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Scientific Visualization Laboratory Design and the Classroom of the Future

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This paper reports an experience on a cost-effective design of a scientific visualization laboratory that was placed in service in the Fall of 1991. The following issues are addressed: the fundamental visualization skills to be taught; budget propositions; fund allocation (among facilities, computers and peripherals); the three available equipment platforms (professional, scientific and popular); facility design of the laboratory; network and multimedia capabilities; and the generic visualization support software. A new dimension of the classroom of the future is to support the exploratory teaching methodology.

EDUCATIONAL SUMMARY

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in computer-assisted laboratories and engineering design laboratories.
2. The paper describes new equipment useful in computer graphics, engineering design and information visualization.
3. The students involved in the use of the equipment are senior undergraduates and graduate students.
4. The new aspect of this contribution is the teaching style with computer-assisted teaching tools.
5. The material presented can be incorporated in engineering teaching through teaching with simulation before physical training, as with flight simulators.
6. The concepts presented have been tested in the classroom. This method of teaching engages students in the act of learning. They are active participants not a passive audience.

INTRODUCTION

VISUALIZATION is the mapping of information to stimulate the minds' eyes of the viewers, to see the unseen, to visualize the invisible and to imagine the indescribable. Visualization emphasizes the techniques of cognitive stimulation while computer graphics emphasizes the techniques of presentation creation. The teaching of visualization promotes the skills needed to build the viewer's inner vision.

Scientific visualization [1–4] employs the latest computer equipment to teach engineering and scientific concepts, to simulate expository experiments, and to perform preliminary design verifications. Since most small or medium size scientific and engineering firms lack in-house expertise to research the advancement of computing capabilities, they often fail to benefit from the latest development. Frequently raised questions are: 'What can a scientific visualization laboratory contribute to the teaching of engineering and sciences?', 'How to design a cost-effective scientific visualization laboratory?', 'What equipment should one invest in?', 'How to match equipment with peripherals?', 'What does one need to record a simulated experiment for future playback?', and finally 'How much would it cost?' Often the true answers are camouflaged under the interest of the commercial, profit-motivated vendors.

This paper is organized into five parts: (i) a brief peek into the near future in scientific visualization to impart a sense of direction, (ii) a summary of the necessary skills for the next generation of scientists and engineers, (iii) a blueprint of the planning of a Scientific Visualization Laboratory, the platforms of the computing equipment, network and multimedia support, and application tools, (iv) a hint of the types of courses to be offered in such an environment, (v) a summary on the capability and cost trade-off among the variety of computers and peripheral equipment, and (vi) an expository note on the exploratory teaching methodology in the future classroom.

A PEEK INTO THE FUTURE

The information era is driven by cost-effective computation power. The triple-mega desktop machines of the 1980s (mega-instructions per second, megabytes of memory and megabaud transmission speed) will be replaced by the triple-giga machines of the 1990s. The future machines will be speedy enough to support live animation, high-quality display for realistic cinematic presentations, near-continuous color range for critical art work, and integrated audio, video, and telecommunication capabilities. It will be an intelligent, affordable, indispensable machine and also serves as videophone, and high-definition television. What impact would this type of machines have on the teaching and practice of engineers and scientists.

There is a renewed interest in the integration of computers into education. Two decades have passed since the World Conference on Computers in Education in 1970, at Amsterdam, Netherlands, where Bitzer presented the PLATO project, Papert his LOGO language, and ACM the curriculum 68. The International Conference on Computer Graphics and Education convened in April, 1991, at Barcelona, Spain, where R. Philips demonstrated the concept of electronics books, and J. Raymond the animated digital slide show [5]. Traditional books are multimedia: one could flip to any page, write on them, draw on them and erase from them. Comparatively, current books on computers support far less multimedia activities. A prototype electronics textbook [6], implemented by R. Philips [7], supports context browsing by hypertext [8], demand-animation in real time to demonstrate algorithmic dynamics, and digital audio signal editing to leave reader messages in the book.

There is a great deal of research in the field of virtual reality, which is closely related to the training of engineers and scientists. Flight simulators can reduce the training cost of pilots. Simulated excavation activities can stimulate the students' interest in archeology [9]. The Vesalius Project demonstrated the viability of simulated gross anatomy study [10]. The commercial Animated Dissection of Anatomy for Medicine software supports computer-aided dissection with the cursor serving as a scalpel. Simulated stress and strain analysis assists in the teaching of civil engineering subjects. Visualization in fluid flow, earth science, quantum physics and molecular chemistry [1] can enhance the effectiveness of their teaching. Although it will not replace the experience of learning in the real world, simulation can reduce the educational cost during the early, basic training stages.

