Virtual Reality in The Chemical Engineering Classroom

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I. Background

Virtual Reality

Virtual reality, VR, is an emerging computer interface that utilizes immersive interactive three-dimensional graphics as well as audio, psychology, special hardware, and numerous other mechanisms to produce simulations so realistic that users believe (if only for a few moments) that what they are experiencing is "real" [1]. In addition to high-speed graphics, VR can be enhanced through wired clothing, body tracking sensors, tactile and force feedback systems, spatialized sound, and even olfactory displays. Some of the earliest uses of VR have been in medical and military applications, where budgets are large and the consequences of even small errors are sufficient to justify the expense of high-quality equipment and initial software development. More recently VR has been used for computational fluid dynamics visualization, operator training, construction engineering, maintenance planning, and EPA site remediation.

Although high quality VR still requires prohibitively expensive computers and equipment, it is now possible to deliver VR simulations of a somewhat lower quality on student affordable personal computers. This opens the door to the initial development of VR modules for educational purposes, and as the capabilities of personal computers continue to grow, so will the overall quality of educational VR programs.

In order to explore the potential of educational VR, a number of modules have been created at the University of Michigan. The specific goals in developing these modules are threefold:

1. To produce modules with as much practical use to as many students as possible.

2. To determine the optimal applicability of virtual reality to engineering education.

3. To develop a knowledge base of techniques for the display of, and interaction with, scientific and technological information and concepts in a virtual world, that can later be applied to practical engineering problems

This paper will discuss the current status of these modules, with emphasis on developments that have occurred since 1996 publications [2-3], and on implementation guidelines for educators who may wish to use the modules. Instructions are provided at the end of this paper on how to download the modules free of charge via the world wide web and how to install and run the modules. Recommended and optional computer hardware and peripherals are also discussed.

Educational Benefits of Virtual Reality

There are several important educational benefits offered by virtual reality. These benefits are not the same for all students, and some of the benefits are both complex and subtle, which means that they will not be inherently apparent to all students or educators. The benefits of educational VR are also difficult to measure, because they tend to be long-term rather than immediate, and because VR is best used to enhance other educational methods rather than as a stand-alone tool.

One of the strongest benefits of educational VR is the reinforcement of material that has been taught through other channels, thereby increasing the long-term retention of course material. Dale Edgar [4] has shown that we only remember 10% of what we read, and 20% of what we hear, but that we retain up to 90% of what we learn through active participation. Allowing students to explore through immersive interactive simulation the same concepts that were previously covered in class will not teach them any new material; However it will reinforce the material that they have learned elsewhere, improving the overall learning process.

Another benefit of educational VR addresses different learning styles [5]. Some students learn very well from oral lectures and written words. These verbally oriented students generally excel under traditional educational methods, and do not need additional assistance from virtual reality. Other students, however, are more visually oriented, and do not fully understand the words until they can see an illustration of the concepts. VR can help this latter group to visualize the material covered in class and texts, thereby improving overall understanding and comprehension. Of course all students have some mix of verbal and visual learning skills, so the degree of benefits offered by virtual reality will vary greatly from student to student and from application to application.

Of course one cannot ignore the fact that (for some students at least) virtual reality can be quite exciting and fun. While it is easy to discount the "gee-whiz" effect, anything that increases students' interest and enthusiasm for their classes must have a positive impact.

Special Constraints of Educational VR

Developing VR programs for educational purposes imposes a unique set of goals and constraints on the developer. First and foremost, the programs must be accessible to students. This means that (versions of) the programs must run well on the types of computers commonly available to students, without requiring a lot of specialized equipment. It is important to consider home computers as well as university owned machines, and to remember that not all universities and students are fortunate enough to own the latest equipment. At the same time, high powered computers and special VR peripherals should be supported for those who have access to them.

Traditional simulation programs (e.g. ASPEN) have the goal of producing results that are accurate and useful to practicing engineers. These programs use convergence tolerances near 10^{-6}, and take as much computer time as necessary to solve the problem. VR developers, on the other hand, strive to refresh the screen 20 to 30 times per second or even faster in some cases. Anything less than 20 Hz refresh rate reduces the believability and effectiveness of the simulation. (Some of the modules described later in this paper go as low as 5 Hz as a

compromise between realism / level-of-detail and performance speed, but this is sub-optimal.) Since a major portion of the (student-affordable) computing power is consumed with graphics calculations, this leaves on the order of 1/50 of a second to complete all engineering calculations.

