Pan

PERSONAL COMPUTER

COMPUTER NEWS LIBRARY

LANGUAGE LIBRARY

FUNDAMENTAL FORTH

RICHARD OLNEY & MICHAEL BENSON

Pan/Personal Computer News
Computer Library

Richard Olney and Michael Benson

Fundamental Forth

Pan Books London and Sydney

First published 1985 by Pan Books Ltd,
Cavaye Place, London SW10 9PG
in association with Personal Computer News
9 8 7 6 5 4 3 2 1

ISBN 0 330 28960 8
Photoset by Parker Typesetting Service, Leicester
Printed and bound in Great Britain by
Richard Clay (The Chaucer Press) Ltd, Bungay, Suffolk

Contents

Introduction

Despite massive support from the old computer establishment the BASIC programming language has now been widely discredited at every level. There are various suitable alternatives available for home users, and as the market matures these are becoming increasingly popular. This book is about a powerful computer programming language called Forth. Because of the nature of this language learning about Forth means learning about the way that computers actually operate. This makes it the ideal choice for those who want to learn general computer skills through programming.

The book is divided into the two sections. The first contains a general background to computers and programming languages. It assumes no previous experience. The second section teaches Forth 'at the keyboard' and relies on the reader having access to a standard version of Forth (and of course a computer to run it on!). Chapter 3 includes advice on how to choose a good system.

Forth is a 'living language', which means that you can endlessly extend and improve your system. It also means that there is always more to learn. Even an experienced Forth programmer is constantly experimenting with new techniques and applications. This book can only describe the facilities Forth offers and point to some of the ways in which they might be used. It is only through programming itself that you can really master this unique language.

Section 1: Background

1 About computers

1.1 A brief history

Computing really began when man first started to count, and in this sense our fingers were the world's first computers. These are fairly limited in their application, however, and particularly inconvenient when it comes to storing numbers over a period of time! This has encouraged mankind to develop more efficient methods of dealing with numbers. Some of the most notable of these (leaving aside computers for the moment) are the use of an abacus for performing calculations and paper and ink as a means of long term storage. At the lowest level these are the functions with which a computer is mainly concerned – the storage, retrieval and processing of numerical information.

The first attempts to build automatic calculating machines were prompted by the rise of commerce in the seventeenth century. The most famous of these attempts was by man called Blaise Pascal. Later, in the eighteenth century, J. M. Jacquard built an automatic loom which used perforated cards as a means of storing its instructions. This development laid the foundations for an aspect of computing which is not merely concerned with the processing and storage of numbers, but with control over electronic and mechanical devices. It also provided a guideline for methods by which instructions and information could be fed into the computer itself.

The Analytical Engine designed by Charles Babbage in the nineteenth century is generally accepted as the world's first digital computer, even though its construction was never completed. The basic elements of its design were to correspond almost exactly to those of a modern computer, despite its mechanical rather than electronic basis. Unfortunately Babbage was too far ahead of his time, in much the same way as Leonardo Da Vinci was in designing flying machines, and he lacked the necessary support technology to make his dream a reality. Thus neither he nor his co-worker Ada Lovelace were able to convince those funding the operation of the ultimate merits of their machine, and financial support was withdrawn.

It was not until 75 years after Babbage's death that the first electronic computer emerged in 1946. It was called ENIAC, which stands for Electronic Numeral Integrator and Calculator. This huge machine occupied 3000 cubic feet of space, contained 18000 vacuum tubes (valves), weighed 30 tons and consumed 200 kilowatts of power.

Since ENIAC, important developments in computers have been marked by 'generations'. The table gives a brief description with approximate dates.

Generation	*Dates*	*Description*
First	1945–1954	Valve computers.
Second	1954–1965	Valves replaced by transistors.
Third	1965–today	Integrated circuits replace transistors; containing a number of transistors on the same 'chip' of semiconductor material.
Fourth	1972–	Large Scale Integration or LSI. Huge numbers of electronic components integrated onto a single chip. This has led to complete computers on a single semiconductor device.

You may be wondering by now where Forth fits into all this. Forth is a programming language designed by Charles Moore using an IBM 1130 – a third generation computer. Moore was so impressed by the results of his work that he considered it constituted a fourth generation language, but the 1130 only allowed five character names, so he settled on 'Forth'. As it turned out he could not have chosen a more appropriate name, since the language is perfectly suited for use with modern day microprocessors.

We are now moving towards what has been hailed as the fifth generation in computing. This revolves around machines which can perform many tasks at the same time (parallel processors) and attempts to make computers behave more like human beings (as in Artificial Intelligence – see section 2.3). It has been claimed that these developments spell doom for traditional programming languages, allowing people to communicate with computers using normal everyday conversation. Whether or not this will be the case remains to be seen, but there will always be a need for tools to develop these complex programs and languages – building the interface between the mechanics of the computer and the workings of the human mind.

1.2 Species of computer

The first commereially used computers were monsters called mainframes. These generally have hundreds of users at terminals from which they can communicate with a huge central resource. Because these machines were concerned mainly with the processing of large volumes of information the part of a company responsible for them became known as the data process-

ing or DP department. Clearly such installations required a very large DP department, and sometimes this even led to the formation of a new subsidiary company just to perform this function.

As demands on computers became more sophisticated the traditional mainframe setup began to prove itself less than satisfactory. Integrating the activities of large numbers of users and programmmers can be very complex. General purpose programs designed to fulfil a number of requirements often end up inadequate for any of them. Despite the immense power of mainframes, peak time demands from users can still cause bottlenecks resulting in an unacceptable delay in the computer's 'response time'. Apart from all this the cost of such a computer is well beyond the range of all but the mega-corporations.

The next stage of computer development brought with it smaller, more manageable computers dubbed 'minis'. These might have between one and fifty users, thus catering for the needs of smaller businesses. Large companies often install minicomputers in each of their subsidiaries, linking them together in what is called a network. This kind of arrangement is known as distributed processing. Although the operation of minicomputers tends to follow the pattern of mainframes, the smaller DP departments are able to concentrate on the specific requirements of particular users. Another bonus is that if the machine breaks down far fewer people are affected!

Although some of the minicomputers available are quite small, their installation still requires a considerable investment, both in terms of equipment and staff (not to mention training and consultancy). Computing therefore remained the exclusive right of business, government and universities until the advent of microprocessors in the mid-seventies.

Microprocessor technology brought with it small, cheap machines called microcomputers, which have since found their way into millions of homes throughout the world. It is this type of computer with which this book is concerned. At the time of writing the microcomputer industry is still having growing pains. Early home computers used cassettes to load in programs. This meant that the computer was unable conveniently to store and retrieve volumes of information, which has traditionally been the machine's main function! In fact the only kinds of program which can be run effectively without access to stores of information are games and simulations, which explains the proliferation of such applications.

Now that home users have begun to demand more than just games, cassette storage is being replaced by a more widespread use of disk drives, allowing much faster access to information. Although this demands a rather higher initial investment, it opens the doors to a flood of new software covering a bewildering variety of subjects. It is also good news for Forth – which is completely unworkable using cassette storage.

Microcomputers themselves come in a variety of different forms, rang-

ing from small hand-held devices to powerful multi-user systems. Home computers tend to fall somewhere between these extremes, but may offer quite sophisticated facilities. They can generally talk to one another through networks or be used to control external equipment like robots. Through Forth the full potential of these exciting machines can be realized.

1.3 The main elements of a computer

The main function of a computer is to allow us to store and retrieve large volumes of information (*data*) with ease and to manipulate them at high speed. In order for this to be possible the computer must have a number of attributes; eyes or ears to allow it to receive the data we send, a memory (possibly both long term and short term), a brain with which to process the data, and a voice to tell us the answers. Diagram 1.1 shows the main elements of a computer, the arrows indicating the directions in which information or data is allowed to travel.

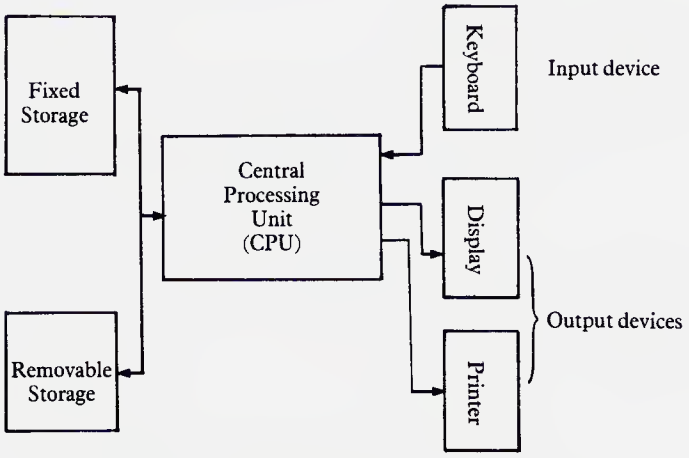


Diagram 1.1. Main elements of a computer

Communication between man and machine takes place through the input and output devices collectively known as *peripherals*. The diagram shows a system using three peripherals; a keyboard for input and two output devices, a display unit (or VDU) and a printer. This is a common enough set-up on small systems, but in practice the processor may be able to communicate with many peripherals of both types. The memory (where data is stored) is shown in two parts. The fixed storage is the computer's own internal memory, known as 'core' on large mainframe computers – a

term rarely applied to smaller machines. The removable storage allows the computer's long term memory to be expanded. It usually consists of disk and/or tape drives through which data may be electronically recorded onto a magnetic surface, and read back at some later point by the CPU. These drives are known as *mass storage* devices and are peripherals capable of both input and output. By the addition of multiple mass storage devices, a computer's immediate memory can be expanded to enormous capacity. They also give the computer the capacity for an almost limitless archival memory, since libraries of tapes and disks may be built up and used in the drive as and when required.

The *central processing unit* or CPU is the computer's 'brain'. Its thought processes are governed by the programs that drive it. Through these programs the CPU monitors its input devices for data, transmits data to its output devices and manages all communication with memory. It also performs any arithmetic necessary. The CPU carries out these tasks at enormous speed so it can sometimes create the illusion of doing many things at the same time, which is not in fact the case. On very large computers the CPU may consist of racks of printed ciruit boards packed with electronic components, whereas on a home computer it is normally a single electronic component called a microprocessor. The principles of operation are, however, much the same.

The computational power of a processor is often gauged in terms of the *data width*. This is the maximum size for one piece of data which can be manipulated in one go. The width of data is measured in *bits* and a bit number is assigned to the processor to indicate its data width. Generally, the higher the bit number of the processor the greater its computational power. Microcomputer systems commonly use either 8-bit or 16-bit processors.

1.4 Communicating with the machine

The computer is an electronic device which communicates by sending and receiving electrical pulses down wires.

Electrical pulses may be used to encode and transmit information over distances. The early telegraph systems used this technique, employing a circuit breaker to transmit messages in the form of mixed long and short pulses called Morse code. In fact computer communications owe a great deal to telegraphy. Thus when we type the letter 'A' at a computer keyboard it sends electrical pulses to the CPU representing the code for that letter. When the computer wants to display an 'A' the appropriate code is sent to the screen which then lights up the correct dot pattern. Internally the computer collects these pulses – storing and manipulating them as electronic numbers. A number which is eight bits wide has space to record a total of eight pulses, and can be stored in a quantity of memory

called a *byte*. Bytes are discussed in the next section, but it is worth noting that eight bits are all that is required for each of the typographic characters to have its own unique code.

As mentioned in the previous section a computer may be connected to a number of peripheral devices capable of input, output or both. Those mentioned so far are the keyboard, disk drive, printer and VDU, but there is in fact an infinite variety of possibilities. Examples of other input devices include bar code readers (used in supermarkets and warehouses to transmit product information to a computer for stock control), light-pens and digitizer pads for transmitting pictorial information in computer graphics; circuit breakers in alarm systems; and traffic censors for a computer controlled traffic light. Output devices include the traffic lights themselves; plotters for drawing; sound synthesizers for musical applications; and machine tools such as lathes in precision engineering. In fact today almost any piece of electro-mechanical equipment can be connected in some way as a peripheral to a computer. Many of these contain processors of their own so that the central processor is monitoring and controlling a whole cluster of 'slave' processors each of which is performing a different task. In this way extremely powerful systems may be built up – providing the necessary programs can be written to drive them.

1.5 The memory

The memory is an essential part of the computer, without which the processor would be extremely limited in its usefulness. Memory was briefly described in section 1.3 in terms of its fixed and removable components, and its actual operation is discussed in the context of Forth programming in Chapter 4. It is, however, worth taking a slightly more detailed look at some of its general characteristics before proceeding with the rest of this book in order to clarify some of the terms used.

A processor has access to two types of memory in which it may store data for later retrieval. Several small memory elements are part of the processor itself. These are called the processor's registers and are typically 8 bits wide on an 8-bit processor and 16 bits wide on a 16-bit processor. They are used as temporary storage for data while the processor is carrying out computations. In addition to the registers the processor has access to a much larger quantity of external memory. This forms the bulk of the fixed memory in diagram 1.1. In order to be able to express exactly how much memory is available to the processor, a standard unit of memory – the *byte* – is used. To give an idea of how much memory a byte is, each character typed in at a word processor keyboard and stored in the memory occupies one byte. A page of typewritten A4, therefore, might occupy 1500–2000 bytes.

In order to appreciate better how all this business of bits, bytes and electrical pulses fits together consider the 'pinball memory' element shown

in diagram 1.2. The memory element consists of a row of eight pinball firing chambers, each of which is loaded with a ball. After the ball in the left-most chamber has been fired it passes over the flip up barrier, and up the ball channel containing the trigger. When the ball passes over the trigger the barrier flips up leaving a record that the ball has passed that way. Thus if someone else has been playing and we come into the room we can tell by a glance at the barriers which balls have been fired. The barriers have 'remembered' it. Each of the flip-up barriers and its trigger mechanisms is equivalent to one bit of memory, and the whole unit is equivalent to one byte. A single bit can record events on one 'channel'. It tells us one of two things, either something happened (a ball passed over the trigger) or nothing happened (no ball passed). All eight channels can be monitored simultaneously so that if we fire a pattern of balls it will be reflected in the state of the barriers afterwards – a barrier being 'high' if a ball passed and 'low' if none passed.

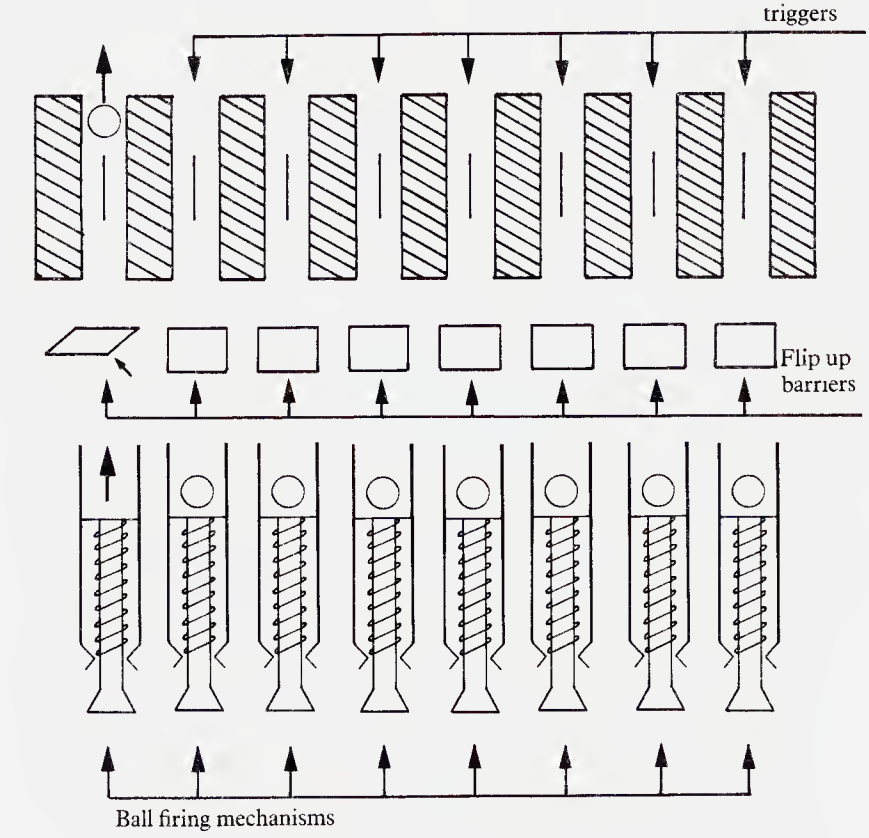


Diagram 1.2. Pinball memory

The electronic memory of a computer operates in a similar manner, the events recorded are electrical signals travelling along wires, one wire for each bit in the cell. If an event occurs the bit stores up an electric charge, if none occurs it does not. The bits are said to be in a high or low state according to whether anything has happened to them. There are a 256 possible bit patterns in a single byte of memory. This allows a byte to be used as an electronic number in the range 0 (all bits low) to 255 (all bits high), and explains how it is possible to encode all the typographic characters including punctuation using only 8 bits.

If a byte holds just one letter of the alphabet then clearly a very large number of bytes would be needed to remember even one chapter of this book. Generally when discussing how much memory is available on a computer system the units Kilobyte and Megabyte are used. A Kilobyte, or 1K , is approximately 1,000 bytes, a megabyte about a million. Why these are approximate is explained in Chapter 7. Thus a computer system with 16 Kilobytes of internal memory is referred to as a 16K machine. A typical home computer might have say 48K or 64K, a large minicomputer perhaps 2 or 3 Megabytes.

The memory discussed above is called 'read/write' memory since it can be altered by the processor as well as read back. This is commonly called RAM (random access memory). We have seen how this operates by storing up electric charge, but what happens to this charge when the computer is turned off? In short it disappears, and the computer 'forgets' everything. It so happens that the programs which drive the computer are held in memory and in forgetting these the computer reverts to a useless pile of electronics. On mainframe computers the power is never turned off, and great precautions are taken to ensure that the power can never go down accidentally. On smaller machines however this approach is completely impractical due to the expense. To get round this problem programs and data essential to the basic operation of the computer are stored on a different kind of memory, which is able to retain its information after the power has been disconnected. In this type of storage the data is actually a permanent part of the circuitry and can never be altered. For this reason it is known as 'read only memory' or ROM. Part of the fixed storage of a computer is always ROM, so when we talk of a 48K machine it should be made clear whether this is total storage or RAM since only the RAM is available for the user's data and programs.

Frequently a computer application will require that information be stored over a long period of time, or require more information than can be held in the computer's internal memory. To accommodate this the data in RAM must be moved somewhere else before the power is turned off. In these cases mass storage devices are used as a long term read/write memory, data being transferred to and from RAM by the processor as needed.

1.6 What can you use computers for?

To begin with computers were used to process and store large amounts of numeric information, perhaps representing financial transactions or legal contracts. Commercial computing has thus tended to use the technology to replace existing manual systems. A filing cabinet and attendant clerk might be replaced by a small database for instance. Although the widespread use of computers in business has transformed office life, their mode of operation is still based on traditional administrative systems, it is only the quantity and type of support personnel required that has changed.

Microprocessors, providing cheap computing power in a convenient package, are transforming the nature of applications. Remember that they need not necessarily be attached to screens or printers to communicate with humans – they can for instance be used to control a robotic arm or a space satellite. Although more traditional applications like spreadsheets and word processors are still very popular amongst microcomputer users, more specialist packages are emerging covering subjects from gardening to graphic design, not to mention the vast number of games. It is reasonable to assume that in ten years' time the variety of software available will equal that of books, and that as a result microcomputers will be as widespread as televisions.

Because of the immense potential for microprocessor applications programming has been transformed from a challenging but essentially monotonous and repetitive task into a highly creative and rewarding pursuit. This has made it appealing just as a hobby even when the programmer has no particular application in mind. Whatever your reason might be for wanting to learn programming, the choice of Forth as a language is one you will never regret.

2 About programming

2.1 What is a computer program?

Although the machine described in Chapter 1 has the potential to operate as a computer, in order for it to do so it must be told exactly what actions to perform. A computer program is a sequence of such actions and when the computer is performing them it is said to be 'executing' the program. In practice all computer systems are executing some program all the while the power is connected. The computer equipment required to execute the programs is collectively referred to as hardware, whilst the programs which make the hardware useful are called software.

The part of the computer responsible for executing programs is the processor, often called the central processing unit or CPU. It has an innate ability to carry out a limited number of operations, which may be combined into sequences to build up more complex functions. The memory of a computer can be viewed as an array of discrete elements which may be accessed individually by the processor. Each element is assigned a number for purposes of identification, and this is called a memory address or simply address. Memory is said to start at address zero. The programs that a computer executes consist of lists of numbers held in memory in consecutive addresses. These numbers represent codes instructing the processor to carry out particular actions. There are a limited number of instructions available for any particular processor, collectively known as the processor's instruction set. The processor begins executing instructions at the start of memory and continues working towards the end of memory. The action of finding the next instruction and executing it is called the instruction cycle, and the efficiency of this process largely determines the overall speed of execution of the programs. In order to keep track of where in memory the next instruction is to be found the processor maintains a counter in an element of internal memory, called the program counter, which is adjusted at each execution of the instruction cycle. Don't worry if all this sounds confusing – it is not necessary to understand the internal workings of the processor to begin writing computer programs!

A computer program in the form just described is called a *machine code* program, since it has been coded into a language which the processor can understand. All programs executed directly by the processor are machine

code programs. In order to produce machine code programs for the processor to execute – without the need to think exclusively in terms of numbers – computer languages are used. These are programs which translate more-or-less day-to-day language instructions from the programmer into the appropriate code for the processor. The use of computer languages is the main topic of this chapter and is discussed in detail in the following sections.

In order to be even remotely usable a computer must have a portion of its memory permanently loaded with a set of machine code programs which enable communication with the human users, providing the ability to read keystrokes from a keyboard and display things on the screen for instance. These programs are collectively called the system software or *operating system*. In order to be permanent they must be programmed into special memory devices called *Read Only Memory* (ROM). When data is programmed into ROM it effectively becomes part of the electronic circuitry and cannot afterwards be altered or removed. It remains there even when the computer is turned off. Since these programs are permanently assembled into the machine as part of a hardware device, the term *firmware* has been used to distinguish them from non-permanent pieces of software.

In addition to ROM, the computer has a certain amount of read/write memory known as RAM (for Random Access Memory) which can be altered by the processor during program execution. This type of memory is called 'volatile memory' – since all information it contains is lost when the power is turned off. The system's RAM may be used to hold programs for the processor to execute. These must be loaded into the memory either from the keyboard or more usually from a mass storage device such as a disk drive or tape machine. The use of such a device allows much larger programs to be placed in memory without using expensive ROM and also allows the same general purpose piece of hardware to be used for a wide variety of specific applications.

Very often on a disk based system the major part of the system software is held on disk, while firmware contains only those programs required to establish communication between the processor and all the equipment connected to it. When power to the machine is turned on the firmware simply sets up the communications and starts loading up the RAM from disk. Once this is done the processor executes one of the programs in RAM. The firmware which gets a computer started in this way is called a *bootstrap* program.

Typically, system software loaded from disk contains a number of general utility programs which may be invoked by the user typing in a command at the keyboard. These programs allow the user to deal more easily with the routine tasks of computing such as disk copying, loading and running programs etc. It is also possible that the user wishes to write programs, in which case a further set of utility programs must be

employed, which are dedicated to the task of generating the neeessary machine code.

2.2 Levels of programming

The various programs described in the previous section clearly all have to be written at some point. This means that someone has to decide what the program should do, find an appropriate sequence of processor instructions to achieve that end, and finally get the appropriate codes into the correct place in memory. The initial specification of the program in the programmer's native tongue may have consisted of very few statements. The processor, however, only performs very simple functions such as adding two numbers together. It may therefore take a very large number of processor instructions to perform even a trivial task. The relationship between a program's specification and the actual computer activity is a question of levels. The task is first specified by a few 'high level' statements each of which will correspond to a large number of 'low level' processor instructions. Writing the program may be thought of as a process of successive translations from native language down to processor instruction codes. Over the years a large number of programming languages and utilities have become available to provide short cuts in this translation process.

The first level of compromise between man and machine came with the provision of *assembly languages*. An assembly language program consists of a sequence of statements in text form, which are to be translated into machine code. The text itself is referred to as the source code, and may reside on disk, in RAM, or simply hand written on paper. The statements consist of short mnemonics designed to reflect in some way the operation which the processor will perform. There is one mnemonic for each of the processor's instructions. These will be mixed with other statements and numbers which refer to the data on which the instructions are to operate. The process of translating the source code into a machine code program is *program assembly* and the result is called an *object code* program.

The task of assembly may be performed manually simply by looking up the appropriate codes in a reference book, but that still leaves the task of loading the object code into RAM. More usually an assembler program is used to produce the object code automatically. To load an object code program into RAM a further program called a loader is used. The initial assembly language source code is normally produced using a text editing program and saved onto disk. This is then assembled and the object code loaded into the correct place in RAM. Any good assembler should perform all these tasks and a good few more with relative ease.

Assembly language is known as a low level language because it deals directly with machine instructions. Each different type of processor has its

own specific assembly language, so that source code written for one cannot be used to generate object code for another without employing a specially designed 'cross-assembler'. Another disadvantage of programming in assembly language is that because large numbers of machine instructions may be required to perform a task, the source code tends to be very long-winded. Furthermore since the whole program is described in terms of machine instructions, rather than in terms of the particular application, it is easy to lose sight of what a program was supposed to be doing when it comes to fixing the inevitable faults. This difficulty can be overcome to some extent by extensive annotation of the program, but this produces even bulkier source code for the programmer to plough through when tracing faults. The use of assemblers has, however, allowed other higher level languages to be written in order to achieve a more concise notation.

Programming in a high level language allows program statements to specify more complex operations of a computer application in a readable language, without direct reference to the actual machine instructions that will eventually be performed. The translation of the high level source code into object code is done using a compiler. The high level language statements do not relate directly to particular machine operations, but each will be translated into a sequence of many instructions. This leads to far fewer statements in the source code and enables more complex programs to be written and tested. The high level language may then be used to write other even higher level languages and program generators, so that ever more complex tasks may be specified to the computer in a reasonably concise form.

2.3 Languages

We have seen that different languages are used at various levels of programming. This is not the only reason for differences between programming languages. As computers have developed a vast selection of languages has come into existence. At the lowest level this is because each new processor understands a unique set of instructions, but languages have also been developed to handle certain sorts of application or be geared towards particular kinds of computer equipment.

The best example of a computer language designed for use in a specific application area is COBOL, which stands for COmmon Business Orientated Language. As you might expect this is used almost entirely for commercial applications. The sort of functions which Cobol provides are particularly suitable for the storage, retrieval and simple processing of large volumes of information.

Languages such as COBOL are perfect for large sophisticated computer installations, where programmers are protected from the actual operation of the computer so that they can concentrate on churning out volumes of

code. As far as microcomputers are concerned, however, they have two significant disadvantages. One is that they tend to use a fair bit of memory – a resource that is still relatively limited on most micros (though this may soon change!) More importantly, they give very little direct control over the machine, tending to impose their own features onto applications. Since a microcomputer is generally entirely under the control of a single user, a programmer should expect total control over all its facilities.

Another way in which programming languages are seen to differ is the ease with which they can be learnt and used. BASIC, for instance, was specifically designed for use by a beginner with little or no knowledge of computers. In this case the general approach is to present the potential programmer with a small set of simple functions. Each program then consists of a list of numbered lines containing these functions.

Whether or not BASIC is easy to learn is a matter of opinion, but one thing is sure – it is very difficult to use. An analogy with natural human language explains why this should be the case. If, for intance, Russian consisted of only one hundred words, it would be very easy to learn all of them by heart. The problem would come when we actually wanted to say something – being restricted to such a small vocabulary! Another difficulty with BASIC is that in general only one program can reside in the machine at a time. This means that for any non-trivial program the list of instructions becomes very long, and eventually completely unmanageable. The result of all this is that even though BASIC is provided on nearly all home computers it is rarely used for professional software development. Where it is used much of the work may be done by machine code routines, with BASIC providing just the outer level calling sequence (the next section of this chapter looks at this in more detail).

One feature of a language which is considered particularly important by software developers is its portability. This simply means how easily it can be made to run on many different types of computer. The degree of portability of a programming language depends upon the number of machines on which it has been implemented, and on the number of different 'dialects' (i.e. variations) of the language which exist. BASIC, for instance, is used on a vast range of machines, but its overall portability is limited because of the many different dialects used.

Typically the choice of language to be used in a large computer installation or software house depends almost entirely on the availability of qualified programmers. For this reason the well established institutionalized languages, having already attracted considerable investment as far as training is concerned, tend to be self perpetuating. This highlights the fact that traditional high level languages often bear little relationship to the way the computer itself operates. Expert COBOL or BASIC programmers may have little or no knowledge of computers *per se*, and their skills might consequently be restricted in their application.

For the home user the choice of languages presents quite different problems. On the one hand the language needs to be relatively easy to learn, but it must also allow the programmer to achieve serious results without spending months on development. It also helps if it encourages a general awareness of the way the computer actually works.

Many of those who have rushed out over the past few years to furnish thmselves with mirocomputers have assumed that BASIC was the only way to program these beasts. The result has undoubtedly been many frustrating hours spent poring over huge ungainly program listings, followed by the eventual acceptance of failure – normally interpreted as personal incompetence rather than a failing of the language itself. In the next chapter we shall see why Forth offers an attractive and accessible alternative to this situation.

One other area of software which we should mention in this section is termed *Artificial Intelligence* (AI). Many different definitions have been given to this phrase. In general it involves making computers appear to behave like human beings. This means that they must exhibit qualities normally associated with thinking or intelligence. Some have described this field as a sort of meta-computing, suggesting that it covers those functions computers cannot at present perform, such that once a problem posed by artificial intelligence has been solved it becomes a part of computer science.

Artifical intelligence is a synthesis of computer science and psychology which is still at a very primitive stage. Like any other area of computing, however, its adherents have a pet language which they consider particularly suitable for the problem at hand, in this case Lisp. Lisp is based on a type of programming called list processing, which is literally the manipulation of lists of words and numbers. Similar facilities are offered by the language Logo, which is particularly suitable for children and beginners.

One of the facets of artificial intelligence which is being increasingly applied to microcomputer applications is natural language processing, allowing the user to converse with the computer in normal conversation. Note that list processing is appropriate here since sentences are literally lists of words. Many of the more sophisticated AI techniques, however, make heavy demands on computer resources, and so are still impractical as far as contemporary microcomputers are concerned.

2.4 Compilers and interpreters

In terms of operation there are two broad categories of high level language. Those which are compiled and those which are interpreted. A *compiled* language is one which uses source code to produce machine object code, which is later executed directly by the processor. An *interpreted* language

does not produce object code, but translates statements in the source directly and executes built in functions to achieve the desired effect. The interpreter does this translation while the applications program is running, and thus necessarily executes more slowly than the equivalent compiled program. Most small microcomputer systems come with a built in language interpreter, normally some dialect of BASIC. The reason that interpreters rather than compilers are used is that they are much easier to develop and are consequently less expensive.

A compiled program consists of actual machine code to be executed directly by the processor without the need of further assistance from the compiler, hence it does not carry the same speed penalty as an interpreted language. The translation is said to take place at *compile-time* (while the program is compiling) rather than at *run-time* (while the program is executing). The object code produced, however, is normally less efficient than that produced by an assembly language program, and at times this may become critical. To accommodate this situation most compilers allow for the incorporation of assembly language *subroutines* into the object code of the high level program. A subroutine is a small general purpose piece of code which may be executed repeatedly by one program, or used by many different programs. The inclusion of assembler subroutines is frequently achieved by writing them separately using the assembler and then incorporating them into the high level program by means of a utility program called a linker. The linker may be either a separate program or an integral part of the compiler. It is normally invoked by the inclusion of statements in the high level source code known as compiler directives. These statements are not compiled into object code but direct the compiler program to perform some task at compile time, such as invoking the linker.

In addition to the use of linkers, some kind of subroutine library facility is useful in a compiler. This allows the programmer to accumulate named subroutines in an organized fashion so that they may be accessed directly by the compiler. They may be either assembly language or high level, and the facility should allow the routines to be linked in to any new source program. This allows later source code to be much more concise since only the name of the routine need be included with a compiler directive rather than all the program statements of the routine. The use of this type of facility can greatly speed the development of applications programs, especially as more comprehensive programming resources are accumulated.

If you have found all this a little confusing – don't panic. Because Forth is literally just a library of subroutines special libraries are unnecessary. Similarly since Forth and assembly language programs can be mixed quite freely there is no need to worry about linkers or separate assemblers. As we shall explain in the next chapter these are just some of the ways Forth integrates and simplifies the various elements of a microcomputer system.

2.5 Application design

In traditional computing the development of applications has been given two distinct phases, with different skills (and hence personnel) required for each one. The first phase is the analysis of a real life problem (such as a company's stock control procedures) to decide where and how the computer fits in. The problem is described with reference to the computer's prospective role. This description is then used by the programmer to produce actual code. This job of systems analysis is, in fact, generally considered more prestigious than programming itself.

Smaller computer installations have blurred the distinction between systems analysis and programming, so that both functions may be performed by a single individual, called a programmer-analyst. Nevertheless a great deal of attention is paid to the design stage of an application.

Because the home computer industry has tended to present programming as an isolated activity many amateur programmers give far too little thought to the pre-programming phase of application development. It is essential that the specific aims and requirements of an application be analysed into a general plan of action before coding itself begins. It is worth giving some thought at this point as to what form such a task might take, since it must precede even the most elementary programming.

A microprocessor performs a long series of very simple tasks extremely quickly. This gives the illusion of it performing quite complex tasks at a satisfactory speed. The actual performance depends upon the processor itself, the programming language used, and the complexity of the task. The main point is that in order to describe a complex task to a computer it must invariably be split into a sequence of much simpler functions.

We shall see later how Forth encourages this process. You should always be aware, however, of the importance of good application design. Never begin actually to code a program until you are sure you have a clear idea of exactly what you want the computer to do. To illustrate how this might work diagram 2.1 shows how the simple task of making instant coffee might be analysed, using a device known as a flowchart.

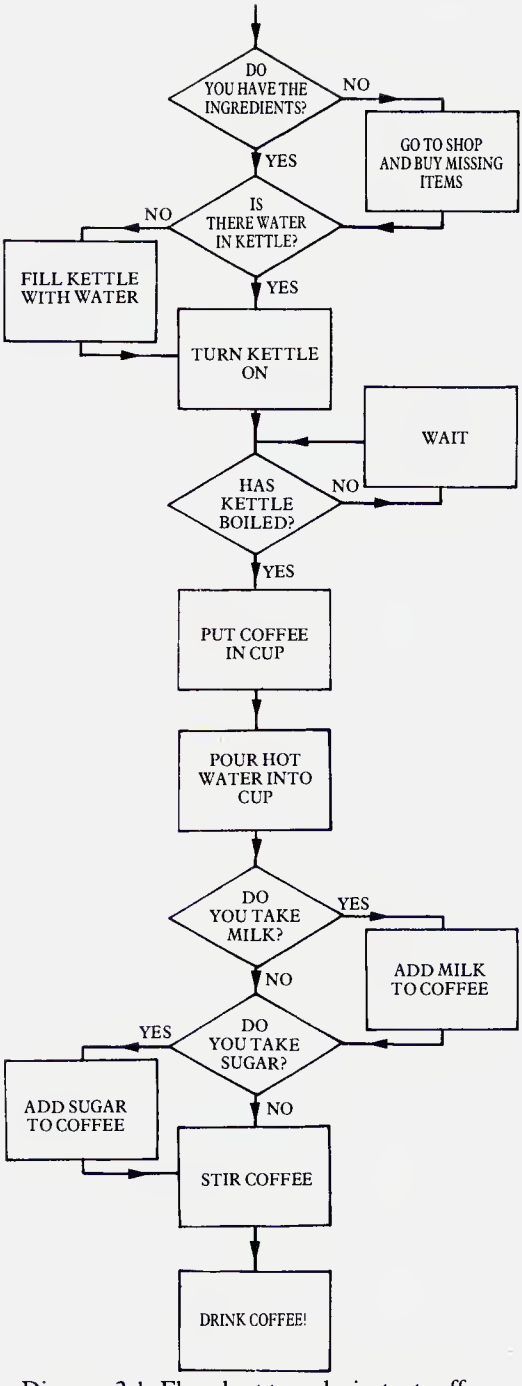


Diagram 2.1. Flowchart to make instant coffee

A technique commonly used by Forth programmers at the design stage attempts to present the main elements of a task in a form known as pseudo-code. This is sort of cross between English and Forth program code. The pseudo-code for our coffee making task might look like this:

```
HAVE-INGREDIENTS?  NOT IF BUY-INGREDIENTS THEN
WATER-IN-KETTLE?  NOT IF FILL-KETTLE THEN
TURN-KETTLE-ON
BEGIN BOILED? UNTIL
COFFEE>CUP
WATER>CUP
MILK? IF ADD-MILK THEN
SUGAR? IF ADD-SUGAR THEN
STIR-COFFEE
DRINK-COFFEE
```

As you will see, one of the beauties of Forth is that the final program of an application looks almost exactly like the pseudo code shown above. If you can make any sense of this list of instructions you are already well on the way to being a Forth programmer

2.6 Testing and debugging

'Bug' is a word so commonly used by computer programmers that it is rapidly becoming a part of everyday conversation. It refers to a programming error which has caused some unexpected (and usually undesirable) result. A simple fact, that you may as well come to terms with right now, is that hardly any programs work perfectly the first time. Even the most skilful programmers spend a very significant proportion of their time testing and 'debugging' their programs.

Bugs do, of course, vary in their seriousness. Sometimes they cause the machine to cease functioning altogether. This is known as a system crash and can often only be remedied by turning the machine off and on again. Because Forth allows the programmer total control over the computer it is easy for a beginner to cause a crash of this kind. Do not be put off, the seriousness of the condition caused by a programming error in no way relates to the gravity of the error itself.

Because it is very hard to imagine beforehand exactly how an application might look, programs always need unforeseen modifications during final testing. This may be to correct bugs, for performance tuning or just for cosmetic reasons.

If it is vital that an application is bug-free before it is used it will often be subjected to a process known as 'destructive testing'. As you might imagine this means trying every possible way to cause an error. It makes

the (generally correct) assumption that if the program is to be used by a large number of people then eventually everything that possibly can go wrong will do so! Unfortunately even the most rigorous testing will often overlook that million-to-one chance condition, leaving an obscure bug lurking somewhere in the code. For this reason one of the cardinal rules of programming is to make all programs as simple as possible – debugging a complex program a year after it was written can be a daunting task!

Even if you are writing programs solely for your own use considerable effort needs to be put into initial testing, though some bugs can be corrected as and when they start causing problems. Diagram 2.2 shows a complete program development cycle. Note that the actual act of coding is only one element of the cycle.

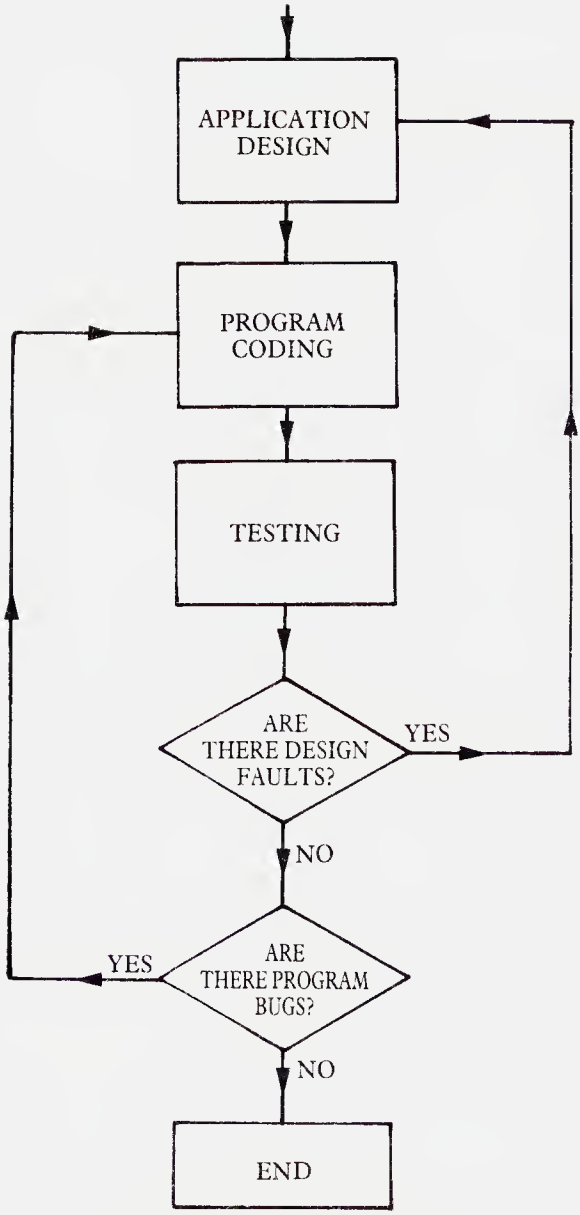


Diagram 2.2. Program development cycle

3 About Forth

3.1 How is Forth different?

Forth differs from other microcomputer languages in that it offers a complete integrated development environment. A good Forth is at once a compiler, interpreter, operating system, low level language and high level language, leading to immense flexibility. It is fast, with execution speeds up to ten times faster than BASIC, yet the programs can take up less memory than machine code! The complete control over the machine which it offers means that no application is beyond its capabilities.

