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SOFTWARE REVIEWS

The purpose of this section is to provide reviews of the wide variety of computer software and related material available for use by economists. Products reviewed will include economics, statistics, econometries and related packages, as well as other functional software and computer books used by academic economists. From time to time overview articles relating to computer software available in particular areas of economics will be published.

Software publishers who wish to have their product reviewed or require further information should contact the Software Review Editor.

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ECONOMIC COMPUTING IN THE 1990s; RECENT DEVELOPMENTS IN PERSONAL COMPUTER HARDWARE*

Christopher J. Hammond

Desktop computers are becoming increasingly important in economics teaching and research. The development of advanced statistical packages has greatly benefited econometricians, while the diverse range of software available has stimulated new applications and wider computer usage in economics generally. Recent innovations in hardware design will increase processing power and support larger, more complex tasks, while changes in system design (architecture) and the operating system will increase flexibility, permitting more sophisticated applications.

Although a variety of small computers are available, the IBM compatible Personal Computer (PC) and its disk-operating system (DOS) have been the mainstay of economic computing. The PC's popularity may be attributed to the characteristics of its architecture, including openness, enabling the integration of third-party devices; its capacity for expansion and limited proprietary interests, enabling competition in the supply of compatible systems.

* The comments of the editor and referees of the Journal on an earlier version of the paper are appreciated. The perspective and opinions expressed are, of course, my own. A longer paper outlining the technical issues is available on request from the author.

On the other hand, innovations in processor design highlight the limitations of the PC and have led to the development of new architectures, requiring more advanced operating systems.

Many computer users have little interest in system design and operation, largely because hardware standards focus attention on the capabilities of software. Although the discussion of new standards is already under way (Birchenhall, 1990), the complexity of system specification, linked to extensions of the architecture, differentiating one machine from another, make an understanding of hardware essential for rational purchasing. With these considerations in mind, this paper develops a perspective on small-computer technology and the changing nature of personal computer hardware, as it affects the economist.

The arguments are developed primarily with reference to the PC, including the IBM Personal System, although Section IV considers some alternatives. Section I outlines developments in the system components, but is not exhaustive. Peripherals, such as printers are excluded, as are many storage devices. The development of communications networks and portables also merit separate, detailed consideration. Section II examines some limitations of PC architecture, together with changes in the design of the microprocessor, around which the system is built. Developments in system architecture and operating systems are considered in Section III and some conclusions drawn in Section V.

I. THE PERSONAL COMPUTER SYSTEM

The popularity of the PC is partly due to the development of the critical system unit components. With a minimal specification, the original PC was expressly designed for expansion, but more significantly, while capacity has increased broadly in line with user requirements, compatibility has been maintained by raising processing power with the architecture largely unchanged, so that applications developed for earlier systems can be run on newer machines.

Increases in capacity and performance have been recorded for most system components. Empirical work in economics has been greatly affected by advances in data storage, where demands for increased capacity have been met through the development of high speed drives and high density media. Floppy disk drives with a capacity exceeding a megabyte (Mb) are now standard and as the number and sophistication of applications has increased, the volume of data and program code required has expanded, making a hard disk drive essential. Hard disk capacity has increased and restrictions on the use of the disk have been removed, with the maximum size of a DOS partition being raised from 32 Mb to 4 Gb (Gigabytes) under DOS 4·0. Greater flexibility has also been achieved with the development of devices such as the tape streamer and Bernoulli drive, supporting portable high-capacity media such as the data cartridge and tape cassette.

Further increases in capacity are possible using techniques supporting yet higher-recording densities. Laser-based optical disk drives have attracted considerable interest, being less restrictive than the compact disk (CD-ROM) in write-once-read-many applications and especially suitable when using large data sets such as census or survey data. Re-recordable optical disks are also attractive but, when compared with magnetic media, have a relatively poor access rate for routine work. Further advances in magnetic storage appear likely using a vertically polarised disk, supporting yet greater densities, raising the potential capacity of a $3\frac{1}{2}$-inch disk to 4 Mb.

