The Global Research Village:

How Information and Communication Technologies Affect the Science System

FOREWORD

This study was undertaken as a contribution to OECD's *Science, Technology and Industry Outlook 1998,* published in July 1998. It is also intended as a background report to the international conference "Global Research Village II: Maximising the Benefits of Information Technology for Science" which will be held in Sintra, Portugal, on 17-18 September 1998. The report was discussed by the Group on the Science System and by the Committee for Scientific and Technological Policy. It is declassified on the responsibility of the Secretary-General of the OECD.

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INTRODUCTION

As information and communication technologies (ICT) have become essential tools for science, governments need to understand their role in the science system in order to develop appropriate science policies. This report looks at how the use of ICT has influenced science in five areas and the implications for the science system. This report addresses both the widespread use and growing capabilities of computers and the linkages they make possible in the areas of communication among scientists, access to scientific information, scientific instruments, electronic publishing in science, and science education and training. It discusses the potential of experimental applications as well as more mature ones. Overall effects on the science system will depend on how use of ICT evolves in terms of the specific characteristics of each field of science.

While this report seeks to describe the impact of ICT on the science system, it does not seek to provide detailed policy advice to OECD governments. It draws on the international conference on the Global Research Village held in Denmark in 1996 (OECD, 1996*a*), which was organised jointly by the Danish Ministry for Research and Information Technology and the OECD and examined the implications of ICT for world science and the science policy implications. At the 1996 Conference, the OECD was asked to prepare a report on quantitative and qualitative trends in the development of information technology (IT) infrastructure and the impact on the science system. A follow-up conference will be held in Portugal in September 1998. This report is intended as a contribution to the ongoing discussion.

TECHNOLOGIES UNDERLYING THE CHANGING SCIENCE SYSTEM

A wide range of developments in ICT, covering hardware, software and networking technologies, underlie ongoing changes in the science system. They include significant improvements in computing power and storage capacity and better networking and search technologies. Such developments have allowed scientists to make rapidly increasing use of Internet and ICT tools. However, there are concerns that the Internet is becoming inadequate for certain scientific purposes. Several governments and universities have recently taken initiatives to develop faster networking technologies to meet the needs of science.

ICT-related changes underlying the evolving science system have three main sources: technological change in the ICT industry (mostly driven by needs unrelated to science); scientists' efforts to develop their own tools; and government programmes specifically designed to foster developments in ICT and apply them to scientific needs, e.g. the US High-Performance Computing and Communications (HPCC) programme.

Main technological developments

Conventional computers solve problems by performing programme instructions one at a time in a strict sequence. Electronics manufacturers have provided users with increasing computing power at decreasing cost for many years, essentially by squeezing a greater number of ever smaller transistors and other components onto chips, thanks to continuous advances in lithographic techniques (*Science*, 1996*a*). They have also found alternative ways of getting more processing power from computers, for example by using reduced instruction set computer chips (RISC) or special-purpose chips to perform designated tasks faster than a general-purpose processor (*New Scientist*, 1996).

The supercomputers used for research generally have custom-made, expensive processors which provide better performance. Up to the late 1980s, vector supercomputers were the most powerful computers. They were the only option for researchers with truly large problems, who used them to perform calculations simultaneously on long strings of numbers, i.e. vectors (Pool, 1995). The research potential of parallel computers has been demonstrated more recently. These multiprocessor machines break major programming tasks down into smaller problems which they solve simultaneously. This method remains quite difficult, however, and cannot be used to solve all problems.

Cheaper off-the-shelf components and software have generally contributed to increased use of information technology. A new generation of extremely powerful off-the-shelf commodity chips is also at the heart of an emerging standard parallel architecture (Matthews, 1996). These chips, which can function equally well alone and in concert (a requirement of parallel architectures), are perfect for low-cost parallel computers. Even working on their own, these chips attain speeds of up to 200, 300 or 600 million flops (floating point operations per second). Many off-the shelf components are also available for certain scientific instruments. Plug-in circuit cards allow new features to be added to personal computers (PCs) without much adjustment. Complex software, increasingly available for Windows '95, contributes to the use of technology by non-specialists at lower cost.

Various storage and information delivery technologies continue to co-exist. Traditional storage systems such as the CD-ROM (compact disk – read only memory) are still being used by publishers, particularly where current Internet access limitations would result in very slow access, e.g. when the package contains great quantities of data. New products that combine CD-ROM data with information on the World Wide Web (WWW) or online services give publishers the opportunity to deliver huge amounts of data on CD-ROM and then use the Internet to offer updates or transactions. The Digital Video Disk (DVD) can store seven times as much data as a CD-ROM and deliver a moving picture quality that outshines laser disks. It is particularly useful for multimedia publishing and will enable educational software, in particular, to incorporate more video. The mass-storage industry continues to develop technologies that can handle increasing quantities of data, thereby satisfying the needs of scientists carrying out large-scale simulations, experiments and observation projects.

Electronic networks constitute the infrastructure which provides scientists with new means of communication that give them access to data, information and software in cyberspace, allow them to share and control remote instruments, and that link distant learners to virtual classrooms and campuses. Scientists currently have access to various types of networks, including campus, national and international research networks, which are increasingly interconnected. For instance, in early 1997, the French RENATER network connected 1 200 laboratory networks to 300 campus networks and to 20 regional networks. A national interconnection network links the regional networks to Europe and the rest of the world.

The main network, the Internet, began in the late 1960s as a network providing a limited number of researchers with shared interactive communication among computing systems at different locations. It has become a network of networks that can be accessed by anyone with a computer and a modem. Since 1991, the WWW has been a very powerful and convenient way to navigate through the world's collection of networked computers. Through hypertext links, it connects information on the network to other sites. Special graphical interfaces known as Web browsers, such as Netscape Navigator, Microsoft Internet Explorer and Netcom NetCruiser, allow users to read hypertext.

Rapid advances in computing power and the explosive growth in network connectivity have generally enhanced the use of distributed systems. The potential of networking several computers to perform tasks similar to those performed by supercomputers is also being tested. In addition, systems capable of co-ordinating different types of computers, including traditional supercomputers, parallel computers, workstations and PCs, are emerging (*Economist*, 1996*a*). Hardware and software for using a network of workstations as a distributed computing system on a building-wide scale are being developed (National Science and Technology Council, 1995).

The development and use of digital data and information rely on a broad range of technologies. Non-digital data requires data acquisition technology, such as optical character recognition, while direct use of data collections requires database management systems. Text analysis and information retrieval techniques (including text, index and image compression, indexing, routing, filtering and visualisation techniques) sometimes enhanced by artificial intelligence, are needed to index, search, retrieve and present information. Furthermore, data mining technologies can be used to sift large amounts of data for useful patterns.

Methods for handling information help users more effectively search, learn about, organise and use data and information. Search tools, for example, can go through millions of articles from current and back issues of electronic journals in almost any discipline. They help users navigate online services and save time. Search engines such as Altavista, Excite, Infoseek, Lycos, Web

Crawler and Yahoo constantly burrow through and catalogue Internet documents. There are also limited area search engines that index only Internet resources relevant to a specific subject and thus raise the speed and efficiency of searches. Internet search technology is still, however, in its infancy.

Many ICT applications used by scientists, such as access to databases, information services and e-mail, were originally based on narrowband technologies;[1] broadband technologies were only needed for video applications. However, the growth of the Internet and new interactive – often multimedia – applications has led to a rapidly growing demand for high bandwidth technology, which may also be needed to process large amounts of data.

Some indications of ICT use

While there is little systematic analysis of ICT use rates, various studies include estimates that broadly indicate how usage varies. It varies significantly by field of science and by region. For example, mathematicians and physicists make significant use of e-mail, with respectively 34 and 24 per cent reporting e-mail addresses as early as 1991, when experimental biologists had yet to adopt this technology in large numbers. Ornithologists in North America still had low rates of e-mail use by 1993 (Walsh, 1997; Table 1).

Table 1. E-mail use across scientific disciplines

Discipline	Region	Year	E-mail use (in per cent)
Experimental biology	United States	1991	9
Mathematics	United States	1991	34
Physics	United States	1991	24
All fields	Australia United States United Kingdom	1992	39
Ornithology	United States	1993	15
Aerospace	United States	1993	74
Engineering/chemistry	United States	1994	82
Sociology	United States	1994	75
Political science	United States	1994	67
Philosophy	United States	1994	55

Source: Walsh, 1997.

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[1] Bandwidth measures the number of bits than can be transmitted across a particular channel per second.

However, by then, the technology was beginning to diffuse rapidly. Almost 74 per cent of aerospace engineers in industry, government and academia used a network by 1993, although only 50 per cent had access to external networks such as the Internet. Use among academics (rather than industry or government employees) and scientists (rather than engineers or managers) was nearly universal (Table 2). Analysis, database work and word-processing were the most common uses in 1993. There were still significant differences in usage by field. Internet use by chemists, sociologists, political scientists and philosophers at Jesuit colleges and universities in the United States varied from 82 per cent for chemists to 55 per cent for philosophers (Table 1 above).

By 1993, 30 per cent of the value of the US stock of scientific instruments consisted of computers and data handling instruments. Furthermore, 29 per cent of all chairs of academic science and engineering departments surveyed ranked some type of computer as their highest priority in terms of instruments needed (National Science Foundation, 1996).

In France, more than half of all scientists and university professors used a computer by 1993, a significant increase from 1991 (Table 2). Use was higher for researchers and teachers in higher education. In Japan, 76 per cent of all researchers and engineers used the Internet and electronic mail in 1993, primarily for communication with other researchers, conferencing, and retrieval of information, data and software (Japan Science and Technology Agency, 1996). Computer use was even higher in Canada, with almost all science and engineering workers using computers in the workplace by 1994. The rapid expansion of the Internet since these surveys suggests that e-mail and Internet use by scientists has expanded sharply. In many scientific disciplines, Internet and e-mail use may now be almost universal.

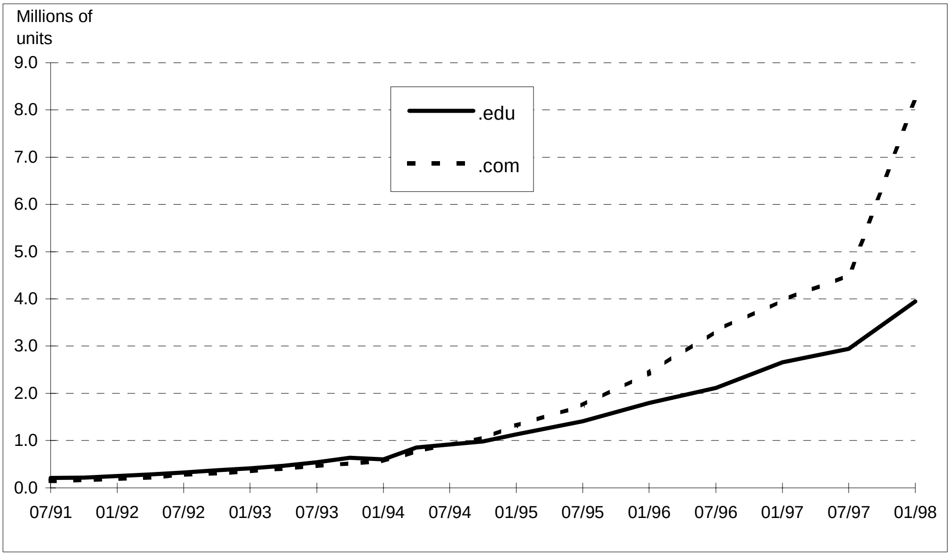
The Internet itself continues to expand rapidly. While commercial and personal uses now grow faster than research uses, the number of host names at US universities (*.edu) also continues to grow rapidly (Figure 1). Unfortunately, these data say little about Internet diffusion to universities outside the United States. However, trends in Internet use in the workplace across the OECD area suggest a rapid increase, which may suggest that Internet use by scientists is also rapidly expanding.

Table 2. Computer network use across scientific disciplines

Occupation	Total	Total	Analysis	Communi-cations	Data-base	E-mail	Graphics	Program-ming	Spread-sheet	Word-processing
	United States									
	1989	1993								
Mathematical and computer scientists	92.8	95.7	63.2	57.8	60.9	57.5	43.0	58.4	47.6	65.9
Natural scientists	73.0	85.0	51.2	27.7	42.0	28.2	25.4	12.7	30.1	54.8
Engineers	81.6	84.8	39.4	32.9	35.6	31.0	34.3	24.8	36.3	48.9
Engineering and science technicians	62.4	66.4	25.6	17.3	24.4	15.2	18.8	13.0	16.0	24.2
All occupations	43.2	40.7	11.0	13.6	14.8	9.2	7.3	5.6	10.2	19.1
	France									
	1991	1993								
Professors and scientists	47.0	55.5								
Higher education lecturers and researchers	71.0									
All occupations	34.0	39.3								
	Canada									
	1989	1994								
Science and engineering workers	77.6	95.0								
All occupations	33.8	48.0								

Source: US Department of Commerce, 1989 and 1993; *Ministère du Travail, de l' Emploi, et de la Formation Professionelle*, 1993 and 1994; Statistics Canada, 1994.

Figure 1. Number of Internet hosts worldwide [1]



1. The survey method was changed in January 1998. Earlier data are not strictly comparable.

Source: Network Wizards, April 1998.

Towards faster computer and communications technologies

The growing accessibility of the Internet has raised some problems for science users. Quality has sometimes been affected and congestion has increased. As scientists may require high-speed access and considerable bandwidth to transmit large volumes of data, these problems have become quite serious for some science applications. In the short run, congestion can be eased by a mix of technical solutions and pricing schemes (OECD, 1997*a*). In the longer run, further research may be required to solve the congestion problem and improve Internet access for science users.

Some efforts are already under way to develop a faster network. Three US initiatives will provide participating universities with new network services and online connections about 100 times faster than the present Internet's. The Very High Speed Network Backbone Service (VBNS) of the National Science Foundation (NSF) is the cornerstone of the US government's effort to upgrade the existing Internet's backbones, the primary hubs of data transmission. Internet2 is a co-operative effort by universities to create a faster and better computer network among their institutions and will add to the capabilities of the VBNS by developing software for the new network and by upgrading campus networks. Next Generation Internet (NGI) is a US government proposal to support efforts for both advanced networking and applications research.

