second part discusses those parts of the language which are useful (usually for getting more efficient and smaller code) but which are not necessary for the new user. This is *not* a reference manual. Details and special cases will be skipped ruthlessly, and no attempt will be made to cover every language feature. The order of presentation is hopefully pedagogical instead of logical. Users who would like the full story should consult the *C Reference Manual* by D. M. Ritchie [1], which should be read for details anyway. Runtime support is described in [2] and [3]; you will have to read one of these to learn how to compile and run a C program.

We will assume that you are familiar with the mysteries of creating files, text editing, and the like in the operating system you run on, and that you have programmed in some language before.

2. A Simple C Program

```
main( ) {
      printf("hello, world");
}
```

A C program consists of one or more *functions,* which are similar to the functions and subroutines of a Fortran program or the procedures of PL/I, and perhaps some external data definitions. `main` is such a function, and in fact all C programs must have a `main`. Execution of the program begins at the first statement of `main`. `main` will usually invoke other functions to perform its job, some coming from the same program, and others from libraries.

One method of communicating data between functions is by arguments. The parentheses following the function name surround the argument list; here `main` is a function of no arguments, indicated by ( ). The {} enclose the statements of the function. Individual statements end with a semicolon but are otherwise free-format.

`printf` is a library function which will format and print output on the terminal (unless some other destination is specified). In this case it prints

```
hello, world
```

A function is invoked by naming it, followed by a list of arguments in parentheses. There is no CALL statement as in Fortran or PL/I.

3. A Working C Program; Variables; Types and Type Declarations

Here's a bigger program that adds three integers and prints their sum.

```
main( ) {
      int a, b, c, sum;
      a = 1;  b = 2;  c = 3;
      sum = a + b + c;
      printf("sum is %d", sum);
}
```

Arithmetic and the assignment statements are much the same as in Fortran (except for the semicolons) or PL/I. The format of C programs is quite free. We can put several statements on a line if we want, or we can split a statement among several lines if it seems desirable. The split may be between any of the operators or variables, but *not* in the middle of a name or operator. As a matter of style, spaces, tabs, and newlines should be used freely to enhance readability.

C has four fundamental *types* of variables:

`int`	integer (PDP-11: 16 bits; H6070: 36 bits; IBM360: 32 bits)
`char`	one byte character (PDP-11, IBM360: 8 bits; H6070: 9 bits)
`float`	single-precision floating point
`double`	double-precision floating point

There are also *arrays* and *structures* of these basic types, *pointers* to them and *functions* that return them, all of which we will meet shortly.

All variables in a C program must be declared, although this can sometimes be done implicitly by context. Declarations must precede executable statements. The declaration

```
int a, b, c, sum;
```

declares `a, b, c,` and `sum` to be integers.

Variable names have one to eight characters, chosen from A-Z, a-z, 0-9, and _, and start with a non-digit. Stylistically, it's much better to use only a single case and give functions and external variables names that are unique in the first six characters. (Function and external variable names are used by various assemblers, some of which are limited in the size and case of identifiers they can handle.) Furthermore, keywords and library functions may only be recognized in one case.

4. Constants

We have already seen decimal integer constants in the previous example — 1, 2, and 3. Since C is often used for system programming and bit-manipulation, octal numbers are an important part of the language. In C, any number that begins with 0 (zero!) is an octal integer (and hence can't have any 8's or 9's in it). Thus 0777 is an octal constant, with decimal value 511.

A "character" is one byte (an inherently machine-dependent concept). Most often this is expressed as a *character constant,* which is one character enclosed in single quotes. However, it may be any quantity that fits in a byte, as in `flags` below:

```
char quest, newline, flags;
quest = '?';
newline = '\n';
flags = 077;
```

The sequence '\n' is C notation for "newline character", which, when printed, skips the terminal to the beginning of the next line. Notice that '\n' represents only a single character. There are several other "escapes" like '\n' for representing hard-to-get or invisible characters, such as '\t' for tab, '\b' for backspace, '\0' for end of file, and '\\' for the backslash itself.

`float` and `double` constants are discussed in section 26.

5. Simple I/O — getchar, putchar, printf

```
main( ) {
        char c;
        c = getchar( );
        putchar(c);
}
```

`getchar` and `putchar` are the basic I/O library functions in C. `getchar` fetches one character from the standard input (usually the terminal) each time it is called, and returns that character as the value of the function. When it reaches the end of whatever file it is reading, thereafter it returns the character represented by '\0' (ascii NUL, which has value zero). We will see how to use this very shortly.

`putchar` puts one character out on the standard output (usually the terminal) each time it is called. So the program above reads one character and writes it back out. By itself, this isn't very interesting, but observe that if we put a loop around this, and add a test for end of file, we have a complete program for copying one file to another.

`printf` is a more complicated function for producing formatted output. We will talk about only the simplest use of it. Basically, `printf` uses its first argument as formatting information, and any successive arguments as variables to be output. Thus

```
printf ("hello, world\n");
```

is the simplest use — the string "hello, world\n" is printed out. No formatting information, no variables, so the string is dumped out verbatim. The newline is necessary to put this out on a line by itself. (The construction

```
"hello, world\n"
```

is really an array of `chars`. More about this shortly.)

More complicated, if `sum` is 6,

```
printf ("sum is %d\n", sum);
```

prints

```
sum is 6
```

Within the first argument of `printf`, the characters "%d" signify that the next argument in the argument list is to be printed as a base 10 number.

Other useful formatting commands are "%c" to print out a single character, "%s" to print out an entire string, and "%o" to print a number as octal instead of decimal (no leading zero). For example,

```
n = 511;
printf ("What is the value of %d in octal?", n);
printf ("  %s! %d decimal is %o octal\n", "Right", n, n);
```

prints

```
What is the value of 511 in octal?  Right! 511 decimal is 777
octal
```

Notice that there is no newline at the end of the first output line. Successive calls to `printf` (and/or `putchar`, for that matter) simply put out characters. No newlines are printed unless you ask for them. Similarly, on input, characters are read one at a time as you ask for them. Each line is generally terminated

by a newline (\n), but there is otherwise no concept of record.

6. If; relational operators; compound statements

The basic conditional-testing statement in C is the `if` statement:

```
c = getchar( );
if( c == '?' )
      printf("why did you type a question mark?\n");
```

The simplest form of `if` is

```
if (expression) statement
```

The condition to be tested is any expression enclosed in parentheses. It is followed by a statement. The expression is evaluated, and if its value is non-zero, the statement is executed. There's an optional `else` clause, to be described soon.

The character sequence '==' is one of the relational operators in C; here is the complete set:

```
==    equal to (.EQ. to Fortraners)
!=    not equal to
>     greater than
<     less than
>=    greater than or equal to
<=    less than or equal to
```

The value of ''expression relation expression'' is 1 if the relation is true, and 0 if false. Don't forget that the equality test is '=='; a single '=' causes an assignment, not a test, and invariably leads to disaster.

Tests can be combined with the operators `'&&'` (AND), `'||'` (OR), and `'!'` (NOT). For example, we can test whether a character is blank or tab or newline with

```
if( c==' ' || c=='\t' || c=='\n' )  . . .
```

C guarantees that `'&&'` and `'||'` are evaluated left to right — we shall soon see cases where this matters.

One of the nice things about C is that the `statement` part of an `if` can be made arbitrarily complicated by enclosing a set of statements in {}. As a simple example, suppose we want to ensure that `a` is bigger than `b`, as part of a sort routine. The interchange of `a` and `b` takes three statements in C, grouped together by {}:

```
if (a < b) {
      t = a;
      a = b;
      b = t;
}
```

As a general rule in C, anywhere you can use a simple statement, you can use any compound statement, which is just a number of simple or compound ones enclosed in {}. There is no semicolon after the } of a compound statement, but there *is* a semicolon after the last non-compound statement inside the {}.

The ability to replace single statements by complex ones at will is one feature that makes C much more pleasant to use than Fortran. Logic (like the exchange in the previous example) which would require several GOTO's and labels in Fortran can and should be done in C without any, using compound statements.

7. While Statement; Assignment within an Expression; Null Statement

The basic looping mechanism in C is the `while` statement. Here's a program that copies its input to its output a character at a time. Remember that '\0' marks the end of file.

```
main( ) {
```

```
        char c;
        while( (c=getchar( )) != '\0' )
              putchar(c);
}
```

The `while` statement is a loop, whose general form is

```
while (expression) statement
```

Its meaning is

```
(a) evaluate the expression
(b) if its value is true (i.e., not zero)
            do the statement, and go back to (a)
```

Because the expression is tested before the statement is executed, the statement part can be executed zero times, which is often desirable. As in the `if` statement, the expression and the statement can both be arbitrarily complicated, although we haven't seen that yet. Our example gets the character, assigns it to `c`, and then tests if it's a '\0''. If it is not a '\0', the statement part of the `while` is executed, printing the character. The `while` then repeats. When the input character is finally a '\0', the `while` terminates, and so does `main`.

Notice that we used an assignment statement

```
c = getchar( )
```

within an expression. This is a handy notational shortcut which often produces clearer code. (In fact it is often the only way to write the code cleanly. As an exercise, re-write the file-copy without using an assignment inside an expression.) It works because an assignment statement has a value, just as any other expression does. Its value is the value of the right hand side. This also implies that we can use multiple assignments like

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

Evaluation goes from right to left.

By the way, the extra parentheses in the assignment statement within the conditional were really necessary: if we had said

```
c = getchar( ) != '\0'
```

`c` would be set to 0 or 1 depending on whether the character fetched was an end of file or not. This is because in the absence of parentheses the assignment operator '=' is evaluated after the relational operator '!='. When in doubt, or even if not, parenthesize.

Since `putchar(c)` returns `c` as its function value, we could also copy the input to the output by nesting the calls to `getchar` and `putchar`:

```
main( ) {
        while( putchar(getchar( )) != '\0' ) ;
}
```

What statement is being repeated? None, or technically, the *null* statement, because all the work is really done within the test part of the `while`. This version is slightly different from the previous one, because the final '\0' is copied to the output before we decide to stop.

8. Arithmetic

The arithmetic operators are the usual '+', '–', '*', and '/' (truncating integer division if the operands are both `int`), and the remainder or mod operator '%':

```
x = a%b;
```

sets `x` to the remainder after `a` is divided by `b` (i.e., `a` mod `b`). The results are machine dependent unless

a and b are both positive.

In arithmetic, char variables can usually be treated like int variables. Arithmetic on characters is quite legal, and often makes sense:

```
c = c + 'A' - 'a';
```

converts a single lower case ascii character stored in c to upper case, making use of the fact that corresponding ascii letters are a fixed distance apart. The rule governing this arithmetic is that all chars are converted to int before the arithmetic is done. Beware that conversion may involve sign-extension — if the leftmost bit of a character is 1, the resulting integer might be negative. (This doesn't happen with genuine characters on any current machine.)

So to convert a file into lower case:

```
main( ) {
        char c;
        while( (c=getchar( )) != '\0' )
                if( 'A'<=c && c<='Z' )
                        putchar(c+'a'-'A');
                else
                        putchar(c);
}
```

Characters have different sizes on different machines. Further, this code won't work on an IBM machine, because the letters in the ebcdic alphabet are not contiguous.

9. Else Clause; Conditional Expressions

We just used an else after an if. The most general form of if is

```
if (expression) statement1 else statement2
```

the else part is optional, but often useful. The canonical example sets x to the minimum of a and b:

```
if (a < b)
        x = a;
else
        x = b;
```

Observe that there's a semicolon after x=a.

C provides an alternate form of conditional which is often more concise. It is called the "conditional expression" because it is a conditional which actually has a value and can be used anywhere an expression can. The value of

```
a<b ? a : b;
```

is a if a is less than b; it is b otherwise. In general, the form

```
expr1 ? expr2 : expr3
```

means "evaluate expr1. If it is not zero, the value of the whole thing is expr2; otherwise the value is expr3."

To set x to the minimum of a and b, then:

```
x = (a<b ? a : b);
```

The parentheses aren't necessary because '?:' is evaluated before '=', but safety first.

Going a step further, we could write the loop in the lower-case program as

```
while( (c=getchar( )) != '\0' )
        putchar( ('A'<=c && c<='Z') ? c-'A'+'a' : c );
```

If's and else's can be used to construct logic that branches one of several ways and then rejoins, a common programming structure, in this way:

```
if(. . .)
      {. . .}
else if(. . .)
      {. . .}
else if(. . .)
      {. . .}
else
      {. . .}
```

The conditions are tested in order, and exactly one block is executed — either the first one whose if is satisfied, or the one for the last else. When this block is finished, the next statement executed is the one after the last else. If no action is to be taken for the "default" case, omit the last else.

For example, to count letters, digits and others in a file, we could write

```
main( ) {
      int let, dig, other, c;
      let = dig = other = 0;
      while( (c=getchar( )) != '\0' )
            if( ('A'<=c && c<='Z') || ('a'<=c && c<='z') )  ++let;
            else if( '0'<=c && c<='9' )  ++dig;
            else  ++other;
      printf("%d letters, %d digits, %d others\n", let, dig, other);
}
```

The '++' operator means "increment by 1"; we will get to it in the next section.

10. Increment and Decrement Operators

In addition to the usual '–', C also has two other interesting unary operators, '++' (increment) and '––' (decrement). Suppose we want to count the lines in a file.

```
main( ) {
      int c,n;
      n = 0;
      while( (c=getchar( )) != '\0' )
            if( c == '\n' )
                  ++n;
      printf("%d lines\n", n);
}
```

++n is equivalent to n=n+1 but clearer, particularly when n is a complicated expression. '++' and '––' can be applied only to int's and char's (and pointers which we haven't got to yet).

The unusual feature of '++' and '––' is that they can be used either before or after a variable. The value of ++k is the value of k *after* it has been incremented. The value of k++ is k *before* it is incremented. Suppose k is 5. Then

```
x = ++k;
```

increments k to 6 and then sets x to the resulting value, i.e., to 6. But

```
x = k++;
```

first sets x to to 5, and *then* increments k to 6. The incrementing effect of ++k and k++ is the same, but their values are respectively 5 and 6. We shall soon see examples where both of these uses are important.

11. Arrays

In C, as in Fortran or PL/I, it is possible to make arrays whose elements are basic types. Thus we can make an array of 10 integers with the declaration

```
int x[10];
```

The square brackets mean *subscripting;* parentheses are used only for function references. Array indexes begin at *zero,* so the elements of `x` are

```
x[0], x[1], x[2], . . . , x[9]
```

If an array has `n` elements, the largest subscript is `n-1` .

Multiple-dimension arrays are provided, though not much used above two dimensions. The declaration and use look like

```
int name[10] [20];
n = name[i+j] [1] + name[k] [2];
```

Subscripts can be arbitrary integer expressions. Multi-dimension arrays are stored by row (opposite to Fortran), so the rightmost subscript varies fastest; `name` has 10 rows and 20 columns.

Here is a program which reads a line, stores it in a buffer, and prints its length (excluding the newline at the end).

```
main( ) {
      int n, c;
      char line[100];
      n = 0;
      while( (c=getchar( )) != '\n' ) {
            if( n < 100 )
                  line[n] = c;
            n++;
      }
      printf("length = %d\n", n);
}
```

As a more complicated problem, suppose we want to print the count for each line in the input, still storing the first 100 characters of each line. Try it as an exercise before looking at the solution:

```
main( ) {
      int n, c; char line[100];
      n = 0;
      while( (c=getchar( )) != '\0' )
            if( c == '\n' ) {
                  printf("%d0, n);
                  n = 0;
            }
            else {
                  if( n < 100 ) line[n] = c;
                  n++;
            }
}
```

12. Character Arrays; Strings

Text is usually kept as an array of characters, as we did with `line[ ]` in the example above. By convention in C, the last character in a character array should be a '\0' because most programs that manipulate character arrays expect it. For example, `printf` uses the '\0' to detect the end of a character array

when printing it out with a '%s'.

We can copy a character array `s` into another `t` like this:

```
i = 0;
while( (t[i]=s[i]) != '\0' )
      i++;
```

Most of the time we have to put in our own '\0' at the end of a string; if we want to print the line with `printf`, it's necessary. This code prints the character count before the line:

```
main( ) {
      int n;
      char line[100];
      n = 0;
      while( (line[n++]=getchar( )) != '\n' );
      line[n] = '\0';
      printf("%d:\t%s", n, line);
}
```

Here we increment `n` in the subscript itself, but only after the previous value has been used. The character is read, placed in `line[n]`, and only then `n` is incremented.

There is one place and one place only where C puts in the '\0' at the end of a character array for you, and that is in the construction

```
"stuff between double quotes"
```

The compiler puts a '\0' at the end automatically. Text enclosed in double quotes is called a *string;* its properties are precisely those of an (initialized) array of characters.

13. For Statement

The `for` statement is a somewhat generalized `while` that lets us put the initialization and increment parts of a loop into a single statement along with the test. The general form of the `for` is

```
for( initialization; expression; increment )
      statement
```

The meaning is exactly

```
initialization;
while( expression ) {
      statement
      increment;
}
```

Thus, the following code does the same array copy as the example in the previous section:

```
for( i=0; (t[i]=s[i]) != '\0'; i++ );
```

This slightly more ornate example adds up the elements of an array:

```
sum = 0;
for( i=0; i<n; i++)
      sum = sum + array[i];
```

In the `for` statement, the initialization can be left out if you want, but the semicolon has to be there. The increment is also optional. It is *not* followed by a semicolon. The second clause, the test, works the same way as in the `while`: if the expression is true (not zero) do another loop, otherwise get on with the next statement. As with the `while`, the `for` loop may be done zero times. If the expression is left out, it is taken to be always true, so

```
for( ; ; ) . . .
```

and

```
while( 1 ) ...
```

are both infinite loops.

You might ask why we use a `for` since it's so much like a `while`. (You might also ask why we use a `while` because...) The `for` is usually preferable because it keeps the code where it's used and sometimes eliminates the need for compound statements, as in this code that zeros a two-dimensional array:

```
for( i=0; i<n; i++ )
      for( j=0; j<m; j++ )
            array[i][j] = 0;
```

14. Functions; Comments

Suppose we want, as part of a larger program, to count the occurrences of the ascii characters in some input text. Let us also map illegal characters (those with value>127 or <0) into one pile. Since this is presumably an isolated part of the program, good practice dictates making it a separate function. Here is one way:

```
main( ) {
      int hist[129];          /* 128 legal chars + 1 illegal group */
      ...
      count(hist, 128); /* count the letters into hist */
      printf( ... );        /* comments look like this; use them */
      ...         /* anywhere blanks, tabs or newlines could appear */
}

count(buf, size)
    int size, buf[ ]; {
      int i, c;
      for( i=0; i<=size; i++ )
            buf[i] = 0;             /* set buf to zero */
      while( (c=getchar( )) != '\0' ) {   /* read til eof */
            if( c > size || c < 0 )
                  c = size;         /* fix illegal input */
            buf[c]++;
      }
      return;
}
```

We have already seen many examples of calling a function, so let us concentrate on how to *define* one. Since `count` has two arguments, we need to declare them, as shown, giving their types, and in the case of `buf`, the fact that it is an array. The declarations of arguments go *between* the argument list and the opening '{'. There is no need to specify the size of the array `buf`, for it is defined outside of `count`.

The `return` statement simply says to go back to the calling routine. In fact, we could have omitted it, since a return is implied at the end of a function.

What if we wanted `count` to return a value, say the number of characters read? The `return` statement allows for this too:

```
      int i, c, nchar;
      nchar = 0;
      ...
      while( (c=getchar( )) != '\0' ) {
            if( c > size || c < 0 )
                  c = size;
            buf[c]++;
            nchar++;
```

```
        }
        return(nchar);
```

Any expression can appear within the parentheses. Here is a function to compute the minimum of two integers:

```
min(a, b)
    int a, b; {
      return( a < b ? a : b );
}
```

To copy a character array, we could write the function

```
strcopy(s1, s2)         /* copies s1 to s2 */
    char s1[ ], s2[ ]; {
      int i;
      for( i = 0; (s2[i] = s1[i]) != '\0'; i++ );
}
```

As is often the case, all the work is done by the assignment statement embedded in the test part of the `for`. Again, the declarations of the arguments `s1` and `s2` omit the sizes, because they don't matter to `strcopy`. (In the section on pointers, we will see a more efficient way to do a string copy.)

There is a subtlety in function usage which can trap the unsuspecting Fortran programmer. Simple variables (not arrays) are passed in C by "call by value", which means that the called function is given a copy of its arguments, and doesn't know their addresses. This makes it impossible to change the value of one of the actual input arguments.

There are two ways out of this dilemma. One is to make special arrangements to pass to the function the address of a variable instead of its value. The other is to make the variable a global or external variable, which is known to each function by its name. We will discuss both possibilities in the next few sections.

15. Local and External Variables

If we say

```
f( ) {
      int x;
      • • •
}
g( ) {
      int x;
      • • •
}
```

each `x` is *local* to its own routine — the `x` in `f` is unrelated to the `x` in `g`. (Local variables are also called "automatic".) Furthermore each local variable in a routine appears only when the function is called, and *disappears* when the function is exited. Local variables have no memory from one call to the next and must be explicitly initialized upon each entry. (There is a `static` storage class for making local variables with memory; we won't discuss it.)

As opposed to local variables, *external variables* are defined external to all functions, and are (potentially) available to all functions. External storage always remains in existence. To make variables external we have to *define* them external to all functions, and, wherever we want to use them, make a *declaration.*

```
main( ) {
      extern int nchar, hist[ ];
      • • •
      count( );
      • • •
}
```

```
count( ) {
      extern int nchar, hist[ ];
      int i, c;
      • • •
}

int   hist[129];  /* space for histogram */
int   nchar;            /* character count */
```

Roughly speaking, any function that wishes to access an external variable must contain an `extern` declaration for it. The declaration is the same as others, except for the added keyword `extern`. Furthermore, there must somewhere be a *definition* of the external variables external to all functions.

External variables can be initialized; they are set to zero if not explicitly initialized. In its simplest form, initialization is done by putting the value (which must be a constant) after the definition:

```
int   nchar 0;
char  flag  'f';
 etc.
```

This is discussed further in a later section.

This ends our discussion of what might be called the central core of C. You now have enough to write quite substantial C programs, and it would probably be a good idea if you paused long enough to do so. The rest of this tutorial will describe some more ornate constructions, useful but not essential.

16. Pointers

A *pointer* in C is the address of something. It is a rare case indeed when we care what the specific address itself is, but pointers are a quite common way to get at the contents of something. The unary operator '&' is used to produce the address of an object, if it has one. Thus

```
int a, b;
b = &a;
```

puts the address of `a` into `b`. We can't do much with it except print it or pass it to some other routine, because we haven't given `b` the right kind of declaration. But if we declare that `b` is indeed a *pointer* to an integer, we're in good shape:

```
int a, *b, c;
b = &a;
c = *b;
```

`b` contains the address of `a` and '`c = *b`' means to use the value in `b` as an address, i.e., as a pointer. The effect is that we get back the contents of `a`, albeit rather indirectly. (It's always the case that '`*&x`' is the same as `x` if `x` has an address.)

The most frequent use of pointers in C is for walking efficiently along arrays. In fact, in the implementation of an array, the array name represents the address of the zeroth element of the array, so you can't use it on the left side of an expression. (You can't change the address of something by assigning to it.) If we say

```
char *y;
char x[100];
```

`y` is of type pointer to character (although it doesn't yet point anywhere). We can make `y` point to an element of `x` by either of

```
y = &x[0];
y = x;
```

Since `x` is the address of `x[0]` this is legal and consistent.

Now `'*y'` gives `x[0]`. More importantly,

```
*(y+1)      gives x[1]
*(y+i)      gives x[i]
```

and the sequence

```
y = &x[0];
y++;
```

leaves `y` pointing at `x[1]`.

Let's use pointers in a function `length` that computes how long a character array is. Remember that by convention all character arrays are terminated with a '\0'. (And if they aren't, this program will blow up inevitably.) The old way:

```
length(s)
    char s[ ]; {
      int n;
      for( n=0; s[n] != '\0'; )
            n++;
      return(n);
}
```

Rewriting with pointers gives

```
length(s)
    char *s; {
      int n;
      for( n=0; *s != '\0'; s++ )
            n++;
      return(n);
}
```

You can now see why we have to say what kind of thing `s` points to — if we're to increment it with `s++` we have to increment it by the right amount.

The pointer version is more efficient (this is almost always true) but even more compact is

```
for( n=0; *s++ != '\0'; n++ );
```

The `'*s'` returns a character; the `'++'` increments the pointer so we'll get the next character next time around. As you can see, as we make things more efficient, we also make them less clear. But `'*s++'` is an idiom so common that you have to know it.

Going a step further, here's our function `strcopy` that copies a character array `s` to another `t`.

```
strcopy(s,t)
    char *s, *t; {
      while(*t++ = *s++);
}
```

We have omitted the test against '\0', because '\0' is identically zero; you will often see the code this way. (You *must* have a space after the '=': see section 25.)

For arguments to a function, and there only, the declarations

```
char s[ ];
char *s;
```

are equivalent — a pointer to a type, or an array of unspecified size of that type, are the same thing.

If this all seems mysterious, copy these forms until they become second nature. You don't often need anything more complicated.

17. Function Arguments

Look back at the function `strcopy` in the previous section. We passed it two string names as arguments, then proceeded to clobber both of them by incrementation. So how come we don't lose the original strings in the function that called `strcopy`?

As we said before, C is a "call by value" language: when you make a function call like `f(x)`, the *value* of `x` is passed, not its address. So there's no way to *alter* `x` from inside `f`. If `x` is an array (`char x[10]`) this isn't a problem, because `x` *is* an address anyway, and you're not trying to change it, just what it addresses. This is why `strcopy` works as it does. And it's convenient not to have to worry about making temporary copies of the input arguments.

But what if `x` is a scalar and you do want to change it? In that case, you have to pass the *address* of `x` to `f`, and then use it as a pointer. Thus for example, to interchange two integers, we must write

```
flip(x, y)
    int *x, *y; {
      int temp;
      temp = *x;
      *x = *y;
      *y = temp;
}
```

and to call `flip`, we have to pass the addresses of the variables:

```
flip (&a, &b);
```

18. Multiple Levels of Pointers; Program Arguments

When a C program is called, the arguments on the command line are made available to the main program as an argument count `argc` and an array of character strings `argv` containing the arguments. Manipulating these arguments is one of the most common uses of multiple levels of pointers ("pointer to pointer to ..."). By convention, `argc` is greater than zero; the first argument (in `argv[0]`) is the command name itself.

Here is a program that simply echoes its arguments.

```
main(argc, argv)
    int argc;
    char **argv; {
      int i;
      for( i=1; i < argc; i++ )
            printf("%s ", argv[i]);
      putchar('\n');
}
```

Step by step: `main` is called with two arguments, the argument count and the array of arguments. `argv` is a pointer to an array, whose individual elements are pointers to arrays of characters. The zeroth argument is the name of the command itself, so we start to print with the first argument, until we've printed them all. Each `argv[i]` is a character array, so we use a `'%s'` in the `printf`.

You will sometimes see the declaration of `argv` written as

```
char *argv[ ];
```

which is equivalent. But we can't use `char argv[][]`, because both dimensions are variable and there would be no way to figure out how big the array is.

Here's a bigger example using `argc` and `argv`. A common convention in C programs is that if the first argument is '–', it indicates a flag of some sort. For example, suppose we want a program to be callable as

```
prog –abc arg1 arg2 ...
```

where the '–' argument is optional; if it is present, it may be followed by any combination of a, b, and c.

```
main(argc, argv)
    int argc;
    char **argv; {
       . . .
       aflag = bflag = cflag  = 0;
       if( argc > 1 && argv[1][0] == '-' ) {
             for( i=1; (c=argv[1][i]) != '\0'; i++ )
                   if( c=='a' )
                         aflag++;
                   else if( c=='b' )
                         bflag++;
                   else if( c=='c' )
                         cflag++;
                   else
                         printf("%c?\n", c);
             --argc;
             ++argv;
       }
       . . .
```

There are several things worth noticing about this code. First, there is a real need for the left-to-right evaluation that && provides; we don't want to look at `argv[1]` unless we know it's there. Second, the statements

```
--argc;
++argv;
```

let us march along the argument list by one position, so we can skip over the flag argument as if it had never existed — the rest of the program is independent of whether or not there was a flag argument. This only works because `argv` is a pointer which can be incremented.

19. The Switch Statement; Break; Continue

The `switch` statement can be used to replace the multi-way test we used in the last example. When the tests are like this:

```
if( c == 'a' ) . . .
else if( c == 'b' ) . . .
else if( c == 'c' ) . . .
else . . .
```

testing a value against a series of *constants,* the switch statement is often clearer and usually gives better code. Use it like this:

```
switch( c ) {

case 'a':
      aflag++;
      break;
case 'b':
      bflag++;
      break;
case 'c':
      cflag++;
      break;
default:
      printf("%c?\n", c);
```

```
            break;
      }
```

The `case` statements label the various actions we want; `default` gets done if none of the other cases are satisfied. (A `default` is optional; if it isn't there, and none of the cases match, you just fall out the bottom.)

The `break` statement in this example is new. It is there because the cases are just labels, and after you do one of them, you *fall through* to the next unless you take some explicit action to escape. This is a mixed blessing. On the positive side, you can have multiple cases on a single statement; we might want to allow both upper and lower case letters in our flag field, so we could say

```
case 'a':   case 'A':      . . .
case 'b':   case 'B':      . . .
 etc.
```

But what if we just want to get out after doing `case 'a'` ? We could get out of a `case` of the `switch` with a label and a `goto`, but this is really ugly. The `break` statement lets us exit without either `goto` or label.

```
switch( c ) {

case 'a':
      aflag++;
      break;
case 'b':
      bflag++;
      break;
   . . .
}
/* the break statements get us here directly */
```

The `break` statement also works in `for` and `while` statements — it causes an immediate exit from the loop.

The `continue` statement works *only* inside `for`'s and `while`'s; it causes the next iteration of the loop to be started. This means it goes to the increment part of the `for` and the test part of the `while`. We could have used a `continue` in our example to get on with the next iteration of the `for`, but it seems clearer to use `break` instead.

20. Structures

The main use of structures is to lump together collections of disparate variable types, so they can conveniently be treated as a unit. For example, if we were writing a compiler or assembler, we might need for each identifier information like its name (a character array), its source line number (an integer), some type information (a character, perhaps), and probably a usage count (another integer).

```
      char  id[10];
      int   line;
      char  type;
      int   usage;
```

We can make a structure out of this quite easily. We first tell C what the structure will look like, that is, what kinds of things it contains; after that we can actually reserve storage for it, either in the same statement or separately. The simplest thing is to define it and allocate storage all at once:

```
struct {
      char  id[10];
      int   line;
      char  type;
      int   usage;
```

```
} sym;
```

This defines `sym` to be a structure with the specified shape; `id, line, type` and `usage` are *members* of the structure. The way we refer to any particular member of the structure is

```
structure-name . member
```

as in

```
sym.type = 077;
if( sym.usage == 0 ) ...
while( sym.id[j++] ) ...
  etc.
```

Although the names of structure members never stand alone, they still have to be unique — there can't be another `id` or `usage` in some other structure.

So far we haven't gained much. The advantages of structures start to come when we have arrays of structures, or when we want to pass complicated data layouts between functions. Suppose we wanted to make a symbol table for up to 100 identifiers. We could extend our definitions like

```
char  id[100][10];
int   line[100];
char  type[100];
int   usage[100];
```

but a structure lets us rearrange this spread-out information so all the data about a single identifer is collected into one lump:

```
struct {
      char  id[10];
      int   line;
      char  type;
      int   usage;
} sym[100];
```

This makes `sym` an array of structures; each array element has the specified shape. Now we can refer to members as

```
sym[i].usage++;   /* increment usage of i-th identifier */
for( j=0; sym[i].id[j++] != '\0'; ) ...
  etc.
```

Thus to print a list of all identifiers that haven't been used, together with their line number,

```
for( i=0; i<nsym; i++ )
      if( sym[i].usage == 0 )
            printf("%d\t%s\n", sym[i].line, sym[i].id);
```

Suppose we now want to write a function `lookup(name)` which will tell us if `name` already exists in `sym`, by giving its index, or that it doesn't, by returning a −1. We can't pass a structure to a function directly — we have to either define it externally, or pass a pointer to it. Let's try the first way first.

```
int   nsym  0;    /* current length of symbol table */

struct {
      char  id[10];
      int   line;
      char  type;
      int   usage;
} sym[100];       /* symbol table */

main( ) {
      ...
```

```
        if( (index = lookup(newname)) >= 0 )
              sym[index].usage++;          /* already there ... */
        else
              install(newname, newline, newtype);
        ...
}
lookup(s)
    char *s; {
        int i;
        extern struct {
              char  id[10];
              int   line;
              char  type;
              int   usage;
        } sym[ ];
        for( i=0; i<nsym; i++ )
              if( compar(s, sym[i].id) > 0 )
                    return(i);
        return(-1);
}

compar(s1,s2)           /*  return 1 if s1==s2, 0 otherwise */
    char *s1, *s2; {
        while( *s1++ == *s2 )
              if( *s2++ == '\0' )
                    return(1);
        return(0);
}
```

The declaration of the structure in `lookup` isn't needed if the external definition precedes its use in the same source file, as we shall see in a moment.

Now what if we want to use pointers?

```
struct  symtag {
        char  id[10];
        int   line;
        char  type;
        int   usage;
} sym[100], *psym;

        psym = &sym[0];  /* or p = sym; */
```

This makes `psym` a pointer to our kind of structure (the symbol table), then initializes it to point to the first element of `sym`.

Notice that we added something after the word `struct`: a "tag" called `symtag`. This puts a name on our structure definition so we can refer to it later without repeating the definition. It's not necessary but useful. In fact we could have said

```
struct      symtag {
        ... structure definition
};
```

which wouldn't have assigned any storage at all, and then said

```
struct      symtag      sym[100];
struct      symtag      *psym;
```

which would define the array and the pointer. This could be condensed further, to

```
struct      symtag      sym[100], *psym;
```

The way we actually refer to an member of a structure by a pointer is like this:

```
ptr -> structure-member
```

The symbol '->' means we're pointing at a member of a structure; '->' is only used in that context. `ptr` is a pointer to the (base of) a structure that contains the structure member. The expression `ptr->structure-member` refers to the indicated member of the pointed-to structure. Thus we have constructions like:

```
psym->type = 1;
psym->id[0] = 'a';
```

and so on.

For more complicated pointer expressions, it's wise to use parentheses to make it clear who goes with what. For example,

```
struct { int x, *y; } *p;
p->x++increments x
++p->xso does this!
(++p)->x    increments p before getting x
*p->y++     uses y as a pointer, then increments it
*(p->y)++   so does this
*(p++)->y   uses y as a pointer, then increments p
```

The way to remember these is that `->`, `.` (dot), `( )` and `[ ]` bind very tightly. An expression involving one of these is treated as a unit. `p->x`, `a[i]`, `y.x` and `f(b)` are names exactly as `abc` is.

If `p` is a pointer to a structure, any arithmetic on `p` takes into account the acutal size of the structure. For instance, `p++` increments `p` by the correct amount to get the next element of the array of structures. But don't assume that the size of a structure is the sum of the sizes of its members — because of alignments of different sized objects, there may be "holes" in a structure.

Enough theory. Here is the lookup example, this time with pointers.

```
struct symtag {
      char  id[10];
      int   line;
      char  type;
      int   usage;
} sym[100];

main( ) {
      struct symtag *lookup( );
      struct symtag *psym;
      . . .
      if( (psym = lookup(newname)) )     /* non-zero pointer */
            psym -> usage++;        /* means already there */
      else
            install(newname, newline, newtype);
      . . .
}

struct symtag *lookup(s)
    char *s; {
      struct symtag *p;
      for( p=sym; p < &sym[nsym]; p++ )
            if( compar(s, p->id) > 0)
                  return(p);
```

```
        return(0);
}
```

The function `compar` doesn't change: '`p->id`' refers to a string.

In `main` we test the pointer returned by `lookup` against zero, relying on the fact that a pointer is by definition never zero when it really points at something. The other pointer manipulations are trivial.

