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WORKSTATIONS IN EDUCATION AND TRAINING

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Preface

This report was prepared by a multidisciplinary team of researchers. Dr. Delayne Hudspeth is an Associate Professor of Curriculum and Instruction, Dr. David Kendrick is a Professor of Economics, Dr. Sten Thore is a Research Fellow in the IC2 Institute and teaches in the Department of Economics. The graduate student research assistants involved in the project are pursuing degrees in Colleges of Business, Liberal Arts, and Engineering. I am a member of the faculty in the Department of Electrical and Computer Engineering.

This is a final report of work on DARPA Project MDA972-91-K-0003. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressly or implied, of the Defense Advanced Research Projects Agency or the U. S. Government.

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1. INTRODUCTION

The advent of the computer workstations introduces a major new opportunity for education and training. These machines are so fast and have such abundant memory and storage that they facilitate the use of high quality color and sound as an instructional medium under the full control of the teacher and the student. Moreover, these machines can be tied together in local, national and, indeed, international networks so that images and sounds stored on large and distant servers are available at the stroke of a key to the probing student.

This report considers the state-of-the-art of workstation hardware and networks in the year 2000. It reviews the state of the art in education software and it considers the economics of the workstations, networks and software. In this framework, the report reviews the bottlenecks which are likely to hinder efforts to take full advantage of workstations in education and training, and some policy options that need to be addressed to minimize the impact of the bottlenecks.

This report is the product of the first phase of a three phase project. The scope of this first phase has been limited to conducting an initial review of the state of the art, identifying the trends in use of computers for delivery of educational and training services, documenting those hardware and software features and attributes that show particular promise in allowing for expanded use of computer workstations in the education and training markets, and performing an initial assessment identifying the categories of benefits and costs that will be associated with developing and using the hardware and software attributes identified.

Using computers to help deliver education and training services is not new. Computer-assisted education and training (CAET) has been used in elementary schools, secondary schools, higher education, adult education, military training, factory training, and small businesses. The next section (Section 2) summarizes pertinent literature on what have been the measured benefits of many of these past efforts. The overall sense of these studies is that significant gains can be attributed to use of computers in education and training. The authors of this report, however, believe that the real potential for advancement lies in the next decade as technological gains in computation, communications, and display capabilities, configured into computer workstations, make possible a realization of the electronic classroom that has heretofore only existed in dreams.

What the future holds technologically is the subject of Section 3 of the report. Advances in workstation capabilities identified in this chapter, and the pace with which the advances will likely be made, suggest that the technology opportunities may far outstrip the abilities of our educational institutions to utilize them.

Section 4 of the report classifies education and training software and comments upon the state of the art. Though there are many brilliant examples of software that have stimulated learning in a variety of contexts, the growing technological capabilities and ever rising implicit expectations of each new generation of learners will necessitate more and better computer-assisted learning tools.

Section 5 then reports what we believe might be significant bottlenecks to realizing the hardware and software potential the coming decade offers. Several areas in which DARPA and the Department of Defense can exercise leadership and stimulate the growth of products and an infrastructure that will facilitate use of computer workstations in education and training are identified.

2. THE BENEFITS OF COMPUTER-ASSISTED EDUCATION AND TRAINING

Computer-assisted education and training (CAET) has been used in elementary schools, secondary schools, higher education, adult education, military training, factory training and small businesses. Applications include reading, writing, foreign language, speech education, math, chemistry, biology, social studies, adult literacy, accounting, bank training, teacher training, and higher level learning.

The benefits of CAET include availability, flexibility, consistency, efficiency, individualized instruction, and economies of scale [1]. The same computer program can be used to create the design of the course, evaluate the results of the class, and assist in the administrative functions associated with training. CAET can also help overcome the difficulties of bilingual training [2]. One advocate claims that CAET produces 30% more learning in 40% less time at 30% less cost than traditional classroom teaching [3]. Others lend support to this claim [4]. Simulators for expensive equipment, such as airplanes, have been found to be even more cost effective. The Educational Computer Corporation has found that simulator training can reduce life cycle and procurement costs by as much as 75% [5].

The benefits of CAET are attributed to a number of sources. One is that students are allowed to proceed at their own pace [6]. The testing features of CAET can help target the students' effort. Pre-tests allow students to quickly step through material they already know, while post-tests guide students toward material requiring further study. Another source may be that students find CAET non-threatening [7]. A major question is whether the entertainment aspect of computers or the ability of the computer to present information in a form that is more accessible for the learners is the reason for the eagerness with which children use computers. Research is showing that accessibility is the key. Using computers helps realize all forms of intelligence in the learning experience [8].

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[1] Ganger, 1990; Madlin, 1988: Ross, 1988, and *Training*, 1989.
[2] Zarley, 1988-2.
[3] Perlman, 1990.
[4] Ross, 1988; Wehr, 1988.
[5] Rushby, 1989.
[6] Wehr, 1988.
[7] Sebrell, 1989.
[8] Thornburg, 1989.

With all the hype surrounding the benefits associated with CAET, it is of interest to see whether the expectations have been validated in controlled experimental conditions. The short answer to that question is, yes (See Appendix E). The general finding is that there is a small but statistically significant gain associated with the use of computers in education and training even with today's limited software and equipment base.

The data for this finding come from evaluations and research of a variety of CAET programs or systems. The evaluations cover a broad spectrum of applications-- reading, writing, chemistry, etc. The desire to compare the results has spawned its own methodology. The difficulty is that the evaluations are not always directly comparable. Consequently, overall reviews use "meta-analysis." [9] The intent is to formalize the procedure for comparing evaluations performed by many different investigators. In comparing results meta-analysis takes into account the effect size of the result and its statistical significance. Effect size is defined as follows:

$$E = (\mu_e - \mu_c) / SD_c$$

E is effect size, μ_e is the mean of the experimental group, μ_c is the mean of the control group and SD_c is the standard deviation of the control group.

Although most evaluations of CAET find the effect size to be small, in every study it is positive and significant. The general finding is an effect size is on the order of 0.42 standard deviations. This translates into moving an average student, i.e. one in the 50th percentile, up to about the 66th percentile. This finding holds across a wide spectrum of applications and leveis of instruction. However, there is some evidence that CAET is most effective at the elementary school level and declines through secondary school and higher education [10].

Four studies looked specifically at interactive video (IV) and interactive video disc (IVD)[11]. Bosco (1986) looked at evaluations that ranged across all levels of instruction from elementary school to higher education, military training and industrial training. Not all the evaluations included a control group so effect size could not be calculated. Bosco used a

[9] The method is described in Glass, 1976.

[10] Niemiec and Walberg, 1987.

[11] Hannifin, 1985, defines interactive video as "any video program in which the sequence and selection of messages are determined by the user's response to the material."

simple box score method. His overall findings are weakly positive. Fletcher (1990) compared 28 studies including 13 military training, 4 industrial training and 11 higher education. Effect sizes were calculated for each group and across a number of criteria. The strongest results were found in higher education studies-- .69 vs. .39 and .51 for military training and industrial training, respectively. Studies were also compared across outcomes for knowledge, performance and retention. All results were positive. The largest positive results were found in time to complete instruction. The average effect size was 1.20. This suggests that IV can play a significant role in reducing time needed to achieve the same learning outcome.

Clark (1983) cautions that the observed results in the recent meta-analyses may be attributable to reasons other than the training method. Clark states, "the best current evidence is that media are mere vehicles that deliver instruction but do not influence student achievement." The observed positive results may be a product of the degree of effort put into instructional design. Presumably, the students in the control groups would fare better if the same degree of effort was put into conventional instruction material. This possibility is partly addressed by Kulik, Kulik, and Cohen (1980). They discuss the effect of having the same or different instructors teach the control and experimental groups. They find that with the same instructor, the difference in performance nearly disappears.

The reader is reminded that these studies are based upon results of education and training activities that are based upon use of computer hardware with capabilities we associate with personal computers and very limited use of local area networks (LAN's). As such, they represent only the tip of the iceberg when one considers what might be possible with CAET ten years into the future. The next section attempts to project how the hardware capabilities might evolve over the next ten years.

3. WORKSTATIONS IN THE YEAR 2000

There have been rapid advances in all aspects of computer hardware and software for the past thirty years. Improvements in microelectronic circuit fabrication and manufacture have made possible a doubling of the amount of computing power placed on a single integrated circuit chip about every three years since the early 1970's [12]. Improvements in materials and disk design have resulted in tremendous strides in data storage [13]. More recent advances in video display technologies combined with various data compression techniques hold promise for widespread application of video capabilities that are now the exclusive domain of only the most advanced television and motion picture studios [14].

What will the capabilities of these technologies be in the year 2000? If past trends continue, ten years into the future will see three generations of computer chips come and go. The chips that are the subject of today's R&D will just be coming to market fruition in the year 2000. Trying to project the capabilities this far into the future, when the pace of technological advance is as rapid as it is in this field, is very difficult. Nonetheless, recognizing the risks involved, we venture a look ahead to the year 2000 for three classes of machines-- a ten thousand dollar machine, a one thousand dollar machine, and a state-of-the-art portable. Also we look at the network capabilities to which these machines will be connected (Appendices B and D provide additional detail). The projections are offered so that an explicit framework is available for assessing the potential of the technologies in education and training applications.

a. A Ten Thousand Dollar Machine

By the year 2000 we expect ten thousand dollar workstations to have about 500 megabytes of memory, 1.5 gigabytes of hard disk storage, and microprocessors which will function at 1,500 million instructions per second (MIPS) and 500 million floating point operations per second (MFLOPS). These machines will have color CRT displays with the same or better resolution as high definition television (4,096 pixels by 4,096 pixels). They will be connected over networks operating at bandwidths of 1-10 gigabytes per second -- some 20-200 times faster than the present Ethernets.

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[12] See for example Bajorek, 1989 and Takata, 1989.
[13] See Funk, 1989.
[14] See Kotzle, 1989 and Yoffie and Wint, 1987.

Software will be available to compress files by a factor of 100 to 1,000 or more, and this combined with the processing, storage and networking capabilities described above will permit the real time display and manipulation of portrait quality images and compact disk quality stereo sound in educational environments. By this time commercial servers (see below) with terabytes of storage will begin to store, for immediate retrieval, relatively small but interesting portions of major libraries.

In the year 2000, the ten thousand dollar workstation will have two interesting and less expensive cousins. These are discussed below.

b. A One Thousand Dollar Machine

This machine will be the equivalent in cost to the current Macintosh Classic, which is about $1,000. It will have a processor that will function at 150 MIPS and 50 MFLOPS with 50 megabytes of memory and with a 150 megabyte hard disk. The display will have grown to 2,048 by 2,048 colorful pixels. This machine will have less processing capability than its more expensive relative but it will be connected to the same high speed network and thus have high speed access to information on distant servers.

c. Portable

The other cousin of the year 2000 workstation will be the portable, costing anywhere from $1,000 to $10,000 depending upon its weight and attributes. It will weigh anywhere from one to fifteen pounds. It will have a color flat panel display ranging from 1,024 by 1,024 pixels to 2,048 by 2,048 pixels. Its hard disk will store about 75-750 megabytes and it will have processing speeds of 75-750 MIPS and 25-250 MFLOPS.

d. Networks and Servers

By the year 2000 local area networks will have made the transition from Ethernet speeds of 10 megabits per second to a new standard of 1-10 gigabits per second. Educational servers will exist on the network with terabytes of storage. These machines will be able to download a ten minute video clip with CD quality sound to a workstation in 30 seconds or less.

Reference works of all kinds will be available on the servers and film and VCR tape materials will begin to be available. A substantial portion of the world's music, maps, and high resolution photographs will begin to be offered via servers.