At the same time, student-affordable head-mounted displays (HMDs) can have visual resolutions as low as 200x300 pixels. This resolution makes it impossible for the user to distinguish more than one or at most two digits of precision, and also makes it impractical to display text or numerical results, except for a few small items in very large font.

All this means that the VR developer must concentrate on the goal of delivering an effective educational experience, and not yield to the temptation to perform rigorous engineering calculations while the VR program is running. Educational VR can be an effective mechanism for illustrating concepts, trends, ideas, and cause-and-effect relationships, but it is not an appropriate tool for calculating or displaying detailed results. (After all, we have other tools for those tasks.) Gross simplifications and the use of pre-calculated results can both help deliver effective and believable simulations without requiring extensive run-time calculations.

II. Overview of The VR Modules

Three major and half a dozen minor VR modules have been produced for use in undergraduate chemical engineering courses. The two most significant modules, Vicher 1 and Vicher 2, relate to chemical kinetics and reactor design, while the third major module is a safety related application for use in chemical plant design or safety courses. The minor modules were developed to explore different capabilities of educational VR, in areas of thermodynamics, fluid flow, crystal structures, and azeotropic distillation. This section provides a very brief overview of these modules; additional details can be found in previously published papers [2-3,6].
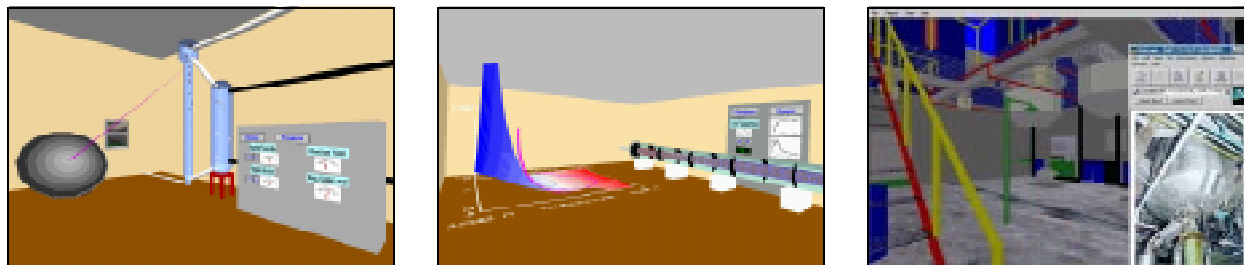

Figure 1: Sample Images from Vicher 1, Vicher 2, and Safety.

Vicher 1

Vicher 1 addresses heterogeneous catalytic reaction mechanisms, and industrial responses to decaying catalyst. Vicher 1 includes three reaction engineering rooms and three microscopic environments, in addition to the introductory welcome center. The reactor rooms include the time-temperature room for the study of slow catalyst decay, the moving-bed room for the study of medium rates of catalyst decay, and the transport reactor room (shown above in Figure 1a) for the study of rapid catalyst decay. All the reactors can be made transparent, and most can be operated using virtual control panels. Of course students are always free to fly inside the reactors for a closer look. The most interesting microscopic area is the inside of the catalyst pore,

(shown in Figure 3a), in which up to 100 molecules diffuse, adsorb, react, and desorb according to heterogeneous catalytic reaction mechanisms. Because this area can get quite congested, students can also fly through the walls to the area shown in Figure 3b, in which there is a single molecule that reacts repeatedly and predictably, with labels describing each step of the process. All three of the major modules include extensive "help" systems, as described below.

Vicher 2

Vicher 2 is similar in nature and format to Vicher 1, though not as large as the former application. The subject of Vicher 2 is non-isothermal chemical reaction kinetics, as illustrated in three different reaction rooms accessed from a central welcome center. The non-isothermal packed bed reactor room shows temperature profiles down the length of a jacketed packed bed reactor in which an exothermic reaction occurs. There is also a three-dimensional kinetics surface in this room, and color coding is used to relate the mathematics to the physical reactor. The second reaction area of Vicher 2 is the staged reactor area (shown above in Figure 1b), in which material flows through four reactors in series with a furnace providing heating before each reactor. A two-dimensional kinetics overlay is related to the physical equipment through color coding and through interconnected tracers that move over the surface and the equipment. The third reaction area in Vicher 2 is the multiple steady states room, which illustrates a classic control problem for exothermic reactions occurring in jacketed continuous stirred reactors (CSTRs). Color coding is also used in this room to indicate temperature changes. All three Vicher 2 areas contain transparent reactors, and two of the three allow students to explore different operating conditions through the use of virtual control panels.