The only complexity is the set of lines like

```
struct symtag *lookup( );
```

This brings us to an area that we will treat only hurriedly — the question of function types. So far, all of our functions have returned integers (or characters, which are much the same). What do we do when the function returns something else, like a pointer to a structure? The rule is that any function that doesn't return an `int` has to say explicitly what it does return. The type information goes before the function name (which can make the name hard to see). Examples:

```
char f(a)
    int a; {
       . . .
}

int *g( ) { . . . }

struct symtag *lookup(s) char *s; { . . . }
```

The function `f` returns a character, `g` returns a pointer to an integer, and `lookup` returns a pointer to a structure that looks like `symtag`. And if we're going to use one of these functions, we have to make a declaration where we use it, as we did in `main` above.

Notice th parallelism between the declarations

```
        struct symtag *lookup( );
        struct symtag *psym;
```

In effect, this says that `lookup( )` and `psym` are both used the same way — as a pointer to a strcture — even though one is a variable and the other is a function.

21. Initialization of Variables

An external variable may be initialized at compile time by following its name with an initializing value when it is defined. The initializing value has to be something whose value is known at compile time, like a constant.

```
int   x     0;    /* "0" could be any constant */
int   a     'a';
char  flag  0177;
int   *p    &y[1];      /* p now points to y[1] */
```

An external array can be initialized by following its name with a list of initializations enclosed in braces:

```
int   x[4]  {0,1,2,3};        /* makes x[i] = i */
int   y[ ]  {0,1,2,3};        /* makes y big enough for 4 values */
char  *msg  "syntax error\n"; /* braces unnecessary here */
char *keyword[ ]{
      "if",
      "else",
      "for",
      "while",
      "break",
      "continue",
      0
```

```
};
```

This last one is very useful — it makes `keyword` an array of pointers to character strings, with a zero at the end so we can identify the last element easily. A simple lookup routine could scan this until it either finds a match or encounters a zero keyword pointer:

```
lookup(str)       /* search for str in keyword[ ] */
    char *str; {
      int i,j,r;
      for( i=0; keyword[i] != 0; i++) {
            for( j=0; (r=keyword[i][j]) == str[j] && r != '\0'; j++ );
            if( r == str[j] )
                  return(i);
      }
      return(-1);
}
```

Sorry — neither local variables nor structures can be initialized.

22. Scope Rules: Who Knows About What

A complete C program need not be compiled all at once; the source text of the program may be kept in several files, and previously compiled routines may be loaded from libraries. How do we arrange that data gets passed from one routine to another? We have already seen how to use function arguments and values, so let us talk about external data. Warning: the words *declaration* and *definition* are used precisely in this section; don't treat them as the same thing.

A major shortcut exists for making `extern` declarations. If the definition of a variable appears *before* its use in some function, no `extern` declaration is needed within the function. Thus, if a file contains

```
f1( ) { ... }
int foo;
f2( ) { ... foo = 1; ... }
f3( ) { ... if ( foo ) ... }
```

no declaration of `foo` is needed in either `f2` or or `f3`, because the external definition of `foo` appears before them. But if `f1` wants to use `foo`, it has to contain the declaration

```
f1( ) {
      extern int foo;
      ...
}
```

This is true also of any function that exists on another file — if it wants `foo` it has to use an `extern` declaration for it. (If somewhere there is an `extern` declaration for something, there must also eventually be an external definition of it, or you'll get an "undefined symbol" message.)

There are some hidden pitfalls in external declarations and definitions if you use multiple source files. To avoid them, first, define and initialize each external variable only once in the entire set of files:

```
int   foo   0;
```

You can get away with multiple external definitions on UNIX, but not on GCOS, so don't ask for trouble. Multiple initializations are illegal everywhere. Second, at the beginning of any file that contains functions needing a variable whose definition is in some other file, put in an `extern` declaration, outside of any function:

```
extern      int   foo;
f1( ) { ... }
    etc.
```

The #include compiler control line, to be discussed shortly, lets you make a single copy of the external declarations for a program and then stick them into each of the source files making up the program.

23. #define, #include

C provides a very limited macro facility. You can say

```
#define     name        something
```

and thereafter anywhere "name" appears as a token, "something" will be substituted. This is particularly useful in parametering the sizes of arrays:

```
#define     ARRAYSIZE   100
      int   arr[ARRAYSIZE];
        . . .
      while( i++ < ARRAYSIZE ) . . .
```

(now we can alter the entire program by changing only the define) or in setting up mysterious constants:

```
#define     SET         01
#define     INTERRUPT   02    /* interrupt bit */
#define     ENABLED     04
   . . .
if( x & (SET | INTERRUPT | ENABLED) ) . . .
```

Now we have meaningful words instead of mysterious constants. (The mysterious operators '&' (AND) and '|' (OR) will be covered in the next section.) It's an excellent practice to write programs without any literal constants except in #define statements.

There are several warnings about #define. First, there's no semicolon at the end of a #define; all the text from the name to the end of the line (except for comments) is taken to be the "something". When it's put into the text, blanks are placed around it. Good style typically makes the name in the #define upper case — this makes parameters more visible. Definitions affect things only after they occur, and only within the file in which they occur. Defines can't be nested. Last, if there is a #define in a file, then the first character of the file *must* be a '#', to signal the preprocessor that definitions exist.

The other control word known to C is #include. To include one file in your source at compilation time, say

```
#include "filename"
```

This is useful for putting a lot of heavily used data definitions and #define statements at the beginning of a file to be compiled. As with #define, the first line of a file containing a #include has to begin with a '#'. And #include can't be nested — an included file can't contain another #include.

24. Bit Operators

C has several operators for logical bit-operations. For example,

```
x = x & 0177;
```

forms the bit-wise AND of x and 0177, effectively retaining only the last seven bits of x. Other operators are

|	inclusive OR
^	(circumflex) exclusive OR
~	(tilde) 1's complement
!	logical NOT
<<	left shift (as in x<<2)
>>	right shift (arithmetic on PDP-11; logical on H6070, IBM360)

25. Assignment Operators

An unusual feature of C is that the normal binary operators like '+', '–', etc. can be combined with the assignment operator '=' to form new assignment operators. For example,

```
x =- 10;
```

uses the assignment operator '=–' to decrement x by 10, and

```
x =& 0177
```

forms the AND of x and 0177. This convention is a useful notational shortcut, particularly if x is a complicated expression. The classic example is summing an array:

```
for( sum=i=0; i<n; i++ )
      sum =+ array[i];
```

But the spaces around the operator are critical! For instance,

```
x = -10;
```

sets x to –10, while

```
x =- 10;
```

subtracts 10 from x. When no space is present,

```
x=-10;
```

also decreases x by 10. This is quite contrary to the experience of most programmers. In particular, watch out for things like

```
c=*s++;
y=&x[0];
```

both of which are almost certainly not what you wanted. Newer versions of various compilers are courteous enough to warn you about the ambiguity.

Because all other operators in an expression are evaluated before the assignment operator, the order of evaluation should be watched carefully:

```
x = x<<y | z;
```

means "shift x left y places, then OR with z, and store in x.'' But

```
x =<< y | z;
```

means "shift x left by y|z places", which is rather different.

26. Floating Point

We've skipped over floating point so far, and the treatment here will be hasty. C has single and double precision numbers (where the precision depends on the machine at hand). For example,

```
double sum;
float avg, y[10];
sum = 0.0;
for( i=0; i<n; i++ )
      sum =+ y[i];
avg = sum/n;
```

forms the sum and average of the array y.

All floating arithmetic is done in double precision. Mixed mode arithmetic is legal; if an arithmetic operator in an expression has both operands int or char, the arithmetic done is integer, but if one operand is int or char and the other is float or double, both operands are converted to double. Thus if i and j are int and x is float,

```
(x+i)/j          converts i and j to float
x + i/j          does i/j integer, then converts
```

Type conversion may be made by assignment; for instance,

```
int m, n;
float x, y;
m = x;
y = n;
```

converts x to integer (truncating toward zero), and n to floating point.

Floating constants are just like those in Fortran or PL/I, except that the exponent letter is 'e' instead of 'E'. Thus:

```
pi = 3.14159;
large = 1.23456789e10;
```

printf will format floating point numbers: ''%w.df'' in the format string will print the corresponding variable in a field w digits wide, with d decimal places. An e instead of an f will produce exponential notation.

27. Horrors! goto's and labels

C has a goto statement and labels, so you can branch about the way you used to. But most of the time goto's aren't needed. (How many have we used up to this point?) The code can almost always be more clearly expressed by for/while, if/else, and compound statements.

One use of goto's with some legitimacy is in a program which contains a long loop, where a while(1) would be too extended. Then you might write

```
mainloop:
   . . .
   goto mainloop;
```

Another use is to implement a break out of more than one level of for or while. goto's can only branch to labels within the same function.

28. Acknowledgements

I am indebted to a veritable host of readers who made valuable criticisms on several drafts of this tutorial. They ranged in experience from complete beginners through several implementors of C compilers to the C language designer himself. Needless to say, this is a wide enough spectrum of opinion that no one is satisfied (including me); comments and suggestions are still welcome, so that some future version might be improved.

References

C is an extension of B, which was designed by D. M. Ritchie and K. L. Thompson [4]. The C language design and UNIX implementation are the work of D. M. Ritchie. The GCOS version was begun by A. Snyder and B. A. Barres, and completed by S. C. Johnson and M. E. Lesk. The IBM version is primarily due to T. G. Peterson, with the assistance of M. E. Lesk.

[1] D. M. Ritchie, *C Reference Manual.* Bell Labs, Jan. 1974.

[2] M. E. Lesk & B. A. Barres, *The GCOS C Library.* Bell Labs, Jan. 1974.

[3] D. M. Ritchie & K. Thompson, *UNIX Programmer's Manual.* 5th Edition, Bell Labs, 1974.

[4] S. C. Johnson & B. W. Kernighan, *The Programming Language B.* Computer Science Technical Report 8, Bell Labs, 1972.

UNIX Assembler Reference Manual

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0. Introduction

This document describes the usage and input syntax of the UNIX PDP-11 assembler *as*. The details of the PDP-11 are not described; consult the DEC documents "PDP-11/20 Handbook" and "PDP-11/45 Handbook."

The input syntax of the UNIX assembler is generally similar to that of the DEC assembler PAL-11R, although its internal workings and output format are unrelated. It may be useful to read the publication DEC-11-ASDB-D, which describes PAL-11R, although naturally one must use care in assuming that its rules apply to *as*.

As is a rather ordinary two-pass assembler without macro capabilities. It produces an output file which contains relocation information and a complete symbol table; thus the output is acceptable to the UNIX link-editor *ld*, which may be used to combine the outputs of several assembler runs and to obtain object programs from libraries. The output format has been designed so that if a program contains no unresolved references to external symbols, it is executable without further processing.

1. Usage

as is used as follows:

as [**—**] $file_1$ ...

If the optional "—" argument is given, all undefined symbols in the current assembly will be made undefined-external. See the **.globl** directive below.

The other arguments name files which are concatenated and assembled. Thus programs may be written in several pieces and assembled together.

The output of the assembler is placed on the file *a.out* in the current directory. If there were no unresolved external references, and no errors detected, *a.out* is made executable; otherwise, if it is produced at all, it is made non-executable.

2. Lexical conventions

Assembler tokens include identifiers (alternatively, "symbols" or "names"), temporary symbols, constants, and operators.

2.1 Identifiers

An identifier consists of a sequence of alphanumeric characters (including period "**.**", underscore "_", and tilde "~" as alphanumeric) of which the first may not be numeric. Only the first eight characters are significant. When a name begins with a tilde, the tilde is discarded and that occurrence of the identifier generates a unique entry in the symbol table which can match no other occurrence of the identifier. This feature is used by the C compiler to place names of local variables in the output symbol table without having to worry about making them unique.

2.2 Temporary symbols

A temporary symbol consists of a digit followed by "f" or "b". Temporary symbols are discussed fully in §5.1.

2.3 Constants

An octal constant consists of a sequence of digits; "8" and "9" are taken to have octal value 10 and 11. The constant is truncated to 16 bits and interpreted in two's complement notation.

A decimal constant consists of a sequence of digits terminated by a decimal point "**.**". The magnitude of the constant should be representable in 15 bits; i.e., be less than 32,768.

A single-character constant consists of a single quote "′" followed by an ASCII character not a new-line. Certain dual-character escape sequences are acceptable in place of the ASCII character to represent new-line and other non-graphics (see *String statements*, §5.5). The constant's value has the code for the given character in the least significant byte of the word and is null-padded on the left.

A double-character constant consists of a double quote "" followed by a pair of ASCII characters not including new-line. Certain dual-character escape sequences are acceptable in place of either of the ASCII characters to represent new-line and other non-graphics (see *String statements*, §5.5). The constant's value has the code for the first given character in the least significant byte and that for the second character in the most significant byte.

2.4 Operators

There are several single- and double-character operators; see §6.

2.5 Blanks

Blank and tab characters may be interspersed freely between tokens, but may not be used within tokens (except character constants). A blank or tab is required to separate adjacent identifiers or constants not otherwise separated.

2.6 Comments

The character "/" introduces a comment, which extends through the end of the line on which it appears. Comments are ignored by the assembler.

3. Segments

Assembled code and data fall into three segments: the text segment, the data segment, and the bss segment. The text segment is the one in which the assembler begins, and it is the one into which instructions are typically placed. The UNIX system will, if desired, enforce the purity of the text segment of programs by trapping write operations into it. Object programs produced by the assembler must be processed by the link-editor *ld* (using its "—n" flag) if the text segment is to be write-protected. A single copy of the text segment is shared among all processes executing such a program.

The data segment is available for placing data or instructions which will be modified during execution. Anything which may go in the text segment may be put into the data segment. In programs with write-protected, sharable text segments, data segment contains the initialized but variable parts of a program. If the text segment is not pure, the data segment begins immediately after the text segment; if the text segment is pure, the data segment begins at the lowest 8K byte boundary after the text segment.

The bss segment may not contain any explicitly initialized code or data. The length of the bss segment (like that of text or data) is determined by the high-water mark of the location counter within it. The bss segment is actually an extension of the data segment and begins immediately after it. At the start of execution of a program, the bss segment is set to 0. Typically the bss segment is set up by statements exemplified by

```
lab: . = .+10
```

The advantage in using the bss segment for storage that starts off empty is that the initialization information need not be stored in the output file. See also *Location counter* and *Assignment statements* below.

4. The location counter

One special symbol, "**.**", is the location counter. Its value at any time is the offset within the appropriate segment of the start of the statement in which it appears. The location counter may be assigned to, with the restriction that the current segment may not change; furthermore, the value of "**.**" may not decrease. If the effect of the assign-

ment is to increase the value of "**.**", the required number of null bytes are generated (but see *Segments* above).

5. Statements

A source program is composed of a sequence of *statements*. Statements are separated either by new-lines or by semicolons. There are five kinds of statements: null statements, expression statements, assignment statements, string statements, and keyword statements.

Any kind of statement may be preceded by one or more labels.

5.1 Labels

There are two kinds of label: name labels and numeric labels. A name label consists of a name followed by a colon (:). The effect of a name label is to assign the current value and type of the location counter "**.**" to the name. An error is indicated in pass 1 if the name is already defined; an error is indicated in pass 2 if the "**.**" value assigned changes the definition of the label.

A numeric label consists of a digit *0* to *9* followed by a colon (:). Such a label serves to define temporary symbols of the form "*n*b" and "*n*f", where *n* is the digit of the label. As in the case of name labels, a numeric label assigns the current value and type of "**.**" to the temporary symbol. However, several numeric labels with the same digit may be used within the same assembly. References of the form "*n*f" refer to the first numeric label "*n*:" *f*orward from the reference; "*n*b" symbols refer to the first "*n*:" label *b*ackward from the reference. This sort of temporary label was introduced by Knuth [*The Art of Computer Programming, Vol I: Fundamental Algorithms*]. Such labels tend to conserve both the symbol table space of the assembler and the inventive powers of the programmer.

5.2 Null statements

A null statement is an empty statement (which may, however, have labels). A null statement is ignored by the assembler. Common examples of null statements are empty lines or lines containing only a label.

5.3 Expression statements

An expression statement consists of an arithmetic expression not beginning with a keyword. The assembler computes its (16-bit) value and places it in the output stream, together with the appropriate relocation bits.

5.4 Assignment statements

An assignment statement consists of an identifier, an equals sign (=), and an expression. The value and type of the expression are assigned to the identifier. It is not required that the type or value be the same in pass 2 as in pass 1, nor is it an error to redefine any symbol by assignment.

Any external attribute of the expression is lost across an assignment. This means that it is not possible to declare a global symbol by assigning to it, and that it is impossible to define a symbol to be offset from a non-locally defined global symbol.

As mentioned, it is permissible to assign to the location counter "**.**". It is required, however, that the type of the expression assigned be of the same type as "**.**", and it is forbidden to decrease the value of "**.**". In practice, the most common assignment to "**.**" has the form ".=.+*n*" for some number *n;* this has the effect of generating *n* null bytes.

5.5 String statements

A string statement generates a sequence of bytes containing ASCII characters. A string statement consists of a left string quote "<" followed by a sequence of ASCII characters not including newline, followed by a right string quote ">". Any of the ASCII characters may be replaced by a two-character escape sequence to represent certain non-graphic characters, as follows:

\n	NL	(012)
\t	HT	(011)
\e	EOT	(004)
\0	NUL	(000)
\r	CR	(015)
\a	ACK	(006)
\p	PFX	(033)
\\	\	
\>	>	

The last two are included so that the escape character and the right string quote may be represented. The same escape sequences may also be used within single- and double-character constants (see §2.3 above).

5.6 Keyword statements

Keyword statements are numerically the most common type, since most machine instructions are of this sort. A keyword statement begins with one of the many predefined keywords of the assembler; the syntax of the remainder depends on the keyword. All the keywords are listed below with the syntax they require.

6. Expressions

An expression is a sequence of symbols representing a value. Its constituents are identifiers, constants, temporary symbols, operators, and brackets. Each expression has a type.

All operators in expressions are fundamentally binary in nature; if an operand is missing on the left, a 0 of absolute type is assumed. Arithmetic is two's complement and has 16 bits of precision. All operators have equal precedence, and expressions are evaluated strictly left to right except for the effect of brackets.

6.1 Expression operators

The operators are:

(blank)	when there is no operator between operands, the effect is exactly the same as if a "+" had appeared.
+	addition
—	subtraction
*	multiplication
\/	division (note that plain " / " starts a comment)
&	bitwise **and**
|	bitwise **or**
>>	logical right shift
<<	logical left shift
%	modulo
!	*a* ! *b* is *a* **or** (**not** *b*); i.e., the **or** of the first operand and the one's complement of the second; most common use is as a unary.
^	result has the value of first operand and the type of the second; most often used to define new machine instructions with syntax identical to existing instructions.

Expressions may be grouped by use of square brackets " [ ] ". (Round parentheses are reserved for address modes.)

6.2 Types

The assembler deals with a number of types of expressions. Most types are attached to keywords and used to select the routine which treats that keyword. The types likely to be met explicitly are:

undefined
: Upon first encounter, each symbol is undefined. It may become undefined if it is assigned an undefined expression. It is an error to attempt to assemble an undefined expression in pass 2; in pass 1, it is not (except that certain keywords require operands which are not undefined).

undefined external
: A symbol which is declared **.globl** but not defined in the current assembly is an undefined external. If such a symbol is declared, the link editor *ld* must be used to load the assembler's output with another routine that defines the undefined reference.

absolute
: An absolute symbol is one defined ultimately from a constant. Its value is unaffected by any possible future applications of the link-editor to the output file.

text
: The value of a text symbol is measured with respect to the beginning of the text segment of the program. If the assembler output is link-edited, its text symbols may change in value since the program need not be the first in the link editor's output. Most text symbols are defined by appearing as labels. At the start of an assembly, the value of "**.**" is text 0.

data
: The value of a data symbol is measured with respect to the origin of the data segment of a program. Like text symbols, the value of a data symbol may change during a subsequent link-editor run since previously loaded programs may have data segments. After the first **.data** statement, the value of "**.**" is data 0.

bss
: The value of a bss symbol is measured from the beginning of the bss segment of a program. Like text and data symbols, the value of a bss symbol may change during a subsequent link-editor run, since previously loaded programs may have bss segments. After the first **.bss** statement, the value of "**.**" is bss 0.

external absolute, text, data, or bss
: symbols declared **.globl** but defined within an assembly as absolute, text, data, or bss symbols may be used exactly as if they were not declared **.globl**; however, their value and type are available to the link editor so that the program may be loaded with others that reference these symbols.

register
: The symbols

  r0 ... **r5**
  fr0 ... **fr5**
  sp
  pc

  are predefined as register symbols. Either they or symbols defined from them must be used to refer to the six general-purpose, six floating-point, and the 2 special-purpose machine registers. The behavior of the floating register names is identical to that of the corresponding general register names; the former are provided as a mnemonic aid.

other types
: Each keyword known to the assembler has a type which is used to select the routine which processes the associated keyword statement. The behavior of such symbols when not used as keywords is the same as if they were absolute.

6.3 Type propagation in expressions

When operands are combined by expression operators, the result has a type which depends on the types of the operands and on the operator. The rules involved are complex to state but were intended to be sensible and predictable. For purposes of expression evaluation the important types are

undefined
absolute
text

data
bss
undefined external
other

The combination rules are then: If one of the operands is undefined, the result is undefined. If both operands are absolute, the result is absolute. If an absolute is combined with one of the ''other types'' mentioned above, or with a register expression, the result has the register or other type. As a consequence, one can refer to r3 as ''r0+3''. If two operands of ''other type'' are combined, the result has the numerically larger type (not that this fact is very useful, since the values are not made public). An ''other type'' combined with an explicitly discussed type other than absolute acts like an absolute.

Further rules applying to particular operators are:

+	If one operand is text-, data-, or bss-segment relocatable, or is an undefined external, the result has the postulated type and the other operand must be absolute.
—	If the first operand is a relocatable text-, data-, or bss-segment symbol, the second operand may be absolute (in which case the result has the type of the first operand); or the second operand may have the same type as the first (in which case the result is absolute). If the first operand is external undefined, the second must be absolute. All other combinations are illegal.
^	This operator follows no other rule than that the result has the value of the first operand and the type of the second.
others	It is illegal to apply these operators to any but absolute symbols.

7. Pseudo-operations

The keywords listed below introduce statements which generate data in unusual forms or influence the later operations of the assembler. The metanotation

[stuff] . . .

means that 0 or more instances of the given stuff may appear. Also, boldface tokens are literals, italic words are substitutable.

7.1 **.byte** *expression* [**,** *expression*] . . .

The *expression*s in the comma-separated list are truncated to 8 bits and assembled in successive bytes. The expressions must be absolute. This statement and the string statement above are the only ones which assemble data one byte at at time.

7.2 **.even**

If the location counter "**.**" is odd, it is advanced by one so the next statement will be assembled at a word boundary.

7.3 **.if** *expression*

The *expression* must be absolute and defined in pass 1. If its value is nonzero, the **.if** is ignored; if zero, the statements between the **.if** and the matching **.endif** (below) are ignored. **.if** may be nested. The effect of **.if** cannot extend beyond the end of the input file in which it appears. (The statements are not totally ignored, in the following sense: **.if**s and **.endif**s are scanned for, and moreover all names are entered in the symbol table. Thus names occurring only inside an **.if** will show up as undefined if the symbol table is listed.)

7.4 **.endif**

This statement marks the end of a conditionally-assembled section of code. See **.if** above.

7.5 **.globl** *name* [**,** *name*] . . .

This statement makes the *names* external. If they are otherwise defined (by assignment or appearance as a label) they act within the assembly exactly as if the **.globl** statement were not given; however, the link editor *ld* may be used to combine this routine with other routines that refer these symbols.

Conversely, if the given symbols are not defined within the current assembly, the link editor can combine the output of this assembly with that of others which define the symbols.

As discussed in §1, it is possible to force the assembler to make all otherwise undefined symbols external.

7.6 **.text**
7.7 **.data**
7.8 **.bss**

These three pseudo-operations cause the assembler to begin assembling into the text, data, or bss segment respectively. Assembly starts in the text segment. It is forbidden to assemble any code or data into the bss segment, but symbols may be defined and "**.**" moved about by assignment.

7.9 **.comm** *name* **,** *expression*

Provided the *name* is not defined elsewhere, this statement is equivalent to

```
.globl  name
name = expression ^ name
```

That is, the type of *name* is ''undefined external'', and its value is *expression*. In fact the *name* behaves in the current assembly just like an undefined external. However, the link-editor *ld* has been special-cased so that all external symbols which are not otherwise defined, and which have a non-zero value, are defined to lie in the bss segment, and enough space is left after the symbol to hold *expression* bytes. All symbols which become defined in this way are located before all the explicitly defined bss-segment locations.

8. Machine instructions

Because of the rather complicated instruction and addressing structure of the PDP-11, the syntax of machine instruction statements is varied. Although the following sections give the syntax in detail, the 11/20 and 11/45 handbooks should be consulted on the semantics.

8.1 Sources and Destinations

The syntax of general source and destination addresses is the same. Each must have one of the following forms, where *reg* is a register symbol, and *expr* is any sort of expression:

syntax	words	mode
reg	0	0+*reg*
(*reg*) +	0	2+*reg*
— (*reg*)	0	4+*reg*
expr (*reg*)	1	6+*reg*
(*reg*)	0	1+*reg*
* *reg*	0	1+*reg*
* (*reg*) +	0	3+*reg*
* — (*reg*)	0	5+*reg*
* (*reg*)	1	7+*reg*
* *expr* (*reg*)	1	7+*reg*
expr	1	67
$ *expr*	1	27
* *expr*	1	77
* $ *expr*	1	37

The *words* column gives the number of address words generated; the *mode* column gives the octal address-mode number. The syntax of the address forms is identical to that in DEC assemblers, except that ''*'' has been substituted for ''@'' and ''$'' for ''#''; the UNIX typing conventions make ''@'' and ''#'' rather inconvenient.

Notice that mode ''*reg'' is identical to ''(reg)''; that ''*(reg)'' generates an index word (namely, 0); and that addresses consisting of an unadorned expression are assembled as pc-relative references independent of the type of the expression. To force a non-relative reference, the form ''*$expr'' can be used, but notice that further indirection is

impossible.

8.3 Simple machine instructions

The following instructions are defined as absolute symbols:

clc
clv
clz
cln
sec
sev
sez
sen

They therefore require no special syntax. The PDP-11 hardware allows more than one of the ‘‘clear’’ class, or alternatively more than one of the ‘‘set’’ class to be **or**-ed together; this may be expressed as follows:

clc | clv

8.4 Branch

The following instructions take an expression as operand. The expression must lie in the same segment as the reference, cannot be undefined-external, and its value cannot differ from the current location of ‘‘**.**’’ by more than 254 bytes:

br	**blos**	
bne	**bvc**	
beq	**bvs**	
bge	**bhis**	
blt	**bec**	(= **bcc**)
bgt	**bcc**	
ble	**blo**	
bpl	**bcs**	
bmi	**bes**	(= **bcs**)
bhi		

bes (‘‘branch on error set’’) and **bec** (‘‘branch on error clear’’) are intended to test the error bit returned by system calls (which is the c-bit).

8.5 Extended branch instructions

The following symbols are followed by an expression representing an address in the same segment as ‘‘**.**’’. If the target address is close enough, a branch-type instruction is generated; if the address is too far away, a **jmp** will be used.

jbr	**jlos**
jne	**jvc**
jeq	**jvs**
jge	**jhis**
jlt	**jec**
jgt	**jcc**
jle	**jlo**
jpl	**jcs**
jmi	**jes**
jhi	

jbr turns into a plain **jmp** if its target is too remote; the others (whose names are contructed by replacing the ‘‘b’’ in the branch instruction’s name by ‘‘j’’) turn into the converse branch over a **jmp** to the target address.

8.6 Single operand instructions

The following symbols are names of single-operand machine instructions. The form of address expected is discussed in §8.1 above.

clr	**sbcb**
clrb	**ror**
com	**rorb**
comb	**rol**
inc	**rolb**
incb	**asr**
dec	**asrb**
decb	**asl**
neg	**aslb**
negb	**jmp**
adc	**swab**
adcb	**tst**
sbc	**tstb**

8.7 Double operand instructions

The following instructions take a general source and destination (§8.1), separated by a comma, as operands.

mov
movb
cmp
cmpb
bit
bitb
bic
bicb
bis
bisb
add
sub

8.8 Miscellaneous instructions

The following instructions have more specialized syntax. Here *reg* is a register name, *src* and *dst* a general source or destination (§8.1), and *expr* is an expression:

jsr	*reg,dst*	
rts	*reg*	
sys	*expr*	
ash	*src , reg*	(or, **als**)
ashc	*src , reg*	(or, **alsc**)
mul	*src , reg*	(or, **mpy**)
div	*src , reg*	(or, **dvd**)
xor	*reg , dst*	
sxt	*dst*	
mark	*expr*	
sob	*reg , expr*	

sys is another name for the **trap** instruction. It is used to code system calls. Its operand is required to be expressible in 6 bits. The alternative forms for **ash**, **ashc**, **mul**, and **div** are provided to avoid conflict with EAE register names should they be needed.

The expression in **mark** must be expressible in six bits, and the expression in **sob** must be in the same segment as "**.**", must not be external-undefined, must be less than "**.**", and must be within 510 bytes of "**.**".

8.9 Floating-point unit instructions

The following floating-point operations are defined, with syntax as indicated:

cfcc
setf
setd

seti		
setl		
clrf	*fdst*	
negf	*fdst*	
absf	*fdst*	
tstf	*fsrc*	
movf	*fsrc, freg*	(= ldf)
movf	*freg, fdst*	(= stf)
movif	*src, freg*	(= ldcif)
movfi	*freg, dst*	(= stcfi)
movof	*fsrc, freg*	(= ldcdf)
movfo	*freg, fdst*	(= stcfd)
movie	*src, freg*	(= ldexp)
movei	*freg, dst*	(= stexp)
addf	*fsrc, freg*	
subf	*fsrc, freg*	
mulf	*fsrc, freg*	
divf	*fsrc, freg*	
cmpf	*fsrc, freg*	
modf	*fsrc, freg*	
ldfps	*src*	
stfps	*dst*	
stst	*dst*	

fsrc, *fdst*, and *freg* mean floating-point source, destination, and register respectively. Their syntax is identical to that for their non-floating counterparts, but note that only floating registers 0—3 can be a *freg*.

The names of several of the operations have been changed to bring out an analogy with certain fixed-point instructions. The only strange case is **movf**, which turns into either **stf** or **ldf** depending respectively on whether its first operand is or is not a register. Warning: **ldf** sets the floating condition codes, **stf** does not.

9. Other symbols

9.1 `..`

The symbol "`..`" is the *relocation counter*. Just before each assembled word is placed in the output stream, the current value of this symbol is added to the word if the word refers to a text, data or bss segment location. If the output word is a pc-relative address word which refers to an absolute location, the value of "`..`" is subtracted.

Thus the value of "`..`" can be taken to mean the starting core location of the program. In UNIX systems with relocation hardware, the initial value of "`..`" is 0.

The value of "`..`" may be changed by assignment. Such a course of action is sometimes necessary, but the consequences should be carefully thought out. It is particularly ticklish to change "`..`" midway in an assembly or to do so in a program which will be treated by the loader, which has its own notions of "`..`".

9.2 System calls

The following absolute symbols may be used to code calls to the UNIX system (see the **sys** instruction above).

break	**nice**
chdir	**open**
chmod	**read**
chown	**seek**
close	**setuid**
creat	**signal**
exec	**stat**
exit	**stime**
fork	**stty**
fstat	**tell**
getuid	**time**
gtty	**umount**

link	**unlink**
makdir	**wait**
mdate	**write**
mount	

Warning: the **wait** system call is not the same as the **wait** instruction, which is not defined in the assembler.

10. Diagnostics

When an input file cannot be read, its name followed by a question mark is typed and assembly ceases. When syntactic or semantic errors occur, a single-character diagnostic is typed out together with the line number and the file name in which it occurred. Errors in pass 1 cause cancellation of pass 2. The possible errors are:

)	parentheses error
]	parentheses error
>	string not terminated properly
*	indirection (*) used illegally
.	illegal assignment to "**.**"
A	error in address
B	branch address is odd or too remote
E	error in expression
F	error in local ("f" or "b") type symbol
G	garbage (unknown) character
I	end of file inside an **.if**
M	multiply defined symbol as label
O	word quantity assembled at odd address
P	phase error— "**.**" different in pass 1 and 2
R	relocation error
U	undefined symbol
X	syntax error

A Tutorial Introduction to the UNIX Text Editor

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Introduction

Ed is a ''text editor'', that is, an interactive program for creating and modifying ''text'', using directions provided by a user at a terminal. The text is often a document like this one, or a program or perhaps data for a program.

This introduction is meant to simplify learning *ed.* The recommended way to learn *ed* is to read this document, simultaneously using *ed* to follow the examples, then to read the description in section I of the UNIX manual, all the while experimenting with *ed.* (Solicitation of advice from experienced users is also useful.)

Do the exercises! They cover material not completely discussed in the actual text. An appendix summarizes the commands.

Disclaimer

This is an introduction and a tutorial. For this reason, no attempt is made to cover more than a part of the facilities that *ed* offers (although this fraction includes the most useful and frequently used parts). Also, there is not enough space to explain basic UNIX procedures. We will assume that you know how to log on to UNIX, and that you have at least a vague understanding of what a file is.

You must also know what character to type as the end-of-line on your particular terminal. This is a ''newline'' on Model 37 Teletypes, and ''return'' on most others. Throughout, we will refer to this character, whatever it is, as ''newline''.

Getting Started

We'll assume that you have logged in to UNIX and it has just said ''%''. The easiest way to get *ed* is to type

```
ed      (followed by a newline)
```

You are now ready to go – *ed* is waiting for you to tell it what to do.

Creating Text – the Append command "a"

As our first problem, suppose we want to create some text starting from scratch. Perhaps we are typing the very first draft of a paper; clearly it will have to start somewhere, and undergo modifications later. This section will show how to get some text in, just to get started. Later we'll talk about how to change it.

When *ed* is first started, it is rather like working with a blank piece of paper – there is no text or information present. This must be supplied by the person using *ed;* it is usually done by typing in the text, or by reading it into *ed* from a file. We will start by typing in some text, and return shortly to how to read files.

First a bit of terminology. In *ed* jargon, the text being worked on is said to be ''kept in a buffer.'' Think of the buffer as a work space, if you like, or simply as the information that you are going to be editing. In effect the buffer is like the piece of paper, on which we will write things, then change some of them, and finally file the whole thing away for another day.

The user tells *ed* what to do to his text by typing instructions called ''commands.'' Most commands consist of a single letter, which must be typed in lower case. Each command is typed on a separate line. (Sometimes the command is preceded by information about what line or lines of text are to be affected – we will discuss these shortly.) *Ed* makes no response to most commands – there is no prompting or typing of messages like ''ready''. (This silence is preferred by experienced users, but sometimes a hangup for beginners.)

The first command is *append,* written as the letter

```
a
```

all by itself. It means ''append (or add) text lines to the buffer, as I type them in.'' Appending is rather like writing fresh material on a piece of paper.

So to enter lines of text into the buffer, we just type an ''a'' followed by a newline, followed by the lines of text we want, like this:

```
a
```

```
Now is the time
for all good men
to come to the aid of their party.
.
```

The only way to stop appending is to type a line that contains only a period. The "**.**" is used to tell *ed* that we have finished appending. (Even experienced users forget that terminating "**.**" sometimes. If *ed* seems to be ignoring you, type an extra line with just "**.**" on it. You may then find you've added some garbage lines to your text, which you'll have to take out later.)

After the append command has been done, the buffer will contain the three lines

```
Now is the time
for all good men
to come to the aid of their party.
```

The "a" and "**.**" aren't there, because they are not text.

To add more text to what we already have, just issue another "a" command, and continue typing.

Error Messages – "?"

If at any time you make an error in the commands you type to *ed,* it will tell you by typing

```
?
```

This is about as cryptic as it can be, but with practice, you can usually figure out how you goofed.