FUNDAMENTAL SKILLS

Most students with an undergraduate degree enter gainful, professional careers. What do employers expect from future computer-literate engineers and scientists? Outlined below is a list of skills that will supplement future careers in engineering and sciences, where computation—especially computer-assisted information visualization—will play an increasingly engaging role.

- Knowledge about tools: tool selection and usage, both hardware and software, their trade-off, interdependencies, and availabilities.
- Information presentation skills: to use color, texture, icons and analysis tools, to present both collected and calculated statistical information [11,12], and to practice design visualization in engineering and sciences.
- Media integration: to unify input from digital sources, i.e. compact disk, digital video, imagery graphics, and analog sources, i.e. photographic cameras, prints, analog video tapes, etc., and output to the same.
- Aspects of human cognition in color, depth, texture, motion, contrast, etc.
- Procedural knowledge: from idea generation to concept implementation, including information collection, processing, and presentation, multimedia integration, animation with or without sound effects;
- To promote visual thinking: to enhance understanding and to stimulate intellectual curiosities beyond the material objectives [13–15].
- Visual confirmation: to communicate is to convince.
- Finally, three advanced areas may be included in a post *undergraduate* curriculum: advanced algorithm development, special application development and parallel processing.

The design objective of a scientific visualization laboratory is to deliver a cost-effective environment to realize the expectations listed above. The choice of computing facilities depends on the available financial and other resources. Discussed in the following four sections are the planning aspects of a multipurpose scientific visualization laboratory, the available equipment platforms, the issues of multimedia integration and the necessary generic software tools [16].

PLANNING A VISUALIZATION LABORATORY

One needs adequate physical space, financial resources, a good knowledge in system integration, and infinite patience to undertake such a project. Computer-equipped teaching facilities support three tutoring styles: the teacher-centered instructional style, the activity-centered experimental style and the student-centered exploratory style. This paper focuses on the student-centered style. One must distinguish the functions of the laboratories from that of the classrooms and design the laboratories to fulfil the projected usages.

The laboratory should have adequate space to house the open-access computers, to store the limited-access peripheral equipment, and to provide an audiovisual environment for project review [17]. The project review space may double as an equipment overflow space. The peripheral storage area needs to be secured separately without impeding the normal student activities in the laboratory. A supervisor office is optional. Shown in Fig. 1 and Table 1 are the actual schematic