Safety

The first safety related application developed for this project is a hazard and operability analysis of a polyether-polyol pilot plant, as shown above in Figure 1c. The VR model allows students to walk around the plant and observe the layout and relationships of different pieces of equipment, and their proximity to important environmental concerns, such as nearby housing and a river that provides drinking water to a large metropolitan area. There is an associated help system (as is also true for Vicher 1 and Vicher 2), which shows photographs of the actual site. These photographs provide a level of detail that is not otherwise possible for student-affordable VR.

Preliminary evaluations of this module indicate that it is not highly effective in its current form, due to a lack of clear direction for student participants. This result is not surprising, considering the small amount that students would likely learn from an unescorted and undirected visit to a real chemical plant. Changes are planned for this module to add specific tasks and problems to be studied, as well as more information regarding the safety concerns, a point scoring system to provide incentive for participation, and immediate feedback regarding right and wrong answers.

Minor Applications

In addition to the major modules, a half-dozen minor modules have also been developed, to explore the capabilities of educational VR, and as proof-of-concept vehicles. (Shown below in Figure 2.) Crystal structure and fluid flow modules were developed to illustrate the abilities of

VR to explore three-dimensional spatial relationships. The fluid flow module also makes use of color to convey information, and is a very simple example of how VR could be used to illustrate computational fluid dynamics (CFD) results. Data visualization is explored in PVT, thermodynamics, and azeotropic distillation residue curve applications. The first of these uses the shape, size, color, and sound of a single icon to simultaneously display pressure, volume, temperature, and entropy information respectively. The second application mentioned shows the relationship between different thermodynamic variables, (specifically Maxwell's thermodynamic relationships), using a set of moving color-coded vectors on four energy surfaces. Modifying the pressure or volume of the system causes all the vectors to adjust to new positions and angles, according to changes in other system variables and derivatives. The azeotropic residue curve application is a preliminary attempt to extend common graphical engineering techniques to higher order dimensions.
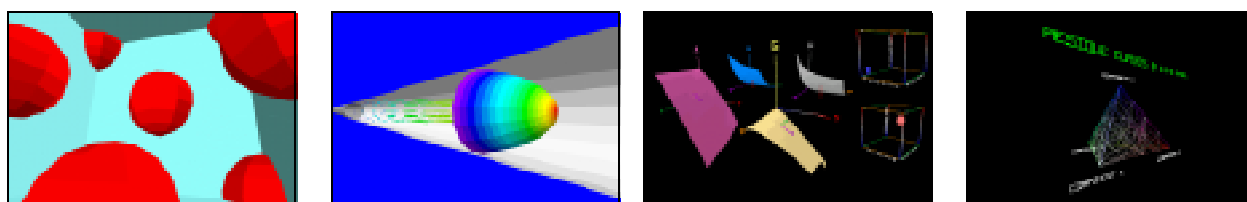

Figure 2: Images from Crystal Structure Exploration, Fluid Flow Visualization, Thermodynamic Applications, and Azeotropic Residue Curves

III. Major Improvements and Changes Since 1996

Multiple Platform Support

The initial development of the modules required original creation of virtual buildings, reactors, pipes, and other three-dimensional objects, as well as graphical images, sound files, a program structure, and of course all the computer code necessary to make the modules active, reactive, and interactive. Once that work was completed, relatively little (though not insignificant) work was required to port the programs over to other platforms, (so long as the desired target platform is supported by the underlying library used to develop the modules [7].) The modules were originally developed for Windows 3.1 (no longer supported), and are now available for Windows NT, Windows 95, and Silicon Graphics (SGI) platforms. Some of the changes that had to be implemented to support these additional platforms included the upgrading of the help system to an HTML format (see below) and timing adjustments using real-time information to prevent the modules from running excessively fast on high-end systems. Support has also been added for certain high-end devices on SGI systems, such as the FakeSpace BOOM[8] device and the CAVE display system [9,10]