Writing text out as a file – the Write command "w"

It's likely that we'll want to save our text for later use. To write out the contents of the buffer onto a file, we use the *write* command

```
w
```

followed by the filename we want to write on. This will copy the buffer's contents onto the specified file (destroying any previous information on the file). To save the text on a file named "junk", for example, type

```
w junk
```

Leave a space between "w" and the file name. *Ed* will respond by printing the number of characters it wrote out. In our case, *ed* would respond with

```
68
```

(Remember that blanks and the newline character at the end of each line are included in the character count.) Writing a file just makes a copy of the text – the buffer's contents are not disturbed, so we can go on adding lines to it. This is an important point. *Ed* at all times works on a copy of a file, not the file itself. No change in the contents of a file takes place until you give a "w" command. (Writing out the text onto a file from time to time as it is being created is a good idea, since if the system crashes or if you make some horrible mistake, you will lose all the text in the buffer but any text that was written onto a file is relatively safe.)

Leaving ed – the Quit command "q"

To terminate a session with *ed,* save the text you're working on by writing it onto a file using the "w" command, and then type the command

```
q
```

which stands for *quit.* The system will respond with "%". At this point your buffer vanishes, with all its text, which is why you want to write it out before quitting.

Exercise 1:

Enter *ed* and create some text using

```
a
. . . text . . .
.
```

Write it out using "w". Then leave *ed* with the "q" command, and print the file, to see that everything worked. (To print a file, say

```
pr filename
```

or

```
cat filename
```

in response to "%". Try both.)

Reading text from a file – the Edit command "e"

A common way to get text into the buffer is to read it from a file in the file system. This is what you do to edit text that you saved with the "w" command in a previous session. The *edit* command "e" fetches the entire contents of a file into the buffer. So if we had saved the three lines "Now is the time", etc., with a "w" command in an earlier session, the *ed* command

```
e junk
```

would fetch the entire contents of the file "junk" into the buffer, and respond

```
68
```

which is the number of characters in "junk". *If anything was already in the buffer, it is deleted first.*

If we use the "e" command to read a file into the buffer, then we need not use a file name after a subsequent "w" command; *ed* remembers the last file name used in an "e" command, and "w" will write on this file. Thus a common way to operate is

```
ed
e file
[editing session]
w
q
```

You can find out at any time what file name *ed* is remembering by typing the *file* command "f". In our case, if we typed

```
f
```

ed would reply

junk

Reading text from a file – the Read command "r"

Sometimes we want to read a file into the buffer without destroying anything that is already there. This is done by the *read* command "r". The command

r junk

will read the file "junk" into the buffer; it adds it to the end of whatever is already in the buffer. So if we do a read after an edit:

e junk
r junk

the buffer will contain *two* copies of the text (six lines).

Now is the time
for all good men
to come to the aid of their party.
Now is the time
for all good men
to come to the aid of their party.

Like the "w" and "e" commands, "r" prints the number of characters read in, after the reading operation is complete.

Generally speaking, "r" is much less used than "e".

Exercise 2:

Experiment with the "e" command – try reading and printing various files. You may get an error "?", typically because you spelled the file name wrong. Try alternately reading and appending to see that they work similarly. Verify that

ed filename

is exactly equivalent to

ed
e filename

What does

f filename

do?

Printing the contents of the buffer – the Print command "p"

To *print* or list the contents of the buffer (or parts of it) on the terminal, we use the print command

p

The way this is done is as follows. We specify the lines where we want printing to begin and where we want it to end, separated by a comma, and followed by the letter "p". Thus to print the first two lines of the buffer, for example, (that is, lines 1 through 2) we say

1,2p (starting line=1, ending line=2 p)

Ed will respond with

Now is the time
for all good men

Suppose we want to print *all* the lines in the buffer. We could use "1,3p" as above if we knew there were exactly 3 lines in the buffer. But in general, we don't know how many there are, so what do we use for the ending line number? *Ed* provides a shorthand symbol for "line number of last line in buffer" – the dollar sign "$". Use it this way:

1,$p

This will print *all* the lines in the buffer (line 1 to last line.) If you want to stop the printing before it is finished, push the DEL or Delete key; *ed* will type

?

and wait for the next command.

To print the *last* line of the buffer, we could use

$,$p

but *ed* lets us abbreviate this to

$p

We can print any single line by typing the line number followed by a "p". Thus

1p

produces the response

Now is the time

which is the first line of the buffer.

In fact, *ed* lets us abbreviate even further: we can print any single line by typing *just* the line number – no need to type the letter "p". So if we say

$

ed will print the last line of the buffer for us.

We can also use "$" in combinations like

$–1,$p

which prints the last two lines of the buffer. This helps when we want to see how far we got in typing.

Exercise 3:

As before, create some text using the append command and experiment with the "p" command. You will find, for example, that you can't print line 0 or a line beyond the end of the buffer, and that attempts to print a buffer in reverse order by saying

3,1p

don't work.

The current line – "Dot" or "."

Suppose our buffer still contains the six lines as above, that we have just typed

1,3p

and *ed* has printed the three lines for us. Try typing just

p (no line numbers).

This will print

to come to the aid of their party.

which is the third line of the buffer. In fact it is the last (most recent) line that we have done anything with. (We just printed it!) We can repeat this "p" command without line numbers, and it will continue to print line 3.

The reason is that *ed* maintains a record of the last line that we did anything to (in this case, line 3, which we just printed) so that it can be used instead of an explicit line number. This most recent line is referred to by the shorthand symbol

. (pronounced "dot").

Dot is a line number in the same way that "$" is; it means exactly "the current line", or loosely, "the line we most recently did something to." We can use it in several ways – one possibility is to say

.,$p

This will print all the lines from (including) the current line to the end of the buffer. In our case these are lines 3 through 6.

Some commands change the value of dot, while others do not. The print command sets dot to the number of the last line printed; by our last command, we would have "." = "$" = 6.

Dot is most useful when used in combinations like this one:

.+1 (or equivalently, .+1p)

This means "print the next line" and gives us a handy way to step slowly through a buffer. We can also say

.–1 (or .–1p)

which means "print the line *before* the current line." This enables us to go backwards if we wish. Another useful one is something like

.–3,.–1p

which prints the previous three lines.

Don't forget that all of these change the value of dot. You can find out what dot is at any time by typing

.=

Ed will respond by printing the value of dot.

Let's summarize some things about the "p" command and dot. Essentially "p" can be preceded by 0, 1, or 2 line numbers. If there is no line number given, it prints the "current line", the line that dot refers to. If there is one line number given (with or without the letter "p"), it prints that line (and dot is set there); and if there are two line numbers, it prints all the lines in that range (and sets dot to the last line printed.) If two line numbers are specified the first can't be bigger than the second (see Exercise 2.)

Typing a single newline will cause printing of the next line – it's equivalent to ".+1p". Try it. Try typing "^" – it's equivalent to ".–1p".

Deleting lines: the "d" command

Suppose we want to get rid of the three extra lines in the buffer. This is done by the *delete* command

d

Except that "d" deletes lines instead of printing them, its action is similar to that of "p". The lines to be deleted are specified for "d" exactly as they are for "p":

starting line, ending line d

Thus the command

4,$d

deletes lines 4 through the end. There are now three lines left, as we can check by using

1,$p

And notice that "$" now is line 3! Dot is set to the next line after the last line deleted, unless the last line deleted is the last line in the buffer. In that case, dot is set to "$".

Exercise 4:

Experiment with "a", "e", "r", "w", "p", and "d" until you are sure that you know what they do, and until you understand how dot, "$", and line numbers are used.

If you are adventurous, try using line numbers with "a", "r", and "w" as well. You will find that "a" will append lines *after* the line number that you specify (rather than after dot); that "r" reads a file in *after* the line number you specify (not necessarily at the end of the buffer); and that "w" will write out exactly the lines you specify, not necessarily the whole buffer. These variations are sometimes handy. For instance you can insert a file at the beginning of a buffer by saying

0r filename

and you can enter lines at the beginning of the buffer by saying

0a
. . . *text* . . .
.

Notice that ".w" is *very* different from

.
w

Modifying text: the Substitute command "s"

We are now ready to try one of the most important of all commands – the substitute command

s

This is the command that is used to change individual words or letters within a line or group of lines. It is

what we use, for example, for correcting spelling mistakes and typing errors.

Suppose that by a typing error, line 1 says

Now is th time

– the "e" has been left off "the". We can use "s" to fix this up as follows:

1s/th/the/

This says: "in line 1, substitute for the characters 'th' the characters 'the'." To verify that it works (*ed* will not print the result automatically) we say

p

and get

Now is the time

which is what we wanted. Notice that dot must have been set to the line where the substitution took place, since the "p" command printed that line. Dot is always set this way with the "s" command.

The general way to use the substitute command is

starting–line, ending–line s/*change this*/*to this*/

Whatever string of characters is between the first pair of slashes is replaced by whatever is between the second pair, in *all* the lines between starting line and ending line. Only the first occurrence on each line is changed, however. If you want to change *every* occurrence, see Exercise 5. The rules for line numbers are the same as those for "p", except that dot is set to the last line changed. (But there is a trap for the unwary: if no substitution took place, dot is *not* changed. This causes an error "?" as a warning.)

Thus we can say

1,$s/speling/spelling/

and correct the first spelling mistake on each line in the text. (This is useful for people who are consistent misspellers!)

If no line numbers are given, the "s" command assumes we mean "make the substitution on line dot", so it changes things only on the current line. This leads to the very common sequence

s/something/something else/p

which makes some correction on the current line, and then prints it, to make sure it worked out right. If it didn't, we can try again. (Notice that we put a print command on the same line as the substitute. With few exceptions, "p" can follow any command; no other multi-command lines are legal.)

It's also legal to say

s/ . . . //

which means "change the first string of characters to *nothing*", i.e., remove them. This is useful for deleting extra words in a line or removing extra letters from words. For instance, if we had

Nowxx is the time

we can say

s/xx//p

to get

Now is the time

Notice that "//" here means "no characters", not a blank. There *is* a difference! (See below for another meaning of "//".)

Exercise 5:

Experiment with the substitute command. See what happens if you substitute for some word on a line with several occurrences of that word. For example, do this:

a
the other side of the coin
.
s/the/on the/p

You will get

on the other side of the coin

A substitute command changes only the first occurrence of the first string. You can change all occurrences by adding a "g" (for "global") to the "s" command, like this:

s/ . . . / . . . /gp

Try other characters instead of slashes to delimit the two sets of characters in the "s" command – anything should work except blanks or tabs.

(If you get funny results using any of the characters

^ . $ [* \

read the section on "Special Characters".)

Context searching – "/ . . . /"

With the substitute command mastered, we can move on to another highly important idea of *ed* – context searching.

Suppose we have our original three line text in the buffer:

Now is the time
for all good men
to come to the aid of their party.

Suppose we want to find the line that contains "their" so we can change it to "the". Now with only three lines in the buffer, it's pretty easy to keep track of what line the word "their" is on. But if the buffer contained several hundred lines, and we'd been making changes, deleting and rearranging lines, and so on, we would no longer really know what this line number would be. Context searching is simply a method of specifying the desired line, regardless of what its number is, by specifying some context on it.

The way we say ‘‘search for a line that contains this particular string of characters’’ is to type

/*string of characters we want to find*/

For example, the *ed* line

/their/

is a context search which is sufficient to find the desired line – it will locate the next occurrence of the characters between slashes (‘‘their’’). It also sets dot to that line and prints the line for verification:

to come to the aid of their party.

‘‘Next occurrence’’ means that *ed* starts looking for the string at line ‘‘.+1’’, searches to the end of the buffer, then continues at line 1 and searches to line dot. (That is, the search ‘‘wraps around’’ from ‘‘$’’ to 1.) It scans all the lines in the buffer until it either finds the desired line or gets back to dot again. If the given string of characters can’t be found in any line, *ed* types the error message

?

Otherwise it prints the line it found.

We can do both the search for the desired line *and* a substitution all at once, like this:

/their/s/their/the/p

which will yield

to come to the aid of the party.

There were three parts to that last command: context search for the desired line, make the substitution, print the line.

The expression ‘‘/their/’’ is a context search expression. In their simplest form, all context search expressions are like this – a string of characters surrounded by slashes. Context searches are interchangeable with line numbers, so they can be used by themselves to find and print a desired line, or as line numbers for some other command, like ‘‘s’’. We used them both ways in the examples above.

Suppose the buffer contains the three familiar lines

Now is the time
for all good men
to come to the aid of their party.

Then the *ed* line numbers

/Now/+1
/good/
/party/–1

are all context search expressions, and they all refer to the same line (line 2). To make a change in line 2, we could say

/Now/+1s/good/bad/

or

/good/s/good/bad/

or

/party/–1s/good/bad/

The choice is dictated only by convenience. We could print all three lines by, for instance

/Now/,/party/p

or

/Now/,/Now/+2p

or by any number of similar combinations. The first one of these might be better if we don’t know how many lines are involved. (Of course, if there were only three lines in the buffer, we’d use

1,$p

but not if there were several hundred.)

The basic rule is: a context search expression is *the same as* a line number, so it can be used wherever a line number is needed.

Exercise 6:

Experiment with context searching. Try a body of text with several occurrences of the same string of characters, and scan through it using the same context search.

Try using context searches as line numbers for the substitute, print and delete commands. (They can also be used with ‘‘r’’, ‘‘w’’, and ‘‘a’’.)

Try context searching using ‘‘?text?’’ instead of ‘‘/text/’’. This scans lines in the buffer in reverse order rather than normal. This is sometimes useful if you go too far while looking for some string of characters – it’s an easy way to back up.

(If you get funny results with any of the characters

^ . $ [* \

read the section on ‘‘Special Characters’’.)

Ed provides a shorthand for repeating a context search for the same string. For example, the *ed* line number

/string/

will find the next occurrence of ‘‘string’’. It often happens that this is not the desired line, so the search must be repeated. This can be done by typing merely

//

This shorthand stands for ‘‘the most recently used context search expression.’’ It can also be used as the first string of the substitute command, as in

/string1/s//string2/

which will find the next occurrence of ‘‘string1’’ and replace it by ‘‘string2’’. This can save a lot of typing. Similarly

??

means ‘‘scan backwards for the same expression.’’

Change and Insert – "c" and "i"

This section discusses the *change* command

c

which is used to change or replace a group of one or more lines, and the *insert* command

i

which is used for inserting a group of one or more lines.

"Change", written as

c

is used to replace a number of lines with different lines, which are typed in at the terminal. For example, to change lines ".+1" through "$" to something else, type

.+1,$c
. . . type the lines of text you want here . . .
.

The lines you type between the "c" command and the "." will take the place of the original lines between start line and end line. This is most useful in replacing a line or several lines which have errors in them.

If only one line is specified in the "c" command, then just that line is replaced. (You can type in as many replacement lines as you like.) Notice the use of "." to end the input – this works just like the "." in the append command and must appear by itself on a new line. If no line number is given, line dot is replaced. The value of dot is set to the last line you typed in.

"Insert" is similar to append – for instance

/string/i
. . . type the lines to be inserted here . . .
.

will insert the given text *before* the next line that contains "string". The text between "i" and "." is *inserted before* the specified line. If no line number is specified dot is used. Dot is set to the last line inserted.

Exercise 7:

"Change" is rather like a combination of delete followed by insert. Experiment to verify that

start, end d
i
. . . text . . .
.

is almost the same as

start, end c
. . . text . . .
.

These are not *precisely* the same if line "$" gets deleted. Check this out. What is dot?

Experiment with "a" and "i", to see that they are similar, but not the same. You will observe that

line–number a
. . . text . . .
.

appends *after* the given line, while

line–number i
. . . text . . .
.

inserts *before* it. Observe that if no line number is given, "i" inserts before line dot, while "a" appends after line dot.

Moving text around: the "m" command

The move command "m" is used for cutting and pasting – it lets you move a group of lines from one place to another in the buffer. Suppose we want to put the first three lines of the buffer at the end instead. We could do it by saying:

1,3w temp
$r temp
1,3d

(Do you see why?) but we can do it a lot easier with the "m" command:

1,3m$

The general case is

start line, end line m *after this line*

Notice that there is a third line to be specified – the place where the moved stuff gets put. Of course the lines to be moved can be specified by context searches; if we had

First paragraph
. . .
end of first paragraph.
Second paragraph
. . .
end of second paragraph.

we could reverse the two paragraphs like this:

/Second/,/second/m/First/–1

Notice the "–1" – the moved text goes *after* the line mentioned. Dot gets set to the last line moved.

The global commands "g" and "v"

The *global* command "g" is used to execute one or more *ed* commands on all those lines in the buffer that match some specified string. For example

g/peling/p

prints all lines that contain "peling". More usefully,

g/peling/s//pelling/gp

makes the substitution everywhere on the line, then prints each corrected line. Compare this to

1,$s/peling/pelling/gp

which only prints the last line substituted. Another subtle difference is that the ‘‘g’’ command does not give a ‘‘?’’ if ‘‘peling’’ is not found where the ‘‘s’’ command will.

There may be several commands (including ‘‘a’’, ‘‘c’’ ‘‘i’’ ‘‘r’’, ‘‘w’’, but not ‘‘g’’); in that case, every line except the last must end with a backslash ‘‘\’’:

```
g/xxx/.–1s/abc/def/\
.+2s/ghi/jkl/\
.–2,.p
```

makes changes in the lines before and after each line that contains ‘‘xxx’’, then prints all three lines.

The ‘‘v’’ command is the same as ‘‘g’’, except that the commands are executed on every line that does *not* match the string following ‘‘v’’:

```
v/ /d
```

deletes every line that does not contain a blank.

Special Characters

You may have noticed that things just don’t work right when you used some characters like ‘‘.’’, ‘‘*’’, ‘‘$’’, and others in context searches and the substitute command. The reason is rather complex, although the cure is simple. Basically, *ed* treats these characters as special, with special meanings. For instance, *in a context search or the first string of the substitute command only,*

```
/x.y/
```

means ‘‘a line with an x, *any character,* and a y,’’ *not* just ‘‘a line with an x, a period, and a y.’’ A complete list of the special characters that can cause trouble is the following:

```
^  .  $  [  *  \
```

Warning: The backslash character \ is special to *ed.* For safety’s sake, avoid it where possible. If you have to use one of the special characters in a substitute command, you can turn off its magic meaning temporarily by preceding it with the backslash. Thus

```
s/\\.\*/backslash dot star/
```

will change ‘‘\.*’’ into ‘‘backslash dot star’’.

Here is a hurried synopsis of the other special characters. First, the circumflex ‘‘ ^ ’’ signifies the beginning of a line. Thus

```
/^string/
```

finds ‘‘string’’ only if it is at the beginning of a line: it will find

```
string
```

but not

```
the string...
```

The dollar-sign ‘‘$’’ is just the opposite of the circumflex; it means the end of a line:

```
/string$/
```

will only find an occurrence of ‘‘string’’ that is at the end of some line. This implies, of course, that

```
/^string$/
```

will find only a line that contains just ‘‘string’’, and

```
/^.$/
```

finds a line containing exactly one character.

The character ‘‘.’’, as we mentioned above, matches anything;

```
/x.y/
```

matches any of

```
x+y
x–y
x y
x.y
```

This is useful in conjunction with ‘‘*’’, which is a repetition character; ‘‘a*’’ is a shorthand for ‘‘any number of a’s,’’ so ‘‘.*’’ matches any number of anythings. This is used like this:

```
s/.*/stuff/
```

which changes an entire line, or

```
s/.*,//
```

which deletes all characters in the line up to and including the last comma. (Since ‘‘.*’’ finds the longest possible match, this goes up to the last comma.)

‘‘[’’ is used with ‘‘]’’ to form ‘‘character classes’’; for example,

```
/[1234567890]/
```

matches any single digit _ any one of the characters inside the braces will cause a match.

Finally, the ‘‘&’’ is another shorthand character - it is used only on the right-hand part of a substitute command where it means ‘‘whatever was matched on the left-hand side’’. It is used to save typing. Suppose the current line contained

```
Now is the time
```

and we wanted to put parentheses around it. We could just retype the line, but this is tedious. Or we could say

```
s/^/(/
s/$/)/
```

using our knowledge of ‘‘^’’ and ‘‘$’’. But the easiest way uses the ‘‘&’’:

```
s/.*/(&)/
```

This says ‘‘match the whole line, and replace it by itself surrounded by parens.’’ The ‘‘&’’ can be used several times in a line; consider using

```
s/.*/&?  &!!/
```

to produce

```
Now is the time?  Now is the time!!
```

We don't have to match the whole line, of course: if the buffer contains

the end of the world

we could type

/world/s//& is at hand/

to produce

the end of the world is at hand

Observe this expression carefully, for it illustrates how to take advantage of *ed* to save typing. The string "/world/" found the desired line; the shorthand "//" found the same word in the line; and the "&" saved us from typing it again.

The "&" is a special character only within the replacement text of a substitute command, and has no special meaning elsewhere. We can turn off the special meaning of "&" by preceding it with a "\":

s/ampersand/\&/

will convert the word "ampersand" into the literal symbol "&" in the current line.

Summary of Commands and Line Numbers

The general form of *ed* commands is the command name, perhaps preceded by one or two line numbers, and, in the case of *e, r* and *w,* followed by a file name. Only one command is allowed per line, but a *p* command may follow any other command (except for *e, r, w* and *q).*

a (append) Add lines to the buffer (at line dot, unless a different line is specified). Appending continues until "." is typed on a new line. Dot is set to the last line appended.

c (change) Change the specified lines to the new text which follows. The new lines are terminated by a ".". If no lines are specified, replace line dot. Dot is set to last line changed.

d (delete) Delete the lines specified. If none are specified, delete line dot. Dot is set to the first undeleted line, unless "$" is deleted, in which case dot is set to "$".

e (edit) Edit new file. Any previous contents of the buffer are thrown away, so issue a *w* beforehand if you want to save them.

f (file) Print remembered filename. If a name follows *f* the remembered name will be set to it.

g (global) g/---/commands will execute the commands on those lines that contain "---", which can be any context search expression.

i (insert) Insert lines before specified line (or dot) until a "." is typed on a new line. Dot is set to last line inserted.

m (move) Move lines specified to after the line named after *m.* Dot is set to the last line moved.

p (print) Print specified lines. If none specified, print line dot. A single line number is equivalent to "line-number p". A single newline prints ".+1", the next line.

q (quit) Exit from ed. Wipes out all text in buffer!!

r (read) Read a file into buffer (at end unless specified elsewhere.) Dot set to last line read.

s (substitute) s/string1/string2/ will substitute the characters of 'string2' for 'string1' in specified lines. If no line is specified, make substitution in line dot. Dot is set to last line in which a substitution took place, which means that if no substitution took place, dot is not changed. *s* changes only the first occurrence of string1 on a line; to change all of them, type a "g" after the final slash.

v (exclude) v/---/commands executes "commands" on those lines that *do not* contain "---".

w (write) Write out buffer onto a file. Dot is not changed.

.= *(dot value)* Print value of dot. ("=" by itself prints the value of "$".)

! (temporary escape)
Execute this line as a UNIX command.

/-----/ Context search. Search for next line which contains this string of characters. Print it. Dot is set to line where string found. Search starts at ".+1", wraps around from "$" to 1, and continues to dot, if necessary.

?-----? Context search in reverse direction. Start search at ".–1", scan to 1, wrap around to "$".

UNIX for Beginners

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In many ways, UNIX is the state of the art in computer operating systems. From the user's point of view, it is easy to learn and use, and presents few of the usual impediments to getting the job done.

It is hard, however, for the beginner to know where to start, and how to make the best use of the facilities available. The purpose of this introduction is to point out high spots for new users, so they can get used to the main ideas of UNIX and start making good use of it quickly.

This paper is not an attempt to re-write the *UNIX Programmer's Manual;* often the discussion of something is simply "read section x in the manual." (This implies that you will need a copy of the *UNIX Programmer's Manual.)* Rather it suggests in what order to read the manual, and it collects together things that are stated only indirectly in the manual.

There are five sections:

1. Getting Started: How to log in to a UNIX, how to type, what to do about mistakes in typing, how to log out. Some of this is dependent on which UNIX you log into (phone numbers, for example) and what terminal you use, so this section must necessarily be supplemented by local information.
2. Day-to-day Use: Things you need every day to use UNIX effectively: generally useful commands; the file system.
3. Document Preparation: Preparing manuscripts is one of the most common uses for UNIX. This section contains advice, but not extensive instructions on any of the formatting programs.
4. Writing Programs: UNIX is an excellent vehicle for developing programs. This section talks about some of the tools, but again is not a tutorial in any of the programming languages that UNIX provides.
5. A UNIX Reading List. An annotated bibliography of documents worth reading by new users.

I. GETTING STARTED

Logging In

Most of the details about logging in are in the manual section called "How to Get Started" (pages *iv-v* in the 5th Edition). Here are a couple of extra warnings.

You must have a UNIX login name, which you can get from whoever administers your system. You also need to know the phone number. UNIX is capable of dealing with a variety of terminals: Terminet 300's; Execuport, TI and similar portables; video terminals; GSI's; and even the venerable Teletype in its various forms. But note: UNIX will not handle IBM 2741 terminals and their derivatives (e.g., some Anderson-Jacobsons, Novar). Furthermore, UNIX is strongly oriented towards devices with *lower case.* If your terminal produces only upper case (e.g., model 33 Teletype), life will be so difficult that you should look for another terminal.

Be sure to set the switches appropriately on your device: speed (if it's variable) to 30 characters per second, lower case, full duplex, even parity, and any others that local wisdom advises. Establish a connection using whatever magic is needed for your terminal. UNIX should type "login:" at you. If it types garbage, you may be at the wrong speed; push the 'break' or 'interrupt' key once. If that fails to produce a login message, consult a guru.

When you get a "login:" message, type your login name *in lower case.* Follow it by a RETURN if the terminal has one. If a password is required, you will be asked for it, and (if possible) printing will be turned off while you type it, again followed by a RETURN. (On M37 Teletypes always use NEWLINE or LINEFEED in place of RETURN).

The culmination of your login efforts is a percent sign "%". The percent sign means that UNIX is ready to accept commands from the terminal. (You may also get a message of the day just before the percent sign or a notification that you have mail.)

Typing Commands

Once you've seen the percent sign, you can type commands, which are requests that UNIX do something. Try typing

```
date
```

followed by RETURN. You should get back something like

Sun Sep 22 10:52:29 EDT 1974

Don't forget the RETURN after the command, or nothing will happen. If you think you're being ignored, type a RETURN; something should happen. We won't show the carriage returns, but they have to be there.

Another command you might try is **who**, which tells you everyone who is currently logged in:

who

gives something like

```
pjp    ttyf   Sep 22 09:40
bwk    ttyg   Sep 22 09:48
mel    ttyh   Sep 22 09:58
```

The time is when the user logged in.

If you make a mistake typing the command name, UNIX will tell you. For example, if you type

whom

you will be told

whom: not found

Strange Terminal Behavior

Sometimes you can get into a state where your terminal acts strangely. For example, each letter may be typed twice, or the RETURN may not cause a line feed. You can often fix this by logging out and logging back in. Or you can read the description of the command **stty** in section I of the manual. This will also tell you how to get intelligent treatment of tab characters (which are much used in UNIX) if your terminal doesn't have tabs. If it does have computer-settable tabs, the command **tabs** will set the stops correctly for you.

Mistakes in Typing

If you make a typing mistake, and see it before the carriage return has been typed, there are two ways to recover. The sharp-character ''#'' erases the last character typed; in fact successive uses of ''#'' erase characters back to the beginning of the line (but not beyond). So if you type badly, you can correct as you go:

dd#atte##e

is the same as ''date''.

The at-sign ''@'' erases all of the characters typed so far on the current input line, so if the line is irretrievably fouled up, type an ''@'' and start over (on the same line!).

What if you must enter a sharp or at-sign as part of the text? If you precede either ''#'' or ''@'' by a backslash ''\'', it loses its erase meaning. This implies that to erase a backslash, you have to type two sharps or two at-signs. The backslash is used extensively in UNIX to indicate that the following character is in some way special.

Readahead

UNIX has full readahead, which means that you can type as fast as you want, whenever you want, even when some command is typing at you. If you type during output, your input characters will appear intermixed with the output characters, but they will be stored away by UNIX and interpreted in the correct order. So you can type two commands one after another without waiting for the first to finish or even begin.

Stopping a Program

You can stop most programs by typing the character ''DEL'' (perhaps called ''delete'' or ''rubout'' on your terminal). There are exceptions, like the text editor, where DEL stops whatever the program is doing but leaves you in that program. You can also just hang up the phone. The ''interrupt'' or ''break'' key found on most terminals has no effect.

Logging Out

The easiest way to log out is to hang up the phone. You can also type

login name–of–new–user

and let someone else use the terminal you were on. It is not sufficient just to turn off the terminal. UNIX has no time-out mechanism, so you'll be there forever unless you hang up.

Mail

When you log in, you may sometimes get the message

You have mail.

UNIX provides a postal system so you can send and receive letters from other users of the system. To read your mail, issue the command

mail

Your mail will be printed, and then you will be asked

Save?

If you do want to save the mail, type *y,* for ''yes''; any other response means ''no''.

How do you send mail to someone else? Suppose it is to go to ‘‘joe’’ (assuming ‘‘joe’’ is someone’s login name). The easiest way is this:

mail joe
now type in the text of the letter
on as many lines as you like ...
after the last line of the letter
type the character “control–d”,
that is, hold down “control” and type
a letter “d”.

And that’s it. The ‘‘control-d’’ sequence, usually called ‘‘EOT’’, is used throughout UNIX to mark the end of input from a terminal, so you might as well get used to it.

There are other ways to send mail — you can send a previously prepared letter, and you can mail to a number of people all at once. For more details see **mail** (I).

The notation **mail** (I) means the command **mail** in section (I) of the *UNIX Programmer’s Manual.*

Writing to other users

At some point in your UNIX career, out of the blue will come a message like

Message from joe...

accompanied by a startling beep. It means that Joe wants to talk to you, but unless you take explicit action you won’t be able to talk back. To respond, type the command

write joe

This establishes a two-way communication path. Now whatever Joe types on his terminal will appear on yours and vice versa. The path is slow, rather like talking to the moon. (If you are in the middle of something, you have to get to a state where you can type a command. Normally, whatever program you are running has to terminate or be terminated. If you’re editing, you can escape temporarily from the editor — read the manual.)

A protocol is needed to keep what you type from getting garbled up with what Joe types. Typically it’s like this:

Joe types ‘‘write smith’’ and waits.
Smith types ‘‘write joe’’ and waits.
Joe now types his message (as many lines as he likes). When he’s ready for a reply, he signals it by typing (o), which stands for ‘‘over’’.
Now Smith types a reply, also terminated by (o).
This cycle repeats until someone gets tired; he then signals his intent to quit with (o+o), for ‘‘over and out’’.
To terminate the conversation, each side must type a ‘‘control–d’’ character alone on a line. (‘‘Delete’’ also works.) When the other person types his ‘‘control–d’’, you will get the message “EOT” on your terminal.

If you write to someone who isn’t logged in, or who doesn’t want to be disturbed, you’ll be told. If the target is logged in but doesn’t answer after a decent interval, simply type ‘‘control-d’’.

On-line Manual

The UNIX Programmer’s Manual is typically kept on-line. If you get stuck on something, and can’t find an expert to assist you, you can print on your terminal some manual section that might help. It’s also useful for getting the most up-to-date information on a command. To print a manual section, type ‘‘man section-name’’. Thus to read up on the **who** command, type

man who

If the section in question isn’t in part I of the manual, you have to give the section number as well, as in

man 6 chess

Of course you’re out of luck if you can’t remember the section name.

II. DAY-TO-DAY USE

Creating Files — The Editor

If we have to type a paper or a letter or a program, how do we get the information stored in the machine? Most of these tasks are done with the UNIX ‘‘text editor’’ **ed**. Since **ed** is thoroughly documented in **ed** (I) and explained in *A Tutorial Introduction to the UNIX Text Editor,* we won’t spend any time here describing how to use it. All we want it for right now is to make some *files*. (A file is just a collection of information stored in the machine, a simplistic but adequate definition.)

To create a file with some text in it, do the following:

ed (invokes the text editor)
a (command to ‘‘ed’’, to add text)
now type in
whatever text you want ...
. (signals the end of adding text)

At this point we could do various editing operations on the text we typed in, such as correcting

spelling mistakes, rearranging paragraphs and the like. Finally, we write the information we have typed into a file with the editor command "w":

```
w junk
```

ed will respond with the number of characters it wrote into the file called "junk".

Suppose we now add a few more lines with "a", terminate them with ".", and write the whole thing out as "temp", using

```
w temp
```

We should now have two files, a smaller one called "junk" and a bigger one (bigger by the extra lines) called "temp". Type a "q" to quit the editor.

What files are out there?

The **ls** (for "list") command lists the names (not contents) of any of the files that UNIX knows about. If we type

```
ls
```

the response will be

```
junk
temp
```

which are indeed our two files. They are sorted into alphabetical order automatically, but other variations are possible. For example, if we add the optional argument "-t",

```
ls –t
```

lists them in the order in which they were last changed, most recent first. The "-l" option gives a "long" listing:

```
ls –l
```

will produce something like

```
–rw–rw–rw–  1 bwk   41 Sep 22 12:56 junk
–rw–rw–rw–  1 bwk   78 Sep 22 12:57 temp
```

The date and time are of the last change to the file. The 41 and 78 are the number of characters (you got the same thing from **ed**). "bwk" is the owner of the file — the person who created it. The "-rw-rw-rw-" tells who has permission to read and write the file, in this case everyone.

Options can be combined: "ls -lt" would give the same thing, but sorted into time order. You can also name the files you're interested in, and **ls** will list the information about them only. More details can be found in **ls** (I).

It is generally true of UNIX programs that "flag" arguments like "-t" precede filename arguments.

Printing Files

Now that you've got a file of text, how do you print it so people can look at it? There are a host of programs that do that, probably more than are needed.

One simple thing is to use the editor, since printing is often done just before making changes anyway. You can say

```
ed junk
1,$p
```

ed will reply with the count of the characters in "junk" and then print all the lines in the file. After you learn how to use the editor, you can be selective about the parts you print.

There are times when it's not feasible to use the editor for printing. For example, there is a limit on how big a file **ed** can handle (about 65,000 characters or 4000 lines). Secondly, it will only print one file at a time, and sometimes you want to print several, one after another. So here are a couple of alternatives.

First is **cat**, the simplest of all the printing programs. **cat** simply copies all the files in a list onto the terminal. So you can say

```
cat junk
```

or, to print two files,

```
cat junk temp
```

The two files are simply concatenated (hence the name "cat") onto the terminal.

pr produces formatted printouts of files. As with **cat**, **pr** prints all the files in a list. The difference is that it produces headings with date, time, page number and file name at the top of each page, and extra lines to skip over the fold in the paper. Thus,

```
pr junk temp
```

will list "junk" neatly, then skip to the top of a new page and list "temp" neatly.

pr will also produce multi-column output:

```
pr –3 junk
```

prints "junk" in 3-column format. You can use any reasonable number in place of "3" and **pr** will do its best.

It should be noted that **pr** is *not* a formatting program in the sense of shuffling lines around and justifying margins. The true formatters are **roff**, **nroff**, and **troff**, which we will get to in the section on document preparation.

There are also programs that print files on a high-speed printer. Look in your manual

under **opr** and **lpr**. Which to use depends on the hardware configuration of your machine.

Shuffling Files About

Now that you have some files in the file system and some experience in printing them, you can try bigger things. For example, you can move a file from one place to another (which amounts to giving a file a new name), like this:

mv junk precious

This means that what used to be ‘‘junk’’ is now ‘‘precious’’. If you do an **ls** command now, you will get

precious
temp

Beware that if you move a file to another one that already exists, the already existing contents are lost forever.

If you want to make a *copy* of a file (that is, to have two versions of something), you can use the **cp** command:

cp precious temp1

makes a duplicate copy of ‘‘precious’’ in ‘‘temp1’’.

Finally, when you get tired of creating and moving files, there is a command to remove files from the file system, called **rm**.

rm temp temp1

will remove all of the files named. You will get a warning message if one of the named files wasn’t there.

Filename, What’s in a

So far we have used filenames without ever saying what’s a legal name, so it’s time for a couple of rules. First, filenames are limited to 14 characters, which is enough to be descriptive. Second, although you can use almost any character in a filename, common sense says you should stick to ones that are visible, and that you should probably avoid characters that might be used with other meanings. We already saw, for example, that in the **ls** command, ‘‘ls -t’’ meant to list in time order. So if you had a file whose name was ‘‘-t’’, you would have a tough time listing it by name. There are a number of other characters which have special meaning either to UNIX as a whole or to numerous commands. To avoid pitfalls, you would probably do well to use only letters, numbers and the period. (Don’t use the period as the first character of a filename, for reasons too complicated to go into.)