Like more traditional languages Forth begins life as a selection of named functions. These are known as *words*, and the original set of them is called the 'nucleus' or 'kernel'. Using a language like BASIC generally means that only one program can be resident in memory at a time, and that each program must be defined entirely in terms of the reserved words supplied. This results in long program listings which can be impossible to follow, and whose overall structure is often chaotic. Not so Forth ! The essence of Forth is short highly structured programs. By structured we mean here that the organization of the source code is closely related to the actual task it represents – though as you will see the term has a much greater significance with respect to programming itself.

Forth allows a virtually unlimited number of programs to co-exist on the machine. Each of these programs becomes a part of the language just like the words in the nucleus, and can itself be used in other programs. Forth programming is thus a process of successively increasing the power of the language until a complex task can be defined in terms of a small number of powerful functions. By carefully choosing program names so that they reflect their function high level Forth programs can be made to look almost like English (or any other language come to that!). We will be looking more closely at how this works in section 3.3.

Earlier we said that Forth was a compiler and an interpreter. This means that as well as being used within other programs, each Forth word can also be used interactively from the keyboard. The elements of any program can thus be run one by one, and problems quickly isolated. Testing, editing and recompiling programs is remarkably quick and easy on a good Forth system, since extensive applications containing many different programs can be compiled in only a few minutes.

Although Forth is very fast it still runs considerably slower than the equivalent machine code. This is no problem, since, if necessary, routines can be defined using an assembler exactly as if they were Forth words, and subsequently they can be used freely in programs. In practice, however, this is only done occasionally with extremely time-critical routines and will not be discussed in any depth in this book.

As well as being flexible and extensible, Forth is above all accessible. This means that every aspect of the language is open to change by the programmer. A good Forth system can be reconfigured to create completely new programming environments. Although it does not provide any high level application-specific functions, with careful planning any programmer can develop a powerful set of his or her own, regardless of the specific nature of their requirements. All this combines to make Forth the ideal development tool for any microcomputer application.

3.2 Drawbacks and limitations

Having sung Forth's praises throughout the previous section it seems only fair to offer a few words of warning about some of the potential pitfalls. You may have noticed that the phrase 'a good Forth' has cropped up several times already in this chapter. This implies that there is such a thing as a bad Forth system, and indeed this is very much the case. Bad Forth compilers are very easy to write, and there are a great many of them around, especially for the smaller home computers. To be fair some of these machines are simply not capable of supporting a very good Forth for reasons we will discuss shortly. Too frequently, however, it is simply down to a complete lack of appreciation in both the supplier and the potential buyer of what a Forth system really should look like. The last section of this chapter outlines the essential features you should look for when buying a new system.

The use of cassettes has conspired to give Forth a bad name amongst home users because it is quite simply not designed for use with such devices. Your system must include at least one disk drive if you are hoping to undertake any serious Forth programming. Fortunately the use of cassettes as removable storage is now dying out, with a consequent rise in the popularity of Forth. Another factor which has adversely affected Forth implementations on home machines is the widespread use of the 6502 processor. For various reasons this processor is particularly inappropriate for running Forth, though reasonable implementations do exist.

The complete control over the machine and lack of error checking provided by Forth can be alarming to a beginner. Invariably mistakes are made which result in a complete system crash, and to an inexperienced user the code responsible can seem impossible to trace. This problem soon passes as the possible sources of such errors become more familiar.

Some low level Forth words may seem strange at first, having odd single-character names. A good example is the word ! – which stores a value in memory. These can make source code look completely unreadable at first glance. The trick is to learn to pronounce such words by a more descriptive name; a Forth programmer will naturally think of the word 'store' upon encountering an exclamation mark. As with any language (computer or otherwise) it is the significance or meaning with which a word is naturally imbued that counts, not its appearance. Another thing to remember is that any Forth function can be redefined or renamed, so that if desired a word called **STORE** could easily be added with the function of !.

Finally, the approach to program development demanded by Forth is dramatically different from that of languages like BASIC. It demands much more attention to application design, and a deeper analysis of the problem at hand. This means that experienced BASIC programmers might actually find Forth more difficult to master than a complete computer novice would, since the former will probably attempt to impose inappropriate preconceptions. The effort of learning is well worthwhile, however, since it opens up a whole new world of programmming freedom.

3.3 Forth words

We have already mentioned that Forth is composed of a large selection of words, and that programming involves progressively combining these to produce new words of increased functional power. To illustrate this let us take another look at the coffee making task described in section 2.4. The first line of our pseudo-code reads:

HAVE-INGREDIENTS? NOT IF BUY-INGREDIENTS THEN

Clearly the various words involved must have some method of communicating with one another. **HAVE-INGREDIENTS?** decides whether or not the appropriate ingredients for making coffee are available, and communicates the results of that decision to **NOT**. The decision is reversed by **NOT** and transmitted to **IF** which only allows **BUY-INGREDIENTS** to execute if the answer is yes (as in, yes we have no ingredients!). We will be looking at the actual way in which Forth words communicate with one another in the next section. For the present purposes we shall allow words to communicate the results of decisions only.

The following is an imaginary set of words which make up the language 'Cofforth'. We shall combine these words into further words to produce the high level functions in our pseudo-code program. Where a word leaves the result of a decision for use by another word its name is followed by (---answer). If a word expects to use the result of a decision left by another word then its name is followed by (answer---).

```
OPEN-CUPBOARD
Opens the cupboard door.

LOOK-INSIDE
Looks inside the cupboard and lists the contents.

AVAILABLE? ( ---answer)
Checks the list of cupboard contents for coffee
ingredients.

CLOSE-CUPBOARD
Closes cupboard door.

NOT ( answer---answer)
Reverses the decision received. ie yes becomes
no and vice-versa.

IF ( answer---)
If the decision received is 'yes' then all functions
between IF and THEN are executed, otherwise they are
not.

MAKE-SHOPPING-LIST
List those items not already available.

WALK-TO-SHOPS
Go to local shop.

BUY-ITEMS
Purchase the goods on the list.

GO-HOME
Return home.
```

The function **HAVE-INGREDIENTS?** can now be defined as follows:

```
HAVE-INGREDIENTS? :  OPEN-CUPBOARD
                     LOOK-INSIDE
                     AVAILABLE?
                     CLOSE-CUPBOARD
```

Notice that the decision left by **AVAILABLE?** is not used by **CLOSE-CUPBOARD** and so it is still present when **HAVE-INGREDIENTS?** ends. Similarly the word **BUY-INGREDIENTS** could be defined:

```
BUY-INGREDIENTS :  MAKE-SHOPPING-LIST
                   WALK-TO-SHOPS
                   BUY-ITEMS
                   GO-HOME
```

We can now give a name to our line of pseudo-code and make the entire thing a new word called **ASSEMBLE** which assembles the ingredients necessary to make the coffee:

```
ASSEMBLE : HAVE-INGREDIENTS? NOT
           IF BUY-INGREDIENTS THEN
```

We will be looking more closely into how Forth words are actually created in Chapter 5.

3.4 The stack

In the previous section we saw how Forth words might be combined into programs. We decided that in order for this to work the words must have some way of communicating with one another. There are several ways in which this can be achieved, but by far the most important is the Forth *stack*. A stack is like a pile of numbers, arranged so that any numbers added go onto the top of the pile, and only the very topmost number can be removed. This arrangement is called 'last in first out' (LIFO). The use of a stack is by no means confined to Forth, but it is a key concept which must be understood before embarking on any Forth programming.

Whenever a number is used in Forth it is placed on the top of the stack, to be subsequently retrieved by the word that uses it. This means that in calculations, for instance, the numbers involved must be placed on the stack before the relevant operator is executed. Consider the following:

```
2 + 3
```

Although this is the way we are used to writing arithmetic expressions, if you think about the way they are mentally evaluated it becomes apparent that no actual addition can be performed until both numbers have been read. If you are not convinced try covering up the 3 with a piece of paper and see if the remaining expression makes any sense! Because of its use of the stack Forth notation, although unfamiliar to begin with, is very close to the way we actually deal with numbers, so that instead of the expression above we would write:

```
2 3 +
```

This would have the following effect on the stack:

```
2      The number 2 is placed
       on top of the stack.
```

3 The number 3 is placed on the top of the stack. The number 2 thus becomes the second stack item.

\+ Both numbers are taken off the stack, added together, and the result (5) is placed on the stack.

The notation used in Forth is called 'reverse Polish', but it should be stressed that this is entirely the result of the use of a stack – not just an arbitrary rule of syntax. The key thing to remember is that any numbers which a word uses must be on the stack before the word is executed. The arithmetic operators +, −, / and * (for multiply) are Forth words just like any other and thus each of them expects two items on the stack, which it will replace with a result. We will be looking at the stack and Forth arithmetic in much greater depth later on. For the moment, here are some examples of expressions in standard ('infix') notation translated into Forth.

INFIX	FORTH
10 * 4	10 4 *
5 + 2 + 8	5 2 + 8 + or 5 2 8 + +
10 * (2 + 4)	2 4 + 10 * or 10 2 4 + *
(18 − 2) / 8	18 2 − 8 /

Taking the last of these the effect on the stack would be:

18 The number 18 is placed on the top of the stack.

2 The number 2 is placed on the top of the stack. The number 18 now becomes the second stack item.

− The numbers 2 and 18 are taken off the stack, 2 is subtracted from 18, and the result (16) is placed on the top of the stack.

8 The number 8 is placed on the top of the stack. The number 16 left by – becomes the second stack item.

/ The numbers 16 and 8 are taken from the stack, 16 is divided by 8, and the result (2) is placed on the top of the stack.

3.5 How to choose a system

There are four main dialects of Forth currently in use. FIG-Forth is based on guidelines developed by the Forth Interest Group, whilst Forth-79 and Forth-83 were prescribed by the Forth Standards Team. Full glossaries covering each of them are included in the appendices. These three standards are in the public domain, that is there is no copyright on producing such a system. Conformity to one of the standards is thus in no sense an expression of quality. PolyForth is a propriety product of Forth Inc. in California. Their systems are generally of an extremely high quality, though well beyond the price range of most home users. In practice many Forth systems are a compromise between the various standards, and most have their own eccentricities. As long as the system is well documented, however, you should have no problem in coming to terms with these.

As we pointed out in section 3.2, there are a great many poor Forth implementations for home computers which can easily persuade an inexperienced user that the language itself is unworkable. In addition to this, Forth is no fun using cassette storage and at least one disk drive is essential if you are really to come to grips with the language. Indeed good disk handling is an essential feature of a good Forth system. For this reason you should check that the Forth word BLOCK is implemented before buying any system (see Chapter 10). This word is fundamental to Forth's disk handling. Systems which do not implement it tend to be too bound up with the machine's operating system (or worse, have been designed for cassette!), and have often been developed by someone with little experience of Forth programming.

A good Forth should include a source editor and a full mnemonic assembler. There are no standards as far as editors are concerned, but in time most of them can be adapted to suit your requirements. It is usual for a Forth system to include a large selection of extensions and utilities as source. These serve both as example programs and as general purpose routines for use in your own applications. They also demonstrate that the system is usable, since it has actually been used to develop programs,

which is reassuring! Disk management, debugging aids and printer support are amongst the most useful extensions you might look for.

If your computer runs one of the standard operating systems like CP/M or MS-DOS you may find that some Forths run under the operating system whilst others are 'native'. Native systems use their own input/output routines and thus do not require that the operating system be loaded in order to run Forth. They tend to be rather simpler to use, if only because you do not have to come to terms with the operating system as well as Forth, and they generally run somewhat faster. Because native systems do not use the operating system, however, they may not keep pace with changes in hardware.

As with any other language the quality of documentation is important when choosing a system. It should take the form of some introductory and general material, a full Forth memory map (see section 4.3) with details of all the important locations, and a comprehensive glossary much like the one at the end of this book.

Finally the quality of a Forth system is, of course, bound to be reflected in its price. To some extent your requirements will depend upon your intended use of Forth. If you are planning to use it for professional programming you should try to explain what you want to do in as much detail as possible to any potential supplier, since there are likely to be extensions available – possibly at extra cost – which will make things easier for you.

Section 2:
At the keyboard

The rest of this book assumes that you are kitted out with a computer running some standard version of Forth. References are made to Forth '79, Forth '83, FIG-Forth and PolyForth so that it doesn't matter which implementation you are using so long as it is not unacceptably non-standard.

The manual that came with your Forth should include full instructions on getting the language up and running, and you must follow these carefully. You will need to equip yourself with at least one spare floppy disk (assuming you have a disk drive) to keep your work on.

When you load Forth you will generally be presented with some kind of title or menu and the text cursor will appear as a flashing underline or box underneath this. It is at the position of the text cursor that all characters typed in at the keyboard will appear. Try keying in HELLO and note the position of the characters. At this point although the word has appeared on the screen it has not yet been sent to the computer itself. To do this you must press the key marked <RETURN> or <ENTER>. Remember that you will always have to press this key at the end of any text you enter before the computer will respond to it. We will use the symbol <RETURN> to indicate where this should be used.

If you typed in:

HELLO <RETURN>

Forth will have responded by echoing the word followed by a question mark, so the line will now look like this:

HELLO HELLO ?

This means that Forth does not yet understand the word HELLO. As you try the examples in this book you will find yourself making inevitable typing errors, which may sometimes result in odd messages. If this happens you should keep trying until the desired result occurs and Forth responds with 'ok' which means it has understood your request and acted on it. Try keying in:

PAD <RETURN>

and you should find that the 'ok' appears immediately the return key is pressed (don't worry about what **PAD** means for the moment). Now key in:

10 <RETURN>

Forth again responds with 'ok', although nothing appears to have happened. What has in fact happened is that the number 10 has been put on the top of the stack. It can be retrieved by typing:

. <RETURN>

Whenever a number is keyed in it is always placed on the top of the stack. When you key something in, Forth first checks whether it is an executable word (i.e. whether it is in the 'dictionary'). If it is not, then Forth tries to convert it to a number. Any string (delimited by a space) that can neither be found in the dictionary nor interpreted as a number is echoed on the screen with a question mark.

Forth is an interactive language, which means that all Forth words can be tried out simply by keying them in. It is essential to experiment with new words as you come across them until you are completely happy with the way they work. Only by using Forth can you ever hope to really understand it.

Occasionally if you make a particularly fatal error your machine may cease to accept any input from the keyboard, or it may develop other chaotic symptoms. This effect is known as a 'system crash' and is familiar to all Forth programmers. It means that you will have to turn off your computer and reload Forth from the beginning.

Finally bear in mind that this book is designed to complement – not replace – the documentation that came with your Forth system. As Forth words and concepts are introduced you should find out what the documentation that comes with your system has to say about them. It may be that certain words have not been implemented or behave in a non-standard fashion. Until you know otherwise you should assume that words operate in the way described in your user manual as opposed to this book.

4 Mapping your memory

4.1 How memory works

The previous chapters have discussed computer memory in general terms from a number of different angles. The concepts of bytes, bits, and addresses have also been introduced with little explanation as to how they all fit together. In this chapter the use of memory is examined more closely and some simple Forth words are introduced. It is recommended that the reader experiment with these words at the keyboard of a Forth system, within the restrictions outlined, for only by doing so will any practical appreciation of computer use of memory be acquired. Some of this chapter may seem confusing to those unfamiliar with computers; don't worry, it will all become clear as you gain experience in Forth programming.

In Chapter 1 memory was described as consisting of a large number of discrete elements called bytes, each being 8 bits wide and capable of storing a number in the range 0–255. It was also stated, in Chapter 2, that for purposes of identification each byte is assigned a number called an address. This warrants some clarification. The relationship between the address of a byte and the value it contains (its data) may be thought of as being analagous to a bank's safety deposit box system. Each of the safety deposit boxes in the bank has its own unique number, which must be produced if we are to gain access to the box. The box number is equivalent to the address, the box to the byte element and the valuables inside to the data contained within the byte. This analogy is limited but fairly useful. We imagine the memory as being a number of safety deposit boxes arranged adjacent to one another. The boxes are not actually numbered but we know that the box at one end is number 0 and that therefore the one at the opposite end is the last address. If we wish to examine the contents of box 10, we must open the door of the box which is 10 along from box 0. In practice the computer plays bank manager and all we need to do is to specify the box number and whether we wish to make a deposit, a withdrawal or merely gloat over the contents for a while. Here are two Forth words which allow the contents of any byte of memory to be examined from the keyboard. Note that the words enclosed in brackets are just comments which represent the effect of the word on the stack. Those to the left of the dashes indicate the state of the stack before execution of the word and those to the right the state after.

C@ (address---data)

'C-fetch'. Takes the address given on the stack and returns the contents of that byte.

. (data---)

'Dot'. Takes the byte data from the stack and displays it on the screen.

C@ may be used to retrieve the byte contents of any memory location by first specifying the address number and then typing C@. The desired address may be placed on the stack ready for C@ to find simply by typing it in at the keyboard before keying in C@, e.g. typing:

100 C@ . <RETURN>

will display the contents of address 100. Ensure that a space is left between each of the words typed, since the Forth interpreter needs spaces to tell where one word stops and another begins.

The number displayed by C@ . will always lie in the range 0–255, since as we have said there are only 256 possible high/low bit patterns using byte width memory. Clearly it would be extremely limiting if we were always confined to this range, but before we look at how larger numbers may be accommodated let us take a closer look at how the numbers are constructed from bit patterns.

One of the simplest and most common computations is counting. A computer may use a byte of memory as a digital counter just like a mileage counter in an automobile. Each of the bits in the byte operates as a digit in the counter but instead of the usual values 0–9 each may only have one of two values: 0 or 1. A 1 corresponds to a high state of the bit, a 0 to low. The changes in bit pattern for an incrementing byte counter are shown opposite.

Bit pattern	Count value
00000000	0
00000001	1
00000010	2
00000011	3
00000100	4
.	
.	
.	
.	
11111000	248
11111001	249
11111010	250
11111011	251
11111100	252
11111101	253
11111110	254
11111111	255
00000000	0

When referring to the individual bits in a byte it is conventional to use a numbering system; the bit shown leftmost is bit 7 and the rightmost bit 0. As with the digital counters we encounter in daily life the leftmost digit is the most significant and the rightmost the least significant. A number whose digits may only have two values is called a binary number, and the word 'bit' is an abbreviation for the phrase 'binary digit'. The counter shown above is a binary counter which starts at zero and is successively incremented. Counting continues until all the bits are set to 1, and on the next count it goes round the clock and the entire byte is reset to zeros.

In order to use memory for counting numbers higher than 255 it is necessary to employ more bits to represent the number. This may be done by using two consecutive byte addresses as a single 'cell' of memory, provided that the count can be made to carry over into the next byte. On a 16-bit computer this is automatically provided for within the processor's instruction set, but an 8-bit processor may require extra programming. Forth is a natural 16-bit language that makes the computer behave as if it were a 16-bit machine even if it only has an 8-bit processor. In fact the vast majority of memory operations in Forth use 16-bit cells. An extended 16-bit binary counter is shown overleaf.

Cell bit pattern		Count value
High byte	Low byte	
00000000	11111111	255
00000001	00000000	256
00000001	00000001	257
00000001	00000010	258
.		
.		
.		
00000010	00000000	512
00000010	00000001	513
.		
.		
00000011	00000000	768
00000011	00000001	769
.		
.		
.		
11111111	11111100	65532
11111111	11111101	65533
11111111	11111110	65534
11111111	11111111	65535
00000000	00000000	0

As you can see the use of a second byte greatly increases the range of numbers which may be represented in memory so that any number in the range 0–65535 may be accommodated. The 16-bit count value is constructed in memory so that the 8 least significant bits occupy the lower address and the 8 most significant the next address. The following Forth words may be used to perform a 16-bit count and display the results.

@ (addr---number)
'Fetch'. Returns the contents of the the 16-bit cell starting at the given address.

U. (data---)
'U-dot'. Displays the data item on the top of stack as a value in the range 0–65535.

PAD (---addr)
Returns a safe address for general use.

! (number,addr---)
'Store'. Sets the contents of the given address to the number.

+! (number,addr---)
'Plus-store'. Adds number to the contents of the given address.

The unsigned contents of any 16-bit cell of memory may be displayed using:

@ U. <RETURN>

in the same way as for bytes using C@ . This is a completely harmless activity. The words ! and +! alter the contents of memory and must not be used indiscriminately since certain parts of memory are vital to the correct operation of the Forth system. The Forth word **PAD** returns to the stack the address of the start of an area of memory set aside as general purpose, normally about 64 bytes long. This address may be used quite freely and should be used in all initial experiments. The contents of **PAD** may be set equal to any value in the range 0–65535 using !, the desired value being placed on the stack prior to executing **PAD**. Thus the phrase:

0 PAD ! <RETURN>

sets the contents to 0 whilst:

20 PAD ! <RETURN>

sets it to 20. The contents of the cell may also be incremented by a given quantity using +! which expects the same input parameters as ! but adds the number into the cell rather than merely storing it there. Thus successive:

2 PAD +! <RETURN>

operations will count the value in **PAD** up by increments of 2. The contents of **PAD** may be displayed at any time by typing:

PAD @ U. <RETURN>

An equivalent word to !, present on all Forths, to operate on byte values only is C! and some systems also employ a C+! for maintaining single byte counts.

Words introduced in this section:

@ (addr---n)
'Fetch'. Returns the contents of the the 16-bit cell starting at the given address.

C@ (addr---n)
'C-fetch'. Takes the address given on the stack and returns the contents of that byte.

. (n---)
'Dot'. Takes the byte data from the stack and displays it on the screen.

U. (un---)
'U-dot'. Displays the data item on the top of the stack as a value in the range 0–65535.

PAD (---addr)
Returns a safe address for general use.

! (n,addr---)
'Store'. Sets the contents of the cell at the given address to the number.

+! (n,addr---)
'Plus-store'. Adds number to the contents of the cell at the given address.

C! (b,addr---)
'C-Store'. Sets the contents of the given address to the byte value.

C+! (b,addr---)
'C-Plus-store'. Adds byte value to the contents of the given address.

4.2 Addresses and data

As we have seen, computer memory stores binary numbers and both 8-bit and 16-bit values have been used. What else can it store? The answer is nothing, binary numbers are the limit as far as computers are concerned. We may use larger numbers; 24-bit; 32-bit; 48-bit and so on by employing extra bytes and thus greatly extending the numeric range, but these are still just numbers. Since many computer applications require the processing of essentially non-numeric information, text or images for instance, it must be numerically encoded before the computer can handle it. This means that whilst we are restricted to the processing of numbers, the only real limitation on the information we can handle is our imagination in encoding the data. For example the binary number representing 65 held in a single byte of memory may in one set of circumstances be treated as literally the value 65, or in another context as a numerically encoded letter 'A'. This section looks at some of the many diverse ways of interpreting data items in memory, and in the process introduces a few simple Forth words which may be tried from the keyboard so that you can get a feel for the way in which these words interpret their data prior to to writing any programs.

The simplest interpretation of the contents of a memory cell is that employed in the last section, where it is treated as a count value – literally a number between 0 and 65535. This is the interpretation placed on the value by U. which displays the value on the top of the stack as an ordinary number falling in that range. The word . ('dot') treats the numbers in a

slightly different way, although the basic action is very similar.

65535 . <RETURN> −1 ok

−1 U. <RETURN> 65535 ok

In neither instance is the anticipated result given, the word . treats 65535 as if it were −1, and the word U. does the opposite. The reason for this is that both -1 and 65535 are represented internally by the computer using the same 16-bit binary number (1111111111111111). This is tied up with the way in which computers perform arithmetic, as we will see in chapter 8, but it is important to appreciate that different words will interpret a value in different ways. When . executes it treats only the least significant 15 bits (bits 0–14) as representing the size of the number. Bit 15 (leftmost) – ordinarily the most significant bit of the value – is seen as the sign of the number, a 1 indicating that the number is negative, a 0 positive. Most of the Forth arithmetic functions also treat cell values in this way, allowing us thus to incorporate the processing of minus numbers into our programs. The use of bit 15 as a sign bit clearly cuts down the range of absolute values we can represent in a single cell. The maximum value for the magnitude of a 16-bit number is +32768, with any values greater than this being treated as negative. The total range of signed values on which we can operate is −32768 to +32768. By contrast U. treats the whole of a 16-bit number as representing the value, as do all the memory operations (@ C@ ! C! +! and C+! so far) which use the top stack value as an unsigned value representing the memory address. As negative memory addresses are not allowed the full positive range 0–65535 can be used. Thus Forth systems naturally address 65535 bytes, or 64K of memory.

In order to investigate further the properties of signed and unsigned numbers the following Forth arithmetic words may be used in conjunction with those words already introduced to perform very simple calculations.

1+ (n---n+1)
Returns the given value incremented by 1.

2+ (n---n+2)
Returns the given value incremented by 2.

@ (n1,n2---n1+n2)
Returns the sum of n1 and n2.

– (n1,n2---n1-n2)
Returns the difference between n1 and n2.

The words 1+ and 2+ act on a single stack parameter, leaving the value incremented by 1 and 2 respectively. Some Forth systems (notably Forth-79) also have a pair of complementary words 1– and 2– for carrying out the corresponding decrements.

The words + and – are Forth's general purpose addition and subtraction routines. They both require that two values be on the stack which are effectively removed during execution and replaced with the result. The order in which these two values are placed on the stack is unimportant for the addition since 6 + 3 is the same as 3 + 6, but in the case of subtraction the order is critical. Using – the top stack value is subtracted from the value immediately below it, and the difference returned. Here are some examples of the results of Forth arithmetic, others should be tried until you are happy about the concept of signed and unsigned numbers within the computer.

```
Ø 1+ 1+ 1+ . <RETURN>  3 ok

Ø 2+ 2+ 2+ . <RETURN>  6 ok

Ø 2+ 1+ .    <RETURN>  3 ok

-1 1+ .      <RETURN>  Ø ok

6 1Ø + .     <RETURN>  16 ok

6 -1Ø + .    <RETURN>  -4 ok

-6 1Ø + .    <RETURN>  4 ok

-6 -1Ø + .   <RETURN>  -16 ok

6 1Ø - .     <RETURN>  -4 ok

1Ø 6 - .     <RETURN>  4 ok

-1Ø 6 - .    <RETURN>  -16 ok

1Ø -6 + .    <RETURN>  4 ok

-1Ø -6 - .   <RETURN>  -4 ok
```

Note that when displaying the minus numbers produced by Forth arithmetic using U. the higher the value of the signed number the lower the unsigned number displayed.

– 1 U. <RETURN> 65535 ok

– 2 U. <RETURN> 65534 ok

– 3 U. <RETURN> 65533 ok

It has already been mentioned that typographic characters can be coded into 8-bit binary numbers, and it is in this form that text is transmitted between the computer and its peripherals (such as keyboard, screen or printer). The complementary Forth words **KEY** and **EMIT** deal with the input and output of single character data between keyboard character data between keyboard and computer, and between computer and screen, respectively.

EMIT (character value---)
Treats the top stack item as an 8-bit character code and displays the appropriate character at the screen.

KEY (---character value)
Waits for a keystroke and returns the character code associated with that key.

When trying values with **EMIT** only numbers greater than 31 should be used, since the codes 0–31 are used for other purposes and do not yield a printable character. The following results should be obtained from **EMIT**:

```
65 EMIT <RETURN> Aok
66 EMIT <RETURN> Bok
67 EMIT <RETURN> Cok
```

These are the character codes for the first three letters of the alphabet, in upper case. Notice that there is no space between the character displayed and the 'ok' issued by Forth. The character code for a space is 32, and this is used so frequently that a special word **SPACE** is defined to perform 32 **EMIT**. To assist in the layout of screen displays the word **SPACES** is also defined to perform **SPACE** a number of times according to the top value on the stack.

```
10 SPACES 65 EMIT SPACE <RETURN>          A ok
8 SPACES 65 EMIT SPACE <RETURN>         A ok
```

The complementary function of collecting input from the keyboard is performed by **KEY** which requires no stack parameters. Entering:

```
KEY <RETURN>
```

suspends any further operations until a key has been pressed, whereupon the character code associated with that key is returned to the stack and an 'ok' issued. Thus typing:

```
KEY . <RETURN>
```

followed by a keystroke allows the character code for any of the keys at your keyboard to be determined.

In order to simplify the task of textual data transmission between the

many diverse types of computer and peripheral a number of standard codings have been adopted. The most notable of these is ASCII which stands for American Standard Code for Information Interchange. This is the code system employed by almost all Forth systems, although the occasional variation is encountered. The character codes used above are ASCII, i.e. 65 is ASCII for 'A', 32 for 'space' etc.

So far we have referred to addresses and data as if they were completely distinct from one another, but with Forth this need not always be the case. An address can be treated as a piece of data or a data item as an address. Certain Forth words treat any 16-bit number as a machine address, the memory operations are examples of this. They require that the topmost stack value specify the address on which they are to operate but care nothing of how that address got there. Thus the address may have been produced as the result of a calculation as in the following phrase:

PAD 80 + @ . <RETURN>

which displays the contents of the cell which begins 80 bytes upwards in memory from **PAD**. The actions on the stack are as follows:

Operation	Stack

PAD	---addr
80	---addr,80
+	---addr+80
@	---data
.	---

Here we have specified the address for @ relative to a known location (**PAD**) by means of a computation. This technique is called *relative addressing* and turns out to be a very valuable tool in programming. The ease with which Forth is able to process addresses as if they were data is largely responsible for its great flexibility and examples of computed addresses will appear in many of the programs in this book.

Another method of manipulating memory addresses, known as *indirect addressing*, is also used extensively in Forth. Here instead of directly specifying the actual address on which we wish to operate we specify an address where the computer will find the address for the operation. The address which holds the effective address is know as a *pointer*, since it points the computer to the desired location.

Suppose we are to operate on three data items in contiguous memory cells starting at **PAD**+80. We may set up the location **PAD** to act as a pointer to this data with the commmands:

PAD 80 + PAD ! <RETURN>

which compute the address of the first cell and store that value in **PAD**. To examine the contents of that cell we can use:

PAD @ @ . <RETURN>

which retrieves the effective address of the data with the first @, and the data itself with the second. This may seem a round-about method of retrieving the data but it offers possibilities not allowed for by directly specifying the effective address. This will not be fully appreciated until it comes to writing programs, but to get the feel of the technique use the following sequence of commands to alter the contents of the three memory cells:

```
1 PAD @ ! <RETURN>

-stores 1 in 1st cell.


2 PAD +!  <RETURN>

-points to next cell.


2 PAD @ ! <RETURN>

-stores 2 in 2nd cell.


2 PAD +!  <RETURN>

-points to next cell.


3 PAD @ ! <RETURN>

-stores 3 in 3rd cell.


PAD @ @ . <RETURN>  3 ok

-contents of 3rd cell.
```

```
-2 PAD +! <RETURN>

-point to previous cell.


PAD @ @ . <RETURN>  2 ok

-contents of 2nd cell.


-2 PAD +! <RETURN>

-point to previous cell.


PAD @ @ . <RETURN>  1 ok

-contents of 1st cell.
```

Forth programs make extensive use of pointers since in many cases it greatly simplifies the processing.

So far all data have been treated as separate values, a character, an address or a number. In many instances however we require to process whole clusters of associated data. For example, if we wish to display the message 'Good Morning' on the screen it is not convenient to perform this with a whole series of **EMIT** operations on the individual characters, particularly since the letters have meaning only by virtue of their association with the other letters in the message. This message could be held in memory as a sequence of 12 ASCII codes in consecutive bytes. A region of memory used to store a string of associated data is referred to as a *memory string* and the text message as an *ASCII string*.

There are a number of Forth words which operate on strings of data, some of which will be used here to show how a memory string can be specified. A memory string has two qualities by which it may conveniently be identified. It has a starting point (a byte in memory containing the first element of the string) known as its base address, and it extends for a given number of bytes through memory and thus has a length or character count. The following words operate on whole strings of memory:

EXPECT (addr,count---)
Awaits a stream of keystrokes to the maximum number given or until a carriage return, and stores the ASCII codes in successive bytes of memory beginning at the given address.

TYPE (addr,count---)
Types out the string of 'count' characters beginning at the given address.

BLANK (addr,count---)
Stores ASCII 32 in each of the elements of the specified string.

ERASE (addr,count---)
Stores zeros in each element of the specified string.

FILL (addr,count,char---)
Stores the data value given on the top of the stack in each element of the string specified immediately below.

In each case the memory string to be operated on is specified by placing first the base address on the stack, and then the string length in bytes. Try the following:

```
PAD 20 BLANK <RETURN> ok
PAD 20 TYPE <RETURN>                              ok
PAD 20 EXPECT <RETURN> Good Morning <RETURN> ok
PAD 20 TYPE <RETURN> Good Morning          ok
```

First, a string of 20 bytes is 'blanked' using **BLANK** (on some Forth systems this word has the name **BLANKS**). Typing out the contents of the 20 bytes starting at **PAD** shows that this has been done successfully. The computer is then instructed to **EXPECT** a string of up to 20 characters from the keyboard. Execution is suspended until either 20 characters have been received or a **RETURN** is detected (in which case **EXPECT** ceases operation immediately). Each of the characters keyed in is stored in the string starting at **PAD** as shown in diagram 4.1.

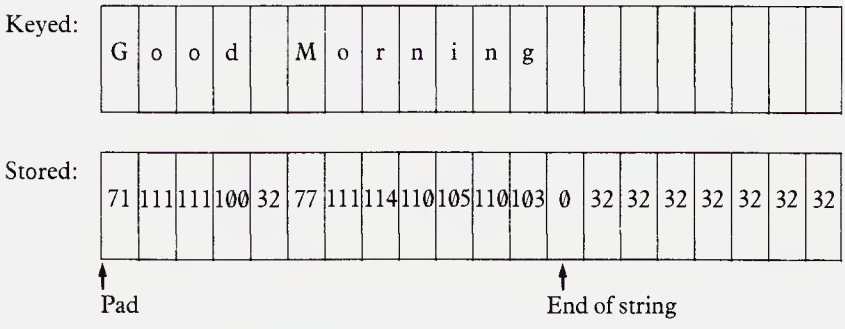


Diagram 4.1. A 20 character string at PAD

Many Forth implementations contain the word **DUMP**, which will display the contents of each byte of a string. This may be used to examine the character codes of the string beginning at **PAD** as follows:

```
PAD 20 DUMP <RETURN> 71 111 111 100 32 77 111 114
110 105 110 103 0 0 32 32 32 32 32 32 ok
```

Using a method somewhat similar to the indirect addressing described above, it is common practice to allow a string to specify its own length by using the first byte in the string to hold a character count for the rest of the string. If stored in this form the message 'Good Morning' at **PAD** would be constructed as shown in diagram 4.2.

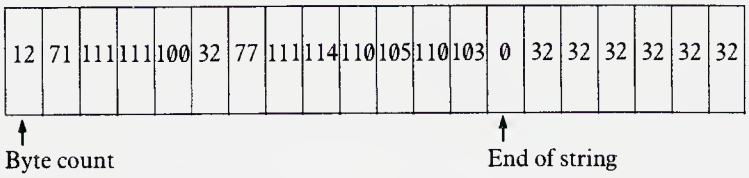


Diagram 4.2. A character string with byte count

It could be displayed by the sequence:

Operation	Stack

PAD 1+	---addr
PAD C@	---addr count
TYPE	---

This method of storing strings is particularly convenient for programming and allows strings to be packed together in memory rather than allocating space which may just hold blank characters.

ASCII strings are not the only data treated as string data. A string may be a list of discrete data items which have some other linking factor. For example, a memory string might be used to hold the number of units of electricity consumed by a household in each of the months of the year. We may wish to operate on all the data, e.g. sum it to get a yearly figure, on groups of data as for quarterly information, or on the individual monthly figures. It would be convenient if we could specify the data we wish to access in terms of the month. This may be done by arranging the data in memory as shown in diagram 4.3, assuming that each month is allocated one byte only.

Diagram 4.3. Monthly consumption array

The first byte in the string contains the number of elements in the rest of the string; data for a given month may be addressed by adding the month number (Jan=1 Dec=12) to the base address (**PAD**). Thus the month number specifies the 'byte offset' into the string. The data for March could be displayed by:

```
PAD 3 + C@ . <RETURN>
```

Strings which are accessed in this way are normally known as data tables or *arrays* and the method of generating the address of an element as *indexed addressing*. In this case the month number acts as an index into the table.

Since tables are often used to accumulate numeric data the Forth word **ERASE** may be used to set all the values in the table to zero. It is used in exactly the same form as **BLANK(S)**, requiring a base address and a byte count. A further word **FILL** is of more general use allowing strings to be filled with any byte data. It requires an additional stack parameter as the top stack value, with the address and count directly beneath. Its operation is otherwise similar to that of **ERASE** and **BLANK**.

Computer memory may thus hold a wide variety of data types, as well as machine instructions for execution by the processor. In order efficiently to utilize the memory space available, regions of memory are normally dedicated to particular uses. For instance, data transfers between the computer and its peripherals generally take place via regions of memory called *buffers*, key codes from the keyboard being sent to a keyboard input buffer, and text for display being transmitted via some output buffer. It is also customary to have all the programs together in one region of memory separate from the data, to save the processor having to jump around all over memory to execute its programs. In most languages the way in which the memory is organized is transparent to the user, but programming in Forth allows such direct control over the use of memory that it is important for you to be conscious of how the various regions of memory are organized at an early stage. We normally describe memory organization in terms of a *memory map* – a diagram and/or list of important addresses showing the functions of different areas of memory.

Words introduced in this section:

1+ (n---n+1)
Returns the given value incremented by 1.

2+ (n---n+2)
Returns the given value incremented by 2.

1– (n---n–1)

Returns the given value decremented by 1.

2– (n---n+2)
Returns the given value decremented by 2.

+ (n1,n2---n1+n2)
Returns the sum of n1 and n2.

– (n1,n2---n1–n2)
Returns the difference between n1 and n2.

EMIT (char---)
Treats the top stack item as an 8-bit character code and displays the appropriate character at the screen.

KEY (---char)
Waits for a keystroke and returns the character code associated with that key.

EXPECT (addr,ct---)
Awaits a stream of keystrokes but to the maximum number given or until a carriage return, and stores the ASCII codes in successive bytes of memory beginning at the given address.

TYPE (addr,ct---)
Types out the string of 'count' characters beginning at the given address.

SPACE (---)
Types out one space at the output device.

SPACES (n--)
Types out n spaces at the output device.

BLANK (addr,ct---)
Stores ASCII 32 in each of the elements of the specified string.

ERASE (addr,ct---)
Stores zeros in each element of the specified string.

FILL (addr,ct,char---)
Stores the data value given on the top of the stack in each element of the string specified immediately below.

DUMP (addr,ct---)
Types out the byte content of each element of the string described.

4.3 The Forth memory map

When writing Forth programs, it is possible to utilize any portion of memory for virtually any purpose, the choice is entirely with the programmer. However, Forth itself occupies and uses some of the space available and it is important that user programs do not interfere with this. Although the physical addresses vary from one Forth system to the next, due to differences in the hardware, the basic layout of the memory is fairly standard. The actual addresses of various important locations can be investigated from the keyboard.

Diagram 4.4 is a simplified Forth memory map showing most of the main elements of the system. The regions of memory are shown, starting with the system variables at the lowest addresses and ending with the disk block buffers at the highest. To the right of the main diagram three important locations are indicated along with the operations which will place that address on the stack. Other important elements of Forth will be encountered later in this book but for the next few chapters we need only be aware of those shown.

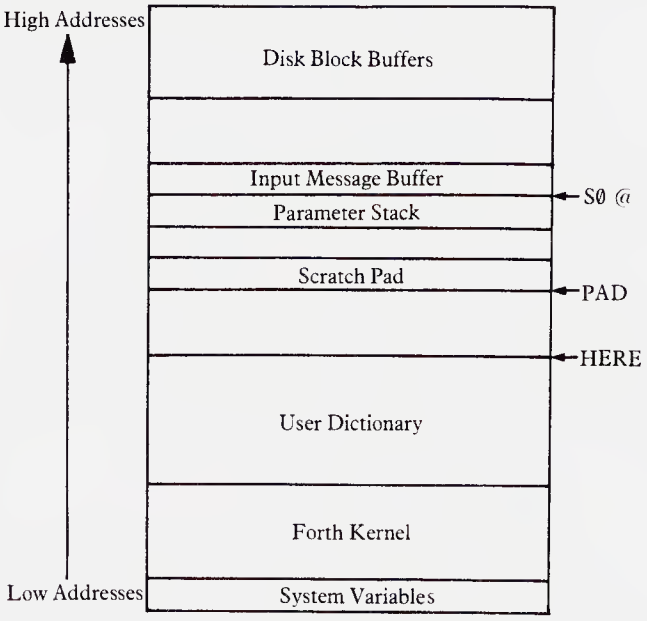


Diagram 4.4. A simple Forth memory map

The System Variables are shown occupying the bottom memory addresses. This is a region of memory used by Forth to hold data critical to its operation. Arbitrarily tinkering with the contents of these addresses will inevitably cause a system crash.

Above the system variables two regions are shown, the Forth kernel or *nucleus* and the user dictionary. Between them these comprise the *dictionary*, where all the Forth words are held. The nucleus comprises those Forth words already defined in the system, new words written by the user being compiled into the user dictionary. The two regions are not physically distinguishable since new words are compiled into the dictionary in exactly the same form as those already present. The current top of the dictionary can be found by typing:

HERE U. <RETURN>

This is the address where the compiler will add new words and is adjusted automatically as compilation takes place. When the Forth system is first purchased and loaded the value returned by **HERE** will be the next free location above the top of the nucleus. This value will increase as new Forth commands are added.