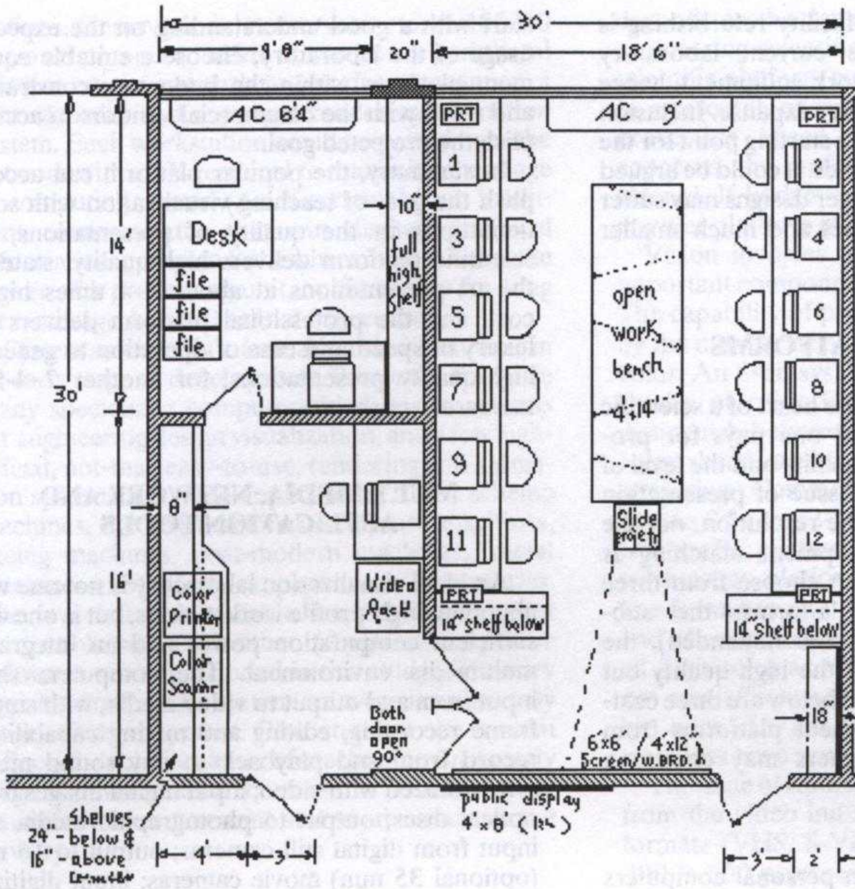

Fig. 1. Scientific visualization laboratory.

Table 1. Space utilization statistics

	Normal			Overflow	
	Area (sq. ft)	No. of stations	Area/station (sq. ft)	No of stations	Area/station (sq. ft)
Laboratory	580	12	48.3	16	36.3
Laboratory, storage	767	14	54.8	18	42.6
Laboratory, storage, supervisor	910	14	65.0	18	50.5

drawing and the space utilization statistics of the laboratory that was completed in the Fall of 1991.

The space utilization statistics fall within the general range of 32–48 sq. ft per workstation [19], excluding supervisor and storage areas. Some states impose building codes on the minimal legal space per workstation. (For example, the State of New Jersey requires 35 sq. ft of space for a basic workstation and 60 for a station in computer-aided design applications.) Spaces around the walls are functionally inert, hence it is wise to place the computers and equipment against the walls. Communication corridors must be maintained between the audio–video display area and the rest of the laboratory. To support 15 computers, the final budget of $232,280 was allocated to three approximately equal parts: the cost of the computers ($81,200); the software and peripheral equipment ($22,480 and $72,200 respectively); and facility refurbishing ($56,400), which includes laboratory space, furnishings, networking and non-digital audiovisual equipment. Cost distribution among hardware, peripherals and facility refurbishing is approximately 1:1:1. (The current laboratory includes some existing network equipment, hence the slightly lower actual facility expanse. Inclusion of the cost estimate serves as a starting point for the designers of similar laboratories. It could be argued that laboratories of much larger designs may suffer from instructional deficiencies and much smaller ones cost deficiencies.)

EQUIPMENT PLATFORMS

Computing equipment is the heart of a scientific visualization laboratory, and one pays for processing speed, presentation quality and the level of integration. In practice, the issue of presentation quality is centered around the resolution, *not* the raw processing speed. Equipment matching *is* resolution matching. One can choose from three distinct resolution-based platforms: the sub-broadcast quality level (not recommended), the popular broadcast level and the high-quality but non-standard level. Presented below are three cost-effective, progressive equipment platforms from which the laboratory designers may choose a starting configuration.

The popular platform

The systems are based on personal computers that support the television class of resolutions, the NTSC, PEL, S-VHS classes of equipment, from 15 to 35 kHz in frequencies. Affordability is achieved at the expense of presentation quality. For example, a video encoder or genlock board may cost from $500 to $5000.

The scientific platform

Based on the current generation of workstations, this platform supports high-resolution display in the range 35–50 kHz. The equipment, with similar capabilities as the popular platform, often costs 2–4 time more. For example, a video scan converter may cost from $5000 to $30,000.

The professional platform

Processing speed, in both CPU and graphics processing, is the major concern in the movie industry, in live broadcasting or in commercial applications. This platform may be based on high-end workstations and specialized commercial systems. The resolution is in the high end of the 50 kHz range, with fast display regeneration. Some real-time animation is possible with this class of equipment. One is best advised to have an open-budget.

Commercial vendors are either specialized, offering one type of equipment for special applications, or vertically integrated, offering a broad spectrum of equipment. With a cost-effective framework in mind, the laboratory designers can work with the commercial vendors to complete successful designs. The project architect should start with a good understanding on the expected usage of the laboratory; choose a suitable equipment platform within the budgetary constraints; and work with the commercial vendors to accomplish the projected goal.

In summary, the popular platform can accomplish the goal of teaching visualization with some limitations in the quality of presentations; the scientific platform delivers high-quality, state-of-the-art presentations at about 2–4 times higher cost; and the professional platform delivers the luxury of speed and ease of operation to generate high-quality presentations, for another 2–4-fold increase in cost.