On to some more positive suggestions. Suppose you’re typing a large document like a book. Logically this divides into many small pieces, like chapters and perhaps sections. Physically it must be divided too, for **ed** will not handle big files. Thus you should type the document as a number of files. You might have a separate file for each chapter, called

chap1
chap2
etc...

Or, if each chapter were broken into several files, you might have

chap1.1
chap1.2
chap1.3
...
chap2.1
chap2.2
...

You can now tell at a glance where a particular file fits into the whole.

There are advantages to a systematic naming convention which are not obvious to the novice UNIX user. What if you wanted to print the whole book? You could say

pr chap1.1 chap1.2 chap1.3 .....

but you would get tired pretty fast, and would probably even make mistakes. Fortunately, there is a shortcut. You can say

pr chap*

The ‘‘*’’ means ‘‘anything at all’’, so this translates into ‘‘print all files whose names begin with ‘chap’ ’’, listed in alphabetical order. This shorthand notation is not a property of the **pr** command, by the way. It is system-wide, a service of the program that interprets commands (the ‘‘shell’’ **sh** (I)). Using that fact, you can see how to list the files of the book:

ls chap*

produces

chap1.1
chap1.2
chap1.3
...

The ‘‘*’’ is not limited to the last position in a filename — it can be anywhere. Thus

rm *junk*

removes all files that contain ‘‘junk’’ as any part of their name. As a special case, ‘‘*’’ by itself matches every filename, so

```
pr *
```

prints all the files (alphabetical order), and

```
rm *
```

removes *all files*. (You had better be sure that's what you wanted to say!)

The ''*'' is not the only pattern-matching feature available. Suppose you want to print only chapters 1 through 4 and 9 of the book. Then you can say

```
pr chap[12349]*
```

The ''[...]'' means to match any of the characters inside the brackets. You can also do this with

```
pr chap[1–49]*
```

''[a-z]'' matches any character in the range *a* through *z*. There is also a ''?'' character, which matches any single character, so

```
pr ?
```

will print all files which have single-character names.

Of these niceties, ''*'' is probably the most useful, and you should get used to it. The others are frills, but worth knowing.

If you should ever have to turn off the special meaning of ''*'', ''?'', etc., enclose the entire argument in quotes (single or double), as in

```
ls "?"
```

What's in a Filename, Continued

When you first made that file called ''junk'', how did UNIX know that there wasn't another ''junk'' somewhere else, especially since the person in the next office is also reading this tutorial? The reason is that generally each user of UNIX has his own ''directory'', which contains only the files that belong to him. When you create a new file, unless you take special action, the new file is made in your own directory, and is unrelated to any other file of the same name that might exist in someone else's directory.

The set of all files that UNIX knows about are organized into a (usually big) tree, with your files located several branches up into the tree. It is possible for you to ''walk'' around this tree, and to find any file in the system, by starting at the root of the tree and walking along the right set of branches.

To begin, type

```
ls /
```

''/'' is the name of the root of the tree (a convention used by UNIX). You will get a response something like this:

```
bin
dev
etc
lib
tmp
usr
```

This is a collection of the basic directories of files that UNIX knows about. On most systems, ''usr'' is a directory that contains all the normal users of the system, like you. Now try

```
ls /usr
```

This should list a long series of names, among which is your own login name. Finally, try

```
ls /usr/your–name
```

You should get what you get from a plain

```
ls
```

Now try

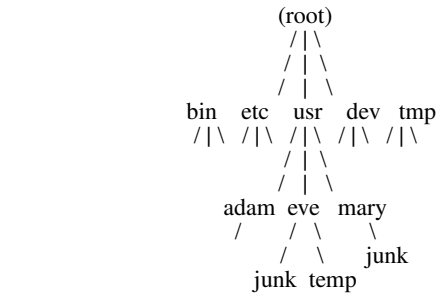
```
cat /usr/your–name/junk
```

(if ''junk'' is still around). The name

```
/usr/your–name/junk
```

is called the ''pathname'' of the file that you normally think of as ''junk''. ''Pathname'' has an obvious meaning: it represents the full name of the path you have to follow through the tree of directories to get to a particular file. It is a universal rule in UNIX that anywhere you can use an ordinary filename, you can use a pathname.

Here is a picture which may make this clearer:



Notice that Mary's ''junk'' is unrelated to Eve's.

This isn't too exciting if all the files of interest are in your own directory, but if you work with someone else or on several projects concurrently, it becomes handy indeed. For example, your friends can print your book by saying

pr /usr/your–name/chap*

Similarly, you can find out what files your neighbor has by saying

ls /usr/neighbor–name

or make your own copy of one of his files by

cp /usr/your–neighbor/his–file yourfile

(If your neighbor doesn't want you poking around in his files, or vice versa, privacy can be arranged. Each file and directory can have read-write-execute permissions for the owner, a group, and everyone else, to control access. See **ls** (I) and **chmod** (I) for details. As a matter of observed fact, most users most of the time find openness of more benefit than privacy.)

As a final experiment with pathnames, try

ls /bin /usr/bin

Do some of the names look familiar? When you run a program, by typing its name after a "%", the system simply looks for a file of that name. It looks first in your directory (where it typically doesn't find it), then in "/bin" and finally in "/usr/bin". There is nothing magic about commands like **cat** or **ls**, except that they have been collected into two places to be easy to find and administer.

What if you work regularly with someone else on common information in his directory? You could just log in as your friend each time you want to, but you can also say "I want to work on his files instead of my own". This is done by changing the directory that you are currently in:

chdir /usr/your–friend

Now when you use a filename in something like **cat** or **pr**, it refers to the file in "your-friend's" directory. Changing directories doesn't affect any permissions associated with a file — if you couldn't access a file from your own directory, changing to another directory won't alter that fact.

If you forget what directory you're in, type

pwd

("print working directory") to find out.

It is often convenient to arrange one's files so that all the files related to one thing are in a directory separate from other projects. For example, when you write your book, you might want to keep all the text in a directory called book. So make one with

mkdir book

then go to it with

chdir book

then start typing chapters. The book is now found in (presumably)

/usr/your–name/book

To delete a directory, see **rmdir** (I).

You can go up one level in the tree of files by saying

chdir ..

".." is the name of the parent of whatever directory you are currently in. For completeness, "." is an alternate name for the directory you are in.

Using Files instead of the Terminal

Most of the commands we have seen so far produce output on the terminal; some, like the editor, also take their input from the terminal. It is universal in UNIX that the terminal can be replaced by a file for either or both of input and output. As one example, you could say

ls

to get a list of files. But you can also say

ls >filelist

to get a list of your files in the file "filelist". ("filelist" will be created if it doesn't already exist, or overwritten if it does.) The symbol ">" is used throughout UNIX to mean "put the output on the following file, rather than on the terminal". Nothing is produced on the terminal. As another example, you could concatenate several files into one by capturing the output of **cat** in a file:

cat f1 f2 f3 >temp

Similarly, the symbol "<" means to take the input for a program from the following file, instead of from the terminal. Thus, you could make up a script of commonly used editing commands and put them into a file called "script". Then you can run the script on a file by saying

ed file <script

Pipes

One of the novel contributions of UNIX is the idea of a *pipe*. A pipe is simply a way to connect the output of one program to the input of another program, so the two run as a sequence of processes — a pipe-line.

For example,

```
pr f g h
```

will print the files "f", "g" and "h", beginning each on a new page. Suppose you want them run together instead. You could say

```
cat f g h >temp
pr temp
rm temp
```

but this is more work than necessary. Clearly what we want is to take the output of **cat** and connect it to the input of **pr**. So let us use a pipe:

```
cat f g h | pr
```

The vertical bar means to take the output from **cat**, which would normally have gone to the terminal, and put it into **pr**, which formats it neatly.

Any program that reads from the terminal can read from a pipe instead; any program that writes on the terminal can drive a pipe. You can have as many elements in a pipeline as you wish.

Many UNIX programs are written so that they will take their input from one or more files if file arguments are given; if no arguments are given they will read from the terminal, and thus can be used in pipelines.

The Shell

We have already mentioned once or twice the mysterious "shell," which is in fact **sh** (I). The shell is the program that interprets what you type as commands and arguments. It also looks after translating "*", etc., into lists of filenames.

The shell has other capabilities too. For example, you can start two programs with one command line by separating the commands with a semicolon; the shell recognizes the semicolon and breaks the line into two commands. Thus

```
date; who
```

does both commands before returning with a "%".

You can also have more than one program running *simultaneously* if you wish. For example, if you are doing something time-consuming, like the editor script of an earlier section, and you don't want to wait around for the results before starting something else, you can say

```
ed file <script &
```

The ampersand at the end of a command line says "start this command running, then take further commands from the terminal immediately." Thus the script will begin, but you can do something else at the same time. Of course, to keep the output from interfering with what you're doing on the terminal, it would be better to have said

```
ed file <script >lines &
```

which would save the output lines in a file called "lines".

When you initiate a command with "&", UNIX replies with a number called the process number, which identifies the command in case you later want to stop it. If you do, you can say

```
kill process–number
```

You might also read **ps** (I).

You can say

```
(command–1; command–2; command–3) &
```

to start these commands in the background, or you can start a background pipeline with

```
command–1 | command–2 &
```

Just as you can tell the editor or some similar program to take its input from a file instead of from the terminal, you can tell the shell to read a file to get commands. (Why not? The shell after all is just a program, albeit a clever one.) For instance, suppose you want to set tabs on your terminal, and find out the date and who's on the system every time you log in. Then you can put the three necessary commands (**tabs**; **date**; **who**) into a file, let's call it "xxx", and then run it with either

```
sh xxx
```

or

```
sh <xxx
```

This says to run the shell with the file "xxx" as input. The effect is as if you had typed the contents of "xxx" on the terminal. (If this is to be a regular thing, you can eliminate the need to type "sh"; see **chmod** (I) and **sh** (I).)

The shell has quite a few other capabilities as well, some of which we'll get to in the section on programming.

III. DOCUMENT PREPARATION

UNIX is extensively used for document preparation. There are three major *formatting* programs, that is, programs which produce a text with justified right margins, automatic page numbering and titling, automatic hyphenation, and the like. The simplest of these formatters is **roff**, which in fact is simple enough that if you type almost any text into a file and "roff" it, you

will get plausibly formatted output. You can do better with a little knowledge, but basically it's easy to learn and use. We'll get back to **roff** shortly.

nroff is similar to **roff** but does much less for you automatically. It will do a great deal more, once you know how to use it.

Both **roff** and **nroff** are designed to produce output on terminals, line-printers, and the like. The third formatter, **troff** (pronounced ''tee-roff''), instead drives a Graphic Systems phototypesetter, which produces very high quality output on photographic paper. This paper was printed on the phototypesetter by **troff**.

Because **nroff** and **troff** are relatively hard to learn to use effectively, several ''packages'' of canned formatting requests are available which let you do things like paragraphs, running titles, multi-column output, and so on, with little effort. Regrettably, details vary from system to system.

ROFF

The basic idea of **roff** (and of **nroff** and **troff**, for that matter) is that the text to be formatted contains within it ''formatting commands'' that indicate in detail how the formatted text is to look. For example, there might be commands that specify how long lines are, whether to use single or double spacing, and what running titles to use on each page. In general, you don't have to spell out all of the possible formatting details. Most of them have ''default values'', which you will get if you say nothing at all. For example, unless you take special precautions, you'll get single-spaced output, 65-character lines, justified right margins, and 58 text lines per page when you **roff** a file. This is the reason that **roff** is so simple — most of the decisions have already been made for you.

Some things do have to be done, however. If you want a document broken into paragraphs, you have to tell **roff** where to add the extra blank lines. This is done with the ''.sp'' command:

```
this is the end of one paragraph.
.sp
This begins the next paragraph ...
```

In **roff** (and in **nroff** and **troff**), formatting commands consist of a period followed by two letters, and they must appear at the beginning of a line, all by themselves. The ''.sp'' command tells **roff** to finish printing any of the previous line that might be still unprinted, then print a blank line before continuing. You can have more space if you wish; ''.sp 2'' asks for 2 spaces, and so on.

If you simply want to ensure that subsequent text appears on a fresh output line, you can use the command ''.br'' (for ''break'') instead of ''.sp''.

Most of the other commonly-used **roff** commands are equally simple. For example you can center one or more lines with the ''.ce'' command.

```
.ce
Title of Paper
.sp 2
```

causes the title to be centered, then followed by two blank lines. As with ''.sp'', ''.ce'' can be followed by a number; in that case, that many input lines are centered.

''.ul'' underlines lines, and can also be followed by a number:

```
.ce 2
.ul 2
An Earth–shaking Paper
.sp
John Q. Scientist
```

will center and underline the two text lines. Notice that the ''.sp'' between them is not part of the line count.

You can get multiple-line spacing instead of the default single-spacing with the ''.ls'' command:

```
.ls 2
```

causes double spacing.

If you're typing things like tables, you will not want the automatic filling-up and justification of output lines that is done by default. You can turn this off with the command ''.nf'' (no-fill), and then back on again with ''.fi'' (fill). Thus

```
this section is filled by default.
.nf
here lines will appear just
as you typed them —
no extra spaces, no moving of words.
.fi
Now go back to filling up output lines.
```

You can change the line-length with ''.ll'', and the left margin (the indent) by ''.in''. These are often used together to make offset blocks of text:

```
.ll −10
.in +10
this text will be moved 10
spaces to the right and the
lines will also be shortened 10
characters from the right. The
```

```
"+" and "−" mean to change
the previous value by that
much. Now revert:
.ll +10
.in −10
```

Notice that ".ll +10" adds ten characters to the line length, while ".ll 10" makes the line ten characters *long*.

The ".ti" command indents (in either direction) just like ".in", except for only one line. Thus to make a new paragraph with a 10-character indent, you would say

```
.sp
.ti +10
New paragraph ...
```

You can put running titles on both top and bottom of each page, like this:

```
.he "left top"center top"right top"
.fo "left bottom"center bottom"right bottom"
```

The header or footer is divided into three parts, which are marked off by any character you like. (We used a double quote.) If there's nothing between the markers, that part of the title will be blank. If you use a percent sign anywhere in ".he" or ".fo", the current page number will be inserted. So to get centered page numbers with dashes around them, at the top, use

```
.he ""− % −""
```

You can skip to the top of a new page at any time with the ".bp" command; if ".bp" is followed by a number, that will be the new page number.

The foregoing is probably enough about **roff** for you to go off and format most everyday documents. Read **roff** (I) for more details.

Hints for Preparing Documents

Most documents go through several versions (always more than you expected) before they are finally finished. Accordingly, you should do whatever possible to make the job of changing them easy.

First, when you do the purely mechanical operations of typing, type so subsequent editing will be easy. Start each sentence on a new line. Make lines short, and break lines at natural places, such as after commas and semicolons, rather than randomly. Since most people change documents by rewriting phrases and adding, deleting and rearranging sentences, these precautions simplify any editing you have to do later.

The second aspect of making change easy is not to commit yourself to formatting details too early. For example, if you decide that each paragraph is to have a space and an indent of 10 characters, you might type, before each,

```
.sp
.ti +10
```

But what happens when later you decide that it would have been better to have no space and an indent of only 5 characters? It's tedious indeed to go back and patch this up.

Fortunately, all of the formatters let you delay decisions until the actual moment of running. The secret is to define a new operation (called a *macro),* for each formatting operation you want to do, like making a new paragraph. You can say, in all three formatters,

```
.de PP
.sp
.ti +10
..
```

This *defines* ".PP" as a new **roff** (or **nroff** or **troff**) operation, whose meaning is exactly

```
.sp
.ti +10
```

(The ".." marks the end of the definition.) Whenever ".PP" is encountered in the text, it is as if you had typed the two lines of the definition in place of it.

The beauty of this scheme is that now, if you change your mind about what a paragraph should look like, you can change the formatted output merely by changing the definition of ".PP" and re-running the formatter.

As a rule of thumb, for all but the most trivial jobs, you should type a document in terms of a set of macros like ".PP", and then define them appropriately. As long as you have entered the text in some systematic way, it can always be cleaned up and re-formatted by a judicious combination of editing and macro definitions. The packages of formatting commands that we mentioned earlier are simply collections of macros designed for particular formatting tasks.

One of the main differences between **roff** and the other formatters is that macros in **roff** can only be lines of text and formatting commands. In **nroff** and **troff**, macros may have arguments, so they can have different effects depending on how they are called (in exactly the same way that the ".sp" command has an argument, the number of spaces you want).

Miscellany

In addition to the basic formatters, UNIX provides a host of supporting programs. **eqn**

and **neqn** let you integrate mathematics into the text of a document, in a language that closely resembles the way you would speak it aloud. **spell** and **typo** detect possible spelling mistakes in a document. **grep** looks for lines containing a particular text pattern (rather like the editor's context search does, but on a whole series of files). For example,

```
grep "ing$" chap*
```

will find all lines ending in the letters ''ing'' in the series of files ''chap*''. (It is almost always a good practice to put quotes around the pattern you're searching for, in case it contains characters that have a special meaning for the shell.)

wc counts the words and (optionally) lines in a set of files. **tr** translates characters into other characters; for example it will convert upper to lower case and vice versa. This translates upper into lower:

```
tr "[A–Z]" "[a–z]"
```

diff prints a list of the differences between two files, so you can compare two versions of something automatically (which certainly beats proofreading by hand). **sort** sorts files in a variety of ways; **cref** makes cross-references; **ptx** makes a permuted index (keyword-in-context listing).

Most of these programs are either independently documented (like **eqn** and **neqn**), or are sufficiently simple that the description in the *UNIX Programmer's Manual* is adequate explanation.

IV. PROGRAMMING

UNIX is a marvelously pleasant and productive system for writing programs; productivity seems to be an order of magnitude higher than on other interactive systems.

There will be no attempt made to teach any of the programming languages available on UNIX, but a few words of advice are in order. First, UNIX is written in C, as is most of the applications code. If you are undertaking anything substantial, C is the only reasonable choice. More on that in a moment. But remember that there are quite a few programs already written, some of which have substantial power.

The editor can be made to do things that would normally require special programs on other systems. For example, to list the first and last lines of each of a set of files, say a book, you could laboriously type

```
ed
e chap1.1
1p
$p
e chap1.2
1p
$p
 etc.
```

But instead you can do the job once and for all. Type

```
ls chap* >temp
```

to get the list of filenames into a file. Then edit this file to make the necessary series of editing commands (using the global commands of **ed**), and write it into ''script''. Now the command

```
ed <script
```

will produce the same output as the laborious hand typing.

The pipe mechanism lets you fabricate quite complicated operations out of spare parts already built. For example, the first draft of the **spell** program was (roughly)

```
cat ... (collect the files)
| tr ... (put each word on a new line,
        delete punctuation, etc.)
| sort  (into dictionary order)
| uniq (strip out duplicates)
| comm       (list words found in text but
        not in dictionary)
```

Programming the Shell

An option often overlooked by newcomers is that the shell is itself a programming language, and since UNIX already has a host of building-block programs, you can sometimes avoid writing a special purpose program merely by piecing together some of the building blocks with shell command files.

As an unlikely example, suppose you want to count the number of users on the machine every hour. You could type

```
date
who | wc –l
```

every hour, and write down the numbers, but that is rather primitive. The next step is probably to say

```
(date; who | wc –l) >>users
```

which uses ''>>'' to *append* to the end of the file ''users''. (We haven't mentioned ''>>'' before — it's another service of the shell.) Now all you have to do is to put a loop around this, and ensure that it's done every hour. Thus, place the following commands into a file, say ''count'':

```
: loop
(date; who | wc –l) >>users
sleep  3600
goto loop
```

The command **:** is followed by a space and a label, which you can then **goto**. Notice that it's quite legal to branch backwards. Now if you issue the command

```
sh  count  &
```

the users will be counted every hour, and you can go on with other things. (You will have to use **kill** to stop counting.)

If you would like "every hour" to be a parameter, you can arrange for that too:

```
: loop
(date; who | wc – l) >>users
sleep  $1
goto loop
```

"$1" means the first argument when this procedure is invoked. If you say

```
sh count 60
```

it will count every minute. A shell program can have up to nine arguments, "$1" through "$9".

The other aspect of programming is conditional testing. The **if** command can test conditions and execute commands accordingly. As a simple example, suppose you want to add to your login sequence something to print your mail if you have some. Thus, knowing that mail is stored in a file called 'mailbox', you could say

```
if –r mailbox  mail
```

This says "if the file 'mailbox' is readable, execute the **mail** command."

As another example, you could arrange that the "count" procedure count every hour by default, but allow an optional argument to specify a different time. Simply replace the "sleep $1" line by

```
if $1x = x sleep 3600
if $1x != x sleep $1
```

The construction

```
if $1x = x
```

tests whether "$1", the first argument, was present or absent.

More complicated conditions can be tested: you can find out the status of an executed command, and you can combine conditions with 'and', 'or', 'not' and parentheses — see **if** (I). You should also read **shift** (I) which describes how to manipulate arguments to shell command files.

Programming in C

As we said, C is the language of choice: everything in UNIX is tuned to it. It is also a remarkably easy language to use once you get started. Sections II and III of the manual describe the system interfaces, that is, how you do I/O and similar functions.

You can write quite significant C programs with the level of I/O and system interface described in *Programming in C: A Tutorial,* if you use existing programs and pipes to help. For example, rather than learning how to open and close files you can (at least temporarily) write a program that reads from its standard input, and use **cat** to concatentate several files into it. This may not be adequate for the long run, but for the early stages it's just right.

There are a number of supporting programs that go with C. The C debugger, **cdb**, is marginally useful for digging through the dead bodies of C programs. **db**, the assembly language debugger, is actually more useful most of the time, but you have to know more about the machine and system to use it well. The most effective debugging tool is still careful thought, coupled with judiciously placed print statements.

You can instrument C programs and thus find out where they spend their time and what parts are worth optimising. Compile the routines with the "-p" option; after the test run use **prof** to print an execution profile. The command **time** will give you the gross run-time statistics of a program, but it's not super accurate or reproducible.

C programs that don't depend too much on special features of UNIX can be moved to the Honeywell 6070 and IBM 370 systems with modest effort. Read *The GCOS C Library* by M. E. Lesk and B. A. Barres for details.

Miscellany

If you *have* to use Fortran, you might consider **ratfor**, which gives you the decent control structures and free-form input that characterize C, yet lets you write code that is still portable to other environments. Bear in mind that UNIX Fortran tends to produce large and relatively slow-running programs. Furthermore, supporting software like **db**, **prof**, etc., are all virtually useless with Fortran programs.

If you want to use assembly language (all heavens forfend!), try the implementation language LIL, which gives you many of the advantages of a high-level language, like decent control flow structures, but still lets you get close to the machine if you really want to.

If your application requires you to translate a language into a set of actions or another language, you are in effect building a compiler, though probably a small one. In that case, you should be using the **yacc** compiler-compiler, which helps you develop a compiler quickly.

V. UNIX READING LIST

General:

UNIX Programmer's Manual (Ken Thompson, Dennis Ritchie, and a cast of thousands). Lists commands, system routines and interfaces, file formats, and some of the maintenance procedures. You can't live without this, although you will probably only read section I.

The UNIX Time-sharing System (Ken Thompson, Dennis Ritchie). CACM, July 1974. An overview of the system, for people interested in operating systems. Worth reading by anyone who programs. Contains a remarkable number of one-sentence observations on how to do things right.

Document Preparation:

A Tutorial Introduction to the UNIX Text Editor. (Brian Kernighan). Bell Laboratories internal memorandum. Weak on the more esoteric uses of the editor, but still probably the easiest way to learn **ed**.

Typing Documents on UNIX. (Mike Lesk). Bell Laboratories internal memorandum. A macro package to isolate the novice from the vagaries of the formatting programs. If this specific package isn't available on your system, something similar probably is. This one works with both **nroff** and **troff**.

Programming:

Programming in C: A Tutorial (Brian Kernighan). Bell Laboratories internal memorandum. The easiest way to start learning C, but it's no help at all with the interface to the system beyond the simplest IO. Should be read in conjunction with

C Reference Manual (Dennis Ritchie). Bell Laboratories internal memorandum. An excellent reference, but a bit heavy going for the beginner, especially one who has never used a language like C.

Others:

D. M. Ritchie, UNIX Assembler Reference Manual.

B. W. Kernighan and L. L. Cherry, A System for Typesetting Mathematics, Computing Science Tech. Rep. 17.

M. E. Lesk and B. A. Barres, The GCOS C Library. Bell Laboratories internal memorandum.

K. Thompson and D. M. Ritchie, Setting Up UNIX.

M. D. McIlroy, UNIX Summary.

D. M. Ritchie, The UNIX I/O System.

A. D. Hall, The M6 Macro Processor, Computing Science Tech. Rep. 2.

J. F. Ossanna, NROFF User's Manual — Second Edition, Bell Laboratories internal memorandum.

D. M. Ritchie and K. Thompson, Regenerating System Software.

B. W. Kernighan, Ratfor—A Rational Fortran, Bell Laboratories internal memorandum.

M. D. McIlroy, Synthetic English Speech by Rule, Computing Science Tech. Rep. 14.

M. D. McIlroy, Bell Laboratories internal memorandum.

J. F. Ossanna, TROFF Users' Manual, Bell Laboratories internal memorandum.

B. W. Kernighan, TROFF Made Trivial, Bell Laboratories internal memorandum.

R. H. Morris and L. L. Cherry, Computer Detection of Typographical Errors, Computing Science Tech. Rep. 18.

S. C. Johnson, YACC (Yet Another Compiler-Compiler), Bell Laboratories internal memorandum.

P. J. Plauger, Programming in LIL: A Tutorial, Bell Laboratories internal memorandum.

Index

RATFOR — A Rational Fortran

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Fortran programs are hard to read, write and debug. To make program development easier, RATFOR provides a set of decent control structures:

statement grouping
completely general **if - else** statements
while, **for** and **do** for looping
break and **next** for controlling loop exits

and some "syntactic sugar":

free form input (e.g., multiple statements/line)
unobtrusive comment convention
translation of >, >=, etc., into .GT., .GE., etc.
"define" statement for symbolic parameters
"include" statement for including source files

RATFOR not only makes programming in Fortran more enjoyable, but also allows structured programming, in the sense of coding without GOTO's. RATFOR programs tend to be markedly easier to write, read, and make correct than their equivalents in standard Fortran.

RATFOR is a preprocessor, translating the input into standard Fortran constructions. RATFOR programs may readily be written so the generated Fortran is portable; program transferability is easy to achieve. RATFOR is written in itself, so it is also portable.

The grammar of RATFOR is as follows:

```
prog    : stat
        | prog  stat
stat    : if( condition ) stat
        | if( condition ) stat else stat
        | while( condition ) stat
        | for( initialization; condition; increment ) stat
        | do do-part stat
        | break
        | next
        | digits  stat
        | { prog }
        | anything unrecognizable
```

In the grammar above, condition can be any legal Fortran condition like "'A .EQ. B'," i.e., anything that could appear in a legal Fortran logical IF statement. stat is, of course, any Fortran or RATFOR statement, or any collection of these enclosed in braces.

The while statement performs a loop while some specified condition is true. The test is performed at the *beginning* of the loop, so it is possible to do a while zero times, which can't be done with a Fortran DO.

The for statement is a somewhat generalized while statement that allows an initialization and an incrementing step as well as a termination condition on a loop. initialization is any single *Fortran* statement, which gets done once before the loop begins. increment is any single *Fortran* statement, which gets done at the end of each pass through the loop, before the test.

for and while are useful for backward loops, chaining along lists, loops that must be done zero times, and similar things which are hard to express with a DO statement, and obscure to write out directly.

The do statement is like a Fortran DO, except that no label or CONTINUE is needed. The **do-part** that follows the do keyword has to be something that can legally go into a Fortran DO statement.

A break causes an immediate exit from a for, while or do to the following statement. The next statement causes an immediate transfer to the increment part of a for or do, and the test part of a while. Both break and next refer to the innermost enclosing for, while or do.

Statements can be placed anywhere on a line; long statements are continued automatically. Multiple statements may appear on one line, if they are separated by semicolons. No semi-colon is needed at the end of a line, if RATFOR can guess whether the statement ends there. Lines ending with any characters obviously a continuation, like plus or comma, are assumed to be continued on the next line. Any statement that begins with an all-numeric field is assumed to be a Fortran label, and placed in columns 1-5. PP A '#' character in a line marks the beginning of a comment; the comment is terminated by the end of a line.

Text enclosed in matching single or double quotes is converted to nH... by RATFOR, but is otherwise unaltered. Characters like '>', '>=', and '&' are translated into their longer Fortran equivalents '.GT.', '.GE', and '.AND', except within quotes.

Any string of alphanumeric characters can be defined as a name; thereafter, whenever that name occurs in the input (delimited by non-alphanumerics) it is replaced by the rest of the definition line (comments are stripped off).

An entire source file may be included by saying ''include filename'' at the appropriate place.

YACC − Yet Another Compiler-Compiler

Stephen C. Johnson

ABSTRACT

Computer program input generally has some structure; in fact, every computer program which does input can be thought of as defining an ‘‘input language’’ which it accepts. The input languages may be as complex as a programming language, or as simple as a sequence of numbers. Unfortunately, standard input facilities are restricted, difficult to use and change, and do not completely check their inputs for validity.

Yacc provides a general tool for controlling the input to a computer program. The Yacc user describes the structures of his input, together with code which is to be invoked when each such structure is recognized. Yacc turns such a specification into a subroutine which may be invoked to handle the input process; frequently, it is convenient and appropriate to have most of the flow of control in the user´s application handled by this subroutine.

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

Yacc is written in C[7], and runs under UNIX. The subroutine which is output may be in C or in Ratfor[4], at the user´s choice; Ratfor permits translation of the output subroutine into portable Fortran[5]. The class of specifications accepted is a very general one, called LALR(1) grammars with disambiguating rules. The theory behind Yacc has been described elsewhere[1,2,3].

Yacc was originally designed to help produce the ‘‘front end’’ of compilers; in addition to this use, it has been successfully used in many application programs, including a phototypesetter language, a document retrieval system, a Fortran debugging system, and the Ratfor compiler.

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YACC − Yet Another Compiler-Compiler

Stephen C. Johnson

Section 0: Introduction

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

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

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

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

```
July 4, 1776
```

might be matched by the above rule.

As we mentioned above, an important part of the input process is carried out by the lexical analyzer. This user routine reads the true input stream, recognizing those structures which are more conveniently or more efficiently recognized directly, and communicates these recognized tokens to the parser. For historical reasons, the name of a structure recognized by the lexical analyzer is called a *terminal symbol* name, while the name of a structure recognized by the parser is called a *nonterminal symbol* name. To avoid the obvious confusion of terminology, we shall usually refer to terminal symbol names as *token names*.

There is considerable leeway in deciding whether to recognize structures by the lexical analyzer or by a grammar rule. Thus, in the above example it would be possible to have other rules of the form

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

    . . .

month_name : ´D´ ´e´ ´c´ ;
```

Here, the lexical analyzer would only need to recognize individual letters, and month_name would be a nonterminal symbol. Rules of this sort tend to be a bit wasteful of time and space, and may even restrict the power of the input process (although they are easy to write). For a more efficient input process, the lexical analyzer itself might recognize the month names, and return an indication that a month_name was seen; in this case, month_name would be a token.

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

As an example of the flexibility of the grammar rule approach, we might add to the above specifications the rule

date : month ´/´ day ´/´ year ;

and thus optionally allow the form

7/4/1776

as a synonym for

July 4, 1776

In most cases, this new rule could be ‘‘slipped in’’ to a working system with minimal effort, and a very small chance of disrupting existing input.

Frequently, the input being read does not conform to the specifications due to errors in the input. The parsers produced by Yacc have the very desirable property that they will detect these input errors at the earliest place at which this can be done with a left-to-right scan; thus, not only is the chance of reading and computing with bad input data substantially reduced, but the bad data can usually be quickly found. Error handling facilities, entered as part of the input specifications, frequently permit the reentry of bad data, or the continuation of the input process after skipping over the bad data.

In some cases, Yacc fails to produce a parser when given a set of specifications. For example, the specifications may be self contradictory, or they may require a more powerful recognition mechanism than that available to Yacc. The former cases probably represent true design errors; the latter cases can often be corrected by making the lexical analyzer more powerful, or by rewriting some of the grammar rules. The class of specifications which Yacc can handle compares very favorably with other systems of this type; moreover, the constructions which are difficult for Yacc to handle are also frequently difficult for human beings to handle. Some users have reported that the discipline of formulating valid Yacc specifications for their input revealed errors of conception or design early in the program development.

The next several sections describe the basic process of preparing a Yacc specification; Section 1 describes the preparation of grammar rules, Section 2 the preparation of the user supplied actions associated with these rules, and Section 3 the preparation of lexical analyzers. In Section 4, we discuss the diagnostics produced when Yacc is unable to produce a parser from the given specifications. This section also describes a simple, frequently useful mechanism for handling operator precedences. Section 5 discusses error detection and recovery. Sections 6C and 6R discuss the operating environment and special features of the subroutines which Yacc produces in C and Ratfor, respectively. Section 7 gives some hints which may lead to better designed, more efficient, and clearer specifications. Finally, Section 8 has a brief summary. Appendix A has a brief example, and Appendix B tells how to run Yacc on the UNIX operating system. Appendix C has a brief description of mechanisms and syntax which are no longer actively supported, but which are provided for historical continuity with older versions of Yacc.

Section 1: Basic Specifications

As we noted above, names refer to either tokens or nonterminal symbols. Yacc requires those names which will be used as token names to be declared as such. In addition, for reasons which will be discussed in Section 3, it is usually desirable to include the lexical analyzer as part of the specification file; it may be useful to include other programs as well. Thus, every specification file consists of three sections: the *declarations, (grammar) rules,* and *programs.* The sections are separated by double percent ‘‘%%’’ marks. (The per-cent ‘‘%’’ is generally used in Yacc specifications as an escape character.)

In other words, a full specification file looks like

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

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

```
%%
rules
```

Blanks, tabs, and newlines are ignored except that they may not appear in names or multi-character reserved symbols. Comments may appear wherever a name or operator is legal; they are enclosed in /* . . . */, as in C and PL/I.

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

```
A : BODY ;
```

A represents a nonterminal name, and BODY represents a sequence of zero or more names and literals. Notice that the colon and the semicolon are Yacc punctuation.

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

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

```
'\n'   represents newline
'\r'   represents return
'\''   represents single quote "'"
'\\'   represents backslash "\"
'\t'   represents tab
'\b'   represents backspace
'\xxx' represents "xxx" in octal
```

For a number of technical reasons, the nul character ('\0' or 000) should never be used in grammar rules.

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

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

can be given to Yacc as

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

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

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

```
empty :   ;
```

As we mentioned above, names which represent tokens must be declared as such. The simplest way of doing this is to write

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

in the declarations section. (See Sections 3 and 4 for much more discussion). Every name not defined in the declarations section is assumed to represent a nonterminal symbol. If, by the end of the rules section, some nonterminal symbol has not appeared on the left of any rule, then an error message is produced and Yacc halts.

The left hand side of the *first* grammar rule in the grammar rules section has special importance; it is taken to be the controlling nonterminal symbol for the entire input process; in technical language it is called

the *start symbol.* In effect, the parser is designed to recognize the start symbol; thus, this symbol generally represents the largest, most general structure described by the grammar rules.

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

It is the job of the user supplied lexical analyzer to return the endmarker when appropriate; see section 3, below. Frequently, the endmarker token represents some reasonably obvious I/O status, such as ‘‘end-of-file’’ or ‘‘end-of-record’’.

Section 2: Actions

To each grammar rule, the user may associate an action to be performed each time the rule is recognized in the input process. This action may return a value, and may obtain the values returned by previous actions in the grammar rule. In addition, the lexical analyzer can return values for tokens, if desired.

When invoking Yacc, the user specifies a programming language; currently, Ratfor and C are supported. An action is an arbitrary statement in this language, and as such can do input and output, call subprograms, and alter external vectors and variables (recall that a ‘‘statement’’ in both C and Ratfor can be compound and do many distinct tasks). An action is specified by an equal sign ‘‘=’’ at the end of a grammar rule, followed by one or more statements, enclosed in curly braces ‘‘{’’ and ‘‘}’’. For example,

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

and

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

are grammar rules with actions in C. A grammar rule with an action need not end with a semicolon; in fact, it is an error to have a semicolon before the equal sign.

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

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

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

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

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

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

As a more concrete example, we might have the rule