This high speed network, with access to enormous amounts of information on a national and international scale, will probably be the single most significant change in the way in which computers are used in the year 2000. The technological opportunities will present numerous challenges in many areas of business and government. The challenge focused upon here is how to capitalize upon the hardware, software, and networking capabilities that will be available to improve delivery of education and training services in our country. To what extent might this be beneficial? What will hinder these developments? Before turning to potential bottlenecks, we review the software for education and training.

4. EDUCATIONAL AND TRAINING SOFTWARE

With continuing trends of decreasing hardware costs, software costs will be a critical component of the costs of using workstations for education and training in the year 2000. What kinds of software will be available and how will they be used in education and/or training? This section attempts to answer this question.

In what follows the various types of education and training software are classified as either general education software or one of two kinds of training-related software based upon whether it is primarily directed to imparting a knowledge base or job related skills.

Though, traditionally, educational objectives were accomplished via textbooks, blackboards, and instructors, with the advent of the use of the computer new methods of presentation and learning are possible. Educational courseware is defined to be set of programmed lessons on a specific topic or field of study. Training-related software is classified into workplace tools and virtual world software. Workplace tools include applications software such as spreadsheets, text processors, and some computer aided design programs. When a student uses workplace tools during training, he or she is doing on the computer exactly or almost exactly what the individual would be doing in a real work situation once the lesson is mastered. This is the mode by which a large part of training is accomplished today.

Virtual world software enables creation of simulated environments. Such computer simulation environments have application in flight training, business planning, or air traffic control. Unlike workplace tools, however, virtual world software is seldom used directly on the job.

a. Educational Courseware

General education courseware will likely exploit all the capability that the workstations of the year 2000 can offer - in terms of memory, disk storage, processing power etc. Whether the courseware is in a classroom setting or is stored on distributed databases, it will involve high network traffic with stringent demands on response time. For development of good quality courseware, new presentation tools are needed. These tools should be easy to use and make for easy development of courseware. But the main determinant of quality will be the experts who create the courseware. Good presentations should go together with high quality content. Several educational software packages (such as IBM's Linkway system) are currently being developed, enabling a teacher with little or no computer experience to incorporate graphics, animation, music, video and photographs into a lesson where there were previously only still pictures and the lecturer's voice.

The courseware available is most usefully analyzed by grouping it by type of teaching environment. There is first the classical classroom setting with a teacher, blackboard and students arrayed at their desks. There is new software in the making to provide substantial gains in efficiency in this setting.

A second environment is self-paced learning environment or the one-on-one, i.e. one student-one computer, in which the student engages in a learning process with the computer as mentor and aide. This is probably what comes to mind when most people think about computers and education.

A third setting is the hypermedia mode. This is much like the self-paced learning in that it is one student-one computer, but it is radically different in that the student rather than the computer provides most of the structure for the learning experience. In one-on-one the instruction is organized as a graph as in the sense of graph theory. The designer anticipates the major paths that the students will follow in accomplishing a well defined learning objective. In contrast, using hypermedia techniques the student is invited to branch in whatever direction he or she chooses and may feel richly rewarded when exploring areas of knowledge the instructor had not anticipated.

i. Classroom Courseware

By the year 2000 microcomputers in the classroom will be networked mini-workstations with extremely high speed communication. Software is developed now which will enable the teacher to control video from laser disks or VCR's, sound from compact disk or DAT tapes, and presentation slides from the machines' own hard disks in an array of ways that enable the class to work together. The software also provides the teacher with maximum feedback on students' progress. For example, a short instructional segment on setting the switches properly in a helicopter before takeoff can be followed by a short quiz on the proper settings. The teacher can keep the students' attention spans at higher levels because of multi-media and the demand for feedback. The teacher knows immediately, from the feedback, whether the pace of the instruction should be slowed down or increased.

Courseware of this type has the potential of high motivation Another important advantage is that the students need not be present in the same room as the instructor, only connected to the network. The response time on these networks to be quite short to be effective.

ii. Self-paced Learning Courseware

Self paced learning (one-on-one) courseware can be an extension of the classroom courseware. This software can and will be designed to permit the students to branch off either during the period of formal instruction or in some later laboratory period. In this mode, small quizzes can be used to inform the teacher of the students' progress, to provide each student with feedback on his own progress, and to repeat those parts of the material which were not mastered on the first pass. For a motivated student, they provide flexibility to learn at his or her own pace.

This kind of self-paced learning courseware is the basis of the system, purported to be the largest multi-vendor network in the world, developed at the Massachusetts Institute of Technology[15]. Called "Athena", it comprises 1100 workstations available around the clock for students and faculty. Its electronic mail feature, allows students to file written reports and teachers to correct them. For a language lesson, a student can call up a windowed videotape presentation of a native speaking in his own dialect. Examples of self-paced learning courseware are seen in math modeling software like SIGMA (Simulation Graphical Modeling and Analysis system)[16] and others[17]. This kind of software comes with sets of test problems, tutorials etc. designed to develop concepts rather than just explain the mechanics of the subject.

iii. Hypermedia Courseware

Hypermedia courseware is also used in a one-student one-computer teaching environment, but its essential feature is multiple path computing. Consider the two roles of any manual or textbook:

(i) To provide a source of data on the subject matter at hand. Typically, such a presentation is "linear" (a book on gardening deals with plants from A to Z, a text on Napoleon's wars proceeds chronologically.)

(ii) To effect understanding and learning on the part of the student, i.e. to set up associations within the student's brain between various parts of the text internally, and between the text and other external information stored in the brain of the

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[15] See Freedman, 1988.

[16] See Schruben, 19xx. SIGMA was developed at Cornell University and marketed by The Scientific Press. The SIGMA software is accompanied by a set of questions and suggested solutions. These are designed to teach the student how to build discrete event simulation models. The book accompanying the software is more of an introduction to event graphs and discrete event simulation than a software manual.

[17] See Thompson, 1990.

student. Such understanding is typically hierarchical (such as an ability to discuss and evaluate a particular garden visited during a field trip; or forming an opinion as to whether Napoleon's war on Russia was well planned).

The difficulty with conventional learning methods, such as the classroom lecture, is that it takes on only role (i), but leaves the student entirely on his or her own when it comes to (ii). The student passively takes lecture notes, copying in his notebook the lecture notes of the teacher. But the real task at hand is not to transmit lecture notes but to communicate understanding. Understanding can actually be delayed by forcing the student to study the information in its ordered linear progression, rather than permitting the student immediately to embark upon the task of setting up tentative hierarchical hypotheses, searching toward understanding by an experimental inquisitive process of the mind.

Hypermedia courseware will allow the student great flexibility in what is referred to above as mode (ii) learning. The student, seated in front of the workstation, may at any point during the presentation of text, video, or computed material, set off in any direction, backwards or forwards in the program flow, to search for answers to questions that may have presented themselves in his or her mind. There are multiple paths leading through the software, the branching decisions to be made by the student. Such flexibility will allow the student to sweep through at an accelerated pace some sections of the program, exploring other sections in depth, returning for review, or vaulting forward to gain an advance vantage point for the understanding of material yet to come.

An example might be a student who begins reading about the Ottoman empire and finds a reference to the city of Basar. He clicks on this word and is presented with a map of that region of Turkey. He wants to see the region in a larger setting and clicks on an option that expands the map to cover parts of Greece and Bulgaria. He requests a map of that region in 1250 and it appears. He sees a symbol for a key battle on the map and clicks on the symbol to obtain a portion of an old movie about this battle. This is the kind of unstructured learning which is the joy of many students.

The development of this kind of teaching medium requires (i) high quality scanners and scanning software for both words and graphics as well as video and audio capture and playback devices. It also requires the input of knowledgeable scholars who can anticipate the possible tracks that learners may want to follow through the literature and films. Work along these lines has occurred in the Intermedia project at Brown University and at many other universities around the country [18]. The demands for hypermedia courseware should dramatically increase as the hardware and networking capabilities discussed previously become reality.

b. Workplace Tools

In some learning situations, the learner does on the computer exactly or almost exactly what he or she will be doing in a work situation once the lesson is mastered. The accounting student doing exercises with Lotus 1-2-3 on a high speed microcomputer in a university classroom is using exactly the same tool that the individual will be using once he or she takes a job working for Exxon in Houston. The database system used to learn inventory management is no different than the database used to manage those inventories after graduation. The CAD/CAM package used to train budding engineers is exactly the same package which they will use their first day on the job. In each case the computer is not solely an aide to education because it is both the learning tool and the workplace tool. Improvements in the software and hardware of tomorrow's workstations will lead to direct improvements in the productivity of workers who use the tools.

c. Virtual World Software

Perhaps the most daunting challenge facing future educators is to use advanced computational capabilities to teach tacit knowledge. As computers and automated machinery take over the simpler functions of human labor, the real bottleneck in the future economy may become precisely those human faculties that are not easily handed over to pre-programmed software or hardware, but which are still the perogative of the human mind. Imparting non-computable "tacit knowledge" is facilitated with use of simulated environments categorized here as virtual world software.

"Information" is usually defined to be computable, meaning that it can be transmitted digitally. But much engineering and business competence and expertise is not directly computable, such as negotiating skill or management skills. Such qualities have been referred to as "tacit knowledge". It can be described not in terms of bits of information but in terms of insight, experience, gestalt, and judgement.

Though tacit knowledge may not be computable per se, the workstation can be used to set up an array of varied simulated environments where the student can test his or her ability to make sound judgements and sound decisions. Examples might be nuclear reactor incidents,

[18] See Dezell, 1990.

air traffic control situations, or stormy weather patterns in a flight simulator. The teaching of tacit knowledge has been facilitated using interactive video, followed up by computerized post-simulation analysis including a critical evaluation of the performance of the student. Two factors seem to be important here: realism and the opportunity to make errors and to have the errors analyzed. Making errors and correcting errors stimulates the creation of control mechanisms (feedback) in the brain that are part of the learning process.

These environments are characterized by role playing. There are many possible applications that might be classified according to the number of operators involved.

i. One Operator Virtual Worlds

Examples of one operator virtual worlds occur in the training of pilots, air traffic controllers, process control operators, and oil field operators.

The detailed forecasts the hardware that will become available in the year 2000 is easier to do than similar forcasts on the software side. We would like to point out, however, the potential of voice recognition systems. Such systems are still in their infancy, but rapid progress fuelled by a host of commercial applications may be expected. It then becomes possible for a human to engage in a "conversation" with the computer, the computer decoding spoken words and responding in a preprogrammed fashion. Using video, audio, and other media the computer may create a virtual world where the student is asked to respond to situations, as they are created, with spoken rather than written commands.

Consider this possibility for a lesson in the French language: the media in front of the student creates the setting of a railway station in Paris. Through interactive video, the student approaches the ticket counter and engages the clerk in conversation, ordering a second class ticket to Lyon. The computer decodes the broken words of the student, correcting both pronunciation and grammar. Next, the student chooses to approach the candy shop to buy a chocolate bar, etc. Although no single such software package exists today, all these things can be done on a computer today, albeit in a much more simplified setting. Note that to learn a foreign language is not just understanding. It is also very much, perhaps mainly, training -- repetition. The computer is a teacher that never gets tired.

An interesting software sector that no doubt has a great future in education and training is computer games. It is also one the most profitable and best selling software sectors. Some recent games point the way of the future. One of them is the "Moonbase Lunar Colony

Simulator"[19]. This - - as many computer games - - is a game of survival, where the player step by step extends a colony on the moon, building living quarters, greenhouses, solar electricity generators etc., but all the time operating on a limited budget and facing the risk of a variety of natural disasters. Playing this game repeatedly, the student acquires a feel for the magnitude and nature of these various risks and learns how to safeguard against them. As a result, a trained student scores much better than a novice. In brief, the game enables the student to gain "experience". The computer has imparted "tacit knowledge" to the student.