MULTIMEDIA, NETWORK AND APPLICATION TOOLS

An ideal visualization laboratory is not one with abundant high-profile workstations, but is one with sufficient computation power and an integrated multimedia environment. The computers shall: input from and output to video media, with single-frame recording, editing and mixing capabilities; record from and playback to any sound media synchronized with video; input digital images from optical discs; output to photographic media and input from digital still cameras; output to 16 mm (optional 35 mm) movie cameras; input digitized information, in color or in gray scale, from flat media (three-dimensional scanner highly desirable); output to color printers (the most popular output media); optional output to plotter in some applications, but mandatory in engineering design; optional input from manual digitizers.

The current multimedia evolution is focused on live-video, realistic scene generation, wide color bandwidth and high-resolution graphics. The features listed above are available in various formats and are often not input/output compatible with each other. The video subsystem is the most difficult to assemble. Commercial components are not integrated as a system and the terminology is plagued with broadcast jargons. The computing community desires an integrated multimedia environment.

The focus on networking is on adequate performance and load balancing. Ethernet-based systems are popular in office automation applications. They provides adequate support to message transactions, but show performance strain to system or bit-mapped applications. The network performance is marginal in a small laboratory environment with less than 10 workstations. (The once popular diskless systems cannot be adequately supported on a network that is based on the Ethernet standard. The Ethernet standard was designed around 1970 for office automation applications. It lacks the bandwidth to support modern multimedia applications.)

To balance the load, laboratory capabilities are distributed among the computers as animation stations, fileservers, printerservers, etc. A 486/50 personal computer is introduced as a peripheral handler on the network to interface a scanner, a film recorder and a second rendering–animation system. Each workstation could be paired over the network with an X-terminal to maximize the usage of computing power. (An X-terminal is an intelligent communicator that can display graphical information generated elsewhere but it lacks the power of a processing unit, or the ability for long term storage, hence it sells at a discount.)

System software in information visualization is in an early stage of development. Presently, there are many specialized computer-aided design systems for engineering design visualization, and a few high-priced, not-that-easy-to-use, rendering and animation systems for video applications. Color scheme machines, lighting machines, sculpture machines, ageing machines, post-modern machines, fractal machines exist mostly on paper or in laboratories. The few that are available are not inpu/-output compatible with each other. (Application-specific softwares are not included in this study.) The very popular multimedia system software is in an early stage of development. The state of the system reflects the volatile nature of a technology in its early stage of development. It represents both an opportunity for the venturesome and an adventure for the unwary.

CURRICULUM REALIZATION

To address the design issues of a scientific visualization laboratory is to address the nature of education in the next generation. Information visualization is a creative, individual activity, the basic approach to its teaching could be unorthodox, different from the traditional cycle of lectures, homeworks, reviews and examinations. The course may be project based, oriented for community learning, student-centered, goal driven, bounded to reference books, oriented for activities, interdisciplinary (many believe this is necessary), based on team discussions, graded by pier reviews and individually tailored. The instructor serves to design and tune the projects, to support the students to accomplish their goals. Within this variety lies the strength of the course, namely that it can be adapted for individual institutions with specialized emphasis. Since this paper focuses on the design of visualization laboratories and the classroom of the future, we cover the curriculum design aspect only in its essence, and without any specifics. In the next section, we return the focus to the core issue of competing cost and performance considerations.

PERFORMANCE COST CONSIDERATIONS

First, one considers the aspect of computation speed. A cost-effective computation platform depends on the demand of the applications. In an engineering-scientific teaching environment, the scientific platform could be an appropriate choice. In a research or commercial environment, where processing speed and quality are the major concerns, the professional platform may be considered. If budget is a major constraint, then the popular platform may be the choice.

Vision involves perception, hence color is an important component in a visualization laboratory. The capability of presenting color is characterized by the number of bits used to define the individual color. An 8-bit system provides the user with 256 shades of color for each rendering. (One must distinguish between the availability of millions of color shades and the ability to used them in each rendering.) Common color depth varies from 8-, to 16-, to 24-, to 32-bit. The 8-bit format is popular with the PC platform and the 24-bit format with the workstation platform. Image transformation from one format to another can produce unpredictable and often unpleasant side-effects, such as treating all 8-bit color as 1-bit (black and white). It is also not cost-effective to retrofit 8-bit machines to 24-bit ones. In an education environment, 8-bit machines have served admirably well.