Above the top of the user dictionary lies a region of memory used as a general purpose work region available to the user. The address of the start of this region is returned by **PAD** which we have already encountered. It normally extends for at least 64 bytes (32 cells) above **PAD**. The address returned by **PAD** is always computed relative to the top of the dictionary, the exact offset varying from one system to the next. As **HERE** increases so too does **PAD** so that this 'scratch pad' region is seen as floating a fixed distance above the user dictionary. The byte offset between **HERE** and **PAD** may be determined by typing:

PAD HERE – . <RETURN>

and will often be 32 bytes in length. The space between **HERE** and **PAD** is used by the Forth system, but within certain restrictions can also be used by the programmer.

At an unspecified distance above **PAD** lie the *input message buffer* and the *parameter stack*. The input message buffer is used by Forth to receive messages from the keyboard. It is from here that the interpreter interprets the commands we issue it at the keyboard. The start location of the input message buffer is held in a pointer. The address of this pointer can be found by typing:

S0 U. <RETURN>

and the location of the first byte in the buffer by typing:

S0 @ U. <RETURN>

Note that on some systems the word **TIB** (Terminal Input Buffer) may take the place of **S0**. The input message buffer normally extends upwards in memory for 80 bytes. When the system receives a <RETURN> from the keyboard, or when 80 characters have been received since the last <RETURN>, Forth transfers the whole line just typed to a string pointed to by **S0**, the overall effect being the same as the sequence **S@ 80 EXPECT**.

The region immediately below **S0** is reserved for the parameter stack, known simply as the stack – the place where Forth words find their parameters. So far the stack has just been described as a pile of numbers without any explanation as to what form this 'pile' might take. The stack is a region of memory which is described by two pointers. One pointer (**S0**) contains an address related to the bottom or base of the stack, the second pointer (given various names including SP for stack pointer and 'S) points to the current top of the stack. Each number in the pile occupies a single cell of memory. Initially the stack is empty and the contents of the stack pointer are set to 2 less than the contents of **S0**, this being the address of the cell where the first number will be placed. If you have a 79-Standard Forth the word **SP@** may return the address of the top of the stack, and can be used in conjunction with **U.** to investigate the operation of the stack.

Placing a number on the stack has the effect of storing that number in the cell pointed to by SP and decrementing the contents of the pointer by two, so that it points to the cell immediately below that just used. Thus as successive values are added to the stack, the top of stack moves down through memory towards **PAD** and low address numbers. The stack is said to 'grow down' in memory while the dictionary 'grows up'. The stack pointer is not allowed to drop below the value in **S0** and if it does so an error message is issued by the system to say that the stack is empty. The act of removing a value from the stack has only one effect. The contents of the stack pointer are incremented by two so that the next cell up is pointed to. There is a fixed amount of memory allocated for stack use which varies from one system to the next, but is always at least 48-bytes. This provides sufficient room for 24 stack parameters at any one time, which is always sufficient.

At the top of the memory lie the disk block buffers through which all data transfers between Forth and the disk take place. Each of these buffers is normally 1024 bytes (1K) in length and there should be at least two available for efficient disk handling. The way Forth communicates with a disk is discussed fully in Chapter 10. The buffers are used to edit programs onto the disk as well as for general data processing.

Words introduced in this section:

S0 (--addr)
Variable containing the initial value for the stack pointer i.e. the address of the bottom of the stack. On most systems this also indicates the start address of the input message buffer.

HERE (---addr)
Returns the address of the next available dictionary location.

SP@ (---addr)
Return the address of the top of the stack (before SP@ is executed).

5 Defining new words

5.1 Colon definitions

In section 3.3 we saw how the set of words provided by the language Cofforth might be combined in more powerful functions to program a coffee-making task. You may not be suprised to learn that none of these words are provided by Forth itself! The previous chapter introduced some real Forth words, and this small set is already enough to start creating some programs of your own. Remember that all the words you define can subsequently be treated just as if they were a natural part of Forth – indeed in a sense they are.

Before we start defining any new words let's take a look at the set of words already available. Try typing:

VLIST <RETURN>

You should find that a long list of words scrolls up the screen. If it doesn't work it may be that the facility is not available – PolyForth for instance does not include **VLIST** – in which case you should ignore the next paragraph. Similarly the exact result of **VLIST** will vary, some systems printing out only the first three characters of each word. Don't worry about what any of the words actually means for the moment, just try to make a note of the very first word that appears when you use **VLIST**.

Now key in the following:

: HELLO ." HI THERE " ; <RETURN>

If you make a typing error (like leaving out a space) keep trying until Forth responds with 'ok', then do a **VLIST** again. This time you should find that **HELLO** is the first word typed out. You have added a word to the Forth dictionary. To execute your new program simply type:

HELLO <RETURN>

Forth will respond by printing out:

HI THERE ok

on the same line. The general format for defining new Forth words therefore is:

: (Name) (Code to execute) ;

The colon at the beginning (which is itself a Forth word) tells Forth to compile a new *colon definition*, with the name which follows. Any character except a space can be used in the name. The semicolon tells Forth that the definition is complete and that it is to stop compiling. Note that unlike before, when Forth executed the words you entered immediately, the code within a colon definition is not executed until the word being created is used. So instead of typing out **HI THERE** when you first entered it, it does so when the word **HELLO** is entered.

In the definition of **HELLO** we used a word which you have not yet come across. It looks like this:

."

and is pronounced 'dot-quote'. This word will type out everything following it until it finds a quote ("). We will be using ." together with the words you met in the previous chapter to create some more simple programs. Another word we will be using is **CR** which stands for carriage return. This has a similar effect to pressing the return key in that it moves the text cursor down one line. It means that the words typed out by ." can be positioned on different lines of the screen.

You should already have defined a word called **HELLO** which simply types out HI THERE. To show the versatility of Forth we are going to ignore this and define **HELLO** again with a slightly different action. Type in the following (remember the spaces):

: HELLO CR ." HI THERE " ; <RETURN>

You may find that a message is typed out to the effect that **HELLO** is being redefined but this shouldn't matter. Now try using **HELLO** just as before by simply typing it in followed by <RETURN>. You should find that the words 'HI THERE ok' are typed on the line underneath **HELLO**. Now define another similar word, which uses **HELLO**, as follows:

: ASK-NAME HELLO ." WHAT IS YOUR NAME?" ; <RETURN>

Executing **ASK-NAME** will type out:

HI THERE WHAT IS YOUR NAME? ok

on the line underneath. If it doesn't you have almost certainly made a typing error. Don't worry! Even the most experienced programmers make mistakes all the time. You should think about what actually has happened and look at what you have done to achieve it, until you discover the problem. This is the process called 'debugging'.

Now we will define a word to *input* a name entered from the keyboard.

By input we mean that the name typed in will be transferred to an area of memory for safekeeping. You may remember that the Forth word **PAD** leaves an address on the stack pointing to an area of memory especially set aside for such use. We will allow up to twenty characters (i.e.letters) for the name, which will thus occupy twenty bytes of memory. Before the name is entered we must clear the area of memory we are about to use with **BLANK** (**BLANKS** on some systems). Our word thus looks like this:

```
: GET-NAME PAD 20 BLANK PAD 20 EXPECT ; <RETURN>
```

Looking at the definition of this word we can see that the phrase **PAD** 20 appears twice. Its function is to leave the appropriate numbers on the stack to describe an area of memory to **BLANKS** and **EXPECT**. It makes sense, therefore, since we are bound to want to access this area of memory later on, to define a separate word whose code is simply **PAD** 20:

```
: STASH ( --addr,count) PAD 20 ; <RETURN>
```

The bit enclosed in brackets is a comment which has no effect on **STASH** (you can leave it out if you like). In fact the opening bracket is a Forth word which causes everything up to a closing bracket to be ignored. This is why it must be followed by a space. The comment between the brackets represents the effect of the word **STASH** on the stack. It means that **STASH** will leave an address with a count on the top of it.

We can now redefine **GET-NAME** using our new word:

```
: GET-NAME STASH BLANK STASH EXPECT ;
```

The process of identifying duplicate sections of code and defining them as separate words is called 'factoring out', and is one of the most satisfying aspects of Forth programming.

If you type in **GET-NAME** (followed by <RETURN>) the text cursor should appear just in front of the word, waiting for you to type in a name. You will need to press <RETURN> again (or type in twenty characters) before Forth says 'ok'. When you are happy that the words **ASK-NAME** and **GET-NAME** are working properly they can be combined in a word to perform both functions:

```
: IDENTIFY ASK-NAME GET-NAME ; <RETURN>
```

This is our main input routine and consists of a prompt (**ASK-NAME**) and an opportunity to enter up to twenty characters from the keyboard into the computer's memory.

Having input a name into the computer we now need a way of retrieving it. You have already come across a word which types out the contents of an area of memory to the screen called **TYPE**, and as it happens it expects to find an address and a count on the stack, which is exactly what our word **STASH** provides. Our new word looks like this:

: SAY-NAME STASH TYPE ; <RETURN>

You can check this works by executing **GET-NAME** immediately followed by **SAY-NAME**:

GET-NAME SAY-NAME <RETURN>

Next we will define a word to preface the name with a greeting:

: BE-NICE CR ." NICE TO MEET YOU " ; <RETURN>

The two words above can be combined into an *output* routine as follows:

: ACKNOWLEDGE BE-NICE SAY-NAME ; <RETURN>

Finally, we can use the input and output routines we have created to define a word which asks your name and then uses it to reply:

: MEETING IDENTIFY ACKNOWLEDGE ; <RETURN>

Try executing **MEETING** a few times entering different names to convince yourself that it works.

Let us now look back at the words we have just defined. This will allow you to start afresh if you have run into problems, and also to study the way in which they are built up.

```
: HELLO CR ." HI THERE " ;


: ASK-NAME HELLO ." WHAT IS YOUR NAME ? " ;


: STASH ( --addr,count) PAD 20 ;


: GET-NAME STASH BLANKS STASH EXPECT ;


: IDENTIFY ASK-NAME GET-NAME ;


: SAY-NAME STASH TYPE ;


: BE-NICE CR ." NICE TO MEET YOU " ;
```

```
: ACKNOWLEDGE BE-NICE SAY-NAME ;


: MEETING IDENTIFY ACKNOWLEDGE ;
```

You have seen how words can be added to the dictionary. It follows that there must be some way of removing these. Consider the order in which the words in this section were defined. Bearing in mind that the most recently defined words are added to the top of the dictionary, we can represent the order of our words as follows – with the last word defined at the top of the list just as with VLIST:

```
MEETING
ACKNOWLEDGE
BE-NICE
SAY-NAME
IDENTIFY
GET-NAME
STASH
ASK-NAME
HELLO
```

Let us suppose that for some reason we had decided to remove **BE-NICE** from our list of words. Because **ACKNOWLEDGE** uses **BE-NICE** it could no longer operate if the latter were not present. Clearly the word **ACKNOWLEDGE** will therefore also have to be removed. **ACKNOWLEDGE** is in turn a vital part of **MEETING** – so this too must go. In this way the removal of **BE-NICE** has a snowball effect on the portion of the dictionary above it.

Although the removal of a word may not necessarily affect all the words above it, because of the way Forth operates it is essential that when one word is removed all words defined after it (i.e. above it in the dictionary) are removed as well. Such is the action of the Forth word **FORGET**. This expects to be followed by the name of one of the words in the dictionary. It will then remove this word and every other word defined since its creation. Thus if you type in:

FORGET BE-NICE <RETURN>

then the three words **MEETING**, **ACKNOWLEDGE** and **BE-NICE** will all disappear and **SAY-NAME** will become the topmost word in the dictionary. If we wanted to remove all the words we had just created then **FORGET HELLO** would reset the dictionary to its original state (well nearly!).

One final point about **FORGET** concerns words which have been defined more than once. In this case **FORGET** will act on the most recent definition only (i.e.the one which is highest in the dictionary). This means that if you

have followed this section through, the word **HELLO** will in fact have to be forgotten twice to clear the dictionary, since it was defined twice.

You should try creating some other programs of your own and then using **VLIST** and **FORGET** to see the effect on the dictionary. Note that if you redefine a word only the most recent definition will be accessible, but that the original version can be 'uncovered' by **FORGET**ting the word once. It is essential that you understand how to create and remove words before continuing with this chapter.

Words introduced in this section:

VLIST
Lists out all the words in the dictionary. Not available on all systems.

: (NAME)
Colon. Creates a new Forth word with the name (NAME) and compiles the code which follows until a ; is reached.

;
Semi-colon. Terminates a colon definition and causes Forth to stop compiling.

."
Dot-quote. Prints out at the terminal the string which follows it up until a single quote. On some systems this word can only be used within programs.

CR
Carriage return. Moves the text cursor to the beginning of the next line on the screen.

FORGET (NAME)
Removes the word (NAME) and all subsequent definitions from the dictionary.

(
Causes Forth to ignore the text that follows up until a closing bracket.

5.2 Editing program source on disk

When you key in colon definitions the words are compiled and added to the Forth dictionary, but the source code (i.e.what you actually key in) is lost as soon as it disappears off the screen. This means that if you make a mistake the whole word must be typed in again. It also means that the entire set of words must be re-entered if you turn the computer off, since new definitions in the dictionary are not normally saved. Clearly this is

impractical from a programming point of view, so it is vital that we find some way of saving the source programs.

As we have said already, Forth programming is impractical using cassette based storage and this section assumes your system includes at least one disk drive and has standard Forth disk-handling facilities. It is recommended that you study the documentation covering the editor for your particular version of Forth, since they vary enormously in operation and thus we can only discuss general principles.

In order to start editing programs onto disk you must first prepare an empty work disk. Most computers require disks to be formatted before they are used. This simply prepares the disk for the expectations of a particular machine or operating system. Where appropriate the format utility should be well documented in the manuals that came with your system. It may be directly accessible from Forth, or you may have to do it from the operating system.

For editing purposes Forth views the disk as a number of contiguous blocks of memory called 'screens', each of which is normally 1K (1024 bytes) long. The exact number of screens available will depend on the capacity of your disk drive. Each of the screens is assigned a number starting at zero, much like memory addresses.

When you have prepared a disk and it is positioned in the drive type:

```
10 LIST <RETURN>
```

You should find that screen number 10 of the disk is listed out on the screen as 16 lines of 64 characters each (16 * 64 = 1024), and that each line begins with a line number (0 to 15). The latter are purely for reference purposes. At the top of the listing there should be some indication of which screen number it is. At the moment the screen will be full of the character generated by formatting – which is not always blank.

To clear the editing screen we must first enter the Forth editor. The editor commands are usually held in a different vocabulary to other Forth words. The concept of vocabularies is discussed in Chapter 11 and for the moment all you need to know is that by typing:

```
EDITOR <RETURN>
```

a number of words are made available that would not otherwise be accessible. Bear in mind that Forth needs very little convincing to reverse the action of this word, thus denying access to the editor. If you suddenly find that Forth is not accepting editor commands then type in **EDITOR** and try again.

Having listed out screen number 10 it has now become current, which means that all editing commands will act upon it. The current editing screen is usually held in an address given by the word **SCR**. Thus the phrase:

SCR @ . <RETURN>

should now print out 10. On some systems (notably Polyforth) the word which clears a screen makes use of this fact and does not require the screeen number to be used again. In this case the following will clear the screen to blanks (ASCII 32) and list the screen out again:

WIPE <RETURN>

Many Forth systems do not include this word, and in such cases the following must be used instead:

10 CLEAR <RETURN>

If you tried **WIPE** without success you may have to re-declare the **EDITOR** vocabulary before **CLEAR** can be used. **CLEAR** does not list out the blanked screen, and to do this you can simply type:

L <RETURN>

rather than use **LIST** again. **L** lists out the current editing screen – but you must be in the editor vocabulary to use it. Try listing out and clearing some other screen numbers using the words above.

You will need to read the documentation that came with your system to find out how source code is actually edited onto the disk screens, since there are few standards in this area. Some implementations use a screen editor which allows use of the cursor keys and means that text is entered directly onto the screen. Others include a line editor, where single character commands are used to insert and delete strings of text. You should spend some time acquainting yourself with all the commands available on your system.

Because of the way Forth handles disks the editing screens are held in memory whilst they are in use. To write the information back to the disk itself you must use the word **SAVE-BUFFERS**, ar alternatively **FLUSH**. Once you have done this successfully the source code is safely stored on the disk, and can be listed out at any time by **LIST**ing the appropriate screen number.

When source programs have been edited onto the disk they can be compiled by typing:

10 LOAD <RETURN>

This literally treats the screen pointed to by the number on the stack as if it were input from the keyboard, and it thus interprets the screen. Programs defined using : and ; are hence compiled into the dictionary.

One final word which may be useful at this stage is **INDEX**. This is again not available on all systems. It expects two numbers on the stack, both representing screen numbers. It will list out the first 64 characters of each

screen between (and including) the two numbers given. Thus:

```
10 20 INDEX <RETURN>
```

will list out the first 64 characters of screens 10 to 20 inclusive. Because of the action of **INDEX** it is customary to use the first 64 characters of each screen (i.e. the first line) for some description of the code which follows – enclosed in brackets just like stack comments.

As an exercise try editing the definitions created in the previous section onto screen 10, then try out the various words in this section.

It is recommended that from now on you edit all programs onto disk and compile them using **LOAD**, since this is the way that Forth programmers operate. Only short experimental programs should be defined directly from the keyboard. For this reason the example programs in the rest of this book will not be terminated with <RETURN>, since it is assumed they will be put onto disk. Where words or phrases are to be keyed in directly we will continue to use <RETURN> to indicate that the carriage return key must be pressed at the end.

Words introduced in this section:

LIST (n--)
Lists out the disk screen indicated by the number on the stack as 16 lines of 64 characters. Makes the screeen current.

EDITOR
Allows access to the EDITOR vocabulary.

SCR (--addr)
Leaves the address containing the current editing screen number.

WIPE
PolyForth word. Initializes the current editing screen to blanks and lists it out.

CLEAR (n--)
Initializes the screen number indicated by the number on the stack to blanks.

L
Lists out the current editing screen as in **LIST**.

INDEX (low,high--)
Lists out the first 64 characters of the screen numbers between low and high (inclusive).

LOAD (n--)
Interprets the screen indicated by the number on the stack as if were keyboard input.

5.3 Variables and constants

Colon definitions are not the only kind of Forth word, but rather represent the most important class of words. We will be looking more deeply at classes of words, and how to create your own variations, in Chapter 12. For present purposes you just need to be aware of two other classes of words (apart from colon definitions) which are provided with a Forth system.

You have already met some words which leave addresses on the stack as pointers to important locations in memory. **PAD** is such a word, leaving an address which varies depending upon the position of the top of the dictionary. Sometimes we want to allocate particular addresses for our own use, generally to hold some variable value.

Imagine you control a fluffy toy factory and want to use a computer to keep a track of your stock. The first thing you must do is to allocate a location in memory which will contain the number of toys in stock. This can be done using the defining word **VARIABLE** (a defining word is simply one which is used to define another word). **VARIABLE** creates a new Forth word with the name that follows, just as : does, except that no code is needed. Instead a cell (i.e. two bytes) of memory is reserved and the new word is given the function of placing the address of this location on the stack. We will call the variable which is to hold the total stock of fluffy toys **FLUFFIES** and it can be created with the phrase:

```
VARIABLE FLUFFIES
```

Note that on some systems (notably FIG Forth) the word **VARIABLE** expects an initial value on the stack in which case you will have to use:

```
0 VARIABLE FLUFFIES
```

Remember that these should be edited onto disk and created using **LOAD**.

If you now type in:

```
FLUFFIES . <RETURN>
```

Forth should print out the address allocated for our stock count. To retrieve the value held in this address we will need to use the word @ (fetch) described in Chapter 4:

```
FLUFFIES @ . <RETURN>
```

We can make a word for this to make life simple. The phrase @ . is used so much in Forth that a special word is provided with this action – ? – and we will use this in our definition:

```
: STOCK? FLUFFIES ? ;
```

Running **STOCK?** should reveal that the variable **FLUFFIES** contains zero –

that is to say we currently have none in stock.

Using the word +! (which increments the value held in the address on the top of the stack by the number underneath) we can define a word which will increase our stock levels depending on how many have been made:

```
: MADE ( n--) FLUFFIES +! ;
```

Note the comment in brackets which means that the word expects a single number on the stack. **MADE** is used as in:

```
20 MADE <RETURN>
```

which would add 20 to the stock level. Try running **MADE** with different values using **STOCK?** to make sure that the stock level has been correctly adjusted. For convenience the following word can be defined to reset the stock level to zero:

```
: NO-FLUFFIES 0 FLUFFIES ! ;
```

As well as producing fluffy toys it helps your cash flow if you can actually sell some as well! You thus need a word that subtracts the number sold from the stock level. The best way to do this involves the use of a new Forth word – **NEGATE**. This reverses the sign of the number on the top of the stack. For example keying in:

```
10 NEGATE . <RETURN>
```

will cause Forth to print −10, whilst:

```
−10 NEGATE . <RETURN>
```

will print out 10. We will be explaining how this works later on, but you should play with **NEGATE** until you are happy with its action. The word which decrements our stock level according to how many have been sold looks like this:

```
: SOLD ( --) NEGATE FLUFFIES '+;
```

and it is used in exactly the same way as **MADE**, expecting the number sold on the top of the stack. Thus:

```
20 SOLD <RETURN>
```

should subtract 20 from our stock level.

Variables like **FLUFFIES** are used frequently in Forth, and they form the basis of more complex uses of memory. The ability to access locations in memory using words instead of addresses is vital to the readability and portability of your programs. Variables provide a means for long term storage of values and as such are an alternative to the stack for passing numbers between programs. If a value needs to be preserved throughout

an application or even across a number of quite different words, it should be assigned as a variable. Just like colon definitions variables are placed in the dictionary and will thus appear in a **VLIST** and can be used with **FORGET**.

Sometimes we want to use in our applications values which we do not expect to change. Such values are called *constants*, and Forth provides a simple way of creating these, just as for variables. There are two differences between a variable and a constant. Firstly, the value of a constant is set up once and for all when it is created and is not changed whilst the programs are being executed. Secondly, whilst a variable leaves the address where a value can be found on the stack, a constant yields the value itself and does not therefore require the use of operators such as @ and !.

Let us suppose that production in our fluffy toy factory had stabilized at twenty per hour. We could use this information to calculate the total number of toys manufactured from the hours worked. First we need to define our hourly production as a constant:

```
20 CONSTANT FLUFFIES-PER-HOUR
```

It can then be used to calculate production over a given number of hours using the arithmetic operator * (multiply). Like + and – this expects two numbers on the stack, it will replace them with their product.

```
: HOURS-WORKED ( n- ) FLUFFIES-PER-HOUR * MADE ;
```

This can then be used just like **MADE**, except that it is past the number of hours that have been worked. Thus typing:

```
8 HOURS-WORKED <RETURN>
```

should increment our stock level (as given by **STOCK**?) by 160.

Similarly we may want to sell our fluffy toys in boxes. We have decided that ten fluffy toys fit nicely into a box, and thus the following is defined:

```
10 CONSTANT FLUFFIES-IN-BOX
```

Our stock level can now be adjusted given the number of boxes sold using the following program:

```
: BOXES-SOLD ( n--) FLUFFIES-IN-BOX * SOLD ;
```

such that the phrase:

```
15 BOXES-SOLD <RETURN>
```

would subtract 150 from the value in **FLUFFIES**.

Our final stock control application, which demonstrates the use of both variables and constants now looks like this:

```
VARIABLE FLUFFIES

: NO-FLUFFIES Ø FLUFFIES ! ;

: STOCK? FLUFFIES ? ;

: MADE ( n--) FLUFFIES +! ;

: SOLD ( n--) NEGATE FLUFFIES +! ;

2Ø CONSTANT FLUFFIES-PER-HOUR

: HOURS-WORKED ( n--) FLUFFIES-PER-HOUR * MADE ;

1Ø CONSTANT FLUFFIES-IN-BOX

: BOXES-SOLD ( n--) FLUFFIES-IN-BOX * SOLD ;
```

You may be thinking that it would be easier just to include 2Ø and 1Ø in our programs instead of the constants **FLUFFIES-PER-HOUR** and **FLUFFIES-IN-BOX**. There are two main advantages to using constants rather than their values. The first is concerned purely with readability. Remember that you may have to correct problems or make changes to programs well after they were originally created. The word **FLUFFIES-IN-BOX** tells you exactly what meaning the value has, whilst just 1Ø gives you no clue as to what it represents.

The other great advantage in using constants is that if, for instance, you started using bigger boxes to pack your fluffy toys you need only change the value set up as **FLUFFIES-IN-BOX** (and recompile the programs) to institute the change throughout the application. This makes the source code much easier to adapt to different constraints, in this case allowing the same code to be used for many different fluffy toy factories simply by changing the values of the constants used. Without the use of constants we would have to search the entire source code for references to the value in question to achieve the same result. In extensive applications this can take considerable time and effort!

Words introduced in this section:

VARIABLE (NAME)
Creates a variable named (NAME) and allocates a cell of memory. When (NAME) is used the address of the cell is left on the stack.

? (addr--)
Equivalent to @ . in that it prints out the contents of the address on the stack.

n **CONSTANT** (NAME)
Creates a constant named (NAME) which when used will leave the value n on the stack.

NEGATE (n--n)
Reverses the sign of the top stack item.

* (n,n--n*n)
Takes the top two stack items and multiplies them together leaving the product.

5.4 Naming conventions

You can see from the names we have chosen for our programs that Forth is not particular about what you choose to call your words. Clearly, however, it pays to use names which actually mean something to you, and which to some extent describe the action of the word. In this way your programs can be made highly readable and may end up looking almost like English.

When a system stores the entire name of a word in the dictionary long names will result in more memory being used. Because Forth is so compact in this respect anyway you shouldn't find that this is a problem except in very large applications. Thus the only disadvantage in using long descriptive names is the time it takes to key the programs in.

Many systems only store the first three characters of a name together with a count of the actual number of characters. In such cases we say that only three characters are significant. This would mean, for instance, that the names **FLUFFIES-MADE** and **FLUFFIES-SOLD** would be indistinguishable to Forth since they both consisting of 13 characters and start with **FLU**. If your system does behave like this you should always bear it in mind when thinking up program names.

Often it is possible to alter the number of significant characters in a program name. Generally up to a maximum of 31 characters can be made significant. The number of significant characters is usually held in a variable called **WIDTH**, though the mechanism by which it is changed

varies. PolyForth treats **WIDTH** as two byte variables (instead of a single cell), one containing the significant characters for the very next word to be created (in **WIDTH**) and the other the default number of significant characters (**WIDTH 1+**). In this case to set the number of significant characters permanently to its maximum of 31 the following phrase must be used:

```
31 WIDTH C! 31 WIDTH 1+ C!
```

Other systems may include **WIDTH** as a constant just for reference purposes. This facet of your system should be well documented in the programmer's manual.

There are two ways in which your words can be made more readable. One is to give them names which relate to their specific function within the application. The words defined in the previous section are a good example of this approach. Another technique involves the use of common prefixes or suffixes (i.e.characters attached to the beginning or end of names) to indicate the sort of action the word has. The word **STOCK?**, for instance, ends with a question mark to indicate that it is expected to retrieve some information.

Although Forth programmers share some similar conventions in terms of word names – at least as regards their general type of function – in the final analysis it is largely a question of personal preference and convenience. It is well worthwhile developing a consistent general approach to the naming of programs for your own applications.

Throughout this book you will find references to standard naming conventions for particular types of Forth word. You should try to integrate these into your own system, since even if nobody else is likely to read your programs it will help you to understand other people's source listings.

6 Making decisions

6.1 The IF...ELSE...THEN structure

One of the most vital facilities in any programming language is the ability to make decisions so that appropriate actions can be performed in a variety of different circumstances. Forth provides a particularly elegant structure in this respect. Three separate Forth words are involved, **IF**, **ELSE** and **THEN**. Each time an **IF** is used it must be matched by a **THEN**, whilst the **ELSE** is optional. They can thus be used in the following ways:

(condition) **IF** (code executed only if condition true) **THEN**

(condition) **IF** (code executed only if condition true)
ELSE (code executed only if condition false)
THEN

Note that the layout of the second example is for cosmetic purposes only (Forth never minds how programs are laid out as long as the words are in the right order). The word **IF** expects a number on the stack which it interprets as a flag. The flag is deemed true if it is not zero and false otherwise. To investigate how this works first define the following programs:

```
: .TRUE  CR ." TRUE CODE EXECUTED" ;
: .FALSE  CR ." FALSE CODE EXECUTED" ;
```

The dot prefix is to indicate that these words print out something to the screen. Now define the following word to inform you of the decision made by **IF**:

```
: FLAG? ( f--) IF .TRUE
               ELSE .FALSE
               THEN ;
```

Try passing a selection of values to this word as in the examples below:

```
1 FLAG? <RETURN>

Ø FLAG? <RETURN>

3 FLAG? <RETURN>

-1 FLAG? <RETURN>

1ØØØ FLAG? <RETURN>
```

It should be clear that the only time that **FLAG?** prints out 'FALSE CODE EXECUTED' is when it finds a zero on the top of the stack. Under all other circumstances it prints 'TRUE CODE EXECUTED'. Note that only the code between the **IF** and the **THEN** is affected by the decision. This can be illustrated by feeding a similar selection of values to the following program:

```
: FLOW ( f--) CR ." BEFORE IF"
     IF   CR ." BETWEEN IF AND ELSE"
     ELSE CR ." BETWEEN ELSE AND THEN"
     THEN CR ." AFTER THEN" ;
```

It cannot be stressed enough that whenever **IF** is used it must find a subsequent **THEN** in the same definition. **ELSE** is optional but can only be used once between each **IF...THEN** pair. If you try to use any of these words without regard for these rules the offending program will either fail to compile or simply not work.

Words introduced in this section:

IF...ELSE...THEN (f--)
If the flag on the stack is non-zero at **IF** execution proceeds as normal to the **ELSE** (or **THEN** in the absence of an **ELSE**) and the code between **ELSE** and **THEN** is ignored. If the flag on the stack is zero the code between the **IF** and the **ELSE** is ignored and execution proceeds from after the **ELSE**. In both cases any code after the **THEN** is executed as normal.

6.2 Using flags

Before we look more closely at how flags are generated the idea warrants some further discussion. Interpreting numbers on the stack as flags is commmon to many Forth words. Although any non-zero value will be treated as true the label is meant to refer to a 1 as opposed to a 0. All the words which perform comparisons introduced in the next section leave one of these two values on the stack. Despite this, with a little care any number can be used as a flag and you will find various examples throughout this book of how to take full advantage of Forth decision making.

It is worth pointing out at this stage that the word **IF** does not care how a flag gets onto the stack, just as long as it is there. In order to make the flow of your programs easier to follow, however, it is best to include the coding which produces a flag (i.e. the condition) in the same program as its consequences. Similarly, if extensive coding is to be used between **IF**, **ELSE** and **THEN** it should be defined as a separate word, as in **FLAG?** above.

6.3 Number comparison

We have seen how the word **IF** expects a number on the stack which it treats as a flag. Clearly this would be very limiting if there were not convenient ways of making complex decisions. Forth provides a number of words to help with this under the general heading of 'comparison'. Their actions are as follows:

= (n,n--f)
Expects two numbers on the stack. Leaves a true flag if they are equal, otherwise leaves a false flag.

< (n1,n2--f)
Less-than. Expects two numbers on the stack. Leaves a true flag if n1 is less than n2, otherwise leaves a false flag. Note that it leaves a false flag if the two numbers are equal, also that it treats the numbers as signed integers.

> (n1,n2--f)
Greater-than. Expects two numbers on the stack. Leaves a true flag if n1 is greater than n2, otherwise leaves a false flag. Note that it leaves a false flag if the two numbers are equal, and that it treats the numbers as signed integers.

U< (n1,n2--f)
U-less-than. Expects two numbers on the stack. Leaves a true flag if n1 is less than n2, otherwise leaves a false flag. Note that it leaves a false flag if the two numbers are equal, and that it treats the numbers as unsigned integers and is hence used mainly for memory addresses.

0= (n--f)
Zero-equal. Expects one number on the stack. Leaves a true flag if it is zero, and a false flag otherwise.

NOT (f--f)
Expects one number in the stack. Leaves a true flag if it is zero, and a false flag otherwise. Its action is exactly as 0= i.e. it reverses the truth value of the item on the stack.

0< (n--f)
Zero-less-than. Expects one number on the stack. Leaves a true flag if it is negative, leaves a false flag if it is positive or zero.

0> (n--f)
Zero-greater-than. Expects one number on the stack. Leaves a true flag if it is positive, leaves a false flag if it is negative or zero.

The simplest of these is = which leaves a 1 if the two numbers on the stack are equal and otherwise a zero. Its action can be demonstrated either by simply typing examples in and printing the flag as in:

13 2 = . <RETURN>
5 5 = . <RETURN>

or by using the following simple program:

```
: EQUAL? ( n,n--) = IF   CR ." NUMBERS ARE EQUAL"
  ELSE CR ." NUMBERS ARE NOT EQUAL"
  THEN ;


12 3 EQUAL? <RETURN>


2 2 EQUAL? <RETURN>
```

The operator = is often used with a constant to determine when some predefined condition has occurred. Suppose you were organizing a rock concert and the venue could only hold 500 people. To keep track of the number of fans arriving the word 1FAN is defined to add one to a variable used as a count:

VARIABLE (FANS)
: 1FAN 1 (FANS) +! ;

Using a constant for the maximum capacity of the venue, a word can be created to issue a message when the hall is full:

```
500 CONSTANT MAXFANS
: FULL? (FANS) @ MAXFANS =
                    IF CR ." FULL HOUSE !" THEN ;
```

These definitions can then be combined to produce a word to be keyed in each time somebody walks through the door:

```
: FAN 1FAN FULL? ;
```

To test this word you should initialize the variable (**FANS**) to about 495 before you start keying in **FAN** – otherwise you'll have to do it 500 times!

It would be much more convenient if we could check in more than one arrival at a time, since people tend to arrive at such events in groups. To increment the head count in (**FANS**) the following simple program can be used:

```
: +FANS ( n--) (FANS) '+! ;
```

If this were used the value of (**FANS**) might never be exactly equal to 500, since a group of 5 might arrive when it was set at 498 giving a total of 503. In order to avoid overcrowding we must therefore check that the value in (**FANS**) does not exceed the maximum capacity; and this must be done before the new arrivals are allowed to enter. We can use @ for this:

```
: CHECK-SPACE (FANS) @ MAXFANS >
                          IF ." NO ROOM" THEN ;

: FANS ( n--) +FANS CHECK-SPACE ;
```

You should try developing some similar programs of your own to investigate the actions of the other comparison words. Remember that all of them can be entered interactively, and as long as you take care to set up the appropriate numbers on the stack their activity can very easily be investigated.

Words introduced in this section:

= (n,n--f)
Expects two numbers on the stack. Leaves a true flag if they are equal, otherwise leaves a false flag.

< (n1,n2--f)
Less-than. Expects two numbers on the stack. Leaves a true flag if n1 is less than n2, otherwise leaves a false flag. Note that it leaves a false flag if the two numbers are equal, and that it treats the numbers as signed integers.

> (n1,n2--f)
Greater-than. Expects two numbers on the stack. Leaves a true flag if n1 is

greater than n2, otherwise leaves a false flag. Note that it leaves a false flag if the two numbers are equal, and that it treats the numbers as signed integers.

U< (n1,n2--f)
U-less-than. Expeets two numbers on the staek. Leaves a true flag if n1 is less than n2, otherwise leaves a false flag. Note that it leaves a false flag if the two numbers are equal, and that it treats the numbers as unsigned integers and is henee used mainly for memory addresses.

0= (n--f)
Zero-equal. Expects one number on the stack. Leaves a true flag if it is zero, and a false flag otherwise.

NOT (f--f)
Expects one number in the stack. Leaves a true flag if it is zero, and a false flag otherwise. Its action is exactly as 0= i.e. it reverses the truth value of the item on the stack.

0< (n--f)
Zero-less-than. Expeets one number on the stack. Leaves a true flag if it is negative, leaves a false flag if it is positive or zero.

0> (n--f)
Zero-greater-than. Expects one number on the stack. Leaves a true flag if it is positive, leaves a false flag if it is negative or zero.

6.4 Logieal operators

Forth provides three more words which are frequently used in conjunetion with IF...ELSE...THEN. These are called *logical operators*, and they effectively eombine the results of two related comparisons into a single flag. The relevant words are AND, OR and XOR. All of these expect two flags on the stack, whieh they replace with a single flag. Beeause of the way they work it is important that they should only be used with genuine flags (i.e. 1 or 0), otherwise they will give unpredictable results. The reason for this will be discussed further, with examples, in Chapter 8.

The operation of each of these words on the possible combinations of flags is illustrated by keying in the following phrases:

```
0 0 AND . <RETURN> 0 ok

0 1 AND . <RETURN> 0 ok

1 0 AND . <RETURN> 0 ok
```

```
1 1 AND . <RETURN> 1 ok

0 0 OR . <RETURN> 0 ok

0 1 OR . <RETURN> 1 ok

1 0 OR . <RETURN> 1 ok

1 1 OR . <RETURN> 1 ok

0 0 XOR . <RETURN> 0 ok

0 1 XOR . <RETURN> 1 ok

1 0 XOR . <RETURN> 1 ok

1 1 XOR . <RETURN> 0 ok
```

You will find numerous examples of the use of logical operators throughout this book, since **AND** and **OR** particularly are amongst the most commonly used Forth words.

Words introduced in this section:

AND (f,f--f)
Expects two numbers on the stack. Returns true if both numbers are true, and false otherwise.

OR (f,f--f)
Expects two numbers on the stack. Returns true if either or both of them are true, and false only if both are false.

XOR (f,f--f)
Exclusive-or. Expects two numbers on the stack. Returns true if only one of these is true, and false if both are true or both are false.

---

7 Using the stack

7.1 Stack manipulation

It has been shown that all Forth words communicate via the stack. All parameters are found on the stack and all results returned there. It often happens that we require the same parameters for more than one word within a single outer program. Consider the following little routine which accepts a 10 character input from the keyboard and echos it back to the screen.

```
: ECHO ( --- ) PAD 10 BLANK
      PAD 10 EXPECT
      SPACE
      PAD 10 TYPE ;
```

The values **PAD** and 10 are used thrice within the confines of a single program to specify the string address. Now suppose we wish to modify the behaviour of **ECHO** so that we may vary the length of the string by leaving the desired length on the stack. The first problem is that we must somehow get the value **PAD** 'under' the count value within **ECHO**. This could be achieved by using a variable to hold the count value while we are working.

```
VARIABLE CHARS ( Character count )

: ECHO ( n --- ) CHARS !
        PAD CHARS @ BLANK
        PAD CHARS @ EXPECT
        SPACE
        PAD CHARS @ TYPE ;
```

This is a perfectly acceptable method, particularly if the phrase **PAD CHARS @** is factored out into a separate word:

```
: STRING ( addr,ct---) PAD CHARS @ ;

: ECHO ( n --- ) CHARS !
        STRING BLANK
        STRING EXPECT
        SPACE
        STRING TYPE ;
```

The first action of **ECHO** is to store its parameter thus removing it from the stack. Only moments later, however, it it is retrieved by **STRING** for **BLANK** to use. This is not particularly efficient. Forth simplifies the use of the stack by providing a set of routines which allows us to conserve stack values and generally to juggle with them. These routines collectively known as the 'stack operators' are particularly speedy and efficient. Mastery of their use is essential to practical Forth programming.

The actual operation of the stack operators is meaningless outside the context of the programs in which they are used and some will not be required until later in the book. They are given here along with their effects on the stack followed by a few short examples of their use, and you should completely familiarize yourself with their action by experimenting at the keyboard and studying the cxamples since no further explanation will be given. To assist in this you should make use of the word .S if it is present on your system. This will print all the values on the stack without removing any of them. If this useful word is not present you can use the definition in Chapter 9. Edit it onto a block, save it, then load it and check its correct operation with the following sequence:

. <RETURN>

Do this repeatedly until the system issues a "stack empty" message then key in:

```
.S <RETURN> Stack empty ok

4 3 2 1 .S <RETURN> 4 3 2 1 ok

.S <RETURN> 4 3 2 1 ok

. <RETURN> 1 ok

.S <RETURN> 4 3 2 ok
```

Any departure from this behaviour means that .S is not working correctly so your source code should be carefully checked against that in the book and any differences corrected before reloading the block. Remember to

clear the stack when you are sure .S is working. Once .S is working correctly it should be used whenever you wish to know the current state of the stack, and may be edited into the sample programs so that their mechanisms may be observed.

All Forth systems include the following stack operators:

Stack before	Name	Stack after	Action
n---	**DUP**	---n,n	Duplicates the top stack value.
n---	**DROP**	---	Discards the top stack value.
n1,n2---	**SWAP**	---n2,n1	Exchanges the top two values.
n1,n2---	**OVER**	---n1,n2,n1	Copies the second value to the top.
n1,n2,n3---	**ROT**	---n2,n3,n1	Rotates the third value to the top.

Consider how these could be used in place of the variable **CHARS** in the execution of **ECHO**:

```
: ECHO ( n---) PAD ( n,addr--)
      SWAP ( addr,n--)
      OVER ( addr,n,addr--)
      OVER ( addr,n,addr,n--)
      BLANK ( addr,n--)
      OVER ( addr,n,addr---)
      OVER ( addr,n,addr,n---)
      EXPECT ( addr,n---)
      SPACE TYPE ;
```

Having set up the parameters in the correct order with **PAD SWAP** the phrase **OVER OVER** is used prior to the first two string operations so as conserve them for later use. The need to duplicate the top two stack values occurs so frequently that it is worthwhile defining a new stack operator for this very purpose. Some systems come already equipped with the word **2DUP**, which may be defined:

```
: 2DUP ( n1,n2--n1,n2,n1,n2) OVER OVER ;
```

This may now be used to simplify the definition of **ECHO** as follows.

```
: ECHO ( n---) PAD SWAP
      2DUP BLANK
      2DUP EXPECT
      SPACE TYPE ;
```

Words introduced in this section:

DUP (n---n,n)
Duplicates the top stack value.