In May 1997, there was a significant breakthrough in European research networking, with the launch by the European Commission of TEN-34 (the trans-European network). This project seeks to strengthen electronic gateways between national research networks in EU Member States with a high-speed infrastructure. It is supported by the European Union's Telematics Applications and European Strategic Programme for Research and Development in Information Technologies (ESPRIT) programmes. The TEN-34 network intends to upgrade the 2 megabit/s international links among national research networks to 34 megabit/s, the capacity of most national networks. At the same time, many national research networks are being upgraded through high-speed research network initiatives. While the initial target for all national networks in Europe is 34 megabit/s, some already aim for 155 megabit/s, e.g. Germany's *Breitband-Wissenschaftsnetz* and SuperJanet in the United Kingdom. There are similar initiatives in OECD countries outside Europe, such as CA*netII in Canada and NACSIS in Japan.

In several OECD countries, HPCC programmes develop technologies and applications and constitute the principal force behind efforts in these areas to meet the challenges of science and engineering. The US HPCC programme started in the early 1990s as the cornerstone of a planning process involving government, industry, and academia. It focuses on the following areas (National Science and Technology Council, 1995):

◊ world-scale information infrastructure technologies that create advanced application building blocks and widely accessible information services;

◊ high-performance and scaleable systems to seamlessly support high-performance and low-end applications;

◊ high-confidence systems that provide availability, reliability, integrity, confidentiality, and privacy;

◊ virtual environments and simulations, which may transform scientific experimentation and industrial practice and play an increasingly important role in education and training;

- user-centred interfaces and tools to provide easier development, navigation, “mining”, and general use of information resources;

- human resources and education, to educate the next generation of industrial and academic leaders in information science and technology and to establish a foundation for new learning technologies.

These research and development (R&D) efforts have already achieved much and will continue to do so over the next decades. For example, while computation speeds of 250 billion flops have already been achieved, the next performance goal for large scientific and engineering problems is a trillion operations per second (teraflops). For software, substantial investments in a broad range of advanced technologies are leading to developments in systems software, programming languages and compilers, application tools, computational techniques, software performance measurement, software sharing, and visualisation. A combination of gigabit speed (billions of bits per second) networking technology and computational science have already demonstrated that massive scientific calculations can be executed across parallel processing systems located more than 1 000 miles apart. These speeds represent a thousand-fold improvement over the fastest networks in existence in 1991. The information infrastructure is also being extended into the mobile environment with wireless technologies (National Science and Technology Council, 1995).

COMMUNICATION AMONG SCIENTISTS

Researchers have used ICT-based communications – or the Internet – mostly as a natural extension of other communications tools. Apart from greatly enhancing the quantity, quality and speed of communication among scientists, ICT use has also had various effects on the organisation of work in science. Collaboration patterns have changed, the science base has widened as more scientists are able to participate, and scientific hierarchies have sometimes been affected. However, for the most part, scientific work has not been revolutionised (Walsh, 1997).

The growth of collaborative arrangements

Improved communication due to ICT may contribute to an increase in the size of professional networks. For example, among oceanographers, intensive e-mail users report larger professional networks. In biology, chemistry, mathematics and physics, collaborations have also increased in size, apparently in association with the use of ICT. In experimental particle physics, the Internet has facilitated experiments in which a large number of people collaborate effectively.

A more significant change in the organisation of science has been the increase in remote collaboration, particularly at international level (Table 3). Computer networks have reduced the need for co-workers to be at a single location. Consequently, a new form of scientific work has emerged, the "extended research group". This is typically a large, unified, cohesive, co-operative research group that is geographically dispersed, yet co-ordinated as if it were at one location and under the guidance of a single director. It provides access to colleagues and to equipment, software and databases that are traditionally part of laboratory organisation, without regard to geography. These "collaboratories" rely heavily on ICT for co-ordinating their work (Box 1).

Table 3. Publications with international collaborators
In per cent of total publications

Field	United States			France			Netherlands
	1981	1986	1991	1982	1990	1995	1993/94
Mathematics	8.8	13.4	17.1	45.5	50.9	40.0	17.9
Physics	8.5	10.5	16.1	36.0	37.3	43.3	28.9
- Astronomy & astrophysics[1]							45.7
Biology	4.8	6.5	10.0				17.7
- Basic				19.2	23.2	18.1	
- Applied & ecology				19.7	25.8	24.4	
Medical research				8.6	11.0	10.9	11.7-19.3
Chemistry	4.7	6.1	9.1	22.3	27.3	20.1	14.5
Earth sciences				32.6	34.1	39.7	18.8
Engineering				25.1	28.0	30.6	7.2-18.9
All fields	8.8	7.5	11.0	19.9	22.9	21.6	17.0

1. Estimate influenced by frequent collaborative use of research and observation facilities in other countries.

Source: National Science Foundation, 1993; *Observatoire des Sciences et des Techniques*, 1997.

One example of ICT-based international collaboration is a collaborative research project in atmospheric physics consisting of scientists at five Canadian sites, two US sites and two sites in another country. All members of the group have Internet addresses and most reported sending several e-mail messages a week to other members. E-mail was preferred to the telephone because scientists who travel may be hard to reach by phone, but can be contacted at their virtual address, because written messages allow time for formulating answers before responding, and because colleagues whose native language is not English preferred written communication.

E-mail over the Internet enables researchers to overcome many barriers to communication due to geographic distance, such as time, costs and language. This seems especially important to researchers in Australia and New Zealand who make much use of the Internet to improve their access to research communities in Europe and North America. E-mail is considered next best to face-to-face interaction and a good medium for facilitating collaboration among scientists. However, many scientists emphasize the importance of establishing common understanding of the research problem through intensive, face-to-face interaction before engaging in computer-mediated collaboration.

Box 1. Examples of collaboratories

Atmospheric and space science

Upper Atmospheric Research Collaboratory (UARC): ground-based observation of ionospheric phenomena using the Sondrestrom Upper Atmospheric Research Facility, at: http://www.sils.umich.edu/UARC/HomePage.html

Collaborative Visualization Project (CoVis): scientific visualisation for K-12 students studying the Earth's atmosphere, at: http://www.covis.nwu.edu

Biology

Worm Community System: data about the *C. Elegans* genome, at: http://csl.ncsa.uiuc.edu/CSLWWW/WCS.html

BioMOO: online discussions about biology, at: http://bioinformatics.weizmann.ac.il:70/0/biomoo

Chemistry

Collaboratory for Environmental and Molecular Science: remote access to nuclear magnetic resonance (NMR) spectrometers, at: http://www.emsl.pnl.gov:2080/docs/collab/CollabHome.html

Medicine

Medical Collaboratory: synchronous and asynchronous remote consultation over radiographs and ultrasound videos, at: http://www.sils.umich.edu/~weymouth/Medical-Collab/index.html

Distributed Health Care Imaging: storage and retrieval of coronary angiograms from Kaiser Permanente's Cardiac Catheterization Laboratory in San Francisco to six Bay Area Kaiser Permanente hospitals, at: http://george.lbl.gov:80/Kaiser/LBL.CRADA.NII.html

InterMED Triad Collaboratory: dictionaries for disease description, at:
http://www.cpmc.columbia.edu/intermed_proj.html,
http://camis.stanford.edu/projects/intermed-web
http://dsg.harvard.edu/public/intermed/InterMed_Collab.html

Teledermatology Program: remote diagnosis of skin lesions in rural Oregon and Kansas, at: gopher://gopher.hpcc.gov/00/grants.contracts/awards/hpcc.health.care.awards.txt

Telemanagement of Neuro-Imaging: remote consultation of computer tomography (CT) and magnetic resonance imaging (MRI) of the brain and spinal cord, at: gopher://gopher.hpcc.gov/00/grants.contracts/awards/hpcc.health.care.awards.txt

Physics

LabSpace: remote access to electron microscopy tools (Argonne) and to an object-oriented programming project at CERN, at: http://www-itg.lbl.gov/DCEEpage/DCEE_Overview.html

Remote Experimental Environment: real-time participation in experiments conducted at the D-IIID tokamak at General Atomics, at: http://www.nersc.gov/Projects/REE/

Beamline 7 Collaboratory: remote access to the Advanced Light Source at Lawrence Berkeley Laboratory to obtain spatially resolved chemical information, at: http://www-itg.lbl.gov/~deba/ALS.DCEE/project.html

Source: Finholt and Olson, 1997.

With tighter links among geographically dispersed scientists, the international community of scholars is becoming denser. For a given research topic, ICT allows the creation of more complex work groups with more fluid structures. Virtual research teams can be formed and link a variety of scientists, each of whom contributes his or her skills to the project. Projects take advantage of networks to obtain access to the precise skills needed, and researchers gain access to projects that demand their skills. As a result, the research topic, rather than geographical proximity, determines collaboration decisions.

For the most part, collaborative arrangements have not yet been revolutionised. ICT-based communication has been adopted in a way that reproduces local social relations and research practices. Thus, while the social structure has changed somewhat owing to ICT use, the reorganisation seems largely limited to changing (expanding) participation, with only minor changes in the content of participation. The existing work organisation is reproduced over a wider geographic area and ICT-based communication serves as the link formerly served by face-to-face communication in local collaborations.

There is some debate over whether the variety of new work arrangements made possible by computer networks constitutes a net benefit to those affected. While ICT may facilitate cross-disciplinary collaboration, it may also lead to the fragmentation of research. This might lead to “balkanisation” of science, with researchers using limited communication time to interact only with those in their speciality (Van Alstyne and Brynjolfsson, 1996). While this might be beneficial and achieve economies of scale in certain scientific areas, it might also reduce cross-fertilisation of ideas among disciplines. However, the overall impact of these new forms of organisation on scientific outcomes is not yet clear and whether balkanisation is indeed an issue remains to be seen.

Increased frequency of communication

There is evidence that ICT-based communication contributes to an overall increase in the amount of communication during a research project (Walsh and Bayma, 1996*a*). This may be particularly important in the context of long-term experiments, shift work, and different time zones. Increased communication may increase attachment to the research group, job satisfaction, and commitment, by alleviating feelings of isolation due to irregular hours but also to concentration on a highly specialised endeavour that may not interest local colleagues.

In high energy physics, for example, ICT has allowed researchers to remain involved in long-term experiments even when they are not physically present, thanks to distribution lists, bulletin boards and e-mail and the electronic distribution of pre-prints and other crucial (informal) information. This method of communication allows all members of the collaboration to stay “in the loop”. However, the combination of technologies used and the ways they are used affect the outcome.

By passing research work back and forth, collaborators in different shifts and time zones can have a project that never sleeps. Chemists and biologists, with their loosely coupled and lengthy experiments, also find that the frequent communication permitted by ICT means that the various elements of the research project tend to remain well co-ordinated (Walsh, 1997).

On the other hand, there is evidence that e-mail communication does away with much of the socialising that generally accompanies face-to-face or even phone conversations, thereby resulting in less collegiality and a more alienating work environment. Some scientists view the increased focus of communications on business matters as an advantage of e-mail (reduced time costs) and use it for both remote and local communications (Walsh and Bayma, 1996*b*). Indeed, ICT-based communication may simultaneously integrate and isolate individuals. The result could be a work environment, or community, where the individual is linked to more colleagues but the links are more instrumental or less satisfying.

Effects on status and hierarchy

ICT-based communication can lead to greater decentralisation or less difference in status, because interaction over the Internet provides fewer clues to status, rank, and gender than face-to-face or even mail or phone communication (Walsh, 1997). Group decisions are consequently less influenced by the status of those proposing particular solutions.

Moreover, by its informal nature, e-mail reduces lower-level researchers’ reticence about contacting higher-level ones. It may facilitate the creation of new ties among remote collaborators and give scientists with lower status easier access to their more eminent colleagues with whom they may eventually publish results jointly. On the other hand, it may create even greater disparity in publication rates as top scientists become attached to a greater number of research projects via e-mail contacts. E-mail communication may also allow scientists who previously lacked the access necessary to keep up to date to become active participants and possibly core scientists. So far, no significant correlation has been found between age or institutional prestige and ICT use as a predictor of productivity (Cohen, 1995).

To the extent that status distinctions remain, however, individuals with high status will continue to exert more influence on group decisions. As the technology has been developed, more status cues are being inserted into the communication. E-mail addresses, for example, are evolving from a nondescript assembly of letters and numbers to a combination of family name, institution or company, and country of registration. Also, other mechanisms for introducing the status-reinforcing procedures of earlier communication technologies (mail, telephone) are beginning to appear. For example, high-level scientists increasingly use gatekeepers to screen their e-mail just as they screen letters and calls. Similarly, if ICT violates existing work norms or status distinctions, it may not be used.

New technology can also change part of the basis for existing status distinctions. ICT can, for example, enhance the status of younger colleagues who are more familiar with the latest technology. It may also provide peripheral scientists with wider access to crucial resources – such as computing facilities, software or databases – which have traditionally been unequally distributed. Improved access could reduce the gap between more and less eminent scientists.

The evidence is conflicting, however. A recent study of network use in oceanography found that younger oceanographers who were intensive users of networks were more likely to receive professional recognition than others of their age group who used networks less. Similarly, inland oceanographers who made greater use of networks had more publications than those who used them less (Hesse *et al.*, 1993). On the other hand, another study, which replicated this study, found no evidence of democratisation effects from ICT, such as advantages accruing to those at less prestigious institutions or to younger scientists (Cohen, 1995).

In general, ICT has allowed more scientists to have access to the latest information and thus remain up to date. This has been particularly meaningful for those at less prestigious institutions. However, there is a significant difference between having access and being present. Researchers at top institutions have access to oral information and seminars as well as research papers. They also have access to specialists who know which information and papers are important. The filtering provided by local and informal communication is an important part of the process of finding scientific information. Researchers at large institutions usually also have better access to funding and equipment. Overall, while ICT helps improve access to information, it does not overcome disadvantages due to a lack of direct contact with top scholars in the field. ICT use may thus lead more to a broadening of the science base than to a change in the hierarchy of scientific institutions.

While ICT can be used to provide broad access to resources, it can also be used to limit access. Netnews bulletin boards are generally open to many users and are used to announce new findings, discuss substantive issues, and receive answers to questions from unknown colleagues. More field-specific distribution lists may be announced through direct contact with existing research ties, thus enabling a more specialised exchange of information.

