THE IMPACT OF INFORMATION TECHNOLOGY UPON ECONOMIC SCIENCE*

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Rapid advances in information technology seem likely to change radically its usefulness for the economics profession. This paper reviews the range of existing applications and those that will probably emerge. It also considers the impact these new applications are likely to have on the discipline, and on the social sciences more generally.

Keywords: Economics, information technology, computers, social science.

INTRODUCTION

There is a widely shared perception that a new era is dawning in the application of information technology to the conduct of research and teaching in the natural and social sciences. The past two decades have brought very great advances, indeed. Yet, the prospects seem excellent for improvements in many aspects of information processing, transmission, storage and retrieval to continue at an unabated pace during the coming decade. Computing is expected to grow more powerful, sophisticated and flexible, by an order of magnitude, while networks and advanced visual and other natural interfaces will render the technology "an intellectual utility, widely available, ultimately as ubiquitous as the telephone."[1] In this paper we examine the existing pattern of computer use in the discipline of economics, particularly in the profession's academic branch, and undertake to assess the likely near-term impacts that the ongoing revolution in information technology could have if economists obtain access to augmented computational resources.

Access to improved information technology resources, with all the potential for innovation in research and teaching that this would create, is dependent as much upon conditions primarily within the control of the community of academic economists as it is upon factors that are

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essentially beyond its control. The point we have sought to underscore here is that a computer rich environment which also will prove to be a productive one for economists cannot simply be delivered to the discipline by beneficent external agencies. To be useful, such facilites have to be developed with the active participation of people working within the discipline. The way resources are allocated to the applications software development process, for instance, or to the effective formation and management of specialised networks, will be largely determined by organisational and institutional priorities of university economics faculties. This paper is addressed as much to our colleagues within the discipline, as it is to university administrators, and to outside agencies concerned with promoting the continuing advance of economic knowledge.

THE COMPUTER REVOLUTION

The technical basis for the perception that economics (along with other scientific disciplines) is embarking upon a new era of computer application stems from developments marking a third stage of the computer and information revolution.[2] This stage, in which our society now finds itself, can be distinguished from its predecessors by a number of features. One is the advance that has been achieved in the architecture of high-speed general-purpose scientific computers, including component processors working in parallel as well as other architectural innovations that increase the rate at which logical and numerical operations can be performed.[3] Today's super computers represent one class of such machines.

A second feature is the rapid expansion in distributed information processing capability based on the availability of minicomputers and microcomputers. Falling costs are making such machines — particularly suited to the computing needs of individuals and small groups of specialised users — an increasingly ubiquitous feature of the working environment for many university students, teachers, and researchers.

A third feature has been the development of sophisticated computer graphics capabilites for pictorial representation and data display. Graphic images are only one mode, albeit presently the most fully developed mode of interface between computers and their human users.[4] Visual imagery, representing real objects and processes (e.g., the geographical distribution of production activities and commodity shipments) or abstractions (e.g., the solution set of a dynamic model of the economy) assists users to interpret the information being presented by the computer. To have these images behave dynamically the way the objects or abstractions they represent would behave is especially computationally intensive, because models of realistic complexity typically require the rapidly repeated solution of extensive systems of equations.

A fourth feature is the integration of computers into other technological systems. CAD/CAM (Computer Aided Design and

Manufacturing) constitutes one form which such integration has taken. Another equally obvious form is networking, whereby computers no longer stand alone, but are linked through systems of communication and information transfer, and so can interact with one another (as well as with other types of machines and with humans). The largest general-purpose computer network accessible to those in institutions of higher education, BITNET, presently links well over a thousand computers located on hundreds of university and college campuses in the US and provides connections to academic networks in more than a score of foreign countries. More sophisticated networks, such as NSFNet, developed under National Science Foundation sponsorship, are being created to integrate regional supercomputer centres in the US. ARPANET offers advanced network capabilities to those who have access to it. The services of private networks such as MCI Mail, Compuserve, Genie, and BIX have proven useful to many economists.

If all this were not enough, the prospect for the near future is one of significantly enhanced hardware capabilites at every level in the current hierarchy, from personal to supercomputers. Research is now underway to build machines based on new intergrated circuit (IC) designs and semiconductor materials that will be far faster than current devices. Higher computing speeds alone are not so revolutionary, for they have the effect of transforming information processing systems which were 'compute-bound' (limited by processing capability) into those that are 'input/output-bound'. For example, it is widely projected that advances in computational methods applied in a number of scientific disciplines will create needs for network transmission speeds several orders of magnitude greater than the networks to which most university-based researchers currently have access.[5] Effective electronic transmission of pictorial and graphical information, upon which modern computational-based teaching and research is coming to depend, also calls for substantially higher network speeds than those required for the transmission of simple text. Expanded capabilities for data storage and file encoding standards complementing these connections will be no less important.

Developments affecting these input/output, transmission and storage functions are therefore also critically involved in the new information technology vistas that are opening up before the scientific research community. Optical fibre and related innovations in communications technologies have vastly increased the transmission rates of digital information, and so have augmented possibilities of constructing high-speed computer networks capable of transmitting enormous volumes of data. In addition, significant improvements over existing magnetic tape technology are becoming available, including the use of optical (laser) discs for mass storage and distribution of information.

The realities and future prospects for distributed computing over high-speed networks with links to supercomputers have encouraged the design of individual workstations having special capabilities for programme preparation, editing, and graphical display, as well as very substantial independent computing power. Sophisticated workstations and local area networks (LANs) will make it easier for users to distribute their information storage and processing tasks across a network of linked computers and mass storage devices according to cost and performance criteria for a research task. In this context, sophistication of software is likely to be as significant as hardware sophistication.

What specific forms the emerging technology will take in the future, what resources and modes of organisation may be required for the realisation of its full potential in scientific research and education, and how particular disciplines are likely to be affected by these transformations, are obvious questions for such a prospect to provoke. That does not make these questions any the easier to answer. The whole subject is surrounded by great margins of uncertainty that render attempts at long-range forecasting a rather less productive activity than is the analysis of presently perceived opportunities and problems.

Uncertainties about the narrowly technical aspects of the subject are, in a sense, its least troublesome aspect. Technological revolutions are not simply made by creating new machines, not even general-purpose machines such as the steam engine, the dynamo, the internal combustion engine, or the computer. Technologies are social constructs that evolve and diffuse according to complex processes of adaptation to, and alteration of, the economic and institutional environments into which they have been introduced.