The issue of resolution is driven by the equipment from the video industry. The standard broadcast formats (VHS, S-VHS, PEL, NTSC) are around 400 × 600 pixel resolution and 8-bit color depth (which explains why personal computers support this range of displays). Computer-generated images of this size can be cost-effectively recorded to most video equipment, hence the popularity of the VGA format on personal computers. The scientific and engineering communities, interested in the applications of computer-aided design, engineering and manufacturing, often demand more bandwidth than the video-based formats. This class of end users desires a minimal format of 1000 × 1000 resolution with 8- to 16-bit color depth. Additionally, computers are increasingly being integrated into the commercial art industry, for which higher resolution and 24- to 36-bit color depth are in demand. Due to some technical limitations in the ultimate switching speed of the semiconductor devices, it is unlikely that the resolution of the basic display monitor will be doubled or tripled in the near future.

At present, video-based display technology is limited by its cost-effectiveness at the 2000 × 2000 resolution threshold. Continuous tone printers and photographic image recorders can provide cost-effective solutions with much higher resolution, but without the convenience of an interactive media. The distinction must be made between the creative, interactive, design activities and the high quality, reproduction capabilities. In Table 2, a summary is provided on the trade-off status of major color peripheral categories.

Next, one considers the subject of image sharing. There are two types of images: raster-based images register pixel information, and language-based images register rendering information. Screen

Table 2. Summary of the major color peripherals

Category	Color depth (bits)	Image size (pixels)	Pixel density (d.p.i.)	Cost range ($'000)
Digital monitor images	24	1000 × 1000		>1
Video equipment	8	400 × 600		market
Discrete tone printers	8	8 in. × 10 in.	300	~8
Continuous tone printers	16	8 in. × 10 in.	continuous	>20
Photographic media	16	4000 lines	continuous	~10
Optical scanner	24	8 in. × 10 in.	300	~10

capture operations result in raster-based images, and drawing operations result in language-based images. For each type there are many encoding formats. For the raster type, there are Sun Raster format, Targa format, etc., and for the language type there are PostScript format and HP Graphics Language format, etc. There are about half a dozen popular ones in each type and many less-popular ones, and the distinction is drawn between the PC and workstation orientations. Not all encodings of the same format are the same, i.e. each vendor may produce different versions of the same format. Mismatching encoding and decoding operations will yield failed or distorted images. One needs software tools to translate from one format to another, as well as to view encoded images.

Video technology provides dynamic information presentation capability. There are two working modes to interface computer graphics with video equipment: the continuous and the discrete modes. In the continuous mode, the video machine either plays back and displays continuously on the monitor through the computer, or records continuously from the computer by capturing the monitor display. (The Targa system from Truevision Inc. operates in this fashion.) Continuous-mode hardware is more user friendly and cost-effective but places some constraints on the modeling and rendering software that for every second, the software must display 30 finished images on the monitor. Only relatively simple images can be generated in 1/30 of a second, without the aid of fast and costly hardware. In the discrete mode, the monitor display can be written to or read from a videotape one frame at a time, thus granting the computer the luxury of time to generate images. Both the multicomponent hardware that supports the discrete mode of operation and the software that offers an integrated interface are far more costly than its continuous-mode counterpart.

The proud end-product of a visualization process is usually a hard copy. A hard copy is needed for proof reading, for final rendition, for future playback or for archive. A hard copy device usually understands some—but not all—of the popular image-encoding formats. It often requires the image to be translated for the particular hard copy device. Few translators exist and successive translations result in image quality degradation.

The term 'glue software' is new to the computing industry, but is increasingly becoming popular in multimedia applications. A set of glue software is needed to bridge the different hardware, file and image formats. Glue software mostly provides the service of file format translation and occasionally provides image simulation, such as in the case of color dithering. The quality of glue software varies among the vendors.

A set of cost-effective equipment is a set of balanced, matched equipment. For scientific, engineering computation, processing speed is necessary. This calls for computers based on the RISC architecture chips, Intel Pentium chips, Motorola 68040 chips, etc. Both color and resolution are necessary but not dominant, i.e. 8- or 16-bit color or 800 × 1000 pixel resolution display. For the peripheral, a low-cost color printer for proof-reading and a production quality color printer for final rendition are necessary. Depending on the application, video equipment, plotters, scanners and photographic cameras can be selectively introduced.