Some fields seem to have more potential to benefit from technology than others. Those where interdependence is high, with frequent interaction between collaborators, and those where collaborators are likely to be dispersed – such as mathematics, physics and aerospace – are most likely to benefit. In fields such as ornithology, on the other hand, technical limitations related to the transmission of non-textual information and a relatively slow pace of discovery may limit benefits.

ACCESS TO SCIENTIFIC INFORMATION

Rapid advances in ICT have made it possible to handle digital data and information in large volumes at ever-increasing speeds and have resulted in sharp reductions in the cost of storing, filtering, processing, compressing, and retrieving data for interpretation and retransmission. ICT has increased researchers' ability to access information by supplying them with increasingly powerful tools at decreasing cost, thus enabling new ways of working. Researchers have frequently been the first to use ICT in a new or comprehensive way, as in the case of the Internet. On the whole, this has significantly improved the efficiency of information-based work.

Digital resources for scientists

In the past, traditional libraries held the keys to research and knowledge. Today, "digital libraries" store and manipulate large collections of material in electronic form. The development of digital libraries is closely linked to that of network information systems, which increasingly allow access to resources when and where users desire it. Prodigious quantities of general and sector-specific information are now available off-line on CD-ROMs and online, increasingly over the Internet. With ICT, access to this information can already be obtained at low incremental cost. As systems become more sophisticated, users will benefit from a growing capacity to navigate among information resources at low cost.

Databases

The value of scientific and technical databases to research organisations continues to increase. Estimates suggest that both the amount of data they contain and their total number expand by about 10 per cent a year. Internet tools, in particular, have made information more readily available to a growing base of scientists and engineers, as database service providers have started moving to Web-based systems. Web browsers such as Netscape are excellent database interfaces; their broad acceptance has extended the potential user base to the research community (*R&D Magazine*, 1997*a*).

Scientists in many fields now produce data sets which are accessible via the Internet to colleagues around the globe. The Internet also provides new opportunities for scientists in different countries to combine local data sets into global ones. This is useful for research projects requiring data from around the world, notably in biological and Earth-related sciences, e.g. the Human Genome Project, the International Geosphere-Biosphere Programme. One notable, if experimental, example was the immediate release of data collected by the Hubble Space Telescope (HST) to any astronomer wishing to study it. Standard procedure in astronomy would have been for researchers making the observations to withhold the data for about a year while they analysed them and published the results (*Science*, 1996*b*).

Several factors help make data sets collected by scientific projects available to broad communities of users. Since the tools used to collect, transmit, and analyse data generate or require digital signals, the data are already in digital form and are therefore easily communicated over digital networks in a timely way to scientists world-wide. Furthermore, when scientists have public support for major research projects, they are encouraged to disseminate data widely so as to maintain that support.[2]

Online databases are now among biologists’ main resources. Electronic databases, which have accumulated huge quantities of gene sequence data, enable microbiologists to relatively quickly complete research tasks that they could hardly imagine before the computer (Box 2). Whether in centralised archives or decentralised databases, these resources play a catalytic role in advancing research (Waldrop, 1995). The sequence databases double in content every 12 to 18 months, have about 100 000 Web hits per day from 4 000-5 000 different sites, and usage is increasing seven-fold each year. These databases are financed in various ways: from the public budget, according to usage on the basis of either transactions or connect time, or through sale of physical products such as CD-ROMs and print or subscriptions or a combination thereof.

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[2] In some countries, such as the United States, publicly supported scientific data must be made available to citizens, by law.

Box 2. Major databases for biologists

GenBank is a nucleotide database in the United States that has been a fixture of molecular biology for more than a decade. It started as a simple archive. Since its transfer to the National Center for Biotechnology Information, where many staff members are themselves active researchers in laboratories of the National Institutes of Health, it has evolved into an intricately cross-linked array of databases, where molecular biology researchers can search for similarities among gene and protein sequences. Recent new features are a database of DNA codes for protein, links to MEDLINE, a browsing system, and the possibility to submit queries or add sequences over the World Wide Web (WWW). Software takes each new sequence added and computes its “distance” from each of the existing entries. This allows identification of homologues, which can provide valuable information about the functioning and evolution of the original gene.

Genome Sequence Data Base (GSDB), created in the early 1990s, is an experimental, relational version of GenBank. It allows users to make complex queries. The queries follow links between chunks of information, which might be distributed over several files or even databases. This federation of autonomous and distributed databases creates an environment where researchers can pursue more complex questions than with GenBank.

The *European Molecular Biology Laboratory* and the *DNA Data Bank of Japan* are two other major nucleotide sequence databases. All four major databases regularly exchange newly submitted sequences.

Researchers around the world have been filling a common database with the outcome of sophisticated DNA analysis (sequences of base pairings in a gene common to all cells) of thousands of organisms, including microbes. While the main goal of this database, maintained by researchers at the University of Illinois at Urbana-Champaign, is to gauge evolutionary relationships between organisms, it is also proving to be a useful catalogue of microbial diversity.

Images constitute an important part of research data in astronomy. The Astronomy Digital Image Library aims to support astronomers’ productivity by providing easy access to data via the Web. Its collection of fully processed images permits researchers planning new projects to access previous observations as an aid to sensitivity calculations or exploring new questions. New data may also be compared with previous observations to allow a multi-frequency study of particular objects. Astronomers may also use the library to archive their final processed images and related data and share them with collaborators and colleagues without having to use their own disk space or as a way to present results in a manner that complements the presentation in printed journals (National Center for Supercomputing Applications, 1997).

Many smaller databases cater to projects that are smaller in scale and geographic coverage. An example from the medical sciences is the CD-ROM, *Encyclopaedia of Clinical Practice* (EPIC). This database contains more than 4 million anonymous UK patient records and can aid in general or preliminary medical research by an epidemiologist or primary health-care researcher.

Bibliographic databases provide information on published research. By providing citations, summaries of original research material (abstracts), and various indexes to scientific research literature, they allow scientists and researchers to identify published articles appropriate to their needs. They range from the more than 20 million records contained in On-line Computer Library Center (OCLC) to the millions of citations in online databases for specific disciplines such as MEDLINE, EMBASE, INSPEC and NTIS.[3]

ICT has expanded delivery methods for bibliographic databases and has created better options for storage, search and retrieval. Bibliographic databases were first made available to scientists and researchers in electronic format via commercial online hosts and search service vendors and then via the Internet and the WWW, as well as off-line on CD-ROM. The different electronic delivery modes continue to exist, as their attributes and the needs of users vary, but the Internet is expected to become the primary means of delivery. Online access has many advantages. It is more affordable for academics and librarians, who are often unable to purchase entire databases on CD-ROM. The Internet also enables cross-searching of databases. Nevertheless, many larger institutions continue to purchase databases on CD-ROM, sometimes to bypass Internet traffic jams. Commercial providers, such as the Chemical Abstracts Service (CAS) and Knight-Ridder International (KRI), two of the largest database service providers in the United States, provide access both via traditional online services and via the Web. A wide range of options and formats are available (Box 3).

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3. EMBASE (Elsevier) is Europe’s largest and most important biomedical reference database. It contains more than 6 million records, most with author abstracts, and references published works in biomedicine from some 3 500 journals from 100 countries. INSPEC is the world’s foremost database on physics, electronics, electrical engineering, computing and information technology. NTIS is an engineering database.

Box 3. Database delivery formats and content

STN International (Scientific and Technical information Network, CAS) is a traditional fee-based online search service that provides information from more than 200 scientific, technical, business and patent databases and includes business, regulatory and supplier information. It is aimed at information specialists experienced in command line searches. Dialog and DataStar (KRI) which focus on American business and technology and on European business, medical information and pharmaceutical sources, respectively, provide combined online access to more than 600 databases, with a very powerful search language that would be difficult for the uninitiated.

The Web-based version of STN, STN Easy, introduced at the end of 1996, provides access to selected databases and only includes core bibliographic information. It has no connect-time charges. The Web-based ScienceBase, launched in mid-1996 by KRI, allows users unfamiliar with its search language to access a collection of databases compiled especially for scientists. Dialog Web gives users desiring a more complete Web-based database the capability to browse through all the Dialog databases by topic and supports users with a database directory. Dialog Select, due to be launched in mid-1997, is similar to ScienceBase but allows users access by application or subject matter, e.g. patent information. DataStar Web gives users access to more than 350 of the DataStar databases.

STN has recently added SWETSCAN, a current awareness database offering the tables of contents of more than 13 000 international scholarly and research journals, including publications on technology, medicine and science. The database holds 300 000 records going back to 1993. It has also added WCSA, a bibliographic database containing citations to the world-wide research, technical and trade literature on all aspects of paint and surface coatings. It has 200 000 records dating back to 1976, is updated monthly, and is based on the printed *World Surface Coatings Abstracts* produced by the UK Paint Research Association.

Cambridge Scientific Abstracts has published abstracts and indexes to scientific literature for over 30 years. In addition to its traditional print journal, it now makes its databases available through 13 different commercial online hosts and five CD-ROM vendors. CSA's Web-based Internet Database Service provides access to all its databases and to those of several publishing partners.

The US-based Institute for Scientific Information (ISI) has released The CompuMath Citation Index, previously only available in print, on CD-ROM. The rolling five-year file, to be updated bimonthly, covers close to 350 computer science and mathematics journals, and selected items from 7 300 science, social science, art and humanities journals. Another CD-ROM database on novel organic compounds, the Index Chemicus, offers features such as the ability to zoom on graphical abstracts. The ISI has also begun offering the Web version of its citation databases for delivery via companies' intranets. Called the Web of Science, this new version provides access to the Science Citations Index Expanded, the Social Sciences Citations Index and the Arts and Humanities Citation Index, which collectively index the full text of over 8 000 journals.

UnCover is an online article delivery service, a table of contents database, and a keyword index to nearly 17 000 periodicals. It holds more than 7 million references which are available through a simple online order system and 5 000 citations are added daily. UnCover covers the periodical collections of some of the major university and public libraries in the United States; coverage has been extended to libraries in Europe and Australia.

Reliability, security and speed of access do not seem to be an issue for most users of Web-based systems (*R&D Magazine*, 1997*a*). Nevertheless, KRI also offers an intranet Web-based database service, KR@Site, which maintains database content at a local site and does not permit external access from the Web. The service is for users who find the Internet too slow, or those who want to protect their own database. Some Web-based services offer access to journals from various publishers at a single point. This reduces difficulties related to software incompatibility, administration, and management of passwords for users who typically access information from many publishers.

The new technologies also allow information providers to address scientists directly. Biosys, for example, has provided abstracting and indexing services to the life science community for about 70 years. It has changed significantly over the decades, evolving from an organisation relying on volunteers to one with more than 300 paid staff on both sides of the Atlantic. In the 1970s, mainly owing to the advent of online technology, its target audience shifted from scientists to librarians. Further technological innovation, notably networking, has enabled Biosys to focus again on the scientist. It offers its databases to all UK universities via the Joint Academic Network (JANET) and has similar arrangements – 50 in all – around the world. Networks have thus allowed the company to reach the scientific researcher directly. The company is planning to use the Internet, first by working with its vendor partners and then by directly offering content on the Web.

The situation differs substantially among disciplines, however, for both numeric and bibliographic databases. For materials engineering, ICT-based distribution of information seems to be generally lagging, with numeric databases on materials available only in-house, notably in universities and in companies. There is insufficient demand for broader distribution of the data. In terms of bibliographic information, the cost of CD-ROMs as compared to hard-copy directories and of investment in technology for what are mostly small manufacturers limits the market for these products (*Information World Review*, 1997).

As information providers turn to the Web, they also add new features to their services. The Web site of the Institute of Physics – which covers 31 journal titles – includes a virtual filing cabinet which enables physicists to annotate, label and store articles from journals to which they subscribe. Users can personalise the menu, pre-set search facilities, configure PostScript downloads, and create a table of contents. An intelligent client-server application, SciFinder, allows users to build structures with a new structure editor, to access chemical databases and more than 1 900 journals through an Internet connection to CAS, and to search the CHEMCATS database which has information on 370 000 commercially available chemicals from more than 40 catalogues. Users of MicroPatent can use a new patent-searching tool, PatentSearch, which allows a search on a CD-ROM to be combined with delivery via the Internet.

Other types of textual information have also been compiled and stored in databases. Information on patents and trademarks as well as on research activities are valuable for scientists (Box 4). Some full-text databases of classic works no longer copyrighted are also being assembled and made available online.

Box 4. Some textual databases

The French online service Questel-Orbit includes trademark and company information. The Community Marks database covers all EU trademarks applied for via the OHMI (*Office d'harmonisation des marchés intérieurs*), including full trademark details.

IRLMARK contains the full text of all Irish trademarks. The company has recently upgraded its Imagination software to enhance document display, allowing items of interest to be reprocessed to a format closely resembling the original document, and enabling searches without prior knowledge of commands or database structures.

In Japan, the Patent On-Line Information System is provided by the Japan Patent Information Organisation and the Japan Information Center of Science and Technology (JICST). It involves a comprehensive database of documents available online.

Bowker-Saur has made its European Research and Development Database available online via a new EU-funded online business support system, Alpha-DIDO. The database contains information on companies and individuals – 85 000 research professionals – actively involved in R&D in 39 European countries.

The Community of Science is building a Web-based information service that covers it own database and that of other vendors. This Expertise, Inventions and Facilities database consists of 50 000 first-person narratives by scientists about their research. Other databases provided are Funding Opportunities, an international database on research grant information, MEDLINE, and the US Patent Citation Database. In addition to increasing the quantity of information made available to users, it customises delivery to the end-user who receives a daily e-mail providing details of new additions to databases that may be of interest.

In future, users will increasingly benefit from the incorporation of visual and multimedia information into databases; while this will add substantially to storage requirements, falling storage costs will probably keep this from becoming a problem (*R&D Magazine*, 1997*a*). Users will also benefit from improved database search capabilities due to software developments, including systems for gathering and indexing documents using Web crawlers, and from indexes that support actual scientific data as well as documents (Taubes, 1995).