The time scales appropriate for thinking about these processes almost always turn out to be much longer than the ones that appeared realistic to observers who were best informed about the purely technological possibilities at the outset. It is certainly salutary to recall the unhesitating predictions of the imminent arrival of galloping factory automation, soaring industrial productvity, massive worker displacements, social and psychological burdens of learning to cope with greatly extended periods of leisure time, and other ambivalent *sequelae* — all of which were elicited from economic and social pundits by the advent of second generation computers in the 1960s. Few of these predictions have yet come to pass.

Indeed, there is today within the university research community as a whole a growing awareness of the non-technological dimensions of the challenges, as well as of the opportunities; of the gap between the potential that has been created by the onrush of technical advance in computers and communications hardware, on the one hand, and our presently restricted capabilities, on the other hand, for quickly putting these to effective uses by existing organizations — research groups, laboratories, teaching faculties, university administrative cadres, and service/support entities. The dawning prospect that many purely technological constraints upon the collection, processing, storage, distribution and analysis of information can be removed, or at least substantially relaxed, has served to throw into sharper relief some previously little examined features of the educational system and the institutional environment in which academic research is conducted.

This is so especially where these features appear to be inhospitable to the immediate widespread acceptance and implementation of the new technology. The way that children are taught from kindergarten onward, the mathematical literacy of our population, the role defined for university teachers, the present arrangements for the protection of intellectual property rights, the power of established disciplines entrenched within departmental fortifications — all these have, in some serious conversation or another, been identified as 'holding up the show.' Now, to re-examine arrangements and mores that have long been unquestioningly accepted cannot be a bad thing; the periodic compulsion to do so is one of the gifts that technological progress brings to a society. But there is a problem when becoming fixated upon some vision of a distant technological utopia leads many constituent elements of the existing scientific information system to be viewed as merely a collection of unforeseen road-blocks, extraneous binding constraints that can now be identified as requiring removal if the computer revolution is to proceed.[6]

One problem with such diagnoses and prescriptions is that they implicitly assign primacy to engineering developments in setting the agenda for long-run change, and for near-term measures intended to prepare the way for more far-reaching transformations. Yet not everything that can be done with information technologies is worth doing. Nor would it be obviously desirable to change everything that would need to be changed to permit computers to help us more fully in the ways we now see that they can. A further problem, related to the first, is that primacy comes in this way to be awarded to the development and acquisition of computer hardware. It is hardware which appears to be responsible for forcing the pace of change in the rest of the system, especially in its less plastic social and institutional components. It is by no means evident that issues most immediately relating to computer hardware are the ones that should occupy the focus of our attention.

From the viewpoint of all but a few branches of science and engineering, and certainly from that of economics and the other social sciences, the consequence of such an orientation would be to shift responsibility for the provision of the information technology infrastructure to those outside the discipline. It would thereby further strengthen an understandable, and already well-developed disposition to focus upon the task of mobilising the whole gamut of external agencies — ranging from public and private foundations, to university administrations, to computer technologists — behind a campaign to deliver more and better hardware and operating systems. It would distract attention from what could be done immediately to make better use of existing stocks of computing equipment, and from efforts to devise solutions for economic and organisational problems which will otherwise continue to restrict the utilisation of bigger and better hardware endowments. Consequently, in taking up these questions from the vantage point of the discipline of economics, we shall deliberately eschew the long-run perspective in favour of concentrating upon the immediate opportunities and challenges.

POTENTIAL IMPACT ON ACADEMIC ACTIVITIES IN ECONOMICS

Introduction

Improvements in information processing technology are pervasive and ongoing. In examining their impacts on the academic activities of economists, the related but inseparable impacts of improvements in four areas must be considered — computational power, mass storage technology, network and telecommunications capabilities, and workstation sophistication. In economics, unlike some other sciences, no single area provides benefits to the discipline dominating the others. Improvements in mass storage techniques, for example, are likely to be nearly as important for applications in economics research as improvements in computational power. As a consequence, the implementation of new systems that embody improvements in each of these four areas in a balanced fashion may be more crucial for the progress of academic economics research than a concentration upon achieving major advances in the discipline's application of any single area of technology.

The four areas — computational power, mass data storage, networks and telecommunications, and workstations — do not cover the category of complementary software. Yet, algorithms for economic computation most certainly do constitute a significant area of advance in information technology, broadly conceived. The reason for their omission from the list of technical developments reviewed here is that the economic features of software are only indirectly related to the technological advances in microelectronics and material science technology that are responsible for the very rapid decline in prices of information technology. Improvements in information technology are, nonetheless, intimately tied to improvements in software. Design methods for hardware systems are increasingly dependent on advances in algorithms for specification, stimulation, and optimisation of system operation. The economic foundations for examining production processes underlying these advances and drawing conclusions about their likely evolution currently are weak. For example, while quality and performance improvements in software clearly are occurring, measures of these improvements are difficult to come by. Nor is it currently possible to measure the impacts of specific improvements because of synergistic effects in assembling these improvements together in systems. Consequently, predicting the future path of performance improvement or cost reduction of software generally, and algorithmic improvement in particular, is essentially a speculative endeavour. If the production process for these improvements is taken as exogenous, however, it is possible to reach economic conclusions about how these improvements affect the four areas of hardware improvement that can be explicitly measured.

The functional activities of academic economists fall under the familiar headings of teaching, research and dissemination. Each of the four areas of information technology mentioned above is likely to have an impact on these activities of academic economists. Because teaching and dissemination of research results pose similar problems for people working in each sub-area within the discipline, the impact of information technology on these activities can be examined in a general fashion.

Computational power

Improvements in computational power are distributed across the range of information processing equipment. These improvements are important not only for the central processing capabilities of computers, but also for the performance of peripheral and telecommunications equipment. At the high end of central processing capabilities, the computational engines known as supercomputers make it possible to reduce the costs of solving complex systems of equations by numerical methods, thereby providing opportunities for extending current lines of research and embarking upon new ones. Gains in computational power, however, are shared at every level in the size hierarchy of computer systems. The computational capabilities of personal, mid-size computers and mainframe computers are expanding very rapidly and this expansion is likely to continue for the foreseeable future.

Solution of more complex problems is not the only implication of greater computational power. Computational power may aid in simplifying, and in tracing the flow of causation in more complex models, where current resources limit the number of alternative assumptions or range of variations that may be explored. Increased computational power is useful also for efficiently realising higher level user interfaces, making it possible for the economist to communicate with the computer in languages more closely approximating the original statement of a problem, rather than through an extensive process of writing efficient code for problem implementation. Economists working with large-scale linear programmes on mainframe computers have, for some while, made use of special input and output languages for putting the model in the form required by optimisation software, and for processing solutions for presentation of results, such as the OMNI matrix generation software, which is now widely used in industrial applications, and GAMS, developed for similar purposes by the World Bank. The recent emergence of user interfaces — such as GAUSS (for the IBM PC and compatible PC machines)[7] and matrix programming languages — for the statement of linear algebra systems which are common to both optimisation and econometric problem-solving, is an analogous indication of the impact of the augmentation of computational power at the disposal of personal computer users.