DROP (n---)
Discards the top stack value.

SWAP (n1,n2---n2,n1)
Exchanges the top two values.

OVER (n1,n2---n1,n2,n1)
Copies the second stack item to the top.

ROT (n1,n2,n3---n2,n3,n1)
Rotates the third stack item to the top.

2DUP (n1,n2---n1,n2,n1,n2)
Duplicates the top two stack items.

.S (---)
Prints out all numbers on the stack without affecting it.

7.2 The stack and arithmetic

The stack operators described in the previous section are used extensively in conjunction with the arithmetic operators to perform calculations according to mathematical formulae. The following routines will illustrate some of the basic concepts. Among the first examples of stack use given in many introductory texts is a routine to produce the square of a given number. The number must be multiplied by itself so it is appropriate to use **DUP** to generate the correct parameters for * to produce the square. Below are three simple examples of using DUP to produce useful arithmetic results.

```
: SQUARED ( n---n*n) DUP * ;

: CUBED ( n---n*n*n) DUP DUP * * ;

: 2* ( n ---2n) DUP + ;
```

The word **2*** is extremely useful in Forth programming particularly when

calculating addresses and is often a resident part of the system. If it is not then the definition above is the simplest, whereby the number is doubled by adding it to itself.

A simple use of the routines **SQUARED** and **CUBED** is to calculate the volume and surface area of a cube given the length of its sides:

```
VARIABLE SIDE

6 CONSTANT FACES

: INCHES ( n---) SIDE ! ;

: AREA ( ---n) SIDE @ SQUARED ;

: VOLUME ( ---n) SIDE @ CUBED ;

: SURFACE ( ---n) AREA FACES * ;
```

The variable **SIDE** is used to hold the length of a side. In this case the units of length are assumed to be in inches, but any other unit will do just as well. The value of **SIDE** is set by **INCHES** so that:

10 INCHES <RETURN> ok

means we are dealing with a 10 inch cube. The statistics for the cube may now be obtained by keying in:

VOLUME . SURFACE . <RETURN> 1000 600 ok

The cube has a volume of 1000 cubic inches and a total suface area of 600 square inches. The area of any one face of the cube is produced by **AREA** which is then multiplied by the number of faces in a cube (6) defined as the constant **FACES**. Try out these routines for different sizes of cube using **INCHES**. They have the following limitations: when **SIDE** is set to values greater than 40 the operation of **VOLUME** breaks down since a 16-bit number is too small to hold the result of cubing a number greater than this:

40 INCHES VOLUME U. <RETURN> 64000 ok
41 INCHES VOLUME U. <RETURN> 3385 ok

The result given for a 40 inch side falls just within the range of an unsigned 16-bit number (max 65535), and adding just one unit to the side length pushes the **CUBED** result completely out of range. The operation of **SURFACE** breaks down more slowly since we are only squaring and multiplying by 6. The limiting value for **SIDE** is in this case 104 inches.

```
104 INCHES SURFACE U. <RETURN> 64986 ok

105 INCHES SURFACE U. <RETURN> 614 ok
```

A further limitation is that a negative value fed to **INCHES** will make a complete nonesense of **VOLUME**, but then cubes never have negative side lengths!

One thing these routines demonstrate is the variety of different ways by which we perform long term and short term storage. The stack is used to hold values for short periods while they are required for calculations. Thus **CUBED** keeps the initial value on the stack while the square is produced and then multiplies these two values to produce the final result. In other instances a word may hold a value on the stack for even longer periods, but always within the confines of a single definition. When **INCHES** is used to set up **SIDES**, the value is for long term storage, since we may wish to use it for a number of purposes over an indefinite period. The value is held in **SIDE** until we change it again by using **INCHES**. The stack is far too busy a place to be used for long term storage which will carry across the execution of more than one outer level word.

7.3 Looking at the stack in more depth

In addition to the stack operators mentioned your system may include the following:

DEPTH (---n)
Returns to the top of the stack the total number of values on the stack prior to its own execution.

PICK (n---)
Copies to the top of the stack the nth value down, such that 2 **PICK** is equivalent to **OVER**.

ROLL (n---)
Removes the nth stack value from its position in the stack and returns it to the top. All other values are effectively pushed down so that 3 **ROLL** performs the same action as **ROT**.

The words **PICK** and **ROLL** are limited in their uses, since the stack is normally kept as small as possible. They should operate in the following manner.

```
5 4 3 2 1 .S <RETURN> 5 4 3 2 1 ok

5 ROLL .S <RETURN> 4 3 2 1 5 ok

5 ROLL .S <RETURN> 3 2 1 5 4 ok
```

```
3 PICK .S <RETURN> 3 2 1 5 4 1 ok

3 PICK .S <RETURN> 3 2 1 5 4 1 5 ok
```

The word **DEPTH** is, however, a very useful debugging tool, giving an absolute measure of the stack depth. It has been used in the definition of .S to determine how many items are to be printed. The action of **DEPTH** may be observed using the following sequence of commands after first clearing the stack:

```
DEPTH .S <RETURN> 0 ok

DEPTH .S <RETURN> 0 1 ok

DEPTH .S <RETURN> 0 1 2 ok

DEPTH .S <RETURN> 0 1 2 3 ok

DEPTH .S <RETURN> 0 1 2 3 4 ok
```

The Forth word **DROP** is used to remove unwanted values from the stack. Its only function is to increment the stack pointer by two so that the top item is effectively lost. There are a number of regularly occurring instances when this is required. One of the most common being inside the conditional structure **IF**...**ELSE**...**THEN** encountered in the last chapter. As a simple example of this the definition of **INCHES** from the previous section may be changed so as to include a check to ensure that a valid result will be produced by **VOLUME**:

```
: INCHES ( n---) DUP 41 <
        OVER 0> AND
        IF SIDE !
        ELSE DROP ." Side length out of range"
        THEN ;
```

The value given to **INCHES** is first tested non-destructively to ensure it falls in the range 1–40 inclusive, as values outside this range will not yield meaningful results. The value is only stored in **SIDE** if it is greater than zero and less than 41. The conditional flag is generated for the **IF** by the first two lines of code. The effects on the stack are:

Operation	Stack effect
	---n
DUP 41 <	---n,f
OVER 0>	---n,f,f
AND	---n,f

The word 0> is a 79-Standard comparison and may be substituted by 0 > if required. If the resultant flag is false the value is not required for storage and so a **DROP** is executed in the **ELSE** 'clause' of **INCHES** prior to issuing an error message. Note that it is assumed that the word **INCHES** will only be used from the keyboard, rather than in other programs. More generally, the **ELSE** clause would include the word **ABORT** following the message rather than **DROP** since **ABORT** clears the stack and returns control to the keyboard immediately.

Checking whether a value falls within some range of values is a very common operation in computer programming and some Forth implementations include an additional conditional test specifically for this purpose. The word is **WITHIN** which takes three parameters; the value to be tested as third stack parameter, the lower limit of the range as second, and the upper limit plus 1 as the top. If you already have a **WITHIN** on your system it should operate as follows:

```
20 20 30 WITHIN . <RETURN> 1 ok

19 20 30 WITHIN . <RETURN> 0 ok

29 20 30 WITHIN . <RETURN> 1 ok

30 20 30 WITHIN . <RETURN> 0 ok
```

If you do not have a resident **WITHIN** then the following definition is not only a useful addition to the Forth vocabulary, but it is also a classic example of the short term use of the stack in conjunction with comparisons and a logical operation.

```
: WITHIN ( n,lo,hi+1---f) ROT SWAP
        OVER >
        ROT ROT > 0=
        AND ;
```

To fall within range the value must be greater than or equal to the lower limit or, seen another way, the lower limit of the range must not be greater than the value. The condition is generated in this form using the word 0=

to reverse the truth value of the flag so as to read true if the lower limit is not greater. Some systems include the word **NOT** to do this, its action being identical to **0=**. **WITHIN** may now be used to simplify the code for **INCHES** by making the following additions to the source block and reloading.

```
: RANGE ( ---lo hi+1) 0 41 ;

: INCHES ( n ---) DUP RANGE WITHIN
IF SIDE !
ELSE DROP ." Side length out of range"
THEN ;
```

The action of **INCHES** is now much more apparent from reading the source code, since most of the stack manipulation has been removed to a lower level program (**WITHIN**). It is also very easy to adjust the check to operate on a different valid range simply by altering **RANGE**. It should be noted that during the execution of **WITHIN** inside the definition of **INCHES** the stack reaches a maximum depth of five items (immediately following **OVER**), but that as far as **INCHES** is concerned only four items ever appear at one time – immediately following **RANGE**. The actions of the lower level words are transparent to the words which use them; only the before and after stack conditions are significant.

We frequently require that a word should process a value only if it is non-zero. This leads to the use of a structure of the general form:

```
: ACTION ( n---) DUP IF PROCESS ELSE DROP THEN :
```

To overcome the need to employ an **ELSE** clause containing only a **DROP** many Forth systems include the stack operation **?DUP** (**-DUP** in Fig-Forth) which duplicates the top stack item only if if is non-zero. This simplifies the code for the imaginary program **ACTION**:

```
: ACTION ( n---) ?DUP IF PROCESS THEN ;
```

Numerous examples of this techniquc will be encountered in this book, particularly when dealing with controlled repetition. A simple definition of **?DUP** is:

```
: ?DUP ( n--n/n,n) DUP IF DUP THEN ;
```

Words introduced in this section:

DEPTH (---n)
Returns the total number of values on thc stack prior to execution.

PICK (n---)
Copies nth value to the top of the stack, such that 2 **PICK** is equivalent to **OVER**.

ROLL (n---)
Removes the nth stack value from its position and returns it to the top. All other values are effectively pushed down so that 3 **ROLL** performs the same action as **ROT**.

WITHIN (n,lo,hi+1---f)
Leaves true if the number n falls between lo and hi value inclusive, otherwise leaves false.

?DUP (n---n/n,n)
Duplicate the top stack item only if it is not zero.

-DUP (n---n/n,n)
FIG Forth only. Action is same as **?DUP** above.

7.4 The stack versus variables – a short application

As a result of Forth's heavy use of the stack for parameter passing and the efficiency with which the stack operators execute, it is easy for the beginner to run away with the idea that the stack operators should be employed at every opportunity. This is not the case, the key to good Forth programming being structure and simplicity of coding achieved through correct analysis of the problem. Part of the beauty of Forth programs is the ease with which they can be maintained and adapted to cope with new circumstances, due to their extreme modularity. A major factor in program maintenance is the readability of the code and this is certainly not helped by massive clusters of stack operators. The use of named variables, whilst consuming more dictionary space and executing more slowly, leads to far more readable source code and often to a better factored and ultimately more efficient application. This becomes ever more significant the larger the application. In general the bulk of the stack juggling is relegated to a few frequently-used low level words at the heart of the application, the higher level words reading as near to the programmer's native language as possible. The following short application illustrates how most of the facets of Forth covered so far may be combined.

Application
Our fluffy toy company produces cardboard boxes for packaging by cutting templates in the pattern shown in diagram 7.1 from a flat sheet, then folding and glueing up the duplicate faces.

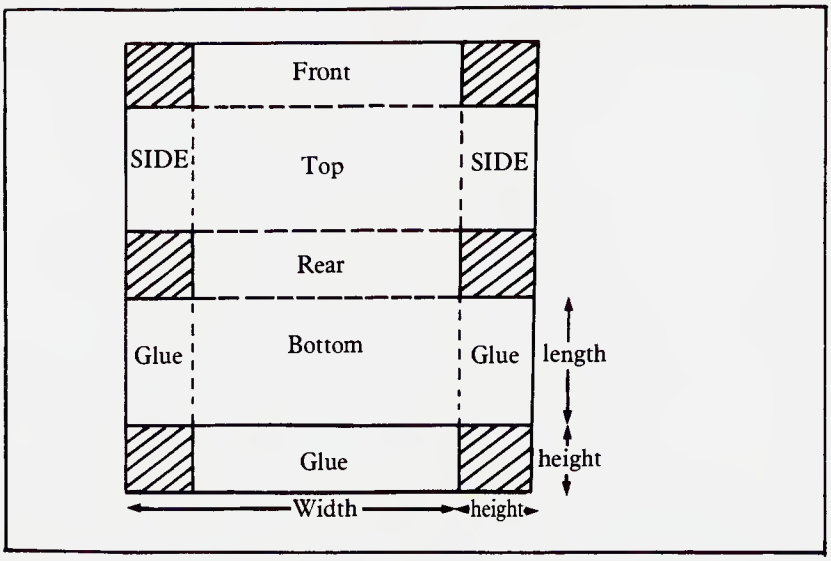


Diagram 7.1. Box template

Batches of different sized boxes must be made and suitable sized sheets ordered as a starting material. In an attempt to optimize production the proprietor decides to write a cardboard-box modelling program for his microcomputer. Consider how this might be approached using Forth as a development medium. The programs will allow experimentation with the dimensions of boxes and sheets so as to find ways of minimizing wastage and determine what materials will be required. The application should also be sufficiently open ended to allow for new functions to be added in the future if required. It will be driven through a set of English language commands issued from the keyboard.

Key commands:

HIGH (n---)
Specify the height of the box.

WIDE (n---)
Specify the width of the box.

LONG (n---)
Specify the length of the box.

SIZE (long,wide---)
Specify the sheet size.

TRY (---)
Test whether a defined box fits on a sheet. If it does the box statistics are printed out, otherwise an appropriate message is issued.

MATERIALS (---)
Print out the number of boxes which can be made from a single sheet, the amount of cardboard used and the total cardboard wastage.

MAKE (n---)
Specify the number of boxes in a batch.

REQUIRED (---)
Print out the number of sheets required to produce a batch.

As far as the calculations are concerned the problems to be solved are similar to those of the CUBE programs. The total volume enclosed by the box may be calculated from:

Volume = length * breadth * height

The total surface area of the completed box can be obtained via the areas of the individual named faces:

Surface = (Top + End + Side) * 2

where:

Top = length * breadth

Side = length * height

End = breadth * height

The total number of box templates obtainable from a single sheet may be computed using the number which fit across and the number which fit down the length:

Boxes = no.across * no.down

where:

no.across = sheet width / template width

no.down = sheet length / template length

and:

template width = (breadth + height) * 2

template length = (length * 2) + (height * 3)

We will use the same principle of setting variables to specify the dimensions of the final box and the starting sheet as was used in the CUBE programs, where **SIDE** was set by **INCHES**.

```
        ( Specify box dimensions )

VARIABLE HEIGHT

VARIABLE BREADTH

VARIABLE LENGTH

: HIGH ( n---) HEIGHT ! ;

: WIDE ( n---) BREADTH ! ;

: LONG ( n---) LENGTH ! ;

 ( Specify sheet size )

VARIABLE SHEET Ø ,

: SIZE ( len,wide---) SHEET ROT OVER ! 2+ ! ;

: AVAILABLE ( ---n) SHEET DUP 2+ @ SWAP @ * ;

        ( Compute Box statistics )

: TOP ( ---n) LENGTH @ BREADTH @ * ;

: END ( ---n) HEIGHT @ BREADTH @ * ;

: SIDE ( ---n) LENGTH @ HEIGHT @ * ;

: VOLUME ( ---n) TOP HEIGHT @ * ;

: SURFACE ( ---n) TOP END SIDE + + 2* ;

: GLUED ( ---n) SIDE 2* END + ;
```

```
: WASTE ( ---n) HEIGHT @ SQUARED FACES * ;

: USED ( ---n) SURFACE WASTE SIDE + + ;
```

The words used to specify the box dimensions should be self-explanatory. In order to avoid a collision of names the sheet size has been treated slightly differently. The variable **SHEET** is used to compile the name and allocate one cell of storage which is to hold the sheet length. An extra cell is reserved for the width and initialized to zero by the phrase 0 , immediately following the definition of **SHEET**. The Forth word , ('comma') takes one value from the stack, stores it in the next available cell in the dictionary (as returned by **HERE**) and increments the contents of the top of the dictionary pointer (in **H** or **DP**) by 2. Try keying in:

HERE DUP U. 0 , @ U. HERE U. <RETURN>

The overall effect is to create a 'double length' variable called **SHEET**. This is set for different sized sheets by **SIZE** which requires two stack parameters; the length and width. The word **AVAILABLE** returns the total area of cardboard available on a single sheet.

The areas of the named faces are returned by **TOP**, **SIDE**, and **END** and these are used in the definition of **SURFACE** to generate the total surface of the box according to the formula given above. Defining these words prior to the definition of **VOLUME** gives us a small bonus, since the word **TOP** does part of the necessary work and must only be multiplied by the contents of height to give the desired result. This leads to a simpler definition than:

: VOLUME (---n) LENGTH @ BREADTH @ HEIGHT @ * * ;

which would have been used otherwise. The total cardboard consumed for each box made is calculated by **USED**, which adds the surface area of the box, the area of duplicate faces to be glued (two sides and an end), and the waste cardboard in the form of the square offcuts. The words **WASTE** and **GLUED** return these latter two values.

```
   ( Materials used )


: ACROSS ( ---n) SHEET 2+ @ BREADTH @ HEIGHT @ 2* + / ;


: DOWN ( ---n) SHEET @ LENGTH @ 2* HEIGHT @ DUP
               2* + + / ;
```

```
: MAKES ( ---n) ACROSS DOWN * ;


: SCRAP ( ---n) AVAILABLE MAKES USED * - ;
```

ACROSS and **DOWN** return the number of templates which will fit across and down a sheet, respectively. They perform their calculations according to the formula given. The width of a template is returned by the phrase:

BREADTH @ HEIGHT @ 2* +

The length of the template (twice the length plus three times the height) is calculated as:

Template length = height + (height + length) * 2

by the phrase:

HEIGHT @ LENGTH @ OVER 2* +

The word **MAKES** returns the total number of boxes per sheet. This enables the total scrap cardboard per sheet to be determined by multiplying the number of boxes per sheet by the cardboard used per box and subtracting from the total cardboard available on a sheet. **SCRAP** performs this task. Although all these results may be output using **U.** the results can be presented in a much more polished form by defining a few output words.

```
        ( Display box dimensions )


: .DIM ( addr---) @ U. ." inches " ;


: .LENGTH ( ---) LENGTH .DIM ." long, " ;


: .HEIGHT ( ---) HEIGHT .DIM ." high " ;


: .WIDTH ( ---) BREADTH .DIM ." wide " ;


: .VOLUME ( ---) VOLUME U. ." cubic inches. " ;


: .BOX ( ---) CR ." The final box will be "
     .LENGTH .WIDTH ." and " .HEIGHT CR
     ." The volume contained will be " .VOLUME ;
```

The phrase @ U. ." inches " has been factored out into the word .DIM since it occurs in each of the dimension display words. This is largely a space saving move, preventing the message 'inches' being compiled three times over. The important box statistics are displayed by .BOX in a descriptive manner.

In order to try boxes for size and give the appropriate output we must include some conditional tests in the definition of the key command TRY. One will be to determine whether such a box can be cut from a given sheet, and – since if any of the box dimensions are zero the results will be absurd – a further test to ensure that all three dimensions have been specified.

```
  ( Try box for size )


: FITS ( ---f) ACROSS 0= DOWN 0= OR NOT ;

: EXISTS ( ---f) LENGTH  @ 0= BREADTH @ 0=  HEIGHT
                 @ 0= OR OR
                 NOT ;


: TRY ( --- ) EXISTS
     IF FITS
        IF .BOX
        ELSE CR ." This box will not fit on a sheet "
        THEN
     ELSE CR ." All three dimensions must be specified "
     THEN ;
```

The conditional test EXISTS returns true if none of the box dimensions contains a zero value. FITS returns true if at least one box can be cut from a sheet. TRY first tests to see if the box exists, and if it does not informs the user that all the box dimensions must be specified for the programs to work, otherwise the box is tested for a fit. If it fits then the box statistics are printed out by .BOX, or else the user is informed that the box will not fit this sized sheet.

The key command MATERIALS must output cardboard usage; the number of boxes per sheet, the total cardboard employed and the total scrap produced.

```
     ( Display material requirement )

: .SHEET ( ---) SHEET DUP 2+ @ U. ." by " @ U. ;

: .MAKES ( ---) MAKES U. ." boxes may be made per "
.SHEET ." inch sheet " ;

: .USED ( ---) ." Each box consumes " USED U.
      ." square inches of scrap per sheet. " ;

: .SCRAP ." This leaves " SCRAP U.  ." square inches
of scrap per sheet. " ;

: MATERIALS ( ---) CR .MAKES CR .USED CR .SCRAP ;
```

The only word here which requires explanation is .**SHEET**, which displays the current sheet size being tested.

Finally, **MAKE** and **REQUIRED** may be defined to specify the number of boxes in a batch and output the number of sheets required for a batch.

```
       ( Batches )

VARIABLE MADE

: MAKE ( n---) MADE ! ;

: SHEETS ( ---n) MADE @ MAKES / ;

: REQUIRED ( ---) CR SHEETS U. .SHEET
." inch sheets are required. " ;
```

Again a variable, **MADE**, is used to facilitate experimentation. It holds the number of boxes in a batch and is set by the key command **MADE**. The number of sheets required is this number divided by the number of boxes per sheet – **MAKES**.

It should be remembered that the above application is subject to the same restrictions on the range of values over which it can successfully operate as were the cube programs. In this case, though, it is more complex to trap this since the calculations involve many more independent variables. Simple tests to exclude negative numbers could be included in each of the words: **HIGH**, **WIDE**, **LONG**, **SIZE** and **MAKE**. This has not been done here for the sake of clarity. Methods of extending the effective range of numeric processing are discussed in the next chapter.

Words introduced in this section:

H (---addr)
Used on some systems as a variable containing the address of the top of the dictionary i.e.the value given by **HERE**.

DP (---addr)
Used on some systems as a variable containing the address of the top of the dictionary, i.e. the value given by **HERE**.

, (n---)
Compiles the number n into the next available cell in the dictionary and increments the dictionary pointer.

8 Numbers and arithmetic

8.1 Number bases

Any number is written down as a sequence of digits, the number 100 has three, 10,000 has five. In everyday life we use a decimal system of numbering, by which we mean that each of the digits in a number can take on any one of 10 different values, i.e. 0 1 2 3 4 5 6 7 8 or 9. A computer works with a binary numbering system where each digit may take on one of only two different values, 0 or 1 (low or high, off or on). The number of values available for a digit in any given numbering system is called the base of the system. Ordinarily, in decimal we are working to base 10, whilst the computer is working to base 2. In practice we may work to any base we choose, although a relatively small selection are in common use.

To observe the effects of changing the number base let us return to digital counters as used in Chapter 4. The example used was a binary counter illustrating how numbers are held in binary form. Consider now digital counters which work to the bases 4, 8 and 10. The results of successive increments on each of the counters are shown overleaf.

Base 4	Base 8	Base 10
000	000	000
001	001	001
002	002	002
003	003	003
010	004	004
011	005	005
012	006	006
013	007	007
020	010	008
021	011	009
022	012	010
023	013	011
030	014	012
031	015	013
032	016	014
033	017	015
100	020	016
...	...	...
...	...	...
333	...	...
000	...	...
	777	...
	000	...

The results show that by the time the decimal counter has reached 16, the base 8 and base 4 counters have reached 20 and 100 respectively. These are three radically different digit patterns, but since they were produced by exactly the same number of increments, the values they represent must be one and the same. The reason is that in each form of number a different significance or 'weight' is attached to the respective digits.

The three counters are initially set to zero and for three counts all three show the same value. On the fourth however the base 4 counter has run out of room in the first digit, so this is reset to zero and the second digit incremented giving the number 10. Four counts later the same thing happens, this time giving 20, then after another four 30. The second digit of this counter is used to record the number of groups of four counts which have passed, and the first digit to record the single counts, so that 23 in base 4 means two fours plus three singles which adds up to 11 decimal (the value shown on the base 10 counter). Eventually the base 4 counter reaches 33 and needs to employ a third digit on the next count. At this point a total of four groups of four counts have passed, so the third

digit is used to record the number of groups of 16 counts. Since this third digit can only count up to three, the highest number that the three digit counter can record is 333, which evaluates to:

(3*16) + (3*4) + 3 = 63

On the 64th count it goes round the clock to give zero. Similar things happen with the base 8 and base 10 counters. In each case the true value of the second digit is obtained by multipying the digit by the base. The third digit must be multiplied by the base twice. Thus on the base 10 counter the three digits represent ones, tens and hundreds, while on the base 8 version they represent ones, eights, and sixty-fours. In each case the highest value any digit may attain is one less than the base of the number.

In more general terms the weight attached to the various digits which compose a number is governed by the base as follows:

Base n:-

Digit.....	4	3	2	1	0
Weight....	$*n^{(4)}$	$*n^{(3)}$	$*n^{(2)}$	$*n^{(1)}$	$*n^{(0)}$
Number....	d4	d3	d2	d1	d0

Value = $d4*n^{(4)} + d3*n^{(3)} + d2*n^{(2)} + d1*n + d0$

The rightmost digit of any number is always a record of units. Each successive digit to the left must be multiplied by the base one more times than its neighbour in order to obtain its true significance. The value represented by the whole number is the sum of all the digits each multiplied by its weighting.

You may well wonder why anyone should wish to operate in a base other than 10 since we deal so naturally with the decimal system. Whilst computers cannot help but work in binary, it would clearly be unreasonable to expect anyone to type in long strings of ones and zeros in order to communicate. Mostly we would like to be able to specify numbers in ordinary decimal format, and leave the computer to convert that string of characters to the equivalent binary number. This is exactly what Forth does when we type in a numeric string at the keyboard and a number is placed in binary form on the stack. The reverse conversion process takes place when we output a number using . or U. Then the top stack value is converted to an ASCII string representing the equivalent decimal number and this is typed out at the screen. The mechanisms by which these string/number conversions take place in input and output are discussed later.

Although for the bulk of our processing we prefer to think of numbers in their decimal representations, there are occasions when the actual bit pattern is of interest. For example the ASCII codes returned by KEY for

the alphabetic characters in upper and lower case begin with 65 (A) and 97 (a) and end with 90 (Z) and 122 (z). The binary representations for these codes are:

A	01000001
a	01100001
Z	01011010
z	01111010

The only difference between the upper and lower case characters is the state of bit 5, which tells us whether or not the shift key was pressed at the same time as the character key. Suppose we wish to write a routine which tests a character to see if it is upper or lower case. It will be used in the form:

```
: TEST ( ---) KEY CAPITAL
     IF ." Upper case "
     ELSE ." Lower case "
     THEN :
```

There are two problems encountered in the coding of CAPITAL, which should return a true flag if the character left by KEY is upper case, otherwise false. First we need a method of testing an individual bit within a number to see whether it is a one or a zero, and secondly we need a method of specifying which bit to test. The solution to the first problem is provided by the logical operators AND, OR and XOR. So far these have only been used to operate on values which are either 1 or 0, such as the results of the conditional tests. In fact the words act simultaneously on each bit of a 16-bit number so as to give the following results:

1111111111111111 1010101010101010 AND

gives:

1010101010101010

1111111111111111 1010101010101010 OR

gives

1111111111111111

1111111111111111 1010101010101010 XOR

gives:

0101010101010101

This explains why only values which are either 1 or 0 should be combined by these operators if they are to be used by a conditional structure. Conditional structures in Forth treat all non-zero values as true, but only a zero as false. The difficulty arises when two true values are combined using **AND** or **XOR** if the values are other than 1. For example both four and eight are reasonable true values if used individually. If these true values are **AND**ed together however a false condition arises rather than the expected true.

```
8 0000000000001000  true

4 0000000000000100  true
```

ANDed gives:

```
0 0000000000000000  false
```

This is clearly a logical nonsense even though the bit-wise logic is correct. Similarly **XOR**ing the same two values results not in the expected false condition but in an erroneous true.

```
8 0000000000001000  true

4 0000000000000100  true
```

XORed gives:

```
0 0000000000001100  true
```

The logical operators thus provide us with a method of testing for upper and lower case, since if the ASCII value is **AND**ed with the binary number 100000 all bits in the result will be set to 0 except bit 5. This will be zero only if it was zero in the original key code. The result of this operation will be either 0, if the character is upper case or 100000 binary for lower case. The desired logic condition for **CAPITAL** could then be generated using **0=** to yield 1 for uppercase and 0 for lower case.

All that is now required is a method of specifying the binary number 100000 to the Forth compiler. One method would be to work out the decimal equivalent and use that in the definition. A better way would be if we could use the binary representation in the program, since it would be much clearer what the program was actually doing and would also save the trouble of performing the binary-to-decimal conversion ourselves. In Forth we may change the working base of the system by altering the contents of the variable **BASE**. The contents of **BASE** can be set to 10 by executing the word **DECIMAL**. This is the default condition for **BASE** adopted on start up. In order to have the Forth interpret binary numeric strings as numbers the contents of **BASE** must be set to two. This is best done by defining a word:

```
: BINARY (---) 2 BASE ! ;
```

If **BINARY** is executed Forth will no longer make any sense of decimal numbers, but it will convert strings of ones and zeros to binary numbers on the stack. It will also output all numbers from the stack in binary format. Try typing:

```
DECIMAL 65 BINARY U. DECIMAL <RETURN> 01000001 ok
```

We now have the tools necessary to construct the word **CAPITAL** and complete the definition of **TEST**.

```
BINARY
: CAPITAL ( char---f) 100000 AND 0= ;
DECIMAL
```

Note that the system base was returned to decimal as soon as it became unnecessary to have it work in binary. This is quite normal practice since leaving Forth in bases other than 10 can be very confusing.

The decimal notation for numbers has the disadvantage that it is very difficult to envisage the bit pattern associated with that number, particularly when 16-bits are involved. On the other hand binary notation is very long-winded and requires many more digits to express the number, consequently they are difficult for humans to remember. In order to reach a compromise between these two systems other number bases are employed. They are the octal base 8 and hexadecimal base 16 systems of numbering. These systems allow us to express numbers in a reasonably concise form without losing sight of the bit pattern which they represent. This is because unlike 10, both 8 and 16 are even powers of 2, which allows us to split up a long binary number into a group of smaller binary numbers and represent each of these with one digit in the octal or 'hex' number. As shown using the base 8 digital counter, each octal digit can represent any value between 0 and 7, and is therefore equivalent to 3 bits of a binary number. To convert a 16-bit binary number to its octal equivalent it is first split up into six 3-bit numbers starting from the right, the least significant. Each of these 3-bit numbers is then converted into one octal digit. Thus the binary value 1101011100111001 is converted as follows:

binary	xx1	101	011	100	111	001
converts to						
octal	1	5	3	4	7	1

Since the 16-bit number is divided up starting from the right, bit 15 forms a 3-bit number which may only take on values of 0 or 1. It is very much easier to relate an octal number to the associated bit pattern since we only need ever work with 3 bits at a time, the larger binary value being built up

by combining these. The octal number 146253 converts thus:

octal	1	4	6	2	5	3
converts to						
binary	xx1	100	110	010	101	011

Use of octal notation is most common when working with 12 or 24-bit numbers since these may be split into an exact number of three-bit groups. For 8, 16 and 32-bit work the hexadecimal system is used. Each digit in a hex number can assume any one of 16 values and may thus be used to represent a 4-bit binary number. In order to use hexadecimal digits some extra symbols are required to represent the values 10 to 15. The alphabetic characters A–F are used for this purpose so that the values on a hexadecimal counter would read as follows.

Hex	Decimal
001	1
002	2
003	3
...	.
009	9
00A	10
00B	11
...	.
00F	15
010	16
...	.
01F	31
020	32
...	.
0FF	255
100	256

Conversion from binary to hex is much the same as for octal except that the binary value is split into groups of 4 bits, each of these representing one hex digit.

binary	1001	1010	1111	0011
converts to				
hex	9	A	F	3

hex	C	0	7	E
converts to				
binary	1100	0000	0111	1110

The hex system allows for a very concise notation, and 4-bit binary numbers are almost as easy to deal with as the 3-bit values used in octal. The Forth system can be set to input and output values in hexadecimal by setting the contents of **BASE** to 16 with the word **HEX**. Try:

65535 HEX U. DECIMAL <RETURN> FFFF ok

The largest possible 16-bit number is FFFF in hexadecimal.

When experimenting with different number bases it is convenient to be able to display a number in a base other than the current working base. To do this the contents of **BASE** must be saved prior to altering it and restored after the output has been done. The routine **.BASE** allows us to specify the base in which the output will be performed.

```
: .BASE ( n,base---) BASE SWAP OVER DUP @
   ROT ROT !
   ROT U.
   SWAP ! ;


: .HEX ( n---) 16 .BASE ;


: .DEC ( n---) 10 .BASE ;


: .OCT ( n---)  8 .BASE ;


: .BIN ( n---)  2 .BASE ;
```

These routines allow numbers to be displayed in all of the common bases without affecting the current working base. One use is if we wish to examine the contents of **BASE** itself to determine what the current base is. If this is attempted using:

BASE ? <RETURN> 10 ok

the result will be 10 no matter what **BASE** is set to, since 10 is 2 in binary, 16 in hexadecimal, 8 in octal and so on. The correct way to display the contents of **BASE** is to use:

BASE @ .DEC

which always displays it in decimal notation. Alternatively the nonsense word BASE? with its elaborate cascade of nested IF structures may be used.

```
: BASE? ( ---) BASE @ DUP 10 =
      IF DROP ." decimal "
      ELSE DUP 16 =
           IF DROP ." hexadecimal "
           ELSE DUP 2 =
      IF DROP ." binary "
      ELSE DUP 8 =
           IF DROP ." octal "
           ELSE ." Base " .
           THEN
       THEN
  THEN
      THEN ;
```

Words introduced in this section:

BASE (---addr)
System variable containing the current number base. If examined with BASE ? will always print 10.

DECIMAL (---)
Sets the system number base to decimal.

HEX (---)
Sets the system number base to sixteen.

8.2 Types of numbers

We have seen how the binary numbers in memory can be interpreted in different ways by different Forth words. The type of number encountered so far have included signed and unsigned 16-bit numbers (usually referred to as single numbers) and 8-bit ASCII values (often called characters). It should be noted that 8-bit values still occupy 16-bit cells on the stack but the whole of the high order byte is set to zero. Before going on to discuss other types of number it is worth examining the operation of signed numbers more closely.

A pair of binary numbers may be added together in the same way as a pair of decimal numbers. They are written out one beneath the other and successive digits are then added together in columns, starting from the right. If the sum of two digits results in a value that exceeds the capacity of a single digit then the overflow is carried forward and added into the next

column. Adding two binary values together is simpler than adding two decimal numbers since there are only three possible results from the sum of two bits. If both are 0 then a 0 results. If one is 0 and the other 1 then a 1 results, and if both are 1 then a 0 results and a 1 is carried forward to be added in the next column. Should this carry mean that three 1's must be added together in the next column the the result will be 1 with a 1 carried.

```
e.g.   10  2      10  2      111   7
       10  2     111  7      111   7
       ---  -     ----  -     ----  --
      100  4    1001  9     1110  14
```

Microprocessors perform binary addition in a very similar manner using a *carry* mechanism. The use of a signed representation for a number allows the processor to use the same addition routines to perform subtraction since adding a negative number gives the same result as subtracting the equivalent positive value. We may use the Forth system to see how this is done with binary values. The definitions UP and DOWN are used to increment and decrement a value by one and display the result non-destructively in binary format.

```
: DOWN ( n--- n-1) 1- DUP .BIN ;


: UP ( n--- n+1) 1+ DUP .BIN ;


Execute the sequence:


0 <RETURN>


DOWN <RETURN> 1111111111111111


DOWN <RETURN> 1111111111111110


DOWN <RETURN> 1111111111111101


DOWN <RETURN> 1111111111111100
```

```
UP <RETURN> 1111111111111Ø1

UP <RETURN> 1111111111111Ø

UP <RETURN> 111111111111111

UP <RETURN> Ø

UP <RETURN> 1
```

The first three values obtained from using **DOWN** must clearly be equivalent to -1, -2, an -3. If we perform an addition using one of these values it should give the same result as the equivalent subtraction.

e.g. $3 - 1$ is the same as $3 + -1$:

```
0000000000000011
1111111111111111
----------------------
10000000000000010
```

The carry produced on adding the first digit pair is passed right though the number and finally appears in bit 16. Since there is no bit 16 in a single number this digit is effectively lost and the result is 0000000000000010 (decimal 2) the 'correct' result. When a computer needs to perform a subtraction the first step is to 'negate' the number to be subtracted, it then adds the two values.

A binary number is negated by a process called *two's complement*. The value of each bit is inverted, all zeros becoming ones and all ones becoming zero. The two's complement can then be obtained by adding one to the result. A bit-wise complement can be produced using the Forth word **XOR**.

```
HEX
: INVERT ( n---n) FFFF XOR ;
DECIMAL
```

Two's complements may be produced and displayed in binary using **SHOW**:

```
: SHOW ( n ---) INVERT 1+ .BIN ;

-1 SHOW <RETURN> 1111111111111111

-2 SHOW <RETURN> 1111111111111110

1 SHOW <RETURN> 1

2 SHOW <RETURN> 10
```

The Forth word **NEGATE** is used to return the two's complement of the top stack value.

```
3 NEGATE . <RETURN> -3 ok

-4 NEGATE . <RETURN> 4 ok

0 NEGATE . <RETURN> 0 ok
```

All Forth arithmetic is performed using the two's complement techniques, although it is completely automatic and therefore transparent to the programmer.

In Chapter 7 we encountered the limits of precision of single numbers when calculating squares and cubes. We were restricted to the cube of numbers less than 40 for unsigned numbers. More generally the results of arithmetic operations are treated as signed values, restricting the magnitude of the result to 32767. This can be a severe restriction in some circumstances, particularly when trying to deal with decimal fractions, there being only 4 'safe' digits with which to work. To increase the number of digits (ie. precision) Forth provides operators which act on pairs of 16-bit values as if they were a single 32-bit number. These are held in two contiguous cells in memory, and thus represent two stack items. Like single numbers, double numbers can be treated as signed or unsigned values, with bit 31 being used as the sign bit. The range of values available is dramatically increased by the use of 32-bit numbers. Signed values in the range +2,147,483,647 to −2,147,483,648 may be represented, giving 9 'safe' decimal digits for results. They give an unsigned maximum of around 4.2 billion!

The Forth interpreter recognizes a double number by the inclusion of a full-stop embedded somewhere within the numeric string. Double numbers may be output as signed values with the word **D.**

```
1.00 D. <RETURN> 100 ok


0.20 D. <RETURN> 20 ok


4321. D.<RETURN>  4321 ok


.4321 D.<RETURN>  4321 ok
```

Note that the inclusion of a point within the number has no significance other than to signal to the interpreter that a double length number is to be produced. Most Forth systems allow punctuation other than a decimal point such as commas, dashes and colons. Since a common use of double numbers is to represent decimal fractions the position at which the point occurred in the string is often recorded somewhere in a system variable called **DPL** ('decimal places') which will always contain the number of digits to the right of the decimal point in the last numeric input string. Input of a single number normally leaves **DPL** set to a negative value. If your system has the word **DPL** numeric input should have the following effects:

```
1234 DPL ? <RETURN> -1 ok

. <RETURN> 1234 ok


1234. DPL ? <RETURN> 0 ok

D. <RETURN> 1234 ok


123.4 DPL ? <RETURN> 1 ok

D. <RETURN> 1234 ok


1.234 DPL ? <RETURN> 3 ok

D. <RETURN> 1234 ok
```

```
.1234 DPL ? <RETURN> 4 ok

D. <RETURN> 1234 ok
```

Words introduced in this section:

NEGATE (n---n)
Reverses the sign of the single number on the top of the stack by returning its two's complement.

DPL (---addr)
A variable containing the number of decimal places used in the most recent numeric input.

8.3 Output formatting

We have seen that double numbers may be used to represent decimal fractions in Forth, and that for this purpose the number of digits to the left of the decimal place in a numeric input string is recorded in a variable called **DPL**. In order to do any processing on decimal fractions, however, we need a method of displaying numbers in a fractional format – since **D.** prints out integers only. There is a set of Forth words which allow us to display numbers in any format we choose, and according to any numeric base. The overall process of output formatting is the conversion of an unsigned double number (the top two stack items) to a string of ASCII characters:

<# (---)
Specify the start of a sequence of number formatting operations.

(ud---ud)
Produces one digit from the low order of the double number and inserts the ASCII value for that digit into the output string. The double number is left divided through by the current base.

HOLD (char---)
Inserts the ASCII value on the stack into the next available position in the output string.

#> (d---addr,ct)
Terminates an output formatting sequence. Clears the unwanted double number from the stack and replaces it with the start address and character count of the output string. The values returned are suitable arguments for **TYPE**.

Number formatting is always performed using unsigned double length values. A formatting sequence is always enclosed by the primitives <# and #> and within these the words # and **HOLD** are used to specify the format of the string produced. Successive digits may be produced from the low order of the stack value such that using # on the double number 1234 will insert the ASCII for 4 into the first position in the string and leave the double number 123 on the stack. The next use of # inserts the ASCII for 3 and leaves 12 on the stack and so on. In order to produce all the remaining digits from a double number the additional primitive #S is defined. Normally #S ignores leading zeros, but it always produces at least one digit so that if it acts on a double number zero then one zero will be inserted into the string. **HOLD** enables punctuation such as decimal points and commas to be embedded into the output string. The words #, **HOLD** and #S must never be used without being enclosed between <# and #>.