Digital library initiatives

There are vast numbers of projects for developing digital libraries. They currently focus on issues of access costs and digitisation technology (Box 5). The key technological issues, however, are how to search and display desired selections from large collections on the Internet. Research on digital libraries concentrates on how to develop the necessary infrastructure to manipulate effectively the massive amounts of Internet information (*Computer*, 1996).

Many traditional libraries which are not yet involved in large-scale digitisation of publications are nevertheless increasing their holdings of electronic documents. These can be powerful tools for research and may reduce subscriptions to printed publications by enabling electronic access to other libraries' holdings. A "free-rider" problem may arise, however, if all libraries follow this policy.

Access to unpublished student research stored at universities is generally limited, thereby reducing the transfer of knowledge contained in unpublished scholarly work. It is estimated that over 10 per cent of all research performed in the hard sciences each year had already been done. Providing electronic access to this data source might improve scientists' productivity by enabling them to focus on the appropriate issues. In the United States, the federal government and the ICT industry are collaborating on the preparation of a digital library of unpublished research. As of the 1997-98 academic year, all graduate students in designated programmes at the Virginia Polytechnic Institute will be required to submit their dissertations/theses in digital form. This project will serve as a prototype for all 400 000 doctoral dissertations/theses written by science and engineering students at American universities each year (Koprowski, 1996).

The Digital Library Initiative (DLI) is the flagship research effort of the US National Information Infrastructure Initiative (Box 5). Ultimately, the digital library would involve an entire network of distributed repositories where objects of any type can be searched within and across indexed collections. With its many partners and large testbeds, the DLI is structured to encourage technology transfer. Once the DLI has stimulated basic research in various enabling technologies and enabled several digital library testbeds, it is expected that IT companies, traditional libraries, publishers, organisations, and users will join forces to develop the knowledge repositories that will play an essential role for all of society in the 21st century. Earlier similar government initiatives such as those for information retrieval technology spawned Dialog and Lexis/Nexis in the 1970s and Lycos and Yahoo Web searchers in the 1990s (*Computer*, 1996).

Box 5. Digital library programmes

In the United States, the NSF, the Advanced Research Projects Agency (ARPA) and the National Aeronautics and Space Administration (NASA) are funding a four-year Digital Library Initiative (DLI) with roughly US$ 1 million per year for each of six projects. Each project spans a wide range of research topics related to large-scale digital libraries, all focused on infrastructure issues. One project looks at receiving materials in electronic format directly from publishers, while another looks at receiving them in paper format and automatically transforming them into digital form. Other projects look at the manipulation of new media such as video and maps, which were previously impossible to index and search. The projects involve university-led consortia, with active participation of client groups, such as specific research communities. They also include commercial enterprises involved in the commercialisation of digital library systems, such as publishers, software houses, stock exchanges, equipment manufacturers, communications companies, libraries, and information and data service providers.

A project at the *Bibliothèque nationale de France* (BNF – National Library of France) involves the provision of 100 000 documents (30 million pages) to academic users in digital form by the end of 1998. Contrary to the practice adopted by the Colorado Alliance of Research Libraries in the United States and the Electronic Document Interchange between Libraries in Europe, where digitisation depends on demand, the French initiative is based on a pre-selected range of manuscripts for digitisation. Researchers will be able to access the digitised documents via computer-assisted terminals located in the BNF (Bouchard, 1996).

The Initiatives for Access project of the British Library was launched in 1993 to investigate hardware and software platforms for the digitisation and subsequent networking of a range of library materials. In addition to enhancing library services and facilitating access, the programme was to establish standards for storage, indexing, retrieval and transmission of data, and to examine copyright issues. One of the projects made the library's major catalogues, which hold over 6 million bibliographic records detailing items from the beginning of printing up to current scientific journals, available over the United Kingdom's Joint Academic Network (JANET) (Purday, 1995).

The US Library of Congress is continuing digitisation efforts begun in 1990. It is digitising core collections of material in the public domain or for which it has permission to disseminate at little or no cost. The Library, which is also the home of the US Copyright Office, is also working on issues of copyright through the Electronic Copyright Management System, which will allow automated copyright registration, and through an electronic journal project which will focus on free journals but will request the publisher's agreement as if it were a for-fee publication (Becker, 1995).

Software sharing

Scientific analysis increasingly involves complex software. Technologies such as satellite imaging systems and particle accelerators collect huge amounts of data, the interpretation of which often requires specialised software. Computer networks can provide wider access to such software. For researchers, one of the most important changes wrought by the Internet, and particularly the WWW, has been the ability to readily upload specialised software code. Transfer and use of software via the Internet have become as essential to many researchers as e-mail. Given the increased sophistication of software and the considerable investment required to develop it, the incentive to share software is increasing.

Programmes that earlier would have been written solely for personal use are now made available over the Internet, where libraries of free software for scientific purposes are growing. With the soaring popularity of the WWW, use of Netlib, which has operated since the mid-1980s, has grown tremendously. There were more than 3 million requests to download programmes in the first six months of 1996, compared with 5 million in all of 1996 and 250 000 in 1993. The Web site contains the source code for scores of programmes relating to research in mathematics and computational science. The HPCC programme funded the National HPCC Software Exchange in September 1994, in order to collect software or software descriptions for high-performance computing systems and make them available on the Web. The exchange also contains a hardware and software vendor catalogue and information about reports, journals and professional associations (National Science and Technology Council, 1995).

Software sharing presents some difficulties, however. Those who borrow programmes need to know how the software works, as this affects the results they obtain. Relevant documentation is often not available, so that scientists tend to write their own programmes instead of using existing ones. Applying software obtained from another sources to the data of interest is also problematic, since most scientific software is prepared for specific purposes and the data must be formatted to meet its requirements. However, these are minor problems compared to the tremendous advantages software sharing can bring.

Implementation issues

Sharing the exponentially growing volume of scientific data presents many challenges. In all disciplines, extensive electronic distribution of scientific data has made it more difficult to categorise data according to quality, including the degree of review and certification. Gaps in quality control, incompatible data streams, inadequate documentation, and difficulties in retaining data over the long run have been particularly acute in observational sciences. In the biological sciences, the variety of attributes and qualifiers relevant to individual observations, combined with differences in terminology and usage, make it increasingly difficult for data suppliers to describe data precisely enough to prevent misinterpretation. The problems are also serious in laboratory physics. The need for qualified support personnel in library systems presents an additional challenge.

The extensive use of ICT has also raised various technical, economic, and legal issues related to data access, many of which cross national boundaries. These issues include congestion on the Internet, the rapid obsolescence of information processing tools, and the vulnerability of networks and data repositories to damage. In addition, as the quantity and use of scientific data have grown, and as budgetary constraints have increased, some governments have begun to privatise the generation and distribution of scientific data, raising fears that the scientific community's access to data could be limited by new pricing practices. Current attempts to expand intellectual property rights models to cover the content of electronic databases may also affect the international flow of scientific data, if the special needs of libraries, educators and researchers are not taken into account (National Research Council, 1997).

It is essential that digital databases of scientific information remain accessible to researchers and educators. Various proposals concerning the international distribution of scientific data are currently being examined by the World Intellectual Property Organisation (WIPO), the European Union, and the US House of Representatives. There are concerns that these proposals do not provide adequate safeguards for the "fair use" of data by the scientific and educational communities. Many would prevent databases that are not copyrighted or patented from being copied to other computers without the permission of those who own or maintain the data. The National Research Council (NRC), a private organisation which provides advice to the US government, recently indicated that these proposals could jeopardise basic scientific research and education (National Research Council, 1997). Access to international databases may also be affected by problems of language and translation.

Network funding disparities in different sectors and countries may also threaten equitable participation in development, a concern relevant for all services that will be provided by information infrastructures. For example, access to the Internet among US academics was nearly universal in the early 1990s but was much less uniform in other countries. Researchers in developing countries also need access to electronic communications, both to acquire information and to provide the data they generate in fields dealing with inherently global issues such as food production, biodiversity, and the prevention and cure of communicable diseases. Increased networking has also uncovered various problems related to identification and authentication of users of networks and library systems which delay co-operation and collaboration in service developments. Progress on copyright issues concerning fair use of digital materials by libraries has been slow.

SCIENTIFIC INSTRUMENTS

ICT developments have also significantly influenced scientific instruments and the way scientists use them. The main development is undoubtedly the ever faster and more powerful computers which make it possible to attack scientific problems that were out of reach just a few years ago. Computers aside, ICT-based tools vary by discipline. In some disciplines, greater computing power has allowed better visualisation of results and has significantly improved modelling, simulation and analysis. In others, scientific instruments have been revolutionised by miniaturisation or the development of virtual instruments. This has significantly lowered the costs of some instruments and has also made them more flexible.

Computational research

Computers are now among the most important instruments used by scientists. Many research problems, such as modelling the global climate, forecasting the weather, molecular modelling to enable new drug therapies, and simulating automobile crashes, require enormous numbers of calculations. Increasingly powerful computers have significantly contributed to the ability of scientists to solve the equations used in this type of research and enable them to perform repetitive computations on huge data sets. Computational research involves complex tasks that force the limits of the most advanced computer systems and permit achievements that would otherwise have been impossible. Computers have, in this respect, revolutionised science.

Key problems in the theory of elementary particles, so complicated that they would have required many years of continuous operation to resolve with the fastest computers available in the early 1980s, have led researchers to design and construct a dedicated supercomputer. In 1995, after about a year of continuous computation, a large 11 gigaflop supercomputer produced its first results, including values for the masses of the proton and seven other hadrons. By that time, the HPCC programme had demonstrated a capability of more than 140 gigaflops, and was on its way towards demonstrating technologies capable of sustaining 1 trillion operations per second (one teraflop) (National Science and Technology Council, 1995). A teraflop machine being built by the Sandia

National Laboratories of New Mexico will carry out its calculations with 9 000 off-the-shelf Pentium Pro chips working in concert (Matthews, 1996).

The tasks that push back the frontiers of scientific research remain the domain of HPCC systems at national research laboratories, government defence centres and weather forecasting centres. Nevertheless, less complex versions of these tasks can be carried out on (networked) PCs and workstations in combination with increasingly sophisticated software. The speeding up enabled by increasingly powerful computing systems is also evident in high-technology industry. Computers have allowed industry researchers to carry out tasks they could not have performed otherwise, thereby enabling more rapid product development cycles and lower design costs. Computer modelling, simulation and visualisation are the main applications driving this process.[4]

The rapid development and proliferation of computer technology has been an important catalyst for several evolving technologies – robotics, computer control and tracking, molecular modelling, and high-speed database search tools – that together have enabled combinatorial chemistry. Combinatorial chemistry makes a large number of new chemical compounds and then screens them for chemical activity in order to build a library. Without computer technology, tracking the novel compounds created during the synthesis and screening procedures would not be feasible (Box 6). Combinatorial techniques are one way in which the pharmaceutical industry can cut costs and development times. Researchers have rapidly adopted them, and this has contributed to strategic alliances between equipment and software suppliers. The techniques also hold promise in areas such as the discovery of new materials.

Changing system interfaces and improving access speeds are also contributing to make chemical development modelling faster. Computer simulations of molecular dynamics have proved extremely useful in biochemistry, notably in drug development. The complexity of such simulations, and their enormous computational requirements, push today’s massively parallel computers to their limits. Many prospective drugs that might harm patients can now be identified and discarded by tinkering with images of molecules on computer screens rather than testing the molecules on animals or in time-consuming cell-culture processes.

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4. Modelling involves the development of mathematical models of natural phenomena. Software is one of the tools researchers use for modelling. In simulations, mathematical models of physical phenomena are translated into computer software that specifies how calculations are performed using observed data and estimates. Visualisation consists of the graphical representation of data.

Box 6. Some applications of computational research in science

Chemistry and pharmacology

- Combinatorial chemistry raises the probability that a new compound will usefully react to a molecular target, such as an AIDS virus, thus shortening the time to market for pharmaceutical products. Previously, researchers trying to create new chemical compounds assembled molecules one at a time in a laboratory in individual test tubes and then screened them against a molecular target, again one at a time (Studt, 1997).
- The "chemically aware Intranet" is a Web-enabling infrastructure and tool kit consisting of servers and Java-based applets.* The applets can be used to develop interfaces for established computational-chemistry software modules. Consequently, a broader range of scientists, on a wider variety of computer platforms, are able to use a company's drug discovery software at an individual intranet site. The system's simple graphical user interfaces can be used to launch modelling calculations on the network server and allow all members of the research team to retrieve the results (*R&D Magazine*, 1997*b*).
- Clinical studies suggest that inhibitors of an enzyme responsible for degrading a neurotransmitter may be useful in enhancing memory in patients with Alzheimer's disease. Designing inhibitors requires an understanding of the active site where binding occurs, including the mechanism of product entry and substrate release. Researchers use simulation to understand the mechanics of the molecular dynamics involved (Concurrent Supercomputer Consortium, 1995).
- Researchers at the University of Surrey have created images of six key enzymes used by the human liver or gut to break down foreign substances. These enzymes degrade 90 per cent of the foreign substances entering the body. By manoeuvring 3-D images of molecules on their screens, they can subject prospective drug molecules to encounters with the enzymes. They can then predict whether a molecule will be broken down by one of them, how fast it will be flushed by the body, and by what chemical mechanism (Coghlan, 1996).

Clinical medicine

- A system using virtual imaging and high-performance computers to improve radiation treatments now takes only 20 minutes instead of hundreds of hours to calculate how radioactive particles and related products interact with cancerous matter. The system gives doctors a better idea of dose distributions.
- Standard bronchoscopy is being augmented with non-invasive imaging of the human bronchial tree. The technique, which combines computer tomography (CT) and specialised software to create accurate 3-D images, can identify lesions on the bronchial wall and helps doctors make precise measurements of bronchial size. It may substantially reduce the number of regular bronchoscopies, which are less accurate and carry a risk of internal bleeding.

Earth and related environmental sciences

- A synthetic aperture radar aboard NASA's Space Shuttle recently returned almost 32 terabits of data on the Earth's surface. These are being used by the international science community to gain better insights into the Earth's ecosystem, climatic and geological processes, the hydrologic cycle and ocean circulation (Concurrent Supercomputer Consortium, 1995).

* Java applets are small programmes that execute specific files and are platform-independent.