For economists with large datafiles and sophisticated applications, disk access rates may be at least as important as capacity. Hard disks transfer data at much higher rates than floppy disks and have improved substantially with the refinement of the disk controller. Despite this, disk performance often remains the critical factor limiting *throughput*; the work done in a given period of time.

Advances in graphics capability have also been achieved, particularly in the number of colours definable and resolution. The high-resolution Hercules monochrome specification easily displaced the Monochrome Display Adaptor which supported only text, whereas colour resolution improvements have been more incremental. For mainly text-based applications, the low cost, monochrome option may be preferred to a colour display, but following the introduction of the video graphics array (VGA) adaptor the difference in resolution is less significant. With the increasing importance of graphics-based econometric techniques, such as non-parametric methods and contour plotting, alongside the enhanced graphics capability of software, a rapid migration to high-resolution colour systems may be anticipated.

Unlike other system components, the VGA adaptor is not fully compatible with earlier devices, in that the VGA output signal requires a special monitor. Further, while the earlier colour (CGA) and enhanced graphics adaptors (EGA) are supported, Hercules graphics are not. Nevertheless, monitors capable of accepting any graphics input signal and VGA-type adaptors supporting the Hercules specification are employed in many 'compatible' systems. This convergence of resolution and support should stimulate migration to a common graphics standard.

The critical component determining the capacity of any computer system is the processor (CPU). Although machines are identified by brand and model name, they are differentiated by the CPU which prevents the interchange of software. PC systems are based on the 80×86 series of processors produced by Intel, while others mostly feature Motorola devices. Above all else, it is the compatibility between successive processors which has underpinned the popularity of the PC and the limited compatibility of newer devices which creates uncertainty about the future.

Few applications are written for a specific processor, most economics and statistics software being programmed in Fortran, Pascal or **C**; a noteworthy exception is *GAUSS*, which has attracted many econometricians because of its efficiency. Each operation requested by the user is achieved by executing a sequence of fundamental instructions supported by the processor. Thus, as applications have become more sophisticated, the object of processor development has been to raise computational power to meet the dramatic increase in processing required and to reduce power consumption, in the interest of portability. Given the emphasis on compatibility, greater power has been achieved mainly by raising the system clock speed, governing the rate at which instructions are executed and to a lesser degree by improving the instruction set.

Performance has been upgraded by adopting successive generations of the processor, through the 8088, 8086, 80286 and subsequently, the more efficient 32-bit 80386 and i(80)486. Two performance indices are often quoted, namely the number of million instructions (MIPS) or operations (MOPS) processed per second. On this basis power has increased from 0·33 MIPS with the 8088 CPU running at a speed of 4·77 megahertz (MHz) to 15 MIPS with the i486 at 25 MHz, but in practice, users are more concerned with the time taken to conduct a task, rather than processor speed *per se*. The benchmark comparisons of software performance reported by Dolton (1988) are a good example. Moreover, in assessing performance, the PC must be treated as a system, the benefits of greater power being realised only when other components complement the processor. Thus, throughput is determined by overall design and not processor speed alone.

Two components of memory may be distinguished, namely, the random access memory (RAM) and the read only memory (ROM) which stores the firmware, or basic input–output system (BIOS). When an application is run both data and program code must be loaded to RAM. Consequently, memory constrains the size of the program and data matrix which can be handled. Limitations on the functional capability of software may be reduced by overlaying, a technique reducing the amount of code by loading the core of the program and adding additional code only when it is needed. Nevertheless, as memory has become cheaper, more sophisticated applications have emerged, many requiring close to the maximum memory accessible under DOS.

Where necessary, memory can often be increased by adding modules. Many newer systems have more than 1 Mb of memory, with only 640 Kb available for conventional DOS applications. Such memory may be accessed directly as *extended memory* using the 80286 and subsequent processors which support *protected mode* addressing, as discussed in Section II. Extended memory should, however, be distinguished from the 16 Mb of *expanded* memory which may be accessed by DOS applications supporting the Lotus, Intel, Microsoft Expanded Memory Specification (EMS). Alternatively, several utilities enable additional memory to be used as a virtual disk drive, in effect, a high speed temporary storage device, capable of accelerating overlayed applications and the use of workfiles due to the higher access rate of RAM.