The use of number formatting is best explained with reference to some examples. For instance to output a double number value representing pounds and pence the definition .**POUNDS** may be used.

```
: . POUNDS ( ud---)
            <# # # 46 HOLD #S 32 HOLD 35 HOLD #>
            TYPE SPACE ;
```

The two digits to the left of the decimal point are produced using # # and then the decimal point is inserted (46 is ASCII for a full stop). The pounds portion of the string is produced by #S and then a space (32 **HOLD**) and a pound sign (35 **HOLD**) are placed at the beginning. 35 is ASCII for the character '#', used in this instance as a substitute pound sign. If your system can display the real thing then the appropriate code may be substituted. Finally the appropriate arguments for **TYPE** are left on the stack by #> which also removes the unwanted double number.

More generally we want to display the results of our double number calculations to a fixed number of decimal places. In the case of values representing decimal currencies two places are normally used. We now have the tools necessary to perform simple 'fixed point' calculations. Suppose we wish to work to two decimal places. A suitable output word could be defined as follows.

```
: #DPLS ( ud---ud ) # # ;


: .FRACTION ( ud---)
   <# #DPLS 46 HOLD #S #>
   TYPE SPACE ;
```

The decimal places are formatted by a separate word #**DPLS** which has

been named with a # prefix to remind us that it must only be used between <# and #>. This operation has been factored out so that it may easily be redefined to cope with a different number of decimal places. We may use this to display the results of double number calculations. Try the following operation:

```
100.00 20.25 D+ .FRACTION <RETURN> 120.25 ok
```

D+ is a double number arithmetic operator. Its action is the same as that of + except that it expects two double numbers as input parameters and returns a double number result. The results of the addition above are 'correct' if all the numbers are viewed as decimal fractions, but only because care was taken with the numbers input. The following sequence gives a 'wrong' result:

```
100.0 20.25 D+ .FRACTION <RETURN> 30.25 ok
```

The error here is not in the addition but in the interpretation we have placed on the numbers input. To us the number 100.0 is exactly the same as the number 100.00 whereas to Forth they are not the same. The two strings will produce a different number on the stack; 100.0 gives the integer value 1000, whereas 100.00 produces the integer 10000. The addition performed by **D+** as with all Forth arithmetic is performed on two integers. The actual addition performed was 1000 + 2025 which equals 3025, which was then displayed with two decimal places. In order to perform fixed point arithmetic successfully using double numbers all numbers input must be 'scaled'. In the above example the 100.0 should be multiplied by 10 to provide for two decimal places. Later on we will be looking at some definitions that automatically perform this scaling function.

Apart from **D+** one other double number operator is always resident on a Forth system. It is **DNEGATE** which returns the two's complement of a double number. Its action is in every way similar to **NEGATE**. By using **DNEGATE** a double number subtraction may easily be defined:

```
: D- ( d1,d2---d1-d2) DNEGATE D+ ;
```

Before using **.FRACTION** with this we need some way of displaying signed double numbers. If **.FRACTION** is used on a negative value it will treat it as a large positive value, and **#S** will attempt to display a huge number of digits. To assist in the display of signed double numbers there is a further number formatting primitive, **SIGN**, which conditionally inserts a minus sign into the string if the third stack item is negative. **SIGN** could be defined in terms of **HOLD**:

```
: SIGN ( n,ud---ud) ROT 0< IF 45 HOLD THEN ;
```

This enables us to format a signed double number given a method of

producing its absolute value. The word **ABS** returns the absolute magnitude of the signed value on the stack. A double number equivalent may be defined using **DNEGATE**:

```
: DABS ( d---ud) DUP 0< IF DNEGATE THEN ;
```

Note that the sign bit of a double number is contained in the high order cell. This can therefore be tested as a single number by **DUP 0<** giving true if the sign bit is set. The value is negated only if it is negative. We may now recode **.FRACTION** so it can handle signed double numbers:

```
: .FRACTION ( d---)
   SWAP OVER DABS
   <# #DPLS 46 HOLD #S SIGN #>
   TYPE SPACE ;
```

The first line of the program saves the sign of the double number as the third stack item, ready for use by **SIGN**. **DABS** is then used to obtain the absolute value of the number prior to formatting. With care fractional additions and subtractions may now be performed and the results displayed.

To format single numbers they must be converted to a double number before using the output formatting primitives. Signed single number values may be formatted by first saving the sign, then producing the absolute value of the number using **ABS**, and finally placing a zero on the stack to act as the high order byte of the double number. The sequence of words which achieves this is:

```
DUP ABS 0
```

and this phrase should prefix any formatting sequence. As a simple example consider the problem of displaying a single number right aligned in a specified column width. Some Forths already have a word to do this called **.R** which takes two stack parameters; the number to be displayed and the column width. Here is a possible definition:

```
: .R ( n,w--- ) SWAP ( save column width)
       DUP ABS 0 ( save sign and make double number)
       <# #S SIGN #> ( format for signed output)
       ROT OVER - SPACES ( print leading spaces)
       TYPE ; ( type output string)
```

Words introduced in this section:

<# (---)
Specifies the start of a sequence of number formatting operations.

(ud---ud)
Produces one digit from the low order of the double number and insert the ASCII value for that digit into the output string. The double number is left divided through by the current base.

HOLD (char---)
Inserts the ASCII value on the stack into the next available position in the output string.

#> (d---addr,ct)
Terminate an output formatting sequence. Clears the unwanted double number from the stack and replace it with the start address and character count of the output string. The values returned are suitable arguments for **TYPE**.

SIGN (n,d---d)
Inserts a minus sign into the next available position in the output string only if n is negative.

8.4 Number input conversion

Until now all numeric input has taken place via the Forth interpreter. Often we want to accept numeric input from within a program, perhaps with a prompt to the user. For this purpose it is useful to have a word which will convert a string input from **EXPECT** to a number on the stack. The Forth interpreter employs a routine which does this, normally called **NUMBER**. **NUMBER** expects a single stack parameter, an address which contains a character count. **NUMBER** converts successive characters in the string working towards high memory. If during this process a valid punctuation mark is encountered a double number will be produced. If a character is found which is neither a valid punctuation mark nor a valid digit then **NUMBER** aborts issuing an error message. **NUMBER** is the word responsible for the setting of **DPL**. The following routine might be used to input a number from the keyboard during execution of another program:

```
: ENTER ( ---d or n)
        PAD DUP 10 2DUP
        BLANK EXPECT
        1- NUMBER ;
```

The value returned by **ENTER** will be a double length value if punctuation is included in the input string, otherwise it will be single length. The inclusion of a minus sign before the number will produce a negative value.

NUMBER is designed to operate in conjunction with another Forth primitive, **WORD**. It requires a single value on the stack representing an ASCII character. **WORD** looks forward from the current position in the input message buffer until it finds the character. The string in between is then copied to the top of the dictionary (**HERE**) with a character count in the first byte. On most systems the address of this count is then returned to the stack. The most common value given to **WORD** is 32, causing it to search for the next space as in:

```
: ECHO 32 WORD COUNT TYPE ;
ECHO XXXX <RETURN> XXXX ok
ECHO Hello <RETURN> Hello ok
```

The word **COUNT** is extremely useful for handling string data. It takes a count address and returns the address incremented by 1 (that of the first character) with the count on top ready for **TYPE**, **FILL** etc. **WORD** can thus very conveniently be used with **NUMBER**. Note that **NUMBER** makes no use of the character count, it merely skips over it.

ENTER will produce a number on the stack from the string that follows it on input:

```
: ENTER 32 WORD NUMBER ;


ENTER 1234 <RETURN>

. <RETURN> 1234 ok


ENTER -12.34

D. <RETURN> -1234 ok
```

All good Forth systems have another string-to-number conversion routine called **CONVERT**. This word is more primitive than **NUMBER**, and is consequently more flexible if more difficult to use. **NUMBER** itself is often defined in terms of **CONVERT**. **CONVERT** is used to convert a portion of a string into a number. It requires two values on the stack; a double number with the count address of the string on the top. As **CONVERT** traverses the string it produces a succession of digits which are added into the double number. Unlike **NUMBER**, **CONVERT** does not abort on encountering a 'non-digital' character; instead it stops execution as normal leaving the

stack with the double number result and the address at which conversion broke down. The operation of **CONVERT** is demonstrated in the following test routines:

```
: DIGITS ( addr --- ) DUP 0 0 ROT CONVERT
    ROT ROT D.
    SWAP - 1- . ." Digits converted" ;


: nn ( addr --- n,addr) 0 0 ROT CONVERT SWAP DROP ;


: DATE ( ---n,n,n) 32 WORD nn nn nn DROP ;
```

DIGITS may be edited into either of the definitions of **ENTER** in place of **NUMBER** since it takes the same parameter. It duplicates the address and places a double number zero on the stack into which the digits can be accumulated. The address is then rotated into the correct position for **CONVERT**. The initial address and that returned by **CONVERT** are used to compute the number of digits converted, and this is displayed along with the value accumulated. **DATE** converts a string representing a date in the form dd.mm.yy into three single numbers on the stack, the top number being the year. The conversion work is done by nn which uses **CONVERT** to produce a single number. Note that **CONVERT** may be used in succession since its input and output stack values are compatible.

Words introduced in this section:

NUMBER (addr---d or n)
Converts the character string at addr1 to a number on the stack. Aborts if string connot be converted.

CONVERT (d1,addr1---d2,addr2)
Converts string at addr1 to double number. New value is added into d1 to produce d2. Addr2 is the address of the first non-convertible character.

8.5 Forth arithmetic

A selection of Forth arithmetic operators has been used so far, and those which perform addition and subtraction and multiplication require little further explanation. All give results which are algebraically correct with respect to the signs of their input parameters, so long as the results fall into the signed range of single numbers. Getting satisfactory results from

calculations using division is rather more tricky. This applies not only to Forth division but to computer division in general.

To a mathematician the result of dividing a number by zero will be infinite. Within computer logic the result of a division by zero is undefined. The result of such a division may be consistent, but will vary between systems. Assuming you never deliberately divide by zero, any such occurrence during program execution indicates a programming error. It is therefore wise to re-define / so that it tests for this condition and aborts execution with a message if it should arise.

```
: / ( n1,n2---n1/n2) DUP
    IF   /
    ELSE ." Division by zero attempted"
ABORT
    THEN ;
```

After a little experimentation with / you should discover a serious limitation on the results produced:

```
10 5 / <RETURN> 2 ok

11 5 / <RETURN> 2 ok

12 5 / <RETURN> 2 ok

13 5 / <RETURN> 2 ok

14 5 / <RETURN> 2 ok

15 5 / <RETURN> 3 ok
```

All the results produced are rounded down so that whilst 2 might be a perfectly reasonable answer in the first 3 divisions, 13 / 5 and 14 / 5 will not give 3 – the nearer answer. The results obtained are the same as when we perform long division when we would say that 14 divided by 5 equals 2 with a remainder of 1. The difference is that normally we will process the remainder in some way, perhaps using it to produce a fraction, or round the result to the nearest integer, whereas in Forth / simply discards remainders.

To allow us to deal with remainders from division, Forth provides two additional operators. They are:

MOD (n1,n2---remainder)
Divides n1 by n2 and returns the remainder of the division.

/MOD (n1,n2---remainder quotient)
Divides n1 by n2 and returns the quotient with the remainder beneath.

A division which will round up or down based on the size of the remainder may be defined by using /MOD. In this example the routine will round up only if the 'fractional' part of the division is greater than 1/2. This condition is met when the remainder is greater than half the divisor, i.e. 100/3 = 3 remainder 10, or 30 and 10 hundredths, so since 50 hundredths is 1/2 the result is rounded down.

```
: /ROUNDED ( n1,n2---n1/n2)
  DUP 2 /  ( ---n1,n2,n2/2)
  ROT ROT ( ---n2/2,n1,n2)
  /MOD ( ---n2/2,rem,quot)
  ROT ROT ( ---quot,n2/2,rem)
  <  ( ---quot,f)
  + ;


14 5 /ROUNDED . <RETURN> 3 ok
```

Note that some systems provide 2/ and 2* as single words. /ROUNDED first computes the number which is nominally 'one half' by halving the divisor. This value is saved for comparison with the remainder produced by /MOD in the phrase:

ROT ROT <

which effectively asks, 'is the remainder greater than one half' and if it is returns a true flag. The need for a conditional structure is avoided by simply adding this flag (either 0 or 1) to the quotient produced by /MOD. When a division is embedded in a more complex calculation the problems associated with getting a reasonable result from the complete calculation become much more tricky. As an example consider how we might calculate the circumference of a circle from its radius using the formula:

circumference = 2 * pi * radius

The problem includes the constant pi, which is not an integer. Ordinarily we might multiply by 3.1428 if the calculation warranted 4 decimal places but we are stuck with integers only. One of the first approximations used for pi was the fraction 22/7. This could be used in the calculation so that;

circumference = 2 * radius * (22 / 7)
This involves two multiplications and a division, and the order in which they occur affects the accuracy of the result. Four possible codings for a circumference routine using the 22/7 approximation are:

```
: CIRC1 ( rad---circ) 2* 22 7 / * ;

: CIRC2 ( rad---circ) 7 / 22 * 2* ;

: CIRC3 ( rad---circ) 2* 7 / 22 * ;

: CIRC4 ( rad---circ) 2* 22 * 7 / ;

: SHOW DUP CIRC1 U. DUP CIRC2 U.
       DUP CIRC3 U. CIRC4 U. ;
```

The table shows the performance of these routines for different magnitudes of the radius, in comparison with the calculator result for exactly the same computation.

Radius	CIRC1	CIRC2	CIRC3	CIRC4	CALCULATOR
10	10	44	44	62	62
100	600	616	616	628	628
1000	6000	6248	6270	62460	6285

In CIRC1 the approximation is divided out before using it in the calculation. Since 22 divided by 7 is 3 in integer arithmetic all we ever compute is 6 * radius. In CIRC2 and CIRC3 we divide by 7 before multiplying by 22, which means that any truncation errors produced by the division are magnified by a factor of 22. The best results are produced by CIRC4, which gives results in accordance with the integer part of the calculator result until it receives a 4-figure input, when its accuracy breaks down. The reason for this is that in order to minimize the error produced by division we have multipled by 22 first. Using 1000 the result is 44000 – a negative number as far as Forth arithmetic is concerned. The division is thus performed on the minus number giving a negative result but since it is displayed with U. the apparently arbitrary value 62460 appears. This can be avoided by putting the 2* at the end of the calculation:

```
: CIRC5 ( rad---circ) 22 * 7 / 2* ;
```

leaving the positive number 22,000 for the division. This leads to reasonable results for the full range of radii 0–1000. If we now try to use CIRC5 with 10000 another snag is encountered. The result of the first operation would be 220,000 – well outside the range of single numbers – giving us no

chance with the rest of the calculation. Fortunately there is a word which overcomes this problem, */ (star slash), which allows us to multiply by a fraction in one step. It requires 3 parameters, a single number, a multiplier, and a divisor.

*/ (n1,n2,n3---n1*n2/n3)

Multiplies n1 by n2 to produce a 32-bit intermediate and divide this by n3 to give a single length result.

What makes this such a useful operation is that the result of the initial multiplication is a double length number, allowing for intermediate values of + or − 20 million. We can incorporate */ into a definition which will compute the circumference of a circle giving good integer results for radii in the the range 0–10,000 thus:

```
: CIRC ( ---c) 22 7 */ 2* ;
```

Similar to */ is the word */MOD which will return the remainder of the division underneath the quotient thus allowing for rounding or other processing. Using */ and */MOD is a very convienient way of handling ratios in Forth programs. One common application for */ is in the calculation of percentages. The definition % returns n2 percent of n1:

```
: % ( n1,n2---n) 100 */ ;
```

This is used in the pricing application at the end of this section to compute discounts based on the quantity of goods ordered.

In addition to those arithmetic operators which use either double or single length data Forth-79 specifies a pair of mixed precision routines for multiplication and division:

U* (un,un---ud)
Multiplies two unsigned 16-bit values leaving an unsigned 32-bit result.

U/MOD (ud,un---urem,uquot)
Divides an unsigned 32-bit value by an unsigned 16-bit value, leaving a single length remainder and quotient – both unsigned.

The main use of these routines is in synthesizing new arithmetic operators of greater precision (see Chapter 9). It is useful to have a selection of mixed length routines to perform signed arithmetic. To assist in this a method of converting a single number into a double number with the same sign is required:

```
: S>D ( n--d) DUP 0<
              SWAP ABS 0
              ROT IF DNEGATE THEN ;
```

The sign of the single number is tested and the flag saved. The number is then converted to its absolute value and a zero placed on the stack as the

high order cell of the new double number. The sign flag is then retrieved as a condition for negating the double number. This may now be used to create mixed addition and subtraction routines:

```
: M+ ( d,n---d) S>D D+ ;
: M- ( d,n---d) S>D D- ;
```

In order to produce a signed mixed multiply, the signs of the numbers can be processed separately and the correct sign applied to the result of an unsigned multiplication:

```
: M* ( n,n---d) 2DUP XOR 0<
                ROT ABS ROT ABS U*
                ROT IF DNEGATE THEN ;
```

The sign of the result is computed by **2DUP XOR** which leaves a minus number if only one of the sign bits is set. The sign flag is generated and saved as the third stack item and the two numbers are converted to their absolute values before multiplying with **U***. The resulting double number is then negated if the third stack item is true.

Application:
A supplier of fluffy toys deals with a mixture of wholesale and retail customers. The toys come boxed in 50s, and various discounts are offered on orders over 2 boxes based on the total quantity ordered according to the structure:

Units	Discount
0 – 99	0
100 – 250	2
250 – 499	5
500 – 750	7
750 +	10

The following programs are used to compute discounts and demonstrate the use of Forth arithmetic in a variety of circumstances.

```
( Quantities ordered )


VARIABLE QTY


: ORDERED ( n---) 0 MAX QTY ! ;
```

```
: PACKS ( ---n) QTY @ 50 / ;


 ( Unit price in pence )

200 CONSTANT UNIT


      ( Discounts )

HERE 2 , 5 , 7 , 10 , CONSTANT RATES

: RATE ( ---n) PACKS DUP
      IF 1- 3 MIN 2* RATES + @ THEN ;

: DISCOUNT ( ---n) UNIT RATE % ;

: PRICE ( ---n) UNIT DISCOUNT - ;

: TOTAL ( ---n) QTY @ PRICE * ;

   ( Display results )

: .VALUE ( n---) 100 /MOD . ." pounds "
        . ." pence " ;

: VALUE ( --- ) ." The total value of the order is "
      TOTAL .VALUE ;

: DISCOUNTED ( ---) ." The amount discounted is "
  DISCOUNT QTY @ * .VALUE ;
```

There are a number of points of interest in this application. **ORDERED** is used to set the variable **QTY** to the total toys ordered. It uses the Forth operator **MAX** which has not yet been introduced. **MAX** takes two stack parameters and treats them as signed values. It leaves on the stack whichever was the largest. In this case it is used to exclude negative numbers from **QTY** since **0 MAX** always leaves either a positive value or a zero. **MAX** is one of a pair of special comparison words, the other being **MIN**, which returns the smaller of two signed single numbers. **MIN** is used in the definition of **RATE** to return the discount rate as a percentage according to the number of whole boxes. The number of whole boxes is returned by **PACKS**. Since we are interested in whole packs and not in any excess it is appropriate to use straightforward integer division for this purpose, the truncated answer being the correct one.

The discount rates have been incorporated into the dictionary in the form of a data table. The appropriate discount rate for a given quantity ordered is returned by **RATE**. **RATE** uses the number of whole **PACKS** of toys to compute the address of the correct item in the rates table and return its contents to the stack. If the order is less than one box there is no discount so an **IF...THEN** structure accesses the rates table only if the value returned by **PACKS** is non-zero, otherwise zero is returned. The cell offset into the table is computed by subtracting 1 from the number of boxes, since the first rate is at offset **0**. The phrase **3 MIN** restricts the offset to the bounds of the table. The actual address of the data required is computed by multiplying the offset by two – two bytes per dictionary cell – and adding this to the address returned by **RATES**. It is from this address that the data is finally fetched.

The computation of prices and discounts is based on a unit price held in the constant **UNIT**. This returns the unit value in pence since we have no way of dealing with decimal fractions yet. All monetary values returned are also in pence and it is left to the display output words to convert them into pounds and pence. This is done by **.VALUE** which takes the number of pence from the stack and uses **100 /MOD** to return the number of pounds with the number of additional pence underneath. The output words **VALUE** and **DISCOUNTED** use **.VALUE** to display pence values as pounds and pence. **VALUE** uses the total **VALUE** of the order as returned by **TOTAL**, and **DISCOUNTED** uses the unit discount to compute the total discount and display it.

Words introduced in this section:

/ (n1,n2---n1/n2)
Divides n1 by n2 and leaves quotient rounded toward zero.

MOD (n1,n2---rem)
Divides n1 by n2 and leaves remainder only. Remainder has same sign as n1.

/MOD (n1,n2---rem,quot)
Divides n1 by n2 leaving remainder and quotient.

***/** (n1,n2,n3---n1*n2/n3)
Multiplies n1 by n2 then divides double precision result by n3 giving single precision quotient.

***/MOD** (n1,n2,n3---rem,n1*n2/n3)
Multiplies n1 by n2 then divides double precision result by n3 giving single precision quotient and remainder.

U* (un,un---ud)
Multiplies two unsigned 16-bit values leaving an unsigned 32-bit result.

U/MOD (ud,un---urem,uquot)
Divides an unsigned 32-bit value by an unsigned 16-bit value, leaving a single length remainder and quotient – both unsigned.

9 Repeating yourself

9.1 Control structures

To exccute programs computers work sequentially through a list of machine instructions. If there were no means of redirecting the flow of progam execution the processor would be limited to running right through memory and back round to the beginning again. This would make for very limited programs. Similarly a Forth program works sequentially through a list of higher level instructions. In order to make the computer truly useful we must be able to alter the course of this sequential execution so that portions of code are only executed under certain circumstances, whilst other portions might be executed repeatedly. In order to allow easy specification of the flow paths in a program most languages incorporatc special instructions called 'control structures'. Forth has a good selection of control structures covering both conditional and repetitive execution.

The structure which deals with linear conditional execution is **IF...ELSE...THEN** which acts as a simple software switch selecting one of two paths for the program to follow according to the results of some test. The effect of such a structure on program execution is show in diagram 9.1.

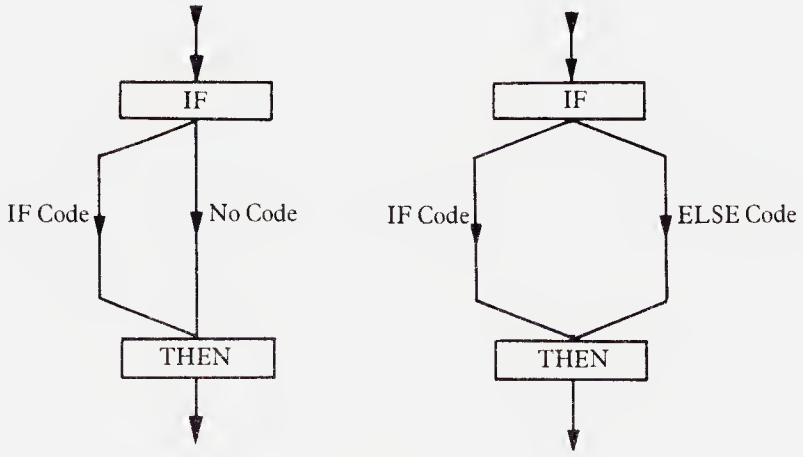


Diagram 9.1. IF . . . ELSE . . . THEN

Computers derive much of their power from the ability to execute simple tasks at very high speeds, so that complex tasks may be eonstrueted by repeating combinations of simple operations.An example of this is the way many eomputers perform multiplication, where, in order to multiply a number by 10, for example, it is added into a total 10 times. In order to allow the programmer eontrol over repetition a set of iterative structures is ineorporated into Forth.

Repetition may be divided into two main categories; definite repetition, and indefinite repetition. An example of the former has already been encountered in SPACES which prints the speeified number of spaees on the sereen. It does so by exeeuting the routine SPACE the number of times indieated by its input parameter. Definite repetition executes a portion of code a fixed number of times. Indefinite repetition, as the name suggests, has no fixed limit on the number of repetitions. It may itself be subdivided into two types; uneonditional (whieh repeats forever), and eonditional (whieh repeats until some condition is met or while some eondition holds true). No explieit example of indefinite repetition has been eneountered yet, although the aetions of the Forth interpreter are an example of the unconditional type, where the keyboard is eontinually monitored for input which is interpreted on receipt of a earriage return. Both conditional and unconditional repetition are eatered for by Forth control struetures.

9.2 Definite repetition – the DO...LOOP

In order to execute a sequence of Forth instructions a fixed number of times the list must be enclosed by the words DO and LOOP. These words must always be contained in a colon definition, and will not work if typed in at the keyboard. DO specifies the start of the instruction sequence and LOOP marks the end of the structure. Control of the repetition is achieved through the parameters passed to DO.

The DO...LOOP strueture keeps traek of the number of passes through the loop by maintaining its own counter. The programmer eontrols the repetition by speeifying the initial and terminal values for the counter as parameters to DO. Eaeh time through the loop the eounter is ineremented by one and compared to the terminal value. If the terminal value has been reached then repetition eeases, and program execution eontinues sequentially with the code following LOOP. When DO executes it takes the top stack item as being the initial value for the count and the second stack item as its terminal value. The value of the count can be returned to the staek from within the structure with the word I which stands for 'index', the name by which this count is known. This is demonstrated in the next definition:

```
: COUNTS ( st end --- ) SWAP DO I . LOOP ;

0 10 COUNTS <RETURN> 0 1 2 3 4 5 6 7 8 9 ok

20 25 COUNTS <RETURN> 20 21 22 23 24 ok

-10 0 COUNTS <RETURN> -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 ok
```

Note that the value of the index is only incremented up to one less than the specified limit. The reason for this is that control over repetition is entirely managed by **LOOP**. The actions of **LOOP** are first to increment the index and then to compare it with the limit. If the index is still less than the limit then the flow of execution is directed back to the code immediately following **DO**. If they are are equal then execution is allowed to pass beyond **LOOP**. Hence the limiting value for the index was never printed out. The effect of the **DO...LOOP** structure on the flow of program execution is shown in diagram 9.2.

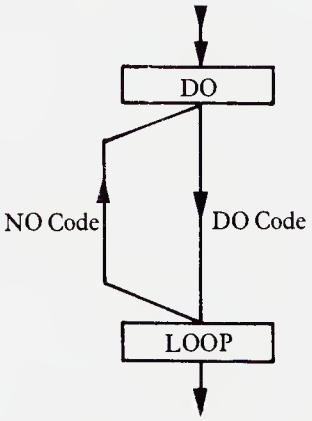


Diagram 9.2. DO . . . LOOP

The initial value to which the index is set is only of interest if the index value is to be used within the structure. Often we merely wish to specify the number of sh to specify the number of times a sequence is to be executed, as in the case of **SPACES**. In such cases the index is normally initialized to zero, as in the following definition:

```
: SPACES ( n---) ?DUP IF 0 DO SPACE LOOP THEN ;
```

The **DO...LOOP** has been encased in an **IF...THEN** structure to avoid execution if **Ø SPACES** is specified. (Remember the index value is not tested until the end of the first pass through the loop.) Note that this is one of the most common uses of the word **?DUP** (**-DUP** on FIG systems). This simple form of **DO...LOOP** can be put to use in recoding the number formatting word **#DPLS** used to produce the fractional part of a numeric output string:

```
: #DIGITS ( n--- ) ?DUP IF Ø DO # LOOP THEN ;


: #DPLS DPL @ #DIGITS ;


: '.' 46 HOLD ;


VARIABLE FIXED


: PLACES ( n---) Ø MAX 6 MIN FIXED ! ;


: .FRACTION ( d---) SWAP OVER DABS
  <# #DPLS '.' #S SIGN #>
  TYPE SPACE ;


: .FIXED ( d---) SWAP OVER DABS
        <# FIXED @ #DIGITS '.' #S SIGN #>
        TYPE SPACE ;


: .CODE ( ud,n---) <# #DIGITS #>
 TYPE SPACE ;
```

The primitive **#DIGITS** is defined to generate the number of digits given on the stack, and is used by the output words **.FRACTION**, **.FIXED** and **.CODE**. The coding of **.FRACTION** is the same as that given in Chapter 8 except that insertion of the decimal point has been factored out into a separate word '.' also used in **.FIXED**. **.FRACTION** now formats the fractional portion of the number as dictated by the current contents of **DPL**, so that if used directly after double number input the display should be in exactly the same form as on input. In the second example **.FIXED** uses **#DIGITS** to format a decimal fraction according to a fixed number of decimal places held in the

variable **FIXED**. It may be made to print 0–6 decimal places by setting **FIXED** with the command **PLACES**. The final example allows an unsigned double number to be displayed as an n digit 'code number' including leading zeros. The number of digits to be generated is given as the top stack value.

The loop index may be used in a number of ways. An extremely simple but useful example is the definition **THRU**, which will **LOAD** a range of disk blocks specified on the stack. The parameters passed are the first and last blocks to be loaded:

```
: THRU ( lo,hi---) 1+ SWAP DO I LOAD LOOP ;
```

The **DO...LOOP** structure is extremely valuable when defining string operations. The basic parameters for all string operations are those which describe the string, i.e. a base address and the number of elements. These parameters may be fed to a **DO...LOOP** structure in various ways so that a sequence of operations may be performed on each element of the string. For instance a simple byte **DUMP** of a portion of memory could be defined by adding the loop index to the base address each time through the loop, and fetching from that byte. The following definition outputs in **HEX** format:

```
: DUMP ( addr,ct ---)
       ?DUP IF 0 DO DUP I + C@ .HEX
                LOOP
            THEN DROP ;
```

Note that a **DROP** is required to remove the unwanted address at the end of the definition. In this definition the base address is held on the stack throughout and the effective address of the string element is calculated on each pass by adding the loop index. Alternatively we could feed the start and limiting address to the **DO...LOOP**, so that the loop index represents an actual address. In this way only one calculation need be performed:

```
: DUMP ( addr,ct---)
       ?DUP IF   OVER + SWAP
                 DO I C@ .HEX
                 LOOP
            ELSE DROP
            THEN ;
```

This time an **ELSE** clause must be introduced to clean the stack when the character count is zero. The display produced by this definition is somewhat untidy for long strings. We can display the contents of just 16 bytes on each screen line using two **DO...LOOP** structures, one nested inside the

other. The innermost loop prints one full line, whilst the outer loop controls the number of lines to be displayed:

```
: DUMP ( addr,ct---)
       CR 16 /MOD ROT SWAP
       ?DUP
       IF Ø DO 16 OVER + DUP ROT
              DO I C@ .HEX
              LOOP CR
          LOOP
       THEN
       SWAP ?DUP
       IF   OVER + SWAP
            DO I C@ .HEX
            LOOP CR
       ELSE DROP
       THEN ;
```

The phrase 16 /**MOD** leaves the number of lines as the top stack value, with the extra bytes as the remainder from the division. The stack is then adjusted to leave the base address of the string and the number of lines as arguments for the outermost loop. Each time through the loop the start and end addresses of the substring are calculated. These addresses are then fed to the inner **DO**...**LOOP** which displays a line of 16 bytes. On exit from the outer loop the extra bytes are displayed by using the remainder from the /**MOD** and whatever address is on the stack to calculate the parameters for another similar **DO**...**LOOP** structure. Whilst this is a reasonable method of coding, the use of nested **DO**...**LOOP**s within a single word often results in obscure source code. It can be avoided by factoring out the inner **DO**...**LOOP** into a separate word:

```
: (DUMP) ( addr,ct ---)
?DUP
IF Ø DO DUP I + C@ .HEX
          LOOP
THEN DROP ;


: DUMP ( addt,ct---)
       16 /MOD ROT SWAP
       ?DUP
       IF Ø DO 16 2DUP (DUMP) CR +
           LOOP
       THEN
```

```
        SWAP ?DUP
        IF   (DUMP)
        ELSE DROP
        THEN ;
```

There is a variation of the **DO**...**LOOP** which allows the loop index to be incremented in steps other than one. This uses the word **+LOOP** instead of **LOOP**. **+LOOP** requires the step size as a stack parameter, but otherwise operates exactly like **LOOP**. The value fed to **+LOOP** is signed so that the loop index may be decremented. This is a useful structure as it allows us to use the loop index to access successive cells in memory working either up or down, according to whether 2 **+LOOP** or −2 **+LOOP** has been specified. For example we may define a word .S which displays the entire contents of the stack non-destructivly:

```
: .S DEPTH ?DUP
     IF   2* SØ @ 2-
          DUP ROT - SWAP 2-
          DO I @ U.
          2 +LOOP
          ." <-Top" CR
     ELSE ." Stack Empty "
     THEN ;
```

It is often useful to include a condition for an early exit inside a **DO**...**LOOP** – a search of a fixed length list for a particular value, for instance, would be terminated if the value was found. Early exit may be forced by including the word **LEAVE** inside a conditional structure. **LEAVE** causes the loop to terminate at the end of the current pass (in Forth-83 immediately). In fact it sets the loop index equal to the loop limit, so that when **LOOP** or **+LOOP** execute a terminal condition is found. Suppose we want to define a string operator to search a specified string for a particular ASCII character. Given the same parameters as **FILL**, it will return the address of the character if found and otherwise a zero. This can be done using the address as the loop index, and terminating the **LOOP** if the character found at the address is the same as the search character:

```
: MEMBER ( addr,ct,char---f)
ROT ROT OVER +
Ø SWAP ROT
DO OVER I C@ =
   IF DROP I LEAVE
   THEN
LOOP SWAP DROP ;
```

The first line of code computes the start and terminal addresses of the string. A false flag is then placed on the stack and the parameters for **DO** moved into position. On each pass the search character is copied **OVER** the flag and compared to the value at the loop index. If these are equal the false flag is replaced by the current value of the index and **LEAVE** executes. Execution continues with the code following **THEN** to the end of the loop and repetition ceases. Should the two values never be equal then the loop runs to completion and the false flag remains untouched. The final **SWAP DROP** removes the unwanted character from the stack.

Some systems, notably PolyForth contain an extremely useful string comparison word called **-TEXT**. This compares two equal length strings to see if they are the same, i.e. eaeh element of the first string equal to the corresponding element of the other. **-TEXT** takes three parameters: the address of the first string, a count of the number of elements to compare, and the address of the second string. It returns a flag whieh may be in any one of three states. If the strings are equal then a zero is returned. If they are not then the eondition of the flag depends on the values of the last pair of elements tested i.e. the first non-equal pair. If the first string is greater than the second a 1 is returned, if the opposite is true a −1. A definition of **-TEXT** may be created using a **DO...LOOP** stucture with an early exit on the first difference in the strings:

```
: -TEXT ( addr1,ct,addr2 ---f)
        SWAP 1
        DO 2DUP C@ SWAP C@ -
           IF   LEAVE
           ELSE 1+ SWAP 1+ SWAP
           THEN
        LOOP
        C@ SWAP C@ - ;
```

On this occasion the addresses of the string elements are carried on the stack. On each pass of the loop a comparison is made by subtraeting the two string elements giving a true value if they are not equal, in which case **LEAVE** will execute. If they are equal then both addresses are incremented to point to the next element. On termination of the loop the eorrect flag is generated by again subtracting the string elements. This also removes the addresses from the staek. The loop limit is set by the character count with the index intialized to 1. Had it been initialized to 0 then when the two strings were equal the string addresses would point to one byte beyond the last elements on exit from the loop. This would not give the appropriate flag when final comparison was made.

Words introduced in this section:

DO...LOOP do: (end+1,start---)
Sets up loop given index range.

DO...+LOOP do: (end+1,start---)
+loop: (n---)
Like **DO...LOOP** but adds stack value of **+LOOP** to index instead of always 1. The loop terminates when the index is greater than or equal to the limit if n>0 or when the index is less than the limit if n<0.

I (---n)
Places current **DO...LOOP** index onto the top of the stack.

LEAVE
Force exit from **DO...LOOP**.

9.3 The return stack

So far no mention has been made of how the **DO...LOOP** keeps track of its index, only that the current value may be returned using **I**. Obviously the stack is not used since **DO** removes the start and end values of the index. In fact **DO** stores these values on a second stack called the *return stack*, from whence they are retrieved by **LOOP** or **+LOOP**. The return stack operates in exactly the same way as the parameter stack, and is a vital part of the Forth system. Its principle function is to hold the address of the routine to which Forth will return after the current operation is complete. This is explained more fully in Chapter 11. The action of **I** is simply to copy the top value from the return stack onto the parameter stack, and its use is therefore not confined to returning the index of a **DO...LOOP** (although this is by far the most common use). The only action of **DO** during program execution is to move the top two items from the parameter stack and place them on the return stack. **LOOP** retrieves them, increments the index and if it is less than the limit then the values are replaced, otherwise they are discarded. Note that a **DO...LOOP** has no nett effect on the return stack. In addition to **I** there are two other words which operate on the return stack. These allow **DO** and **LOOP** to place values there and subsequently remove them. The actions of the return stack operators are sumarized below along with their effects on the stack:

>R (n---)
Removes the top value from the parameter stack and places it on the top of the return stack.

R> (---n)
Removes the top value from the return stack and places it on the top of the parameter stack.

I (---n)
Copies the top value on the return stack onto the parameter stack.

Although I may be used safely at any time, placing arbitrary values on the return stack with **>R** or removing values with **R>** in an uncontrolled way will always cause a system crash. The return stack may, however, be used in a controlled manner for short term storage of values and this can save a good deal of stack manipulation. The general rule for use of the return stack is that any value placed on the return stack must be removed at the same level of the definition and any value removed must be returned there in the same way. Similarly values placed on the return stack directly from the keyboard must be removed before the return key is pressed!

The return stack can be useful when manipulating double number stack values, as shown in the definitions of **2SWAP** and **2OVER** below. Note that these are just as useful for dealing with pairs of single numbers, the address and length of a string for instance. The stack notation in the definitions below is thus shown as single number for clarity. The second set of brackets on each line of code shows the effect on the return stack:

```
: 2SWAP ( n1,n2,n3,n4---n3,n4,n1,n2)
        >R ( ---n1,n2,n3) ( ---n4)
        ROT ROT ( ---n3,n1,n2) ( ---n4)
        R> ( ---n3,n1,n2,n4) ( ---)
        ROT ROT ; ( ---n3,n4,n1,n2) ( ---)


: 2OVER ( n1,n2,n3,n4---n1,n2,n3,n4,n1,n2)
        >R >R ( ---n1,n2) ( ---n4,n3)
        2DUP  ( ---n1,n2,n1,n2) ( ---n4,n3)
        R>  ( ---n1,n2,n1,n2,n3) ( ---n4)
        ROT ROT ( ---n1,n2,n3,n1,n2) ( ---n4)
        R> ( ---n1,n2,n3,n1,n2,n4) ( ---)
        ROT ROT ; ( ---n1,n2,n3,n4,n1,n2)
```

The return stack should be used to avoid over-complex and lengthy juggling with the parameter stack. This can occur when creating new mixed precision arithmetic operators. For example **M/** may be defined to perform signed mixed length division and complement the mixed operators defined in Chapter 8. Difficulty with the stack arises when the sign of the result is computed and the arguments for the division are to be converted to their absolute values. The return stack is used to relieve the situation:

```
: M/ ( d,n---n) 2DUP XOR ( sign of result)
       >R >R DABS ( absolute double number)
       R> ABS ( absolute single number)
       U/MOD SWAP DROP ( discard remainder)
       R> 0< ( result negative?)
       IF NEGATE THEN ;
```

Further examples of return stack use during mixed length arithmetic are contained in the application at the end of this chapter.

Words introduced in this section:

>R (n---)
Move the number on the top of the parameter stack onto the top of the return stack.

R> (---n)
Move the number on the top of the return stack onto the top of the parameter stack.

9.4 Indefinite repetition

The start of a section of code to be repeated an indefinite number of times is always marked by the word **BEGIN**. The end may be marked in one of three ways depending on the type of repetition required. Code to be repeated unconditionally (i.e. forever) is enclosed by a **BEGIN....AGAIN** structure. Since no exit from the loop is possible via **AGAIN** any demonstration program must include a conditional **ABORT** to avoid 'hanging up' the system. The word **WAIT** below issues a message and then goes into an unconditional loop waiting for keys to be pressed. The <SPACE> bar causes the routine to issue a second message and **ABORT**. Keys other than than the space bar are ignored and result in another pass through the loop:

```
: WAIT ( ---) ." Waiting"
     BEGIN KEY 32 =
           IF ." At last" ABORT THEN
     AGAIN ;
```

BEGIN...AGAIN loops are most often used at the outermost level of an application to prevent the system returning to the Forth interpreter.

Conditional repetition is controlled by means of a **BEGIN...UNTIL** structure. This causes all code within the structure to be executed until some condition is true. The truth value of this condition must be left on the

stack and is taken as a parameter by **UNTIL**. If the top stack value is true the **UNTIL** allows execution to continue. If it is false, program execution is directed back to the word immediately following **BEGIN**. The general form of this structure is:

```
: PROCESS  BEGIN code to be repeated
                 terminating condition
           UNTIL
           subsequent code ;
```

It is often useful to be able to display double number values unsigned, and sometimes the word **U.D** is defined for this purpose. A definition may be coded using the number formatting primitive # inside a repeating structure. Each time # executes, one digit is inserted into the output string and the double number on the stack is left, divided through by the contents of **BASE**. All digits barring leading zeros have been extracted when the double number value falls to zero. We can specify the procedure to do this in pseudo code:

```
BEGIN extracting digits
UNTIL the double number = 0


A definition of U.D may be coded:


: U.D ( ud---) <# BEGIN # 2DUP D0= UNTIL #>
      TYPE SPACE :
```

The double number conditional test **D0=** can be defined thus if it is not already present on your system:

```
: D0= ( d---f) OR 0= ;
```

Those Forth systems which do not contain **AGAIN** may achieve the same effect by using the phrase **0 UNTIL**, thus always forcing the flag to false.