Consider the kind of realism that computer games can provide, employing the emerging possibility of combining video and animated video. The computer screen displays a video clip from the lunar surface. In a window on the screen, the student assembles a water storage tank. The student is pleased with the design, and decides to erect it on the lunar surface. Using the mouse, he clicks onto the tank and drags it across the screen, introducing it into the video picture.

ii. Multiple Operator Virtual Worlds

In a multi-person game several students interact with the software at the same time. Multi-person games can be employed to teach students to develop complex reasoned strategies. Examples are negotiating games, and marketing games, such as the well known Carnegie Mellon decision making games, where each team of players directs a separate laundry detergent company. Other examples include bank management and international marketing games. With older computer technology, such games were played over weeks. With a workstation, they can acquire entirely new dimensions of speed and realism.

[19] See Wesson International and KDT Industries, 19xx.

ii. Policy studies

Policy studies virtual worlds are used to do "what if" studies of policy changes. For instance, American Airlines has used simulations to study air traffic in a simulation model called Simmod [20]. Eurotunnel project teams used object-oriented simulations of Eurotunnel terminals to optimize facilities and operating procedures prior to construction[21]. Other software has been used to study the effects of policies designed to limit the emissions of greenhouse gases on global climate, to study the effects of limits of farm subsidies on agricultural production, and to study the effects of limits on growth of strategic weapons on the military balance of power.

iv. Conclusion

Without doubt, education and training stands at the edge of a new era. Courseware and computers and multi-media are on their way into the classroom and they will change the fundamentals of what teachers do, and what students do, during the course of education and training. By the turn of the century most educational facilities will be involved in this revolution. A new educational concept is being born. If the challenge is faced squarely and at an early enough point in time, there is no reason why the U.S., with its solid eminence in the software field, could not emerge as a world leader in the production and deployment of courseware to be used at the workplace, in schools, and in training for both civilian and military purposes.

In particular, we want to point at the emerging possibilities of imparting "tacit knowledge" to the student by the use of suitable courseware. Although, strictly speaking, such knowledge is non-communicable, it yet may be imparted to the student through the creation of virtual worlds where the student can train his or her perception, judgement, and practice strategy formulation and decision making.

The coming revolution will not only expedite the learning processes that formerly took place in schools and training facilities - - it will introduce new potential for the transfer of human experience and abilities.

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[20] See Zarley, 1988-2. Simmod -- available through Federal Aviation Administration is public domain software.

[21] See Salt, 1991.

5. POLICY STRATEGY

What should DARPA and the Department of Defense do? We begin with two premises. The first is that the trends of advancement in workstation hardware and networking capabilities discussed earlier in this report will continue throughout the decade of the 1990's and beyond. The second premise is that DARPA, though small, is an organization that can significantly influence the application of the hardware capabilities being developed. We believe that DARPA has great credibility with key members of Congress on matters of science and technology and their effects on national security. If these premises are correct we think that DARPA should not become involved in the myriad of small issues surrounding the development and evaluation of software for use in education and training. Rather, DARPA should consider two kinds of actions which would permit a relatively small organization to have a large impact.

a. Expenditure

First DARPA should use its credibility with leaders in the Congress to suggest legislation that would provide incentives to state governments to increase greatly the availability of hardware and software in the educational system from kindergarten thru high schools. According to our estimates a budget of less than $7 billion per year would be sufficient to provide one $1,000 workstation for each five students and for each teacher in grades K thru 12 in the year 2000. This budget would also provide for each student $300 for software and an annual stipend of $200 for online database charges and royalty payments for the use of copyrighted materials. The purchase plan is staged over a four year period so that not until the fourth year would all machines be in place. However, this procedure assures that a continuing budget of $7 billion per year would be sufficient to replace the machines each four years as the technology changes. (See Appendix A for details).

Since the public education budget for the year 2000 is projected to be $244 billion, the expenditure of $7 billion on hardware and software would be less than 3% of that total.

Some will argue that in this time of tight budgets there should be no increase in total spending on education. However, in this situation the same goal of one $1,000 workstation per five students can be reached by doing in education what has been done for decades in business, agriculture and industry, i.e., substitution of capital for labor. In this case the labor is teachers and the capital is workstations. However, it is not even necessary to increase the student-teacher ratio. Rather, it is projected that the student-teacher ratio will fall from 17 to 16 between 1990 and 2000. If we forego that decrease and keep the student-teacher ratio at 17 in the year 2000 the savings would be almost sufficient to provide the $7 billion annual budget for workstations. (See Appendix A for details.)

The $7 billion annual budget proposed is sufficient to make a large increase in the demand for educational hardware and software. This demand in turn could exploit the American entrepreneurial system at its best to bring about a widespread and decentralized effort to provide the kinds of hardware and software which will capture the imagination of students and permit a shift from a teaching to a learning focus in the classroom.

However, we do not think that it is sufficient to simply increase funding and this is the source of our second recommendation for a policy strategy. We have great respect for the capability of the American market system to spark creativity and to respond to the needs of the educational system, if there is sufficient demand. However, we also think that there are important bottlenecks in the system where economies of scale are such that sharply directed actions by DARPA can be of great value. One such area identified in the previous chapter relates to the development and transfer into the public sector of low cost software for creating and manipulating interactive virtual world environments. A number of other examples are discussed in the next section.

b. Bottlenecks

i. Courseware Development Software

Consider here the instructor planning a lecture. Presentation software tied to word processing and graphical packages is now widely used. On the workstations of the future this software will be replaced with software to orchestrate video and sound as the instruction draws from CD's, VCR's and laser disks, as well as from graphics stored in the memory of the workstation. The development of software tools which can be used to create courseware is a process which is characterized by major economies of scale. The cost of creating such tools is great but this cost can be spread over many users.

DARPA could help to overcome the initial high cost of creating courseware development software tools by providing research contracts. Also, the Department of Defense could help to provide initial demand for the courseware development tools which would be helpful in defraying the initial cost.

ii. Copyrights

Consider the hypertext mode of instruction. Key material inputs are published works, as well as film and music. All of this material is copyrighted. The market mechanisms for selling the raw material to the computer user are not well developed. Also, the budgetary allowances on the user side are frequently nonexistent. This is emerging as a major bottleneck.

What is needed here is the development of markets which allow the copyright holder to receive a fair return for his or her investment while providing ready and unimpeded access to learning materials by students. The Department of Defense faces the same problem that colleges and schools face and could play a major leadership role in establishing a demand for these copyrights and encouraging the creation of markets to handle remuneration associated with their use.

iii. Networking Needs

Predicting that networks will become more powerful ten years into the future is not difficult. What is difficult is predicting the new growth areas these powerful networks will spawn. The increase in power will take the form of increased bandwidth due largely to an improved transmission medium such as fiber optics. As a result of the higher bandwidth, the networks will accommodate data, audio and video.

A precursor to being able to deliver many of these information services will entail extending fiber optic cabling into businesses and homes. The next logical question to ask is, who will do this? The group that immediately comes to mind is the telecommunication industry. However, current regulations prevent the Bell operating companies from being able to deliver electronic information services, including television. They therefore lack incentive for investing in such a network [22]. That is not to say that the long term results of building the network would not be profitable for them as well as many others, it is just that the benefits are not clearly visible.

The question of how we will get a high-speed network built and what its impact on our economy will be are important questions to be answered, especially when the following situation is taken into account. Japan plans to spend as much as 250 billion dollars by the year 2000 on a fiber optic network. In return, Japan expects to receive a total of one-third of its gross national product from services carried by the fiber optic network by the year

[22] See "Fiber-Optic Network is Urged at Conference," New York Times, p. c6, 1990.

2015 [23]. This illustrates the tremendous impact a future fiber optic network could have on a society.

Michael L. Dertouzos, professor of computer science and electrical engineering at MIT's Laboratory for Computer Science, is stressing the value of a network infrastructure within the United States. He says, "computers will become a truly useful part of our society only when they are linked by an infrastructure like the highway system and the electric power grid, creating a new kind of free market for information services." [24]

DARPA was the creator of the first major computer networks in the country. There are major economies of scale in both the networks themselves and in servers. DARPA could play a key role in the development of the hardware and software which permits networks and servers to be used efficiently by learners of all ages.

iv. Software Platform

One aspect of software adoption is compatibility. An instructor preparing software with a graphical interface faces a very divided market. There are at least three or four major graphical interfaces today, such as Windows, Presentation Manager, the Macintosh Finder and X-Windows. Teaching software prepared by the instructor or by a software development firm is originally designed for one of these interfaces. However, there are major costs in porting the software to other graphical interfaces. A platform is needed for the courseware development. This bottleneck might be removed by a class of software which efficiently ports software from one graphical interface to another. Or alternatively, a higher level interface language might be created which would then write the code for a variety of graphical interfaces.

In summary, we believe that DARPA can amplify efforts in the education and training software area by

(1) providing ideas to the Congressional leadership which could result in sufficient increases in expenditures to make a large impact on hardware and software availability in the schools, and

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[23] Op. cit.
[24] Dertouzos, M.L., 1991.

(2) launching highly targeted research programs to tackle key bottlenecks where economies of scale are important. Such programs might focus upon the four bottlenecks identified above: creating courseware development software, establishing efficient copyright markets, expanding network capabilities, and establishing a suitable education software platform.

By amplifying its efforts in these areas we believe that DARPA can greatly facilitate the realization of the potential benefits that computer assisted education and training offers over the next decade and into the next century. The benefits will accrue to the Department of Defense, the nation, and all Americans.

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Appendix A. Data on Education and Training
by Michael P. Gallaway

"One thing is certain: the learning enterprise is enormous. Formal learning of all kinds, occupies about 77 million people annually and costs as much as $304 billion. In 1988, almost one in every three Americans was a student or a trainee." [1]

This appendix contains data and descriptions of the methodology used to derive cost figures in the body of the report. Section I describes cost estimates associated with equipping public schools with workstation technology. Section II addresses the cost of private industry expenditures on education and training of its workforce. Section III looks at education and training costs incurred by the military. Appendix E will address potential benefits of workstation technology in education and in the training process. Also, interspersed in this appendix are various pieces of background data that may be useful as reference points for discussions carried out in the body of this report.

I. COSTS OF COMPUTER TECHNOLOGY IN THE PUBLIC SCHOOL SETTING

Expenditures on public primary and secondary education in the U.S. have increased steadily during the 1980s - both in current and real dollars. Nominal expenditures increased from $96 billion in 1980 to approximately $204 billion in 1990. In real terms (1989 dollars) total expenditure increased from roughly $150 billion in 1980 to an estimated $195 billion in 1990 [6,8]. Hence, in real terms, public school outlays have increased at a rate of approximately 2.7 percent per year after inflation during the 1980s.

The principle sources of funds for public primary and secondary education are state and local governments. Federal funding of education as a percentage of total revenues has actually dropped during the decade of the 1980s. State governments generate approximately 49-50 percent of total revenues while the local levels account for 41-45 percent. The federal government makes up the remaining 6-9 percent. [6]

A breakdown of public school expenditures reveals that the overwhelming majority of spending is on day-to-day operations. This includes outlays for instruction, administration and plant operation and maintenance. Between 1980 and 1989, these expenditures accounted for roughly 92 percent of total outlays. Capital expenditures which include budgets for high technology equipment account for only 6.5 percent of the 1989 total which translates into a figure slightly more than $12 billion [6]. However, budgets for technology purchases are only a small part of this total. This is evident by the fact that the student-computer ratio in the United States during 1988 was 27 to 1. [9]

Estimating the total cost of equipping our schools for the information age requires a certain amount of speculation due to the difficulty in predicting the rate of technological innovation. Although there is a large amount of uncertainty in estimating the technological capabilities of machines in various price ranges during the year 2000, the cost estimates used in this appendix assume that schools can employ the basic $1,000 machine. All subsequent dollar amounts are given in terms of 1989 dollars.