Notwithstanding technical differences between expanded and extended memory, which need not detain the reader, many PCs are supplied with configuration utilities which enable memory in excess of 640 kb to be allocated between expanded and extended memory. The requirements of software must be checked carefully and memory allocation adjusted accordingly. In any event, the capacity to address more than 640 kb of memory allows the user to access larger data arrays, using DOS software. Several econometric packages capable of accessing larger memory are now available for the 386 processor; these include GAUSS, LIMDEP and RATS, and others are expected to follow.

In economics, where the workload often involves mathematical procedures, the rate of throughput may be substantially improved using the floating point processor (FPP), or math co-processor. Provision of a socket for the co-processor is almost universal in desktop systems, making installation relatively easy. The advantage of the FPP is that large numbers, which the CPU must process in parts and rebuild, are processed whole. Many of the programs used by economists can be run without the FPP, but are capable of testing for its presence and utilising its processing power; a few, such as LIMDEP-386 and some versions of SHAZAM, make use of FPP specific features and will not operate without it.

A wide range of manufacturer and third-party options may also be added to the PC with little difficulty. Many options add specific functions to the system, such as a modem, whereas others, including accelerator boards and memory cards, enhance system performance. These are beyond the scope of this review, but some may radically change economists' working patterns. In particular, the combination of an efficient portable PC and a high-speed modem enables work to be undertaken almost anywhere.

Yet more powerful and reliable systems are presaged by technical changes in the system components. High speed memory chips are already available, with much larger and faster devices in prospect. Shorter intervals are observed between the release of more powerful processors and as tolerances in chip manufacture improve, advances in performance and reliability are achieved through system integration. However, it cannot be assumed that future demands will simply be met by further upgrading existing devices.

II. DEVELOPMENTS IN SYSTEM DESIGN

Despite the refinement of the individual system components, more powerful processors and improved software have revealed several limitations of the PC architecture, including the memory constraint, already familiar to many econometricians.

The memory restriction, associated with DOS, originates in the system of memory addressing and persists because of the emphasis on compatibility. Using the *real mode* addressing system employed in the original 8088 based design, only 640 kb are directly addressable by the user, whereas with the 80286 and subsequent processors, up to 4 Gb may be accessed in protected mode, without restriction, enabling the processing of larger tasks.

In protected mode, memory addresses are allocated to *environments*, one of which the default environment, supports DOS and real mode addressing, subject to the 640 kb restriction. However, having established a DOS environment, any remaining memory may be allocated to other environments and although switches between environments are not explicitly supported by the 80286, they may be induced. Consequently, a protected mode application can be run from DOS and the limitations of real mode overcome without a protected mode operating system, provided control is returned to DOS before calling the operating system or BIOS. DOS extender software conducting the mode switching and input–output (IO) activities is available in several forms and built in to some DOS software, notably Lotus 1-2-3 and GAUSS-386.

A less elegant, but effective technique supporting larger applications involves the transfer of data from memory to the hard disk. Although disk operations reduce the rate of throughput, several 80386 utilities use the technique, to provide a *virtual memory* capability, storing pages of memory on disk to provide effective memory beyond that installed in the system. This method is employed in econometric software for the 386 processor, such as LIMDEP and GAUSS (VM), to achieve near mainframe levels of performance.

A further constraint revealed by high-speed processors is the relatively slow rate at which data is transferred between the CPU and memory, which may leave the processor idle some of the time. Taken together these delays involve a substantial increase in processing time. One solution is the use of high access rate RAM, but cost makes this impractical. Instead, greater continuity in the flow of data may be achieved using the cache technique, where a small area of high speed static RAM, cache memory, is established between the CPU and main memory.

The basis of memory cacheing is the fact that the memory addresses required are frequently ones accessed earlier. Transfers to and from main memory are therefore written to cache, so that data required in subsequent calls may be accessed at high speed. In effect, memory is read in the background and instructions executed at or near the speed of the processor. However, cacheing is prone to technical problems and must be managed by a dedicated controller, making the method relatively expensive. In similar fashion, an area of RAM, the disk cache, may be used to store data normally held on disk. Data written to disk may also be cached, increasing the speed of disk intensive tasks and reducing wear and tear on both disks and drives.