```
expression: ´(´ expression ´)´ ;
```

We wish the value returned by this rule to be the value of the expression in parentheses. Then we write

```
expression: ´(´ expression ´)´    = { $$ = $2 ; }
```

As a default, the value of a rule is the value of the first element in it ($1). This is true even if there is no explicit action given for the rule. Thus, grammar rules of the form

```
A: B ;
```

frequently need not have an explict action.

Notice that, although the values of actions are integers, these integers may in fact contain pointers (in C) or indices into an array (in Ratfor); in this way, actions can return and reference more complex data structures.

Sometimes, we wish to get control before a rule is fully parsed, as well as at the end of the rule. There is no explicit mechanism in Yacc to allow this; the same effect can be obtained, however, by introducing a new symbol which matches the empty string, and inserting an action for this symbol. For example, we might have a rule describing an ‘‘if’’ statement:

```
statement: IF ´(´ expr ´)´ THEN statement
```

Suppose that we wish to get control after seeing the right parenthesis in order to output some code. We might accomplish this by the rules:

```
statement:  IF ´(´ expr ´)´ actn THEN statement
        = { call action1 }

actn:   /* matches the empty string */
        = { call action2 }
```

Thus, the new nonterminal symbol actn matches no input, but serves only to call action2 after the right parenthesis is seen.

Frequently, it is more natural in such cases to break the rule into parts where the action is needed. Thus, the above example might also have been written

```
statement:  ifpart THEN statement
        = { call action1 }

ifpart:     IF ´(´ expr ´)´
        = { call action2 }
```

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

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

creates a node with label L, and descendants n1 and n2, and returns a pointer to the newly created node. Then we can cause a parse tree to be built by supplying actions such as:

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

in our specification.

The user may define other variables to be used by the actions. Declarations and definitions can appear in two places in the Yacc specification: in the declarations section, and at the head of the rules sections, before the first grammar rule. In each case, the declarations and definitions are enclosed in the marks ‘‘%{’’ and ‘‘%}’’. Declarations and definitions placed in the declarations section have global scope, and are thus known to the action statements and the lexical analyzer. Declarations and definitions placed at the head of the rules section have scope local to the action statements. Thus, in the above example, we might have included

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

in the declarations section, or, perhaps,

```
%{ static int variable; %}
```

at the head of the rules section. If we were writing Ratfor actions, we might want to include some COMMON statements at the beginning of the rules section, to allow for easy communication between the actions and other routines. For both C and Ratfor, Yacc has used only external names beginning in ‘‘yy’’; the user should avoid such names.

Section 3: Lexical Analysis

The user must supply a lexical analyzer which reads the input stream and communicates tokens (with values, if desired) to the parser. The lexical analyzer is an integer valued function called yylex, in both C and Ratfor. The function returns an integer which represents the type of the token. The value to be associated in the parser with that token is assigned to the integer variable yylval. Thus, a lexical analyzer written in C should begin

```
yylex ( ) {
        extern int yylval;
        . . .
```

while a lexical analyzer written in Ratfor should begin

```
integer function yylex(yylval)
        integer yylval
        . . .
```

Clearly, the parser and the lexical analyzer must agree on the type numbers in order for communication between them to take place. These numbers may be chosen by Yacc, or chosen by the user. In either case, the ‘‘define’’ mechanisms of C and Ratfor are used to allow the lexical analyzer to return these numbers symbolically. For example, suppose that the token name DIGIT has been defined in the declarations section of the specification. The relevant portion of the lexical analyzer (in C) might look like:

```
yylex( ) {
        extern int yylval;
        int c;
        . . .
        c = getchar( );
        . . .
        if( c >= ´0´ && c <= ´9´ ) {
                yylval = c−´0´;
                return(DIGIT);
        }
        . . .
```

The relevant portion of the Ratfor lexical analyzer might look like:

```
integer function yylex(yylval)
        integer yylval, digits(10), c
        . . .
        data digits(1) / "0" /;
        data digits(2) / "1" /;
        . . .
        data digits(10) / "9" /;
        . . .
#   set c to the next input character
        . . .
        do i = 1, 10 {
                if(c .EQ. digits(i)) {
                        yylval = i−1
                        yylex = DIGIT
                        return
                }
        }
        . . .
```

In both cases, the intent is to return a token type of DIGIT, and a value equal to the numerical value of the digit. Provided that the lexical analyzer code is placed in the programs section of the specification, the identifier DIGIT will be redefined to be equal to the type number associated with the token name DIGIT.

This mechanism leads to clear and easily modified lexical analyzers; the only pitfall is that it makes it important to avoid using any names in the grammar which are reserved or significant in the chosen language; thus, in both C and Ratfor, the use of token names of ‘‘if’’ or ‘‘yylex’’ will almost certainly cause severe difficulties when the lexical analyzer is compiled. The token name ‘‘error’’ is reserved for error handling, and should not be used naively (see Section 5).

As mentioned above, the type numbers may be chosen by Yacc or by the user. In the default situation, the numbers are chosen by Yacc. The default type number for a literal character is the numerical value of the character, considered as a 1 byte integer. Other token names are assigned type numbers starting at 257. It is a difficult, machine dependent operation to determine the numerical value of an input character in Ratfor (or Fortran). Thus, the Ratfor user of Yacc will probably wish to set his own type numbers, or not use any literals in his specification.

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

There is one exception to this situation. For sticky historical reasons, the endmarker must have type number 0. Note that this is not unattractive in C, since the nul character is returned upon end of file; in Ratfor, it makes no sense. This type number cannot be redefined by the user; thus, all lexical analyzers should be prepared to return 0 as a type number upon reaching the end of their input.

Section 4: Ambiguity, Conflicts, and Precedence

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

```
expr :  expr ´−´ expr ;
```

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

expr − expr − expr

the rule would permit us to treat this input either as

(expr − expr) − expr

or as

expr − (expr − expr)

(We speak of the first as *left association* of operators, and the second as *right association).*

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

expr − expr − expr

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

expr − expr

matches the right side of the grammar rule above. One valid thing for the parser to do is to *reduce* the input it has seen by applying this rule; after applying the rule, it would have reduced the input it had already seen to expr (the left side of the rule). It could then read the final part of the input:

− expr

and again reduce by the rule. We see that the effect of this is to take the left associative interpretation.

Alternatively, when the parser has seen

expr − expr

it could defer the immediate application of the rule, and continue reading (the technical term is *shifting)* the input until it had seen

expr − expr − expr

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

expr − expr

Now it can reduce by the rule again; the effect is to take the right associative interpretation. Thus, having read

expr − expr

the parser can do two legal things, a shift or a reduction, and has no way of deciding between them. We refer to this as a *shift/reduce conflict.* It may also happen that the parser has a choice of two legal reductions; this is called a *reduce/reduce conflict.*

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

Yacc has two disambiguating rules which are invoked by default, in the absence of any user directives to the contrary:

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

Rule 1 implies that reductions are deferred whenever there is a choice, in favor of shifts. Rule 2 gives the user rather crude control over the behavior of the parser in this situation, but the proper use of reduce/reduce conflicts is still a black art, and is properly considered an advanced topic.

Conflicts may arise because of mistakes in input or logic, or because the grammar rules, while consistent, require a more complex parser than Yacc can construct. In these cases, the application of

disambiguating rules is inappropriate, and leads to a parser which is in error. For this reason, Yacc always reports the number of shift/reduce and reduce/reduce conflicts which were resolved by Rule 1 and Rule 2.

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

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

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

Here, we consider IF and ELSE to be tokens, cond to be a nonterminal symbol describing conditional (logical) expressions, and stat to be a nonterminal symbol describing statements. In the following, we shall refer to these two rules as the *simple-if* rule and the *if-else* rule, respectively.

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

```
IF ( C1 ) IF ( C2 ) S1 ELSE S2
```

can be structured according to these rules in two ways:

```
IF ( C1 ) {
        IF ( C2 ) S1
}
ELSE S2
```

or

```
IF ( C1 ) {
        IF ( C2 ) S1
        ELSE S2
}
```

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

```
IF ( C1 ) IF ( C2 ) S1
```

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

```
IF ( C1 ) stat
```

and then read the remaining input,

```
ELSE S2
```

and reduce

```
IF ( C1 ) stat ELSE S2
```

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

On the other hand, we may *shift* the ELSE and read S2, and then reduce the right hand portion of

```
IF ( C1 ) IF ( C2 ) S1 ELSE S2
```

by the if-else rule to get

```
IF ( C1 ) stat
```

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

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

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

IF (C1) IF (C2) S1

In general, there may be many conflicts, and each one will be associated with an input symbol and a set of previously read inputs. The previously read inputs are characterized by the *state* of the parser, which is assigned a nonnegative integer. The number of states in the parser is typically two to five times the number of grammar rules.

When Yacc is invoked with the verbose (−v) option (see Appendix B), it produces a file of user output which includes a description of the states in the parser. For example, the output corresponding to the above example might be:

```
23: shift/reduce Conflict (Shift 45, Reduce 18) on ELSE

State 23

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

    ELSE shift 45
    .    reduce 18
```

The first line describes the conflict, giving the state and the input symbol. The state title follows, and a brief description of the grammar rules which are active in this state. The underline "_" describes the portions of the grammar rules which have been seen. Thus in the example, in state 23 we have seen input which corresponds to

IF (cond) stat

and the two grammar rules shown are active at this time. The actions possible are, if the input symbol is ELSE, we may shift into state 45. In this state, we should find as part of the description a line of the form

stat : IF (cond) stat ELSE_stat

because in this state we will have read and shifted the ELSE. Back in state 23, the alternative action, described by ".", is to be done if the input symbol is not mentioned explicitly in the above actions; thus, in this case, if the input symbol is not ELSE, we should reduce by grammar rule 18, which is presumably

stat : IF ´(´ cond ´)´ stat

Notice that the numbers following "shift" commands refer to other states, while the numbers following "reduce" commands refer to grammar rule numbers. In most states, there will be only one reduce action possible in the state, and this will always be the default command. The user who encounters unexpected shift/reduce conflicts will probably want to look at the verbose output to decide whether the default actions are appropriate. In really tough cases, the user might need to know more about the behavior and construction of the parser than can be covered here; in this case, a reference such as [1] might be consulted; the services of a local guru might also be appropriate.

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

```
expr : expr OP expr
```

and

```
expr : UNARY expr
```

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

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

```
%left ´+´ ´−´
%left ´*´ ´/´
```

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

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

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

```
%right ´=´
%left ´+´ ´−´
%left ´*´ ´/´

%%

expr :
        expr ´=´ expr |
        expr ´+´ expr |
        expr ´−´ expr |
        expr ´*´ expr |
        expr ´/´ expr |
        NAME ;
```

might be used to structure the input

```
a = b = c*d − e − f*g
```

as follows:

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

When this mechanism is used, unary operators must, in general, be given a precedence. An interesting situation arises when we have a unary operator and a binary operator which have the same symbolic representation, but different precedences. An example is unary and binary ´−´; frequently, unary minus is given the same strength as multiplication, or even higher, while binary minus has a lower strength than multiplication. We can indicate this situation by use of another keyword, %prec, to change the precedence level associated with a particular grammar rule. %prec appears immediately after the body of the grammar rule, before the action or closing semicolon, and is followed by a token name or literal; it causes the precedence of the grammar rule to become that of the token name or literal. Thus, to make unary minus have the same precedence as multiplication, we might write:

```
%left ´+´ ´−´
%left ´*´ ´/´

%%

expr :
        expr ´+´ expr |
        expr ´−´ expr |
        expr ´*´ expr |
        expr ´/´ expr |
        ´−´ expr %prec ´*´ |
        NAME ;
```

Notice that the precedences which are described by %left, %right, and %nonassoc are independent of the declarations of token names by %token. A symbol can be declared by %token, and, later in the declarations section, be given a precedence and associativity by one of the above methods. It is true, however, that names which are given a precedence or associativity are also declared to be token names, and so in general do not need to be declared by %token, although it does not hurt to do so.

As we mentioned above, the precedences and associativities are used by Yacc to resolve parsing conflicts; they give rise to disambiguating rules. Formally, the rules work as follows:

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

There are a number of points worth making about this use of disambiguation. There is no reporting of conflicts which are resolved by this mechanism, and these conflicts are not counted in the number of shift/reduce and reduce/reduce conflicts found in the grammar. This means that occasionally mistakes in the specification of precedences disguise errors in the input grammar; it is a good idea to be sparing with precedences, and use them in an essentially ‘‘cookbook’’ fashion, until some experience has been gained. Frequently, not enough operators or precedences have been specified; this leads to a number of messages about shift/reduce or reduce/reduce conflicts. The cure is usually to specify more precedences, or use the %prec mechanism, or both. It is generally good to examine the verbose output file to ensure that the conflicts which are being reported can be validly resolved by precedence.

Section 5: Error Handling

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

It is generally not acceptable to stop all processing when an error is found; we wish to continue scanning the input to find any further syntax errors. This leads to the problem of getting the parser ‘‘restarted’’ after an error. The general class of algorithms to do this involves reading ahead and discarding a number of tokens from the input string, and attempting to adjust the parser so that input can continue.

To allow the user some control over this process, Yacc provides a simple, but reasonably general, feature. The token name ‘‘error’’ is reserved for error handling. This name can be used in grammar rules; in effect, it suggests places where errors are expected, and recovery might take place. The parser attempts to find the last time in the input when the special token ‘‘error’’ is permitted. The parser then behaves as though it saw the token name ‘‘error’’ as an input token, and attempts to parse according to the rule encountered. The token at which the error was detected remains the next input token after this error token is processed. If no special error rules have been specified, the processing effectively halts when an error is detected.

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

As a common example, the user might include a rule of the form

```
statement :  error ;
```

in his specification. This would, in effect, mean that on a syntax error the parser would attempt to skip over the statement in which the error was seen. (Notice, however, that it may be difficult or impossible to tell the end of a statement, depending on the other grammar rules). More precisely, the parser will scan ahead, looking for three tokens that might legally follow a statement, and start processing at the first of these; if the beginnings of statements are not sufficiently distinctive, it may make a false start in the middle of a statement, and end up reporting a second error where there is in fact no error.

The user may supply actions after these special grammar rules, just as after the other grammar rules. These actions might attempt to reinitialize tables, reclaim symbol table space, etc.

The above form of grammar rule is very general, but somewhat difficult to control. Somewhat easier to deal with are rules of the form

```
statement :  error ´;´ ;
```

Here, when there is an error, the parser will again attempt to skip over the statement, but in this case will do so by skipping to the next ‘‘;’’. All tokens after the error and before the next ‘‘;’’ give syntax errors, and are discarded. When the ‘‘;’’ is seen, this rule will be reduced, and any ‘‘cleanup’’ action associated with it will be performed.

Still another form of error rule arises in interactive applications, where we may wish to prompt the user who has incorrectly input a line, and allow him to reenter the line. In C we might write:

```
inputline:     error ´\n´ prompt inputline
        = { $$ = $4; };

prompt:        /* matches no input */
        = {  printf( "Reenter last line: " ); };
```

There is one difficulty with this approach; the parser must correctly process three input tokens before it is prepared to admit that it has correctly resynchronized after the error. Thus, if the reentered line contains errors in the first two tokens, the parser will simply delete the offending tokens, and give no message; this is clearly unacceptable. For this reason, there is a mechanism in both C and Ratfor which can be used to force the parser to believe that resynchronization has taken place. One need only include a statement of the form

```
yyerrok ;
```

in his action after such a grammar rule, and the desired effect will take place; this name will be expanded, using the ‘‘# define’’ mechanism of C or the ‘‘define’’ mechanism of Ratfor, into an appropriate code sequence. For example, in the situation discussed above where we want to prompt the user to produce input, we probably want to consider that the original error has been recovered when we have thrown away the previous line, including the newline. In this case, we can reset the error state before putting out the prompt message. The grammar rule for the nonterminal symbol prompt becomes:

```
prompt:     /* matches no input */
        = {
                yyerrok;
                printf( "Reenter last line: " );
        } ;
```

There is another special feature which the user may wish to use in error recovery. As mentioned above, the token seen immediately after the ‘‘error’’ symbol is the input token at which the error was discovered. Sometimes, this is seen to be inappropriate; for example, an error recovery action might take upon itself the job of finding the correct place to resume input. In this case, the user wishes a way of clearing the previous input token held in the parser. One need only include a statement of the form

```
yyclearin ;
```

in his action; again, this expands, in both C and Ratfor, to the appropriate code sequence. For example, suppose the action after error were to call some sophisticated resynchronization routine, supplied by the user, which attempted to advance the input to the beginning of the next valid statement. After this routine was called, the next token returned by yylex would presumably be the first token in a legal statement; we wish to throw away the old, illegal token, and reset the error state. We might do this by the sequence:

```
statement :  error
        = {
                resynch( );
                yyerrok ;
                yyclearin ;
        } ;
```

These mechanisms are admittedly crude, but do allow for a simple, fairly effective recovery of the parser from many errors, and have the virtue that the user can get ‘‘handles’’ by which he can deal with the error actions required by the lexical and output portions of the system.

Section 6C: The C Language Yacc Environment

The default mode of operation in Yacc is to write actions and the lexical analyzer in C. This has a number of advantages; primarily, it is easier to write character handling routines, such as the lexical analyzer, in a language which supports character-by-character I/O, and has shifting and masking operators.

When the user inputs a specification to Yacc, the output is a file of C programs, called ‘‘y.tab.c’’. These are then compiled, and loaded with a library; the library has default versions of a number of useful routines. This section discusses these routines, and how the user can write his own routines if desired. The name of the Yacc library is system dependent; see Appendix B.

The subroutine produced by Yacc is called ‘‘yyparse’’; it is an integer valued function. When it is called, it in turn repeatedly calls ‘‘yylex’’, the lexical analyzer supplied by the user (see Section 3), to obtain input tokens. Eventually, either an error is detected, in which case (if no error recovery is possible) yyparse returns the value 1, or the lexical analyzer returns the endmarker token (type number 0), and the parser accepts. In this case, yyparse returns the value 0.

Three of the routines on the Yacc library are concerned with the ‘‘external’’ environment of yyparse. There is a default ‘‘main’’ program, a default ‘‘initialization’’ routine, and a default ‘‘accept’’ routine, respectively. They are so simple that they will be given here in their entirety:

```
main( argc, argv )
int argc;
char *argv[ ]
{
        yyinit( argc, argv );
        if( yyparse( ) )
                return;
        yyaccpt( );
}

yyinit( ) { }

yyaccpt( ) { }
```

By supplying his own versions of yyinit and/or yyaccpt, the user can get control either before the parser is called (to set options, open input files, etc.) or after the accept action has been done (to close files, call the next pass of the compiler, etc.). Note that yyinit is called with the two ‘‘command line’’ arguments which have been passed into the main program. If neither of these routines is redefined, the default situation simply looks like a call to the parser, followed by the termination of the program. Of course, in many cases the user will wish to supply his own main program; for example, this is necessary if the parser is to be called more than once.

The other major routine on the library is called ‘‘yyerror’’; its main purpose is to write out a message when a syntax error is detected. It has a number of hooks and handles which attempt to make this error message general and easy to understand. This routine is somewhat more complex, but still approachable:

```
extern int yyline;  /* input line number */

yyerror(s)
char *s;
{
        extern int yychar;
        extern char *yysterm[ ];

        printf("\n%s", s );
        if( yyline )
                printf(", line %d,", yyline );
        printf(" on input: ");
        if( yychar >= 0400 )
                printf("%s\n", yysterm[yychar−0400] );
        else switch ( yychar ) {
        case ´\t´: printf( "\\t\n" ); return;
        case ´\n´: printf( "\\n\n" ); return;
        case ´\0´: printf( "$end\n" ); return;
        default: printf( "%c\n" , yychar ); return;
        }
}
```

The argument to yyerror is a string containing an error message; most usually, it is ‘‘syntax error’’. yyerror also uses the external variables yyline, yychar, and yysterm. yyline is a line number which, if set by the user to a nonzero number, will be printed out as part of the error message. yychar is a variable which contains the type number of the current token. yysterm has the names, supplied by the user, for all the tokens which have names. Thus, the routine spends most of its time trying to print out a reasonable name for the input token. The biggest problem with the routine as given is that, on Unix, the error message does not go out on the error file (file 2). This is hard to arrange in such a way that it works with both the portable I/O library and the system I/O library; if a way can be worked out, the routine will be changed to do this.

Beware: This routine will not work if any token names have been given redefined type numbers. In this case, the user must supply his own yyerror routine. Hopefully, this ‘‘feature’’ will disappear soon.

Finally, there is another feature which the C user of Yacc might wish to use. The integer variable yydebug is normally set to 0. If it is set to 1, the parser will output a verbose description of its actions, including a discussion of which input symbols have been read, and what the parser actions are. Depending on the operating environment, it may be possible to set this variable by using a debugging system.

Section 6R: The Ratfor Language Yacc Environment

For reasons of portability or compatibility with existing software, it may be desired to use Yacc to generate parsers in Ratfor, or, by extension, in portable Fortran. The user is likely to work considerably harder doing this than he might if he were to use C.

When the user inputs a specification to Yacc, and specifies the Ratfor option (see Appendix B), the output is a file of Ratfor programs called ‘‘y.tab.r’’. These programs are then compiled, and provide the desired subroutine.

The subroutine produced by Yacc which does the input process is an integer function called ‘‘yypars’’. When it is called, it in turn repeatedly calls ‘‘yylex’’, the lexical analyzer supplied by the user (see Section 3). Eventually, either an error is detected, in which case (if no error recovery is possible) yypars returns the value 1, or the lexical analyzer returns the endmarker (type number 0), and the parser accepts. In this case, yypars returns 0.

Unlike the C program situation (see Section 6C) there is no library of Ratfor routines which must be used in the loading process. As a side effect of this, *the user must supply a main program which calls yypars*. A suggested Ratfor main program is

```
integer yypars
n = yypars(0)
if( n .EQ. 0 ) {
        . . . here if the program accepted
} else {
        . . . here if there were unrecoverable errors
}
end
```

Notice that there is no easy way for the user to get control when an error is detected, since the Fortran language provides only a very crude character string capability.

There is another feature which the Ratfor user might wish to use. The argument to yypars is normally 0. If it is set to 1, the parser will output a verbose description of its actions, including a discussion of which input symbols have been read, and what the parser actions are. During the input process, the value of this debug flag is kept in a common variable yydebu, which is available to the actions and may be set and reset at will.

Statement labels 1 through 1000 are reserved for the parser, and may not appear in actions; note that, because Ratfor has a more modern control structure than Fortran, it is rarely necessary to use statement labels at all; the most frequent use of labels in Ratfor is in formatted I/O.

Because Fortran has no standard character set and not even a standard character width, it is difficult to produce a lexical analyzer in portable Fortran The usual solution is to provide a routine which does a table search to get the internal type number for each input character, with the understanding that such a routine can be recoded to run far faster for any particular machine.

Finally, we must warn the user that the Ratfor feature of Yacc has been operational for a much shorter time than the other portions of the system. If past experience is any guide, the Ratfor support will develop and become more powerful and better human engineered in response to user complaints and requirements. Thus, the potential Ratfor user might do well to contact the author to discuss his own particular needs.

Section 7. Hints for Preparing Specifications

This section contains miscellaneous hints on preparing efficient, easy to change, and clear specifications. The individual subsections are, more or less, independent; the reader seeing Yacc for the first time may well find that this entire section could be omitted.

Input Style

It is difficult to input rules with substantial actions and still have a readable specification file. The following style hints owe much to Brian Kernighan, and are officially endorsed by the author.

a. Use all capital letters for token names, all lower case letters for nonterminal names. This rule comes under the heading of ‘‘knowing who to blame when things go wrong.‘‘

b. Put grammar rules and actions on separate lines. This allows either to be changed without an automatic need to change the other.

c. Put all rules with the same left hand side together. Put the left hand side in only once, and let all following rules begin with a vertical bar.

d. Indent rule bodies by one tab stop, and action bodies by two tab stops.

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

Common Actions

When several grammar rules have the same action, the user might well wish to provide only one code sequence. A simple, general mechanism is, of course, to use subroutine calls. It is also possible to put a label on the first statement of an action, and let other actions be simply a goto to this label. Thus, if the user had a routine which built trees, he might wish to have only one call to it, as follows:

```
expr :
        expr ´+´ expr =
        {  binary:
                $$ = btree( $1, $2, $3 );
        } |
        expr ´−´ expr =
        {
                goto binary;
        } |
        expr ´*´ expr =
        {
                goto binary;
        } ;
```

Left Recursion

The algorithm used by the Yacc parser encourages so called ‘‘left recursive’’ grammar rules: rules of the form

```
name : name rest_of_rule ;
```

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

```
list :
        item |
        list ´,´ item ;
```

and

```
sequence :
        item |
        sequence item ;
```

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

If the user were to write these rules right recursively, such as

```
sequence :
        item |
        item sequence ;
```

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

The user should also consider whether a sequence with zero elements has any meaning, and if so, consider writing the sequence specification with an empty rule:

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

Once again, the first rule would always be reduced exactly once, before the first item was read, and then the second rule would be reduced once for each item read. Experience suggests that permitting empty sequences leads to increased generality, which frequently is not evident at the time the rule is first written. There are cases, however, when the Yacc algorithm can fail when such a change is made. In effect, conflicts might arise when Yacc is asked to decide which empty sequence it has seen, when it hasn´t seen enough to know! Nevertheless, this principle is still worth following wherever possible.

Lexical Tie-ins

Frequently, there are lexical decisions which depend on the presence of various constructions in the specification. For example, the lexical analyzer might want to delete blanks normally, but not within quoted strings. Or names might be entered into a symbol table in declarations, but not in expressions.

One way of handling these situations is to create a global flag which is examined by the lexical analyzer, and set by actions. For example, consider a situation where we have a program which consists of 0 or more declarations, followed by 0 or more statements. We declare a flag called ‘‘dflag’’, which is 1 during declarations, and 0 during statements. We may do this as follows:

```
%{
        int dflag ;
%}
%%
program :
        decls  stats ;

decls :
        = /* empty */
        {
                dflag = 1;
        } |
        decls declaration ;

stats :
        = /* empty */
        {
                dflag = 0;
        } |
        stats statement ;

        . . .  other rules . . .
```

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

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

Bundling

Bundling is a technique for collecting together various character strings so that they can be output at some later time. It is derived from a feature of the same name in the compiler/compiler TMG [6].

Bundling has two components − a nice user interface, and a clever implementation trick. They will be discussed in that order.

The user interface consists of two routines, ‘‘bundle’’ and ‘‘bprint’’.

```
bundle( a1, a2, . . ., an )
```

accepts a variable number of arguments which are either character strings or bundles, and returns a bundle, whose value will be the concatenation of the values of a1, . . ., an.

```
bprint( b )
```

accepts a bundle as argument and outputs its value.

For example, suppose that we wish to read arithmetic expressions, and output function calls to routines called ‘‘add’’, ‘‘sub’’, ‘‘mul’’, ‘‘div’’, and ‘‘assign’’. Thus, we wish to translate

```
a = b − c*d
```

into

```
assign(a,sub(b,mul(c,d)))
```

A Yacc specification file which does this is given in Appendix D; this includes an implementation of the bundle and bprint routines. A rule and action of the form

```
expr:
        expr ´+´ expr =
        {
                $$ = bundle( "add(", $1, ",", $3, ")" );
        }
```

causes the returned value of expr to be come a bundle, whose value is the character string containing the desired function call. Each NAME token has a value which is a pointer to the actual name which has been read. Finally, when the entire input line has been read and the value has been bundled, the value is written out and the bundles and names are cleared, in preparation for the next input line.

Bundles are implemented as arrays of pointers, terminated by a zero pointer. Each pointer either points to a bundle or to a character string. There is an array, called *bundle space,* which contains all the bundles.

The implementation trick is to check the values of the pointers in bundles − if the pointer points into bundle space, it is assumed to point to a bundle; otherwise it is assumed to point to a character string.

The treatment of functions with a variable number of arguments, like bundle, is likely to differ from one implementation of C to another.

In general, one may wish to have a simple storage allocator which allocates and frees bundles, in order to handle situations where it is not appropriate to completely clear all of bundle space at one time.

Reserved Words

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

A number of ways of making this easier are under advisement, and one will probably be supported eventually. Until this day comes, I suggest that the keywords be *reserved;* that is, be forbidden for use as variable names. There are powerful stylistic reasons for preferring this, anyway (he said weakly . . .).

Non-integer Values

Frequently, the user wishes to have values which are bigger than integers; again, this is an area where Yacc does not make the job as easy as it might, and some additional support is likely. Nevertheless, at the cost of writing a storage manager, the user can return pointers or indices to blocks of storage big enough to contain the full values desired.

Previous Work

There have been many previous applications of Yacc. The user who is contemplating a big application might well find that others have developed relevant techniques, or even portions of grammars. Yacc specifications appear to be easier to change than the equivalent computer programs, so that the ‘‘prior art’’ is more relevant here as well.

Section 8: User Experience, Summary, and Acknowledgements

Yacc has been used in the construction of a C compiler for the Honeywell 6000, a system for typesetting mathematical equations, a low level implementation language for the PDP 11, APL and Basic compilers to run under the UNIX system, and a number of other applications.

To summarize, Yacc can be used to construct parsers; these parsers can interact in a fairly flexible way with the lexical analysis and output phases of a larger system. The system also provides an indication of ambiguities in the specification, and allows disambiguating rules to be supplied to resolve these ambiguities.

Because the output of Yacc is largely tables, the system is relatively language independent. In the presence of reasonable applications, Yacc could be modified or adapted to produce subroutines for other machines and languages. In addition, we continue to seek better algorithms to improve the lexical analysis and code generation phases of compilers produced using Yacc.

This document would be incomplete if I did not give credit to a most stimulating collection of users, who have goaded me beyond my inclination, and frequently beyond my ability, in their endless search for ‘‘one more feature’’. Their irritating unwillingness to learn how to do things my way has usually led to my doing things their way; most of the time, they have been right. B. W. Kernighan, P. J. Plauger, S. I. Feldman, C. Imagna, M. E. Lesk, and A. Snyder will recognize some of their ideas in the current version of Yacc. Al Aho also deserves recognition for bringing the mountain to Mohammed, and other favors.

References

1 Aho, A.V. and Johnson, S.C., ‘‘LR Parsing’’, Computing Surveys, Vol 6, No 2, June 1974, pp. 99-124.

2 Aho, A.V., Johnson, S.C., and Ullman, J.D., ‘‘Deterministic Parsing of Ambiguous Grammars’’, Proceedings of the A.C.M. Symposium on Principles of Programming Languages, October 1973, pp. 1-21; to appear in CACM.

3 Aho, A.V. and Ullman, J.D., Theory of Parsing, Translation, and Compiling. Volume 1 (1972) and Volume 2 (1973), Prentice-Hall, Englewood Cliffs, N.J.

4 Kernighan, B. W., Ratfor, a Rational Fortran

5 Ryder, B. B., ‘‘The PFORT Verifier,’’ Software−Practice and Experience, Vol 4 (1974), pp 359-377.

6 McIlroy, M. D., A Manual for the TMG Compiler-writing Language

7 Ritchie, D. M., C Reference Manual

Appendix A: A Simple Example

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

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

```
%token DIGIT LETTER/* these are token names */
%left ´|´                       /* declarations of operator precedences */
%left ´&´
%left ´+´ ´−´
%left ´*´ ´/´ ´%´
%left UMINUS                    /* supplies precedence for unary minus */
%{                              /* declarations used by the actions */
        int base;
        int regs[26];
%}

%%   /* beginning of rules section */

list :          /* list is the start symbol */
        |       /* empty */
        list stat ´\n´ |
        list error ´\n´ =
        {
                yyerrok ;
        } ;

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

expr :
        ´(´ expr ´)´ =
        {
                $$ = $2 ;
        } |
        expr ´+´ expr =
        {
                $$ = $1 + $3 ;
        } |
```

```
        expr ´−´ expr =
        {
                $$ = $1 − $3 ;
        } |
        expr ´*´ expr =
        {
                $$ = $1 * $3 ;
        } |
        expr ´/´ expr =
        {
                $$ = $1 / $3 ;
        } |
        expr ´%´ expr =
        {
                $$ = $1 % $3 ;
        } |
        expr ´&´ expr
        {
                $$ = $1 & $3 ;
        } |
        expr ´|´ expr
        {
                $$ = $1 | $3 ;
        } |
        ´−´ expr  %prec UMINUS
        {
                $$ = − $2 ;
        } |
        LETTER
        {
                $$ = regs[$1] ;
        } |
        number ;

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

%%              /* start of programs */

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

```
        int c ;

        while( (c=getchar( )) == ´ ´ )
                ;
        if( c >= ´a´ && c <= ´z´ ) {
                yylval = c − ´a´ ;
                return( LETTER ) ;
        }
        if( c >= ´0´ && c <= ´9´ ) {
                yylval = c − ´0´ ;
                return( DIGIT ) ;
        }
        return( c ) ;
}
```

Appendix B: Use of Yacc on Unix

Suppose that the Yacc specification is on a file called yfile. If the actions are in C, Yacc is invoked by

```
yacc yfile
```

The output appears on file y.tab.c To compile the parser and load it with the Yacc library, use the command

```
cc y.tab.c −ly
```

If Yacc is invoked with the option −v:

```
yacc −v yfile
```

a verbose description of the parser is produced on file y.output. The C user should consult section 6C for more information about the run time environment.

If the actions are in Ratfor, the user should invoke Yacc with the option −r:

```
yacc −r yfile
```

The Ratfor output appears on file y.tab.r It may be compiled by

```
rc −2 y.tab.r
```

Note that when Yacc is used to produce Ratfor programs, there is no need to load these programs with any library.

If the −v action is also invoked:

```
yacc −rv yfile
```

a verbose description of the parser is produced on file y.output. The Ratfor user should consult section 6R for more information about the run time environment.

Appendix C: Old Features Supported but not Encouraged

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

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

   The use of multi-character literals is likely to mislead those unfamiliar with Yacc, since it suggests that Yacc is doing a job which must be actually done by the lexical analyzer.
3. Most places where % is legal, backslash "\" may be used. In particular, \\ is the same as %%, \left the same as %left, etc.
4. There are a number of other synonyms:

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

5. The curly braces "{" and "}" around an action are optional if the action consists of a single C statement. (They are always required in Ratfor).

Appendix D: An Example of Bundling

The following program is an example of the technique of bundling; this example is discussed in Section 7.

```
/* warnings:
1. This works on Unix; the handling of functions with a variable number of arguments is different on
   different systems.
2. A number of checks for array bounds have been left out to avoid obscuring the basic ideas, but
   should be there in a practical program.
    */


%token NAME

%right ´=´
%left ´+´ ´−´
%left ´*´ ´/´

%%

lines :
        = /* empty */
        {
                bclear( ) ;
        } |
        lines expr ´\n´ =
        {
                bprint( $2 ) ;
                printf( "\n" ) ;
                bclear( ) ;
        } |
        lines error ´\n´ =
        {
                bclear( ) ;
                yyerrok;
        } ;

expr :
        expr ´+´ expr =
        {
                $$ = bundle( "add(", $1, ",", $3, ")" );
        } |
        expr ´−´ expr =
        {
                $$ = bundle( "sub(", $1, ",", $3, ")" );
        } |
        expr ´*´ expr =
        {
                $$ = bundle( "mul(", $1, ",", $3, ")" );
        } |
        expr ´/´ expr =
```

```
        {
                $$ = bundle( "div(", $1, ",", $3, ")" );
        } |
        ´(´ expr ´)´ =
        {
                $$ = $2;
        } |
        NAME ´=´ expr =
                $$ = bundle( "assign(", $1, ",", $3, ")" );
        } |
        NAME ;

%%

#define        nsize 200
char   names[nsize], *nptr { names };

#define        bsize 500
int    bspace[bsize], *bptr { bspace };

yylex( )
{
        int c;

        c = getchar( );
        while( c == ´ ´ )
                c = getchar( );
        if( c>=´a´ && c<=´z´ ) {
                yylval = nptr;
                for( ; c>=´a´ && c<=´z´; c=getchar( ) )
                        *nptr++ = c;
                ungetc( c );
                *nptr++ = ´\0´;
                return( NAME );
        }
        return( c );
}

bclear( )
{


        nptr = names;
        bptr = bspace;
}

bundle( a1,a2,a3,a4,a5 )
{
        int i, j, *p, *obp;

        p = &a1;
        i = nargs( );
        obp = bptr;
```

```
        for( j=0; j<i; ++j )
                *bptr++ = *p++;
        *bptr++ = 0;
        return( obp );
}

bprint( p )
int *p;
{

        if( p>=bspace && p< &bspace[bsize] ) /* bundle */
                while( *p != 0 )
                        bprint( *p++ );
        else printf( "%s",  p );
}
```

-

The Unix I/O System

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This paper gives an overview of the workings of the Unix I/O system. It was written with an eye toward providing guidance to writers of device driver routines, and is oriented more toward describing the environment and nature of device drivers than the implementation of that part of the file system which deals with ordinary files.