The near-term utility for economic research of very large increments in computational power is by no means self-evident. The degree of scientific understanding generated by increasingly sophisticated mathematical modelling is uncertain and gains in model complexity, therefore, may not, in and of themselves, lead to better economics. Constructing models whose sheer complexity requires analysis by extensive application of numerical methods will not necessarily advance researchers' insights into the workings of real economic processes. Instead, as in some other sciences, prior knowledge about the effectiveness of a technique for advancing knowledge is unknown, and it is therefore appropriate, even with limited resources, to diversify the stock of techniques available.

For these reasons, we are unable to conclude that improvement of computational power alone offers the most promising opportunity for achieving progress in economics. Indeed, recent improvements in computational power have already uncovered more fundamental technical constraints, including limitations in user interfaces and techniques for data manipulation. These pose more significant barriers to both the wider and more sophisticated use of information technology systems in economics. Increases in computational power are likely, however, to test the proposition that a higher degree of model complexity is necessary for improving the predictive value of economic knowledge. In addition, improvements in computational power will be significant in increasing the sophistication of graphic display devices and telecommunications networks.

Mass storage technology

Improvements in mass storage technology promise to have a major impact on the conduct of empirical economics, if, but only if, they lead to the creation and distribution of new data resources. Currently, magnetic tape technology is the primary method of distributing significant data sets within the profession. While magnetic tape storage technology offers a relatively inexpensive and high capacity medium for this purpose, it erects some major hurdles for the analysis process. Efficient access to data on tape for purposes of statistical analysis usually requires the creation of magnetic disk files that are relatively costly under the prevailing technological conditions. The recurrent translation of raw data on tape to disc and back to tape, in order to save disc storage charges, is costly in terms of the division of labour between analysis and programming overhead in research projects. Software for managing tape storage technology has notable deficiencies in its ability to document changes and transformations of data at various stages in the process of analysis.[8]

Lack of generally accepted standards for data storage and manipulation greatly complicates the process of data sharing and publication of economic data sets. This problem is a direct consequence of the proliferation of file format standards used by application programmes or defined by hardware manufacturers.[9] While some of the problems of standardisation may be independent of improvement in data storage technology, the onset of new storage technologies will renew opportunities for implementing common practices or standards. It remains uncertain whether the economics research community, and the public and private sector sources from which it draws its data, will find it advantageous to develop more standard formats for data storage. Efforts to develop conversion methods, or gateways to bridge incompatibilties, may be more appropriate than efforts to reduce the number of standards. It is clear, however, that high capacity media such as read/write optical or magneto-optical discs will offer the advantages of inexpensive data distribution with the opportunity to design improved methods of keeping track of successive, variant, analyses.

As is the case with improvements in computational power, the potential for designing higher level interfaces that permit the user to document data transformations and analyses might be one consequence of more specialised data management systems based on new mass storage technologies. Developing common specifications of recording formats or bridges between formats and improving data documentation methods will be necessary for more effective use of these new technologies.

Networks and telecommunications

Improvements in network and telecommunications facilities may have a significant effect upon the conduct of research, by virtue of their ability to link geographically dispersed economists with shared ideas of specialised interest into larger and more productive research problem networks. In addition, the linking of personal computers by local area networks (LANs) is a useful method of sharing among users the fixed cost of sophisticated peripherals, such as laser printers, high capacity disc drives, tape drives, and data plotting devices, as well as site-licensed software. When the new systems of high capacity storage media mentioned above begin to be applied, LANs and telecommunications networks will allow the sharing of large libraries of information whose economic feasibility will be enhanced by the opportunity to spread the fixed costs of such storage systems across a number of users.

LANs also are likely to create communities of interest among economists, who increasingly are distributed throughout various departmental faculties, professional schools and research institutes of major universities. Since economists, regardless of their disciplinary specialisation or their affiliation with schools of business administration, law, medicine, public health, and engineering, share a number of common information technology problems, the development of a common resource is likely to encourage productive interactions among people who hitherto have not collaborated in a systematic way. LANs, however, are not an unmixed blessing. Anyone with information technology experience is likely to recount as many stories of frustration — if not outright disaster — as they are of satisfying successes, and a LAN's collective property increases the opportunities for the sharing of both kinds of experience during the learning process.

In addition to LAN technology, improvements in microelectronics are also likely to lead to major improvements in the telecommunication data. At a rudimentary level, use of BITNET, the inter-university communications network, is currently providing researchers with a reasonably effective electronic mail capability. BITNET's capabilities for transferring graphic and other large data files is still quite limited. The addressing and message transfer facilities of BITNET do, however, appear to be a worthwhile foundation upon which to build future capabilities. Improvements in data telecommunications make it possible to contemplate co-operative activities spanning universities, both domestically and internationally. Sharing of databases, co-operative development of data or software resources, and active research collaborations using information networks are all potentially fruitful activities that may arise from improvements in communications technology. Unfortunately, relatively few such activities are likely to occur without a reconsideration of the incentive structure created by current patterns of research and teaching financal support.

Workstations

The term 'workstation' is a relatively recent one and reflects the increasing sophistication of both desktop computer technology and the distribution of computational resources in networks. Presently, the computer hardware used in economics takes the form of terminals and personal computers. Of course, these two categories overlap when software is employed to make personal computers emulate communication terminals.

The computational power of personal computers is rapidly approaching the level attained by advanced minicomputers of a decade ago, and, with the prospective progress of mass storage technology, may achieve almost identical overall capabilities. Because of the rapid price reduction afforded by technical advances, however, the desktop computer is likely to be tailored to much more specific uses.

The workstation concept extends the use of personal computers to the role of being a node in a LAN, or an originating or sending device for telecommunication of data. Of equal or greater importance, the concept anticipates greater sophistication in the use of desktop computers for performing local computational, display, and other functions. Workstations are now most familiar in the context of engineering design, where enhanced graphics capabilities are coupled with sophisticated software to create an interactive environment useful for design and simulation. Ideally, such workstations are able to draw upon external resources for extensive or prolonged computations, while maintaining a sophisticated, friendly interface with the user. What constitutes a user-friendly interface will vary of course, depending on the needs and training of the people involved. The engineer's friendly interface is likely to bear only a vague resemblance to the economist's.