As with the **DO...LOOP** structure the test for termination is performed after one pass is complete. This means that the code within the **BEGIN...UNTIL** is always executed at least once. Although this can be avoided by appropriate placing of **IF...ELSE...THEN** a more versatile structure is provided to handle conditional repetition. This is the **BEGIN...WHILE...REPEAT**. Here the terminal condition is performed part way through the loop. **WHILE** acts in a similar fashion to **IF**. If **WHILE** finds a true value on the stack the program execution continues until **REPEAT** is encountered, when it is directed back to the code following **BEGIN**. If

WHILE finds a false flag the loop is exited and execution restarts with the code following **REPEAT**. The general form of use is:

```
: PROCESS BEGIN code always executed
                terminal condition
          WHILE code to be executed on true
          REPEAT
          subsequent code ;
```

Note that the logic value which causes repetition to cease is the opposite from that used by **BEGIN**...**UNTIL**. The code following **BEGIN** is always executed at least once whereas that following **WHILE** is conditional. By performing the conditional test immediately after **BEGIN**, and placing all code to be repeated between **WHILE** and **REPEAT**, the loop is effectively pretested – and thus may not execute at all. An example of the use of this structure is the routine below which waits for one of the numeric keys to be pressed and returns the value of the corresponding digit (any other keystrokes being ignored).

```
: RANGE ( ---lo,hi+1) 48 58 ;


: NUMERIC ( ---n) BEGIN KEY
                        DUP RANGE WITHIN NOT
                  WHILE DROP
                  REPEAT 48 - ;
```

The routine goes straight into the loop and waits for a key. If the value returned falls in the range of the decimal digits then the loop is exited, and the digit produced by subtracting 48 (ASCII '0'). If the character is not in range then the loop continues, the character being discarded, and **KEY** executes again.

The usage of the various Forth control structures is best illustrated in the context of an application and the Value Added Tax reckoner in the next section uses most of the techniques discussed in this chapter.

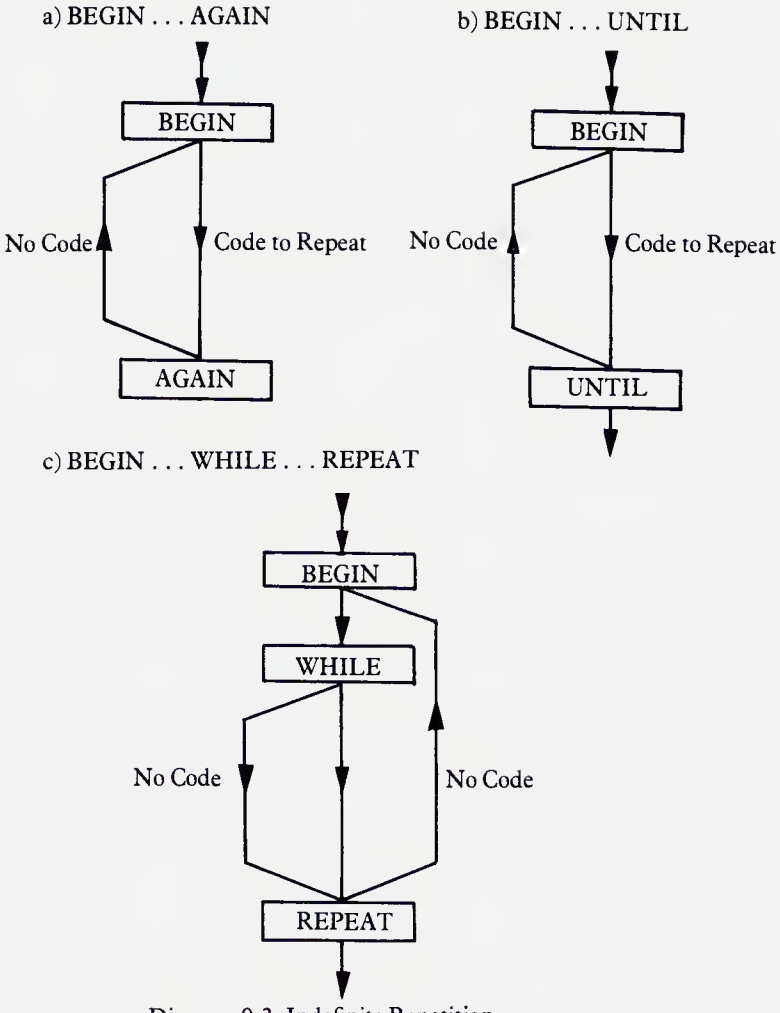


Diagram 9.3. Indefinite Repetition

Words introduced in this section:

BEGIN...AGAIN
Loops back to **BEGIN** unconditionally from **AGAIN**.

BEGIN...UNTIL until: (f---)
Loops back to **BEGIN** until the flag is true at **UNTIL**.

BEGIN...WHILE...REPEAT while: (f---)
Loop while the flag is true at **WHILE**. **REPEAT** loops unconditionally to **BEGIN**. If flag is false at **WHILE** execution continues after **REPEAT**.

9.5 Application – a handy tax reckoner

A common problem for small businesses registered for VAT is calculating the amount of tax paid on a VAT inclusive invoice. This occurs because items purchased though retail outlets for cash, such as petrol, include the VAT in the price and this must then be reclaimed each quarter. Calculating three months VAT can be a time consuming task, especially if large numbers of receipts are involved, and is an ideal task for a computer.

Specification:
The programs will allow the user to enter a batch of gross receipt figures, compute the nett and tax portions for each, and display the results of one batch entry in columns with the accumulated totals for the batch.

All computations must give results in a suitable form to be accurate when displayed to two decimal places, and so are best handled using fixed precision arithmetic on double number values. The input from the user must therefore be converted to pence before any further processing takes place. As successive items are entered the values must be stored for display at the end of a batch and added into batch totals. Suitable storage must therefore be arranged. One method is to use double length indexed variables or arrays for this purpose, so that the following phrase provides the address of the 'nth' double number in a batch of gross figures:

```
n GROSS
```

This is convenient for the batch display since a **DO...LOOP** may be used with the loop index being used to generate the addresses of successive items.

The program will also have the option of processing more than one batch. At the end of each batch the user is queried as to whether another batch is required. The accumulated totals of successive batches will be held in a set of grand totals and displayed at the end of each batch.

Programs:

a. Calculations
Throughout this application we need to perform multiplications and divisions on double numbers and get double number results. So far none of the Forth arithmetic operators will do this, so others must be constructed. The mixed length routines **U*** and **U/MOD** may be used as tools for this purpose:

```
      ( Mixed precision arithmetic )


: T* ( ud,un---ut) DUP >R ( save multiplier )
 SWAP >R ( save high order cell)
 U* ( multiply low order)
    ( leaves carry on top of stack)
 R> R> U* ( multiply high order)
 ROT M+ ; ( add in carry)


: T/MOD ( ut---un,ud) >R I ( keep divisor )
    U/MOD ( divide high order)
    R> SWAP >R ( retrieve divisor)
      ( save high result)
    U/MOD ( dive low order)
    R> ; ( restore high result)


: M*/MOD ( ud,un,un---un,ud) >R T* R> T/MOD ;


: M*/ ( ud,un,un---ud) M*/MOD ROT DROP ;
```

The routine **M*/** which discards the remainder is used throughout this application.

b. Input and output

To control input scaling and output format the idea of using a variable to contain the position of the fixed decimal point introduced in the previous chapter is developed. Output is performed according to the value fixed using the definitions of **#DIGITS** and '.' given in section 9.1. The routine **D.R** prints a signed double number as a fixed point decimal fraction right aligned in a column whose width is specified by the top stack item. This is achieved by subtracting the length of the output string from the column width, and printing that number of spaces before typing the string:

```
 ( Fixed Point Output )


VARIABLE FIXED


: PLACES ( n---) 0 MAX 5 MIN FIXED ! ;
```

```
: F.R ( d,n---) >R SWAP OVER DABS
       <# FIXED @ #DIGITS '.' #S SIGN #>
       R> OVER - SPACES TYPE ;
```

Scaled input is achieved by using the difference between the values in DPL and FIXED to produce a scaling factor by which the input number will by multiplied or divided as appropriate. The scaling factors themselves are held in a table whose start address is returned by FACTORS. This table is accessed through the word FACTOR which returns a scaling factor governed by the top stack item, so that 2 FACTOR produces the factor for a scale up or down of two decimal digits. Since scaling will be performed on the results of NUMBER, and these may be either double or single in length, the contents of DPL must be tested before any scaling can be done to determine whether a double or single number is to be scaled. A single length integer input may be brought into the correct scale with a mixed multiply by the contents of FIXED. For a double number the 'direction' of scaling must be determined as well as the amount. This is done by subtracting the contents DPL from the contents of FIXED. The absolute difference governs the scaling factor, and the sign of the difference the direction. If DPL is less than FIXED then a scale up is required and the result of the subtraction is positive. If it is greater, then a scale down is required and the difference is negative. The actual scaling operation is performed using M*/ to multiply by FACTOR/1 for a scale up, or 1/FACTOR for a scale down.

```
    ( Scaling Input )


HERE 1Ø , 1ØØ , 1ØØØ , 1ØØØØ , CONSTANT FACTORS


: FACTOR ( n ---n) 1- 3 MIN 2* FACTORS + @ ;


: DOUBLE ( d---d )
FIXED @ DPL @ - ?DUP
IF DUP Ø< ( 1 = scale down)
   SWAP ABS FACTOR 1 ( set for scale up)
   ROT ( direction flag)
   IF SWAP THEN ( scale down)
   M*/ ( scale)
THEN ;


: SINGLE ( n---d) FIXED @ FACTOR M* ;
```

```
: SCALE ( n/d---d)
        DPL @ 0<
        IF   SINGLE
        ELSE DOUBLE
        THEN ;


10 CONSTANT COLUMN


: ENTER ( ---d) CR ." Gross Value: "
       PAD DUP COLUMN 2DUP BLANK EXPECT
       1- NUMBER SCALE ;
```

ENTER produces consistently scaled numeric input. The constant **COLUMN** is used by all the numeric display words in the application as an argument for **D.R** and the value may be altered to suit a particular display.

c. Storage and display

To process batches of ten items at a time we require three 10 element double number arrays for gross value, nett value and tax. In addition three 32-bit batch totals and three 32-bit grand totals are needed. The word **CELLS** is defined to allow us to reserve a number of cells of dictionary space for storage, initialize them all to zero and attach a name for reference in programs. It uses its stack parameter as an argument for a **DO...LOOP** which compiles in zeros. The maximum number of cells which may be reserved in this way is 255. **CELLS** compiles the cell count into the first byte of the memory string. The first element in each array is therefore at an address one greater than that returned by the name. To reserve space for double length numbers, twice as many cells as there are elements in the array must be specified. The start address of a double length element within the array is computed by **ELEMENT**, which takes the address of the count byte with the element number on top as stack arguments. Two words are defined for re-initializing the arrays to zero; **0GRAND**, which is used only once at the start to zero the grand totals, and **CLEAR** which clears all variables associated with a batch, and is used prior to processing each batch of items. The variable **ADDED** is used to control batch operations, containing the number of items added to the current batch. It is accessed through the words **+ITEM** to increment the contents and **ITEMS** to return the number of items added. **ADDED** is cleared for each new batch by **CLEAR**.

```
       ( Storage )

: CELLS ( n---) HERE OVER Ø MAX 255 MIN C, SWAP Ø
       DO Ø , LOOP CONSTANT ;

: ELEMENT ( addr,n---addr) OVER C@ MOD 2* 2* + 1+ ;

2Ø CELLS GROSS 2Ø CELLS NETT 2Ø CELLS TAX

12 CELLS TOTAL 12 CELLS GRAND

VARIABLE ADDED

: ITEMS ( ---n) ADDED @ ;

: +ITEM ( --- ) 1 ADDED +! ;

: CLEAR ( --- ) Ø ADDED ! GROSS COUNT ERASE NETT COUNT
                ERASE
                TAX COUNT ERASE TOTAL COUNT ERASE ;

: ØGRAND ( --- ) GRAND COUNT ERASE ;
```

The arrays can now be redefined to act as indexed variables, thus simplifying their use in later programs:

```
    ( Array access )

: GROSS ( n---addr) GROSS SWAP ELEMENT ;

: NETT ( n---addr) NETT SWAP ELEMENT ;

: TAX ( n---addr) TAX SWAP ELEMENT ;

: TOTAL ( n---addr) TOTAL SWAP ELEMENT ;

: GRAND ( n---addr) GRAND SWAP ELEMENT ;
```

More sophisticated methods of producing named 'data structures' are discussed in Chapter 12.

Separate display words are defined for the elements of each array. They take the element number as a parameter, and display the contents right aligned. .ROW displays one row of figures as determined by its stack parameter. .HEAD displays the column headings. Both these words use the definition TAB which skips over a column width. A whole batch of figures is displayed by .BATCH if the contents of ADDED are non-zero. After printing the column headings a DO...LOOP is set up to print successive rows of figures. A row is displayed only if the GROSS figure is non-zero.

```
        ( Display )


: .POUNDS ( addr,---) 2@ COLUMN F.R ;


: .GROSS ( n---) GROSS .POUNDS ;


: .NETT ( n---) NETT .POUNDS ;


: .TAX ( n---) TAX .POUNDS ;


: .TOTALS ( n---) ." Batch Totals:" 7 SPACES
3 Ø DO I TOTAL .POUNDS LOOP ;


: .GRAND ( n---) ." Grand Totals:" 7 SPACES
        3 Ø DO I GRAND .POUNDS LOOP ;


: TAB COLUMN SPACES ;


: .HEAD ( ---) TAB TAB
      ."      Goods" ."        VAT" ."      Total"
      CR CR ;


: .ROW ( n---) TAB TAB DUP .NETT DUP .TAX .GROSS ;
```

```
: .BATCH ( ---) ITEMS ?DUP
        IF CR CR .HEAD 0
           DO I GROSS 2@ D0= NOT
           IF I .ROW CR THEN
           LOOP CR
           .TOTALS CR
       ELSE ." No items added to batch"
       THEN CR ;
```

d. Processing

The basic computation to be performed on each item entered is a simple one. If VAT is charged on goods at RATE percent of the goods value, then the gross invoice value is obtained by applying the formulae:

VAT = GOODS * RATE/100
TOTAL = GOODS + VAT

The GOODS and VAT figures may be calculated from the gross figure from the formulae:

GOODS = TOTAL * 100 / (100 + RATE)
VAT = TOTAL * RATE / (100 + RATE)

These can be implemented using M*/ to multiply the gross figure by the appropriate ratio. The definitions **GOODS** and **VAT** below do this taking the gross value as a stack input. This is not quite good enough for tax purposes, however, because of the rounding which takes place. VAT on a purchase is generally consistently rounded either up or down, usually down. This means that when calculating back from an inclusive total the figures for GOODS and VAT may not add back to the original figure. The results are therefore corrected by adjusting the GOODS value appropriately. **BALANCE** takes care of this leaving the correct GOODS and VAT figures on the stack. The VAT rate is set to 15% with the constant **RATE**.

```
 ( Process single item )


15 CONSTANT RATE ( % VAT )


: GOODS ( tot---gds) 100 DUP RATE + M*/ ;


: VAT ( tot---vat) RATE DUP 100 + M*/ ;
```

```
: BALANCE ( tot---vat,gds) 2DUP >R >R 2DUP
                           VAT 2SWAP GOODS
                           2OVER 2OVER D+
                           R> R> D< M+ ;


: PROCESS ( tot---) 2DUP ITEMS GROSS 2!
  BALANCE ITEMS NETT 2! ITEMS TAX 2!
  ." Nett Value: " ITEMS .NETT
  ." Taxed: " ITEMS .TAX ;
```

A batch of items is processed by placing the above routines inside a **BEGIN...WHILE...REPEAT** structure. The exit condition for the loop is when the batch is full – when 10 items have been added – or when a negative number is entered as a gross value (allowing premature exit for short batches):

```
  ( Process one batch )


: +TOTAL ( addr,n---) SWAP >R TOTAL DUP 2@
    R> 2@ D+ ROT 2! ;


: +TOTALS ( ---) ITEMS DUP NETT 0 +TOTAL
        DUP TAX 1 +TOTAL
        GROSS 2 +TOTAL ;


: ROOM ( ---f) ITEMS 11 < ;


: BATCH ( ---) CLEAR
      BEGIN ENTER
            DUP 0< NOT ROOM AND
      WHILE PROCESS
            +TOTALS +ITEM
      REPEAT 2DROP .BATCH ;
```

The routine **+TOTAL** adds the double number contents of a given address into the batch total specified by the top stack item. The batch totals are assigned as follows:

0 TOTAL – NETT value
1 TOTAL – TAX value
2 TOTAL – GROSS value

Successive batches of figures are processed by the definition **RECKON**, which first zeros the grand totals and sets the arithmetic to two decimal places of precision. After each batch is processed the grand totals are updated and displayed. The batch totals are added into the corresponding grand totals by +**GRAND** which uses the index of a **DO**...**LOOP** to access the correct elements in each of the arrays. It should be noted that the address of the **GRAND** total is kept on the return stack while the addition is performed, and that during this time the loop index cannot be accessed since it is no longer the top item on the return stack. At the end of each pass through the loop in **RECKON** the user is queried as to whether to continue by **ENOUGH**, which returns a true flag if no further batches are to be processed. This routines ignores all keys other than Y or N. The flag is generated on exit from the loop by the test 'N' = which generates the truth condition governing exit from the **BEGIN**...**UNTIL** structure:

```
 ( Update Grand Totals )


: +GRAND ( ---) 3 Ø DO I TOTAL 2@
     I GRAND DUP >R 2@ D+ R> 2!
  LOOP ;



   ( Process batches )


89 CONSTANT 'Y'

78 CONSTANT 'N'

: ENOUGH ( ---f) ." Process another batch?  ( Y or N )"
        BEGIN KEY DUP 'Y' =
              OVER 'N' = OR NOT
        WHILE DROP
        REPEAT 'N' = ;

: RECKON ( ---) ØGRAND 2 PLACES
       BEGIN BATCH
             +GRAND .GRAND
             CR CR ENOUGH
       UNTIL ;
```

10 Using disks

10.1 Virtual memory

You should already be using floppy disks to store your programs, and may have noticed that listing out source screens does not always demand a disk access. This is because information held on the disk is always moved into memory before you can use it, so that if for instance you type:

```
10 LIST <RETURN>
10 LIST <RETURN>
```

screen number 10 of the disk will already be in memory by the second LIST, and there is thus no need to look at the disk again. In fact Forth always treats the disk as if it resided in RAM. This use of disk storage is known as *virtual memory*, and the process of moving sections of memory to and from the disk is traditionally called *paging*.

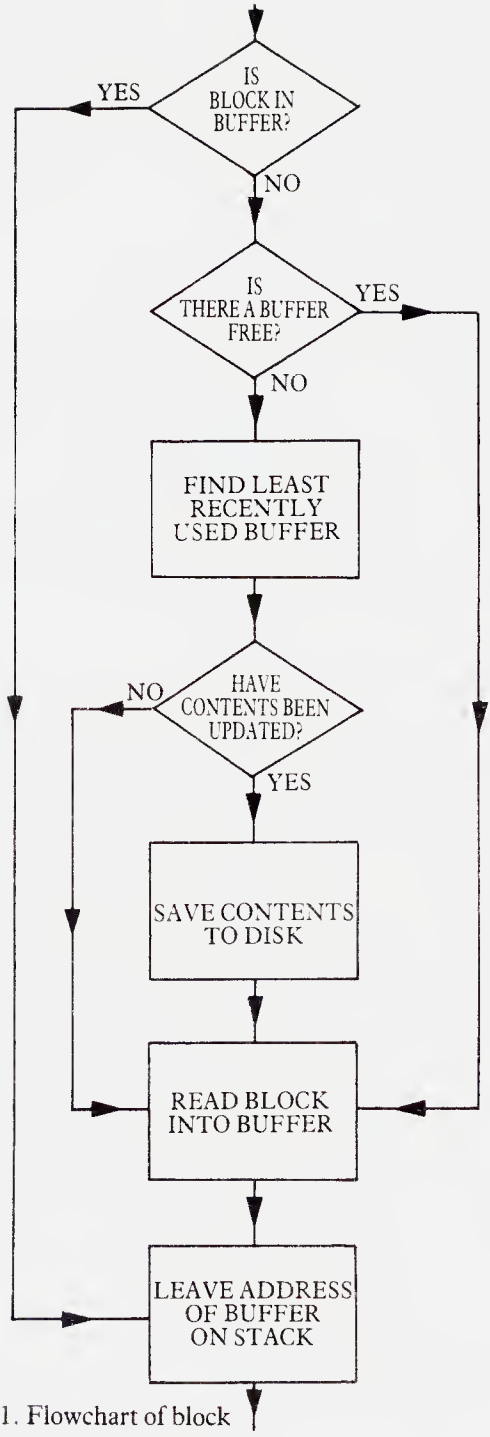
So far we have used the word 'screen' when referring to areas of disk memory. These are each 1024 characters or bytes on nearly all Forth systems. At a more fundamental level, when we are concerned with storing other information apart from programs on disk, we talk of 'blocks'. The size of these varies between Forth implementations, but usually they are the same size as an editing screen – that is 1024 bytes. Forth '79 systems contain a constant called B/BUF which should yield the system buffer length.

The Forth memory map in Chapter 4 showed an area at the top of memory called the disk buffers. This is especially reserved for holding information from the disk. Every Forth system has at least two (usually four) 1K buffers each of which can, of course, hold one disk block.

The heart of Forth's disk handling is the word BLOCK. It expects a disk block number on the stack and returns the start address of one of the buffers. In between it takes care of any disk access necessary. The exact action of BLOCK is shown in flowchart form in diagram 10.1.

Its action can be investigated by using it to call up a selection of blocks from disk and typing out the resulting address as in:

```
10 BLOCK U. <RETURN>
11 BLOCK U. <RETURN>
etc.
```



Diag 10.1. Flowchart of block

You should find that using **BLOCK** in this way yields a cyclic repetition of a short sequence of numbers. These are the start addresses of your disk buffers. You can check that the information from the disk is indeed in memory by typing out the first line of a block whose contents are known:

```
10 BLOCK 64 TYPE <RETURN>
```

As you may have guessed this is the essence of the Forth word **INDEX** which could be defined as:

```
: INDEX ( low,high--) 1+ SWAP
    DO CR I DUP .
       BLOCK 64 TYPE
    LOOP ;
```

BLOCK not only reads in the required block but also makes it current. On most Forth systems including Forth '79 and FIG Forth implementations the current block number can be found at the address pointed to by the contents of the variable **PREV**. You can investigate this by keying in:

```
10 BLOCK . <RETURN>
PREV @ . <RETURN>
PREV @ @ . <RETURN>
```

PREV in fact contains an address two bytes before the start of the buffer containing the current block. Put another way, the number of the block in any particular disk buffer can be found two bytes before its start address. Again this can be investigated with the following:

```
10 BLOCK 2- @ . <RETURN>
```

Note that PolyForth systems use a rather different system involving an array of block numbers beginning at **PREV**. In this case the current disk block can be found with:

```
PREV DUP @ + 2+ 2+ @ . <RETURN>
```

The flowchart of **BLOCK** shows that it will write back to disk blocks that are updated if it is necessary to free a buffer. The current block can be marked as updated using the word **UPDATE**, which has no effect on the stack. **UPDATE** acts on the address we were investigating above. On systems other than PolyForth the block number is simply turned negative using **NEGATE**:

```
: UPDATE PREV @ DUP @ ABS NEGATE SWAP ! ;
```

Note the **ABS** ensures that a block is never un-updated by a second **NEGATE**! PolyForth systems have a similar action but in this case the sign bit of the block number is set. The difference between these actions can be demonstrated by running the following definitions of **NEGATE** and **SET**:

```
HEX

: NEGATE ( n--n) 1- FFFF XOR ;

: SET ( n--n) 8000 OR ;

DECIMAL
```

The important thing to remember is that any block marked by **UPDATE** will be written to disk at some later point by **BLOCK**. It is not written down immediately, however, so the new contents will be lost if you turn your computer off before the relevant disk buffer is next used. To be sure that the contents of all updated buffers are written back to disk immediately you can use the word **SAVE-BUFFERS** (or **FLUSH** in PolyForth). Alternatively the word **EMPTY-BUFFERS** does just what you would expect – clears the disk buffers regardless of whether they have been updated. In this case any new information in them will be lost forever.

Part of the action of **BLOCK**, that of allocating a buffer to a disk block, is performed by the word **BUFFER**. This takes care of writing back any appropriate updated block, but does not actually read the new block from the disk. It can thus be used to allocate a buffer area for usage not necessarily concerned with disk I/O.

Words introduced in this section:

B/BUF (--n)
Forth '79 constant. Yields the length in bytes of each disk block.

BLOCK (n--addr)
Expects a block number on the stack. If the block is already in a buffer leaves the start address of the buffer. If not finds the least recently used buffer, writes the contents back to disk if updated, reads the new block into the freed buffer, and leaves the address of the buffer on the stack. Makes the block number current.

UPDATE
Marks the current disk block as updated.

SAVE-BUFFERS
Immediately writes all updated disk blocks in the buffers down to disk.

FLUSH
PolyForth word for **SAVE-BUFFERS**.

EMPTY-BUFFERS
Clears all disk buffers without writing any information back to disk even if a block has been marked as updated.

BUFFER (n--addr)
Used in **BLOCK**. Expects a block number on the stack. Finds the least recently used buffer, writes the contents back to disk if updated, and leaves the address of the buffer on the stack. Makes the block number current. Does not read in any information from the disk.

10.2 Writing to disk

We have discussed the main Forth words concerned with disk access, and in this section we will be using these alongside words you already know to organize simple messages on the disk. First you should insert a clean disk into your drive (or format one if necessary) to ensure that no source is lost. Edit the programs which follow onto blocks 10 to 20 so that blocks 30 to 40 can safely be used for testing. We want two main words. The first will put a message onto the disk in the position specificd and give it a name. The second will retrieve the message according to arguments left by the execution of that name.

For the moment we will view a disk block in much the same way as the editor does – as 16 lines of 64 characters each (assuming a 1K block size). In this way each of our messages will take up one line. The position of a message on the disk can thus be represented as two numbers – a block number and a line number.

In order for the following programs to work you will need a definition for the word **2CONSTANT**, which operates just like **CONSTANT** but with two numbers (or a double number) as a value. We will be discussing the technique used for this in more depth later in the book. For now you should create and test the folllowing:

```
: 2CONSTANT ( d--) CREATE , ,
                   DOES> ( --d) 2@ ;
```

If your system does not include **2@** (called **D@** on some systems) a definition can be found in Chapter 8. The above word will not work on FIG systems, where the following will achieve the same result:

```
: 2CONSTANT ( d--) <BUILDS , ,
                   DOES> ( --d) 2@ ;
```

If we are accessing areas of disk by block number and line number we will need a program to read in the appropriate block and calculate the actual address of the line we want:

```
: ADDR (blk,line--addr) 64 * SWAP BLOCK + ;
```

All Forth disk handling involves this kind of technique. To specify any particular part of the disk we use two numbers, a block number and an

offset into the block. A routine such as the one above is then created and used whenever information is transferred to and from the disk to ensure that the correct block number is in memory.

The program which puts our 64 character messages onto the disk must perform two functions. It will expect a block number and line number on the stack. First the message itself must be placed in the desired place on the disk; and secondly it must create a new word – which we can give an appropriate name – to retrieve the original block and line number so that the message can be subsequently located. The latter will be taken care of by 2CONSTANT, which we will include at the end of our word. The definition looks like this:

```
: CALL-MSG" ( blk,line--)
    2DUP ADDR ( blk,line,destination address)
    DUP 64 BLANK ( clear line in disk buffer)
    >R ( save dest address on return stack)
    34 WORD ( look ahead for quote)
    COUNT ( count of string moved to HERE)
    R> ( retrieve destination address)
    SWAP ( source addr, dest addr, count)
    CMOVE UPDATE ( --blk,line)
    2CONSTANT ;
```

This word can be used as in:

```
30 0 CALL-MSG" MESSAGE TEXT" TEST <RETURN>
```

in which case executing the word **TEST** should leave a zero on the top of the stack with 30 underneath it. If you then list out block 30 you should find that the words 'MESSAGE TEXT' appear on line 0.

Having already defined the word **ADDR** to convert a block number and line number to a buffer address it is a simple task to retrieve the text pointed to by the arguments left by **TEST** with the following:

```
: MESSAGE ( blk,line--) ADDR 64 -TRAILING TYPE ;
TEST MESSAGE <RETURN>
```

This technique is very similar to the way that many Forth systems arrange their error messages. When you are using it bear in mind that the maximum block number allowed will depend on the capaeity of your disk drive, and that block 0 is sometimes not available for update.

10.3 Simple filing

The messages we put onto the disk in the last section were all very well, but there are many more effective ways to store information. The first case we

shall look at is concerned with saving streams of byte data. It might be used for simple data acquisition, where the data source would probably be some peripheral connected to the computer through one of its ports. We will be using **KEY** to simulate this, so that we will in fact be saving a stream of ACSII codes.

For convenience we will define the first block available for data storage as a constant:

```
30 CONSTANT START
```

This allows us to define the following word which gives an address representing the appropriate position on the disk for any byte offset above the start of our storage area.

```
: ADDR ( offset--addr) 1024 /MOD START + BLOCK + ;
```

Note the use of **/MOD** in this word. The quotient returned will represent a block offset above **START**, whilst the remainder is the byte offset into the block. A simple DO..LOOP can now be used to put data into our storage area:

```
: GET ( n--) 0 DO KEY I ADDR C!
            UPDATE
            LOOP ;
```

where **GET** expects a number on the stack representing how many keystrokes are desired, as in:

```
20 GET <RETURN>
```

To test this properly you will need to try numbers greater than 1024 so that the data stream covers more than one block. This will demand a large number of keystrokes, and you may prefer to replace the word **KEY** with a constant ASCII value (such as 65 for 'A') and just fill the blocks with it.

To retrieve the data two definitions are used, one to look at the contents of a particular byte offset:

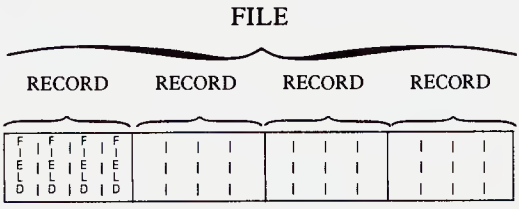
```
: SEE ( n--) ADDR C@ . ;
```

and the other to display a section of the data stream given the beginning and end offsets:

```
: SHOW ( low,high--) 1+ SWAP
                     DO I SEE LOOP ;
```

Generally we need to store information on the disk in a more structured form than this. Suppose we wanted to keep the names, telephone numbers and addresses of all our friends on the disk. We can think of the disk file just as we might an address book, and in it we keep records of a number of people, each of which includes a number of separate pieces of information.

We call the entry for each person a *record* and the pieces of information contained in them a *field* (see diagram 10.2).



Diag 10.2. Files, records and fields

In order to simplify matters we will decide beforehand how many records our file is allowed to contain,the length of each record, and the maximum byte count of each fiield. We byte count of each field. We will reserve one block of the disk for a *directory*, a sort of index to all the records on the file. This consists of a byte array where each byte represents one record, so that its length depends on the maximum records allowed. Each record is initially available for information and its directory entry contains a zero. To enable us to retrieve a record by the first character of the person's name, we will store its ASCII value in the directory when the record is used.

The routines to access the directory are thus defined in terms of the directory block and the maximum available records:

```
30 CONSTANT DIRECTORY

100 CONSTANT MAX-RECS

: ENTRY ( recno--addr) DIRECTORY BLOCK + ;

: STATUS ( recno--char) ENTRY C@ ;

: DELETE ( recno--) ENTRY 0 SWAP C! ;

: NEW-FILE DIRECTORY BLOCK MAX-RECS ERASE UPDATE ;

: ADD ( char--recno) 1 ( default flag)
      MAX-RECS 0 DO I STATUS NOT
                          IF DROP I ENTRY C!
                          I 0 LEAVE
                          THEN
                LOOP
      IF CR ." File full !" CR ABORT
      THEN ;
```

The word **ADD** above expects on the stack the ASCII code for the first character of the name to be stored. The word **ABORT** will immediately cause control to be passed back to the keyboard if the file is full. It also has the effect of clearing the stack and is thus often used to escape from this kind of error condition. Note that upon returning from an **ABORT** Forth does not issue its 'ok'.

Next we must decide how many bytes each record and its constituent fields will take up on the disk. For simplicity it is best to choose a record length which will divide evenly into the block length so that an exact number of records will fit onto each block.

```
128 CONSTANT REC-LEN


25 CONSTANT SURNAME


25 CONSTANT GIVEN


14 CONSTANT TEL


64 CONSTANT ADDRESS
```

The file itself will begin on the block above the directory:

```
: FILE-START ( --blk) DIRECTORY 1+ ;
```

so that the start address of each record can be calculated thus:

```
: ADDR ( recno--addr)
       B/BUF REC-LEN / ( records per block)
       /MOD ( --recs left, blks)
       FILE-START + BLOCK
       SWAP REC-LEN * + ( add byte offset) ;
```

To add a record we first need the surname of the person to be entered, since the first character of this is to be placed in the directory. We will thus use 32 **WORD**, and follow our keyword with the required name. A check is included to ensure that some name is actually entered. The word **GET-NAME** takes care of all of this and also moves the surname into the appropriate record. It leaves on the stack the address in the disk buffer where the next field is to be placed:

```
: GET-NAME ( --addr)
  32 WORD COUNT ?DUP
  IF    OVER C@ ADD
        ADDR SURNAME
        2DUP BLANK
        2DUP + >R
        DROP SWAP
        CMOVE UPDATE
        R>
  ELSE CR ." No name !"
        CR ABORT
  THEN ;
```

The address left by this word can now be used to enter each field in turn with the following:

```
: PUT ( addr,n--addr)
      2DUP BLANK ( erase field)
      2DUP EXPECT ( enter information)
      + ;  ( increment buffer address)


: FILE GET-NAME
       CR ." Given name ?" CR
       GIVEN PUT
       CR ." Telephone no ?" CR
       TEL PUT
       CR ." Address ?" CR
       ADDRESS PUT DROP ;
```

This should now add a record to your file and prompt you for information if used as in:

FILE OLNEY <RETURN>

A similar technique can be used to display information, first for a single record number:

```
: SHOW ( addr,n--addr)
       2DUP -TRAILING TYPE + ;


: DISPLAY ( recno--)
 CR ." Record number: "
 DUP . ADDR
 CR ." Surname: "
 SURNAME SHOW
 CR ." Given name: "
 GIVEN SHOW
 CR ." Telephone no: "
 TEL SHOW
 CR ." Address: "
 ADDRESS SHOW DROP ;
```

This last word expects a record number on the stack, which is not a particulary convenient way to retrieve our information. Having saved the first letter of the surname in the directory, however, we can define the following to display all entries under a given letter:

```
: ONE-LETTER ( chr--)
      MAX-RECS Ø DO I STATUS OVER =
                   IF I DISPLAY THEN
                 LOOP DROP ;


: LETTER 32 WORD 1+ C@ ONE-LETTER ;
```

used as in:

LETTER O <RETURN>

A similar word displays all entries on the file (in no particular order):

```
: ALL MAX-RECS Ø DO I STATUS
                     IF I DISPLAY THEN
                  LOOP ;
```

Words introduced in this section:

ABORT
Halts execution of the program and passes control to the Forth interpreter. Clears both parameter stack and return stack. Does not print 'ok' on return.

---

11 Exploring the Forth system

11.1 The Forth interpreter

The time has come to look more closely at the way the Forth system operates. On power up Forth immediately enters an interpretive loop, which monitors the keyboard for input, and on receipt of a carriage return attempts to interpret it. The name of this routine is **QUIT** and a definition of it might be:

```
: QUIT BEGIN QUERY INTERPRET AGAIN ;
```

QUERY awaits up to 80 characters of input (or until a carriage return) and transfers the input string to the input message buffer. As you may have guessed it uses **EXPECT** to achieve this. **INTERPRET** attempts to interpret all the words in the buffer as valid Forth. When a program executes **ABORT** both the return stack and parameter stack are reset and execution begins again with **QUIT**. **QUIT** itself may be called from within a program to return control to the interpreter, but unlike **ABORT** will not clear the parameter stack.

INTERPRET acts on each word in the input string in turn, first attempting to find a matching name in the Forth dictionary, and then if no match is found trying to convert the string to a number according to the current base. If a word is encountered which is neither in the dictionary nor a valid number then it aborts with an error message and **QUIT** executes again. The routine which conducts the dictionary search for **INTERPRET** is **FIND** (79-Standard) which returns a true value if the next word in the input stream is found in the dictionary, and false if it is not. **FIND** uses 32 **WORD** to look ahead in the input and transfer the string to **HERE** before starting the search. Should the string not be found it is conveniently placed for **NUMBER** to attempt conversion. Should **NUMBER** fail in the attempt it executes **ABORT** and **INTERPRET** terminates. It is **WORD** which makes the decision as to whether the input is to be taken from the disk buffers or from the input message buffer. This decision is based on the contents of a variable called **BLK**, set to zero while keyboard input is in progress. **WORD** begins scanning for a space (or other delimiting character) at an address given by adding the contents of a character pointer to the start address of the input buffer. The character pointer is in a variable called **>IN** (**IN** in

FIG Forth). When **WORD** terminates it leaves the contents of >**IN** incremented by the length of the string transferred to **HERE**, plus any leading spaces there may have been. When **INTERPRET** begins execution the contents of >**IN** are set to zero. A definition for **INTERPRET** could thus be written:

```
: INTERPRET Ø >IN !
   BEGIN FIND ?DUP
         IF EXECUTE ?STACK
         ELSE HERE NUMBER
         THEN
   AGAIN ;
```

The word **EXECUTE** uses the true value left by **FIND** to execute the routine associated with the name just found in the dictionary. ?**STACK** tests the stack for underflow after the word has been executed, and aborts with the *stack empty* error message if necessary. There are two possible exits from **INTERPRET** if erroneous input is encountered, one through the **ABORT** in **NUMBER** and the other through ?**STACK**. There is, however, no immediately apparent exit from **INTERPRET** if all input is correct. The usual method of exit from **INTERPRET** makes use of the 'null' character (ASCII Ø), which **EXPECT** appends to the input string when **QUERY** executes. The null represents the name of a routine in the dictionary, and is thus found by **FIND** and executed. This routine activates a word called **EXIT** which abandons one level of execution causing a jump out of **INTERPRET** and back to **QUIT**. **EXIT** may be called explicitly in a program and its effects can be seen in the following demonstration:

```
: TEST ." Returning " EXIT ." abandoned" ;


TEST <RETURN> Returning ok


: TEST TEST ." to outer level" ;


TEST Returning to outer level ok
```

Words introduced in this section:

QUERY
Inputs a string of up to 8Ø characters from the terminal to the input buffer.

INTERPRET
Attempts to interpret the string of characters in the input buffer, delimited by a null (ASCII 0).

>IN (---addr)
System variable containing the characters offset into the input buffer (called **IN** in FIG Forth).

QUIT
Returns control to the outer interpreter without clearing the parameter stack or printing any message.

EXIT
Terminates the colon definition currently executing and returns to the next outermost level of execution.

FIND
Returns the compilation address (cfa) of the next word in the input stream. If the word is not found leaves a zero.

11.2 Dictionary structure

Since the Forth system is so heavily dependent on dictionary searches for both interpreting and compiling, the dictionary is structured in a way which allows it to be searched very efficiently. The Forth dictionary like other dictionaries consists of a list of named entries. These entries; the colon definitions, constants and variables, are stored in the order in which they are defined, the oldest being at the bottom of the dictionary and the latest at the top. The dictionary entries are of variable length and may be interspersed with unnamed regions of data and code. The entries are held in the form of a 'backward linked list', each entry containing a pointer to the previous entry – ending with the first entry in the dictionary. The pointers which link the routines together are automatically set up by the compiler.