Of prime importance in estimating expenditures for technology in our schools are projections of the number of individuals that will be using the technology. Table 1 summarizes projections of student enrollment and teacher requirements for public schools in the U.S. in selected years. Student numbers peaked during the 1970s with the baby boom generation passing through the education system. Since that time, the number of students has dropped but is back on an upward trend as the children of baby boomers have begun migrating through the system. Table 1 shows that public school enrollments are expected to remain relatively steady between 1990 and 2000 with an increase of only .8 percent per year. Since annual enrollment growth is expected to be very small, only enrollment estimates for 2000 will be used in in the following discussion to estimate costs of equipping public schools for the information age.

Table 1: Estimated public school enrollment and teacher requirements for selected years (in thousands)

	1990	1995	2000
Students K-12	40,801	43,682	44,186
Teachers K-12	2,401	2,602	2,772

SOURCE: *Projections of Education Statistics to 2001*

The assumptions used to derive cost estimates are as follows. It is assumed that each computer will cost $1,000, i.e. the current cost of a Macintosh Classic. These machines are purchased at a rate of one computer for every teacher and one computer for every five students. In addition, student machines are projected to require $300 in software to operate and have online database charges and royalty payments for copyrighted materials of $200 per computer per year. Computers used by teachers are assumed to require $300 in software and $300 per year in online database and royalty costs. In addition, teachers will require approximately $500 worth of additional hardware to be used with their computers. These assumptions are summarized in Table 2.

Table 2: Assumptions used in deriving cost estimates. (1989 dollars)

	Computer	Additional Hardware a	Software	Royalties & Online Time b
Student Computers (1:5)	$1,000	0	$300	$ 800
Teacher Computers (1:1)	$1,000	$500	$300	$1,200

a) Additional Hardware includes additional devices such as a CD player, VCR and a videodisk player.
b) Royalties & Online time includes online charges for databases and royalty payments for copyrighted materials used from those sources. Per year assumptions are found by dividing these totals by four.

It is postulated that the necessary technology will be purchased during a four year cycle i.e. computers are replaced every four years and purchases are staggered uniformly over the four year period. In this way, as the technology becomes outdated it can be replaced with more advanced systems and software. The figures are broken down by category in Table 3 below and are summed to show the total cost over each four year cycle. Accordingly, the yearly budget allocated to the procurement of technology will be approximately $6.72 billion ($26.88 / 4 or roughly $7 billion) per year. This estimated cost of technology compares to a projected total public education budget of approximately $244 billion in 2000.[25] Therefore, technology purchases represent only about 2.75 percent of the total projected real expenditures for 2000 or a per student cost of just over $150 per year.

Table 3: Total cost of supplying computers to public school students and teachers in grades K-12. (In Billions)

	Computer	Additional Hardware a	Software	Royalties & Online Time b	Total
Students	8.84	0	2.65	7.07	18.56
Teachers	2.77	1.39	.83	3.33	8.32
Total	11.61	1.39	3.48	10.40	26.88

a) Additional Hardware includes additional devices such as a CD player, VCR and a videodisk player.
b) Royalties & Online time includes online charges for databases and royalty payments for copyrighted materials used from those sources.

[25] This figure is extrapolated from current expenditure estimates, where current expenditures for the year 2000 are assumed to comprise approximately 92 percent of total expenditures for that year. This assumes a ratio of current to total expenditures equal to that of the 1980s. The source for projected current expenditures is the average of the middle-low and middle-high projections from the U.S. Department of Education [8].

If schools substitute capital for labor instead of financing new technology entirely with the addition of new revenue, it is shown that expenditures on new technology can be largely offset by cost savings associated with this substitution. Currently, the U.S. Department of Education is projecting that the student-teacher ratio will fall from 16.99 in 1990 to 15.94 in the year 2000. [8] It is hypothesized that with the introduction of workstation technology in the classroom, teachers will be able to handle a slightly larger number of students. In particular, it is assumed that instead of allowing the student-teacher ratio to fall to 15.94 in 2000, that ratio will be 16.94 or an increase of one student per teacher over the projected level. Note that this still allows a minor decline from the 16.99 level of 1990.

Given this assumption, schools will require approximately 163,600 fewer teachers than is forecast by the Department of Education. Therefore, schools will realize cost savings on labor and at the same time they will not need to purchase as many workstations for their instructors. Wage savings alone represent approximately $5.6 billion dollars per year.[26] In addition, schools will need $123 million less in technology purchases per year. The total yearly saving for these two factors represent $5.72 billion. These savings will offset roughly 85 percent of the total projected costs in Table 3. If employee benefits are also considered, it is likely that nearly 93 percent of the total outlays for technology could be deferred.[27]

II. PRIVATE INDUSTRY EXPENDITURE ON EDUCATION AND TRAINING

Private Industry spends substantial resources each year on training and educating its workforce. Formal training expenditures amount to approximately $30 billion (1 to 2 percent of employers' payrolls) with another $180 billion being used for informal training. [2,9]

Formalized instruction includes formal classroom instruction administered by training employees or outside consultants, computerized instruction or training designed and administered by a training consultant from outside the company. Informal training includes activities typically thought of as on-the-job training such as watching others perform their

[26] These figures are found by multiplying the number of positions left unfilled (163,300) by the mean of the medium-low and medium-high projections of the average real salary of instructors in the year 2000 as reported by the Department of Education. [8]

[27] Assuming benefit costs are proportional to 10 percent of an educator's annual salary.

jobs or being assisted in doing their tasks by another employee. Therefore, informal training methods are not formal in the sense of being presented in a controlled atmosphere.

It should be noted that formal training expenditures in the U.S. are likely to grow since two-thirds of the U.S. work force of 2000 is currently employed. [5] Efforts aimed at retraining these individuals leave a large potential for computer based learning. This is also reinforced by the shift in the workplace towards a greater reliance on the use of formal training methods and away from informal methods. Additionally, given the fact that jobs in 2000 will be even more dependent on computer based technology, it is reasonable to assume that this will contribute to the increased use of computer based learning.

Much has been said about the failure of public schools in the U.S. In particular it has been said that it is producing too many graduates that cannot read their own diplomas. Setting this argument aside, the headlines tell us that there are roughly 27 million adults in the United States who are functionally illiterate. This means that their basic skills (reading, writing and math) are below the fifth-grade level. Hence, for a large group of Americans,. there is a gap between skill level they bring to the job market and the skill level demanded in the workforce

It is argued that one of the reasons this problem has increased in urgency is that, while schools continue at the pace of the 1950's and 1960's, industry has continued to increase the basic skill levels demanded of its employees. The adoption of automation technology combined with new management techniques that require more input from individual employees has left business demanding less brawn and more brain from its workers. Hence, currently employed workers and new entrants to the job market need to upgrade their basic skills to keep up with a ever changing work environment.

Technology based education and training may not the manna from heaven that will solve all our problems, but it has distinct advantages that can be exploited by the educational system, private industry and the military. While some say computer based learning is impersonal, it is a very efficient method of delivering very personalized learning programs to a large number of people. In particular it is one of the few tools that can be utilized to efficiently replace the teacher as the center of instruction, controlling the pace and content that is being presented. Through the use of certain software products, learners are able to controi the content and pace of their instruction thus making it more personal and interesting. Additionally, this technology allows for a greater amount of flexibility as opposed to traditional teaching and training methods.

III. MILITARY EXPENDITURE ON EDUCATION AND TRAINING

Training is important for almost every job that one may pursue; however, there are few fields that are more training intensive than the military. Because military action comes at infrequent intervals, the primary mission of the military is preparation and training of its forces should their services be required. Training has been broken down into two key components. The first is "individual training and education" which is defined by the Department of Defense as, "[Training of individual military members in formal courses conducted by organizations whose predominant mission is training: this training is to be differentiated from training activities conducted by operational units incidental to their primary combat, combat support, or combat service support missions." [4] The latter class of described activities make up the second type of training which will not be heavily emphasized in this appendix because computer based learning systems are not easily applied to these types of training activities.

There are several factors that help drive up the amount of effort and resources the military spends training its new recruits and upgrading the skills of those in continued service. The principle factor is that the military is an all volunteer force and that the average military career is relatively short. The resulting high turnover rate requires recruitment and training on a continuous basis. In addition, the vast majority of new recruits are young and are drawn from the least skilled segment of the population. The third factor contributing to the high cost of military training is that many of the job skills required of military service are not directly transferable from civilian jobs. As a result, few recruits can be assigned positions without prior formal training.

According to the Institute for Defense Analyses, expenditures for the initial individual training of recruits, officers, pilots and specialized technicians in the U.S. totaled $17.5 billion in fiscal year 1985. An overwhelming majority of this (75 percent) resulted from the entry of new personnel into military service. [7] These figures are not surprising given the fact that the military loses from 15 to 20 percent of its forces from one year to the next. [3]

Individual training in the military is concentrated -- expenditure-wise and personnel-wise -- in three key areas. These are specialized skill training, initial recruit training and flight training. In sum, the military budgeted $19.2 billion for individual training for fiscal year 1991. These figures are given in Table 4 below. Specialized skill training is the most important in terms of cost and man hours, accounting for roughly 26 percent ($5 billion) of the total FY 1991 individual training budget and consuming approximately 58 percent of the projected total man-years devoted to individual training. Initial recruit training activities are expected to take 7.3 percent of the budgeted funds, but consume over 20 percent of the total man-years. Flight training on the other hand is expected to use only 2.3 percent of the total man-years, yet use 14.4 percent of the training budget.

Table 4: Expenditures on individual training in the military, FY 1991.

	Expenditure (In Billions)	Percent
Recruit	$1.5	7.3
Army One-Station Unit	.4	2.0
Officer Acquisition	.5	2.7
Flight	2.8	14.4
Specialized Skills	4.9	25.7
Professional Development Education	.7	3.5
Medical	.8	4.0
Other `Support Costs'	7.8	40.4
TOTAL [a]	19.2	100.0

a) May not add to total due to rounding error.

Source: *Military Manpower Training Report*, FY 1990

The use of computerized training and education appears to be a feasible alternative in the military. According to the Department of Defense, "Some skills can be acquired through experience and on-the-job training. The vast majority, however, are most effectively and efficiently learned through formal courses."[4] Computers can be incorporated most efficiently when they are used to replace or supplement formal courses. It is this opportunity that is seen as the area in which the Department of Defense can work to overcome the initial hurdles that exist to promote the spreading of computerized instruction.

IV. References to Appendix A

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APPENDIX B. HARDWARE PROJECTIONS
by Walid R. Touma

Electronics and VLSI have been the main technology drivers of the computer industry for the past 20 years and they will be for at least ten more years. ICs are integral to every hardware component in a workstation. The better the IC manufacturing process technologies, the higher the production yields and the lower the IC costs. This behavior is represented by the introduction of enhanced, faster and more compact ICs every six to twelve months; furthermore, microprocessors and IC memories are finding their way into the display drivers and the hard disk controllers, hence enhancing the monitor's resolution and speeding up the I/O.