A conceptual tool for thinking through the implications of these developments has been the notion of professional workbenches. Like other useful metaphors, the 'workbench' notion has the appeal of structuring thinking about how an entire system and its components might relate to one another. A workbench contains a number of tools, and an economist's workbench would include methods to generate graphical, symbolic, and narrative representations of economic concepts; resources for entering, transforming, and displaying data; techniques for estimating statistical relationships and solving equations; and resources for managing communications with external computational or communication resources.

The promise of the workbench metaphor would be fulfilled were it possible to co-ordinate such an array of tools through a common user-interface, and to employ them in generating documents or software. The problem with this metaphor is that it presently seems to require substantial, if not complete, uniformity of equipment, in order to reduce the fixed development costs of such a system. If the hardware is, of necessity, highly uniform, workbenches should at least cater for the individual, idiosyncratic research needs of users.

The very rapid rate of change in personal computers and the many divergent standards for user interface, communication, and graphics display appear to form a significant barrier to the development of such systems for the general university research community. Nonetheless, experimental implementation efforts, such as the Andrew project at Carnegie-Mellon University, are probably necessary for a better understanding of design consideration and user patterns. How soon the results of such projects can be embodied in a single, general-purpose, university research workbench remains unclear. It may be quite undesirable to attempt to standardise on a particular type of personal computer for developing a workbench and, consequently, more efficacious to devote resources to designing user-interfaces with a capacity for managing collections of software tools that may be assembled to form discipline-specific systems. Thinking about what components might be necessary for such a system and how to connect them, even at an earlier stage of development, could be quite productive in increasing the near-term utility of workstations for economists.

Summary

Advances in the four areas of information technology just discussed are likely to make a significant impact upon the way the study of economic phenomena is pursued. Improvements confined to any single area are unlikely to have as important effects as incremental and co-ordinated improvements which are distributed across all four. For example, improvements in computational power alone will strain economists' existing capabilities for data management, communications, and the user interface to computer systems. Another way to make the same point is to observe that improvements in any single area are likely to reveal technical constraints, and also organisational and institutional constraints affecting other areas of information technology. For this reason, closer consideration must be given to the specific uses of information technology within economics, and to the economic and organisational issues in improving this utilisation. Both are necessary before detailed conclusions can be reached about improving the information technology resources available to the academic economics community.

IMPACT OF INFORMATION TECHNOLOGY ON TEACHING AND DISSEMINATION ACTIVITIES

Despite the growing use of information technology in economics during the last 20 years, the teaching and dissemination environments in which academic economists work have been endowed with very modest stocks of computer equipment. Teaching at the undergraduate and graduate levels offers different opportunities for the employment of information technologies. And at the graduate level, it is useful to draw distinctions between the training of academic economists and the economic education of other professionals, in schools of business, medicine, law, education, engineering, and public administration. In dissemination activities, a central focus continues to be professional publication in journals with peer refereed review procedures, although in the past decade there appears to have been a significant increase in conference exchanges, conference volumes, and the systematic circulation of working papers. Disclosure of underlying data, and the replicability of empirical work continues to be an issue among economists, since preparation of datasets for quantitative analysis often introduces arithmetic transformations or other operations that cannot be readily documented within the space constraints imposed by a professional journal article.

Computer aided instruction

The development of information technology resources for economics instruction must be characterised as primitive, at best. Aside from specific training in the use of statistical tools, the application of computer aided instruction (CAI) in economics is at a very early stage of development. Mastery of economic theory requires facility in relating premises to conclusions. Traditionally, this facility was gained by utilising mathematical models and their graphical representation as tools for reasoning. By manipulating the graphical and mathematical specification of models, novice economists eventually develop a working knowledge of the underlying deductive structures of economic theory and an ability to extend or reformulate these structures in ways applicable to new problems. In recent years, modest progress has been made in developing CAI methods for helping attain this deductive reasoning facility. Whether CAI will help develop a deeper level of understanding or increase the number of individuals who can successfully perform deductive economic reasoning is, at present, unknown. It does seem likely, nevertheless, that CAI will prove increasingly useful in the early stages of economic instruction since it makes abstractions more tangible and responsive to the control of the individual student.

Examples of CAI methods include simulation of decision-making at the level of the firm for instruction in business management, and simple models of macroeconomic behaviour in which students can explore the intertemporal effects of shocks in investment or government spending. Instructional software that devotes attention to the graphical display of information is much less common in economics than in the physical sciences, although comparative static and dynamic operation of mathematically straightforward models plays an important role in both subject areas. Instead, economics CAI most often is a direct extension of textbook based and problem set methods that require simple deductions or involve solutions of simple optimisation problems or market price models. Clearly, even with existing technology, there are major opportunities for improving instructional software available to the economics profession. In this area, the historical lack of access to personal computers by large student populations has been a limiting constraint on the development of more sophisticated CAI software.

As greater stocks of personal computers and the possibilities of instructional workstations are realised, software for instructional purposes is likely to be the primary constraint facing increased use of information technology in economics. Teaching of theory concepts using CAI methods could extend existing programmed learning and computer diagnosis techniques which have been applied to introductory economics. Improved graphics technology could reduce growing dependence upon formal mathematics for presentation of theory and permit development of new forms of intuition about abstract economic relationships. Students could be exposed to larger and richer data bases early in their undergraduate and graduate careers, allowing them to develop a much better understanding of economic relationships and enhancing their training in econometric and other quantitative methods. Use of networks would allow students to gain direct experience with experimental economics methods. And networks would also permit exchange of CAI software and design concepts.

Network dissemination

The use of information technology in the dissemination of research results is also at a relatively primitive state. No well-identified network of research economists has emerged within the public access network system, and only limited exchanges among research economists are known to us. There are no common standards for the transfer of data or symbolic text. Even the existing facilities for the inter-university exchange of simple electronic messages, such as BITNET, have only recently begun to be utilised by small numbers of academic economists. Recent improvements in network capabilities and access suggest that this area is poised for rapid growth in the near future, although problems of publicity, co-ordination, and access will need to be resolved. Dissemination would be significantly aided by capability for symbol processing and transmission, and transmission of graphic material. These are vital for working paper distribution in electronic form, as well as for preparation of hard copy manuscripts for conventional publication.

One area where networks have had a significant impact is in common access to bibliographic databases, such as Economic Literature Index (ELI) and SOCIAL SCISEARCH. By providing citation, key word, abstract, author and title searching, these databases provide a standard, concrete basis for references made to the literature. They also allow economists to track lines of research, identify work related to research interests and to prospect promising veins of future inquiry. Greater familiarity with these tools in the course of graduate education would improve both the scholarship and productivity of future research scholars.[10]

Increasing sophistication in the capabilities of telecommunications networks is likely to improve the dissemination of research results and work in progress, providing another avenue for interaction. The organisation of seminars on specific interest areas through data networks may be a useful method of exploiting this increasing sophistication. Here again, improvements in software are likely to play a pivotal role in convincing economist-users that such systems are a worthwhile supplement to existing methods of communications.