The technology of the computational man–machine interface is fast moving. In a short four years, the popular theme has evolved from photo-realistic rendering, to scientific visualization, to multimedia integration, and lately to virtual reality. Swept behind this wind of changes is the basic issue of what impact the latest technology exerts on the teaching of engineering and science topics, and what demands it places on teaching facilities. In the next section, we present a glimpse of the future classroom and a new dimension in teaching methodology: exploratory learning.

CLASSROOM OF THE FUTURE

To present the classroom of the twenty-first century, one starts with the future form of education. What can computating power contribute to instructional teaching? What form will evolve to make teaching more effective, learning more fun and education more cost-effective? The new form of education will integrate exploratory learning as part of the traditional instructional teaching. Learning may be aided by multimedia information access, which would be favorably compared with Guttenberg-inspired paper media and post-World War II audio-isual teaching aids. There may be virtual laboratories to provide cost-effective, initial training. These issues will be elaborated here and glimpses of some pioneer cases presented [17,18].

Outwardly, the classrooms of the future will increasingly look like computer laboratories, and as computer laboratories they will not look very different from what exists today. There will be workstations, printing stations and other support equipment. The similarity stops at the outward appearance. Functionally the classrooms of the future will be very different from today's computer laboratories.

In 1991, a laboratory was designed and constructed at the Villanova University to explore the impact of information visualization in education and the teaching of it. To educate is to open the mind's inner eyes. The laboratory is functionally divided into three major areas to support the activities of visual thinking and intellectual stimulation.

- The laboratory itself
  - An area for the workstations
  - An area for exploratory discussion
  - An area for visual presentation
- The auxiliary area (optional)
  - An area as the nerve center of the laboratory (File depository and network control)

Contrary to common intuition, the area for the workstations demands the least attention. They could be placed anywhere in the laboratory. The area reserved for discussion and presentation requires a high degree of activity correlation among the users. It must support intensive visual traffic and be the activity center of the future classroom. The form of future teaching may be enhanced by computer-aided exploratory techniques. The relationship between the teacher and the students may be a co-operative one. The 'Let me show you' teaching style may be complemented by the 'Let me assist, while you discover'. Project discussion and presentation will become the core components of the curriculum.

To support this mode of teaching, information must flow freely, from the confinement of one workstation, from one platform to another, from spatial graphics to computer animation, to video playback, to broadcast. This is the epitome of the multimedia technology. Two essential issues behind this technology are standardization and communication bandwidth. Non-standard information platform will not survive the evolution, and optical communication network is a crucial requirement. With the advent of digital high-definition television and videophones by the year 2000, classrooms and buildings of the future must be properly equipped to support this trend. Optical networks should reach wherever the power supply reaches and network outlets be as common as power outlets.

Our experimental prototype laboratory is networked with today's technology, i.e. Ethernet transmitting at the rate of 10 million baud. An existing building was refurbished with all network cables being routed to the ceiling where they were interconnected together and further to the external world. It provided the first taste of a multimedia classroom and more are desired. All machines in the laboratory are equipped with floppy disk drives and none was ever used. A living analogy would be the situation of letter writing versus telephone conversation. With the phone, fewer letters were written and more conversations exchanged. Publications are sent internationally over e-mail, programming problems are broadcast over the network, solutions are received within days from obscure corners of the world, and finally job positions are announced on the network. Digital networks of the twenty-first century will be as popular as the telephone systems of the twentieth. Only they are better. Over the network, live audio and video broadcasts can be carried. Such will be the classroom of the future.

Available on the workstations will be virtual laboratories. Training under simulation is not new. Flight simulators like the Link Trainers have existed since 1929. The NASA Ames Research Center has developed a virtual wind tunnel, the Johnson Space Center with the University of Houston developed a virtual physics laboratory. Two virtual laboratories were developed at the Villanova University. A virtual botanical laboratory allows the students to design and grow plants, the ultimate designer's garden. With it one can experience biological systems by growing natural plants as well as unnatural ones. A virtual juggler trains the students to juggle balls. The idea is similar to the flight simulators, except the computer-based ones are 2000 times more cost-effective than the physical ones.

Such activities demonstrate the possible future course of classroom utilization, the form of education and cost-effective learning. While virtual laboratories can accelerate the initial learning curve and reduce the high cost of education, they are not the real training. For medical professionals, engineers of all kinds, aeroplane pilots, ocean liner captains and many other professionals, training with the real equipment is still necessary. With the aid of the new technology in the twenty-first century, the total cost of training can be reduced, with education being made more effective, and learning more fun.

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