Box 6. Some applications of computational research in science (continued)

- Analytical tools for satellite imagery have generated accurate 2-dimensional maps of ground displacement – used to study earthquake activity – for 40 000 pixels (picture elements), and plans are under way to boost this number to 4 million. In contrast, technology for workstations can only provide information about ground displacements for a few hundred pixel locations scattered throughout an image (Concurrent Supercomputer Consortium, 1995).
- The ability to correctly image complex geologies is a key to reducing the risk and cost associated with oil and gas exploration. It is expected that predicted processor performance improvements over the next several years should make it possible to process such data in real time (*R&D Magazine*, 1997*b*).
- Atmospheric data gathered by sensors at surface stations, on weather balloons, in aircraft, on ships, and on satellites are collected by the World Meteorological Organisation in Geneva and made available to member researchers via the Internet. A special programme, Unidata, was conceived as a means to enhance participating universities' ability to acquire and use atmospheric data.

Engineering

- Computer visualisation techniques have also been used to create a 3-D reconstruction of the microstructure of materials. This may contribute to the understanding of microstructural development and to the design of new materials. Previously, the principal tools for probing microstructures in materials were electron microscopes and conventional optical examination.
- In the area of product design, Caterpillar is currently using virtual reality (VR) to design new earth-moving equipment. Where it once took a year to put together a new prototype, it now takes only three weeks. Caterpillar's 1996 new backhoe loader was almost entirely designed using the computer animated virtual environment (CAVE). General Motors' engineers are building car interiors using computer code and use the virtual environment to evaluate various aesthetic, ergonomic, and engineering aspects of prototype designs.

Physics

- Physics researchers often use cluster models to analyse interactions of atomic or molecular species with gallium arsenide (GaAs) crystals. These can be of technical importance in modern manufacturing processes such as digital etching, surface cleaning, and atomic layer growing. A recent high-performance computer programme, in combination with newly developed software, has allowed significant improvements in this type of modelling, thus enabling researchers to carry out experiments on the interaction of free GaAs clusters with ammonia (Concurrent Supercomputer Consortium, 1995).

Visualisation has also grown in importance. Graphics, the core of visualisation activity, require a great deal of computation and memory. Computer graphics can help scientists working on large-scale scientific problems to visualise large amounts of numerical data and find new relationships. Rapid, 3-D high-resolution colour display is essential for understanding simulation results. Enormous quantities of remote-sensing data about the Earth's environment are being created and stored at an increasing rate. Computers have always played a prominent role in the visualisation of high-resolution imagery supplied by remote sensing. In order for this valuable information to be disseminated, it must be delivered in useable form to those who interpret it. High-performance computers and fast networks can be used to quickly provide animated, customised data.

Powerful new analytical tools for satellite imagery, which may contain millions of pixels, can now extract information about physical processes that previously remained buried within large data sets. The enormous computational demands of these tools are satisfied by the computational power of high-performance computers and recent developments in the fields of machine learning and data mining. The same tools and techniques can be applied to problems such as global change, monitoring of tectonic activity, and measurements of land-cover dynamics due to urbanisation and global climate change. Images are also an important part of biomedical knowledge. New computational technologies that provide three-dimensional images to supplement traditional two-dimensional biological and medical images, including computer tomography (CT) and magnetic resonance imaging (MRI), are currently being developed (Box 6).

Virtual reality technology creates computer-generated simulations and 3-D visualisation of the physical world, with which the operator can interact directly. CAVE (computer animated virtual environment) is used for a wide range of applications, including molecular modelling for drug and product design, medical imaging, manufacturing, cosmology and education.[5] It consists of a multi-person, room-sized, surround-screen, surround-sound, projection-based virtual reality (VR) environment. Images are projected in 3-D onto the walls and floor and viewed with stereoscopic glasses by users who are immersed in computer-generated simulations of data. More than 20 CAVEs or related systems have been installed, one of which is at the German National Research Centre for Information Technology in Bonn. CAVE systems have also already been commercialised.

In engineering, modelling software developed over the past decade has made it possible to computerise the prototype process, allowing researchers to design and analyse complex products using information technology before producing actual parts. Components can now be evaluated on a computer for fit, function, interference with other parts, strength, and cost and production aspects. VR is helping in the design of automobiles, aircraft interiors, submarines and

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[5] CAVE was developed by the Electronic Visualization Laboratory at the University of Illinois in Chicago in 1991. Caterpillar used the CAVE system at the National Center for Supercomputing Applications.

factories (Box 6). It can enhance product quality and reduce time to market, and plays a significant role in ensuring the cost-effective manufacture of products. However, VR cannot be used to model all aspects of a product. The databases that underlie VR increase in complexity and size as more product attributes and their interactions are included. Most road-holding characteristics of vehicles remain beyond the capabilities of current VR technologies.

Virtual laboratories

The "collaboratory" is an integrated, tool-oriented computing and communications system which supports scientific collaboration. It allows researchers to concentrate on the purpose and results, rather than the mechanics, of communication. It has been defined as "a centre without walls in which ... researchers can perform their research without regard to geographic location, interacting with colleagues, accessing instrumentation, sharing data and computational resources, and accessing information in digital libraries" (National Research Council, 1993). It is an environment in which networked facilities permit all of a scientists' instruments and information to be virtually local, whatever their physical location.

Collaboratories provide new ways to co-ordinate large-scale research projects and to access remote data and researchers. ICT has already made collaborative research possible by wire, as demonstrated by the operation of complex experimental devices such as the Tokamak Test Fusion Reactor at Princeton University in the United States. Video-conferencing has also existed for a number of years. However, the state of the art of video communications, telecommunications and data-exchange tools will need to advance further to create seamless electronic platforms for collaborative research. The basic technical requirements for a collaboratory relate to data and software sharing, control of remote instruments, and communication with remote colleagues.

Scientists increasingly use remotely controlled instruments. Remote control improves researchers' access to scarce scientific equipment and may contribute to more efficient use of resources in a time of budget restraint. For example, browser software allows researchers anywhere to use instrumentation at the University of Illinois. They can conduct MRI scans from their PC or laptop. The system (NmrScope) is available on the Web through a University of Illinois server. Once a sample has been delivered to the university, an authorised researcher can connect to the server, which shows a form indicating instrument settings and a menu of possible functions (move slice forward, zoom on, etc.). The experiment is carried out at the click of a screen button and the resulting image is returned to the researcher's computer screen (*Inside R&D*, 1996).

Controlling instruments through a computer network and collecting data regardless of the instrument's location is particularly beneficial in cases where instruments are inaccessible and the environment is unfriendly for collecting data. This is important in space physics, for example, where ground-based instruments are positioned in remote locations and space-based instruments may need to be repositioned while a mission is in progress. In physical oceanography, the ability to perform real-time reading of remote instruments can save time and money and result in a greater volume of higher-quality data.

Many projects involving remote control of instruments are under way; the Hubble Space Telescope is a classic example. The HST must operate most of the time autonomously, since it is not in direct communication with its controllers for more than half of its orbit. It must be able to receive occasional instructions from the ground and transmit data to Earth when communication links are available. Other sharable instruments include electron microscopes, particle accelerators and colliders, autonomous underwater vehicles, pilot-less aircraft and autonomous land rovers.

Several collaboratories involving remote control of instruments are also under way. In the United States, the Pacific Northwest National Laboratory in Richland, Washington, has developed an environmental and molecular sciences collaboratory which permits remote operation of the laboratory's two nuclear magnetic resonance (NMR) spectrometers and other instruments. The US Department of Energy has launched the Diesel Combustion Collaboratory Project, which links researchers at three government laboratories and the University of Wisconsin, Madison, with the aim of designing diesel engines that produce less pollution.

A system provided by the Upper Atmospheric Research Collaboratory, University of Michigan, Ann Arbor, links researchers in six American universities with a US-funded radar in Greenland that continuously monitors the upper atmosphere, allowing researchers to observe the interaction between the solar wind and the Earth's atmosphere. In the past, the researchers had to fly to the station, sit in a trailer with instrument displays, record the data on computer tapes or disks, take these back to their laboratory and analyse them over the next few months. Since 1993, researchers observe the data over the Internet directly from instruments connected to a radar. The software on the researchers' home computers includes a text-based chat window through which they can discuss the data and send instructions to technical staff in Greenland.

Network characteristics currently constitute an important obstacle to wider introduction of remote instrument control and collaboratories. The current lack of bandwidth means that scientists often cannot use the Internet to send data to participants in a collaboratory.[6] Owing to transmission problems, not only may a crucial instruction fail to reach a remotely controlled instrument, but the instrument may even be damaged (National Research Council, 1993). Another difficulty is the need to ensure that all participants update their software as changes are made in software on the collaboratory's central computer. Java, the new Internet computer language, is expected to solve this problem, as Java "applets" can be automatically updated from a central library.

Virtual instruments

A scientific instrument typically acquires data by collecting the output of a sensor, turning the readings into an electrical signal, analysing the signal - usually with the help of a microprocessor inside the instrument - and presenting the analysed data in a meaningful way. Until recently, this required dedicated benchtop instruments for each of several types of measurement (temperature, pressure, voltage, etc.). During the 1990s, multipurpose workstations and PCs, together with software systems that provide graphical programming capabilities, replaced many of these dedicated instruments.

The instruments become "virtual" as the user, rather than the instrument maker, determines precisely what the equipment does by matching the software to the sensor needed for each measurement. Technicians who required expensive instruments for each specific test can now create their own by changing programme settings. This dispenses with many of the costly parts of a traditional instrument. For example, a combination of chip-testing equipment that performed only a limited number of tests at a cost of US$ 220 000 could be replaced by a more versatile virtual instrument built from off-the-shelf parts at a cost of US$ 8 000. Similarly, ventilation systems built for factories and offices can be tested with a single piece of equipment that can be

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[6] These problems are not insurmountable, however, and a range of options are available to tackle the bandwidth problem (OECD, 1997*a*).

reprogrammed endlessly to mimic the demands of different buildings (*Economist*, 1996*b*).

The tremendous increase in the processing power of PCs has contributed to the realisation of “virtual” instruments. It has supported extensive software-based developments that have simplified complex tasks such as data acquisition and monitoring, modelling and visualising. Visual programming software technologies have allowed faster development of software which is also more easily understood and easily reused to solve different problems. New software and regular upgrades add functionality without requiring users to learn new programming techniques, and also allow faster execution. The latest version of the instrument programming language LABVIEW, for example, provides multithreading, distributed computing tools, graphical differencing tools and instrument wizards to set them all up (*R&D Magazine*, 1998).[7] Software is now frequently compatible with Microsoft’s Windows. Graphical output can increasingly be embedded in standard word processors, PowerPoint presentations, Web pages, lab notebooks, reports or other graphics programmes.

In addition, new user-friendly custom interfaces and simple menu choices and control buttons enable users to view results from many test stations. One of the next stages will be to use such software to access, monitor, and control remote data locations, possibly over an Internet with expanded bandwidth capabilities, since current capabilities may not permit real-time control and debugging (*R&D Magazine*, 1997*b*).

More simply, virtual instruments can reduce the number of sensors required for a given task. This is useful in hostile environments where the tendency is to use multiple temperature probes and average readings to compensate for degradation of calibration and accuracy. For instance, the self-verifying sensor (SVS, from AccuTru) ties the basic probe to an electronics package that constantly monitors temperature calibration against established references. Real-time temperature displays and software diagnostics readily identify probe failures when they occur. SVS eliminates the need for multi-sensor units because the sensor’s accuracy is monitored constantly. It could contribute to energy savings, improved quality control, reduced waste and lower

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[7] Multithreading is the ability to separate computer tasks so that they can be executed in parallel on separate threads. This capability has been built into every virtual instrument so that the user does not need to learn a new programming technique. Graphical differencing tools allow developers to compare the difference between versions of LABVIEW programmes.

maintenance costs and has potential applications in many energy-intensive manufacturing processes (Crowford, 1997).

More complex virtual instrumentation may combine various technologies, such as high-speed digital recording and massively parallel computing. In the case of radio astronomy, for example, conventional special-purpose analog filter bank spectrometers and auto-correlators used in pulsar astronomy, which typically took years to design and develop, were replaced by a general-purpose, software-based digital system implemented in as little as nine months (Concurrent Supercomputer Consortium, 1995).

Miniaturisation

Miniaturisation is a driving force in the development of electronic, biomedical and electromechanical systems. Instrument packages and measurement tools continue to shrink in weight, volume and energy needs and augment in performance, sometimes by orders of magnitude. Over the next decade, the capability of microanalytical instrumentation may be further revolutionised, as technologies of chemistry, biochemistry, micro-machining, electronics, and microelectronic fabrication are combined. Currently, micro-instrumentation is developing along two lines: biomedical, chemical and micro-fluidic systems on the one hand; and physics-based systems on the other.

ICT is not the only source of miniaturisation, but the growth in micro-instrumentation does depend in part on developments in micro-machined, micro-electromechanical system (MEMS) components which contribute to size reductions for sensors and electronics. Systems "on-a-chip" are being developed and tested for many applications, with many more envisaged. All the manipulations typically carried out by a chemist with beakers and test tubes can now be performed on a very small platform. These tiny micro-machined devices, which look like microscope slides, are capable of sophisticated chemical analysis. Chemists and biochemists are increasingly applying new micro-chemical processing to on-a-chip integration of sample treatment, chemical processing, separation, detection and analysis.

The principles that have shrunk the chemistry lab to the size of a chip are the same as those that for decades led the way in the miniaturisation of electrical circuits. The new device is an optical version of the common computer microchip, but it uses tiny lenses and filters instead of transistors and diodes. It is typically made of glass, silicon, or quartz and is etched with hairline pathways for sample liquids or powdered solids, rather than for electricity.

Depending on the chip coating, different materials can be analysed. Tiny amounts of test samples are examined under laser light, which turns the chip into an inexpensive sensor. The moving samples interact with a fluorescent dye in a separation channel on the chip and the fluorescent glow given off by the sample is analysed on a computer, giving quick, reliable results (Cable News Network, 1996 and 1997).