Professional work in economic theory is symbol-intensive. As such, it creates a substantial demand for word/symbol processing and related computer systems aimed at making productivity gains in the preparation of manuscripts and exchange of work in progress. At present, this demand has been only partially addressed with existing technical typing systems, such as TEX, relatives of the Unix TROFF system, and specialised word processing programmes for personal computers. The lack of standards for symbolic text exchange is a substantial current barrier to realising the potential gains from these systems. Such standards, ideally, would substantially reduce lengthy delays and costly re-entry of manuscripts as they move from one author's desk to those of their collaborators and colleagues, and thence to professional journals. Achieving standards in this area is by no means trivial because of the diversity of notational convention currently in use and the continuing innovation in symbolic expression. To cite two relatively recent developments, set theoretical notation and the notation of linear algebra are now widespread in the profession, although both were uncommon 20 years ago.

INFORMATION TECHNOLOGY AND ECONOMIC RESEARCH

The modest historical and contemporary stocks of computer equipment available to economists for research must be contrasted with the rapid declines in the cost of such equipment and the commitment of many universities to furnish their faculties and students with basic computer and telecommunications facilities. We shall briefly comment on the way in which a significant augmentaion of computer resources is likely to transform each of the four previously identified methodological sub-disciplines. At the outset, however, we may note a number of common impacts which the trends we have reviewed in information technology are likely to have upon the conduct of economic research.

With regard to computational resources, most economic research performed on computers during the past 20 years has shared central university facilities with large users in the natural sciences, users whose requirements determined the access costs and configuration of services available to others. This state of affairs had some notable beneficial properties. Many scientific and engineering problems share common features with those encountered in economics, so economists have shared in the benefits of standardised numerical techniques developed for other disciplines. Personal computers, however, probably still account for the most rapidly growing segment of computer usage within the profession.[11] The use of personal computers is no doubt primarily facilitated by the existence of word processing and other office automation tasks that economists share with other professionals. Personal computers also have an important role in networks and telecommunications, where they are used for terminal emulation and control of file transfer processes. As the processing and storage power of personal computers increases, economists will be able to perform an increasing share of research locally. Many problems will, however, require the computational power of much larger machines.

Economists have been very slow to use the new supercomputer technology and only very few have used a significant amount of processor time on these machines. There are at least three posible explanations for this: (1) economic research may not require these resources, (2) access to them may be limited, and (3) there may be problems in assimilating the new technology. There is good reason to suspect the last of these is the most critical problem.[12] Supercomputers seem formidable to many economists; they seem new, complicated, and distant. There is still very little software, and many machines still run in old-fashioned batch mode. Software is constantly changing as each piece of existing code is re-optimised for the new machines. There are many bugs, and often documentation is poor: hardware development has far out-paced software. Further, the machines are administered by a distant bureaucracy, and funding often appears somewhat uncertain from year to year. Despite the far more limited capabilities of smaller mainframes, minicomputers, and personal computers, these are, by comparison, familiar and friendly. There are huge volumes of well-designed software with excellent user interface (often graphical), and a greater fund of knowledge (though somewhat dispersed) exists among colleagues and students for solving most hardware/software problems. In addition, the mistakes that are the natural concomitant of learning remain private when made on the novice's personal computer, whereas novice supercomputer-users are obliged to experiment in a more public arena.

Some of the difficulties attending the utilisation of supercomputers can be blamed on their communal property aspect, but many of their problems are part of the natural turmoil inherent in the adoption of new technology and hence may be expected to dissipate as the new knowledge diffuses. To a large extent, however, non-specialists are unnecessarily deterred from using supercomputers because to understand and use them effectively requires a substantial time investment, and this is likely to become obsolete quite soon as new technologies are still being rapidly introduced. The number of supercomputer centres is very small, so it is very unlikely that good software will be developed privately for these machines without some sort of governmental assistance. The most likely strategy for overcoming these problems is to give higher priority to the development of machine transparent software that allows workstations and supercomputers to talk the same language. Analysis of typical algorithms reveals that most processor time is consumed in calls to a relatively small number of basic linear algebra 'kernels' that are relatively simple and can be highly optimised on a machine-by-machine basis by systems programmers familiar with the intimate details of each machine.

The remedy for these software problems, however, often is far from straight-forward. Seemingly simple solutions may be thwarted by institutional (rather than by purely technical) obstacles. Consider the following concrete instance, related to us by John Rust of the University of Wisconsin (Madison).

> I had talked to Lee Edlefsen about converting GAUSS for the Cray-2 supercomputer. He estimated it would require about one man-year of effort, not a large amount relative to typical hardware costs. Chris Sims [of the University of Minnesota] and I attempted to write a National Science Foundation proposal to fund this conversion, however it quickly became apparent that it would be very difficult to fund the conversion in a mutually acceptable way: the public domain restrictions inherent in government

> funding were inconsistent with Edlefsen's ownership rights for GAUSS. A possibility of NSF funding for site licenses has its own problems: once converted, the marginal cost of adding additional sites is essentially zero, so it is not at all clear how to price them. Furthermore, it's difficult to convince supercomputer centres to pay for site licenses unless a sufficiently large number of users demand the software. However, this is a chicken and egg problem: there can be no demand until the software exists and becomes known. Because of these problems, we decided to abandon the conversion project . . .

Incremental improvement across the range of computational power appears imminent in the immediately foreseeable future. Whether modifications of prevailing institutional arrangement for the development and utilisation of software interfaces or incentives will favour outcomes that are socially optimal, or even cost-minimising, remains highly uncertain. Clearly, considerably more concerted efforts are called for if improvements of the latter sort are to be made responsive to the more specialised requirements of economists who seek to exploit augmented computational power in academic research.

In the area of mass storage technology, advances are likely to make data on economic behaviour widely available to the profession, stimulating broader investigation and richer analyses of economic activity from all disciplinary perspectives. Mass storage technology will also have a major impact on those sub-disciplines where data-oriented research is the primary focus.

Improvements in networking and telecommunications technology shared throughout the discipline are likely to take two forms. First, there are the gains of specialisation to be had by overcoming the barriers of distance. As in other fields, the division of economics into a growing number of sub-disciplines has the natural consequence that researchers in any sub-discipline are geographically dispersed, meeting one another relatively infrequently and communicating largely through the media of correspondence and working papers. The momentum of collaborations initiated in gradute school or during visits is often dissipated with the geographcal separation of researchers. This problem is compounded by the mobility of tenured economics faculty and the high turnover rates of younger, untenured faculty, which is characteristic of the leading research universities.