ICs Supply Model: CPUs and DRAMs

In modeling the dynamics of the supply of ICs, the following assumptions are used:

- Technologies are being developed and will be developed to deal with any physical manufacturing barriers during the period of study.
- Cleaner manufacturing technologies will be developed so that manufacturing yields increase, or at least remain constant.
- Better IC testing techniques will be developed to deal with the higher density and higher complexity chips, and hence improve the reliability of the chips.

In the model's equations, several parameters and variables will be introduced. What follows are the variables and the parameters definitions:

0	the first year of the study period
t	the year the study is performed in
FS	the feature size of the IC manufacturing process, in microns
ML	the number of masking levels used in the IC manufacturing process
WD	the wafer diameter, in centimeters
WC	the wafer cost, in dollars
DA	the die area, in cm^2
DPW	the number of dies per wafer
TDPW	the number of test dies per wafer
DY	the die yield, in percent
WY	the wafer yield, in percent
DPUA	the number of defects per unit area
ADTT	the average die test time, in seconds

TCPH	the die testing cost per hour, in dollars
CUD	the cost of a manufactured, untested die, in dollars
CTD	the cost of a tested die, in dollars
MIPS	the number of million instructions per second
MIPSPER	MIPS per square centimeter
MFLOPS	the number of million floating point instructions per second
MFLOPSPER	MFLOPS per square centimeter
MEMORY	the size of the DRAM memory, in megabytes
MEMPER	the number of megabytes (DRAM) per square centimeter
SPEED	the speed of operation of the IC, in megaHertz
TRANSISTORS	the number of transistors on an IC, in millions

The input data to the model have been collected from two sources:

- "Computer Architecture: A Quantitative Approach" by Hennessy and Patterson [10], where several of the initial parameter values like die areas and die yield values are provided.
- "Class Notes for EE396K, MOS-IC Process Integration" by Al Tasch [22], where the behavior of feature size and wafer size is provided.

The equations of the model are presented below, with time being the main independent variable:

$$ML_t = \lceil 2^{0.07*(t-1960)} \rceil$$

$$FS_t = 10^{1.4 - 0.055*(t-1960)}, \text{ (microns)}$$

$$WD_t = 10^{0.48 + 0.0252*(t-1960)}, \text{ (cm)}$$

$$DPW_t = \frac{\pi * WD_t^2}{4*DA_t} - \frac{\pi * WD_t}{(2*DA_t)^{0.5}} - TDPW_t$$

$$DPUA_t = DPUA_0 * \frac{FS_0}{FS_t} * \frac{ML_t}{ML_0} * \frac{ML_t}{6}$$

$$DY_t = WY_t * \left(1 + \frac{DPUA_t * DA_t}{ML_t}\right)^{-ML_t}$$

$$ADTT_t = ADTT_0 * \frac{FS_0}{FS_t} * \frac{DA_t}{DA_0} * \frac{ML_t}{ML_0}$$

$$TCPH_t = TCPH_0 - 3 * (t - 1960)$$

$$CUD_t = \frac{WC_t}{DPW_t * DY_t}$$

$$CTD_t = CUD_t + \frac{TCPH_t * ADTT_t}{DY_t * 3600}$$

$$MIPS_t = MIPS_0 * (\frac{FS_0}{FS_t})^2 * \frac{DA_t}{DA_0} * \frac{ML_t}{ML_0}$$

$$MFLOPS_t = MFLOPS_0 * (\frac{FS_0}{FS_t})^2 * \frac{DA_t}{DA_0} * \frac{ML_t}{ML_0}$$

$$MEMORY_t = MEMORY_0 * (\frac{FS_0}{FS_t})^2 * \frac{DA_t}{DA_0} * \frac{ML_t}{ML_0}$$

Depending on whether the IC is a CPU or a DRAM, different circuit operation speeds and different number of transistors are used; the following equations capture the mentioned parameters, and depending on what type of IC it is, the values $SPEED_0$ and $TRANSISTORS_0$ are adjusted:

$$SPEED_t = SPEED_0 * (\frac{FS_0}{FS_t})^2 * \frac{DA_t}{DA_0} * \frac{ML_t}{ML_0}$$

$$TRANSISTORS_t = TRANSISTORS_0 * (\frac{FS_0}{FS_t})^2 * \frac{DA_t}{DA_0} * \frac{ML_t}{ML_0}$$

For a fixed capacity IC, fixed MIPS, MFLOPS or DRAM, the die sizes will vary, affecting the die yields and the die costs; the corresponding die area equations for each type of fixed capacity IC are:

- CPU: MIPS

$$DA_t = \frac{MIPSPER_t}{MIPSPER_0} * (\frac{FS_t}{FS_0})^2 * \frac{ML_0}{ML_t}$$

- CPU: MFLOPS

$$DA_t = \frac{MFLOPSPER_t}{MFLOPSPER_0} * (\frac{FS_t}{FS_0})^2 * \frac{ML_0}{ML_t}$$

- DRAM: MBytes

$$DA_t = \frac{MEMPER_t}{MEMPER_0} * (\frac{FS_t}{FS_0})^2 * \frac{ML_0}{ML_t}$$

What follows is the set of input values and parameters used in the model; the user is asked to input them manually so that different initial values could be chosen:

Current year = 1990

Study period = 11 years

Current #wafer-defects per unit area = 2

Current #test-dies/wafer = 2

Current wafer cost ($) = 550

Current wafer yield = 0.9

Current testing cost/hour ($) = 250

Current average die test time = 20

Current #MIPS/sq(cm) = 12.5

Current #MFLOPS/sq(cm) = 3

Current #MB/sq(cm) = 0.5

Current speed (MHz)/sq(cm) = 13

Current #transistors/sq(cm) = 600,000

The simulation model is coded in C, and a Sun4/110 machine was used to obtain the results.

Results: Projections of Costs of Fixed Capabilities CPUs and DRAMs

As the capability of the IC is fixed, the die area decreases over time due to the decrease in the feature size and the increase in the number of masking levels. As the die area decreases, the good dies increase and the die costs decrease. What follows captures the previously described behavior for fixed MIPS, MFLOPS and DRAM(MB) ICs:

Projections for a 100 MIPS chip.

Year	Yield	Die Area	Feature	Cost/Tested	Cost/MIPS
1990	0.001	8.00	0.562	36042.45	360.42
1991	0.003	6.21	0.495	10718.60	107.19
1992	0.006	4.82	0.437	3498.99	34.99
1993	0.012	3.74	0.385	1251.34	12.51
1994	0.023	2.90	0.339	491.27	4.91
1995	0.041	2.25	0.299	212.47	2.12
1996	0.070	1.75	0.263	101.58	1.02
1997	0.110	1.36	0.232	53.81	0.54
1998	0.162	1.05	0.204	31.57	0.32
1999	0.225	0.82	0.180	20.46	0.20
2000	0.296	0.64	0.158	14.55	0.15

Projections for a 25 MFLOPS chip.

Year	Yield	Die Area	Feature	Cost/Tested	Cost/MFLOPS
1990	0.001	8.33	0.562	44245.64	1769.83
1991	0.002	6.47	0.495	12956.01	518.24
1992	0.005	5.02	0.437	4168.85	166.75
1993	0.011	3.90	0.385	1469.70	58.79
1994	0.021	3.03	0.339	568.62	22.74
1995	0.038	2.35	0.299	242.26	9.69
1996	0.064	1.82	0.263	114.07	4.56
1997	0.102	1.42	0.232	59.50	2.38
1998	0.153	1.10	0.204	34.40	1.38
1999	0.214	0.85	0.180	21.98	0.88
2000	0.284	0.66	0.158	15.43	0.62

Projections for a 4 megabyte DRAM chip.

Year	Yield	Area	Feature	Cost/Tested	Cost/MByte
1990	0.001	8.00	0.562	36042.45	9010.61
1991	0.003	6.21	0.495	10718.60	2679.65
1992	0.006	4.82	0.437	3498.99	874.75
1993	0.012	3.74	0.385	1251.34	312.84
1994	0.023	2.90	0.339	491.27	122.82
1995	0.041	2.25	0.299	212.47	53.12
1996	0.070	1.75	0.263	101.58	25.40
1997	0.110	1.36	0.232	53.81	13.45
1998	0.162	1.05	0.204	31.57	7.89
1999	0.225	0.82	0.180	20.46	5.11
2000	0.296	0.64	0.158	14.55	3.64

Magnetic Hard Disk Supply Model

In modeling the dynamics of the supply of magnetic hard disks, the following assumptions are used:

- Cleaner manufacturing technologies will be developed so that manufacturing yields increase or, at least, remain constant.

- Better disk testing techniques will be developed to deal with the higher density disks, and hence improve their reliability.

In presenting the model's equations, several parameters and variables are ntroduced. What follows are the variables and the parameters definitions:

0	the first year of the study period
t	the year the study is performed in
TP	the track pitch, in microns
BCL	the bit cell length, in microns
HGS	the head-gap spacing, in microns
HMS	the head-medium spacing, in microns
MT	the magnetic medium thickness, in microns
HSW	the read/write head setup width, in cm
R	the hard disk radius, in inches
DD	the hard disk diameter, in inches
DH	the hard disk height, in inches
DPERCM	the number of disks per cm of height
X	the number of tracks on each disk
Y	the number of track pitches on each disk
AC	the areal capacity per disk, in megabytes
VC	the volumetric capacity per hard disk, in megabytes
MIPS	the number of million instructions per second
DR	the hard disk data rate, in megabytes/s
CMB	the cost per megabyte, in $/MB
CD	the cost of the hard disk, in $

The input data to the model are collected from three sources:

- "Magnetic Recording Handbook" by Mee and Daniel [16], where data on the cost per megabyte of disk and the disk areal densities are provided.
- "Trends in Recording and Control and Evolution of Subsystem Architectures for Data Storage" by Bajorek [1], COMPEURO-89, where data on the track pitch, the bit cell length, the read/write head and medium spacing, the read/write head gap, and the medium thickness are provided.
- "Future Trends of Storage Systems" by Takata [21], COMPEURO-89, where historical data on the price per megabyte is presented.