It is assumed that the reader has a good knowledge of the overall structure of the file system as discussed in the paper "The Unix Time-sharing System." Moreover the present document is intended to be used in conjunction with a copy of the system code, since it is basically an exegesis of that code.

Device Classes

There are two classes of device: *block* and *character.* The block interface is suitable for devices like disks, tapes, and DECtape which work, or can work, with addressible 512-byte blocks. Ordinary magnetic tape just barely fits in this category, since by use of forward backward spacing any block can be read, even though blocks can be written only at the end of the tape. Block devices can at least potentially contain a mounted file system. The interface to block devices is very highly structured; the drivers for these devices share a great many routines as well as a pool of buffers.

Character-type devices have a much more straightforward interface, although more work must be done by the driver itself.

Devices of both types are named by a *major* and a *minor* device number. These numbers are generally stored as a word with the minor device number as the low byte and the major device number as the high byte. The major device number selects which driver will deal with the device; the minor device number is not used by the rest of the system but is passed to the driver at appropriate times. Typically the minor number selects a subdevice attached to a given controller, or one of several similar hardware interfaces.

The major device numbers for block and character devices are used as indices in separate tables; they both start at 0 and therefore overlap.

Overview of I/O

The purpose of the *open* and *creat* system calls is to set up entries in three separate system tables. The first of these is the *u_ofile* table, which is stored in the system's per-process data area *u.* This table is indexed by the file descriptor returned by the *open* or *creat,* and is accessed during a *read, write,* or other operation on the open file. An entry contains only a pointer to the corresponding entry of the *file* table, which is a per-system data base. There is one entry in the *file* table for each instance of *open* or *creat.* This table is per-system because the same instance of an open file must be shared among the several processes which can result from *forks* after the file is opened. A *file* table entry contains flags which indicate whether the file was open for reading or writing or is a pipe, and a count which is used to decide when all processes using the entry have terminated or closed the file (so the entry can be abandoned). There is also a 32-bit file offset which is used to indicate where in the file the next read or write will take place. Finally, there is a pointer to the entry for the file in the *inode* table, which contains a copy of the file's i-node. Notice that an entry in the *file* table corresponds precisely to an instance of *open* or *creat;* if the same file is opened several times, it will have several entries in this table. However, there is at most one entry in the *inode* table for a given file. Also, a file may enter the *inode* table not only because it is open, but also because it is the current directory of some process or because it is a special file containing a currently-mounted file system.

An entry in the *inode* table differs somewhat from the corresponding i-node as stored on the disk; the modified and accessed times are not stored, and the entry is augmented by a flag word containing information about the entry, a count used to determine when it may be allowed to disappear, and the device and i-number whence the entry came.

During the processing of an *open* or *creat* call for a special file, the system always calls the device's *open* routine to allow for any special processing required (rewinding a tape, turning on the data-terminal-ready lead of a modem, etc.). However, the *close* routine is called only when the last process closes a file, that is, when the i-node table entry is being deallocated. Thus it is not feasible for a device to maintain, or depend on, a count of its users, although it is quite possible to implement an exclusive-use device which cannot be reopened until it has been closed.

When a *read* or *write* takes place, the user's arguments and the *file* table entry are used to set up the variables *u.u_base, u.u_count,* and *u.u_offset* which respectively contain the (user) address of the I/O target area, the byte-count for the transfer, and the current location in the file. If the file referred to is a character-type special file, the appropriate read or write routine is called; it is responsible for transferring data and updating the count and current location appropriately as discussed below. Otherwise, the current location is used to calculate a logical block number in the file. If the file is an ordinary file the logical block number must be mapped (possibly using an indirect block) to a physical block number; a block-type special file need not be mapped. In any event, the resulting physical block number is used, as discussed below, to read or write the appropriate device.

Character device drivers

The *cdevsw* table specifies the interface routines present for character devices. Each device provides five routines: open, close, read, write, and special-function. Any of these may be missing. If a call on the routine should be ignored, (e.g. *open* on non-exclusive devices which require no setup) the *cdevsw* entry can be given as *nulldev;* if it should be considered an error, (e.g. *write* on read-only devices) *nodev* is used.

The *open* routine is called each time the file is opened with the full device number as argument. The second argument is a flag which is non-zero only if the device is to be written upon.

The *close* routine is called only when the file is closed for the last time, that is when the very last process in which the file is open closes it. This means it is not possible for the driver to maintain its own count of its users. The first argument is the device number; the second is a flag which is non-zero if the file was open for writing in the process which performs the final *close.*

When *write* is called, it is supplied the device as argument. The per-user variable *u.u_count* has been set to the number of characters indicated by the user; for character devices, this number may be 0 initially. *u.u_base* is the address supplied by the user from which to start taking characters. The system may call the routine internally, so the flag *u.u_segflg* is supplied which indicates, if *on,* that *u.u_base* refers to the system address space instead of the user's.

The *write* routine should copy up to *u.u_count* characters from the user's buffer to the device, decrementing *u.u_count* for each character passed. For most drivers, which work one character at a time, the routine

cpass( )

is used to pick up characters from the user's buffer. Successive calls on it return the characters to be written until *u.u_count* goes to 0 or an error occurs, when it returns −1. *Cpass* takes care of interrogating *u.u_segflg* and updating *u.u_count.*

Write routines which want to transfer a probably large number of characters into an internal buffer may also use the routine

iomove(buffer, offset, count, flag)

which is faster when many characters must be moved. *Iomove* transfers up to *count* characters into the *buffer* starting *offset* bytes from the start of the buffer; *flag* should be *B_WRITE* (which is 0) in the write case. Caution: the caller is responsible for making sure the count is not too large and is non-zero. As an efficiency note, *iomove* is much slower if any of *buffer+offset, count* or *u.u_base* is odd.

The device's *read* routine is called under conditions similar to *write,* except that *u.u_count* is guaranteed to be non-zero. To return characters to the user, the routine

passc(c)

is available; it takes care of housekeeping like *cpass* and returns −1 as the last character specified by *u.u_count* is returned to the user; before that time, 0 is returned. *Iomove* is also usable as with *write;* the flag should be *B_READ* but the same cautions apply.

The ‘‘special-functions’’ routine is invoked by the *stty* and *gtty* system calls as follows:

*(*p) (dev, v)*

where *p* is a pointer to the device's routine, *dev* is the device number, and *v* is a vector. In the *gtty* case, the device is supposed to place up to 3 words of status information into the vector; this will be returned to the caller. In the *stty* case, *v* is 0; the device should take up to 3 words of control information from the array *u.u_arg[0...2].*

Finally, each device should have appropriate interrupt-time routines. When an interrupt occurs, it is turned into a C-compatible call on the devices's interrupt routine. The interrupt-catching mechanism makes the low-order four bits of the ''new PS'' word in the trap vector for the interrupt available to the interrupt handler. This is conventionally used by drivers which deal with multiple similar devices to encode the minor device number. After the interrupt has been processed, a return from the interrupt handler will return from the interrupt itself.

A number of subroutines are available which are useful to character device drivers. Most of these handlers, for example, need a place to buffer characters in the internal interface between their ''top half'' (read/write) and ''bottom half'' (interrupt) routines. For relatively low data-rate devices, the best mechanism is the character queue maintained by the routines *getc* and *putc.* A queue header has the structure

```
struct {
        int     c_cc;   /* character count */
        char    *c_cf;  /* first character */
        char    *c_cl;  /* last character */
} queue;
```

A character is placed on the end of a queue by

putc(c, &queue)

where *c* is the character and *queue* is the queue header. The routine returns −1 if there is no space to put the character, 0 otherwise. The first character on the queue may be retrieved by

getc(&queue)

which returns either the (non-negative) character or −1 if the queue is empty.

Notice that the space for characters in queues is shared among all devices in the system and in the standard system there are only some 600 character slots available. Thus device handlers, especially write routines, must take care to avoid gobbling up excessive numbers of characters.

The other major help available to device handlers is the sleep-wakeup mechanism. The call

sleep(event, priority)

causes the process to wait (allowing other processes to run) until the *event* occurs; at that time, the process is marked ready-to-run and the call will return when there is no process with higher *priority.*

The call

wakeup(event)

indicates that the *event* has happened, that is, causes processes sleeping on the event to be awakened. The *event* is an arbitrary quantity agreed upon by the sleeper and the waker-up. By convention, it is the address of some data area used by the driver, which guarantees that events are unique.

Processes sleeping on an event should not assume that the event has really happened; they should check that the conditions which caused them to sleep no longer hold.

Priorities can range from 127 to −127; a higher numerical value indicates a less-favored scheduling situation. A process sleeping at negative priority cannot be terminated for any reason, although it is conceivable that it may be swapped out. Thus it is a bad idea to sleep with negative priority on an event which might never occur. On the other hand, calls to *sleep* with non-negative priority may never return if the process is terminated by some signal in the meantime. Incidentally, it is a gross error to call *sleep* in a routine called at interrupt time, since the process which is running is almost certainly not the process which should go to sleep. Likewise, none of the variables in the user area ''*u.*'' should be touched, let alone changed, by an interrupt routine.

If a device driver wishes to wait for some event for which it is inconvenient or impossible to supply a *wakeup,* (for example, a device going on-line, which does not generally cause an interrupt), the call

sleep(&lbolt, priority)

may be given. *Lbolt* is an external cell whose address is awakened once every 4 seconds by the clock interrupt routine.

The routines

spl4( ), spl5( ), spl6( ), spl7( )

are available to set the processor priority level as indicated to avoid inconvenient interrupts from the device.

If a device needs to know about real-time intervals, then

timeout(func, arg, interval)

will be useful. This routine arranges that after *interval* sixtieths of a second, the *func* will be called with *arg* as argument, in the style

*(*func)(arg)*

Timeouts are used, for example, to provide real-time delays after function characters like new-line and tab in typewriter output, and to terminate an attempt to read the 201 Dataphone *dp* if there is no response within a specified number of seconds. Notice that the number of sixtieths of a second is limited to 32767, since it must appear to be positive, and that only a bounded number of timeouts can be going on at once. Also, the specified *func* is called at clock-interrupt time, so it should conform to the requirements of interrupt routines in general.

An example

The driver for the paper-tape reader/punch is worth examining as a fairly simple example of many of the techniques used in writing character device handlers. The *pc11* structure contains a state (used for the reader), an input queue, and an output queue. A structure, rather than three individual variables, was used to cut down on the number of external symbols which might be confused with symbols in other routines.

When the file is opened for reading, the *open* routine checks to see if its state is not *CLOSED;* if so an error is returned since it is considered a bad idea to let several people read one tape simultaneously. The state is set to *WAITING,* the interrupt is enabled, and a character is requested. The reason for this gambit is that there is no direct way to determine if there is any tape in the reader or if the reader is on-line. In these situations an interrupt will occur immediately and an error indicated. As will be seen, the interrupt routine ignores errors if the state is *WAITING,* but if a good character comes in while in the *WAITING* state the interrupt routine sets the state to *READING.* Thus *open* loops until the state changes, meanwhile sleeping on the "lightning bolt" *lbolt.* If it did not sleep at all, it would prevent any other process from running until the reader came on-line; if it depended on the interrupt routine to wake it up, the effect would be the same, since the error interrupt is almost instantaneous.

The open-write case is much simpler; the punch is enabled and a 100-character leader is punched using *pcleader.*

The *close* routine is also simple; if the reader was open, any uncollected characters are flushed, the interrupt is turned off, and the state is set to *CLOSED.* In the write case a 100-character trailer is punched. The routine has a bug in that if both the reader and punch are open *close* will be called only once, so that either the leftover characters are flushed or the trailer is punched, but not both. It is hard to see how to fix this problem except by making the reader and punch separate devices.

The *pcread* routine tries to pick up characters from the input queue and passes them back until the user's read call is satisfied. If there are no characters it checks whether the state has gone to *EOF,* which means that the interrupt routine detected an error in the *READ* state (assumed to indicate the end of the tape). If so, *pcread* returns; either during this call or the next one no characters will be passed back, indicating an end-of-file. If the state is still *READING* the routine enables another character by fiddling the device's reader control register, provided it is not active, and goes to sleep.

When a reader interrupt occurs and the state is *WAITING,* and the device's error bit is set, the interrupt is ignored; if there is no error the state is set to *READING,* as indicated in the discussion of *pcread.* If the state is *READING* and there is an error, the state is set to *EOF;* it is assumed that the error represents the end of the tape. If there is no error, the character is picked up and stored in the input queue. Then, provided the number of characters already in the queue is less than the high-water mark *PCIHWAT,* the reader is enabled again to read another character. This strategy keeps the tape moving without flooding the input queue with unread characters. Finally, the top half is awakened.

Looking again at *pcread,* notice that the priority level is raised by *spl4( )* to prevent interrupts during the loop. This is done because of the possibility that the input queue is empty, and just after the EOF test is made an error interrupt occurs because the tape runs out. Then *sleep* will be called with no possibility of a *wakeup.* In general the processor priority should be raised when a routine is about to sleep awaiting some condition where the presence of the condition, and the consequent *wakeup,* is indicated by an interrupt. The danger is that the interrupt might occur between the test for the condition and the call to *sleep,* so that the *wakeup* apparently never happens.

At the same time it is a bad idea to raise the processor priority level for an extended period of time, since devices with real-time requirements may be shut out so long as to cause an error. The *pcread* routine is perhaps overzealous in this respect, although since most devices have a priority level higher than 4 this difficulty is not very important.

The *pcwrite* routine simply gets characters from the user and passes them to *pcoutput,* which is separated out so that *pcleader* can call it also. *Pcoutput* checks for errors (like out-of-tape) and if none are present makes sure that the number of characters in the output queue does not exceed *PCOHWAT;* if it does, *sleep* is called. Then the character is placed on the output queue. There is a small bug here in that *pcoutput* does not check that the character was successfully put on the queue (all character-queue space might be empty); perhaps in this case it might be a good idea to sleep on the lightning-bolt until things quiet down. Finally *pcstart* is called, which checks to see if the punch is currently busy, and if not starts the punching of the first character on the output queue.

When punch interrupts occur, *pcpint* is called; it starts the punching of the next character on the output queue, and if the number of characters remaining on the queue is less than the low-water mark *PCOLWAT* it wakes up the write routine, which is presumably waiting for the queue to empty.

The Block-device Interface

Handling of block devices is mediated by a collection of routines which manage a set of buffers containing the images of blocks of data on the various devices. The most important purpose of these routines is to assure that several processes which access the same block of the same device in multiprogrammed fashion maintain a consistent view of the data in the block. A secondary but still important purpose is to increase the efficiency of the system by keeping in-core copies of blocks which are being accessed frequently. The main data base for this mechanism is the table of buffers *buf.* Each buffer header contains a pair of pointers *(b_forw, b_back)* which maintain a doubly-linked list of the buffers associated with a particular block device, and a pair of pointers *(av_forw, av_back)* which generally maintain a doubly-linked list of blocks which are ‘‘free,’’ that is, eligible to be reallocated for another transaction. Buffers which have I/O in progress or are busy for other purposes do not appear in this list. The buffer header also contains the device and block number to which the buffer refers, and a pointer to the actual storage associated with the buffer. There is a word count which is the negative of the number of words to be transferred to or from the buffer; there is also an error byte and a residual word count used to communicate information from an I/O routine to its caller. Finally, there is a flag word with bits indicating the status of the buffer. These flags will be discussed below.

Six routines constitute the most important part of the interface with the rest of the system. Given a device and block number, both *bread* and *getblk* return a pointer to a buffer header for the block; the difference is that *bread* is guaranteed to return a buffer actually containing the current data for the block, while *getblk* returns a buffer which contains the data in the block only if it is already in core (whether it is or not is indicated by the *B_DONE* bit; see below). In either case the buffer, and the corresponding device block, is made ‘‘busy,’’ so that other processes referring to it are obliged to wait until it becomes free. *Getblk* is used, for example, when a block is about to be totally rewritten, so that its previous contents are not useful; still, no other process can be allowed to refer to the block until the new data is placed into it.

Given a pointer to a buffer, the *brelse* routine makes the buffer again available to other processes. It is called, for example, after data has been extracted following a *bread.* There are three subtly-different write routines, all of which take a buffer pointer as argument, and all of which logically release the buffer for use by others and place it on the free list. *Bwrite* puts the buffer on the appropriate device queue, waits for the write to be done, and sets the user’s error flag if required.

Bawrite places the buffer on the device’s queue, but does not wait for completion, so that errors cannot be reflected directly to the user. *Bdwrite* does not start any I/O operation at all, but merely marks the buffer so that if it happens to be grabbed from the free list to contain data from some other block, the data in it will first be written out.

Bwrite is used when one wants to be sure that I/O takes place correctly, and that errors are reflected to the proper user; it is used, for example, when updating i-nodes. *Bawrite* is useful when more efficiency is desired (because no

wait is required for I/O to finish) but when it is reasonably certain that the write is really required. *Bdwrite* is used when there is doubt that the write is needed at the moment. For example, *bdwrite* is called when the last byte of a *write* system call falls short of the end of a block, on the assumption that another *write* will be given soon which will re-use the same block. On the other hand, as the end of a block is passed, *bawrite* is called, since probably the block will not be accessed again soon and one might as well start the writing process as soon as possible.

In any event, notice that the routines *getblk* and *bread* dedicate the given block exclusively to the use of the caller, and make others wait, while one of *brelse, bwrite, bawrite,* or *bdwrite* must eventually be called to free the block for use by others.

As mentioned, each buffer header contains a flag word which indicates the status of the buffer. Since they provide one important channel for information between the drivers and the block I/O system, it is important to understand these flags. The following names are manifest constants which select the associated flag bits.

B_READ

This bit is set when the buffer is handed to the device strategy routine (see below) to indicate a read operation. The symbol *B_WRITE* is defined as 0 and does not define a flag; it is provided as a mnemonic convenience to callers of routines like *swap* which have a separate argument which indicates read or write.

B_DONE

This bit is set to 0 when a block is handed to the the device strategy routine and is turned on when the operation completes, whether normally as the result of an error. It is also used as part of the return argument of *getblk* to indicate if 1 that the returned buffer actually contains the data in the requested block.

B_ERROR

This bit may be set to 1 when *B_DONE* is set to indicate that an I/O or other error occurred. If it is set the *b_error* byte of the buffer header may contain an error code if it is non-zero. If *b_error* is 0 the nature of the error is not specified. Actually no driver at present sets *b_error;* the latter is provided for a future improvement whereby a more detailed error-reporting scheme may be implemented.

B_BUSY

This bit indicates that the buffer header is not on the free list, i.e. is dedicated to someone's exclusive use. The buffer still remains attached to the list of blocks associated with its device, however. When *getblk* (or *bread,* which calls it) searches the buffer list for a given device and finds the requested block with this bit on, it sleeps until the bit clears.

B_WANTED

This flag is used in conjunction with the *B_BUSY* bit. Before sleeping as described just above, *getblk* sets this flag. Conversely, when the block is freed and the busy bit goes down (in *brelse)* a *wakeup* is given for the block header whenever *B_WANTED* is on. This strategem avoids the overhead of having to call *wakeup* every time a buffer is freed on the chance that someone might want it.

B_ASYNC

This bit is set by *bawrite* to indicate to the appropriate device driver that the buffer should be released when the write has been finished, usually at interrupt time. The difference between *bwrite* and *bawrite* is that the former starts I/O, waits until it is done, and frees the buffer. The latter merely sets this bit and starts I/O. The bit indicates that *relse* should be called for the buffer on completion.

B_DELWRI

This bit is set by *bdwrite* before releasing the buffer. When *getblk,* while searching for a free block, discovers the bit is 1 in a buffer it would otherwise grab, it causes the block to be written out before reusing it.

B_XMEM

This is actually a mask for the pair of bits which contain the high-order two bits of the physical address of the origin

of the buffer; these bits are an extension of the 16 address bits elsewhere in the buffer header.

B_RELOC

This bit is currently unused; it previously indicated that a system-wide relocation constant was to be added to the buffer address. It was needed during a period when addresses of data in the system (including the buffers) were mapped by the relocation hardware to a physical address differing from its virtual address.

Block Device Drivers

The *bdevsw* table contains the names of the interface routines and that of a table for each block device.

Just as for character devices, block device drivers may supply an *open* and a *close* routine called respectively on each open and on the final close of the device. Instead of separate read and write routines, each block device driver has a *strategy* routine which is called with a pointer to a buffer header as argument. As discussed, the buffer header contains a read/write flag, the core address (including extended-memory bits), the block number, a (negative) word count, and the major and minor device number. The rôle of the strategy routine is to carry out the operation as requested by the information in the buffer header. When the transaction is complete the *B_DONE* (and possibly the *B_ERROR)* bits should be set. Then if the *B_ASYNC* bit is set, *brelse* should be called; otherwise, *wakeup.* In cases where the device is capable, under error-free operation, of transferring fewer words than requested, the device's word-count register should be placed in the residual count slot of the buffer header; otherwise, the residual count should be set to 0. This particular mechanism is really for the benefit of the magtape driver; when reading this device records shorter than requested are quite normal, and the user should be told the actual length of the record. [However the mechanism has not been integrated into normal I/O even on magtape and is used only in ''raw'' I/O as discussed below.]

Notice that although the most usual argument to the strategy routines is a genuine buffer header allocated as discussed above, all that is actually required is that the argument be a pointer to a place containing the appropriate information. For example the *swap* routine, which manages movement of core images to and from the swapping device, uses the strategy routine for this device. Care has to be taken that no extraneous bits get turned on in the flag word.

The device's table specified by *bdevsw* has a byte to contain an active flag and an error count, a pair of links which constitute the head of the chain of buffers for the device *(b_forw, b_back),* and a first and last pointer for a device queue. Of these things, all are used solely by the device driver itself except for the buffer-chain pointers. Typically the flag encodes the state of the device, and is used at a minimum to indicate that the device is currently engaged in transferring information and no new command should be issued. The error count is useful for counting retries when errors occur. The device queue is used to remember stacked requests; in the simplest case it may be maintained as a first-in first-out list. Since buffers which have been handed over to the strategy routines are never on the list of free buffers, the pointers in the buffer which maintain the free list *(av_forw, av_back)* are also used to contain the pointers which maintain the device queues.

A couple of routines are provided which are useful to block device drivers.

iodone(bp) ,

arranges that the buffer to which *bp* points be released or awakened, as appropriate, when the strategy module has finished with the buffer, either normally or after an error. (In the latter case the *B_ERROR* bit has presumably been set.)

When the device conforms to some rather loose standards adhered to by certain DEC hardware, the routine

devstart(bp, devloc, devblk, hbcom)

is useful. Here *bp* is the address of the buffer header, *devloc* is the address of the slot in the device registers which accepts a perhaps-encoded device block number, *devblk* is the block number, and *hbcom* is a quantity to be stored in the high byte of the device's command register. It is understood, when using this routine, that the device registers are laid out in the order

command register
word count
core address
block (or track or sector)

where the address of the last corresponds to *devloc.* Moreover, the device should correspond to the RP, RK, and RF devices with respect to its layout of extended-memory bits and structure of read and write commands.

The routine

geterror(bp)

can be used to examine the error bit in a buffer header and arrange that any error indication found therein is reflected to the user. It may be called only in the non-interrupt part of a driver when I/O has completed *(B_DONE* has been set).

An example

The RF disk driver is worth studying as the simplest example of a block I/O device. Its *strategy* routine checks to see if the requested block lies beyond the end of the device; the size of the disk, in this instance, is indicated by the minor device number. If the request is plausible, the buffer is placed at the end of the device queue, and if the disk is not running, *rfstart* is called.

Rfstart merely returns if there is nothing to do, but otherwise sets the device-active flag, loads the address extension register, and calls *devstart* to perform the remaining tasks attendant on beginning a data transfer.

When a completion or error interrupt occurs, *rfintr* is called. If an error is indicated, and if the error count has not exceeded 10, the same transaction is reattempted; otherwise the error bit is set. If there was no error or if 10 failing transfers have been issued the queue is advanced and *rfstart* is called to begin another transaction.

Raw Block-device I/O

A scheme has been set up whereby block device drivers may provide the ability to transfer information directly between the user's core image and the device without the use of buffers and in blocks as large as the caller requests. The method involves setting up a character-type special file corresponding to the raw device and providing *read* and *write* routines which set up what is usually a private, non-shared buffer header with the appropriate information and call the device's strategy routine. If desired, separate *open* and *close* routines may be provided but this is usually unnecessary. A special-function routine might come in handy, especially for magtape.

A great deal of work has to be done to generate the ''appropriate information'' to put in the argument buffer for the strategy module; the worst part is to map relocated user addresses to physical addresses. Most of this work is done by

physio(strat, bp, dev, rw)

whose arguments are the name of the strategy routine *strat,* the buffer pointer *bp,* the device number *dev,* and a read-write flag *rw* whose value is either *B_READ* or *B_WRITE. Physio* makes sure that the user's base address and count are even (because most devices work in words) and that the core area affected is contiguous in physical space; it delays until the buffer is not busy, and makes it busy while the operation is in progress; and it sets up user error return information.

The magtape driver is the only one which as of this writing provides a raw I/O capability; given *physio,* the work involved is trivial, and amounts to passing back to the user information on the length of the record read or written. (There is some funniness because the magtape, uniquely among DEC devices, works in bytes, not words.) Putting in raw I/O for disks should be equally trivial except that the disk address has to be carefully checked to make sure it does not overflow from one logical device to another on which the caller may not have write permission.

On the Security of UNIX

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Recently there has been much interest in the security aspects of operating systems and software. At issue is the ability to prevent undesired disclosure of information, destruction of information, and harm to the functioning of the system. This paper discusses the degree of security which can be provided under the UNIX system and offers a number of hints on how to improve security.

The first fact to face is that UNIX was not developed with security, in any realistic sense, in mind; this fact alone guarantees a vast number of holes. (Actually the same statement can be made with respect to most systems.) The area of security in which UNIX is theoretically weakest is in protecting against crashing or at least crippling the operation of the system. The problem here is not mainly in uncritical acceptance of bad parameters to system calls— there may be bugs in this area, but none are known— but rather in the lack of any checks for excessive consumption of resources. Most notably, there is no limit on the amount of disk storage used, either in total space allocated or in the number of files or directories. Here is a particularly ghastly shell sequence guaranteed to stop the system:

```
: loop
mkdir x
chdir x
goto loop
```

Either a panic will occur because all the i-nodes on the device are used up or all the disk blocks will be consumed, thus preventing anyone from writing files on the device.

Processes are another resource on which the only limit is total exhaustion. For example, the sequence

```
command&
command&
command&
```

if continued long enough will use up all the slots in the system's process table and prevent anyone from executing any commands. Alternatively, if the commands use much core, swap space may run out, causing a panic. Incidently, because of the implementation of process termination, the above sequence is effective in stopping the system no matter how short a time it takes each command to terminate. (The process-table slot is not freed until the terminated process is waited for; if no commands without "&" are executed, the Shell never executes a "wait.")

It should be evident that unbounded consumption of disk space, files, swap space, and processes can easily occur accidentally in malfunctioning programs as well as at command level. In fact UNIX is essentially defenseless against this kind of abuse, nor is there any easy fix. The best that can be said is that it is generally fairly easy to detect what has happened when disaster strikes, to identify the user responsible, and take appropriate action. In practice, we have found that difficulties in this area are rather rare, but we have not been faced with malicious users, and enjoy a fairly generous supply of resources which have served to cushion us against accidental overconsumption.

The picture is considerably brighter in the area of protection of information from unauthorized perusal and destruction. Here the degree of security seems (almost) adequate theoretically, and the problems lie more in the necessity for care in the actual use of the system.

Each UNIX file has associated with it eleven bits of protection information together with a user identification number and a user-group identification number (UID and GID). Nine of the protection bits are used to specify independently permission to read, to write, and to execute the file to the user himself, to members of the user's group, and to all other users. Each process generated by or for a user has associated with it an effective UID and a real UID, and an effective and real GID. When an attempt is made to access the file for reading, writing, or execution, the user process's effective UID is compared against the file's UID; if a match is obtained, access is granted provided the read, write, or execute bit respectively for the user himself is present. If the UID for the file and for the process fail to match, but the GID's do match, the group bits are used; if the GID's do not match, the bits for other users are

tested. The last two bits of each file's protection information, called the set-UID and set-GID bits, are used only when the file is executed as a program. If, in this case, the set-UID bit is on for the file, the effective UID for the process is changed to the UID associated with the file; the change persists until the process terminates or until the UID changed again by another execution of a set-UID file. Similarly the effective group ID of a process is changed to the GID associated with a file when that file is executed and has the set-GID bit set. The real UID and GID of a process do not change when any file is executed, but only as the result of a privileged system call.

The basic notion of the set-UID and set-GID bits is that one may write a program which is executable by others and which maintains files accessible to others only by that program. The classical example is the game-playing program which maintains records of the scores of its players. The program itself has to read and write the score file, but no one but the game's sponsor can be allowed unrestricted access to the file lest they manipulate the game to their own advantage. The solution is to turn on the set-UID bit of the game program. When, and only when, it is invoked by players of the game, it may update the score file ordinary programs executed by others cannot access the score.

There are a number of special cases involved in determining access permissions. Since executing a directory as a program is a meaningless operation, the execute-permission bit, for directories, is taken instead to mean permission to search the directory for a given file during the scanning of a path name; thus if a directory has execute permission but no read permission for a given user, he may access files with known names in the directory, but may not read (list) the entire contents of the directory. Write permission on a directory is interpreted to mean that the user may create and delete files in that directory; it is impossible for any user to write directly into any directory.

Another, and from the point of view of security, much more serious special case is that there is a ''super user'' who is able to read any file and write any non-directory. The super-user is also able to change the protection mode and the owner UID and GID of any file and to invoke privileged system calls. It must be recognized that the mere notion of a super-user is a theoretical, and usually practical, blemish on any protection scheme.

The first necessity for a secure system is of course arranging that all files and directories have the proper protection modes. Unfortunately, UNIX software is exceedingly permissive in this regard; essentially all commands create files readable and writable by everyone. This means that more or less continuous attention must be paid to adjusting modes properly. If one wants to keep one's files completely secret, it is possible to remove all permissions from the directory in which they live, which is easy and effective; but if it is desired to give general read permission while preventing writing, things are more complicated. The main problem is that write permission in a directory means precisely that; it has nothing to do with write permission for a file in that directory. Thus a writeable file in a read-only directory may be changed, or even truncated, though not removed. This fact is perfectly logical, though in this case unfortunate. A case can be made for requiring write permission for the directory of a file as well as for the file itself before allowing writing. (This possibility is more complicated than it seems at first; the system has to allow users to change their own directories while forbidding them to change the user-directory directory.)

A situation converse to the above-discussed difficulty is also present— it is possible to delete a file if one has write permission for its directory independently of any permissions for the file. This problem is related more to self-protection than protection from others. It is largely mitigated by the fact that the two major commands which delete named files (mv and rm) ask confirmation before deleting unwritable files.

It follows from this discussion that to maintain both data privacy and data integrity, it is necessary, and largely sufficient, to make one's directory inaccessible to others. The lack of sufficiency could follow from the existence of set-UID programs created by the user and the possibility of total breach of system security in one of the ways discussed below (or one of the ways not discussed below).

Needless to say, the system administrators must be at least as careful as their most demanding user to place the correct protection mode on the files under their control. In particular, it is necessary that special files be protected from writing, and probably reading, by ordinary users when they store sensitive files belonging to other users. It is easy to write programs that examine and change files by accessing the device on which the files live.

On the issue of password security, UNIX is probably better than most systems. Passwords are stored in an encrypted form which, in the absence of serious attention from specialists in the field, appears reasonably secure, provided its limitations are understood. Since both the encryption algorithm and the encrypted passwords are available, exhaustive enumeration of potential passwords is feasible up to a point. As a practical test of the possibilities in this

area, 67 encrypted passwords were collected from 10 UNIX installations. These were tested against all five-letter combinations, all combinations of letters and digits of length four or less, and all words in Webster's Second unabridged dictionary; 60 of the 67 passwords were found. The whole process took about 12 hours of machine time. This experience suggests that passwords should be at least six characters long and randomly chosen from an alphabet which includes digits and special characters.

Of course there also exist feasible non-cryptanalytic ways of finding out passwords. For example: write a program which types out "login: " on the typewriter and copies whatever is typed to a file of your own. Then invoke the command and go away until the victim arrives. (It is this kind of possibility that makes it evident that UNIX was not designed to be secure.)

The set-UID (set-GID) notion must be used carefully if any security is to be maintained. The first thing to keep in mind is that a writable set-UID file can have another program copied onto it. For example, if the super-user *(su)* command is writable, anyone can copy the shell onto it and get a password-free version of *su.* A more subtle problem can come from set-UID programs which are not sufficiently careful of what is fed into them. In some systems, for example, the *mail* command is set-UID and owned by the super-user. The notion is that one should be able to send mail to anyone even if they want to protect their directories from writing. The trouble is that *mail* is rather dumb: anyone can mail someone else's private file to himself. Much more serious, is the following scenario: make a file with a line like one in the password file which allows one to log in as the super-user. Then make a link named ".mail" to the password file in some writeable directory on the same device as the password file (say /tmp). Finally mail the bogus login line to /tmp/.mail; You can then login as the super-user, clean up the incriminating evidence, and have your will.

The fact that users can mount their own disks and tapes as file systems can be another way of gaining super-user status. Once a disk pack is mounted, the system believes what is on it. Thus one can take a blank disk pack, put on it anything desired, and mount it. There are obvious and unfortunate consequences. For example: a mounted disk with garbage on it will crash the system; one of the files on the mounted disk can easily be a password-free version of *su;* other files can be unprotected entries for special files. The only easy fix for this problem is to forbid the use of *mount* to unprivileged users. A partial solution, not so restrictive, would be to have the *mount* command examine the special file for bad data, set-UID programs owned by others, and accessible special files, and balk at unprivileged invokers.

DC − An Interactive Desk Calculator

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ABSTRACT

DC is an interactive desk calculator program implemented on the UNIX time-sharing system to do arbitrary-precision integer arithmetic. It has provision for manipulating scaled fixed-point numbers and for input and output in bases other than decimal.

The size of numbers that can be manipulated is limited only by available core storage. On typical implementations of UNIX, the size of numbers that can be handled varies from several hundred digits on the smallest systems to several thousand on the largest.

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DC − An Interactive Desk Calculator

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DC is an arbitrary precision arithmetic package implemented on the UNIX time-sharing system in the form of an interactive desk calculator. It works like a stacking calculator using reverse Polish notation. Ordinarily DC operates on decimal integers, but one may specify an input base, output base, and a number of fractional digits to be maintained.

A language called BC [1] has been developed which accepts programs written in the familiar style of higher-level programming languages and compiles output which is interpreted by DC. Some of the commands described below were designed for the compiler interface and are not easy for a human user to manipulate.

Numbers that are typed into DC are put on a push-down stack. DC commands work by taking the top number or two off the stack, performing the desired operation, and pushing the result on the stack. If an argument is given, input is taken from that file until its end, then from the standard input.

SYNOPTIC DESCRIPTION

Here we describe the DC commands that are intended for use by people. The additional commands that are intended to be invoked by compiled output are described in the detailed description.

Any number of commands are permitted on a line. Blanks and new-line characters are ignored except within numbers and in places where a register name is expected.

The following constructions are recognized:

number

The value of the number is pushed onto the main stack. A number is an unbroken string of the digits 0-9 and the capital letters A−F which are treated as digits with values 10−15 respectively. The number may be preceded by an underscore _ to input a negative number. Numbers may contain decimal points.