Under present conditions, co-operative research endeavours require detailed plans for separating stages of research output so that researchers can independently pursue segments in a general outline of a research plan. Quite possibly many such endeavours are never attempted because the cost of planning and managing such efforts using current technology is perceived to be prohibitive. Of course, the prevailing style of individualistic or limited collaboration research in economics has its own historical momentum, and even very significant improvements in networking and telecommunications technologies will not automatically transform the academic research or teaching into co-operative, teamoriented activities, however productive such a transformation might prove to be.

A second use of networks would be to enhance the exchanges among research economists on problems in their research. Currently, economists using computer networks are more likely to be seeking general information about hardware or software problems than exchanging research insights with colleagues. But this reflects that fact that, until recently, network access meant that users were a self-selected group in which 'computer adepts' were especially heavily represented.

A third respect in which the formation of more extensive and closely integrated research problem networks may prove especially fruitful in economics is through facilitating the intellectual migration of individual researchers from one area of substantive specialisation to another. Not only does the unity of the discipline gain by such movements, but, as has been observed in the natural sciences, the movement of researchers from one narrowly defined problem area to another and the consequent integration of formerly distinct research networks is an important source of scientific innovations.

Advances in workstation technology for the economics profession have the potential for very broad impact. The application of information technology within the profession is currently problem-oriented. Researchers face the task of mastering several different systems in order to have the most basic competence in utilising information technology for their work. Systems relevant for the solution of econometric problems are distinct from those used to develop drafts of technical papers, and these systems are distinct from those that can electronically distribute information to other economists. In other areas economists make use of general purpose tools that must be adapted to their specalised purposes. As a consequence, economists are continually re-inventing techniques in the use of such general purpose tools. A simple example is in the area of graphics technology, where many economists face similar information presentation problems, but must make use of very general purpose systems lacking the most rudimentary tools of graphical representation common to the profession. (For example, drawing a demand curve with constant elasticity becomes a challenging exercise using a general purpose tool.) Development of workstations that integrate applications and provide tools useful for a broad cross section would significantly improve the productivity of economic research. These same workstations could be used as a platform for the development of more specialised applications for smaller user communities. Attaining such goals is not straightforward. Rapid technological progress, and the natural tendency to disagree on what appropriate standards for such systems might be, may delay their implementation.

In addition to hardware improvements, economics has generated a large demand for specialised software to provide more productive tools and familiar interfaces for the conduct of research. Many economic research techniques have required specalised software for their computer implementation, including the majority of advanced econometric techniques. The process of software development is, and continues to be, characterised by a wedge-like pattern of advance: the initial response to new problems takes the form of very narrowly specialised software solutions which subsequently give way to increasingly more general and comprehensive solutions. Economics may yet turn out to be well served by a small number of general purpose software systems. For example, commercial statistical packages, such as SAS and SPSS, have developed strong data management, graphing, and statistical capabilities that challenge more specialised econometric programmes, such as TSP (Time Series Processor). TSP established itself as the *lingua franca* of several, earlier generations of applied econometricians, allowing exchanges of extensions and implementation of new techniques long before they would appear in programmes with more diverse user bases. More recently, new programmes, including GAUSS and RATS (the latter of which is available for use on many different machines) have entered the market to supplement, or in some cases displace, TSP.

EMPIRICAL ECONOMICS

Data collection, management and distribution

These are now overhead support activities because of the large fixed costs of collection and the documentation of machine-readable files. As high speed transmission costs decline, two tendencies may emerge. The social usefulness of specialisation in data collection could increase, since a wider array of users would be served. Pricing access to public data banks, as a way of financing this overhead activity, could emerge, creating a public utility situation in which some regulatory intervention would be necessary. Small projects that generate specialised data sets would be able to make them generally more available by forwarding files for archiving in central facilities.

The long term implications of these tendencies would probably promote beneficial standard-setting in methods of data collection, formatting, and public documentation; replicability of analyses would be enhanced if journals required magnetic memory from data sets to be on deposit within some reasonable period at a central archive, but there are sure to be many obstacles raised against implementation of such a proposal. Unfortunately, even with expanded access to common data bases, individual researchers are likely to edit or otherwise transform the data sets for special purposes, thereby reducing the ease of replication. Nevertheless, replicability of work should be a common professional standard.

Electronic network connections with central data banks, staffed by professionals familiar with the datafile structures and with the population of current users, could greatly raise the productivity of empirical research in economics. Such data bank resources would allow the pooling of information about idiosyncrasies of data sets, and aid the national formation of networks of current investigators who are most experienced in the use of each data set. These benefits would come at the cost of disclosing the identity of the researchers who have recently utilised the specific files, and placing upon them the burden of responding to inquiries, or declining to do so.

Econometrics

While most computer use in economics has taken the form of econometric applications, and, probably, the specific operation of simple regression analysis, the microcomputer revolution has increasingly enabled economists to dispense with reliance upon mainframe facilities maintained for other users. Advances in capabilities of personal computers with regard to memory and speed are thus likely to be of greatest relevance for the ordinary empirical researchers. Specialised software developed by economists for the PC, including programming languages such as GAUSS to serve linear algebra applications, can be expected to augment packages (such as micro-TSP) based on FORTRAN.

The most computer-intensive branch of econometrics is presently found in maximum likelihood estimation of models describing dynamic micro-level behaviour; for instance, labour supply and household savings. The combination of complex MLE models with many (> 30) parameters and panel data sets containing thousands of observations, has meant that relatively few research groups have been able to marshall the necessary computer resources and technical expertise to do work of this type. Among problems faced by researchers are programming non-standard likelihood functions and performing the estimation runs. Complex likelihood surfaces, containing extensive regions which are flat, and multiple local optima, are not unusual in this work. Consequently, careful empirical implementation would be greatly abetted by facilties for high speed computing, affording real time interactive solution and examination of the solutions which satisfy pre-specified convergence criteria.

Simulation analysis

Increasing computational resources are likely to make it less costly and hence more common to use simulation models in economic investigations. This is likely to result in a period of disarray as numbers of researchers seize the opportunity to expand this field of inquiry and create many new models. A period of consolidation in which a common set of conventions for reporting the structure of models and results is likely to follow and would be abetted by rapid reporting of research progress through communication networks. It is, however, unlikely that such conventions can be pre-specified. Nonetheless, analytical methods for determining the relations among simulation structures will be important to the eventual consolidation of method in this field of inquiry.