The next five equations are obtained from [1] as data inputs:

$$TP_t = 300 * 10^{-0.066*(t-1965)}$$

$$BCL_t = 13.2 * 10^{-0.049*(t-1965)}$$

$$HGS_t = 2.8 * 10^{-0.04*(t-1965)}$$

$$HMS_t = 2.11 * 10^{-0.055*(t-1965)}$$

$$MT_t = 2.11 * 10^{-0.0295*(t-1965)}$$

Storage Radius Computation

Disks are usually circular with a particular radius; however, the radius of magnetic media for storage is less than the total disk radius due to the rotational support space requirements. The storage radius, in centimeters, is equal to:

$$R_{\text{storage radius}} = R_{\text{disk radius}} - R_{\text{support radius}}$$

Usually, the hard disk diameter (DD) is provided, hence the disk radius is equal to DD/2. As far as the support diameter, the issue is more complicated. As the diameter of the hard disk increases, the ratio of the support diameter to the total diameter decreases; plotting the support diameters to disk diameters ratios for the corresponding disk diameters, we get the following correlation:

$$\text{Support Diameter } (\%) = -1.8*DD_{in} + 46.75$$

hence the storage radius, in centimeters, is equal to:

$$R_{\text{storage radius}} = \frac{DD_{in}*2.5}{2} - \frac{(-0.018*DD_{in}+0.4675)*DD_{in}*2.5}{2}$$

Volumetric Capacity Computation

Each disk is divided in a series of tracks (called X) and track pitches (called Y). What follows is a computation of X as a function of the storage radius:

$$X_t = Y_t + 1$$

$$BCL_t * X_t + TP_t * Y_t = R_{\text{storage radius}} * 10^4$$

$$X_t = \frac{R_{\text{storage radius}} * 10^4 + TP_t}{BCL_t + TP_t}$$

The disk areal capacity in bits is computed as the sum of the circumferences of the tracks on the disk divided by the length of the bit cell:

$$AC_t = \sum_{p=0}^{\lceil X_t \rceil - 1} \frac{2\pi r_p}{BCL_t}$$

where the track radius is equal to:

$$r_p = R_{\text{disk radius}} * 10^4 - p * TP_t$$

The number of disk media per centimeter is a function of the medium thickness, the head-medium spacing and the head setup width (HSW_t):

$$DPERCM_t = \frac{1}{(MT_t + HMS_t) * 10^{-4} + HSW_t}$$

The head setup width varies with the degree of compactness used in the assembly of the hard disk. It is assumed that the head setup width is decreasing at a rate of 10% a year:

$$HSW_t = HSW_0 * 10^{-0.1*(t-year_0)}$$

The volumetric capacity in megabytes depends on the areal capacity per disk, the number of disks per centimeter. The disk height is converted to centimeters by multiplying it by 2.5 and the volumetric capacity in bits is converted to megabytes by dividing it by $8*10^6$ (8 bits to the byte):

$$VC_t = \frac{AC_t * \lfloor (DPERCM_t * DH * 2.5) \rfloor}{8*10^6}$$

Data Rate and Cost of Hard Disk Computation

The data rate, in megabytes/sec, depends on the bit cell length--the smaller the bit length the higher the data rate, the magnetic read/write gap--the smaller the head gap the higher the data rate, and the speed of the controllers used. If one expresses the controller speed in MIPS, then the data rate can be expressed as:

$$DR_t = DR_0 * \left(\frac{BCL_0}{BCL_t}\right)^{0.2} * \left(\frac{HGS_0}{HGS_t}\right)^{0.1} * \left(\frac{MIPS_t}{MIPS_0}\right)^{0.5}$$

Notice that the speed of the controllers varies as the square root of the MIPS and this is due to communication and data access delays. The choice of the square root is an approximation of the expected behavior over time. The exponents of the bit cell length and the head gap ratios are chosen according to their relative influence on the data rate; they are approximations, too. The DRAM chip capacity behavior is not included in the data rate equation because it is assumed that one can add as much DRAM as needed to the computer in order to meet the data rate of the hard disk.

The cost per megabyte of disk ($) depends on the technological improvements to the disk hardware, i.e., the reduction of the head medium spacing, the track pitch and the medium thickness, and on the increase of the data rate; the ratios' exponents reflect our estimate of how relevant each ratio is to the cost per megabyte behavior over time. A reduction factor ($10^{-0.15*(t-t_0)}$) was introduced which is designed to reflect the competition between different disk manufacturers and the competition between disk and DRAM manufacturers. The number 0.15 resulted from the model tuning process while approximating the behavior presented in [21]:

$$CMB_t = CMB_0 * (\frac{DR_t}{DR_0})^{0.4} * (\frac{HMS_0}{HMS_t})^{0.2} * (\frac{TP_0}{TP_t})^{0.3} * (\frac{MT_0}{MT_t})^{0.1} * 10^{-0.15*(t-t_0)}$$

It is assumed that the cost per megabyte at time 0 (CMB_0) includes the costs of labor and raw materials and they remain constant (in constant dollars) over the study period.

When using these assumptions, the disk cost for given radius and height is:

$$CD_t = VC_t * CMB_t$$

Model Inputs

Since MIPS is a variable introduced in the data rate equation, the ICs supply model output is a part of the hard disk supply model input data. Other input data for the hard disk model are:

Current Year = 1990
Study Period = 11
Current Data Rate = 10 megabytes/s
Current Head Setup Width = 1 cm

The simulation model was coded in C, and a Sun4/110 machine was used to obtain the results.

Projections of Costs per Megabyte of Hard Disk Storage

The cost per megabyte obtained below was compared to the price per megabyte data provided in [21]. If we assume that the manufacturers of hard disks have a 100% markup on their disks, the cost per megabyte will be half the price per megabyte provided. The model's results are within 2 to 4% from the price (cost) data provided in [21]:

Projections of Cost per Megabyte of Magnetic Hard Disk

Year	Cost per megabyte $/MB
1990	3.91
1991	3.22
1992	2.65
1993	2.18
1994	1.79
1995	1.48
1996	1.22
1997	1.00
1998	0.82
1999	0.68
2000	0.56

Display Supply Model: CRTs and LCDs

Display technologies have been evolving for the last century but it was not until the personal computer invaded homes that the market witnessed a flood of innovations from display companies around the world. Japan is the leader in display development and market share [8]. There are different classes of displays but the classes that will prevail in the future are the CRTs and the LCDs for the following reasons:

- The CRTs and LCDs are receiving the highest R&D expenditures [8] and are demonstrating the greatest improvements per R&D dollar spent.
- CRTs are cheap, reliable, bright, and have a high resolution with colors [3, 8].
- LCDs are compact, increasing in size and color capabilities, they have low power consumption, and they have the potential of satisfying high definition television requirements and the display elements are easily addressable with thin film transistors [8, 13, 19].

The disadvantages of CRTs are their high power consumption, their curved face plate and their "volume". The disadvantages of LCDs are their speed and low resolution, for the time being [8]. The other two promising technologies are electroluminescent displays if full color ones are developed [20], and plasma displays once their technology matures and becomes affordable; plasma displays developers are struggling to achieve color capabilities comparable to the CRTs [8].

Since the introduction of workstations in the 80's, the resolution of computer displays has increased by a factor of 2: from the 640x480 to 1200x850 pixels per display. The higher resolution was necessary because of the interactive applications that were developing at the time in the area of CAD/CAM, training and education. However, the only drawback to high resolution was the lack of display adapters fast enough to feed the monitors with bit rates approaching 500 million bits per second [5]. Once VLSI evolved and 5 to 10 MIPS processors were available and affordable, the problems with resolution shifted from VLSI to the areas of display control and pixel mapping [5, 6].

In workstations today, 1 million pixel CRT-based displays are the most common, where each pixel is mapped to an 8 bit memory location specifying its color (256 of them). The cost of the color display in workstations is about five hundred dollars. For black and white ones it is about 300 dollars. The main cost overhead is in the display drivers and adapters needed to provide high refresh rates, high resolution, and a wide array of colors [10].

VLSI technologies are one of the main drivers in display technology. VLSI plays an important role in the display adapters, in the LC-thin-film-transistor addressable displays, and in the overall efficiency of CPU-Display interaction.

The model for the display technologies is not included here.

Workstations in the Year 2000

From the supply models' cost projections available in the previous sections, we present the following hardware costs projections for the year 2000, in 1991 dollars:

Projections of Hardware Costs, Year 2000

$/MIPS	$0.15
$/MFLOPS	$0.62
$/MByte (DRAM)	$3.64
$/MByte (Mag Disk)	$0.56
2048x2048x32 color CRT	$300.
4096x4096x32 color CRT	$1,500.
1024x1024x32 color LCD	$500.
2048x2048x32 color LCD	$1,800.

The displays price (not cost) and resoltuion data are estimated by Howard L. Funk of IBM and the author. A display supply model is under development.

Distribution of Hardware Costs in a Workstation

Since there are several hardware configurations to a fixed price machine, we shall make some assumptions and use some data from [10] to break down the components costs of the workstation as percentages of the total cost:

Breakdown of Hardware Costs in a Workstation

CPU cabinet sheet metal, plastic, power supply, fans, cables, nuts, bolts, manuals, shipping box	3%
CPU board integer unit floating point unit memory management unit + cache	13%= 4%+ 6%+ 3%
DRAM board	39%
Video logic + I/O interfaces	10%
Display monitor	17%
Hard disk	17%
Keyboard and mouse	1%

Source: Reference [10]

Attributes and Capabilities of $1,000 and $10,000 Desktop Workstations

In estimating the capabilities of $1,000 and $10,000 desktop machines, the following assumptions were made:

- $1,000 and $10,000 are the prices of the workstations in the year 2000, in 1991 dollars.
- The basic operating system of the machines, excluding the netware, will be free.
- The monitors data are current prices not costs, so they were subtracted from the total machine price before doing the capabilities allocation to the machines.

- The workstations prices have a 100% markup over costs, one-half the price is used to set the cost: ($1,000 – monitor price)/2 and ($10,000 – monitor price)/2.

Using the machines costs obtained from these assumptions, the hardware capabilities are obtained in two steps:

- multiply the machine cost by the hardware costs breakdown percentages provided above
- divide the resulting data by the projected hardware costs in the year 2000.

The estimated workstation capabilities were rounded off to the nearest "common" numbers:

The $1,000 Desktop

MIPS	MFLOPS	DRAM (MB)	MAG-DISK (MB)	DISPLAY (Color)
150	50	50	150	2048X2048X32 CRT 1024X1024X32 LCD

The $10,000 Desktop

MIPS	MFLOPS	DRAM (MB)	MAG-DISK (MB)	DISPLAY (Color)
1,500	500	500	1,500	4096X4096X32 CRT 2048X2048X32 LCD

The numbers on the MIPS and MFLOPS are high, a 100 times increase over today's performance values.

Attributes and Capabilities of $1,000 and $10,000 Portable Workstations

The portable workstation in the year 2000 will weigh from 1 to 15 pounds, depending on its attributes. The hardware physical limitations for a portable are much more delicate than the desktop's. Achieving good portable computers hardware yields, lighter and smaller components for the same capabilities as the desktop's is very expensive, hence we will assume the portable hardware attributes to have close to half the capabilities of a desktop workstation.

Using the hardware limitation assumption and the steps in the previous section, the capabilities of a \$1,000 and a \$10,000 portable computer in the year 2000 are computed:

The \$1,000 Portable

MIPS	MFLOPS	DRAM (MB)	MAG-DISK (MB)	DISPLAY (Color)
75	25	25	75	1024X1024X32 LCD

The \$10,000 Portable

MIPS	MFLOPS	DRAM (MB)	MAG-DISK (MB)	DISPLAY (Color)
750	250	250	750	2048X2048X32 LCD

We estimate that, for a fixed attributes portable machine, the lighter the weight the higher the price of the machine. To model the dynamics one must take into consideration the weight of every component in the machine. A model to capture this behavior is a topic of current research.

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APPENDIX C. SELECTED REFERENCES ON SOFTWARE AND COURSEWARE

by Ravindra Gajulapalli

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APPENDIX D. NETWORKING PROJECTIONS
by Greg Hoagland

The power of the computer has increased very rapidly in recent years largely due to the advances in very large scale integration (VLSI) technology. However, also enhancing the power and usefulness of computers are computer networks. These networks permit information to flow between computers and between computers and resources such as printers and database servers.

Telecommunication Network and Computer Network

In the past, there has been a relatively clear distinction when referring to a computer network and a telecommunication network. The telecommunication network was geographically widespread and it carried mostly voice from point-to-point and video for network broadcasts, whereas computer networks carried digital data among computers and resources. Recently the distinction between the two types of networks has become increasingly blurred. Telecommunication networks are beginning to handle data. Computer networks, as a result of improved display technology and faster CPU's, have begun to transmit audio and images as well as data. There is also an expectation that video signals will be transmitted over these computer networks to be used, for example, in multimedia presentations.