Early chip-level diagnostic and micro-fluidic systems are currently being refined for quantitative and qualitative chemical analysis, multi-component blood analysis, flow cytometry, and even DNA replication. A specific chip (the GeneChip by Affymetrix), which contains tens of thousands of different fragments of DNA, can now be used to identify any known DNA sequence. It can accomplish in about an hour a procedure that previously took days or even months using the traditional process of gels, glass plates, and electric charges (Mercury Center, 1996). Combined with the Oak Ridge National Laboratory's chemical lab-on-a-chip technology, a polymer fabrication technology developed at Harvard University will soon enable chemical analysis and medical diagnostics with minimal use of reagents and much shorter lab time. The ability to produce polymer lab chips will greatly extend the potential applications of this technology, both inside and outside the laboratory. A portable version is also being developed for field testing, using a portable computer linked to the lab-on-a-chip.

There are also physics-driven applications of the lab-on-a-chip, such as the laser Doppler anemometer on a chip developed for measuring Martian wind velocities. Miniaturised planetary probe/instrument assemblies permitting surveys of large areas of planetary surface have also been designed for future Mars missions. Units weighing less than 2 kg will be deployed from the mother ship, land like bomblets, and penetrate up to 0.5 m into the Martian surface. They can be tethered to a package near the surface, from which an antenna can be extended to transmit data to an orbiting relay above.

These systems have a broad range of other applications, in addition to those in medicine (clinical operations, drug discovery) and crime lab testing (including forensics). These include environmental applications (detection of pollutants) and military applications (detecting biological warfare agents). Tests to identify bacteria, which currently take 36 to 45 hours, could be done in four or five hours with one of the chips recently developed and thus contribute, for example, to the detection of potentially deadly bacteria in food processing.

ELECTRONIC PUBLISHING AND SCIENCE

Electronic publishing can significantly increase the speed of communicating scientific results. It may broaden access to scientific research and allow the inclusion of electronic links. While it might reduce publication costs, this remains unclear and depends on how electronic publication is used. The development of electronic publishing differs significantly among disciplines. The implementation of electronic publishing faces important problems involving peer review, protection of intellectual property, and the archiving of electronic media.

The advantages of electronic publishing

Electronic publishing has been acclaimed as a major advantage of the Internet, and information technologies in general, to the science system. The cost of scientific journals has risen sharply over the past decade, and many universities find it difficult to obtain sufficient funding for their libraries. Electronic publishing has been hailed as a potential solution to this problem, as well as providing additional benefits that make electronic media attractive. Other possible benefits include shorter time between submission and publication, the enabling of multimedia presentations and tailored reading, the inclusion of hypertext links to other relevant material, and the possibility of publishing for oneself.

The claim that electronic publishing can significantly reduce publishing costs has been made in various quarters. Several claim that electronic publishing costs are a quarter of those of print publishing. Many of these estimates, however, do not cover all the costs of operating full-service electronic information services. In fact, commercial publishers discover unexpected costs when establishing electronic journals (Kling and McKim, 1997). For instance, Johns Hopkins University Press is licensing more than 40 humanities journals to universities under a programme called Project Muse. The project has still to break even, despite several hundred university subscribers. About 50 per cent of Muse's costs arise from the development and maintenance of software to validate subscribers and ensure the system's integrity. MIT Press found that while certain costs, such as printing, fell sharply, software costs were substantial; also, they had to engage in greater efforts to market the electronic journals. While these two examples refer to mixed journals, which are distributed both in print and electronic format, the costs of purely electronic journals are not as low as they may seem: many are effectively subsidised. The problem of cost recovery is particularly acute for non-commercial publishers such as scientific societies, many of which derive a large portion of their operating income from journal sales to libraries.

Moreover, the costs of consuming electronic media are not zero (Kling and McKim, 1997). Consumers of science journals are often supported by state-of-the-art networking and computer systems, as well as technical staff. These resources are not free, and many professional users and scientists face difficulties in using electronic media effectively because the social and technical infrastructure of the workplace is underdeveloped. These problems are compounded if research requires collaboration across different technological standards and systems.

While electronic publishing might also reduce the time between manuscript submission and date of publication, this would depend greatly on the character of the electronic publication (Kling and McKim, 1997). Table 4 gives an illustrative example of the time lags involved. The first column shows the conventional scenario, in which all communication is by mail. The second scenario reduces time lags somewhat by using courier mail to send manuscripts and in the peer-review stages. In the third scenario, the manuscript is sent by e-mail, further cutting down transmission time.

The fourth scenario assumes an electronic journal, but one for which a package of articles needs to be available before a new issue is published. Compared with the conventional scenario, this scenario has cut the total time lag by about one month. More gains are made if the editor does not wait for a complete package but allows articles to be published individually in electronic form. The total time lag under this scenario is similar to that of a pre-print system, as used in sub-disciplines of physics, where articles are printed and distributed once they have been accepted by a journal. The shortest time lag – a few days – between sending a manuscript and publication occurs when articles are pre-printed at the time of submission.

Table 4. The speed of scientific communication under different scenarios[1]

In days

	Conventional scenario	**Courier scenario**	**E-mail attachment scenario**	**Electronic journal, with issue packaging**	**Pure electronic journal, with individual articles**	**Pre-print system, article sent at time of acceptance**	**Pre-print system, article sent at time of submission**
Transmission of manuscript[2]	10	4	2	2	2	2	2
Peer review[3]	63-93	51-81	47-77	47-77	47-77	47-77	0
Journal issue packaging[4]	30-120	30-120	30-120	30-120	0	0	0
Journal production	20-80	20-80	20-80	20-80	4	0	0
Delivery of journal[5]	5	5	5	1	1	1	1
Total	128-308	107-287	104-284	100-280	54-84	50-80	3

1. The table shows an illustrative scenario of the impact of electronic publishing, on the time between the sending of an article by the author to a journal, and its delivery in published form to the author. The scenarios assume that the paper is accepted by the chosen journal.
2. This combines the time from author to the editor, and that from the editor to the production manager.
3. This measures the time between the editor's receipt of the manuscript and its acceptance.
4. This is the time taken by the journal editor to produce a sufficient package of articles and send them to production.
5. This measures the time it takes for a subscriber –or the author – to receive the final journal issue.

Source: Based on Kling and McKim, 1997.

The importance of scientific working practices

The appropriateness of systems of electronic publishing differs sharply among disciplines (Kling and McKim, 1997). The most extreme example, with pre-prints made available at the time of submission to a journal, is in high-energy physics. This type of research evolves around a limited number of expensive instruments and involves large collaborative research groups, sometimes with over 400 scientists. Working practices for this type of science differ sharply from those of other disciplines. The collaborative structure of the work and the long time horizons involved mean that the research has been extensively reviewed before submission to a journal. A reviewer is unlikely to find major conceptual errors and is also unlikely to add much in terms of editing. Furthermore, there is little risk of plagiarism. The scientists involved are few and well-known, access to the equipment is extremely restricted, and the time to publication is very short.

This is very different from a discipline like biology. Biological research is quite fragmented and involves many small research groups and individual researchers. Biological research is also easier to extend or copy, and research facilities are common and relatively cheap. Biology researchers are therefore more reluctant to share research prior to publication. Some areas of biology, such as cancer and AIDS research, are also closely linked to commercial applications, and researchers in these fields often work with the private sector. These researchers are often unwilling to share research methods, materials and results, as the work can be lucrative and is often highly competitive. Publication in biology is centred around peer-reviewed journals, and pre-prints are quite rare.

A recent editorial in the *British Medical Journal* proposed a system which treats print publication as the final medium in a process based on significant electronic pre-publication:

> “Researchers might begin a study by posting their protocol on a Web site for review by their peers, possibly followed by a call for collaborators and for assistance in recruiting research subjects. After the research is completed, early drafts of papers would be posted for comments and criticisms, which could then be taken into account in further drafts. At some point the paper would be transferred to a journal’s Web site (if the editors thought it had a chance of

> eventual publication). It might be made available on limited access (to specialist referees and statisticians) or on open access (for anyone to make comments). At some point the raw data from the study would also be posted on the Internet.
>
> After further revisions the electronic version of the paper would be given the journal's imprimatur and made available simultaneously in hard copy and electronic form. The time elapsing between submission and the journal's offer to publish and between ultimate acceptance and publication could dwindle from the current months to days (or even hours)."
>
> (Delamothe, 1996)

Crucial factors determining scientific communication in each discipline are collaborative practices (team composition, sharing of data, commercial character of the research), the use of pre-journal publication formats (pre-prints, working papers or conferences), and the way in which research journals are used (Kling and McKim, 1997). Research journals should be viewed as a package of communicative properties, including announcement, access and trust. The move from print to electronic format may erode these properties and thus erode the (perceived) value of the journal. Pure electronic journals may, for instance, take insufficient steps to announce the journal's availability or may limit access, thus making the journal unavailable to Internet search engines.

Electronic publishing is thus likely to develop a range of formats, depending on each discipline's working practices, in particular differences in peer review. The practice of high-energy physics, which is often used as a model by advocates of electronic publishing, is unlikely to be adopted by scientists in other disciplines. This also implies that the time lag between sending a manuscript and its availability in electronic form is unlikely to be reduced to "a few days". However, electronic publishing *is* likely to speed up scientific publication.

Implementation issues

A number of problems may affect the move to electronic publishing. The first is the potential impact on intellectual property rights. Two issues are critical in this respect, namely how to validate authorship and date of publication, and how to enforce intellectual property rights (Bates, 1994). The problem for governments is to balance the public-good character of scientific research and the need for open access to scientific results with the intellectual property rights held by various stakeholders. Enforcement of property rights is severely handicapped in the case of electronic information, as it is easier to plagiarise ideas, text and graphics stored in this format (Bates, 1994).

Another problem is archiving. Rapidly changing hardware and software may substantially reduce the longevity of electronic information. It remains unclear where responsibility for archiving lies.

There is also a risk that the public might trust unreliable articles. A major point of controversy over electronic media is the extent to which scientists (or others masquerading as scientists) can or will publish unreliable research reports that many people will wrongly trust. This risk is reflected in periodic reports of fraud in biomedical research or in the way that cold-fusion physics was promoted largely by bypassing rigorous research reviews (LaFollette, 1992). Others worry about the risks of “junk science”.

These problems may be difficult to resolve. However, electronic journals can indicate whether the papers they publish have undergone a proper peer-review process. For instance, the Association for Computing Machinery (ACM) has established a digital database for its electronic journals. The database accommodates pre-print practices and allows readers to attach comments to disclosed documents. A subset of the documents in the database is marked as “published”, certifying that they have passed a peer-review process (Denning, 1996). The ACM also guarantees that it will protect authors from copyright infringements. The ACM procedures suggest that the success of electronic publishing will depend greatly on a proper and rigorous process of peer review. Leading scientists may be reluctant to embrace the electronic medium unless proper peer review is guaranteed.

EDUCATION AND TRAINING OF SCIENTISTS

ICT contributes directly to teaching, learning, and research and provides a support function to researchers by enabling access to digital libraries, archives, databases and information services. ICT can have positive effects on learning by opening up access to educational resources, by supporting the learning process, and by supporting skill development. However, this requires efficient planning, and learners, teachers, and institutions that are willing and able to adapt. The enhanced use of ICT in teaching may also help to improve academic productivity, thus enabling scientists to spend more time on research. So far, there is little evidence that this is so. Scientists may also need better education and training to use ICT efficiently for scientific work.

ICT opens up access to education by removing many of the temporal and spatial constraints to information and knowledge. Furthermore, the availability of learning materials based on ICT can greatly improve learning resources. Computers support the learning process by helping to create a student-centred rather than a teacher-centred environment, one which is more flexible and adaptable to individual needs. Working groups formed around the computer can also help prepare learners for a world in which many problems are addressed by teams. Nevertheless, this potential can only be realised with high-quality software and significant efforts by all those involved (OECD, 1997*a*).

Efficient use of ICT allows students to develop the kinds of skills and competencies that many educational reform panels have viewed as essential (OECD, 1997*a*). Basic skills such as arithmetic can be mastered with computer-aided drill and practice, while writing skills can be developed with word processing, which makes writing and revising easier. A deeper understanding of complex scientific concepts in mathematics and science - particularly where experiments are not feasible or are dangerous - can be gained through computer simulations. Last but not least, the use of these technologies for learning may establish familiarity with technologies that are increasingly needed by individuals in a technology-driven society.

Use of ICT in science education and training

Many of the uses of ICT described in previous sections also apply to education and training. Communication between teachers and students is facilitated by these technologies, and both benefit from sharing resources in digital format. ICT may also help science students as it helps researchers, for instance by providing increased computational possibilities and access to remote scientific instruments from the classroom, or by enabling students to participate in actual research.

Two distinctive uses are particularly relevant to science education and training. ICT-based course material (content) usefully supports the understanding of complex scientific phenomena, although it can also supplement conventional classroom activities for many other subjects. This is also true for ICT-based distance education. The use of these technologies for lifelong learning, although not for higher education, was covered extensively in an earlier report (OECD, 1997*a*).

Successful deployment and use of ICT in the classroom still largely depends on pioneering principals and teachers. Nevertheless, data from a recent US survey indicate that it has moved beyond early adopters in higher education institutions into the ranks of mainstream faculty. While data for 1995 reveal that use of ICT in courses is gradually moving beyond routine use, the 1996 survey only found modest gains in the proportion of college courses using such resources, possibly owing to efforts to consolidate earlier gains or implementation issues (Table 5).

In the United States, a third of higher education institutions offered distance education courses in the fall of 1995 and another quarter planned to do so over the following three years, whereas 42 per cent did not offer such courses nor had plans to do so (US Department of Education, 1997). About half of both two-year and four-year public institutions offered distance education courses, but among private institutions, only 2 and 12 per cent, respectively, did so.