One field that is likely to expand most rapidly in relation to the rest of the discipline of economics is the analysis of adaptive nonlinear models of individual decision-making, industry conduct, and the dynamic performance of open and closed economies. The existence of multiple equilibria may give rise to substantial indeterminacy, however, so that reformulation and analysis of the stochastic versions of such models are likely to prove an attractive research strategy. Studying the properties of such models requires substantial computational resources to permit interactive running of large numbers of trials and respecification of model features, such as parameter values. Computer support for sophisticated graphical display of the dynamic behaviour of these models, including derived measures of their performance characteristics, will be important in facilitating analysis of simulation results and identifying new questions for study by analytical as well as numerical methods.

Optimisation and normative applications

This is another area where economists can expect to receive considerable stimulus from access to improved computational capabilities. At present there is a perception that computational considerations significantly constrain the implementation of theoretical insights into the structure of optimisation processes. For example, decision-making under uncertainty applied to problems of stochastic control rapidly becomes infeasible for purposes of real-time implemention, unless the structure of the stochastic process is extremely simplified. Reduced computational costs and greater speed will expand the range of real time applications of optimisation methods; for example, for route scheduling, repair scheduling, and queue management. That will, in turn, enrich the array of applied problems that can be addressed by tool-builders and the data structures available for analysis.

More brute force computing may also shift the focus of some research (e.g., dynamic linear programming models) away from attention to solution feasibility, and towards more realistic levels of complexity. A new form of optimisation analysis likely to flourish in a computer-rich environment is the design of organisations and institutions. Analytical methods have comparatively little power to handle realistic problems of this sort, because the number of links, or connections, between decision-nodes becomes quite large, even in the case of simple organisational structures. Numerical methods consequently would open the way to developing greater analytical insights into organisational performance, as well as advance the study of organisational design. Many of the points we make regarding the teaching of pure theory might be taken to apply also to instruction in principles of decision science, including Bayesian analysis, stochastic control, dynamic programming, and similar subjects.

Experimental economics

Both the development of networked personal computers and increases in computational power are likely to have significant impact on the conduct of experimental economics. Networked personal computers will allow the conduct of experiments with significant numbers of human participants aimed at improving understanding of economic behaviour. One simple advantage to be derived via networking is an increase in the access that experimentalists have to human subjects, at different institutions, who are not already acquainted with their experiments. It has been found that the prior exposure of subjects to participation in similar experiments can materially alter their performance in new experiments; expanding the pool of potential subjects via networking would permit systematic investigations of such phenomena.

Since much real-world economic behaviour is now mediated through computer networks (e.g., the use of networks by traders in financial instruments), experimentation with human behaviour under conditions that emulate, in a controlled fashion, elements of such open-loop adaptive interactions is likely to provide new understanding about economic decision-making processes, human information processing capabilities, and effective interfaces for presenting economic data. The conduct of experimental economics is also likely to be influenced by increases in computational power and changes in computer architecture, since these increase the feasibility of simulating the behaviour of large numbers of interacting agents.

Mathematical theory

In the short run, the direct effects upon the conduct of research in mathematical economics are most likely to be those confined to improved communication of symbolic material, allowing more productive collaboration among small groups of theorists. At the same time, it should be recognised that collaborative research in economic theory in some important respects resembles a body contact sport; currently manifested preferences among theorists for face-to-face interactions with fellow theorists are unlikely to be quickly displaced by communication advances.

Over a somewhat longer run, access to computational facilities will probably increase the use made by economic theorists of symbolic processing programmes for analytical operations involving differentiation, integration and matrix algebra. The capacity to perform rapidly numerical evaluations of complex functions and equation systems, and to display the results graphically, may also be used in a systematic way by economists seeking insights into the mathematical properties of formal models, as a step on the road to obtaining lemmas and theorems by analytical methods. Such developments are already taking place in computational mathematics.

ECONOMIC ISSUES RELEVANT TO THE ROLE OF INFORMATION TECHNOLOGY IN SCIENCE

Fixed cost problems

The use of information technology in economics is strongly influenced by the mechanisms for assigning the costs of not only hardware, but the complementary service activities that are required. If these costs cannot be assigned to groups using the information systems, or to other, external sources of support, hardware will remain under-utilised and the improvements taking place in its performance-cost characteristics will not exert as much impact as they should upon the investigation of economic phenomena.

Like the computer hardware which they complement, these services are characterised by cost structures in which the fixed elements are large in comparison with the variable costs of utilising them. Several implications follow from this.

(a) The fixed costs may be so large that several user-groups have to co-operate in funding the service, or find some outside source to underwrite its provision.

(b) Once established, however, these complementary services significantly reduce the costs of extending greater computational resources throughout the discipline.

(c) Providing a good base of complementary service at the outset can make subsequent updating and upgrading easier, in step with improvements in hardware capabilities.

Examples of important complementary information technology services for research and teaching in academic economics include: (i) database construction and linkage procedures for database integation, (ii) sustained support for cadres of information technician/programmers who have acquired specialised knowledge of the computational research requirements in the various branches of economics, and (iii) design and distribution of interactive instructional tools (programmes and databases) for more effectively training economists, especially those who will make full use of computer-rich environments.

There are problems in pricing services of these complementary fixed-cost facilities, and these difficulties have been most evident in responses to the availability of either subsidised supercomputer facilities or medium and small scale computers. In short, increasing numbers of computer users in universities are choosing to bypass central facilities where complementary services were developed. In terms of marginal cost efficiency for central processor rental, this may be an advance. The loss of the accumulated expertise and skills developed in university computer centres is, however, significant. The complementary services provided by these personnel must now be developed *de novo* by generations of graduate students and faculty responsible for the operation of computer resources within university departments. It is very difficult to measure the aggregate social costs of these developments. Clearly, there are substantial duplications and missed opportunities.

Nor is the unwillingness of users to pay individually their portion of the overhead costs, as demonstrated by their willingness to bypass the central facilities, sufficient evidence to conclude that benefits exceed costs. Effective methods for price discrimination according to user value are simply unavailable, and, as a result, the optimal amount of complementary service cannot be provided using average pricing rules (such as past practices of inflating central processor charges) to cover the costs of these services. In addition, the entire area of complementary information provision is replete with public goods problems.

Public versus private goods issues

Public goods are goods and services which cannot effectively be provided to some users without making them accessible to others. Information itself, being readily transmitted, tends to slip quickly into the public domain unless special efforts are made which render it private property. Information, in the sense we use the term here, must be intelligible to the recipients; undocumented computer code or datasets, therefore, would not qualify as information in that sense. Producers of information goods which do pass into the public domain lose control of both the information content of their work and the ability to extract a financial return from their creations, even though such returns may be needed to sustain their efforts. Scientific communities, like other social groups, have used two mechanisms to support the providers of public information goods. One is the assignment of private property rights in the goods themselves; the other is the direct support (in financial and/or other forms, such as public recognition and praise) of the individuals by the community of users. Which of the two mechanisms will be most appropriate in any specific situation is seldom evident *ex ante.*

Assignment of private property rights allows the providers to commercialise the service and thereby obtain financial compensation for costs of its development, maintenance and future enhancements. But the extension of the service to additional users is inhibited by the imposition of charges that, typically, far exceed the actual incremental costs involved. While direct support of the provider allows additional users to access the service at minimal incremental costs, this support should be structured in such a way as to induce continuing enhancements in response to the user-community's evolving needs.