Several utilities allow memory to be allocated as disk cache, but where the cache is managed by software, both CPU time and memory is taken up, which is then unavailable to applications. Thus, unless the cache is supported by hardware, a trade-off exists between the time taken to access data and process it. Many applications in economics, particularly those used with large data sets, are relatively IO intensive, making disk cache worthwhile, but possibly prohibitive in terms of foregone memory. As faster processors become more firmly established, the speed of storage devices is recognised as a constraint and cacheing disk controllers are becoming a common feature of high-performance systems.

Given the lead time in processor development, the technical foundations of computer design over the next decade are already relatively clear. The apparently 'backward' step taken in introducing the 80386SX processor with an AT-compatible 16-bit data transfer system (bus), enabled the adoption of a more efficient 32-bit instruction set. Other developments increasing computational power include a greater degree of system integration, *Reduced Instruction Set Computer* (RISC) technology and systems in which several processors may be operating in parallel.

Integrated processors, such as the i486, combining the CPU, FPP and memory cache deliver a high rate of throughput more reliably than separate units. The speed and integrity of CPU-memory transfers is increased and floating point operations are conducted at higher rates. The average execution rate of the i486 instruction set is double that of the 80386, although much greater increases may be achieved using more efficient instruction sets.

The 80 × 86 processors are *Complex Instruction Set Computers* (CISC) with a large and sophisticated instruction set. Increases in performance are most readily achieved by raising the clock rate or by developing more efficient instructions. But, as the clock rate approaches the technological limit, future development is likely to be based on RISC processors, capable of delivering the same throughput at a much lower clock rate.

The RISC processor is founded on the observation that in most applications around 80 % of the CISC instructions executed are drawn from a 10 % subset of those available, composed predominantly of the simpler operations. In addition, many complex instructions can be synthesised from simple ones, permitting a reduction in the size and complexity of the instruction set, so that (approximately) one instruction is executed in each clock cycle. Nevertheless, RISC processors have limitations in floating point operations which involve a sequence of instructions. A reduced instruction set may therefore prove counter-productive if a large number of operations are substituted for one complex instruction. Consequently, most econometric applications will be processed more efficiently by integrated RISC and FPP.

A range of modules based on the much publicised Inmos Transputer RISC rated at 10 MIPS are available for the PC, but their appeal rests on developers writing applications for the device. RISC principles are also partially applied in the i486. However, Intel's i860 RISC, delivering a 20-fold improvement in throughput over the 80386, was expressly designed as a PC co-processor, complementing the CISC and extending system architecture. Nevertheless, several RISC, such as the Acorn ARM, Motorola MC88000 and AMD 29000, serve as main processor in other small computer systems.

Although the prediction of future development is hazardous, the foundation of the 'personal workstation', is already well established. Adding to this the prospect of larger, more powerful systems with several processors running in parallel, the PC's successor could meet all but the most extreme demands currently satisfied by mainframe systems. Much less certain is the way in which such power will be managed and the price at which systems will be available. The benefits of new processors will only be realised with sophisticated operating systems, though users appear firmly committed to DOS. Moreover, if proprietary interests are established, the competitive pressure on prices, which accompanied the development of the PC, must also be in doubt.

III. SYSTEM ARCHITECTURE AND OPERATING SYSTEMS

Despite the revision and extension of DOS, to accommodate minor innovations in hardware, the system remains largely unchanged, at a time when increased processing speed and the larger memory available present new opportunities in operating system design. The object of recent development has been to increase productivity through multi-tasking. Demand for a multi-tasking system is evident from the popularity of software such as Sidekick and Windows, which support multiple applications, enabling the user to run several programs, of which only the foreground task is under direct control. However, a distinction must be drawn between systems which suspend the background tasks, enabling their retention and reactivation and *concurrent* systems which continue processing the background task.

Concurrent processing is achieved by allocating the processor to tasks co-resident in memory and requires protected mode addressing. Although only one task is processed in each cycle, all appear to run simultaneously. By scheduling access and diverting the processor from tasks conducting IO activity, the workload will be completed in the shortest time. Throughput may be further increased by conducting elements of a task in parallel.