Table 5. Results from the US survey of IT use in higher education

In per cent

	1994	1995	1996	1997
Planning				
Strategic plan for role of IT			43.4	48.4
Financial plan for IT purchase and replacement[1]	22.0	22.0	28.1	28.9
Technology use				
Proportion of courses using IT resources:				
E-mail	8.0	20.1	25.0	32.8
Computer classrooms	16.0	24.0	24.0	22.6
Computer simulations/exercises	9.0	14.0	14.4	14.5
Presentation handouts	15.1	25.7	28.4	33.0
Commercial courseware	11.0	18.5	18.5	16.9
Multimedia resources	4.0	8.4	11.0	13.4
CD-ROM based material	4.0	9.0	8.9	11.4
WWW pages		6.2	9.2	24.0
Internet resources		10.9	15.3	24.8
In institutions:				
WWW and Internet				
On site		55.2	79.4	
Plan for use in instruction		24.4	30.1	34.2
Plan for use in distance education		12.5	17.5	24.8
Plan for use for off-campus promotion (marketing)		38.1	56.8	58.3
Recognising IT in tenure & promotion committees			12.2	12.2
Mandatory IT requirement for all students[2]		33.1	40.0	40.3
Considering Internet2 access essential by 1999				
Universities				>50
2- and 4-year colleges				<33
Single most important IT issue confronting institution over the next 2-3 years				
Assisting faculty to integrate IT into instrumentation			27.3	29.6
Providing adequate user support			24.1	25.0
Enhancing/expanding user networks			17.6	11.8
Financing the replacement of hardware & software			17.4	20.4
Using IT effectively in distance education			4.1	11.8
Providing universal access to the Internet			5.8	3.4
Mandatory technology/computer fee for students		28.3	36.9	38.5
Campus systems connected to the network		62.5	70.8	81.1

1. 15.1 in 1990.
2. 31.4 in 1992.

Source: Green, 1994; 1995; 1996; 1997.

To supplement the classroom

Technology-mediated instruction can be implemented in various ways. It may simply be included in conventional lecture-centred instruction. ICT can significantly enrich the range of resources traditionally available in a classroom: computer software, videos, resources on the Internet, and hypertext links to relevant reference materials. ICT-based content makes lecture content more vivid than textbooks, and also can be used for practice and testing. Technology-mediated instruction appears to provide positive results in learner productivity, as indicated by higher mean examination scores and shorter instructional time than in traditional teaching, but may increase the instructor's workload (Gifford, 1997).

More and more educational software has become available in recent years. Content-specific computer or video software used for directed instruction is known as courseware (Box 7). It may be created for education and/or aimed at professional scientists and academics involved in both teaching and research. The *Atlas of the Oceans*, for example, can be used in education to illustrate basic principles by taking a point on the globe and comparing data about that point over the year. For the research community, its advantages are the open format of the data, the inclusion of hyperlinks to references, data and video sequences, and the search capabilities available (*Information World Review*, 1996).

When integrated into the curriculum, computer-based integrated learning can offer extensive instructional activities, cover a range of subjects and grades, and be used to teach core academic skills. However, it requires extensive adaptation of teaching methods and organisation. The development of such courses is difficult and involves a broad range of resources and capabilities. The "mediated learning" model, for example, is designed to improve the instructor's pedagogical effectiveness and the student's learning productivity by shifting the role of the instructor, the student, and the textbook to provide a more interactive, individualised environment (Gifford, 1997). It is particularly well suited to courses that are hierarchical, linear and stable in their structure and content, and therefore to a large percentage of lower-level courses in colleges and universities, notably entry-level mathematics.

Box 7. Courseware for science education

Computer software, designed for use by chemistry educators in lecture demonstrations or by individual students, uses interactive animation to demonstrate more than 50 key organic reactions in order to show changes in molecular geometry, solvation, and charge distributions.

*SIRS, Simulations and Interactive Resource*s, *III* (Journal of Chemical Education Software) provides a collection of 23 programmes on CD-ROM designed to support interactive lectures in introductory chemistry. The programmes include animation, illustrations, and simulations of experiments in areas such as the periodic table, atomic structure, chemical thermodynamics, and acid-base equilibrium.

Interactive Physics (Knowledge Revolution) on CD-ROM is an interactive tool that allows teachers and students to explore concepts such as motion, time and distance, but also force equations, energy and mechanics. Using a mouse, students can draw a model on a computer screen, assign values, and run simulations. Measurements can be taken while a simulation runs.

A multimedia CD-ROM (*Atlas of the Oceans: Wind and Wave Climate* from Elsevier Science) integrates reference text, satellite data and digital video sequences of oceans. It focuses on wind and wave parameters from which contour maps and graphs can be produced interactively by the user. It also includes a searchable electronic book on global wind and wave behaviour.

University students may research the Earth system using Earth observation data and information provided over the Internet. The *Earth System Visualiser*, developed by the Earth System Science Community, enables the analysis and comparison of Earth system parameters using a variety of plot types. Students also learn how to evaluate and publish the results of their team research on the Internet.

A WWW site (Hewlett-Packard Co.) contains articles, newsletters, slide presentations, tutorials, and other classroom resources for people who teach engineering. The site also has tools for teaching the basics of electronics, with over than 60 interactive experiments at http://www.hp.com/info/college.lab.

A partnership of faculty, researchers, designers, multimedia developers, and computer scientists has resulted in the development of a first generation of such courses which can be used by campuses across the United States and which are supplemented by an infrastructure that provides support, maintenance, research and continuous improvement of the product. The system is built around a database that captures detailed information on student performance. On the basis of that information, it is claimed that pass rates have improved by 15 per cent on average and by 40 per cent on some campuses, and that retention rates have increased at 80 per cent of campuses. Subsequent course performance data, still being evaluated, suggest that users continue to achieve well in their studies.

In another example, Rensselaer Polytechnic Institute (RPI) replaced its traditional freshmen physics, chemistry and calculus courses, as well as some advanced courses, by ICT-based processes and achieved better outcomes for learners and somewhat lower costs (Table 6). The courseware used for these "studio" courses combines multimedia instructional materials, simulation building tools, calculation tools, and tools to gather and analyse data. The courses require almost no lectures and few contact hours. Learning takes place through guided inquiry supported by a modest amount of reading. Learning-by-doing experiments are carried out in pairs at students' pace at their convenience. Flexible physical arrangements support both group work and mini-lectures. The classes rely on commercial software and hardware developed for research purposes and on courseware developed specifically for the courses.

Table 6. Cost of traditional and studio physics at Rensselaer Polytechnic Institute
In US$

	Salaries	Space	Total
Traditional			
- Lecture	13 333	3 697	17 031
- Recitation	136 250	3 300	139 550
- Laboratory	77 340	6 600	83 944
- Total	226 927	13 597	240 524
Studio model	157 500	12 000	169 500
Difference (in %)	-31%	-12%	-30%

Source: OECD, 1996*b*.

Distance education and virtual universities

Distance education has existed for a long time. However, educational institutions have only recently become engaged in ICT-based distance education. The WWW, for example, can now be used as an integrated interface for distance learning, often called the virtual classroom or the virtual campus. Virtual environments and simulations – which are likely to continue to transform scientific experimentation and industrial practice – are expected to play an increasingly important role in education and training and may help improve student achievement (National Science and Technology Council, 1995).

Broad cost comparisons of traditional and distance education indicate that the fixed costs of institutional buildings, purchase of equipment, and development of textbook material for traditional classes, on the one hand, and, on the other, those for the establishment/extension of telecommunication networks and the purchase/development of materials for distance learning, are not fundamentally different. However, the fixed costs account for a significant proportion of the total budget of distance education, whereas the variable costs that depend on student numbers are more important in traditional education (Danish Ministry of Education, 1993). Once the number of students which makes it worthwhile to establish distance learning has been reached, it is cheaper to provide the course to additional distance learners than it would be to traditional learners.

The principal advantages of the new technologies for distance education are that they effectively break down the distance barriers and that they are increasingly interactive. These technologies are now being used for distance education by a wide range of educational institutions, among them elite private universities for their graduate programmes. It is important to note that the educational significance of recent telecommunication developments lies in the possibilities they offer for guided self-instruction. The quality of the education provided depends ultimately on the quality of the courseware and the courses offered. These have to be conceived, devised and produced to support guided self-instruction.

OECD countries differ considerably in the use made of the opportunities offered by new technologies for distance education. Several European countries and Japan have used them for open universities in an attempt to remove the barriers raised by conventional institutions. Other European countries, such as France, Norway and Sweden, have added distance education to face-to-face education in dual-mode universities. This has also been the case with post-secondary education providers in Australia, Canada, New Zealand, and the United States, where part-time and off-campus students have traditionally been a significant part of enrolments (OECD, 1996*c*).

Elite private institutions, notably in the United States, have been more selective. While these institutions still make limited use of distance education, their presence may add legitimacy to the distance learning movement. They focus their efforts on specialised degree programmes and courses that can be exported internationally to companies and universities (*Chronicle of Higher Education*, 1997*a*). While some of these institutions are just beginning to examine how to expand these programmes, others, such as Stanford University, have been involved in distance education for years, broadcasting graduate courses in engineering to corporate sites throughout the country. Columbia University supplies graduate university courses to companies in Asia. It has already converted courses in art history, chemistry, Earth sciences, and international affairs to Internet-based formats.

Some pilot projects go beyond university-provided courses at a distance. Pilot projects using the UK SuperJanet network in medicine have permitted students at a remote site to view surgical operations via a video camera, to control the camera remotely, and to maintain audio contact with an instructor. In the United States, a high-speed multimedia network, which links five universities involved in the Science and Technology Center for Computer Graphics and Visualisation, is used for courses, seminars, workshops, and other interactions between students and faculty at the five sites. Each participating university contributes a different area of expertise, e.g. three-dimensional computer modelling, software-controlled machinery, VR, computer graphics, and rendering. This NSF-funded network provides graduate students and postdoctoral fellows with a training experience that is, according to the NSF, more than the sum of its parts and creates a model for distance learning at all educational levels. The high-performance network supports simultaneous audio and video conferencing, remote control of interactive software demonstrations, and data and graphics sharing (National Science Foundation, 1995).

The role of scientific instruments

In institutions of higher education, research, teaching, and learning are closely linked. Scientific instruments can be used to combine education and research. The influence of ICT on scientific instrumentation described above can also be observed in the education and training of scientists. Technology, notably new and affordable software and equipment, can contribute to training even in the undergraduate lab.

For instance, new computer technology may help to release students from aspects of laboratory experimentation, such as repeated data collection, which are of limited pedagogical value, and to focus their attention on the meaning of the data, thereby making better use of laboratory time. This is the goal of a US project to integrate computers into the laboratory. It provides computers equipped with interfaced probes and sensors for measuring temperature, pressure, pH, and conductivity that automatically record, plot and analyse data.

New and more affordable information technologies can also help to give the undergraduate, even the high-school student, access to more complex aspects of science. Educational modelling software can now bring molecular modelling, once the territory of theoretical chemists, into the classroom. ICT may sometimes also permit science students in universities to obtain remote access to and control of instruments in national laboratories. This is helpful because universities do not necessarily possess all the scientific instruments that would be useful for teaching science students.[8]

Results achieved with ICT in learning

The effectiveness of ICT for education and training has been examined in various contexts and compared to traditional teaching methods. The studies have consistently claimed that ICT-based instruction is equivalent or superior to conventional methods and may markedly improve achievement and attitude (OECD, 1997*a*). The specific contribution of the Internet to higher education is currently being examined in France and the United Kingdom. New initiatives, which build on experience gained in the use of ICT, may further improve results; one is the French project to network universities specialising in engineering (VISIO-U), which builds on the experience of the *École Nationale Supérieure de Cachan* in the use of ICT.

The conclusions of several of these studies, however, have been questioned. It is generally agreed that tests of student achievement are crude. Also, spending for ICT has frequently displaced spending for other areas, without due evaluation of their relative merits. Moreover, use of ICT has frequently been accompanied by changes in the classroom approach which may themselves have improved learning. Even when use of ICT is clearly successful, there are important caveats: a few recent applications can substantially expand children's

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[8] Recently, a professor of materials science and engineering at Lehigh University demonstrated the feasibility of remote access to and control of an instrument at Oak Ridge National Laboratory (ORNL) via the Internet. Students could control almost 80 per cent of the operations using a computer, could adjust the magnification and other settings and even the movement and position of the specimen, a super-thin metal film. The microscopic image, an array of gold and palladium atoms, was displayed in the lab with an overhead projector. Technicians at ORNL only had to load the specimen and turn on the high-resolution transmission electron microscope. Communications were carried out via a video-teleconferencing system (*Chronicle of Higher Education*, 1997*b*).

understanding of maths and science, but only if they are properly used; also, because the best educational software is usually complex, it is better suited to older students and more sophisticated teachers. The use of ICT requires close examination of specific situations, rather than across-the-board implementation.

In any case, ICT is not equally relevant to all subjects. An emphasis on outcomes, which derives from a focus on individual assessment, has allowed ICT to make significant inroads into foreign languages, mathematics and writing, where outcomes can be easily evaluated. ICT has a strong potential to increase learning in areas of codified knowledge and algorithmic skills. Fields concerned with questions of meaning and value, or of culture and philosophy, may be less suited to extensive computer mediation.

Implementation issues

The classroom revolution foretold decades ago in many OECD countries has failed to take place (OECD, 1997*a*; Geoghegan, 1996). Technology has not diffused throughout education. While technological development, especially of courseware, and technology acquisition still pose many difficulties, human aspects appear also to be a significant constraint. Many educational institutions continue to deploy and use information technologies without due planning (Table 5). As of 1997, less than half (48.4 per cent) of American colleges and universities had a strategic plan for institutional goals and implementation priorities for ICT, and only slightly over a quarter (28.9 per cent) had a financial plan that addressed acquisition, amortization and replacement issues. Funding is frequently based on one-off budget allocations or special appropriations and competes with other needs, such as more teachers, smaller classes, new books, maps, videos, and microscopes for the science lab (*Chronicle of Higher Education*, 1997*c*).

In many countries, scarce funding inhibits the large front-end investments needed to fully exploit the potential advantages of ICT (Massy and Zemsky, 1995). The courseware market may also be constrained by the (small) market for certain languages, as in Finland and Norway. Producing quality courseware is very complex, and product development and improvement is an ongoing process.[9] Although hardware and networks are generally available, costs remain an issue.

In trying to remedy the funding problem, a growing number of universities in the United States are charging students a special technology fee. More than half of all public colleges and universities did so in 1996, with fees ranging from US$ 20 to US$ 200 a year, and some institutions have attempted to charge students on a use basis. While this is intended to cut down on abuse of resources, it could discourage students from using the technology. Fees are used for new multimedia computers, improved software and more online library resources, data and video networks, and high-speed access of on-campus students to Internet, cable television and voice mail (*Chronicle of Higher Education*, 1997*d*). Students opposed the fees a few years ago, but are now willing to pay for services they consider essential, although critics consider that the costs should be included in tuition.