Increased Realism and Accuracy in Vicher 1

Extensive efforts have been made to increase the realism and informational accuracy of the modules, particularly in the microscopic areas of Vicher 1. A literature search of catalytic cracking was performed, and the information used to significantly enhance the Vicher 1 help documentation (see below). The gas-oil cracking chemistry within the pore is modeled as the

cracking of pure butylbenzene, which is sufficiently complex to illustrate all the key reaction steps of gas-oil cracking, but sufficiently simple to yield a manageable number of isomers and a minimum of congestion within the pore. The help document explains both the real gas-oil cracking chemistry and the mechanistic steps of the simplified butylbenzene chemistry.

Samples of catalytic materials were obtained, and photographed under a scanning electron microscope (SEM). These photographs were used to model the virtual catalyst pore areas, and they were also used within the Vicher 1 help document, as shown in Figure 3.

Figure 3: Catalyst Pore Interior and Surface Decorated With SEM Photographic Images, and a SEM Photograph from the Vicher 1 Help System

Improved "Help" Documentation

The original help system was based upon the MS Windows 3.1 help utility, and allowed users running the VR simulations to pop up a small help window while running the VR modules. When support was added for the SGI platform, however, the help system had to be changed, and so an HTML based system was implemented. Besides being cross-platform compatible, HTML provides for the inclusion of more extensive information, many different types of media, and links to resources external to the VR modules. The HTML based help system can be launched from within the VR modules (provided Netscape is present), or it can be run independently by those who cannot or choose not to run the VR modules. Expansion of the help system (particularly in Vicher 1) includes equipment photographs, SEM photographs of catalytic materials, QuickTime VR movies of an industrial site, and links to remote web sites.

Web Distribution of the VR Modules

In November of 1997 a web page was created (see below) which provides free access for anyone who wishes to download the VR modules. As of this writing all the minor modules are available for all platforms (except for the thermodynamics modules, which have sound problems on SGI), and Vicher 1 is available for Windows NT. It is hoped that by the time this paper is presented, all the modules except safety will be available for all platforms. (Preliminary testing has revealed some important changes that need to be made to the safety module before it can be publicly released, as discussed above.)

Since that time, nearly 200 file download requests have been received from over a dozen countries around the world, including requests from students, faculty, and industry. (These numbers include some duplicate requests, but do not account for any duplication that may have occurred at recipients' sites after downloading, and do not include downloads made while

developing and testing the web distribution system.) Surprisingly to us, Windows 95 requests have outnumbered Windows NT requests by about two to one, which will cause us to pay more attention to that platform in the future. Countries represented in the download logs include Argentina, Brazil, Canada, England, Greece, Ireland, Italy, Japan, Mexico, The Netherlands, Portugal, Sweden, Turkey, and of course the United States (from Hawaii to Pennsylvania).

Improved Navigability and User Interface

One of the strengths of VR is that it gives the user the freedom to explore from any desired viewing position or angle. Early testing, however, found that many students became frustrated when they became stuck near the floor level or at some twisted angle of view. Therefore the modules have been modified so that (by default) the viewpoint is constrained to a level view and a reasonable distance from the floor. Advanced users can remove these constraints using suitable keyboard commands. Pull-down menus have also been added, to provide easy access to program adjustments, teleports to other areas, and access to the help system. The operational documentation has been extensively revised and improved, in both on-line and paper versions.

IV. Implementation Guidelines for Educational VR

Required, Suggested, and Optional Hardware

One of the major design goals in developing these modules was to make the programs accessible to as many students nationwide as possible while still supporting high-end computer equipment and peripherals for those who have them. In order to reach this goal, three versions were created for each module - one each for Windows 95, Window NT, and SGI computer platforms. Although several VR-related peripherals are supported, the only required device is a mouse. A sound card is required to hear the audio component, but the programs will run without one.