The dictionary entries are themselves structured for simplicity of use by the system. Each consists of two main parts; the head which contains identity information, and the body which contains data relevant to its execution. The head may be subdivided into three parts; the *name field* which holds the name, the *link field* containing the pointer to the previous entry, and the *code field* which specifies the actual routine to be executed. Dictionary names can be up to 31 characters long, the length being specified in the lowest 5 bits of a count byte which precedes the name. This is the start address of the name field and is called the *name field address* or *nfa*. The nfa of the most recent definition can be returned by the Forth-79 word **LATEST**:

```
: LAST? ( ---) LATEST COUNT 31 AND TYPE ;

LAST? <RETURN> LAST? ok

: XXX ; <RETURN>

LAST? <RETURN> XXX ok
```

The structure of an entry in a typical Forth dictionary is shown in diagram 11.1 and an overall dictionary structure in diagram 11.2

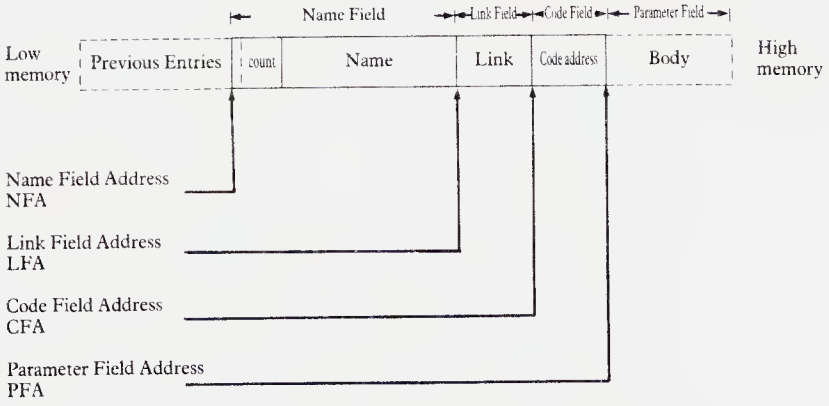


Diagram 11.1. Structure of a dictionary header

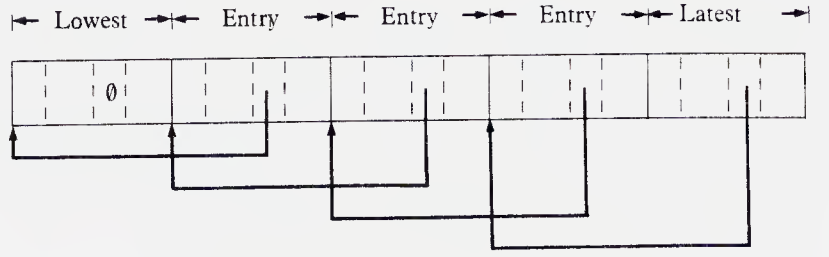


Diagram 11.2. Dictionary Chain Structure

As you can see the link field of an entry points to the nfa of the previous entry. Dictionary searches begin with the latest definition and work back through the list until an entry whose link field contains zero is encountered. This signals that the lowest entry has been reached and terminates the search. The definition below displays the names of all the definitions in the Forth vocabulary, begining with the latest.

```
: VLIST LATEST ( ---nfa)
        BEGIN COUNT 31 AND
              2DUP TYPE
              + ( ---lfa) @ ( link)
              ?DUP 0= ( bottom?)
        UNTIL ;
```

The *link field address* (*lfa*) is calculated by adding the length of the name to the nfa plus one.

The *cfa* specifies the start of the code field, which points to a machine code routine which will be executed called the 'run-time' code. It is the cfa that **FIND** returns when a word has been found in the dictionary. The primitive **EXECUTE** used in the defintion of **INTERPRET** takes the cfa of the definition to be executed as a stack parameter, and hence the true values from **FIND** were conserved using **?DUP**. Here is another example:

```
: PERFORM ( ---) FIND ?DUP IF EXECUTE
                              ELSE ." Can't "
                              THEN ;
```

If you examine the contents of the code field of a number of colon definitions using **CODE?** you will find they all contain the same value.

```
: CODE? FIND ?DUP IF @ U. THEN ;
```

The number displayed is the address of the *run-time* code, and this means that all colon definitions have the same run-time code or behaviour. Similarly all names defined using **VARIABLE** have common run-time behaviour but one that is different from a colon definition. Thus words defined using **VARIABLE** and : and **CONSTANT** represent three classes of dictionary entry distinguishable by their run-time behaviour. Chapter 12 shows how new classes of word with distinctive run-time behaviour may be added to the system. The practice of using run-time routines which are common to a number of procedures is a major contributor to Forth's simplicity and flexiblity. One other class of word will be present in the Forth kernel. These are code definitions and contain a machine code routine in the body of the definition. In these defintions the code field points straight to the pfa of the word, i.e. the cfa + 2. Included among the code definitions will be most of the stack manipulation and 16-bit arithmetic operators, and all the routines which deal with input and output.

The body of a definition consists of a single *parameter field*. In the case of colon definitions this is a list of addresses which are used when the word executes. These are the code field addresses of all the routines called by the definition. The parameter field of an assembler definition contains machine instructions and addresses to be executed directly by the processor. New assembler definitions ean be added to the dictionary using the

defining word **CODE** followed by the name. Instructions for doing this should be contained in your Forth system manual.

The Forth system is designed to spend most of its time executing colon definitions, and employs a software device called the 'address interpreter' or 'inner interpreter' to manage this. The task of the address interpreter is to execute a list of routines. It uses a 16-bit pointer called the 'interpretive pointer' to hold the address of a cell within the parameter field of a colon definition where the cfa of the next routine to be executed can be found. On start up, the interpretive pointer is loaded directly with the pfa of **QUIT** and the address interpreter is activated. In the definition of **QUIT** given above the first cell in the parameter field would contain the cfa of **QUERY**. The address interpeter uses a second pointer, usually called the W-register, to hold an address where the start address of the machine code routine to be executed will be found. Each time the address interpreter acts the W-register is loaded with the contents of the address held in the interpretive pointer. The first value to be loaded when **QUIT** executes is therefore the cfa of **QUERY**. Before going off to execute **QUERY** the address interpreter increments the interpretive pointer by two so that on return from **QUERY** it will be pointing to the cell containing the cfa of **INTERPRET**. The address interpreter then executes the next routine as indirectly pointed to by the W-register, and since **QUERY** is a colon definition the run-time code for a colon definition is executed. The address interpreter must now pass along another list of code field addresses, so the colon-code does three things. It first saves the current contents of the interpretive pointer on the return stack. It then copies the contents of the W-register into the interpretive pointer and adds two so that it points to the pfa of the current colon definition. Lastly it activates the address interpreter and execution continues. The address interpreter now begins working its way through the list of code field addresses in **QUERY**, which may themselves point to colon definitions. Each time a new colon definition is entered another value is pushed onto the return stack. Eventually a code routine will execute which is not colon-code and the address interpreter will be allowed to run to the end of a definition. All machine code routines must return to the address interpreter if the system is to operate correctly and the Forth assembler will contain a word which compiles the necessary code at the end of a code definition. It is usually called **NEXT**.

The final cell in the parameter field of a colon definition always points to **EXIT**, whose cfa is often compiled by a semi-colon. **EXIT** is a code routine which removes the top value from the return stack and loads it into the interpretive pointer before activating the address interpreter. This takes execution back to the next outer level of definition. Thus on reaching the end of **QUERY**, **QUIT EXIT** restores the interpretive pointer so that it again points to the cell containing the cfa of **INTERPRET**. The address interpreter

now loads this into the W-register, and increments the interpretive pointer so it points to the cfa of **AGAIN**.

As you can see the address interpreter is the engine of the Forth system and is constantly humming away in the background. You will be glad to hear, however, that its actions are completely transparent to the programmer except when abusing the return stack.

Words introduced in this section:

CODE (NAME)
Begins compiling an assembler definition with the name that follows.

11.3 Vocabularies

One of the most unusual features of Forth is its use of separate named vocabularies, each containing a sub-set of the dictionary. The principal vocabulary is **FORTH**, which contains nearly all the definitions introduced in this book. There are generally two other resident vocabularies, called **EDITOR** and **ASSEMBLER**. The Forth system is concerned with two vocabularies at any given time. They are the current vocabulary and the context vocabulary. The current vocabulary is the one into which new definitions are added, whilst the context vocabulary determines which words are interpreted. The vocabularies themselves are linked lists within the dictionary, with the bottom entry linking back to the **FORTH** vocabulary (see diagram 11.3).

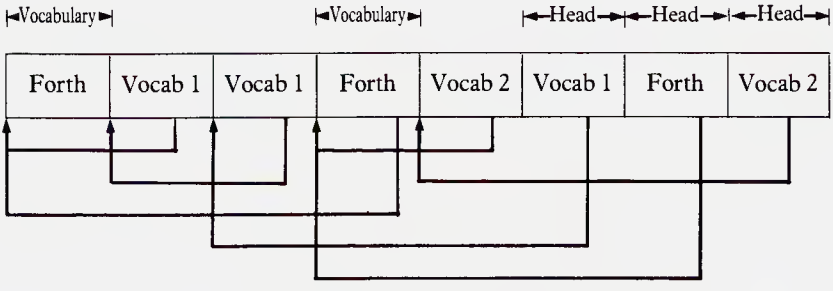


Diagram 11.3. Vocabulary Chains

When a dictionary search is performed it starts with the latest word in the context vocabulary and works back towards **FORTH**. If the word is not found in the context vocabulary the search proceeds back though **FORTH**. No other vocabularies are searched since they do not form part of the same chain. This can be demonstrated by typing:

FORTH VLIST <RETURN>
ASSEMBLER VLIST <RETURN>
EDITOR VLIST <RETURN>

and observing the different results.

The system uses two variables, **CURRENT** and **CONTEXT** as pointers to the base of the current and context vocabularies. A new vocabulary may be defined in the following way:

VOCABULARY GERMAN

VOCABULARY is a 'defining word' similar to **VARIABLE** and **CONSTANT**. It creates a named entry in the current vocabulary (usually **FORTH**) whose parameter field contains the nfa of the latest definition in the defined vocabulary. Initially this will be the nfa of the vocabulary itself. When the vocabulary is executed the run-time code places its parameter field address in **CONTEXT**. When the dictionary is searched by a word such as **FIND** the search does not begin with the address returned by **LATEST** but with that returned by

CONTEXT @ @ <RETURN>

New definitions may be added to a vocabulary by making it current. The word **DEFINITIONS** copies the contents of **CONTEXT** into **CURRENT** so that by executing

GERMAN DEFINITIONS <RETURN>

we have first made **GERMAN** the context vocabulary and then made it current. The variable **CURRENT** now contains the pfa of **GERMAN**. When a defining word (such as colon) is used to create a dictionary entry, the nfa returned by **CURRENT** @ @ is used to make up the link. Try the following:

```
CURRENT @ @ U. <RETURN>

: GREET ." Guten Abend" ;

CURRENT @ @ U. <RETURN>

FORTH DEFINITIONS

CURRENT @ @ U. <RETURN>
```

```
: GREET ." Good Evening" ;


CURRENT @ @ <RETURN>
```

One definition has been added to each of the **GERMAN** and **FORTH** vocabularies. The desired greeting may now be selected by specifying the context for interpretation.

```
GREET <RETURN> Good Evening ok


GERMAN <RETURN>


GREET <RETURN> Guten Abend ok

FORTH <RETURN>
```

The use of vocabularies gives us a method of attaching different meanings to a word, according to the context in which it is used. It is not customary to define a large number of vocabularies within a single application since this can be very confusing. It is more normal to define most of the words in **FORTH** and have only outer level words in the application vocabulary. Thus the vocabularies may be used to distinguish one application from another, and to allow application specific languages be constructed.

Words introduced in this section:

VOCABULARY (NAME)
Create a new vocabulary named (NAME) which becomes the context vocabulary upon execution.

CONTEXT (---addr)
System variable pointing to the vocabulary to be searched by the interpreter.

CURRENT (---addr)
System variable pointing to the vocabulary where new definitions are to be placed.

11.4 Vectored execution

Another method of changing the context of a word is known as vectored

execution. This is an extremely useful technique in programming and particularly easy to implement in Forth. The method uses a variable to hold the address of a definition to be executed. Execution is performed by an outer definition which passes the contents of the variable to **EXECUTE**. In this way by changing the contents of the variable, the execution behaviour of the outer calling word can be altered. The address actually placed in the variable varies between one programming system and another. Some programmers like to use the cfa of the word to be executed, whilst others prefer the pfa. The latter method is used here.

Indirect execution is most often used in coding those parts of an application which may have to be reconfigured. For example if two versions of a program only differed in the language of the messages to the user, the prompt routines might be vectored. Vectored execution may be performed through a word @**EXECUTE** which is resident on some systems. It takes as a parameter the address of an execution vector, i.e. a cell containing the address of the routine to be executed. Execution of the routine is only attempted if the contents of the vector are non-zero. A definition of @**EXECUTE** is

```
: @EXECUTE ( addr---) @ ?DUP IF 2- EXECUTE THEN ;
```

The pfa of a routine is returned by the word ' ('tick') which conducts a dictionary search for the word that follows in the input stream, and aborts if the word is not found. This may be used to load an execution vector. For example the routine **GREET** must print the message 'Good Evening' in English or German depending on where the software is to be used. The same coding for **GREET** can be used in both versions of the program if an execution vector is used.

```
VARIABLE 'MSG

: GREET 'MSG @EXECUTE ;
```

The routines which actually print the messages can be defined later as separate words and the pfa of the appropriate routine loaded into the vector on each version.

```
    ( German version)


: .GERMAN ." Guten Abend " ;


' .GERMAN 'MSG !


GREET <RETURN> Guten Abend ok
```

```
   ( English version)

: .ENGLISH ." Good Evening " ;

' .ENGLISH 'MSG !

GREET <RETURN> Good Evening ok
```

The advantage of this method is that any programs which use **GREET** are unaffected by this change and may therefore be coded before the actual printing routines have been specified. This means that programs can be written and tested before the details have been worked out and then later configured to a specific purpose.

As a more complex example consider a program to control menu type selection of a number of different functions within an application. The program prints out a title and list of numbered options describing the main functions in the application. It then enters a selection loop where the user selects an option by pressing an appropriately numbered key. The selected function is then executed, and the selection program re-entered for another choice. The program may be broken down into the following functions:

DISPLAY (---)
Displays the menu heading and list of numbered options.

CHOOSE (---n)
Waits for a numeric keystroke and returns an option number in the range 0–9.

ALLOWED (n---f)
Takes an option number and returns a true flag if it falls in the allowed range.

SELECT (n---)
Takes an option number and executes the associated function.

The coding of final control program will look like this:

```
: SELECTION ( ---) DISPLAY
 BEGIN CHOOSE DUP ALLOWED
       IF SELECT DISPLAY
       ELSE DROP
       THEN
 AGAIN ;
```

We can begin constructing the components of **SELECTION** without concerning ourselves with details of the functions and their descriptions by making use of execution vectors. The word **CELLS** defined in Chapter 9 has been used to create a pair of indexed vectors each containing **FUNCTIONS** cells intialised to zero:

```
  ( Execution vectors )

VARIABLE HEAD

4 CONSTANT FUNCTIONS

FUNCTIONS CELLS OPTIONS

FUNCTIONS CELLS CHOICES


   ( Indexed vectors )

: OPTION ( n---addr) OPTIONS 1+ SWAP 1- 2* + ;

: CHOICE ( n---addr) CHOICES 1+ SWAP 1- 2* + ;


  ( Display routines )

: .HEAD ( ---) HEAD @EXECUTE ;

: .OPTIONS ( ---) FUNCTIONS 1+ 1
DO I .
   I OPTION @EXECUTE CR
LOOP ;
```

```
: DISPLAY ( ---) CR CR .HEAD CR CR .OPTIONS ;


 ( Function execution )

: SELECT ( n---) CHOICE @EXECUTE ;

( Selection )

: ALLOWED 1 FUNCTIONS WITHIN ;

: CHOOSE ( ---n) BEGIN KEY DUP 48 58 WITHIN NOT
                 WHILE DROP
                 REPEAT 48 - ;
```

OPTION returns the address of the vector to the display routine describing the option, while **CHOICE** returns the vector to the function. All execution is performed using @**EXECUTE**. Exit from the closed loop in **SELECTION** can be provided by loading one of the **CHOICE** vectors with the pfa of **EXIT**:

```
' EXIT FUNCTIONS CHOICE !
```

On executing **SELECTION** a set of numbers representing the option numbers will be displayed on the left, and the program will await a keystroke. Selections 1–3 will cause the menu to display again, selection 4 causes the program to end, and any other keystrokes are ignored. The other vectors may now be loaded up as required.

```
: .DUMMY ." Menu Selection Heading" ;

' .DUMMY HEAD !


: .ONE ." Selects first option " ;


: .TWO ." Selects second option " ;


: .THREE ." Selects third option " ;
```

```
: .FOUR ." Exits selection program " ;

' .ONE 1 OPTION !

' .TWO 2 OPTION !

' .THREE 3 OPTION !

: ONE ." First option executed " ;

: TWO ." Second option executed " ;

: THREE ." Third option executed " ;

' ONE 1 CHOICE !

' TWO 2 CHOICE !

' THREE 3 CHOICE !
```

The operation of **SELECTION** can now be altered at any time simply by writing new run-time routines and loading the vectors. **SELECTION** itself need only be recompiled if the value of **FUNCTIONS** is to be altered.

The Forth system itself makes use of execution vectors for its I/O routines and certain other system functions. The routines **EXPECT**, **TYPE**, **BLOCK** and **BUFFER** are normally vectored because the coding is specific to particular peripherals and so they must be recoded each time Forth is transported to a new machine. Vectoring these routines minimizes the number of changes which need to be made. Another routine commonly vectored is the numeric input conversion **NUMBER**. This allows specialized input routines to replace the standard one in a particular application. The name of the vector for **NUMBER** (if one exists) should be in your Forth system manual along with those of other system vectors.

Words introduced in this section:

' (NAME) (---addr)
Returns pfa of the word that follows. Aborts if the word cannot be found in the context dictionary or **FORTH**.

11.5 The Forth compiler

The distinction between the compiler and the interpreter is not as clear cut in Forth as in other programming systems. All input is interpreted by the interpreter but some Forth words cause compilation to take place when they execute. These are called 'compiling words' and are executed by the compiler rather than compiled. The compiler itself is usually a word called] which has an indefinite loop structure rather like that of **INTERPRET**.] distinguishes a word to be executed from a word to be compiled by checking one of the unused bits in the count byte of the name field. This bit, called the *precedence* bit, is set if the word is to be executed immediately by the compiler. Exactly which bit is the precedence bit varies from one system to the next, but may be determined as follows.

```
: SHOW LATEST C@ .BIN ;


: TEST ; <RETURN>


SHOW <RETURN>


IMMEDIATE <RETURN>


SHOW <RETURN>
```

IMMEDIATE marks the last colon definition in the current vocabulary for immediate execution by the compiler by setting the precedence bit. This should be reflected in the results produced by **SHOW** before and after **IMMEDIATE** was executed.

Within the loop strucure] searches the dictionary for the next word in the input stream, and if found tests the precedence bit. If the precedence bit is set the word is compiled, otherwise it is executed. If the word is not found numeric conversion of the string at **HERE** is attempted, and if this is

successful the stack value is compiled as a literal value. The code for] can be represented thus:

```
: ] ( ---) BEGIN FIND ?DUP ( search)
                  IF IMMEDIATE? ( test string at HERE)
            IF EXECUTE ( immediate word)
               ?STACK ( error if stack underflowed)
            ELSE , ( compile cfa)
            THEN
         ELSE HERE NUMBER ( convert to number)
            LITERAL ( compile number)
         THEN
      AGAIN ;
```

The word **IMMEDIATE?** will return a true flag if the precedence bit was set, and you will need to consult your system manual to find out how to calculate the name field address of a word if you want a definition for it. If a word is not found then compilation of the number is achieved using the Forth word **LITERAL**. **LITERAL** causes compilation of two cells into the word being compilcd. The second cell contains a value taken from the stack at compile time, and the first cell contains the cfa of a routine which will return the value to the stack at run time (and skip the interpretive pointer over the next cell). **LITERAL** may be used inside a colon definition so that the values compiled as literals may be specified as compile time parameters, or from the results of a compile time calculation. Compile time calculations may be performed if the compiler is switched off inside a colon definition. This is done using the immediate word [to mark the start of compile time operations and] to reactivate the compiler at the end. **LITERAL** is used to compile the value into the correct position in the definition and usually follows immediately after]. This technique could have been used in the definitions of **GOODS** and **VAT** in the application at the end of Chapter 9:

```
15 CONSTANT RATE ( % VAT)

: GOODS ( tot---gds) 100 [ RATE 100 + ] LITERAL M*/ ;

: VAT ( tot---vat) RATE [ RATE 100 + ] LITERAL M*/ ;
```

The word [turns the compiler off by causing it to **EXIT** the closed loop. The calculation which follows is then performed by the interpreter leaving the result on the stack. The compiler is turned on again by] (which is not an immediate word) and the stack value taken as a parameter by **LITERAL** and compiled as a literal immediately. Using this method the constant value **RATE** + 100 is computed only at compile timc rather than each time the program executes.

There are two further words in your Forth system which affect the action of the compiler. They are called **COMPILE** and **[COMPILE]**.

[COMPILE] is used in definitions to signal that the next word in the definition is not to be treated as immediate regardless of whether its precedence bit has been set. It is often used to delay the action of a core immediate word until the outer (immediate) definition executes. The following word, used in a definition, will compile into that definition as a literal the square of the number on the stack at the time:

```
: SQR, ( n---) DUP * [COMPILE] LITERAL ;

IMMEDIATE


: TEST [ 4 ] SQR, . ; <RETURN> ok


TEST <RETURN> 16 ok
```

COMPILE is also only used in definitions, and affects the word that follows it. This time the cfa of the word following is compiled into the dictionary when the outer definition executes, rather than compiled into the definiton itself. As you might expect **COMPILE** is generally used in immediate definitions. A good example of the use of **COMPILE** is in the Forth control structures. Although the implementation of these varies between systems they will always have two phases of activity, at compile time and at execution. Generally the word **DO** leaves an address on the stack at compile time for use by **LOOP** in constructing a branch. Sometimes it will also leave an identifier in case it is not appropriately matched. Upon execution of **DO** two values must be moved from the parameter stack onto the return stack. The easiest way to achieve this result is to define **DO** as an immediate word, which compiles a seperate execution time routine into any definition in which it is used:

```
: (DO) SWAP R> SWAP >R SWAP >R >R ;
: DO ( ---addr) COMPILE (DO) HERE ; IMMEDIATE
```

Words introduced in this section:

IMMEDIATE
Marks the last word defined to be executed when encountered in a definiton rather than compiled.

COMPILE (NAME)
Compiles the cfa of the next (non-immediate) word into the dictionary when the current definition executes.

[COMPILE] (NAME)
Compiles the following word into the current definition even if it is immediate.

12 Classes of words

12.1 More about variables and constants

In the previous section you saw how Forth words are constructed in the dictionary. Basically they consist of a header containing the word's name (or the significant portion of it); a cell which points to the next definition in the dictionary (link field); a cell which contains the address of the general code shared by all definitions of that type (code field); and a number of cells containing the code specific to the word (parameter field).

In this section we will be looking more closely at the code field and parameter field (and their contents) with reference to different classes of words.

One of the great strengths of Forth as a development and learning tool is the ease with which simple programs can be used to investigate the workings of the system itself. We will be using the following word to check the contents of the appropriate cells:

```
: CHECK CR ." Code field: "
  [COMPILE] ' DUP 2- U.
  ." Contains: "
  DUP 2- @ U.
  ." Parameter field: "
  DUP U.
  ." Contains: "
  @ U. ;
```

The [COMPILE] is necessary on some systems to prevent ' picking up the address of DUP, rather than the address of the word that follows CHECK when it is executed. It may be redundant in some cases, but it should do no harm to include it.

Let's use CHECK to look at some colon definitions. First create the following words:

```
: PLUS + ;
: MINUS - ;
: DIVIDE / ;
```

Using these with **CHECK** as in:

CHECK PLUS <RETURN>
CHECK MINUS <RETURN>
CHECK DIVIDE <RETURN>

should reveal that the contents of the code field address is the same for all three words. It will in fact be the same for all colon definitions, simply telling Forth to execute the code which follows in the parameter field. For each of the words above the contents of the parameter field address should be the code field address of the operator within the definition. Thus **PLUS** will contain the code field address of +, **MINUS** of – and **DIVIDE** of /. You can verify this using **CHECK**:

CHECK + <RETURN>
CHECK – <RETURN>
CHECK / <RETURN>

Now try a similar investigation of a selection of variables:

```
VARIABLE RED

VARIABLE WHITE

VARIABLE BLUE


CHECK RED <RETURN>
CHECK WHITE <RETURN>
CHECK BLUE <RETURN>
```

Again you should find that the code field contents are the same for all three variables, though different from that found with colon definitions. The parameter field will contain a zero for all these variables. The code field of a variable tells Forth that the action of the word is simply to leave its own parameter field address on the stack, and the address on the stack, and the pfa contains the actual value of the variable. Thus if you key in:

20 RED ! <RETURN>
CHECK RED <RETURN>

you will find that the contents of the parameter field have changed to 20, the new value of the variable **RED**.

Now do the same for a selection of constants such as:

```
1 CONSTANT ONE

2 CONSTANT TWO

3 CONSTANT THREE


CHECK ONE <RETURN>
CHECK TWO <RETURN>
CHECK THREE <RETURN>
```

Yet again the contents of the code field address are common to all constants, and the parameter field contains the value associated with them. This time the code field tells Forth that the word is to leave the contents of its own parameter field on the stack.

Words which share a common code field value are said to belong to the same class. Thus all variables represent one class of words, and all constants another.

12.2 Defining words

In Forth, words used to create other words, such as **VARIABLE** and **CONSTANT**, are called *defining words*. Each will give a special code field value to the words it creates, signifying that they belong to a particular class. One of the most useful facilities Forth offers is the ability to create your own defining words, with which to build up new classes of words. The key to this is a pair of complementary words called **CREATE** and **DOES>**. Their general form is as follows :

```
: DEF-WORD CREATE
           ( code to be executed by DEF-WORD)
           DOES>
           ( code to be executed by word created) ;
```

The following illustrates how this format is used:

```
: CLASS1 CREATE
         ." Compiling new word in Class 1"
         DOES>
         ." Action of word in class 1 with PFA " . ;
```

CREATE looks ahead in the input stream and creates a new header in the dictionary with the first word it finds. When it is finished the top of the dictionary, pointed to by **HERE**, represents the parameter field address of

the new word. The word created will leave this address on the stack when it is executed. FIG systems use the word <BUILDS instead of CREATE, though its action when used in conjunction with DOES> is exactly the same.

DOES> is nearly always used after a CREATE or <BUILDS. It represents the beginning of the 'class code' for the words to be created. This code generally assumes that the parameter field address of the word currently executing is available on the stack. If you create a selection of words with CLASS1 and execute them you'll see how this works:

```
CLASS1 TOM <RETURN>

TOM <RETURN>

CLASS1 DICK <RETURN>

DICK <RETURN>

CLASS1 HARRY <RETURN>

HARRY <RETURN>
```

Here is a definition of VARIABLE using CREATE and DOES> (remember to substitute <BUILDS if CREATE does not exist):

```
: VARIABLE CREATE 0 , DOES> ( -addr) ;
```

In this case there is no code at all between DOES> and the semi-colon. Variables – since all they need to do is leave their pfa on the stack – need no further coding. The action of VARIABLE is to first create a header with the name that follows. Next the word , (comma) compiles a zero into the dictionary at the address given by HERE (i.e. the pfa of the new word). Finally DOES> modifies the code field address of the word created to tell it what to do with the pfa on the stack when it executes, in this case nothing. You should create some new variables using this definition and investigate them as before using CHECK. Note that although this should behave exactly like the VARIABLE indigenous to your system, the code field value it generates will be quite different.

Let's look at another example, this time a definition of CONSTANT:

```
: CONSTANT ( n--) CREATE , DOES> ( --n) @ ;
```

Here the number on the stack when CONSTANT is executed is compiled into the parameter field address of the word created, and this value is then fetched onto the stack when the latter executes.

The word , is one of a small selection used frequently in defining words.

It compiles the value on the stack into the next available cell in the dictionary, and adjusts the dictionary pointers so the cell is subsequently protected from inadvertent overwriting. It can be used several times in succession, so that the following words would allow the creation of double number variables and constants:

```
: 2VARIABLE CREATE 0 , 0 ,
   DOES> ( --addr) ;


: 2CONSTANT ( d--) CREATE , ,
   DOES> ( --d) 2@ ;
```

Words introduced in this section:

CREATE
Creates a header in the dictionary with the name that follows. When executed the new word will leave its parameter field address on the stack.

<BUILDS
FIG Forth only. Creates a header in the dictionary with the name that follows. Equivalent to **CREATE**, but can only be used in conjunction with **DOES>**.

DOES>
Use only with **CREATE** or **<BUILDS**. Begins run time code for class of words. When executed modifies the code field address of the word just created to point to this code.

12.3 Building data structures

One of the most common uses of defining words is in building new *data structures*. By a data structure we mean any portion of memory reserved for special use, whose means of access is determined by its significance to the user. A variable is the simplest sort of data structure in the Forth system. Looking at the definition of **2VARIABLE** in the previous section we can see that four bytes of memory were reserved, with the idea of using them to store double numbers. This class of words could, however, be thought of as containing pairs of single numbers. Their activity remains the same, it is only the interpretation of the results that differs. Taking this further we could reserve any number of cells in the dictionary to hold whole lists of values. Such a structure is traditionally called an *array*.

To create an array we will need to reserve a block of memory in the dictionary. Forth allows us to do this with the word **ALLOT**. This expects a number on the stack representing the number of bytes we want reserved. You can try it at the keyboard like this:

```
HERE U. <RETURN>
10 ALLOT <RETURN>
HERE U. <RETURN>
```

HERE should increase by the number of bytes allotted, in this case 10. Our definition of **ARRAY** will expect on the stack the number of cells in the array to be created, and will need to **ALLOT** twice this number of bytes:

```
: ARRAY ( n--) CREATE 2* ALLOT
              DOES> ( n--addr)
                    SWAP 2* + ;
```

Notice that the coding after **DOES>** calculates the address of any element, assuming that the number of the element (starting at zero) is on the stack with the start address of the memory **ALLOT**ted above it. The following will now create an array called **FRED** with ten cell elements:

```
10 ARRAY FRED <RETURN>
```

The elements are numbered 0 through 9, so that the address of element 2 would be returned by:

```
2 FRED <RETURN>
```

This address may then be used just as if it pointed to an ordinary variable.

The problem with **FRED** is that it will accept any element number, even though only 10 cells have been allotted. This means that:

```
20 FRED <RETURN>
```

gives an address outside the array, which might easily cause disastrous results. The way to avoid this is to include a check in the **DOES>** portion of **ARRAY** to ensure that the element number is within the allotted memory. We can do this by saving the original element count:

```
: ARRAY ( n--)
        CREATE DUP , 2* ALLOT
        DOES> ( n--addr) 2DUP
     @ 0 SWAP WITHIN NOT
     IF ." Out of range."
        ABORT
     THEN
     SWAP 2* + 2+ ;
```

A definition of **WITHIN** can be found in Chapter 7 if it does not already exist on your system. To make the definition above more readable we can factor out the new coding:

```
: RANGE-CHECK ( n,addr--)
     @ 0 SWAP WITHIN NOT
     IF ." Out of range."
        ABORT
     THEN ;


: ARRAY ( n--)
        CREATE DUP , 2* ALLOT
        DOES> ( n--addr)
     2DUP RANGE-CHECK
     SWAP 2* + 2+ ;
```

This gives a general format for creating arrays of many different types. To adapt the coding above for double number arrays, for instance, all we need to do is substitute `4*` for `2*` in both cases. In order to allow you to create byte variables and arrays most Forth systems provide the word **C,** which compiles one byte into the dictionary. This can be used for variables whose value will always be less then 256:

```
: CVARIABLE CREATE 0 C,
                DOES> ( addr--) ;
```

A more interesting use of **C,** is as a defining word which allows you to name ASCII control codes and have them automatically **EMIT**ted:

```
: CTRL ( n--) CREATE C,
             DOES> C@ EMIT ;
```

This could then be used as in:

```
7 CTRL BEL

13 CTRL RET

10 CTRL LF

11 CTRL VT

: CR RET LF ;
```

We might also use **C,** to create a class of masks to enable us to investigate any bit from a given byte value:

```
: MASK CREATE C, DOES> C@ AND ;


2 BASE !

10000000 MASK BIT7

01000000 MASK BIT6

00100000 MASK BIT5

00010000 MASK BIT4

00001000 MASK BIT3

00000100 MASK BIT2

00000010 MASK BIT1

00000001 MASK BIT0

DECIMAL
```

Here is an application designed to help you pick sports teams using two classes of words - players and teams. The defining word for players looks like this:

```
: PLAYER CREATE LATEST ,
         DOES> ( --addr) @ ;
```

This creates a header for the name that follows and then compiles the new word's name field address into its pfa. The name field address is left on the stack when this word executes. **LATEST** does not exist on some systems, on PolyForth, for instance, the equivalent coding would be:

LAST @ @

or

LAST @ @ B/H +

Using **PLAYER** names can be added to the list of players as in:

PLAYER DRIBBLE <RETURN>

Executing **DRIBBLE** would leave its own name field address on the stack, which we can use to type out the name:

DRIBBLE COUNT 31 AND TYPE <RETURN>

The 31 **AND** is needed because only the first five bits of the nfa are used for the count of the name. We now need to create teams in which to put our players. This means another defining word, which looks very similar to our original definition of **ARRAY**:

```
: TEAM ( n--) CREATE DUP,
              2* ALLOT
              DOES> ( --addr) ;
```

With this we can create a named team with space for any number of players:

```
11 TEAM UNITED
```

When executed **UNITED** leaves its own pfa on the stack, representing the cell containing the count of elements in the array. Each cell will represent one player, so that the following will calculate a player's address given the appropriate team's pfa and the player number (in this case 1 to 11):

```
: 'PLAYER ( addr,n--addr) 1- 2* + 2+ ;
```

This can be used to store the nfa given by the player's name into an element of the team array:

```
: PICKED ( addr,addr,n--) 'PLAYER ! ;
```

Used as:

```
DRIBBLE UNITED 1 PICKED <RETURN>
```

The address given by **'PLAYER** also allows us to list out a given member of any team:

```
: .PLAYER ( addr,n--)
 'PLAYER @
 ?DUP IF COUNT 31 AND TYPE
      THEN ;
```

or all of the team:

```
: .PLAYERS ( addr--)
  DUP @ 1+ 1
  DO CR I
     DUP I .PLAYER
  LOOP DROP ;
```

We can thus check that **DRIBBLE** has been **PICKED** for **UNITED** with:

```
UNITED 1 .PLAYER <RETURN>
```

or simply:

```
UNITED .PLAYERS <RETURN>
```

Finally a simple word allows us to drop players from any team:

```
DROPPED ( addr,n--) 'PLAYER 0 SWAP ! ;
```

So that to drop **DRIBBLE** from **UNITED** we would say:

```
UNITED 1 DROPPED <RETURN>
```

Words introduced in this section:

C, (b--)
Compiles a byte value into the top of the dictionary and resets the dictionary pointer accordingly.

APPENDICES

Forth glossaries

The normal stack effect of each word is given in brackets after its name as (stack before --- stack after)

Numbers on the stack are represented as follows:

n	16-bit value.
d	32-bit value.
u	Prefix meaning 'unsigned'.
rem	Remainder.
quot	Quotient.
addr	16-bit address.
f	Flag. Zero means false, non-zero means true.
b	16-bit value within 8-bit range.
char	Value representing ASCII character.

Where a word expects to be followed by a name the notation (NAME) appears after it.
Glossaries are based on information supplied by the Forth Interest Group, P.O. Box 1105, San Carlos, CA 94070, USA.

Appendix A
Forth-79 Standard

Stack Manipulation

DUP (n---n,n)
Duplicate top item on the stack.

DROP (n---)
Discard top item on the stack.

SWAP (n1,n2---n2,n1)
Reverse the positions of the top two items on the stack.

OVER (n1,n2---n1,n2,n1)
Duplicate second item on the stack and place it on the top.

ROT (n1,n2,n3---n2,n3,n1)
Rotate third item on the stack to the top.

PICK (n1---n2)
Copy n1th item on the stack to the top (thus 1 **PICK** = **DUP**, 2 **PICK** = **OVER**).

ROLL (n---)
Rotate nth item on the stack to the stop (thus 2 **ROLL** = **SWAP**, 3 **ROLL** = **ROT**)

?DUP (n--n,(n))
Duplicate top stack value only if non-zero.

>R (n--)
Move top parameter stack item to the top of the return stack. Must be restored with **R>** at same level to avoid unpredictable results.

R> (--n)
Move top return stack item to the top of the parameter stack.

R@ (--n)
Make a copy of the top value of the return stack onto the top of the parameter stack.

DEPTH (--n)
Leave a count of the number of 16-bit numbers on the stack (before **DEPTH** is executed).

Comparison

< (n1,n2 --- f)
Leave true if n1 is less than n2.

= (n1,n2 --- f)
Leave true if n1 equals n2.

> (n1,n2 --- f)
Leave true if n1 is greater than n2.

0< (n --- f)
Leave true if the top item on the stack is less than zero (i.e. negative).

0= (n --- f)
Leave true if the top item on the stack is zero (equivalent to NOT).

0> (n --- f)
Leave true if the top item is greater than zero (i.e. positive).

D< (d1,d2 --- f)
Leave true if d1 is less than d2.

U< (un1,un2 --- f)
Leave true if un1 is less than un2. Treats both numbers as unsigned integers.

NOT (f1 --- f2)
Reverse truth value of the top stack item (equivalent to 0=).

Arithmetic And Logical

+ (n1,n2 --- n1+n2)
Add together top two stack items.

D+ (d1,d2 --- d1+d2)
Add together the two double precision numbers on the stack.

- (n1,n2 --- n1-n2)
Subtract the value on the top of the stack from the value underneath it.

1+ (n --- n+1)
Add one to the top stack item.

1- (n --- n-1)
Subtract one from the stack item.

2+ (n --- n+2)
Add two to the top stack item.

2– (n – – – n–2)
Subtract two from the top stack item.

* (n1,n2 – – – n1*n2)
Multiply together the top two stack items.

/ (n1,n2 – – – quot)
Divide the second item on the stack by the value on top. Quotient is rounded towards zero.

MOD (n1,n2 – – – rem)
Leave remainder from dividing n1 by n2. Remainder has same sign as n1.

/MOD (n1,n2 – – – rem,quot)
Divide n1 by n2 and leave remainder and quotient.

***/MOD** (n1,n2,n3 – – – rem,quot)
Multiply n1 by n2 and divide the result by n3. Uses double precision intermediate.

*/ (n1,n2,n3 – – – quot)
Multiply n1 by n2 and divide the result by n3. Uses double precision intermediate. Leaves quotient only rounded towards zero.

U* (un1,un2 – – – ud)
Multiply together top two stack items as unsigned integers leaving unsigned double precision result.

U/MOD (ud,un – – – urem,uquot)
Divide double number by single giving single remainder and quotient. All values are unsigned.

MAX (n1,n2 – – – max)
Leave the greater of the top two stack items and discard the other.

MIN (n1,n2 – – – min)
Leave the smaller of the top two stack items and discard the other.

ABS (n – – – n)
Remove the sign from the top stack item and leave the absolute value.

NEGATE (n – – – –n)
Reverse the sign at the top stack item (two's complement).

DNEGATE (d – – – –d)
Reverse sign of the double precision number on top of the stack.

AND (n1,n2 – – – and)
Perform logical bitwise **AND** on the top two stack items.

OR (n1,n2 – – – or)
Perform logical bitwise **OR** on the top two stack items.

XOR (n1,n2 – – – xor)
Perform logical bitwise exclusive **OR** on the top two stack items.

Memory

@ (addr – – – n)
Replace address by value held at address. Pronounced 'fetch'.

! (n,addr – – –)
Store value h at address.

C@ (addr – – – b)
Replace address by byte value held at address. Pronounced 'c-fetch'.

C! (b,addr – – –)
Store byte value n at address.

? (addr – – –)
Print out the value held at address.

+! (n,addr – – –)
Add n to value held at address.

MOVE (addr1,addr2,n – – –)
Copy n two byte cells starting at addr1 to memory starting at addr2. Has not effect if n is zero or negative.

CMOVE (addr1,addr2,n – – –)
Copy n bytes starting at addr1 to memory starting at addr2. Has no effect if n is zero or negative.

FILL (addr,n,b – – –)
Fill n bytes of memory beginning at address with byte value.

Control Structures

DO...LOOP do: (end+1,start– – –)
Set up loop given index range

I (– – – n)
Place current loop index on the top of the stack.

J (– – – n)
Return index of next outer **DO...LOOP** in the same definition.

DO...+LOOP do; (end+1,start – – –)
+loop: (– – –)

Like **DO...LOOP** but adds stack value n to index (instead of always adding one). Loop terminates when index is greater than or equal to limit (n>∅), or when index is less than limit (n<∅).

LEAVE (---)
Terminate loop at next **LOOP** or **+LOOP** by setting index equal to limit.

IF...(true code)...**THEN** if: (f---)
If the flag on the top of the stack is true then execute code between the **IF** and **THEN**.

IF...(true code)...**ELSE** if: (f---)
...(false code)...**THEN**
If the flag on the top of the stack is true then execute code between the **IF** and **ELSE**, otherwise execute the code between **ELSE** and **THEN**.

BEGIN...UNTIL until: (f---)
Loop back to **BEGIN** until the flag on the top of the stack at **UNTIL** is true.

BEGIN...WHILE...REPEAT while: (f---)
Loop while flag is true at **WHILE**; **REPEAT** loops unconditionally to **BEGIN**. When flag is false continue from **REPEAT**.

EXIT (---)
Terminate execution of this colon definition. May not be used within a **DO...LOOP**.

EXECUTE (addr---)
Execute dictionary entry at compilation address on the stack. This is the address returned by **FIND**.

Terminal input/output

CR (---)
Do a carriage return and line feed.

EMIT (char---)
Type ASCII value from stack.

SPACE (---)
Type one space.

SPACES (n---)
Type n spaces if n>∅.

TYPE (addr,n---)
Type string of n characters from starting address.

COUNT (addr--- addr+1,n)
Change address of string (preceded by length byte) to form suitable for **TYPE**.

–TRAILING (addr,n1 – – – addr,n2)
Reduce character count of string at address to omit trailing blanks.

KEY (– – – char)
Read single keystroke from the keyboard and leave its ASCII value on the stack.

EXPECT (addr,n – – –)
Read n characters (or until carriage return) from the keyboard and store them as string starting at address. Append null(s) to end of string.