In such social sciences as economics, important sources of information arise from the data-collecting activities of public sector agencies. In some cases, these organisations' principal mission is the publication of such information and the direct distribution of data sets. Advances in information technology can reduce the costs of having such agencies respond to the growing information analysis capabilities of the economics research community. Data gathered by public agencies with the benefit of statutory authority is, in effect, a natural monopoly.[13] Recent decisions regarding the management of government resources have featured an increasing reliance on private parties to publish information collected by public agencies. Public cost savings of such choices may be illusory since the government will bear the costs of fees for the use of data in government supported research. Further, extensive privatisation may adversely affect the long-run ability of public data-gathering organisations to maintain the professional infrastructure necessary to take full advantage of progress in information technologies.

Databases created by academic researchers working with public funding are typically expected to enter the public domain, but too often the data remains incompletely documented and therefore quasi-private. The same problem often occurs when economics researchers develop algorithms for instructional purposes, optimisation routines, or simulation structures. Information technology advances are making it more desirable for researchers (and teachers) to share data and algorithms. Although many economic researchers would benefit greatly from such information pooling activities, few will have the expertise and resources to design, implement, and manage such co-operative arrangements. Funding to support such activities when they arise spontaneously within particular economic research communities constitutes a partial solution to these problems. Deliberate programmes of disseminating technical expertise and successful management models also are likely to be required for realisation of the benefits of wider dataset and algorithm pooling.

Network externalities and standardisation

In the short run, there always will be tradeoffs between the advantages, on the one hand, of using specialised hardware and software to solve the problems encountered by particular research groups in economics, and the benefits, on the other hand, of developing a common set of research tools for the discipline. These latter benefits are network externalities, because, like the advantages derived from belonging to a communications network of one's collegues (e.g., the benefits of sharing collective experience in conceptualisation and solution of problems), the gains that individual researchers (and teams) derive from membership depend upon the direct relevance of the knowledge and experience of others who use the same tools.

Falling costs of the technical engineering aspects of network formation will elicit greater interest and effort to achieve the benefits of standardisation. Currently it appears unlikely that a single, uniform standard can or should be set for the construction of economics information networks. Hence, a priority for external funding support, and collective agreements among researchers, should be the design and implementation of gateways and other types of translation devices to overcome the barriers posed by existing incompatibilities. The near term goal should be to make a wider array of datasets and computational algorithms available for easy use by economics researchers working in diverse and dispersed computing environments.

Achieving the 'optimum gap'

The use of computers in economics has been and will continue to be a process of catching up and falling behind the shifting frontier of information technology. During the 1960s and 1970s, some members of the profession were at the forefront of social science use of large computers for batch-procesing. More recently, however, there has been only modest progress in the adoption of workstations and other advanced computer equipment, including peripherals. This situation is setting the stage for what we expect will be a catch up effort, involving the upgrading of a major portion of the hardware inventory currently in the hands of the profession, and the design of applications software and user interfaces tailored for economists. It follows that minimal specifcations for designing economic workstations and software tools should be adopted quickly. It is less urgent to close completely the existing gap between prevailing average practice and the opportunities defined by frontier technologies. Developing the ideal workbench for computer-using economists should be seen as an incremental and cumulative process.

NOTES AND REFERENCES

1. Abraham Peled, 'The next computer revolution', *Scientific American*, 257, 4, October 1987, p. 57.
2. See Herbert A. Simon, 'The steam engine and the computer: what makes technology revolutionary', *EDUCOM Bulletin*, 22, 1, 1986, pp. 2-5.
3. *cf.* for example, Geoffrey C. Fox and Paul C. Messina, 'Advanced computer architectures', *Scientific American*, 257, 4, October 1987, pp. 44-52.
4. See for example, James D. Foley, 'Interfaces for advanced computing', *Scientific American*, 257, 4, October 1987, pp. 127-35; and James D. Foley and Andries van Dam, *Fundamentals of Interactive Computer Graphics*, Addison-Wesley, Reading, Massachusetts, 1982. On the 'efficiency' of visual presentation of data, see Edward R. Tufte, *The Visual Display of Quantitative Information*, Graphics Press, Cheshire, Connecticut, 1983.
5. See for example, Michael M. Roberts, 'The need for a national higher education computer network', *EDUCOM Bulletin*, 22, 1, 1986, pp. 9-10. The majority of computer users among university researchers today who do have access to networks can transmit data at approximately 10,000 bits per second. By way of contrast, it is projected that in some areas, such as high energy particle physics research or geophysics research using remote sensing, data transmission rates in the range of hundreds of millions of bps will be required.
6. A somewhat more balanced view is given in Simon, *op. cit.*: "It seems equally obvious to me that computers will not revolutionize education until there are massive changes in the organizational and administrative structure of the educational system as well."
7. GAUSS is a general purpose language for stating and solving linear algebra problems. It was developed commercially by Edlefsen for the IBM PC.

8. These deficiencies are directly related to the sequential storage of data on the tape medium. Mass storage systems that can access any portion of their data with little overhead cost permit very different software and data organisation methods. Currently, the high costs of such systems, including large capacity magnetic discs, limit improvements in specialised development of these media for economic research.
9. Many reasons underlie this proliferation and we do not believe a basis currently exists for judging whether the benefits of reducing the number of standards outweigh the private and social costs of such a reduction.
10. See Drucilla Ekwurzel and Bernard Saffran, 'Online information retrieval for economists — the economic literature index', *Journal of Economic Literature*, 23, December 1985, pp. 1728-63.
11. This is a speculative statement since there has been no organised collection of data on patterns of computer use within the economics profession. The statisticians are better informed; see W.F. Eddy, *Computers in Statistical Research: Report of a Workshop*, Institute for Mathematical Statistics, 1986.
12. Our comments on supercomputer use, in this and the next paragraph, owe much to private communication with John Rust of the University of Wisconsin.
13. More generally, many data collection efforts are natural monopolies since, in effect, a single good is being produced with no substitutes. Production of the same good by multiple parties merely guarantees that, since users will pay for only one of the item, the price will be higher. In some cases, however, opportunities for product differentiation may sustain several data gathering efforts.