In the future, this trend of overlapping domains for the telecommunication industry and computer industry is likely to continue and the differences between the two types of networks will become even more hazy. Some evidence of this is the new integrated services digital network (ISDN). It is a digital network being developed by the telecommunications industry that is viewed by many in the telecommunication and computer industry as the highway that will be needed to deliver advanced voice and data services in the future [1]. Similar to the way we think of using phones today, this network will let any two digital phones or computers connected to the network access each other from anywhere in the nation. Another example of the merging of the telecommunication and computer industry is the recent announcement that BellSouth Services and IBM will jointly study emerging high-speed networking technologies, capable of transporting voice, text, image and multimedia information [2]. This trend of cooperation and merging of efforts between the computer and telecommunication industry is likely to continue as networks become larger and more prevalent. The growth of the networking is echoed by many experts. Dr. Craig Fields, president of MCC, has stated that whereas in the eighties the focus of the computer industry was in microprocessor technology, the focus of the nineties will be computer networks [3]. For example, many companies are trying to develop chips that will compress video signals. This is important if we are to be able to send video signals over a computer network because of the high bandwidth requirement of sending uncompressed video. Companies are also concentrating efforts on increasing the bandwidth capabilities of networks.

Results of Future Networks

Predicting that networks will become more powerful ten years into the future is not very difficult. What is difficult is predicting the new growth areas these powerful networks will spawn. The increase in power will take the form of increased bandwidth due largely to an improved transmission medium such as fiber optics. As a result of the higher bandwidths and improved compression techniques, the networks will accommodate data, audio and video.

One industry that is already showing signs of emerging due to networks and will probably become more prevalent as networks become more powerful and more widespread is the electronic information services industry. Compuserve and Prodigy are two examples of electronic information companies in operation today. Future companies may provide a variety of new types of services. For example, there may one day be an electronic movie rental service over a network. The user chooses a movie from a database, and in turn, it is sent over the network to the user's home and played on a monitor. A service like this would require a high-bandwidth network. Supplying educational information that takes advantage of a network's ability to deliver multi-media presentations is another example of an information service that may become common.

A precursor to being able to deliver many of these information services entails two things. First, the powerful networks have to be extended into homes, schools, and businesses. Second, different types of networks need to be able to communicate with one another. As stated earlier, the telecommunication is developing a nationwide network called ISDN which should be available by 1992 [1]. This network, however, will not have the bandwidth capability to carry video. To carry digital video into homes would likely require the network to be a fiber optic network. The likely candidate to extend the networks into homes would be the telecommunication industry. However, regulations prevent the Bell operating companies from being able to deliver electronics information services, including television. They therefore lack incentive for investing in such a network [4]. That is not to say that the long term results of building the network would not be profitable for them as well as many others, it is just that the benefits are not clearly visible. The cost requirement of getting fiber optics extended into homes, schools and businesses would likely be high, especially considering that it is very unlikely that homes, schools and businesses would be unable to utilize all of the bandwidth capability of the fiber optic cable, even if video was being transmitted over the cable. An additional option may be to use satellites to transmit the information into homes. Satellites have a high bandwidth capability but the question arises as to whether they have enough bandwidth to carry the information high bandwidth information to many users at any given time.

The problem of enabling different computer networks to work together is a challenge that is being encountered today. One solution to this is to make sure that networks are open systems, meaning that they follow some type of standard or protocol that enables network components from different vendors to work together. The standard that is being promoted in the United States and internationally is the Open Systems Interconnection (OSI) model. It is difficult, however, to get all vendors to build completely compatible networks, due to network competition. In years past, it was easy for the telecommunication giant AT&T to build a large voice network in which it defined the standards and others adopted them or else were unable to communicate with the rest of the network. Today we do not have one giant company that can sway the agendas of all other companies like that so therefore the companies need to come to an agreement and the OSI standard looks like it may be the network standard that companies follow in the future.

To illustrate how important it is that the United States build a high-speed network system that extends nationwide and what its impact can be on our economy, the following example is given. Japan plans to spend as much as 250 billion dollars by the year 2000 on a fiber optic network. In return, Japan expects to receive a total of one-third of its gross national product from services carried by the fiber optic network by the year 2015 [4]. This illustrates the tremendous impact a network can have on a society.

Michael L. Dertouzos, professor of computer science and electrical engineering at MIT's Laboratory for Computer Science, is also stressing the value of a network infrastructure within the United States. He says, "computers will become a truly useful part of our society only when they are linked by an infrastructure like the highway system and the electric power grid, creating a new kind of free market for information services [5]."

The Present State of Networking

LAN

A common way to characterize a network is according to their size. A network that covers a small area is called a local area network (LAN). LANs generally accommodate between 30 and 300 users. The reason for this is that 90% of offices have under 30 users and 98% have under 300 users [6].

About 80% of the communication done on LANs is done at the local level, such as between a workstation and a file server and mail messages between people working in the same office. Because communication is primarily local, it is important that local networks be fast. Currently most LANs operate at speeds between 1 and 20 megabits per second (Mb/s).

Two popular topologies for LANs are the bus topology like that used by Ethernet, in which the nodes in the LAN all attach directly to a primary bus, and the ring topology like that used by IBM's Token Ring method.

A relatively new standard for fiber optic LANs which is based on the token ring access method is called the fiber distributed data interface (FDDI). It is a 100 Mb/s LAN that is gaining quite a bit of interest, as is evidenced by the fact that Advanced Micro Devices (AMD) has already released an FDDI chip set, and the Advanced Networking Group (ANG) was formed by members such as AMD, AT&T, HP and Sun in the goal of setting up interoperability testing to assure that FDDI products developed by the companies are compatible [7]. FDDI may serve primarily as a backbone network that connects traffic from lower-speed networks and as a high-speed office network for an office requiring a lot of image and graphics transmission.

MAN

Networks that are the size of a city are usually referred to as metropolitan area networks (MAN).

WAN

Large networks, such as those that extend internationally or across the country, are referred to as wide area networks (WAN). Examples of WANs are the Tymenet, NSFnet and DARPA's Arpanet.

The speed of a WAN is usually lower than that of a LAN. However, with the increasing importance of image and video processing, efforts are being made to increase WAN speed. For example, the telecommunications industry is proposing a standard known as broadband integrated service digital network (B-ISDN) that is fast enough to carry data, audio and video [8]. Also, in 1988 the bandwidth of some NSFnet lines was increased from 56 Kb/s to 1.5 Mb/s. While this increase in speed has unclogged many of the old traffic tie-ups, the increased capacity will undoubtedly bring in new customers and new applications that will push the network to the limit again. In response, NSF officials report that 400 million dollars is necessary to increase the network's capacity to a gigabit per second. In fact, a bill to finance the network's expansion has been sponsored by Senator Albert Gore (D-TN) for the last few years but has failed to get through Congress.

TRANSMISSION MEDIUM

Many of the advances to be seen in networking are directly related to the transmission medium used to carry the signal.

Twisted Pair. The least expensive physical media is merely two copper wires twisted together. Due to lack of shielding, this type of cabling is susceptible to interference and attenuation so that it has a maximum bandwidth of about 16 MB/s.

Coaxial Cable. This is a shielded copper wire that is found in applications requiring higher performance than twisted pair can provide. This type of cable is less susceptible to noise interference than twisted pair, but it is much more expensive. It has an upper bandwidth of approximately 500 Mb/s.

Fiber Optics. These are glass or plastic cables that carry a light signal instead of an electric signal. This type of transmission medium is becoming very popular due to the tremendous data rates that are achievable. A single fiber optic system, in theory, could carry up to a billion video channels. Current systems can transmit on the order of 500 video channels. Table D1 compares fiber optics to twisted pair and coaxial cables.

Table D1. Performance of fiber optics, coaxial and twisted pair cables [9].

	Twisted Pair	*Coaxial*	*Fiber Optic*
1. Data rate/km	16 Mb/s	500 Mb/s	1,000+ Mb/s
2. Accessibility to being tapped	easy	easy	difficult
3. Signal radiation	yes	yes	no
4. Potential for explosion (i.e. spark potential)	yes	yes	no
5. Bit error rates	1 in 10^6	1 in 10^6	1 in 10^9+
6. Static problems (i.e. lightning)	yes	yes	no
7. Grounding problems	yes	yes	no
8. Size and weight by data rate	large	large	small

Satellites. Satellites can be used as microwave relays. Microwave signals are uplinked to a satellite from an earth station. The satellite takes the signal and sends it back to earth on a shifted frequency so that it does not interfere with the uplink signal. Some useful aspects of satellite communication are the following. First, satellites have no problem transmitting far distances. In fact, one satellite can have a transmission range or footprint that covers the entire nation. Second, satellites have no difficulty transmitting to difficult to reach places where it might be difficult to get cabling. For example, the Canadians have a satellite phone service for people in the very remote parts of northern Canada where it is not feasible to lay phone cables. Third, services provided over satellites are identical whether they are for large heavily populated cities or for small cities. Finally, satellites are inherently high bandwidth devices [10], [11]. Currently intersatellite links can obtain speeds as high as 50 to 100 Mb/s.

There has been a lot of discussion as to whether fiber optics will replace satellite for long distance communication. Fiber optic cables have greater bandwidth capacity than satellites. Fiber optics transmissions are also more secure from interception than satellite transmissions. However, the question arises as to whether it becomes economical to route fiber optics to areas where the bandwidth requirements are not as high as what fiber optics can provide such as remote areas or directly into homes and businesses, or should fiber optics just be used for trunk lines carrying a high bandwidth of traffic. Satellite transmission does not have that problem because a satellite can just as easily service an area with lower traffic requirements as one with high bandwidth requirements. Something to be considered though is that the types of information transmitted in the future may require the high bandwidth capability of fiber optics. One example that comes to mind might be a high definition television (HDTV) signal. The authors in [10] say that most proposed network systems in the future will be hybrid networks which attempt to integrate satellites and fiber optics to capitalize on the advantages of both.

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APPENDIX E. DATA ON BENEFITS AND COSTS
by Christopher Galbraith

Computer Assisted Education and Training (CAET) has created a great deal of excitement. Nancy Madlin wrote in the November 1987 issue of *Personnel* that CAET "has survived periods of unrealistic hype and disparagement to become a popular training technique." (Madlin, 1988). Many educators feel that it has the potential to enhance the American education system. Applications include: reading, writing, foreign language, speech education, math, chemistry, biology, social studies, adult literacy, accounting, bank training, teacher training, and higher level learning. CAET has been used in elementary schools, secondary schools, higher education, adult education, military training, factory training and small businesses.

General Assessment

The benefits of CAET include availability, flexibility, consistency, efficiency, individualized instruction, and economies of scale (Ganger, 1990; Madlin, 1988; Ross, 1988). The same computer program can be used to create the design of the course, evaluate the results of the class and assist in the administrative functions associated with training (*Training*, 1989). CAET can also help overcome the difficulties of bilingual training (Zarley, 1988). One advocate claims that CAET produces 30% more learning in 40% less time at 30% less cost than traditional classroom teaching (Perlman, 1990). Others lend support to this claim (Ross, 1988; Wehr, 1988). Simulators for expensive equipment, such as airplanes, have been found to be even more cost effective. The Educational Computer Corporation has found that simulation training can reduce life cycle and procurement costs by as much as 75% (Rushby, 1989).

The overall sense of CAET is that it leads to better on-the-job performance (Lookatch, 1989). Why else would it be reported that about 54% of all Fortune 500 companies use some form of CAET, and 81% plan to use CAET within the next few years (Madlin, 1988). In 1985-86 a five month study of Coca-Cola Foods' employees found that CAET increased the efficiency of aseptic package operators. There was a 1.3% increase in efficiency in the computer trained group in comparison to a control group. The measurements were based on machine output and were taken under tightly controlled conditions (Delamontagne and Mack, 1987). Although the gain in efficiency may appear small, its cumulative effect could be great. Historically productivity has risen at just 2% per year. Ford Motor Credit Corp believes its CAET program will reduce training time by

40% and increase efficiency as well (Zarley, 1988). Massachusetts Mutual Life Insurance used CAET to help reduce its 75% turnover rate among new insurance agents and to reduce training times (Borger, 1988).