QUERY (– – –)
Read 80 characters (or until carriage return) from the keyboard and store them in the terminal input buffer. Append null(s) to end of string.

WORD (char – – – addr)
Read the next word from the input stream using char as delimeter, or until null. Leave address of length byte.

Numeric Conversion

BASE (– – – addr)
System variable containing current numeric base.

DECIMAL (– – –)
Set decimal number base.

. (n – – –)
Print number with one trailing blank and sign if negative.

U. (un – – –)
Print unsigned number with one trailing blank.

CONVERT (d1,addr1 – – – d2,addr2)
Convert string at addr1+1 to double number and add value into d1 leaving result d2. Addr2 is address of first non-convertable character.

<# (– – –)
Begin formatting a number on the stack into a string.

(ud1 – – – ud2)
Convert next digit of unsigned double number and add it to the beginning of the output string.

#S (ud – – – 0 0)
Convert all significant digits of unsigned double number into output string.

HOLD (char – – –)

Insert ASCII character into formatted output string. For instance **46 HOLD** inserts a decimal point (full stop).

SIGN (n– – –)
If signed single number n is less than zero insert minus sign at the beginning of a formatted output string.

#> (d– – –addr,n)
End formatting of formatted output string. Drops double number remaining on the stack (usually zero) and leaves appropriate arguments for **TYPE**. The output string is generally held in memory just below **PAD**.

Mass Storage Input/Output

LIST (n– – –)
List out screen n at the terminal and store the value of n in the variable **SCR**.

LOAD (n– – –)
Interpret screen n as if it were keyboard input. When finished return control to keyboard.

SCR (addr– – –)
System variable containing the screen number most recently **LIST**ed.

BLOCK (n– – –addr)
Leave buffer address of block n, reading block from mass storage if necessary.

UPDATE (– – –)
Mark block most recently accessed as modified.

BUFFER (n– – –addr)
Allocate the next memory buffer to block n, writing its contents back to disk if it has been **UPDATE**d. The contents of the block are not read into memory.

SAVE-BUFFERS (– – –)
Write all **UPDATE**d blocks in the buffers to mass storage.

EMPTY-BUFFERS (– – –)
Mark all buffers as empty without writing any information back to mass storage.

Defining Words

: (NAME) (– – –)
Begin compiling colon definition with name (NAME).

; (– – –)
End compiling colon definition.

VARIABLE (NAME) (– – –)
Create a two byte variable named (NAME)
which returns its address when executed.

CONSTANT (NAME) (n– – –)
Create a two byte constant named (NAME) which returns value n when executed.

VOCABULARY (NAME) (– – –)
Create a vocabulary named (NAME) which will become the **CONTEXT** vocabulary when it is executed.

CREATE. . .DOES> does: (– – –addr)
Used to create new defining words with an execution time routine written in high-level **FORTH**.

Vocabularies

CONTEXT (– – –addr)
System variable pointing to vocabulary where names are first searched for.

CURRENT (– – –addr)
System variable pointing to vocabulary where new definitions are put.

FORTH (– – –)
Main vocabulary accessible from all other vocabularies. Execution sets context vocabulary.

DEFINITIONS (– – –)
Sets **CURRENT** vocabulary to **CONTEXT**.

' (NAME) (– –addr)
Find parameter field address of (NAME) in dictionary. If used in definitions compile pfa into the dictionary as a literal. If (NAME) cannot be found an **ABORT** is executed.

FIND (NAME) (– – –addr)
Find the code field address of (NAME) in dictionary. If (NAME) cannot be found in **FORTH** or the **CURRENT** vocabulary leave a zero.

FORGET (NAME) (– – –)
Forget all definitions back to and including (NAME) in the dictionary. Executes an **ABORT** if (NAME) is not in **FORTH** or **CURRENT** vocabularies.

Compiler

, (n---)
Compile the 16-bit number n into the next available cell in the dictionary.

ALLOT (n---)
Set aside n bytes in the dictionary starting at **HERE** and reset dictionary pointer accordingly. If used in a definition adds n bytes to the parameter field address.

."
Print message terminated by ". If used in definition print when executed.

IMMEDIATE (---)
Mark the most recently defined word as immediate, thus causing it to be executed when used in a definition rather than compiled.

LITERAL (n---)
If compiling save n in the dictionary to be placed on the stack when the word is executed.

STATE (---addr)
System variable whose value is non-zero (i.e. true) when compilation is occurring and zero (false) when interpreting.

[(---)
Stop compiling input text and begin executing.

] (---)
Stop executing input text and begin compiling.

COMPILE (NAME) (---)
Compile the code field address of the (non-immediate) word which follows into the dictionary upon execution of the current definition.

[COMPILE] (NAME) (---)
Causes the word that follows to be compiled into the current definition even if it is immediate.

Miscellaneous

((---)
Begin a comment terminated by a). Note that this word must be followed by a space.

HERE (---addr)
Leave the address of the next available dictionary location.

PAD (---addr)
Leave address of a scratch pad area of memory of at least 64 bytes. **PAD**

usually floats a fixed number of bytes above the top of the dictionary.

>IN (---addr)
System variable containing character offset into input buffer.

BLK (---addr)
System variable containing the number of the block currently being interpreted. **BLK** contains zero when interpretation is from the terminal.

ABORT (---)
Clear parameter and return stacks and return control to the keyboard without issuing an 'ok'.

QUIT (---)
Like **ABORT** except does not clear the parameter stack or issue any error message.

79-STANDARD (---)
Verify that system conforms to the FORTH-79 standard.

Appendix B
Forth-79 double number extensions

2! (d,addr---)
Store d in four consecutive bytes starting at addr.

2@ (addr---d)
Fetch onto the stack the contents of the four consecutive bytes starting at addr.

2CONSTANT (NAME) (d---)
Create a double precision constant named (NAME) with the value d in its parameter field. When executed (NAME) will leave the value d on the stack.

2DROP (d---)
Drop the top double number on the stack (i.e. the top two stack items).

2DUP (d---d,d)
Duplicate the top double number on the stack.

2OVER (d1,d2---d1,d2,d1)
Make a copy of the second double number on the stack onto the top of the stack.

2ROT (d1,d2,d3---d2,d3,d1)
Rotate the third double number to the top of the stack.

2SWAP (d1,d2---d2,d1)
Exchange the top two double numbers on the stack.

2VARIABLE (NAME)
Create a variable called (NAME) in the dictionary and assign four bytes for storage in its parameter field. When executed (NAME) will leave the start address of its parameter field on the stack.

D+ (d1,d2---d1+d2)
Add together d1 and d2 leaving their sum **D-** (d1,d2---d1-d2)
Subtract d2 from d1 and leave the difference.

D. (d---)
Display the double number d according to the current base followed by one space. Display a leading sign if negative.

D.R (d,n---)
Display the double number d according to the current base right aligned in a field width n. Display a leading sign if negative.

D0= (d---f)
Leave a true flag if d is equal to zero else false.

D< (d1,d2---f)
Leave a true flag if d1 is less than d2 else false.

D= (d1,d2---f)
Leave a true flag if d1 is equal to d2 else false.

DABS (d---d)
Leave the absolute value of the double number d.

DMAX (d1,d2---d)
Leave the larger of two double numbers.

DMIN (d1,d2---d)
Leave the smaller of two double numbers.

DNEGATE (d---d)
Reverse the sign of the double number on the stack.

DU< (ud1,ud2---f)
Leave a true flag if ud1 is less than ud2 else false. Treat both numbers as unsigned.

Appendix C
Fig-Forth words

Stack Manipulation

DUP (n --- n,n)
Duplicate top item on the stack.

DROP (n ---)
Discard top item on the stack.

SWAP (n1,n2 --- n2,n1)
Reverse the positions of the top two items on the stack.

OVER (n1,n2 --- n1,n2,n1)
Copy the second stack item onto the top.

ROT (n1,n2,n3 --- n2,n3,n1)
Rotate third item on the stack to the top.

PICK (n1 --- n2)
Copy nth item (n2) on the stack top (thus 1 **PICK** = **DUP**, 2 **PICK** = **OVER**).

ROLL (n ---)
Rotate nth item on the stack to the top (thus 2 **ROLL** = **SWAP**, 3 **ROLL** = **ROT**.

-DUP (n--n, (n))
Duplicate top stack value only if non-zero.

>R (n--)
Move top parameter stack item to the top of the return stack. Must be restored with **R>** at same level to avoid unpredictable results.

R> (--n)
Move top return stack item to the top of the parameter stack.

R (--n)
Make a copy of the top value of the return stack onto the top of the parameter stack.

S0 (---addr)
A user variable which holds the initial value for the stack pointer.

SP! (---)
A routine which initializes the stack pointer from SO. User supplied.

SP@ (---addr)
Returns the address of the top of the stack to the top of the stack.

Comparison

< (n1,n2---f)
Return true if n1 is less than n2.

= (n1,n2---f)
Return true if n1 equals n2.

> (n1,n2---f)
Return true if n1 is greater than n2.

0< (n---f)
Return true if the top item on the stack is less than zero (i.e. negative).

0= (n---f)
Return true if the top item on the stack is zero. Reverses the truth value.

Arithmetic And Logical

+ (n1,n2---n1+n2)
Add together top two stack items.

D+ (d1,d2---d1+d2)
Add together the two double precision numbers on the stack.

- (n1,n2---n1-n2)
Subtract the value on the top of the stack from the value underneath it.

1+ (n---n+1)
Add one to the top stack item.

2+ (n---n+2)
Add two to the top stack item.

***** (n1,n2---n1*n2)
Multiply together the top two stack items.

/ (n1,n2---quot)
Divide the second item on the stack by the value on top. Quotient is rounded towards zero.

MOD (n1,n2---rem)
Leave remainder from dividing n1 by n2. Remainder has same sign as n1.

/MOD (n1,n2 – – – rem,quot)
Divide n1 by n2 and leave remainder and quotient.

***/MOD** (n1,n2,n3 – – – rem,quot)
Multiply n1 by n2 to give a 32-bit intermediate and divide by n3 leaving 16-bit remainder and quotient.

***/** (n1,n2,n3 – – – quot)
Multiply n1 by n2 to give a 32-bit intermediate and divide by n3 leaving a 16-bit quotient rounded towards zero.

U* (un1,un2 – – – ud)
Multiply together top two stack items as unsigned integers leaving an unsigned double precision product.

U/ (ud,un – – – urem,uquot)
Divinde double number by single giving single remainder and quotient. All values are unsigned. Equivalent to Forth-79 **U/MOD**.

MAX (n1,n2 – – – max)
Compare the top two numbers and return the larger value.

MIN (n1,n2 – – – min)
Compare the two two numbers and return the smaller value.

ABS (n – – – n)
Convert signed single number to its absolute value.

DABS (d– – –d)
Convert the signed double number to its absolute value.

MINUS (n – – – –n)
Reverse the sign of the top stack item (two's complement). Equivalent to Forth-79 **NEGATE**.

DNEGATE (d – – – –n)
Reverse sign of the double precision number on top of the stack. Equivalent to Forth-79 **DNEGATE**.

AND (n1,n2 – – – and)
Perform logical bitwise **AND** on the top two stack items.

OR (n1,n2 – – – or)
Perform logical bitwise **OR** on the top two stack items.

XOR (n1,n2 – – – xor)
Perform logical bitwise exclusive **OR** on the top two stack items.

Memory

@ (addr – – – n)
Return the contents of the cell address on the stack. Pronounced 'fetch'.

! (n,addr – – –)
Store value n at address. Pronounced 'store'.

C@ (addr – – – b)
Return the byte contents of the address on the stack. Pronounced 'c-fetch'.

C! (b,addr – – –)
Store byte value at address.

? (addr – – –)
Display the 16-bit contents of the cell address.

+! (n,addr – – –)
Add n to the contents of the address and leave the result in that cell.

MOVE (addr1,addr2,n – – –)
Copy n two byte cells starting at addr1 to memory starting at addr2. Executes only for non-zero count values.

CMOVE (addr1,addr2,n – – –)
Copy n bytes starting at addr1 to memory starting at addr2. Executes only for non-zero count values.

FILL (addr,n,b – – –)
Fill n bytes of memory beginning at address with byte value.

Control Structures

DO. . .LOOP do: (end+1,start– – –)
Set up loop given index range.

I (– – – n)
Place current loop index on the top of the stack.

DO. . .+LOOP do; (end+1,start – – –)
+loop: (n – – –)
Like DO. . .LOOP but adds stack value n to index (instead of always adding one). Loop terminates when index is greater than or equal to limit (n>0), or when index is less than limit (n<0).

LEAVE (– – –)
Terminate loop at next LOOP or +LOOP by setting index equal to limit.

IF. . .(true code). . .ENDIF if: (f – – –)

If the flag on the top of the stack is true execute code between the **IF** and **ENDIF**. The Forth-79 word **THEN** may be used interchangably with **THEN** in fig-Forth.

IF. . .(true code). . .**ELSE** if: (f---)
. . .(false code). . .**ENDIF**
If the flag on the top of the stack is true then execute code between the **IF** and **ELSE**, otherwise execute the code between **ELSE** and **ENDIF**.

BEGIN. . .**UNTIL** until: (f---)
Loop back to **BEGIN** until the flag on the top of the stack at **UNTIL** is true.

BEGIN. . .**WHILE**. . .**REPEAT** while: (f---)
Loop while flag is true at **WHILE**; **REPEAT** loops unconditionally to **BEGIN**. When flag is false continue from **REPEAT**.

EXECUTE (addr---)
Execute dictionary entry at compilation address on the stack. This is the address returned by **FIND**.

Terminal Input/Output

. (n---)
Print number with one trailing blank and sign if negative.

.R (n,n---)
Print the second stack value as a signed number, right aligned in a field width specified by the top value.

D. (d---)
Print a double number as a signed integer with one trailing blank.

D.R (d,n---)
Print a double number right aligned in specified field width.

CR (---)
Do a carriage return and line feed.

EMIT (char---)
Type ASCII value from stack.

SPACE (---)
Type one space.

SPACES (n---)
Type n spaces if n>0.

TYPE (addr,n---)
Type string of n characters from starting address.

COUNT (addr – – – addr+1,n)
Change address of string (preceded by length byte) to form suitable for **TYPE**.

–TRAILING (addr,n1 – – – addr,n2)
Reduce charager count of string at address to omit trailing blanks.

DUMP (addr,n– – –)
Print out contents of n bytes starting at address.

KEY (– – – char)
Read single keystroke from the keyboard and leave its ASCII value on the stack.

?TERMINAL (– – –f)
Returns true if the terminal break key has been pressed.

EXPECT (addr,n – – –)
Read n character (or until carriage return) from the keyboard and store them as string starting at address. Append null(s) to end of string.

WORD (char – – – addr)
Read the next word from the input stream using char as delimeter, or until null. Unlike Forth-79 **WORD** does not return address of the length byte.

Numeric Conversion

BASE (– – – addr)
System variable containing current numeric base.

DECIMAL (– – –)
Set decimal number base.

HEX (– – –)
Set hexadecimal number base.

NUMBER (addr– – –)
Convert the string at the given address to a double number. Aborts if conversion is not possible.

<# (– – –)
Begin formatting a number on the stack into a string.

(ud1– – –ud2)
Convert next digit of unsigned double number and add it to the beginning of the output string.

#S (ud– – –0 0)
Convert all significant digits of unsigned double number into output string.

HOLD (char– – –)
Insert ASCII character into formatted output string. For instance **46 HOLD** inserts a decimal point (full stop).

SIGN (n,ud– – –ud)
Insert minus sign into formatted output string if the third stack value is less than zero.

#> (ud– – –addr,n)
End formatting of formatted output string. Drops double number remaining on the stack (usually zero) and leaves appropriate arguments for **TYPE**. The output string is generally held in memory just below **PAD**.

Mass Storage Input/Output

LIST (n– – –)
List out screen n at the terminal and store the value of n in the variable **SCR**.

LOAD (n– – –)
Interpret screen n as if it were keyboard input. When finished return control to keyboard.

SCR (addr– – –)
System variable containing the screen number most recently **LIST**ed.

BLK (– – –)
System variable containing the number of the block to be interpreted. Set to zero when interpreting from the keyboard. Affects the operation of **WORD** and all definitions using **WORD**.

B/BUF (– – –n)
System constant returning the number of bytes in a disk block.

BLOCK (n– – –addr)
Leave buffer address of block n, reading block from mass storage if necessary.

UPDATE (– – –)
Mark block most recently accessed as modified.

BUFFER (n– – –addr)
Allocate the next memory buffer to block n, writing its contents back to disk if it has been **UPDATE**d. The contents of the block are not read into memory.

FLUSH (– – –)
Write all **UPDATE**d blocks in the buffers back to mass storage.

EMPTY-BUFFERS (– – –)
Mark all buffers as empty without writing any information back to mass storage.

Defining Words

: (NAME) (– – –)
Begin compiling colon definition with name (NAME).

; (– – –)
End compiling colon definition.

VARIABLE (NAME) (n– – –)
Create a two byte variable named (NAME) which returns its address when executed and initialize the contents with the value on the stack at compile time.

CONSTANT (n– – –)
Create a two byte constant named (NAME) using the compile time stack value. This value is returned when (NAME) executes.

;CODE (– – –)
Used to start definition of run time code written in assembly language which will be attached to a newly created defining word.

<BUILDS. . .DOES> does: (– – –addr)
Used to create new defining words with an execution time routine written in high-level Forth following **DOES>**.

Vocabularies

VOCABULARY (NAME) (– – –)
Create a vocabulary named (NAME) which will become the **CONTEXT** vocabulary when it is executed.

CONTEXT (– – –addr)
System variable pointing to vocabulary where names are first searched for.

CURRENT (– – –addr)
System variable pointing to vocabulary where new definitions are added.

DEFINITIONS (– – –)
Sets **CURRENT** to point to the same vocabulary as **CONTEXT**.

FORTH (– – –)
Main vocabulary accessible from all other vocabularies. Execution sets context vocabulary.

EDITOR (– – –)

Sets **CONTEXT** to point to the editor vocabulary.

ASSEMBLER (---)
Sets **CONTEXT** to point to the assembler vocabulary.

' (NAME) (--addr)
Search the dictionary for (NAME) and return the parameter field address if found. If used in definitions compile pfa into the dictionary as a literal. If (NAME) cannot be found an **ABORT** is executed.

FORGET (NAME) (---)
Forget all definitions back to and including (NAME) in the dictionary. Executes an **ABORT** if (NAME) is not in **FORTH** or **CURRENT** vocabularies.

VLIST (---)
Print out a list of all names in the **CONTEXT** vocabulary and below.

Compiler

, (n---)
Compile the 16-bit number n into the next available cell in the dictionary.

C, (b---)
Compile the 8-bit value into the next available byte in the dictionary.

ALLOT (n---)
Set aside n bytes in the dictionary starting at **HERE** and reset dictionary pointer accordingly. If used in a definition adds n bytes to the parameter field address.

IMMEDIATE (n---)
Mark the most recently defined word as immediate, thus causing it to be executed when used in a definition rather than compiled.

LITERAL (n---)
If compiling save n in the dictionary to be placed on the stack when the word is executed.

STATE (---addr)
System variable whose value is non-zero (i.e. true) when compilation is in progress and zero (false) when interpreting.

COMPILE (NAME) (---)
Compile the code field address of the (non-immediate) word which follows into the dictionary upon execution of the current definition.

Miscellaneous

((---)
Begin a comment terminated by a). Note than this word must be followed by a space.

HERE (---addr)
Leave the address of the next available dictionary location.

PAD (---addr)
Leave address of a scratch pad area of memory which is a fixed offset from **HERE**, usually 68 bytes. Forth-79 specifies the length of **PAD** but not the location.

IN (---addr)
System variable containing character offset into input buffer. Equivalent to Forth-79 >**IN**.

ABORT (---)
Clear parameter and return stacks and return control to the keyboard without issuing an 'ok'.

QUIT (---)
Like ABORT except does not clear the parameter stack or issue any error message.

Appendix D
Forth-83 Standard

The Forth-83 Standard uses a more extensive stack parameter notation than Forth-79. The abbreviations and their meaning is as follows:

addr	16-bit address in the range 0. . .65535.
b	bit value.
flag	16-bit boolean flag.
8b	8-bit value.
16b	16-bit value.
32b	32-bit value.
char	7-bit value in the range 0. . .127.
d	signed double precision number in the range −2,147,483,648. . .+2,147,483,647.
+d	positive double precision number in the range 0. . .2,147,483,647.
ud	unsigned double precision number in the range 0. . .4,294,967,295.
wd	signed or unsigned double precision number in the range −2,147,483,647. . .4,294,967,285.
n	signed single precision number in the range −32,768. . .32,767.
+n	positive single precision number in the range 0. . .32,767.
u	unsigned single precision number in the range 0. . .65,535.
sys	system compilation.

Stack Manipulation

DUP (16b --- 16b,16b)
Duplicate top item on the stack.

DROP (16b ---)
Discard top item on the stack.

SWAP (16b1,16b2 --- 16b2,16b1)
Reverse the positions of the top two items on the stack.

OVER (16b1,16b2 --- 16b1,16b2,16b1)
Duplicate second item on the stack and place it on top.

ROT (16b1,16b2,16b3 --- 16b2,16b3,16b1)

Rotate third item on the stack to the top.

PICK (+n – – – 16b)
Leave a copy of the nth stack location, not counting the location containing the +n operand; the operand is zero based so that **DUP** is equivalent to **0 PICK** and **OVER** is equivalent to **1 PICK**.

ROLL (+n – – –)
Roll the nth (not counting the position occupied by the +n) stack locations contents to the top of the stack, moving all intervening values down one location; the +n operand is zero based so that **ROT** is equivalent to **2 ROLL** and **0 ROLL** is a null operation.

?DUP (16b– –16b,16b) or (0– – –0,0)
Duplicate top stack value only if non-zero.

>R (16b– –)
Move top parameter stack item to the top of the return stack. Must be restored with **R>** at same level to avoid unpreditable results.

R> (– –16b)
Move top return stack item to the top of the parameter stack.

R@ (– –16b)
Make a copy of the top value of the return stack onto the top of the parameter stack.

DEPTH (– – +n)
Leave a count of the number of 16-bit numbers on the stack (before **DEPTH** is executed).

Comparison

< (n1,n2 – – – flag)
Leave a true flag (–1) if n1 is less than n2.

= (w1,w2 – – – flag)
Leave a true flag (–1) if w1 equals w2.

> (n1,n2 – – – flag)
Leave a true flag (–1) if n1 is greater than n2.

0< (n – – – flag)
Leave a true flag (–1) if the top item on the stack is less than zero (i.e. negative).

0= (w – – – flag)
Leave a true flag (–1) if the top item on the stack is zero.

0> (n – – – flag)

Divide n1 by n2 leaving the floored quotient n4 rounded towards negative infinity. Remainder n3 has same sign as n2 if non–zero: forces an error if n2 equals zero or n4 is out of range.

***/MOD** (n1,n2,n3 – – – n4,n5)
Multiply n1 by n2 to form an intermediate 32-bit value and then divide by n3: result n4 is the remainder with the same sign as n3 if non–zero: result n5 is the floored quotient rounded toward negative infinity: forces an error if n3 equals zero or n4 is out of range.

***/** (n1,n2,n3 – – – n4)
Multiply n1 by n2 to form an intermediate 32-bit value and then divide by n3: result n4 is the floored quotient rounded toward negative infinity: forces an error if n3 equals zero or n4 is out of range.

UM* (u1,u2– – –ud)
Leave the unsigned double-protection product of u1 and u2.

UM/MOD (ud,u1 – – – u2,u3)
Leave the remainder u2 and floored quotient u3 of ud divided by u1: force an error if u1 equals zero or u3 is out of range.

MAX (n1,n2 – – – max)
Leave the greater of the top two stack items and discard the other.

MIN (n1,n2 – – – min)
Leave the smaller of the top two stack items and discard the other.

ABS (n – – – u)
Remove the sign from the top stack item and leave the absolute value.

NEGATE (n – – – –n)
Reverse the sign of the top stack item (two's complement).

DNEGATE (d – – – –d)
Reverse sign of the double precision number on top of the stack.

AND (16b1,16b2 – – – 16b3)
Perform logical bitwise **AND** on the top two stack items.

OR (16b1,16b2 – – – 16b3)
Perform logical bitwise **OR** on the top two stack items.

XOR (16b1,16b2 – – – 16b3)
Perform logical bitwise exclusive **OR** on the top two stack items.

Memory

@ (addr – – – 16b)
Replace address by value at address. Pronounced 'fetch'.

! (16b,addr – – –)
Store value 16b at address.

C@ (addr – – – 8b)
Replace address by byte value 8b held at address. Pronounced 'c-fetch'.

C! (8b,addr – – –)
Store byte value 8b at address.

+! (w,addr – – –)
Add w to value held at address.

CMOVE (addr1,addr2,u – – –)
Copy n bytes starting at addr1 to memory starting at addr2. Has no effect if n is zero or negative.

CMOVE> (addr1,addr2,u – – –)
Move u bytes, starting with the byte at (addr1 + u – 1) to (addr2 + u – 1) and proceeding toward low memory.

FILL (addr,u,8b – – –)
Fill u bytes of memory beginning at address with byte value 8b.

Control Structures

DO (w1,w2 – – –) (– – – sys)
(compiling)
Immediate word to begin an indexed loop, with initial value w2 and limit value w1; all DO loops are performed at least once; sys is balanced during compilation by LOOP or +LOOP; force and error if space is not available for at least three levels of testing.

LOOP (– – –) (sys – – –)
(compiling)
Immediate word to increment the current loop index by 1; terminate the loop if the index is incremented over the (limit – 1) to limit boundary (otherwise repeat the loop); the error check value sys is left by DO during compilation.

+LOOP (n – – –) (sys – – –)
(compiling)
Immediate word to increment the current loop index by n; terminate the loop if the index is incremented over the (limit – 1) to limit boundary (otherwise repeat the loop); the error check value sys is left by DO during compilation.

I (– – – w)
Place current loop index on the top of the stack.

I (– – – w)
Place index of next outer **DO. . .LOOP** in the same definition.

LEAVE (– – –) (compiling)
Immediate word to transfer execution of program to beyond **LOOP** or **+LOOP**. Used as **DO. . .LEAVE. . .LOOP** or **DO. . .LEAVE. . .+LOOP**.

IF. . .(true code). . .**THEN**
if: (flag – – –) (– – – sys) (compiling)
then: (sys – – –) (compiling)
If the flag on the top of the stack is true then execute code between the **IF** and **THEN**.

IF. . .(true code). . .**ELSE**. . .(false code). . .**THEN**
if: (flag – – –) (– – – sys) (compiling)
else: (sys – – – sys) (compiling)
then: (sys – – –) (compiling)
If the flag on the top of the stack is true then execute code between the **IF** and **ELSE**, otherwise execute the code between **ELSE** and **THEN**.

BEGIN. . .UNTIL
begin: (– – – sys) (compiling)
until: (flag – – –) (sys – – –) (compiling)
Loop back to **BEGIN** until the flag on the top of the stack at **UNTIL** is true.

BEGIN. . .WHILE. . .REPEAT
begin: (– – – sys) (compiling)
while: (flag – – –) (sys1 – – – sys2) (compiling)
repeat: (sys – – –) (compiling)
Loop while flag is true at **WHILE**; **REPEAT** loops unconditionally to **BEGIN**. When flag is false continue from **REPEAT**.

EXIT (– – –)
Terminate execution of this colon definition. May not be used within a **DO. . .LOOP**.

EXECUTE (addr – – –)
Execute dictionary entry at compilation address on the stack. This is the address returned by **FIND**.

Terminal Input/Output

CR (– – –)
Do a carriage return and line feed.

EMIT (16b – – –)
Display the ASCII character defined by the lowest 7 bits of 16b on the

current output device; if additional bits are available for display in an environmentally dependant manner, all must be displayed.

SPACE (– – –)
Type one space.

SPACES (+n – – –)

TYPE (addr,+n– – –)
Type +n spaces if n>0
Type string of n characters from starting address.

.((compiling)
Immediate word to output the string up to the delimiting) character.

COUNT (addr1 – – – addr2,+n)
Change address of string (preceded by length byte) to form suitable for **TYPE**.

–TRAILING (addr,+n1 – – – addr,+n2)
Reduce character count of string at address to omit trailing blanks.

KEY (– – – 16b)
Receive the ASCII character defined by the lowest 7 bits of 16b on the current input device; all ASCII codes are permitted; characters are not displayed nor are control characters processed.

EXPECT (addr,+n – – –)
Store characters beginning at addr until a return is encountered or +n characters have been stored; the return is not stored but is displayed (along with all received characters) as a blank.

SPAN (– – –addr)
User variable containing the number of characters received and stored by the last execution of **EXPECT**.

WORD (char – – – addr)
Parses the next word delimited by char (ignoring any leading instances) or the end of the input stream and stores it with its count byte at address; a blank is appended to the character string but is not included in the count; the count equals zero if the input stream is already exhausted; the pointer in **>IN** is updated to indicate the character after the final delimiter.

£TIB (– – –addr)
User variable containing the byte length of the text input buffer.

TIB (– – –addr)
Leave a pointer to the first byte of the terminal input buffer; length of the buffer must be at least 80 characters.

Numeric Conversion

BASE (– – – addr)
User variable containing current I/O radix, in the range of 2–72.

DECIMAL (– – –)
Set decimal number base. (– – –)
Print number with one trailing blank and sign if negative.

U. (u– – –)
Print unsigned number with one trailing blank.

CONVERT (+d1,addr1– – – +d2,addr2)
Convert string at addr1+1 to double number and add value into +d1 leaving result +d2. Addr2 is address of first non-convertable character.

<# (– – –)
Begin formatting a number on the stack into a string.

(+d1– – – +d2)
Convert next digit of unsigned double number and add it to the beginning of the output string.

#S (+d– – – 0 0)
Convert all significant digits of unsigned double number into output string.

HOLD (char– – –)
Insert ASCII character into formatted output string. For instance **46 HOLD** inserts a decimal point (full stop).

SIGN (n– – –)
If signed single number n is less than zero insert minus sign at the beginning of a formatted output string.

#> (32b– – – addr,+n)
End formatting of formatted output string. Drops double number remaining on the stack (usually zero) and leaves appropriate arguments for **TYPE**. The output string is generally held in memory just below **PAD**.

Mass Storage Input/Output

LOAD (u– – –)
Interpret screen n as if it were keyboard input. When finished return control to keyboard.

BLOCK (u– – – addr)
Assign the buffer whose first data byte is at addr to block u and transfer the data if the block is not already in a buffer; prior contents of the buffer

are saved to disk if the update bit is set; if block u is already in a buffer, addr points to it and no data is transferred; buffer contents must be storable (only the data within the last buffer referenced by **BLOCK** or **BUFFER** is valid).

UPDATE (– – –)
Mark block most recently accessed as modified.

BUFFER (u – – – addr)
Similar to **BLOCK** except that block u might not be transferred to the buffer if not already in memory; the contents of the buffer after execution are unspecified.

SAVE-BUFFERS (– – –)
Write all **UPDATE**d blocks in the buffers back to mass storage.

FLUSH
Unassign all block buffers after executing a sequence equivalent to the **SAVE-BUFFERS** operation.

Defining Words

: (NAME) (– – – sys)
Begin compiling colon definition with name (NAME).

; (– – – sys) (compiling)
End compiling colon definition.

VARIABLE (NAME) (– – –)
Create a two byte variable named (NAME) which returns its address when executed.

CONSTANT (NAME) (16b – – –)
Create a two byte constant named (NAME) which returns value 16b when executed.

VOCABULARY (NAME) (– – –)
Compile a definition of (NAME) to initiate a new vocabulary; later execution of (NAME) makes it the first vocabulary in the search order; the sequence (NAME) **DEFINITIONS** makes (NAME) the compilation vocabulary to which new definitions are linked; (NAME) is not immediate.

CREATE (NAME) (compiling)
Create a dictionary entry for (NAME) without constructing any parameter field. When executed (NAME) will leave its pfa on the stack.

DOES> (– – – addr) (compiling)
Used as: (NAME1). . .(CREATE). . .**DOES>**. . . ; Immediate word to define the execution behaviour of any later word (NAME2) defined using

(NAME1); the (**CREATE**) may be **CREATE** or any user defined word that executes **CREATE**; later execution of (NAME2) places its parameter field on the stack before executing the sequence of words between **DOES>** and ; in (NAME1)'s definition.

Vocabularies

FORTH (– – –)
Make **FORTH** the first voeabulary in the search order. Not immediate.

DEFINITIONS (– – –)
Make the compilation vocabulary the same as the first vocabulary in the search order.

' (NAME) (– –addr)
Leave the compilation address addr of (NAME), which must be found within the current search order. Not immediate.

[**'**] (NAME) (– – –addr) (compiling)
Immediate word to compile the compilation address of (NAME) as a literal within a definition. The address is left on the stack upon execution of the definition.

FIND (NAME) (addr1– – –addr2,n)
For a string with a count byte at addr1 search for a matching word name using the current search order; if found addr2 is the matching word's compilation address; n is 1 if the word is immediate (or −1 otherwise); if no match is found addr2 is the same as addr1 and n equals zero.

>BODY (addr1– – –addr2)
Leave the pfa addr2 of the word whose cfa is addr1.

FORGET (NAME) (– – –)
Delete all definitions back to and including (NAME); force an error if (NAME) is not within the current search order or if the compilation vocabulary is removed.

Compiler

, (16b– – –)
Compile the 16-bit number 16b into the next available cell in the dictionary.

ALLOT (w– – –)
Set aside n bytes in the dictionary starting at **HERE** and reset dictionary pointer accordingly. If used in a definition adds n bytes to the parameter field address.

." (compiling)
Immediate word to output the following character string up to the delimiting quote character. Can only be used within programs.

IMMEDIATE
Mark the most recently defined word as immediate, thus causing it to be executed when used in a definition rather than compiled.

LITERAL (16b---) (16b---)
(compiling)
Immediate word to compile a system dependant operation which will return 16b to the stack upon execution.

STATE (---addr)
System variable whose value is non-zero (i.e. true) when compilation is occurring and zero (false) when interpreting. Contents may not be modified by a program.

[(compiling)
Stop compiling input text and begin executing.

] (compiling)
Stop executing input text and begin compiling.

COMPILE (NAME) (---)
Compile the code field address of the (non-immediate) word which follows into the dictionary upon execution of the current definition.

[COMPILE] (NAME) (---)
Causes the word that follows to be compiled into the current definition even if it is immediate.

Miscellaneous

((compiling)
Begin a comment terminated by a). Note that this word must be followed by a space; the comment characters must be entirely contained within the remaining input stream.

HERE (---addr)
Leave the address of the next available dictionary location.

PAD (---addr)
Leave a pointer to the first byte of a floating scratch pad area; the area must contain at least 84 bytes.

>IN (---addr)
System variable containing character offset into input buffer.

BLK (---addr)
System variable containing the number of the block currently being interpreted. **BLK** contains zero when interpretation is from the terminal.

ABORT (---)
Clear parameter and return stacks and return control to the keyboard without issuing an 'ok'.

ABORT" (flag---) (compiling)
Immediate word to output the character string following delimited by a quote character and initiate a system dependant abort if flag is true at execution; the abort routine must at least include all functions of **ABORT**.

QUIT (---)
Like **ABORT** except does not clear the parameter stack or issue any error message.

83-STANDARD (---)
Verify that system conforms to the FORTH-83 standard.

Appendix E
Forth-83 double number extensions

2! (d,addr---)
Store d in four consecutive bytes starting at addr.

2@ (addr---d)
Fetch onto the stack the contents of the four consecutive bytes starting at addr.

2CONSTANT (NAME) (32b---)
Create a dictionary definition for (NAME) which executes by leaving 32b on the stack.

2DROP (d---)
Drop the top double number on the stack (i.e. the top two stack items).

2DUP (d---d,d)
Duplicate the top double number on the stack.

2OVER (d1,d2---d1,d2,d1)
Make a copy of the second double number on the stack onto the top of the stack.

2ROT (d1,d2,d3---d2,d3,d1)
Rotate the third double number to the top of the stack.

2SWAP (d1,d2---d2,d1)
Exchange the top two double numbers on the stack.

2VARIABLE (NAME)
Create a variable called (NAME) in the dictionary and assign four bytes for storage in its parameter field. When executed (NAME) will leave the start address of its parameter field on the stack.

D+ (d1,d2---d1+d2)
Add together d1 and d2 leaving their sum.

D- (d1,d2---d1-d2)
Subtract d2 from d1 and leave the difference.

D2/ (d1---d2)
The operand d1 is shifted right arithmetically, including the sign bit.

D. (d---)
Display the double number d according to the current base followed by one space. Display a leading sign if negative.

D.R (d,+n---)
Display the double number d in the current radix right justified in a field of +n characters; force an error condition if the field width is insufficient.

D0= (wd---flag)
Leave a true flag (−1) if wd is equal to zero else false.

D< (wd1,wd2---flag)
Leave a true flag (−1) if wd1 is less than wd2 else false.

D= (wd1,wd2---flag)
Leave a true flag (−1) if wd1 is equal to wd2 else false.

DABS (d---ud)
Leave the absolute value of the double number d.

DMAX (d1,d2---d)
Leave the larger of two double numbers.

DMIN (d1,d2---d)
Leave the smaller of two double numbers.

DNEGATE (d---d)
Reverse the sign of the double number on the stack.

DU< (ud1,ud2---flag)
Leave a true flag (−1) if ud1 is less than ud2 else false. Treat both numbers as unsigned.

Appendix F
Forth-83 system extension word set

<MARK (– – –addr)
Leave the pointer addr to the destination of a backward branch; the pointer is primarily for later use by **<RESOLVE**.

<RESOLVE (addr– – –)
Used after **?BRANCH** or **BRANCH** at the source of a backward branch to compile a branch address using the destination pointer addr.

>MARK (– – –addr)
Used after **?BRANCH** or **BRANCH** at the source of a forward branch at addr to compile space for a pointer to the destination; the pointer is primarily for later use by **>RESOLVE**.

>RESOLVE (addr– – –)
Used at the destination of a forward branch to compile a branch offset in the space left by **>MARK**, using the source pointer addr.

?BRANCH (flag– – –)
Used as **COMPILE ?BRANCH**. Compile a conditional branch operation; a branch address must immediately follow; it is usually compiled by **<RESOLVE** (backwards branch) or **>MARK** (forward branch); later execution of definition ignores the branch if flag is true or executes it if the flag is false.

BRANCH
Used as **COMPILE BRANCH**. Compile an unconditional branch operation; a branch address must immediately follow; it is usually compiled by **<RESOLVE** (backwards branch) or **>MARK** (forward branch); later execution of definition ignores the branch if flag is true or executes it if the flag is false.

CONTEXT (– – –addr)
User variable specifying the dictionary search order.

CURRENT (– – –addr)
User variable specifying the vocabulary to receive new definitions.

Index

Robert Erskine & Humphrey Walwyn with Paul Stanley and Michael Bews
Sixty Programs for the Sinclair ZX Spectrum £5.95

Sixty Programs for the BBC Micro £5.95

Sixty Programs for the Dragon 32 £5.95

Sixty Programs for the Oric 1 £5.95

Sixty Programs for the Atari £5.95

Sixty Programs for the Commodore 64 £5.95

Sixty Programs for the Vic 20 £5.95

Sixty Programs for the Electron £5.95

Ian Adamson
The Companion to the Oric 1 £5.95

Geoff Wheelwright
The Companion to the BBC Micro £4.95

Keith Bowden
The Companion to the Commodore 64 £5.95

Jeremiah Jones and Geoff Wheelwright
The Companion to the Electron £5.95

Jean Frost
Instant Arcade Games for the Sinclair ZX Spectrum £3.95

Instant Arcade Games for the BBC Micro £3.95

Instant Arcade Games for the Dragon 32 £3.95

Instant Arcade Games for the Electron £3.95

J. J. Clessa
Micropuzzles £2.95

Ian Scales
Spectrum Peripherals Guide £4.95

Tony Takoushi
Best Software Guide: Vic 20/Commodore 64 £3.95

Best Software Guide: Spectrum Games £3.95

Jeff Aughton
Invaluable Utilities for your BBC Micro £5.95

All these books are available at your local bookshop or newsagent, or can be ordered direct from the publisher. Indicate the number of copies required and fill in the form below.

Name_____
(Block letters please)

Address_____

_____

Send to Pan Books (CS Department), PO Box 40, Basingstoke, Hants. Please enclose remittance to the value of the cover price plus: 35p for the first book plus 15p per copy for each additional book ordered to a maximum charge of £1.25 to cover postage and package. Applicable only in the UK.

While every effort is made to keep prices low, it is sometimes necessary to increase prices at short notice. Pan Books reserve the right to show on covers and charge new retail prices which may differ from those advertised in the text or elsewhere.

The **PAN/PCN Computer Language Library** provides comprehensive introductions to the most important of the alternative languages to in-built BASIC, and introduces the types of programming problem to which they can most profitably be applied.

The complete guide to learning and using FORTH on your micro.

If you are frustrated by the restrictions of BASIC then now is the time to branch out into the extendible world of FORTH programming. With the aid of this new book you can get to grips with the fundamental principles of this powerful programming language.

Fast, flexible and easily transportable between computers, perhaps FORTH'S greatest advantage is that you can effortlessly extend and improve the basic system to design and develop your own personalised programming language.

FUNDAMENTAL FORTH assumes no previous experience of microcomputing. The first section contains a general background to computers and programming languages. The second section teaches FORTH 'at the keyboard' and relies on you having access to a standard version of FORTH.

Topics covered include:

Program structures
Adding keywords
Using the Stack
Forth arithmetic
String handling
Using discs
Decision making

ISBN 0-330-28960-8

U.K. **£6.95**