The adoption of ICT-based strategies in traditional institutions may also be delayed because of conservative tendencies (Massy and Zemsky, 1995). The possibilities of ICT are not always well understood by administrators, and training and organisational change may also be needed (OECD, 1996*b*). The full impact of ICT in education and training may become clearer when it is more broadly used. It will be necessary to pay attention to the needs of a broad range of potential users, for instance by placing more emphasis on consultation, training, information and support (Geoghegan, 1996).[10]

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9. To tackle these problems, an increasing number of partnerships between the public and private sector have been built up. Canada's TeleLearning Network of Centers of Excellence, for example, utilises links between universities, industries and government to develop educational tools through design, prototype testing, and evaluation of emerging technologies.

10. A step in the direction of integrating ICT into mainstream education has been taken by several governments and is reflected in their national plans for education. In the United Kingdom, the National Council for Educational Technology (NCET), a government-funded agency, evaluates, promotes and supports the effective use of ICT to raise educational standards. Recent NCET work emphasizes how ICT can help in the science classroom and provides case studies on measurement and control, modelling, handling, and communicating information. It also demonstrates how to get started, by including basic information on available technology. In France, a new network will link the majority of the 84 universities and the main *grandes écoles*, to combine resources dealing with network-based services and support the development of communications strategies in these institutions.

Adequate user support has also been a major problem. As the number of computers on many campuses has doubled or even tripled in recent years, support has lagged far behind, in part because of a lack of appreciation of its importance, but also, more recently, because of the difficulty of hiring and keeping capable support staff at university-level salaries. In 1996, providing adequate user support became the biggest concern among ICT administrators in public colleges in the United States (42 per cent) while only 10 per cent saw enhancing the campus network as a key issue (Green, 1996).

In their promotion and review processes, comparatively few US institutions (12.6 per cent) formally recognise and reward faculty efforts to integrate technology into instruction. This may make the faculty uncertain about the institution's commitment to the integration of technology in teaching (*Chronicle of Higher Education*, 1997*c*).

In terms of distance education courses, factors frequently reported in the United States as keeping institutions from starting or expanding their offerings were programme development costs (43 per cent), limited technological infrastructure to support distance education (31 per cent), and equipment failures and costs of maintaining equipment (23 per cent). Nevertheless, these were not considered major obstacles (US Department of Education, 1997).

ICT is already transforming education. While ICT applications and their benefits will inevitably vary among disciplines, type of institution, and type of student, the potential for using technology to improve learning is too great to ignore. If colleges and universities fail to adapt effectively, other institutions will take up the challenge (Massy and Zemsky, 1995). In the United States, for example, competition for students who do not desire the expensive and labour-intensive education provided by traditional institutions has already increased. The competition takes place between universities in the form of distance learning programmes, but also comes from other organisations which can use ICT-based teaching and learning programmes with built-in assessment protocols.

So far, most ICT-based educational improvements in productivity have led to greater benefits only at greater unit cost, with ICT acting as a quality-enhancing addition. Funding limits the extent of such improvements. For ICT to lead to cost savings, technology would have to replace some activities now being performed by faculty, teaching assistants and support personnel, given that labour accounts for 70 per cent or more of current operating costs. The Rensselaer Polytechnic Institute courses mentioned above are estimated to cost less than the traditional physics course, for example (OECD, 1996*d*; Table 6). However, such substitution requires great care so as not to undermine educational quality.

IMPLICATIONS FOR THE SCIENCE SYSTEM AND THE ROLE OF GOVERNMENTS

The main impacts

Science, particularly at the leading edge, requires funding, time, well-trained scientists and research assistants, access to data and information, access to sometimes expensive scientific instruments, ways to communicate and publish research results, and ways to join in collaborative structures. Recent developments in ICT, and the growth of the Internet in particular, affect many of these requirements, although their impact differs across disciplines.

It is clear that ICT, particularly electronic mail, has enhanced ***communication among scientists***. E-mail and other forms of electronic communication have enabled more frequent and faster communication, have considerably expanded the size of scientific networks, and have reduced geographical barriers, thereby allowing scientists to build more specialised networks. Scientific work has not been revolutionised, however, nor has the hierarchy of scientific institutions changed significantly. While electronic communication allows scientists at peripheral institutions or regions to maintain contact with leading scientific developments, communication is only one need. Access to funding, scientific instruments, and top scientists is important as well. Because better communication may allow scientists in peripheral institutions to keep abreast of leading-edge science, this may expand the science base.

ICT has also improved ***access of scientists to information*** in many forms. Data and information are among the main requirements for scientific research, and much of a researcher's work involves collecting, processing, and transmitting data. ICT has made it possible to store large databases in electronic form, either on the Internet or in other formats, such as CD-ROMs or digital libraries. The information can take many forms and involve data, text or software. ICT has enabled scientists to rapidly access, process and retrieve these sometimes enormous databases. Data availability and the concomitant increase in computing power have freed scientists from their dependency on central processing facilities, but have also increased the need to share data. Efforts under way in the United States may improve scientists' access to unpublished research such as PhD theses and thereby reduce the amount of duplicated research.

ICT has greatly affected scientific instruments and their use by scientists. The most important impact results from the tremendous increase in ***computing power*** and computer use by scientists. This has helped them deal with many complex phenomena and enabled them to use ever larger databases. In some areas, such as genome research, computers have enabled a rapid shift in the science frontier,. Greater computing power has also allowed strong advances in modelling, simulation and visualisation.

Scientific instruments have been revolutionised in other ways as well. Several have been miniaturised and make it possible to place complete laboratories on one chip. This has significantly improved the speed of analysis, simplified the use of more accurate instruments and lowered instrument costs. In some areas, these developments have significantly undercut the position of central laboratories. Furthermore, software has increasingly replaced hardware in many instruments, resulting in increased use of virtual instruments. The diverse uses of some instruments can now increasingly be embedded in software, allowing the user to determine precisely what the instrument does.

From a global perspective, the main role of ICT has been to enable researchers to access and operate scientific instruments over great distances, thereby contributing to the emergence of virtual laboratories. This may allow scientists, and often graduate students as well, to engage in scientific research that they might not otherwise have been able to undertake. The enhanced capacity to acquire and process data may also have reduced dependency on central computing facilities. The position of central facilities may also be undercut by the expanding use of micro-instruments. However, in some areas, central computing facilities and laboratories remain essential. Access time is scarce at many of these facilities and at other expensive instruments and is generally reserved for the top universities and research institutes. Where broader access is possible, however, ICT might facilitate cost-sharing for some expensive scientific instruments.

ICT has also had significant impacts on ***scientific publishing***. It can significantly increase the speed of communicating results and possibly, but by no means surely, reduce the costs of communication and publication. It can make scientific literature more widely available and, through electronic links, point to easily accessed related material. In parts of the science system, electronic publishing has already been transformed by these developments, and the main scientific publishers are in the process of developing electronic journals.

The move to electronic publishing is not a smooth one, however, and differs substantially among disciplines. The main problems relate to guaranteeing appropriate peer review, protection of intellectual property rights (particularly where commercial interests are at stake), archiving and the long-term maintenance of electronically published media, ease of access to electronically published documents, and ensuring cost recovery from electronic media.

The final impact of ICT on science discussed above involves ***education and training***. Two impacts should be distinguished. First, ICT can improve the preparation of scientists for research. It increases access to educational resources, particularly those relevant to science, and can support the process of learning and skill development. It has a strong potential for improving learning in areas where knowledge is codified or algorithmic skills are involved. This use of ICT may better prepare scientists to solve increasingly complex scientific problems. Training is also essential to help scientists use ICT appropriately. Experience with private ICT investments suggests that this is often an important bottleneck, resulting in a long learning curve, so that return on investment is often slow. Scientists are among the best-trained workers in modern economies, so that the experience of private firms may not be entirely relevant to their practices. However, even scientists may need to adjust to new ICT applications, such as collaboratories.

Second, if ICT helps improve the teaching process, university researchers may be able to spend more time pursuing their scientific interests. So far, the available evidence suggests that ICT has not been able to make a significant difference. It has helped improve the quality of teaching but has not resulted in lower unit costs. It should be noted, however, that the measurement of educational output – and particularly its quality – is notoriously difficult, so that productivity estimates are subject to large measurement errors.

Collaboratories reflect many of the major impacts of ICT on the science system. They often share expensive scientific instruments, involve large groups of scientists in many countries and so depend on extensive electronic communication, require sharing data from large-scale experiments, and are often at the forefront of electronic publication of results. Collaboratories may also allow graduate students to participate in scientific experiments and to interact with experts in their field as well as enable small institutions to share sophisticated instruments.

Diversity of disciplines

The impacts of ICT may differ substantially among disciplines, as working practices of scientists differ considerably (Kling and McKim, 1997). The WWW was developed at CERN (European Organization for Nuclear Research – European Laboratory for Particle Physics), a high-energy physics laboratory. This type of research is very capital-intensive and centralised, and instruments are few and shared by many researchers. It involves collaborative research by scientists in many countries. Those involved are well-known, and the publishing culture makes extensive use of pre-prints. The Internet and other ICT developments improve communication among collaborators, may provide wider access to instruments, and are increasingly seen as a good medium for publishing scientific results. In this type of science, the appearance of an article in a journal serves more as a reminder than as new information (Peskin, 1994).

The impacts on other sciences may be quite different (Kling and McKim, 1997). Sub-disciplines of biology are much less capital-intensive and thus less bound by access to scarce scientific instruments. Collaboration is far less advanced, and research is fragmented among many individuals and research groups. Publishing is geared towards peer-reviewed journals and sharing of pre-prints or working papers is relatively limited. Unlike particle physics or astrophysics, sciences like biology, chemistry and computer science may have relatively straightforward commercial applications, and scientific results are often treated as confidential information.

In the humanities and social sciences, ICT, and the Internet in particular, may have yet other impacts. This type of research often does not involve costly scientific instruments, collaborative structures are fewer, and publishing emphasizes refereed journal articles and books. Part of this work may also have a local character. In these areas, access to data and information and easier communication among researchers may be the main impacts. The Internet may also be used for certain types of research based on survey evidence.

The productivity of the science system

Have all these developments lowered the costs of research or improved the productivity of the science system? This is a difficult question and the ongoing transformation of the science system suggests that it is too early for a definite answer. A number of observations can be made, however. First, the developments outlined above can significantly reduce the time needed for certain scientific tasks, primarily computing, communication, data collection, and the execution of certain experiments. This may help reduce costs, although the evidence remains limited. The impacts may also differ substantially among disciplines.

Second, ICT may lead to economies of scale and scope. ICT allows scientists to specialise and work with many researchers on similar problems, sharing data and instruments, thus potentially creating economies of scale. Electronic media may also break down some of the barriers between sciences, thus enabling multidisciplinary work and economies of scope. However, collaborative arrangements are often highly specialised, while an increasing number of scientific breakthroughs cross disciplinary boundaries or are based on co-operation with private industry (OECD, 1997*b*). The growth of electronic communication and collaborative structures might lead to overspecialisation, which could affect science output in the long run. Moreover, electronic communication is more useful for transmitting codified knowledge, i.e. knowledge reflected in patents, publications and other published media, and less so for the diffusion of non-codified knowledge, i.e. know-how or skills embodied in people. The latter is considered to be increasingly relevant in OECD economies (OECD, 1997*b*). It remains to be seen how these developments will affect the science system in the long run.

Third, the use of ICT in science may involve learning costs and thus reduce the potential gains in science productivity. Scientists are among the most skilled workers in the OECD area, but may not necessarily know how to use ICT in the most efficient way. Collaborative work, in particular, requires a substantial investment in learning to use ICT. University education now gives increasing attention to ICT use, but while ICT use is spreading rapidly among established scientists, not all are sufficiently aware of its potential. Private sector experience with ICT suggests that training and organisational change are important to achieving a return on ICT investment. While some institutes and universities may be able to ensure appropriate support, this may not be the case for all. ICT and Internet use are highest at those institutions with sufficient technical support.

Fourth, leading-edge scientific advances remain expensive and, in some cases, costs may still be increasing. Technological advances and the use of ICT may help to reduce costs in some areas but are unlikely to reverse the overall trend. Furthermore, increased science productivity, if it is occurring, may be required simply to maintain the volume and quality of scientific output in a time of tight budgets in most OECD economies. To some extent, ICT may simply be reinforcing patterns that were already emerging, such as joint research and the globalisation of research.

The role for governments

Predicting the impact of ICT on the science system is difficult. The technologies are changing rapidly and their potential and limitations are still poorly understood. Governments will need to be flexible in their policies towards the science system to deal with these changes and will have to continue to monitor and analyse developments. In terms of policy, governments are likely have three distinct roles:

- ◊ First, they need to support the technical infrastructure underlying the ICT used by scientists and ensure network compatibility (OECD, 1996*a*). They need to ensure that scientists have access to a high-speed, low-cost and seamless research network that connects public and private research institutions world-wide.[11] Since the development of ICT infrastructures will be increasingly driven by commercial needs, governments will need to play a role in ensuring that the requirements of the science system are sufficiently met.
- ◊ Second, they need to provide a regulatory framework that ensures and governs access, protects property rights, and allows the development of collaboratory structures. Increasingly, this will require international co-operation, for instance in safeguarding access of scientists to databases – often commercial – to which they have contributed.
- ◊ Third, in funding science they need to give sufficient attention to ICT needs. Among the areas that might require public support are the establishment of electronic databases and the technical support for and ICT training of scientists. Sufficient support for ICT needs will become an important factor in the competitiveness of science systems. Increasingly mobile researchers and students may use access to ICT resources as an important criterion in selecting universities.

The implications of information technology for the science system will go substantially beyond the OECD area and will increasingly involve developing countries. The challenge to policy makers is to achieve an open and productive science system, where scientists world-wide can exchange research results.

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[11] Policy issues related to ICT are discussed in more detail in other studies, e.g. OECD (1997*a*; 1997*c*).

Several developing countries may be sufficiently equipped to benefit from the emerging global research village and to contribute to a broadened science base. In these countries, access to the international science system may also help to reduce the “brain drain”. For others, however, further efforts will be needed to improve telecommunication infrastructures and to strengthen the human resource base.

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