To reap the benefits of contemporary hardware new operating systems and architectures are required. IBM's Micro Channel Architecture (MCA) uses protected mode memory to support multiple tasks and permits the development of multi-processor systems, by passing the control of system resources between processors. In contrast with the PC, in which the CPU controls all other system components, MCA is a multi-master system, in the sense that each processor controls the resources allocated to it and operates at its maximum speed, rather than at or below the speed of the CPU.

Notwithstanding the greater capacity, flexibility and reliability claimed for MCA, user interest has developed relatively slowly. This apparent lack of enthusiasm may be attributable to the slow development of OS/2, the protected mode operating system and the limited range of protected mode software available. Further, although MCA is fully specified, the supply of compatibles has been retarded by questions of legality, but may develop rapidly with the production of third party MCA hardware. On the other hand, several manufacturers have pursued similar objectives by upgrading the PC architecture, developing the *extended industry standard architecture* (EISA), which has the considerable advantage of full backward compatibility with the PC and DOS.

As CPU and memory speed have increased, the bus linking the components has become a bottleneck and performance may be improved by modifying the architecture to meet the demands of the active units. Central to this development is the observation that input–output typically accounts for a small proportion of activity, 90% of operations being conducted in memory. Proponents of EISA argue that the peripherals are already adequately supported, whereas throughput may be raised by increasing the speed of transfers between the CPU and memory. Consequently, a concurrent bus has been developed, with separate memory and IO channels, permitting operation at different speeds. By connecting the CPU, FPP, disk and memory cache systems via a fast 32-bit bus, up to 95% of memory requests may be serviced without delay. Where the system and memory bus have separate controllers, additional processors may also be connected using a 32-bit expansion bus.

Despite scepticism over the longevity of EISA, both Intel and third parties have adopted a neutral position, developing devices for both MCA and EISA, establishing a foundation for the production of compatible systems.

Several operating systems have been developed for small computers, from which the user may select any complementing the BIOS, although in practice choice is often restricted because applications are licensed mainly in an operating system specific, executable form. The operating system therefore acquires a particular significance, because the benefits of innovation are realised only when both users and software developers converge on a system. Two operating systems are currently being discussed, namely OS/2 and UNIX.

Unless DOS is to be almost entirely rewritten, the limit on addressable memory will remain, with the effect that, as the system is expanded and occupies more memory, less workspace is left for applications. However, where DOS applications are able to access expanded or extended memory, many users will have little incentive to adopt a new system. Given the degree of user commitment to DOS, further development appears assured. Several operating systems use the 80386 processor to establish a multi-tasking DOS capability, in effect establishing several 8086-based PC environments in protected memory, managing access to system resources and monitoring activity. Each environment runs DOS with 640 kb of RAM as if memory were being addressed in real mode.

While multi-tasking DOS will benefit all users, the requirements of more sophisticated applications are likely to stimulate an eventual migration to systems designed to address larger memory. Nevertheless, support for DOS is likely to influence the choice of system. OS/2 supports one DOS window, subject to the 640 kb limit, but is frozen when protected mode applications are run to prevent interaction between modes. DOS may also be emulated in software running under UNIX.

Some users, such as applied economists working with large datasets, may be expected to make a more rapid switch to protected mode. OS/2, introduced as an alternative to DOS for protected mode systems, was expected to succeed it as the principal operating system. However, despite its capacity to exploit MCA and modern CISC processors, user reaction has been lukewarm; this may be attributed to several factors including memory requirements, limited support for DOS applications and the modest range of protected mode software available, rather than any fundamental weakness. Indeed, its projected role has recently been re-defined, placing greater emphasis on its portability to RISC-based and larger systems.

Although OS/2 is often compared with DOS, a more relevant relationship is that with Unix. Unix differs from other systems, having originally been designed as an 'open' and reconfigurable system, portable to almost any computer. Despite its reputation of being less user friendly than DOS, Unix is already well established in a multi-user context. With several capacity-enhancing features added and PC applications ported, Unix may offer more immediate opportunities than OS/2. However, there is no Unix standard and software for one form may not run under other implementations. With several forms supporting a range of incompatible processors, the usual practice of supplying applications in executable form is inappropriate and may hinder its adoption. On the other hand, with the adoption of a common applications development framework, such problems may easily be overcome.