+ − * % ^

The top two values on the stack are added (**+**), subtracted (**−**), multiplied (*****), divided (**/**), remaindered (**%**), or exponentiated (^). The two entries are popped off the stack; the result is pushed on the stack in their place. The result of a division is an integer truncated toward zero. See the detailed description below for the treatment of numbers with decimal points. An exponent must not have any digits after the decimal point.

s*x*

The top of the main stack is popped and stored into a register named *x*, where *x* may be any character. If the **s** is capitalized, *x* is treated as a stack and the value is pushed onto it. Any character, even blank or new-line, is a valid register name.

l*x*

The value in register *x* is pushed onto the stack. The register *x* is not altered. If the **l** is capitalized, register *x* is treated as a stack and its top value is popped onto the main stack.

All registers start with empty value which is treated as a zero by the command **l** and is treated as an error by the command **L**.

d

The top value on the stack is duplicated.

p

The top value on the stack is printed. The top value remains unchanged.

f

All values on the stack and in registers are printed.

x

treats the top element of the stack as a character string, removes it from the stack, and executes it as a string of DC commands.

[...]

puts the bracketed character string onto the top of the stack.

q

exits the program. If executing a string, the recursion level is popped by two. If **q** is capitalized, the top value on the stack is popped and the string execution level is popped by that value.

<*x* **>***x* **=***x* **!<***x* **!>***x* **!=***x*

The top two elements of the stack are popped and compared. Register *x* is executed if they obey the stated relation. Exclamation point is negation.

v

replaces the top element on the stack by its square root. The square root of an integer is truncated to an integer. For the treatment of numbers with decimal points, see the detailed description below.

!

interprets the rest of the line as a UNIX command. Control returns to DC when the UNIX command terminates.

c

All values on the stack are popped; the stack becomes empty.

i

The top value on the stack is popped and used as the number radix for further input. If **i** is capitalized, the value of the input base is pushed onto the stack. No mechanism has been provided for the input of arbitrary numbers in bases less than 1 or greater than 16.

o

The top value on the stack is popped and used as the number radix for further output. If **o** is capitalized, the value of the output base is pushed onto the stack.

k

The top of the stack is popped, and that value is used as a scale factor that influences the number of decimal places that are maintained during multiplication, division, and exponentiation. The scale factor must be greater than or equal to zero and less than 100. If **k** is capitalized, the value of the scale factor is pushed onto the stack.

z

The value of the stack level is pushed onto the stack.

?

A line of input is taken from the input source (usually the console) and executed.

DETAILED DESCRIPTION

Internal Representation of Numbers

Numbers are stored internally using a dynamic storage allocator. Numbers are kept in the form of a string of digits to the base 100 stored one digit per byte (centennial digits). The string is stored with the low-order digit at the beginning of the string. For example, the representation of 157 is 57,1. After any arithmetic operation on a number, care is taken that all digits are in the range 0−99 and that the number has no leading zeros. The number zero is represented by the empty string.

Negative numbers are represented in the 100's complement notation, which is analogous to two's complement notation for binary numbers. The high order digit of a negative number is always −1 and all other digits are in the range 0−99. The digit preceding the high order −1 digit is never a 99. The representation of −157 is 43,98,−1. We shall call this the canonical form of a number. The advantage of this kind of representation of negative numbers is ease of addition. When addition is performed digit by digit, the result is formally correct. The result need only be modified, if necessary, to put it into canonical form.

Because the largest valid digit is 99 and the byte can hold numbers twice that large, addition can be carried out and the handling of carries done later when that is convenient, as it sometimes is.

An additional byte is stored with each number beyond the high order digit to indicate the number of assumed decimal digits after the decimal point. The representation of .001 is 1,*3* where the scale has been italicized to emphasize the fact that it is not the high order digit. The value of this extra byte is called the **scale factor** of the number.

The Allocator

DC uses a dynamic string storage allocator for all of its internal storage. All reading and writing of numbers internally is done through the allocator. Associated with each string in the allocator is a four-word header containing pointers to the beginning of the string, the end of the string, the next place to write, and the next place to read. Communication between the allocator and DC is done via pointers to these headers.

The allocator initially has one large string on a list of free strings. All headers except the one pointing to this string are on a list of free headers. Requests for strings are made by size. The size of the string actually supplied is the next higher power of 2. When a request for a string is made, the allocator first checks the free list to see if there is a string of the desired size. If none is found, the allocator finds the next larger free string and splits it repeatedly until it has a string of the right size. Left-over strings are put on the free list. If there are no larger strings, the allocator tries to coalesce smaller free strings into larger ones. Since all strings are the result of splitting large strings, each string has a neighbor that is next to it in core and, if free, can be combined with it to make a string twice as long. This is an implementation of the 'buddy system' of allocation described in [2].

Failing to find a string of the proper length after coalescing, the allocator asks the system for more space. The amount of space on the system is the only limitation on the size and number of strings in DC. If at any time in the process of trying to allocate a string, the allocator runs out of headers, it also asks the system for more space.

There are routines in the allocator for reading, writing, copying, rewinding, forward-spacing, and backspacing strings. All string manipulation is done using these routines.

The reading and writing routines increment the read pointer or write pointer so that the characters of a string are read or written in succession by a series of read or write calls. The write pointer is interpreted as the end of the information-containing portion of a string and a call to read beyond that point returns an end-of-string indication. An attempt to write beyond the end of a string causes the allocator to allocate a larger space and then copy the old string into the larger block.

Internal Arithmetic

All arithmetic operations are done on integers. The operands (or operand) needed for the operation are popped from the main stack and their scale factors stripped off. Zeros are added or digits removed as necessary to get a properly scaled result from the internal arithmetic routine. For example, if the scale of the operands is different and decimal alignment is required, as it is for addition, zeros are appended to the operand with the smaller scale. After performing the required arithmetic operation, the proper scale factor is appended to the end of the number before it is pushed on the stack.

A register called **scale** plays a part in the results of most arithmetic operations. **scale** is the bound on the number of decimal places retained in arithmetic computations. **scale** may be set to the number on the top of the stack truncated to an integer with the **k** command. **K** may be used to push the value of **scale** on the stack. **scale** must be greater than or equal to 0 and less than 100. The descriptions of the individual arithmetic operations will include the exact effect of **scale** on the computations.

Addition and Subtraction

The scales of the two numbers are compared and trailing zeros are supplied to the number with the lower scale to give both numbers the same scale. The number with the smaller scale is multiplied by 10 if the difference of the scales is odd. The scale of the result is then set to the larger of the scales of the two operands.

Subtraction is performed by negating the number to be subtracted and proceeding as in addition.

Finally, the addition is performed digit by digit from the low order end of the number. The carries are propagated in the usual way. The resulting number is brought into canonical form, which may require stripping of leading zeros, or for negative numbers replacing the high-order configuration 99,−1 by the digit −1. In any case, digits which are not in the range 0−99 must be brought into that range, propagating any carries or borrows that result.

Multiplication

The scales are removed from the two operands and saved. The operands are both made positive. Then multiplication is performed in a digit by digit manner that exactly mimics the hand method of multiplying. The first number is multiplied by each digit of the second number, beginning with its low order digit. The intermediate products are accumulated into a partial sum which becomes the final product. The product is put into the canonical form and its sign is computed from the signs of the original operands.

The scale of the result is set equal to the sum of the scales of the two operands. If that scale is larger than the internal register **scale** and also larger than both of the scales of the two operands, then the scale of the result is set equal to the largest of these three last quantities.

Division

The scales are removed from the two operands. Zeros are appended or digits removed from the dividend to make the scale of the result of the integer division equal to the internal quantity **scale**. The signs are removed and saved.

Division is performed much as it would be done by hand. The difference of the lengths of the two numbers is computed. If the divisor is longer than the dividend, zero is returned. Otherwise the top digit of the divisor is divided into the top two digits of the dividend. The result is used as the first (high-order) digit of the quotient. It may turn out be one unit too low, but if it is, the next trial quotient will be larger than 99

and this will be adjusted at the end of the process. The trial digit is multiplied by the divisor and the result subtracted from the dividend and the process is repeated to get additional quotient digits until the remaining dividend is smaller than the divisor. At the end, the digits of the quotient are put into the canonical form, with propagation of carry as needed. The sign is set from the sign of the operands.

Remainder

The division routine is called and division is performed exactly as described. The quantity returned is the remains of the dividend at the end of the divide process. Since division truncates toward zero, remainders have the same sign as the dividend. The scale of the remainder is set to the maximum of the scale of the dividend and the scale of the quotient plus the scale of the divisor.

Square Root

The scale is stripped from the operand. Zeros are added if necessary to make the integer result have a scale that is the larger of the internal quantity **scale** and the scale of the operand.

The method used to compute sqrt(y) is Newton's method with successive approximations by the rule

The initial guess is found by taking the integer square root of the top two digits.

Exponentiation

Only exponents with zero scale factor are handled. If the exponent is zero, then the result is 1. If the exponent is negative, then it is made positive and the base is divided into one. The scale of the base is removed.

The integer exponent is viewed as a binary number. The base is repeatedly squared and the result is obtained as a product of those powers of the base that correspond to the positions of the one-bits in the binary representation of the exponent. Enough digits of the result removed to make the scale of the result the same as if the indicated multiplication had been performed.

Input Conversion and Base

Numbers are converted to the internal representation as they are read in. The scale stored with a number is simply the number of fractional digits input. Negative numbers are indicated by preceding the number with a _. The hexadecimal digits A−F correspond to the numbers 10−15 regardless of input base. The **i** command can be used to change the base of the input numbers. This command pops the stack, truncates the resulting number to an integer, and uses it as the input base for all further input. The input base is initialized to 10 but may, for example be changed to 8 or 16 to do octal or hexadecimal to decimal conversions. The command **I** will push the value of the input base on the stack.

Output Commands

The command **p** causes the top of the stack to be printed. It does not remove the top of the stack. All of the stack and internal registers can be output by typing the command **f**. The **o** command can be used to change the output base. This command uses the top of the stack, truncated to an integer as the base for all further output. The output base in initialized to 10. It will work correctly for any base. The command **O** pushes the value of the output base on the stack.

Output Format and Base

The input and output bases only affect the interpretation of numbers on input and output; they have no effect on arithmetic computations. Large numbers are output with 70 characters per line; a \ indicates a continued line. All choices of input and output bases work correctly, although not all are useful. A particularly useful output base is 100000, which has the effect of grouping digits in fives. Bases of 8 and 16 can be used for decimal-octal or decimal-hexadecimal conversions.

Internal Registers

Numbers or strings may be stored in internal registers or loaded on the stack from registers with the commands **s** and **l**. The command **s***x* pops the top of the stack and stores the result in register **x**. *x* can be any character. **l***x* puts the contents of register **x** on the top of the stack. The **l** command has no effect on the contents of register *x*. The **s** command, however, is destructive.

Stack Commands

The command **c** clears the stack. The command **d** pushes a duplicate of the number on the top of the stack on the stack. The command **z** pushes the stack size on the stack. The command **X** replaces the number on the top of the stack with its scale factor. The command **Z** replaces the top of the stack with its length.

Subroutine Definitions and Calls

Enclosing a string in **[]** pushes the ascii string on the stack. The **q** command quits or in executing a string, pops the recursion levels by two.

Internal Registers − Programming DC

The load and store commands together with **[]** to store strings, **x** to execute and the testing commands '<', '>', '=', '!<', '!>', '!=' can be used to program DC. The **x** command assumes the top of the stack is an string of DC commands and executes it. The testing commands compare the top two elements on the stack and if the relation holds, execute the register that follows the relation. For example, to print the numbers 0-9,

```
[lip1+ si li10>a]sa
0si lax
```

Push-Down Registers and Arrays

These commands were designed for used by a compiler, not by people. They involve push-down registers and arrays. In addition to the stack that commands work on, DC can be thought of as having individual stacks for each register. These registers are operated on by the commands **S** and **L**. **S***x* pushes the top value of the main stack onto the stack for the register *x*. **L***x* pops the stack for register *x* and puts the result on the main stack. The commands **s** and **l** also work on registers but not as push-down stacks. **l** doesn't effect the top of the register stack, and **s** destroys what was there before.

The commands to work on arrays are **:** and **;**. **:***x* pops the stack and uses this value as an index into the array *x*. The next element on the stack is stored at this index in *x*. An index must be greater than or equal to 0 and less than 2048. **;***x* is the command to load the main stack from the array *x*. The value on the top of the stack is the index into the array *x* of the value to be loaded.

Miscellaneous Commands

The command **!** interprets the rest of the line as a UNIX command and passes it to UNIX to execute. One other compiler command is **Q**. This command uses the top of the stack as the number of levels of recursion to skip.

DESIGN CHOICES

The real reason for the use of a dynamic storage allocator was that a general purpose program could be (and in fact has been) used for a variety of other tasks. The allocator has some value for input and for compiling (i.e. the bracket [...] commands) where it cannot be known in advance how long a string will be. The result was that at a modest cost in execution time, all considerations of string allocation and sizes of strings were removed from the remainder of the program and debugging was made easier. The allocation method used wastes approximately 25% of available space.

The choice of 100 as a base for internal arithmetic seemingly has no compelling advantage. Yet the base cannot exceed 127 because of hardware limitations and at the cost of 5% in space, debugging was

made a great deal easier and decimal output was made much faster.

The reason for a stack-type arithmetic design was to permit all DC commands from addition to subroutine execution to be implemented in essentially the same way. The result was a considerable degree of logical separation of the final program into modules with very little communication between modules.

The rationale for the lack of interaction between the scale and the bases was to provide an understandable means of proceeding after a change of base or scale when numbers had already been entered. An earlier implementation which had global notions of scale and base did not work out well. If the value of **scale** were to be interpreted in the current input or output base, then a change of base or scale in the midst of a computation would cause great confusion in the interpretation of the results. The current scheme has the advantage that the value of the input and output bases are only used for input and output, respectively, and they are ignored in all other operations. The value of scale is not used for any essential purpose by any part of the program and it is used only to prevent the number of decimal places resulting from the arithmetic operations from growing beyond all bounds.

The design rationale for the choices for the scales of the results of arithmetic were that in no case should any significant digits be thrown away if, on appearances, the user actually wanted them. Thus, if the user wants to add the numbers 1.5 and 3.517, it seemed reasonable to give him the result 5.017 without requiring him to unnecessarily specify his rather obvious requirements for precision.

On the the other hand, multiplication and exponentiation produce results with many more digits than their operands and it seemed reasonable to give as a minimum the number of decimal places in the operands but not to give more than that number of digits unless the user asked for them by specifying a value for **scale**. Square root can be handled in just the same way as multiplication. The operation of division gives arbitrarily many decimal places and there is simply no way to guess how many places the user wants. In this case only, the user must specify a **scale** to get any decimal places at all.

The scale of remainder was chosen to make it possible to recreate the dividend from the quotient and remainder. This is easy to implement; no digits are thrown away.

References

[1] L. L. Cherry, R. Morris, *BC − An Arbitrary Precision Desk-Calculator Language,*

[2] K. C. Knowlton, *A Fast Storage Allocator,* Comm. ACM **8**, pp. 623-625 (Oct. 1965)

BC − An Arbitrary Precision Desk-Calculator Language

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ABSTRACT

BC is a language and a compiler for doing arbitrary precision arithmetic on the PDP-11 under the UNIX time-sharing system. The output of the compiler is interpreted and executed by a collection of routines which can input, output, and do arithmetic on indefinitely large integers and on scaled fixed-point numbers.

These routines are themselves based on a dynamic storage allocator. Overflow does not occur until all available core storage is exhausted.

The language has a complete control structure as well as immediate-mode operation. Functions can be defined and saved for later execution.

Two five hundred-digit numbers can be multiplied to give a thousand digit result in about ten seconds.

A small collection of library functions is also available, including sin, cos, arctan, log, exponential, and Bessel functions of integer order.

Some of the uses of this compiler are

- to do computation with large integers,
- to do computation accurate to many decimal places,
- conversion of numbers from one base to another base.

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BC − An Arbitrary Precision Desk-Calculator Language

Lorinda Cherry

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Introduction

BC is a language and a compiler for doing arbitrary precision arithmetic on the UNIX time-sharing system [1]. The compiler was written to make conveniently available a collection of routines (called DC [6]) which are capable of doing arithmetic on integers of arbitrary size. The compiler is by no means intended to provide a complete programming language. It is a minimal language facility.

There is a scaling provision that permits the use of decimal point notation. Provision is made for input and output in bases other than decimal. Numbers can be converted from decimal to octal by simply setting the output base to equal 8.

The actual limit on the number of digits that can be handled depends on the amount of storage available on the machine. Manipulation of numbers with many hundreds of digits is possible even on the smallest versions of UNIX.

The syntax of BC has been deliberately selected to agree substantially with the C language [2,3]. Those who are familiar with C will find few surprises in this language.

Simple Computations with Integers

The simplest kind of statement is an arithmetic expression on a line by itself. For instance, if you type in the line:

```
142857 + 285714
```

the program responds immediately with the line

```
428571
```

The operators −, *, /, %, and ^ can also be used; they indicate subtraction, multiplication, division, remaindering, and exponentiation, respectively. Division of integers produces an integer result truncated toward zero. Division by zero produces an error comment.

Any term in an expression may be prefixed by a minus sign to indicate that it is to be negated (the 'unary' minus sign). The expression

```
7+−3
```

is interpreted to mean that −3 is to be added to 7.

More complex expressions with several operators and with parentheses are interpreted just as in Fortran, with ^ having the greatest binding power, then * and % and /, and finally + and −. Contents of parentheses are evaluated before material outside the parentheses. Exponentiations are performed from right to left and the other operators from left to right. The two expressions

```
a^b^c  and  a^(b^c)
```

are equivalent, as are the two expressions

```
a*b*c  and  (a*b)*c
```

BC shares with Fortran and C the undesirable convention that

```
a/b*c  is equivalent to  (a/b)*c
```

Internal storage registers to hold numbers have single lower-case letter names. The value of an expression can be assigned to a register in the usual way. The statement

```
x = x + 3
```

has the effect of increasing by three the value of the contents of the register named x. When, as in this case, the outermost operator is an =, the assignment is performed but the result is not printed. Only 26 of these named storage registers are available.

There is a built-in square root function whose result is truncated to an integer (but see scaling below). The lines

```
x = sqrt(191)
x
```

produce the printed result

```
13
```

Bases

There are special internal quantities, called ‘ibase’ and ‘obase’. The contents of ‘ibase’, initially set to 10, determines the base used for interpreting numbers read in. For example, the lines

```
ibase = 8
11
```

will produce the output line

```
9
```

and you are all set up to do octal to decimal conversions. Beware, however of trying to change the input base back to decimal by typing

```
ibase = 10
```

Because the number 10 is interpreted as octal, this statement will have no effect. For those who deal in hexadecimal notation, the characters A−F are permitted in numbers (no matter what base is in effect) and are interpreted as digits having values 10−15 respectively. The statement

```
ibase = A
```

will change you back to decimal input base no matter what the current input base is. Negative and large positive input bases are permitted but useless. No mechanism has been provided for the input of arbitrary numbers in bases less than 1 and greater than 16.

The contents of ‘obase’, initially set to 10, are used as the base for output numbers. The lines

```
obase = 16
1000
```

will produce the output line

```
3E8
```

which is to be interpreted as a 3-digit hexadecimal number. Very large output bases are permitted, and they are sometimes useful. For example, large numbers can be output in groups of five digits by setting ‘obase’ to 100000. Strange (i.e. 1, 0, or negative) output bases are handled appropriately.

Very large numbers are split across lines with 70 characters per line. Lines which are continued end with \. Decimal output conversion is practically instantaneous, but output of very large numbers (i.e., more than 100 digits) with other bases is rather slow. Non-decimal output conversion of a one hundred digit number takes about three seconds.

It is best to remember that ‘ibase’ and ‘obase’ have no effect whatever on the course of internal computation or on the evaluation of expressions, but only affect input and output conversion, respectively.

Scaling

A third special internal quantity called ‘scale’ is used to determine the scale of calculated quantities. Numbers may have up to 99 decimal digits after the decimal point. This fractional part is retained in further computations. We refer to the number of digits after the decimal point of a number as its scale.

When two scaled numbers are combined by means of one of the arithmetic operations, the result has a scale determined by the following rules. For addition and subtraction, the scale of the result is the larger of the scales of the two operands. In this case, there is never any truncation of the result. For multiplications, the scale of the result is never less than the maximum of the two scales of the operands, never more than the sum of the scales of the operands and, subject to those two restrictions, the scale of the result is set equal to the contents of the internal quantity ‘scale’. The scale of a quotient is the contents of the internal quantity ‘scale’. The scale of a remainder is the sum of the scales of the quotient and the divisor. The result of an exponentiation is scaled as if the implied multiplications were performed. An exponent must be an integer. The scale of a square root is set to the maximum of the scale of the argument and the contents of ‘scale’.

All of the internal operations are actually carried out in terms of integers, with digits being discarded when necessary. In every case where digits are discarded, truncation and not rounding is performed.

The contents of ‘scale’ must be no greater than 99 and no less than 0. It is initially set to 0. In case you need more than 99 fraction digits, you may arrange your own scaling.

The internal quantities ‘scale’, ‘ibase’, and ‘obase’ can be used in expressions just like other variables. The line

```
scale = scale + 1
```

increases the value of ‘scale’ by one, and the line

```
scale
```

causes the current value of ‘scale’ to be printed.

The value of ‘scale’ retains its meaning as a number of decimal digits to be retained in internal computation even when ‘ibase’ or ‘obase’ are not equal to 10. The internal computations (which are still conducted in decimal, regardless of the bases) are performed to the specified number of decimal digits, never hexadecimal or octal or any other kind of digits.

Functions

The name of a function is a single lower-case letter. Function names are permitted to collide with simple variable names. Twenty-six different defined functions are permitted in addition to the twenty-six variable names. The line

```
define a(x){
```

begins the definition of a function with one argument. This line must be followed by one or more statements, which make up the body of the function, ending with a right brace }. Return of control from a function occurs when a return statement is executed or when the end of the function is reached. The return statement can take either of the two forms

```
return
return(x)
```

In the first case, the value of the function is 0, and in the second, the value of the expression in parentheses.

Variables used in the function can be declared as automatic by a statement of the form

```
auto x,y,z
```

There can be only one ‘auto’ statement in a function and it must be the first statement in the definition.

These automatic variables are allocated space and initialized to zero on entry to the function and thrown away on return. The values of any variables with the same names outside the function are not disturbed. Functions may be called recursively and the automatic variables at each level of call are protected. The parameters named in a function definition are treated in the same way as the automatic variables of that function with the single exception that they are given a value on entry to the function. An example of a function definition is

```
define a(x,y){
        auto z
        z = x*y
        return(z)
}
```

The value of this function, when called, will be the product of its two arguments.

A function is called by the appearance of its name followed by a string of arguments enclosed in parentheses and separated by commas. The result is unpredictable if the wrong number of arguments is used.

Functions with no arguments are defined and called using parentheses with nothing between them: b().

If the function *a* above has been defined, then the line

```
a(7,3.14)
```

would cause the result 21.98 to be printed and the line

```
x = a(a(3,4),5)
```

would cause the value of x to become 60.

Subscripted Variables

A single lower-case letter variable name followed by an expression in brackets is called a subscripted variable (an array element). The variable name is called the array name and the expression in brackets is called the subscript. Only one-dimensional arrays are permitted. The names of arrays are permitted to collide with the names of simple variables and function names. Any fractional part of a subscript is discarded before use. Subscripts must be greater than or equal to zero and less than or equal to 2047.

Subscripted variables may be freely used in expressions, in function calls, and in return statements.

An array name may be used as an argument to a function, or may be declared as automatic in a function definition by the use of empty brackets:

```
f(a[ ])
define f(a[ ])
auto a[ ]
```

When an array name is so used, the whole contents of the array are copied for the use of the function, and thrown away on exit from the function. Array names which refer to whole arrays cannot be used in any other contexts.

Control Statements

The ‘if’, the ‘while’, and the ‘for’ statements may be used to alter the flow within programs or to cause iteration. The range of each of them is a statement or a compound statement consisting of a collection of statements enclosed in braces. They are written in the following way

```
if(relation) statement
while(relation) statement
for(expression1; relation; expression2) statement
```

or

```
if(relation) {statements}
while(relation) {statements}
for(expression1; relation; expression2) {statements}
```

A relation in one of the control statements is an expression of the form

```
x>y
```

where two expressions are related by one of the six relational operators <, >, <=, >=, ==, or !=. The relation == stands for 'equal to' and != stands for 'not equal to'. The meaning of the remaining relational operators is clear.

BEWARE of using = instead of == in a relational. Unfortunately, both of them are legal, so you will not get a diagnostic message, but = really will not do a comparison.

The 'if' statement causes execution of its range if and only if the relation is true. Then control passes to the next statement in sequence.

The 'while' statement causes execution of its range repeatedly as long as the relation is true. The relation is tested before each execution of its range and if the relation is false, control passes to the next statement beyond the range of the while.

The 'for' statement begins by executing 'expression1'. Then the relation is tested and, if true, the statements in the range of the 'for' are executed. Then 'expression2' is executed. The relation is tested, and so on. The typical use of the 'for' statement is for a controlled iteration, as in the statement

```
for(i=1; i<=10; i=i+1) i
```

which will print the integers from 1 to 10. Here are some examples of the use of the control statements.

```
define f(n){
auto i, x
x=1
for(i=1; i<=n; i=i+1) x=x*i
return(x)
}
```

The line

```
f(a)
```

will print *a* factorial if *a* is a positive integer. Here is the definition of a function which will compute values of the binomial coefficient (m and n are assumed to be positive integers).

```
define b(n,m){
auto x, j
x=1
for(j=1; j<=m; j=j+1) x=x*(n−j+1)/j
return(x)
}
```

The following function computes values of the exponential function by summing the appropriate series without regard for possible truncation errors:

```
scale = 20
define e(x){
        auto a, b, c, d, n
        a = 1
        b = 1
        c = 1
        d = 0
        n = 1
        while(1==1){
                a = a*x
                b = b*n
                c = c + a/b
                n = n + 1
                if(c==d) return(c)
                d = c
        }
}
```

Some Details

There are some language features that every user should know about even if he will not use them.

Normally statements are typed one to a line. It is also permissible to type several statements on a line separated by semicolons.

If an assignment statement is parenthesized, it then has a value and it can be used anywhere that an expression can. For example, the line

```
(x=y+17)
```

not only makes the indicated assignment, but also prints the resulting value.

Here is an example of a use of the value of an assignment statement even when it is not parenthesized.

```
x = a[i=i+1]
```

causes a value to be assigned to x and also increments i before it is used as a subscript.

The following constructs work in BC in exactly the same manner as they do in the C language. Consult the appendix or the C manuals [2,3] for their exact workings.

x=y=z is the same as	x=(y=z)
x =+ y	x = x+y
x =− y	x = x−y
x =* y	x = x*y
x =/ y	x = x/y
x =% y	x = x%y
x =^ y	x = x^y
x++	(x=x+1)−1
x−−	(x=x−1)+1
++x	x = x+1
−−x	x = x−1

Even if you don't intend to use the constructs, if you type one inadvertently, something correct but unexpected may happen.

WARNING! In some of these constructions, spaces are significant. There is a real difference between x=−y and x= −y. The first replaces x by x−y and the second by −y.

Three Important Things

1. To exit a BC program, type ‘quit’.

2. There is a comment convention identical to that of C and of PL/I. Comments begin with ‘/*’ and end with ‘*/’.

3. There is a library of math functions which may be obtained by typing at command level

```
bc −l
```

This command will load a set of library functions which, at the time of writing, consists of sine (named ‘s’), cosine (‘c’), arctangent (‘a’), natural logarithm (‘l’), exponential (‘e’) and Bessel functions of integer order (‘j(n,x)’). Doubtless more functions will be added in time. The library sets the scale to 20. You can reset it to something else if you like. The design of these mathematical library routines is discussed elsewhere [4].

If you type

```
bc file ...
```

BC will read and execute the named file or files before accepting commands from the keyboard. In this way, you may load your favorite programs and function definitions.

Acknowledgement

The compiler is written in YACC [5]; its original version was written by S. C. Johnson.

References

[1] K. Thompson and D. M. Ritchie, *UNIX Programmer’s Manual,* Fifth Edition (1974)

[2] D. M. Ritchie, *C Reference Manual,*

[3] B. W. Kernighan, *Programming in C: A Tutorial,*

[4] Robert Morris, *A Library of Reference Standard Mathematical Subroutines,*

[5] S. C. Johnson, *YACC, Yet Another Compiler-Compiler,*

[6] R. Morris and L. L. Cherry, *DC − An Interactive Desk Calculator,*

The Portable C Library (on UNIX) *

M. E. Lesk

1. INTRODUCTION

The C language [1] now exists on three operating systems. A set of library routines common to PDP 11 UNIX, Honeywell 6000 GCOS, and IBM 370 OS has been provided to improve program portability. This memorandum describes the UNIX implementation of the portable routines.

The programs defined here were chosen to follow the standard routines available on UNIX, with alterations to improve transferability to other computer systems. It is expected that future C implementations will try to support the basic library outlined in this document. It provides character stream input and output on multiple files; simple accessing of files by name; and some elementary formatting and translating routines. The remainder of this memorandum lists the portable and non-portable library routines and explains some of the programming aids available.

The I/O routines in the C library fall into several classes. Files are addressed through intermediate numbers called *file-descriptors* which are described in section 2. Several default file-descriptors are provided by the system; other aspects of the system environment are explained in section 3.

Basic character-stream input and output involves the reading or writing of files considered as streams of characters. The C library includes facilities for this, discussed in section 4. Higher-level character stream operations permit translation of internal binary representations of numbers to and from character representations, and formatting or unpacking of character data. These operations are performed with the subprograms in section 5. Binary input and output routines permit data transmission without the cost of translation to or from readable ASCII character representations. Such data transmission should only be directed to files or tapes, and not to printers or terminals. As is usual with such routines, the only simple guarantee that can be made to the programmer seeking portability is that data written by a particular sequence of binary writes, if read by the exactly matching sequence of binary reads, will restore the previous contents of memory. Other reads or writes have system-dependent effects. See section 6 for a discussion of binary input and output. Section 7 describes some further routines in the portable library. These include a storage allocator and some other control and conversion functions.

2. FILE DESCRIPTORS

Except for the standard input and output files, all files must be explicitly opened before any I/O is performed on them. When files are opened for writing, they are created if not already present. They must be closed when finished, although the normal *cexit* routine will take care of that. When opened a disc file or device is associated with a file descriptor, an integer between 0 and 9. This file descriptor is used for further I/O to the file.

Initially you are given three file descriptors by the system: 0, 1, and 2. File 0 is the standard input; it is normally the teletype in time-sharing or input data cards in batch. File 1 is the standard output; it is normally the teletype in time-sharing or the line printer in batch. File 2 is the error file; it is an output file, normally the same as file 1, except that when file 1 is diverted via a command line '>' operator, file 2 remains attached to the original destination, usually the terminal. It is used for error message output. These popular UNIX conventions are considered part of the C library specification. By closing 0 or 1, the default input or output may be re-directed; this can also be done on the command line by *>file* for output or *<file* for input.

---

* This document is an abbreviated form of "The Portable C Library", by M. E. Lesk, describing only the UNIX section of the library.

Associated with the portable library are two external integers, named *cin* and *cout.* These are respectively the numbers of the standard input unit and standard output unit. Initially 0 and 1 are used, but you may redefine them at any time. These cells are used by the routines *getchar, putchar, gets,* and *puts* to select their I-O unit number.

3. THE C ENVIRONMENT

The C language is almost exactly the same on all machines, except for essential machine differences such as word length and number of characters per word. On UNIX ASCII character code is used. Characters range from −128 to +127 in numeric value, there is sign extension when characters are assigned to integers, and right shifts are arithmetic. The ''first'' character in a word is stored in the right half word.

More serious problems of compatibility are caused by the loaders on the different operating systems.

UNIX permits external names to be in upper and lower case, up to seven characters long. There may be multiple external definitions (uninitialized) of the same name.

The C alphabet for identifier names includes the upper and lower case letters, the digits, and the underline. It is not possible for C programs to communicate with FORTRAN programs.

4. BASIC CHARACTER STREAM ROUTINES

These routines transfer streams of characters in and out of C programs. Interpretation of the characters is left to the user. Facilities for interpreting numerical strings are presented in section 5; and routines to transfer binary data to and from files or devices are discussed in section 6. In the following routine descriptions, the optional argument *fd* represents a file-descriptor; if not present, it is taken to be 0 for input and 1 for output. When your program starts, remember that these are associated with the ''standard'' input and output files.

COPEN (filename, type)

Copen initiates activity on a file; if necessary it will create the file too. Up to 10 files may be open at one time. When called as described here, *copen* returns a filedescriptor for a character stream file. Values less than zero returned by *copen* indicate an error trying to open the file. Other calls to *copen* are described in sections 6 and 7.

Arguments :

Filename: a string representing a file name, according to the local operating system conventions. All accept a string of letters and digits as a legal file name, although leading digits are not recommended on GCOS.
Type: a character 'r', 'w', or 'a' meaning read, write, or append. Note that the type is a single character, whereas the file name must be a string.

CGETC (fd)

Cgetc returns the next character from the input unit associated with *fd.* On end of file *cgetc* returns '\0'. To signal end of file from the teletype, type the special symbol appropriate to UNIX: EOT (control-D)

CPUTC (ch , fd)

Cputc writes a character onto the given output unit. *Cputc* returns as its value the character written.

Output for disk files is buffered in 512 character units, irrespective of newlines; teletype output goes character by character

CCLOSE (fd)

Activity on file *fd* is terminated and any output buffers are emptied. You usually don't have to call *cclose; cexit* will do it for you on all open files. However, to write some data on a file and then read it back in, the correct sequence is:

```
fd = copen (''file'', 'w');
write on fd ...
cclose (fd);
fd = copen(''file'', 'r');
read from fd ...
```

CFLUSH (fn)

To get buffer flushing, but retain the ability to write more on the file, you may call this routine.

Normally, output intended for the teletype is not buffered and this call is not needed.

CEXIT ([errcode])

Cexit closes all files and then terminates execution. If a non-zero argument is given, this is assumed to be an error indication or other returned value to be signalled to the operating system.

Cexit **must** be called explicitly; a return from the main program is not adequate.

CEOF (fd)

Ceof returns nonzero when end of file has been reached on input unit *fd.*

GETCHAR ()

Getchar is a special case of *cgetc;* it reads one character from the standard input unit. *Getchar ( )* is defined as *cgetc (cin);* it should not have an argument.

PUTCHAR (ch)

Putchar (ch) is the same as *cputc (ch, cout);* it writes one character on the standard output.

GETS (s)

Gets reads everything up to the next newline into the string pointed to by *s.* If the last character read from this input unit was newline, then *gets* reads the next line, which on GCOS and IBM corresponds exactly to a logical record. The terminating newline is replaced by '\0'. The value of *gets* is *s,* or 0 if end of file.

PUTS (s)

Copies the string *s* onto the standard output unit. The terminating '\0' is replaced by a newline character. The value of *puts* is *s.*

UNGETC (ch , fd)

Ungetc pushes back its character argument to the unit *fd,* which must be open for input. After *ungetc ('a', fd); ungetc ('b', fd);* the next two characters to be read from *fd* will be 'b' and then 'a'. Up to 100 characters may be pushed back on each file. This subroutine permits a program to read past the end of its input, and then restore it for the next routine to read. It is impossible to change an external file with *ungetc;* its purpose is only for internal communications, most particularly *scanf,* which is described in section 5. Note that *scanf* actually requires only one character of ''unget'' capability; thus it is possible that future implementors may change the specification of the *ungetc* routine.

5. HIGH-LEVEL CHARACTER STREAM ROUTINES

These two routines, *printf* for output and *scanf* for input, permit simple translation to and from character representations of numerical quantities. They also allow generation or interpretation of formatted lines.

PRINTF ([fd,] control-string, arg1, arg2, ...)

PRINTF ([−1, output-string,] control-string, arg1, arg2, ...)