The benefits of CAET are attributed to a number of sources. One is that students are allowed to proceed at their own pace (Wehr, 1988). The testing features of CAET can help target the students' effort. Pre-tests allow students to quickly step through material they already know, while post-tests guide students toward material requiring further study (Sebrell, 1989). Another source may be that students find CAET non-threatening (Sebrell, 1989). A major question is whether the entertainment aspect of computers or the ability of the computer to present information in a form that is more accessible for the learners is the reason for the eagerness with which children use computers. Research is showing that it is the latter. Using computers helps to utilize all forms intelligence in the learning experience (Thornburg, 1989).

CAET is frequently compared to classroom teaching. Classroom instruction is widely accepted and understood. Courses can be developed and enhances relatively quickly and inexpensively. The major drawbacks are that course quality and effectiveness vary, and class timing and location can be inconvenient (Wehr, 1988). While classroom programs need to be planned in advance, CAET can be scheduled for employee off-peak time (Lookatch, 1989). Technological innovations have made it possible for firms to offer on-demand training (Schaaf, 1989).

The October 8, 1990 issue of *Computerworld* contained two articles debating the question, "Can technology effectively replace human teachers?" In that debate Lewis Perlman argues,

> Ignoring the potential benefits of technology in the classroom is one of the most dangerous myths in America today. By steadfastly maintaining that computers cannot replace teachers, the United States is handicapping itself.....Most computer and telecommunications companies are hesitant to push computers into the classroom for fear of political repercussions and the negative publicity that might ensue when replacing the traditional methods. However, it is precisely the traditional methods that are failing to educate the nations children today.

Glenn Rifkin counters,

> While computers have there place in the classroom as instructional aids, it is a mistake to think they should become the focus of the learning process. Estimates claim there are currently 3.3 million computers in U.S.

> classrooms, and 98% or all school districts in the country are now using computers for instructional purposes. But for all this penetration, there has been no improvement in test scores, nor have more students been drawn into the hard sciences .... Computers may be able to increase students' motivation, as some studies have indicated, but they cannot change a society that places less and less value on education.

Some advocates suggest that computers have a different role to play than traditional classroom instruction. Karen Sheingold, Director of the Center for Technology in Education at Bank Street College of Education, believes that the computer is "not about doing the same thing better. It's really about doing something different." (Chire, 1990). The Center conducted a survey which indicates that innovative uses of computers can change how and what teachers teach, however the survey also reveals that imaginative uses of computers in teaching are rare (Chire, 1990). With the use of computers the role of the teacher changes. Instead of being the dispenser of knowledge, the teacher needs to allow students to explore. "In switching from textbook learning to learning via computer, students become much more active participants in how they learn, and sometime in what they learn as well, " states Christopher O'Mally in the October 1989 issue of *Personal Computing*. The real power of computers lies in there ability to adapt to the individual needs of the student. Rushby (1988) believes that questionnaires that indicate the students preferred learning style should be used. A system has been developed which incorporates a user card that is updated each time the student uses the system, thus allowing the system to adapt to the student's learning style (Rushby, 1988). In an experimental school in Los Angeles, whenever possible, students are encouraged to choose, create and discover for themselves in lieu of reading textbooks (O'Malley, 1989b).

CAET broadens the range of places learning can take place. Because of the falling cost of video cameras and the growing availability of VCR's in many homes and most schools, it is becoming more practical to merge computers and video (Marvelle, 1988).

The strength of CAET lies in its ability to engage the learner. It has been found that simulation training is most effective when it has a high face validity and incorporates enough aspects of reality that users believe they are operating in real situations (Rushby, 1989). A few firms, such as Hewlett Packard, have made large investments in in-house simulation software for high-level training (Coffee, 1990). Another approach is to use the entertainment potential of computers to develop training programs that are both enjoyable and educational. Some game programs have elements of CAET (Coffee, 1990).

There is not universal agreement about the cost savings and ease of implementation of CAET. Some believe that CAET can reduce course development time and provide a wider variety of services (Schaaf, 1989). Others are not so sanguine. In an article generally positive about CAET, it is stated that CAET courses require about four times the development effort and cost in comparison to instructor-led courses (Wehr, 1988). Patricia Galagan (1987) states that CAET "offers speed and convenience, but requires discipline in instructional planning and design."

There are obstacles to implementing CAET. Many factory workers are suspicious of the machines in general. They fear that they will lose their jobs to computers, while others worry that they lack the requisite language skills (Maguire, 1988a). One source of these problems may be that the much of the technology now in use does not fully utilize the capabilities of CAET. "Most programs on the market fail to stimulate students and get them to interact with the program," concludes Jessica Keyes in the October 22, 1990 issue of *Computerworld*, after reviewing the findings of a survey of 250 computer training managers conducted by the National Training and Computer Project (Keyes, 1990). A survey of Australian university and college accounting education found that CAET had mostly occurred at the introductory level. Obstacles to greater implementation are lack of financial resources, staff time, staff experience and educationally suitable software (Kent and Linnegar, 1988).

CAET is still generating a great deal of excitement. Advances in computer technology are increasing the capabilities of computers at the same time that they are becoming less expensive. The greatest potential lies in hypermedia-- the ability for the computer to coordinate sound, pictures and text in a system that adapts to the user. Such systems are only now being developed. Whether they will be more effective then existing technology has yet to be seen.

Research Assessment

In this section results of various technical assessments of CEAT are reviewed. With all the hype surrounding the benefits associated with CAET, it is of interest to see whether the expectations have been validated in controlled experimental conditions. The short answer to that question is, yes. The general finding is that there is a small but statistically significant gain associated with the use of computers in training and education. The "effect size" is on the order of .42 standard deviations. That translates into moving an average student, one in the 50th percentile, up to about the 66th percentile. This finding holds across a wide spectrum of applications and levels of instruction.

The data for this finding come from evaluations of CAET programs or systems. The evaluations are often performed by the developers of the programs. The evaluations, whether performed by the software developer or an independent evaluator, use standard experimental procedure. There is a control group against which the experimental group can be compared. The evaluations cover a broad spectrum of applications-- reading, writing, chemistry, etc. The desire to compare the results has spawned its own methodology.

The difficulty is that the evaluations are not always directly comparable. Most of the reviews use "meta-analysis". The method comes out of Glass (1976). The intent is to formalize the procedure for comparing evaluations performed by many different investigators. Meta-analysis is a big improvement over older methods such as box scores. Box scores amounts to nothing more than counting the number of positive results and the number of negative results.

The first step is to categorize the studies into comparable groups. The taxonomy presented in the various studies by Kulik, et. al. (1980, 1983 1986) is useful.

- I. Level of Instruction
    - A. Elementary
    - B. Secondary
    - C. Higher Education
    - D. Military
    - E. Adult Education

- II. Use of Computer
    - A. Tutorial
        - 1. also called
            - a. Computer Assisted Instruction (CAI)
            - b. Programmed Instruction (PI)
        - 2. characteristics
            - a. interactive
            - b. drill, practice
    - B. Manager
        - 1. called Computer Managed Instruction (CMI)
        - 2. characteristics
            - a. non-interactive
            - b. administers tests
            - c. tracks progress and grades students
    - C. Simulation

1. also called Computer Enhanced Instruction (CEI)

III. Implementation
   A. Supplement
   B. Substitute

This is not a complete taxonomy, however it gives an idea of the number of variable that need to be controlled for. The taxonomy is hierarchical. The first criterion in selecting studies to compare is usually the level of instruction. Within each level the applications used may be any of the three presented above-- tutorial, managed instruction or simulation. Each application my be used as a stand-alone course, i.e. a substitute, or as an addition to the regular curriculum, i.e. a supplement.

When performing meta-analysis, the idea in selection of evaluations is that it be replicable. Selection is not a random. Every study that meets the requisite criteria is included. The most common method is to use ERIC (Educational and Resource Information Center) and CDA (Comprehensive Dissertation Abstracts) to search for studies that meet the pre-specified criteria. The level of instruction is usually the primary criterion. Next there are methodological issues. In order to get an effect size measure there must be a control group against which the experiment group(s) can be compared. Among the studies selected different computer applications-- tutorial, simulation, managed instruction-- may have been tested. It is rare to have enough studies in each category such that cross-application comparisons can be made.

In comparing results meta-analysis takes into account the size of the result and its statistical significance. The heart of the analysis is calculating "effect size." Effect size is defined as follows:

$$E = \mu_e - \mu_c / SD_c$$

E is effect size, μ_e is the mean of the experimental group, μ_c is the mean of the control group and SD_c is the standard deviation of the control group.

As stated in the introduction, the most consistent finding is that there is a small but statistically significant gain from computer assisted education and training. There is also some evidence that CAET is most effective at the elementary school level and declines through secondary school and higher education (Niemiec and Walberg, 1987). This relation holds in two reviews performed by Kulik and his associates (Kulik, Kulik and

Cohen, 1980; Kulik, Kulik and Williams, 1983), not covered in synthesis of reviews by Niemiec and Walberg (1987). In Kulik, Kulik and Cohen (1980) the effect size of CAET in a college setting is found to be only .25, averaged over 54 studies. In Kulik, Kulik and Williams (1983) the effect size for secondary school students is .32 averaged over 48 studies. Interestingly Kulik, Kulik and Schalb (1986), which looked at twenty-four evaluations of adult education, the effect size is .42. Another interesting difference between Kulik, Kulik and Williams (1983) and Kulik, Kulik and Schalb (1986) is that among secondary school students those with low average ability have a larger effect size than those with high average ability. In the study of adult education the finding is exactly the opposite.

Four studies looked specifically at interactive video (IV) and interactive video disc (IVD). Hannifin (1985) defines interactive video as "any video program in which the sequence and selection of messages are determined by the user's response to the material."

Bosco (1986) looked at evaluations that ranged across all levels of instruction from elementary school to higher education, military training and industrial training. Not all the evaluation included a control group, effect size could not be calculated. He used a simple box score method. His overall findings are very weakly positive. Fletcher (1990) compared 28 studies, 13 military training 4 industrial training and 11 higher education. Effect sizes were calculated for each group and across a number of criteria. The strongest results were found in higher education studies-- .69 vs. .39 and .51 for military training and industrial training, respectively. Studies were also compared across outcomes for knowledge, performance and retention. All results were positive. The largest positive results were found in time to complete instruction. The average effect size was 1.20.

The third study (Phillips, Hannafin and Tripp, 1988) addressed the effects of practice and orienting activities on learning from interactive video. They found that practice helped performance, but only on material covered. No generalized knowledge was gained.

Clark (1983) cautions that the observed results in the recent meta-analyses may be attributable to reasons other than the training method. Clark states, "the best current evidence is that media are mere vehicles that deliver instruction but do not influence student achievement." The observed positive results may be a product of degree of effort put into instructional design. Presumably, the students in the control groups would fare better if the same degree of effort was put into conventional instruction material. This possibility is partly addressed by Kulik, Kulik, and Cohen (1980). They discuss the effect of having the same or different instructors teach the control and experimental groups. They find that with the same instructor, the difference in performance nearly disappears. In later study (Kulik, Bangert and Williams, 1983), however, they report an insignificant difference between different instructor and same instructor.

The overall results of the use of computers in education is positive, however there are some question as to what exactly students are reacting. If CAET provides better organized, and more engaging courses than conventional methods, there is good reason to use it. As brought out in the first section of the report, a primary benefit of CAET is its consistency. If it eliminates the variation between teachers, that is a benefit.

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