Recognizing the disadvantage of incompatibility, Unix developers have promoted standardisation through several groups and concepts, including; X/Open, based on AT&T SystemV, POSIX and the Open Software Foundation (OSF). Unix SystemV version 3·2, for the 80386, supports both Unix and Xenix applications, while release 4 jointly developed by AT&T and Microsoft encapsulates both BSD Unix, SystemV and Xenix. Subsequent agreements between AT&T and Sun provoked hostile reaction and development is following two lines: AT&T, through Unix International developing SystemV release 4 and the OSF; IBM's hardware independent AIX. Nevertheless, convergent development is being promoted, with the prospect of an integrated Unix for systems ranging from PCs to mainframes. Unix has also been developed for RISC devices, such as the transputer, while AT&T are committed to the Sun Scalable Processor Architecture (SPARC) RISC. With more widespread use of RISC processors and a greater range of software, Unix could become the standard operating system.

IV. ALTERNATIVE SMALL COMPUTER SYSTEMS

Although the PC is currently the best-supported platform for economic computing, several other systems may be considered; among these the Apple Macintosh (MAC) range is becoming an increasingly important alternative. For many, the attraction is the MAC operating system, but with an FPP installed in most models and specialist applications such as SHAZAM and RATS available, economists may be attracted more by its capacity to address up to 8 Mb of RAM.

The MAC Graphics User Interface (GUI), based on windows, icons, menus and pointers (WIMPs), established a new approach in the use of computers, which has spread to the PC and Unix workstations. Using a common applications design and intuitive operating concepts, the MAC GUI already offers a range of facilities close to the standard envisaged for the PC. Although a GUI increases accessibility, experienced users may prefer to enter commands directly at a prompt, while the requirement that software conform to the MAC design may deter the porting of DOS applications.

Incompatibilities between the MAC and PC, preventing the direct use of DOS software and PC media, are rooted in the MAC architecture and processor, resulting in the development of almost mutually exclusive market segments. To broaden the MAC market, proprietary interest in the architecture has been reduced and the differences addressed. MAC disk drives capable of accessing DOS and OS/2 media are available and emulation of the PC is possible, although technical factors degrade performance. A MAC may also support DOS applications using an adaptor connected to the expansion bus. Adaptors incorporating the critical PC components are expensive and inflexible but may be used to establish a DOS system within a MAC. However, high capacity MAC drives are incompatible with the PC BIOS, while hard disk operations require a separate DOS partition, with the result that data cannot be passed between MAC and PC applications, other than from DOS to MAC using the Clipboard utility.

Apart from operating system and architectural differences, MAC developments and technical limitations mirror those of the PC. Processing power has increased mainly through higher system clock rates and to a lesser extent, more efficient instructions. The Motorola 68020 based MAC II, at 15·7 MHz is comparable with an 80286-based PC, while 32-bit systems compare with the most advanced PCs. Yet more powerful machines may be developed using the 68040, a CISC with RISC-like characteristics. Common features are also observed in the operating system, including multi-tasking based on Apple Unix. However, until relatively recently little third party hardware was available. With efforts to establish the MAC as a business computer DOS applications are being ported and although economics software is limited, with a performance advantage and continued uncertainty over future standards, its potential should not be underestimated.

Despite the popularity of DOS systems, innovation has occurred mainly outside the DOS environment. For example, Atari have played a leading role in developing transputer workstations, while Acorn have developed the Archimedes range around the 32-bit ARM processor. If sufficient software were available, these and other RISC systems, with a minimum of 1 Mb of addressable memory, could play a substantial role in economic computing. With the introduction of the 24 MHz ARM3, rated at 12 MIPS, an Archimedes equipped with a 4 kb memory cache would merit serious consideration. However, PC software may only be run using a DOS emulator, with some degradation of performance.