Printf converts, formats, and prints its arguments under control of the control string. The control string contains two types of objects: plain characters, which are simply copied to the output stream, and conversion specifications, each of which causes conversion and printing of the next successive argument to *printf.*

Each conversion specification is introduced by the character '%'. Following the '%', there may be:

— an optional minus sign '−' which specifies left adjustment of the converted argument in the indicated field;

— an optional digit string specifying a minimum field width; if the converted argument has fewer characters than the field width it will be padded on the left (or right, if the left adjustment indicator has been given) to make up the field width; the padding character is blank normally and zero if the field width was specified with a leading zero (note that this does not imply an octal field width);

— an optional period '.' which serves to separate the field width from the next digit string;

— an optional digit string (the precision) which specifies the maximum number of characters to be printed from a string, or the number of digits to be printed to the right of the decimal point of a floating or double number.

— an optional length modifier 'l' which indicates that the corresponding data item is a *long* rather than an *int.*

— a character which indicates the type of conversion to be applied.

The conversion characters and their meanings are:

d The argument is converted to decimal notation.

o The argument is converted to octal notation.

x The argument is converted to hexadecimal notation.

u The argument is converted to unsigned decimal notation. This is only implemented (or useful) on UNIX.

c The argument is taken to be a single character.

s The argument is taken to be a string and characters from the string are printed until a null character is reached or until the number of characters indicated by the precision specification is exhausted.

e The argument is taken to be a float or double and converted to decimal notation of the form *[−]m.nnnnnnE[−]xx* where the length of the string of *n*'s is specified by the precision. The default precision is 6 and the maximum is 22.

f The argument is taken to be a float or double and converted to decimal notation of the form *[−]mmm.nnnnn* where the length of the string of *n*'s is specified by the precision. The default precision is 6 and the maximum is 22. Note that the precision does not determine the number of significant digits printed in **f** format.

If no recognizable conversion character appears after the '%', that character is printed; thus '%' may be printed by use of the string ''%%''.

As an example of *printf,* the following program fragment

```
int i, j; float x; char *s;
i = 35; j=2; x= 1.732; s = "ritchie";
printf ("%d %f %s\n", i, x, s);
printf ("%o, %4d or %−4d%5.5s\n", i, j, j, s);
```

would print

```
35 1.732000 ritchie
043,      2 or 2    ritch
```

If *fd* is not specified, output is to unit *cout.* It is possible to direct output to a string instead of to a file. This is indicated by −1 as the first argument. The second argument should be a pointer to the string. *Printf* will put a terminating '\0' onto the string.

SCANF ([fd,] control-string, arg1, arg2, ...)

SCANF ([−1, input-string,] control-string, arg1, arg2, ...)

Scanf reads characters, interprets them according to a format, and stores the results in its arguments. It expects as arguments:

1. An optional file-descriptor or input-string, indicating the source of the input characters; if omitted, file *cin* is used;
2. A control string, described below;
3. A set of arguments, *each of which must be a pointer,* indicating where the converted input should be stored.

The control string usually contains conversion specifications, which are used to direct interpretation of input sequences. The control string may contain:

1. Blanks, tabs or newlines, which are ignored.
2. Ordinary characters (not %) which are expected to match the next non-space character of the input stream (where space characters are defined as blank, tab or newline).
3. Conversion specifications, consisting of the character %, an optional assignment suppressing character ∗, an optional numerical maximum field width, and a conversion character.

A conversion specification is used to direct the conversion of the next input field; the result is placed in the variable pointed to by the corresponding argument, unless assignment suppression was indicated by the ∗ character. An input field is defined as a string of non-space characters; it extends either to the next space character or until the field width, if specified, is exhausted.

The conversion character indicates the interpretation of the input field; the corresponding pointer argument must usually be of a restricted type. Pointers, rather than variable names, are required by the ''call-by-value'' semantics of the C language. The following conversion characters are legal:

% indicates that a single % character is expected in the input stream at this point; no assignment is done.

d indicates that a decimal integer is expected in the input stream; the corresponding argument should be an integer pointer.

o indicates that an octal integer is expected in the input stream; the corresponding argument should be a integer pointer.

x indicates that a hexadecimal integer is expected in the input stream; the corresponding argument should be an integer pointer.

s indicates that a character string is expected; the corresponding argument should be a character pointer pointing to an array of characters large enough to accept the string and a terminating '\0', which will be added. The input field is terminated by a space character or a newline.

c indicates that a single character is expected; the corresponding argument should be a character pointer; the next input character is placed at the indicated spot. The normal skip over space characters is suppressed in this case; to read the next non-space character, try *%1s*.

e or **f** indicates that a floating point number is expected in the input stream; the next field is converted accordingly and stored through the corresponding argument, which should be a pointer to a float. The input format for *floats* is a string of numbers possibly containing a decimal point, followed by an optional exponent field containing an E or e followed by a possibly signed integer.

[indicates a string not to be delimited by space characters. The left bracket is followed by a set of characters and a right bracket; the characters between the brackets define a set of characters making up the string. If the first character is not circumflex (^), the input field is all

characters until the first character not in the set between the brackets; if the first character after the left bracket is ^, the input field is all characters until the first character which is in the remaining set of characters between the brackets. The corresponding argument must point to a character array.

The conversion characters *d, o* and *x* may be preceded by *l* to indicate that a pointer to *long* rather than *int* is expected. Similarly, the conversion characters *e* or *f* may be preceded by *l* to indicate that a pointer to *double* rather than *float* is in the argument list. The character *h* will function similarly in the future to indicate *short* data items.

For example, the call

```
int i; float x; char name[50];
scanf ( "%d%f%s", &i, &x, name);
```

with the input line

```
25   54.32E−1  thompson
```

will assign to *i* the value 25, *x* the value 5.432, and *name* will contain *"thompson\0"*. Or,

```
int i; float x; char name[50];
scanf ("%2d%f%*d%[1234567890]", &i, &x, name);
```

with input

```
56789 0123 56a72
```

will assign 56 to *i,* 789.0 to *x,* skip ''0123'', and place the string ''56\0'' in *name.* The next call to *cgetc* will return 'a'.

Scanf returns as its value the number of successfully matched and assigned input items. This can be used to decide how many input items were found. On end of file, −1 is returned; note that this is different from 0, which means that the next input character does not match what you called for in the control string. *Scanf,* if given a first argument of −1, will scan a string in memory given as the second argument. For example, if you want to read up to four numbers from an input line and find out how many there were, you could try

```
int a[4], amax;
char line[100];
amax = scanf (−1, gets(line), "%d%d%d%d", &a[0], &a[1], &a[2], &a[3]);
```

6. BINARY STREAM ROUTINES

These routines write binary data, not translated to printable characters. They are normally efficient but do not produce files that can be printed or easily interpreted. No special information is added to the records and thus they can be handled by other programming systems *if* you make the departure from portability required to tell the other system how big a C item (integer, float, structure, etc.) really is in machine units.

COPEN (name, direction, "i")

When *copen* is called with a third argument as above, a binary stream filedescriptor is returned. Such a file descriptor is required for the remaining subroutines in this section, and may not be used with the routines in the preceding two sections. The first two arguments operate exactly as described in section 3; further details are given in section 7. An ordinary file descriptor may be used for binary I-O, but binary and character I-O may not be mixed unless *cflush* is called at each switch to binary I-O. The third argument to *copen* is ignored.

*CWRITE (ptr, sizeof(*ptr), nitems, fd)*

Cwrite writes *nitems* of data beginning at *ptr* on file *fd. Cwrite* writes blocks of binary information, not translated to printable form, on a file. It is intended for machine-oriented bulk storage of intermediate data. Any kind of data may be written with this command, but only the corresponding *cread* should be expected to make any sense of it on return. The first argument is a pointer to the beginning of a vector of any kind of data. The second argument tells *cwrite* how big the items are. The third argument specifies the number of the items to be written; the fourth indicates where.

CREAD (ptr, sizeof(∗ptr), nitems, fd)

Cread reads up to *nitems* of data from file *fd* into a buffer beginning at *ptr.* *Cread* returns the number of items read.
The returned number of items will be equal to the number requested by *nitems* except for reading certain devices (e.g. the teletype or magnetic tape) or reading the final bytes of a disk file.

Again, the second argument indicates the size of the data items being read.

CCLOSE (fd)

The same description applies as for character-stream files.

7. OTHER PORTABLE ROUTINES

REW (fd)

Rewinds unit *fd.* Buffers are emptied properly and the file is left open.

SYSTEM (string)

The given *string* is executed as if it were typed at the terminal.

NARGS ( )

A subroutine can call this function to try to find out how many arguments it was called with. Normally, *nargs()* returns the number of arguments plus 3 for every *float* or *double* argument and plus one for every *long* argument. If the new UNIX feature of separated instruction and data space areas is used, *nargs()* doesn't work at all.

CALLOC (n, sizeof(object))

Calloc returns a pointer to new storage, allocated in space obtained from the operating system. The space obtained is well enough aligned for any use, i.e. for a double-precision number. Enough space to store *n* objects of the size indicated by the second argument is provided. The *sizeof* is executed at compile time; it is not in the library. A returned value of −1 indicates failure to obtain space.

*CFREE (ptr, n, sizeof(*ptr))*

Cfree returns to the operating system memory starting at *ptr* and extending for *n* units of the size given by the third argument. The space should have been obtained through *calloc*. On UNIX you can only return the exact amount of space obtained by *calloc;* the second and third arguments are ignored.

FTOA (floating-number, char-string, precision, format)

Ftoa (floating to ASCII conversion) converts floating point numbers to character strings. The *format* argument should be either 'f' or 'e'; 'e' is default. See the explanation of *printf* in section 5 for a description of the result.

ATOF (char-string)

Returns a floating value equal to the value of the ASCII character string argument, interpreted as a decimal floating point number.

TMPNAM (str)

This routine places in the character array expected as its argument a string which is legal to use as a file name and which is guaranteed to be unique among all jobs executing on the computer at the same time. It is thus appropriate for use as a temporary file name, although the user may wish to move it into an appropriate directory. The value of the function is the address of the string.

ABORT (code)

Causes your program to terminate abnormally, which typically results in a dump by the operating system.

INTSS ()

This routine tells you whether you are running in foreground or background. The definition of ‘‘foreground’’ is that the standard input is the terminal.

WDLENG ( )

This returns 16 on UNIX. C users should be aware that the preprocessor normally provides a defined symbol suitable for distinguishing the local system; thus on UNIX the symbol *unix* is defined before starting to compile your program.

A. Hardware

UNIX runs on a DEC PDP11/40*, 11/45 or 11/70 with at least the following equipment:

48K to 124K words of managed memory: parity not used,
disk: RP03, RP04, RK05(preferably 2) or equivalent,
console typewriter,
clock: KW11-L or KW11-P,
extended instruction set KE11-E, on 11/40 only.

The system is normally distributed on 9-track tape or RK05 packs.
The following equipment is strongly recommended:

communications controllers such as DL11, DC11 or DH11,
full duplex 96-character ASCII terminals,
9-track tape, or extra disk for system backup.

The minimum memory and disk space specified is enough to run and maintain UNIX. More will be needed to keep all source on line, or to handle a large number of users, big data bases, diversified complements of devices, or large programs. UNIX does swapping and reentrant sharing of user code to minimize main memory requirements. The resident code of UNIX occupies 20-22K depending on configuration.

An 11/40 is not advisable for heavy floating point work, as UNIX on this hardware uses interpreted 11/45 floating point.

B. Software

All the programs available as UNIX commands are listed. Every command, including all options, is issued as just one line, unless specifically noted as ''interactive''. Interactive programs can be made to run from a prepared script simply by redirecting input.

File processing commands that go from standard input to standard output are noted as usable as filters. The piping facility of the Shell may be used to connect filters directly to the input or output of other programs.

Commercially distributed UNIX normally excludes software listed in Section 5, ''Typesetting.'' Source code is included except as noted.

1 Basic Software

This package includes time-sharing operating system with utilities, machine language assembler and the compiler for the programming language C—enough software to write and run new applications and to maintain or modify UNIX itself.

1.1 Operating System

□ UNIX — The basic resident code on which everything else depends. Supports the system calls, and maintains the file system. A general description of UNIX design philosophy and system facilities appeared in the Communications of the ACM, July, 1974. Further capabilities include:
- Automatically supported reentrant code.
- Separate instruction and data spaces on 11/45 and 11/70.
- ''Group'' access permissions allow cooperative projects, with overlapping memberships.
- Timer-interrupt sampling and interprocess monitoring for debugging and measurement.

□ Manual — Printed manuals for UNIX and all its software, except where other manuals exist.
- UNIX Programmer's Manual.
- The UNIX Time-Sharing System, reprint setting forth design principles.
- UNIX for Beginners.

• The UNIX I-O System.
• On the Security of UNIX.

□ (DEV) All I/O is logically synchronous. Normally, invisible buffering makes all physical record structure transparent and exploits the hardware's ability to do overlapped I/O. Unbuffered physical record I/O is available for unusual applications. Drivers for these devices are available; others can be easily written:
• Asynchronous interfaces: DC11, DH11, DL11. Support for most common ASCII terminals.
• Synchronous interface: DP11.
• Automatic calling unit interface: DN11.
• Line printer: LP11.
• Magnetic tape: TU10 and TU16.
• DECtape*: TC11.
• Paper tape: PC11.
• Fixed head disk: RS11, RS03 and RS04.
• Pack type disk: RP03 and RP04, one or more logical devices per physical device, minimum-latency seek scheduling.
• Cartridge-type disk: RK05, one or more physical devices per logical device.
• Null device.
• Physical memory of PDP11, or mapped memory in resident system.
• Phototypesetter: Graphic Systems System/1 through DR11C.
• Voice synthesizer: VOTRAX* through DC11. Includes TOUCH-TONE® input.

□ BOOT Procedures to get UNIX up on a naked machine.

□ Manual Setting up UNIX.

□ MKCONF Tailor device-dependent system code to hardware configuration. Other changes, such as optimal assignment of directories to devices, inclusion of floating point simulator, or installation of device names in file system can then be made at leisure. (As distributed, UNIX can be brought up directly on any acceptable CPU with any acceptable disk, any sufficient amount of core and either clock.)

□ Manual Printed manual on setting up UNIX.

1.2 User Access Control

□ LOGIN Sign on as a new user.
• Verify password and establish user's individual and group (project) identity.
• Adapt to characteristics of terminal.
• Establish working directory.
• Announce presence of mail (from MAIL).
• Publish message of the day.
• Start command interpreter or other initial program.

□ PASSWD Change a password.
• User can change his own password.
• Passwords are kept encrypted for better security.

□ NEWGRP Change working group (project). Protects against changes to unauthorized projects.

1.3 File Manipulation

□ CAT Concatenate one or more files onto standard output. Particularly used for unadorned printing, for inserting data into a pipeline, and for buffering output that comes in dribs and drabs.
• Usable as filter.

□ CP — Copy one file to another. Works on any file without distinction as to contents.

□ PR — Print files with title, date, and page number on every page.
- Multicolumn output.
- Parallel column merge of several files.
- Usable as a filter.

□ OPR — Off line print. Spools arbitrary files to the line printer.
- Usable as a filter.

□ SPLIT — Split a large file into more manageable pieces. Is occasionally necessary for editing (ED).

□ ED — Interactive context editor. Can work on single lines, blocks of lines, or all pattern-selected lines in a given range.
- Finds lines by number or pattern.
- Random access to lines.
- Add, delete, change, copy or move lines.
- Permute or split contents of a line.
- Replace one or all instances of a pattern within a line.
- Combine or split files.
- Escape to Shell (UNIX command language) during editing.
- Patterns may include:
  - specified characters,
  - don't care characters,
  - choices among characters,
  - repetitions of above,
  - beginning of line,
  - end of line.
- All operations may be done globally on every pattern-selected line in a given range.

□ Manual — Introductory manual for ED.

□ DD — Physical file format translator, for exchanging data with foreign systems, especially OS/360.

□ STTY — Sets up options for optimal control of a terminal. In so far as they are deducible from the input, these options are set automatically by LOGIN.
- Half vs. full duplex.
- Carriage return+line feed vs. newline.
- Interpretation of tabs.
- Parity.
- Mapping of upper case to lower.
- Raw vs. edited input.
- Delays for tabs, newlines and carriage returns.

1.4 Manipulation of Directories and File Names

□ RM — Remove a file. Only the name goes away if any other names are linked to the file.

□ LN — "Link" another name (alias) to an existing file.

□ MV — Move a file.
- Used for renaming files or directories.

□ CHMOD — Change permissions on one or more files. Executable by files' owner.

□ CHOWN Change owner of one or more files.

□ CHGRP Change group (project) to which a file belongs.

□ MKDIR Make a new directory.

□ RMDIR Remove a directory.

□ CHDIR Change working directory.

□ FIND Prowl the directory hierarchy finding every file that meets specified criteria.
- These criteria are understood:
  - spelling of name matches a given pattern,
  - creation date in given range,
  - date of last use in given range,
  - permissions,
  - owner,
  - characteristics of device files,
  - boolean combinations of above.
- Any directory may be considered to be the root.
- Specified commands may be performed on every file found.

□ DSW Interactively step through a directory, deleting or keeping files.

1.5 Running of Programs

□ SH The Shell, or command language interpreter. Provides "background" and macro capability when run with a file of commands as input.
- Any executable object file is automatically a command.
- Redirect standard input or standard output.
- Operators to compose compound commands:
  - ';' for sequential execution,
  - '|' for functional composition with output of one command taken directly as input to another running simultaneously,
  - '&' for asynchronous operation,
  - parentheses for grouping.
- Substitutable arguments.
- Construction of argument lists from all file names satisfying specified patterns.
- Collects command usage statistics.

□ IF A conditional statement for Shell programs.
- String comparison.
- Querying file accessibility.

□ GOTO A "go-to" statement for Shell programs.

□ WAIT Wait for termination of asynchronously running processes.

□ EXIT Terminate a Shell program. Useful with IF.

□ ECHO Print remainder of command line. Useful for diagnostic or prompting data in Shell programs, or for inserting data into a pipeline.

□ SLEEP Suspend execution for a specified time.

□ NOHUP Run a command immune to hanging up the terminal.

□ NICE Run a command in low (or high) priority.

□ KILL Terminate named processes.

□ CRON A table of actions to be taken at specified times.
- Actions are arbitrary Shell (SH) scripts.
- Times are conjunctions of month, day of month, day of week, hour and minute. Ranges are specifiable for each.

□ TEE Pass data between processes and divert a copy into a file. Used as a filter.

1.6 Status Inquiries

□ LS List the names of one, several, or all files in one or more directories.
- Alphabetic or temporal sorting, up or down.
- Optional information: size, owner, group, date last modified, date last accessed, permissions, i-node number.

□ FILE Tries to determine what kind of information is in a file by consulting the file system index and by reading the file itself.

□ DATE System date routine. Has considerable knowledge of calendric and horological peculiarities.
- Print present date, day of week, local time.
- May set UNIX's idea of date and time.

□ DF Report amount of free space on file system devices.

□ DU Print a summary of total space occupied by all files in a hierarchy.

□ WHO Tell who's on the system.
- List of presently logged in users, ports and times on.
- Optional history of all logins and logouts.

□ PS Report on all active processes attached to a terminal.
- Gives all commands being executed.
- Can also report on other terminals.
- Extended status information available:
  state and scheduling info,
  priority,
  attached terminal,
  what it's waiting for,
  size.

□ TTY Find name of your terminal.

□ PWD Print name of your working directory.

□ PFE Print type of last floating exception.

1.7 Backup and Maintenance

□ MOUNT Attach a device containing a file system to the tree of directories. Protects against nonsense arrangements.

□ UMOUNT — Remove the file system contained on a device from the tree of directories. Protects against removing a busy device.

□ MKFS — Make a new file system on a device.

□ MKNOD — Make an i-node (file system entry) for a special file. Special files are physical devices, virtual devices, physical memory, etc.

□ TP — Manage file archives on magnetic tape or DEC tape.
- Collect files into an archive.
- Update DECtape archive by date.
- Replace or delete DECtape files.
- Table of contents.
- Retrieve from archive.

□ DUMP — Dump the file system stored on a specified device, selectively by date, or indiscriminately.

□ RESTOR — Restore a dumped file system, or selectively retrieve parts thereof.

□ SU — Temporarily become the super user with all the rights and privileges thereof. Requires a password.

□ DCHECK
□ ICHECK
□ NCHECK

Check consistency of file system.
- Gross statistics:
  - number of files,
  - number of directories,
  - number of special files,
  - spaced used,
  - space free.
- Report of duplicate use of space.
- Retrieval of lost space.
- Report of inaccessible files.
- Check consistency of directories.
- List names of all files.

□ CLRI — Peremptorily expunge a file and its space from a file system. Used in putting damaged file systems together again.

□ SYNC — Force all outstanding I/O on the system to completion. Used to shut down gracefully.

1.8 Accounting

These routines use floating point. The timing information on which the reports are based can be manually cleared or shut off completely.

□ AC — Publish cumulative connect time report.
- Connect time by user or by day.
- For all users or for selected users.

□ SA — Publish Shell accounting report. Gives usage information on each command executed.
- Number of times used.
- Total system time, user time and elapsed time.
- Optional averages and percentages.
- Sorting on various fields.

1.9 Inter-user Communication

□ MAIL — Mail a message to one or more users. Also used to read and dispose of incoming mail. The presence of mail is announced by LOGIN.

□ WRITE — Establish direct terminal communication with another user.

□ WALL — Write to all users.

□ MESG — Inhibit receipt of messages from WRITE and WALL.

1.10 Basic Program Development Package

A kit of fundamental programming tools. Some of these utilities are used as integral parts of the higher level languages described below.

□ AR — Archive and library maintainer. Combines several files into one for housekeeping efficiency. Archive files are used by the link editor LD as libraries.
- Create new archive.
- Update archive by date.
- Replace or delete files.
- Table of contents.
- Retrieve from archive.

□ AS — Assembler. Similar to PAL-11, but different in detail.
- Creates object program consisting of
  code, possibly read-only,
  initialized data or read-write code,
  uninitialized data.
- Relocatable object code is directly executable without further transformation.
- Object code normally includes a symbol table.
- Combines source files.
- Local labels.
- Conditional assembly.
- ‘‘Conditional jump’’ instructions become branches or branches plus jumps depending on distance.

□ Manual — Printed manual for the assembly language.

□ Library — The basic run-time library. These routines are used freely by all system software.
- Formatted writing on standard output.
- Time conversions.
- Convert integer and floating numbers to ASCII and vice versa.
- Elementary functions: sin, cos, log, exp, atan, sqrt, gamma.
- Password encryption.
- Quicksort.
- Buffered character-by-character I/O.
- Random number generator.
- Floating point interpreter for 11/40’s and non-floating point machines.

□ (LIBP) — An elaborated I/O library.
- Formatted input and output.
- Ability to put characters back into input streams.

□ Manual — Printed manual for LIBP.

□ DB — Interactive post-mortem debugger. Works on core dump files, such as are produced by all program aborts, on object files, or on any arbitrary file.
- Symbolic addressing of files that have symbol tables.
- Octal, decimal or ASCII output.
- Symbolic disassembly.
- Octal or decimal patching.

□ OD — Dump any file.
- Output options include:
  - octal or decimal by words,
  - octal by bytes,
  - ASCII,
  - opcodes,
  - hexadecimal,
  - any combination of the above.
- Range of dumping is controllable.

□ LD — Link edit. Combine relocatable object files. Insert required routines from specified libraries.
- Resulting code may be sharable.
- Resulting code may have separate instruction and data spaces.

□ NM — Print the namelist (symbol table) of an object program. Provides control over the style and order of names that are printed.

□ SIZE — Report the core requirements of one or more object files.

□ STRIP — Remove the relocation and symbol table information from an object file to save space.

□ TIME — Run a command and report timing information on it.

□ PROF — Construct a profile of time spent per routine from statistics gathered by time-sampling the execution of a program. Uses floating point.
- Subroutine call frequency and average times for C programs.

1.11 The Programming Language "C"

□ CC — Compile and/or link edits programs in the C language. The UNIX operating system, most of the subsystems and C itself are written in C.
- Full general purpose language designed for structured programming.
- Data types:
  - character,
  - integer,
  - float,
  - double,
  - pointers to all types,
  - arrays of all types,
  - structures of all types,
  - functions returning all types.
- Operations intended to give access to full machine facility, including to-memory operations and data-sensitive pointer arithmetic.
- Macro preprocessor for parameterized code and inclusion of standard files.
- All procedures recursive, with parameters by value.
- Natural coercions.

• True compiled object code capitalizing on addressing capability of the PDP11.
• Runtime library gives access to all system facilities.

□ Manuals — Printed manual and tutorial for the C language.

□ CDB — An interactive debugger tailored for use with C.
• Usable in real time or post-mortem.
• The debugger is a completely separate process from the debuggee. No debugging code is loaded with debuggee.
• Prints all kinds of data in natural notation:
character,
integer (octal and decimal),
float,
double,
machine instructions (disassembled).
• Stack trace and fault identification.
• Breakpoint tracing.

2 Other Languages

2.1 FORTRAN

□ FC — Compile and/or link-edit FORTRAN IV programs. Object code is ''threaded''. Relies heavily on floating point.
• Idiosyncracies:
free form, lower-case source code,
no arithmetic statement functions,
unformatted I/O requires record lengths agree,
no BACKSPACE,
no P FORMAT control on input.
• Handles mixed-mode arithmetic, general subscripts and general DO limits.
• 32-bit integer arithmetic.
• Free format numeric input.
• Understands these nonstandard specifications:
LOGICAL*1, *2, *4,
INTEGER*2, *4,
REAL*4, *8,
COMPLEX*8, *16,
IMPLICIT.

□ RC — ''Ratfor'', a preprocessor that adds rational control structure à la C to FORTRAN.
• Else, for, while, repeat...until statements.
• Symbolic constants.
• File insertion.
• Compound statements.
• Can produce genuine FORTRAN to carry away.

□ Manual — Printed manual for Ratfor.

2.2 Other Algorithmic Languages

□ BAS — An interpreter, similar in style to BASIC, that allows immediate execution of unnumbered statements, or deferred execution of numbered statements.
• Statements include:
comment,

dump,
for...next,
goto,
if...else...fi,
list,
print,
prompt,
return,
run,
save.

- All calculations double precision.
- Recursive function defining and calling.
- Builtin functions include log, exp, sin, cos, atn, int, sqr, abs, rnd.
- Escape to ED for complex program editing.
- Usable as a filter.

□ DC — Programmable reverse Polish desk calculator. Has named storage locations as well as conventional stack for holding integers or programs.

- Unlimited precision decimal arithmetic.
- Appropriate treatment of decimal fractions.
- Arbitrary input and output radices, in particular binary, octal, decimal and hexadecimal.
- Operators include:
  + − * /
  remainder, power, square root,
  load, store, duplicate, clear,
  print, enter program text, execute.
- Usable as a filter.

□ BC — A C-like interface to the desk calculator DC.

- All the capabilities of DC with a high-level syntax.
- Arrays and recursive functions.
- Immediate evaluation of expressions and evaluation of functions upon call.
- Arbitrary precision elementary functions: exp, sin, cos, atan, J_n.
- Go-to-less programming.
- Usable as a filter.

□ Manual — Printed manual for BC.

□ SNO — An interpreter very similar to SNOBOL 3.

- Limitations:
  function definitions are static,
  pattern matches are always anchored,
  no built-in functions.
- Usable as a filter.

□ Manual — Reprint of basic article.

2.3 Macroprocessing

□ M6 — A general purpose macroprocessor.

- Stream-oriented, recognizes macros anywhere in text.
- Integer arithmetic.
- Usable as a filter.

□ Manual Printed manual for M6.

2.4 Compiler-compilers

□ TMG A classical top-down compiler-compiler language. Provides a formalism for syntax-directed translation. Produces driving tables to be loaded with a standard interpreter.
• Resulting compilers can have arbitrary tables kept in paged secondary store.
• Integer arithmetic capability.
• Syntactic function capability (similar to ALGOL 68 metaproductions).

□ Manual Printed manual for the TMG compiler-writing system.

□ YACC An LR(1)-based compiler writing system. During execution of resulting parsers, arbitrary C-language, Ratfor or FORTRAN functions may be called to do code generation or semantic actions.
• BNF syntax specifications.
• Handles precedence relations.
• Accepts formally ambiguous grammars with non-BNF resolution rules.
• Optimizes space taken by driving tables.

□ Manual Printed manual for the YACC compiler-writing system.

3 Word Processing

□ ROFF A typesetting program for terminals. Easy for nontechnical people to learn, and good for most ordinary kinds of documents. Input consists of data lines intermixed with control lines, such as

```
.sp 2      insert two lines of space
.ce        center the next line
```

• Justification of either or both margins.
• Automatic hyphenation.
• Generalized running heads and feet, with even-odd page capability, numbering, etc.
• Definable macros for frequently used control sequences (no substitutable arguments).
• All 4 margins and page size dynamically adjustable.
• Hanging indents and one-line indents.
• Absolute and relative parameter settings.
• Optional legal-style numbering of output lines.
• Multiple file capability.

□ CREF Make cross-reference listings of a collection of files. Each symbol is listed together with file, line number, and text of each line in which it occurs.
• Assembler or C language.
• Gathering or suppressing references to selected symbols.
• Last symbol defined may replace line number.
• Various ways to sort output available.
• Selective print of uniquely occurring symbols.

□ INDEX Make cross-reference indexes of English text.
• Handles lists of specific index terms or excluded terms.
• Handles words hyphenated across lines.
• Understands TROFF and NROFF output, so can gather references according to final pagination.
• Output capabilities like CREF.
• Frequency counts.

□ FORM Form letter generator. Remembers any number of forms and stock phrases such as names and addresses. Output usually intended to be ROFFed.
• Anything that is typed in can be remembered for later use.

• Runs interactively, querying only for those items that are not in its memory.
• Any item may call for the inclusion of other items. For example, full name, address, first name, title, etc., may be separately retrieved from one name key.

□ FED — Editor for the memory used by FORM. Extract any item, turn it over to context editor ED for editing, and put it back when done.
• List names of selected items.
• Print contents of selected item.

□ SORT — Sort or merge ASCII files line-by-line.
• Sort up or down.
• Sort lexicographically or on numeric key.
• Multiple keys located by delimiters or by character position.
• May sort upper case together with lower into dictionary order.
• Usable as a filter.

□ UNIQ — Collapse successive duplicate lines in a file into one line.
• Publishes lines that were originally unique, duplicated, or both.
• May give redundancy count for each line.
• Usable as a filter.

□ TR — Do one-to-one character translation according to an arbitrary code.
• May coalesce selected repeated characters.
• May delete selected characters.
• Usable as a filter.

□ DIFF — Report line changes, additions and deletions necessary to bring two files into agreement.
• May produce an editor script to convert one file into another.

□ COMM — Identify common lines in two sorted files. Output in up to 3 columns shows lines present in first file only, present in both, and/or present in second only.

□ CMP — Compare two files and report disagreeing bytes.

□ GREP — Print all lines in a file that satisfy a pattern of the kind used in the editor ED.
• May print all lines that fail to match.
• May print count of hits.
• Usable as a filter.

□ WC — Count the lines and "words" (blank-separated strings) in a file.
• Usable as a filter.

□ TYPO — Find typographical errors. Statistically analyzes all the words in a text, weeds out several thousand familiar ones, and publishes the rest sorted so that the most improbably spelled ones tend to come to the top of the list.

□ GSI — Simulate Model 37 Teletype facilities on GSI-300, DASI and other Diablo-mechanism terminals.
• Gives half-line and reverse platen motions.
• Approximates Greek letters and other special characters by overstriking.
• Usable as a filter.

□ COL — Canonicalize files with reverse line feeds for one-pass printing.
• Usable as a filter.

4 Novelties

Source code for game-playing programs is not distributed.

□ SPEAK — Driver for Vocal Interface's VOTRAX speech synthesizer. Reads input text and utters it.
- Associative memory allows pronunciation rules for whole words or word fragments to be added, changed, deleted or queried.
- Can use different memories for different languages.
- Usable as a filter to make the output of any other program audible.

□ CHESS — This chess-playing program scored 1-2-1 and 3-0-1 in the 1973 and 1974 Computer Chess Championships.

□ BJ — A blackjack dealer.

□ CUBIC — An accomplished player of 4×4×4 tic-tac-toe.

□ MOO — A fascinating number-guessing game.

□ CAL — Prints a calendar of specified month and year.

□ UNITS — Converts amounts between different scales of measurement. Knows hundreds of units. For example, how many km/sec is a parsec/megayear?

□ TTT — A tic-tac-toe program that learns. It never makes the same mistake twice.

□ QUIZ — Tests your knowledge of Shakespeare, Presidents, capitals, etc.

□ WUMP — Hunt the wumpus, thrilling search in a dangerous cave.

5 Typesetting

This software is distributed separately as an enhancement to UNIX.

5.1 Formatters

High programming skill is required to exploit the formatting capabilities of these programs, although unskilled personnel can easily be trained to enter documents according to canned formats. Terminal-oriented and typesetter-oriented formatters are sufficiently compatible that it is usually possible to define interchangeable formats.

□ NROFF — Advanced typesetting for terminals. Style similar to ROFF, but capable of much more elaborate feats of formatting, at a price in ease of use.
- All ROFF capabilities available or definable.
- Completely definable page format keyed to dynamically planted "interrupts" at specified lines.
- Maintains several separately definable typesetting environments (e.g. one for body text, one for footnotes, and one for unusually elaborate headings).
- Arbitrary number of output pools can be combined at will.
- Macros with substitutable arguments, and macros invocable in mid-line.
- Computation and printing of numerical quantities.
- Conditional execution of macros.
- Tabular layout facility.
- Multicolumn output on terminals capable of reverse line feed, or through the postprocessor COL.
- Usable as a filter

□ Manual — Printed manual for NROFF.

□ TROFF — Advanced phototypesetting for the Graphic Systems System/1. Provides facilities like NROFF, augmented as follows. This Summary was typeset by TROFF.
- Vocabulary of several 102-character fonts (4 simultaneously) in 15 sizes.
- Positions expressible in inches, centimeters, ems, points, machine units or arithmetic combinations thereof.
- Access to character-width computation for unusually difficult layout problems.
- Overstrikes, built-up brackets, horizontal and vertical line drawing.
- Dynamic relative or absolute positioning and size selection, globally or at the character level.
- Terminal output for rough sampling of the product, usually needs a wide platen. Not a substitute for NROFF.
- Usable as a filter.

□ Manuals — Printed manual and tutorial for TROFF.

□ EQN — A mathematical typesetting preprocessor for TROFF. Translates easily readable formulas, either in-line or displayed, into detailed typesetting instructions. Formulas are written in a style like this:

sigma sup 2 ~=~ 1 over N sum from i=1 to N (x sub i - x bar) sup 2

which produces this:

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N} (x_i - \bar{x})^2$$

- Automatic calculation of size changes for subscripts, sub-subscripts, etc.
- Full vocabulary of Greek letters, such as ‘gamma’, ‘GAMMA’.
- Automatic calculation of large bracket sizes.
- Vertical ‘‘piling’’ of formulae for matrices, conditional alternatives, etc.
- Integrals, sums, etc. with arbitrarily complex limits.
- Diacriticals: dots, double dots, hats, bars.
- Easily learned by nonprogrammers and mathematical typists.
- Usable as a filter.

□ Manual — Printed manual for EQN.

□ NEQN — A mathematical typesetting preprocessor for NROFF. Prepares formulas for display on Model 37 Teletypes with half-line functions and 128-character font.
- For Diablo-mechanism terminals, filter output through GSI.
- Same facilities as EQN within graphical capability of terminal.

□ TBL — A preprocessor for NROFF/TROFF that translates simple descriptions of table layouts and contents into detailed typesetting instructions.
- Computes column widths.
- Handles left- and right-justified columns, centered columns and decimal-point alignment.
- Places column titles.

□ MS — A standardized manuscript layout for use with NROFF/TROFF.
- Page numbers and draft dates.
- Cover sheet and title page.
- Automatically numbered subheads.
- Footnotes.
- Single or double column.
- Paragraphing, display and indentation.
- Numbered equations.

5.2 UNIX Programmer's Manual

□ MAN — Print specified manual section on your terminal.

□ Manual — Machine-readable version of the UNIX Programmer's Manual.
- System overview.
- All commands.
- All system calls.
- All subroutines in assembler, C and FORTRAN libraries.
- All devices and other special files.
- Formats of file system and kinds of files known to system software.
- Boot procedures.

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