The demand for more powerful free-standing systems has been met by Unix workstations, but with new architectures and more efficient processors increasing the capacity of small systems, the performance difference is narrowing. Given the development of a range of powerful, multi-tasking systems, a low cost 'personal workstation' may soon be available. A system supporting integrated Unix, but capable of running DOS would support a broad range of software. Whether the workstation will continue to serve specialist requirements will depend on the choice of operating system, the range of software available and the price of larger and more powerful PCs, but with IBM launching a Unix based desktop RISC system and workstation vendors marketing PC compatibles, the distinction is already blurred.

The IBM RS/6000 RISC based Unix systems resemble the personal system, but are not PC compatible. Nevertheless, their architecture is expected to support existing MCA adaptors and by simulating the PC, a concurrent DOS environment may be established. Using cache and similar techniques, the system outpaces many other machines running Unix, achieving a 27·5 MIPS execution rate at 20 MHz and may occupy an important position, bridging existing standards.

V. SUMMARY AND CONCLUSIONS

The popularity of small computers may be attributed to several factors, not least convenience. Although technologically more advanced systems were available, the PC standard emerged, due largely to the characteristics of its architecture. The capacity and openness of the design, complemented by enhancement of the individual system components permitted increases in processing capacity and larger, more sophisticated applications. Liquid crystal and gas plasma display units, together with $3\frac{1}{2}$-inch disks have resulted in miniaturisation and reduced weight, making systems portable. However, barring radical developments in display and power supply technology, desktop systems are likely to continue to outperform portables.

Using 32-bit processors, the PC attains rates of throughput approaching workstation standards, but despite this and the ingenuity demonstrated in upgrading the PC, high speed processors have revealed technical problems, casting doubt on the capacity of the architecture to meet future demands. Increasing resort to *ad hoc* extensions of the architecture also signal a constraint on future development, yet the PC's life may be extended using RISC-like processors. On the other hand, modern processors may induce the use of new operating systems and architectures.

With the technical foundations of future computer design already well established, personal computing appears poised to undergo substantial change. Migration to a 32-bit standard is already underway, while RISC, multi-master systems and the development of parallel processing may be expected. Software development will undoubtedly continue to demand further increases in processing power, although greater flexibility should enable parallel processing in larger and more complex tasks, while simple tasks requiring more modest resources may be conducted concurrently.

For many economists, the shortcoming of the PC has been the memory limit, which has acquired greater significance with the increasing range of PC-specific software. However, existing software reveals substantial differences in what can be achieved. Although technically the limit was removed with the introduction of protected mode memory addressing and the 80286 processor, several further hurdles must be overcome if end-users are to benefit. Such fundamental change will require new operating systems and standards, if the greater processing capacity available through parallel processing and multi-mastering is to be exploited. Consequently, a critical influence will be the response of specialist software producers to user demands for software running under several operating systems.

Until new standards are established, commitment to DOS will continue to influence the use of increased capacity. Initial applications such as the development of operating environments supporting multiple DOS sessions may slow the development of protected mode applications. On the other hand, systems capable of concurrent processing may produce significant benefits in reducing the time spent loading applications and waiting for processes to complete, while protected mode applications supported by DOS extenders may meet the immediate demands of many economists. In the transition to a new standard, two issues must be resolved by users, including economists: first, the specification of system architecture, the main contenders being MCA and EISA, each supporting multiple masters and secondly, the choice of multi-tasking operating system, where OS/2 and Unix are available.

Despite the advantages claimed for MCA and OS/2, interest has developed relatively slowly, although compatible systems are now becoming more widely available. In part, this may be explained by IBM's strategy which requires a change of both architecture and operating system. User reaction may also reflect the attraction of EISA, which has the advantage of greater PC compatibility, while uncertainty over future standards may encourage timely consideration of alternative systems, including the MAC and Unix systems.

The foundations of the development of a 'personal workstation', handling larger tasks with greater efficiency, are already laid, but whether a new universal standard can be established is a matter for debate. With the technical distinction between the PC and workstation narrowing and the prospect of a unified Unix, at a time when the range of alternatives to the PC is increasing, power users and those with sophisticated applications may favour Unix and the prospect of machine independent software.

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