The minor modules involve relatively simple graphics, and should run reasonably well on any computer that supports the aforementioned operating systems. The major modules (Vicher 1, Vicher 2, and Safety), however, will benefit greatly from high speed graphics accelerator cards. The Windows NT versions are built on OpenGL graphics and are best run with graphics cards that perform hardware level OpenGL graphics acceleration, and in particular, hardware level texture map acceleration. The particular card that we use is the GLZ-1T board set from InterGraph corporation. This card is no longer sold as a stand alone card, but any InterGraph or comparable computer with performance matching the GLZ-1T board set will suffice. Some of the graphics chipsets known to work well with PC based virtual reality (though not specifically tested with the modules described here) include 3D Labs Permedia/GLINT, 3Dfx VooDoo, Matrox Mystique, and the Rendition Verite. Other features to look for in a VR graphics card are at least 4MB of video RAM (more is better) and hardware level z-buffering and texture mapping.   See also http://www.sense8.com/indy3d/index.html for more information.

The Windows 95 versions are built on DirectX graphics, and video cards that accelerate this standard will definitely improve performance. In the absence of Direct-X compatible graphics cards, the Windows 95 programs rely on DLL files that support the DirectX standard. Not all computers have these files, but they are available free of charge by downloading the file

"idx5rdat.exe" from Microsoft at "http://www.microsoft.com/msdownload/directx/dxf/sdk5.0".
("Windows 95" is technically a misnomer here, as these modules will run on any system supporting Direct X graphics, including Windows NT.)

The Silicon Graphics versions have been tested successfully on O2, Indigo2, and ONYX2 computers. They should run equally well on any SGI computer, although obviously faster graphics and texture mapping capabilities will improve performance.

Although the mouse is the only required device, a number of special VR peripheral devices are supported for those who have them. For simple three-dimensional viewing, CrystalEyes glasses from StereoGraphics corporation [11] are supported, which deliver true stereoscopic display on an ordinary computer monitor (provided the monitor supports a 120 Hz refresh rate.)

Two different head-mounted display (HMD) systems have been used for this project. The first are the "i-glasses" from Virtual I/O corporation, which include a stereoscopic HMD and built in head tracker for as little as $500. Unfortunately Virtual I/O went bankrupt selling these units at this low price; However another company bought the rights, and will reportedly be selling these HMDs for $1000 by the time this paper is presented. VRiChEL modules also currently support the Logitech acoustic head tracker, which can be used with any HMD that uses a separate tracker. (We use the Logitech tracker in conjunction with an HMD from General Reality [12]; Our original cost was $3000 in 1994 for the head tracker and eyewear combined.) Other trackers, such as the electromagnetic models sold by Ascension [13] and Polhemus [14] can be easily accommodated upon request.

The SGI versions support some very high-end display devices, namely the BOOM and the CAVE. The BOOM (Binocular Omni Orientation Monitor) from FakeSpace corporation [8] consists of two small monitors mounted on a counterweighted articulated arm. This arrangement provides for high resolution color stereo display with low effective weight as well as high precision tracking of the user's viewpoint. The CAVE was originally developed by the Electronic Visualization Laboratory at the University of Illinois in Chicago [9], and is currently sold by Division incorporated [10]. A CAVE consists of a cubic room in which the walls and the floor are stereoscopic display screens. Driven by very powerful SGI computers, CAVEs produce simulation environments so realistic that it can be very difficult to distinguish them from reality.

Downloading The Modules

Each of the VR modules is composed of multiple files when installed. For purposes of distribution, however, all files required for any given module are bundled into a single (compressed) package, along with PDF format documentation files and a small HTML page that provides links to related resources. These packages can be downloaded free of charge by accessing the VRiChEL (Virtual Reality in Chemical Engineering Laboratory) web site at:

<div align="center">http: / / www.engin.umich.edu / labs / vrichel.</div>

Users accessing this URL can follow a link to the file download page, where they provide their name, e-mail address, and a few other items of information, and check boxes for which programs they would like. A computer program then processes this information and (if it is sufficiently

complete) generates a fresh web page containing links to the requested programs. Users can then download and save the desired installation packages. It is recommended that users install and test one of the minor modules first, to ensure that they run properly on their computer hardware, before attempting to install the major modules.

Installing The Modules

The Windows NT and Windows 95 versions are delivered as self-extracting compressed executable files (using InstallShield software [15]), and the Silicon Graphics versions are tar archives. To install the Windows versions, users simply run the executable program that was downloaded and answer the questions regarding the desired storage location, program group, etc. The uninstall package that is included ensures that the entire process is reversible. Installation of the Windows versions will create a new program group, with icons for the executable programs, documentation, web access, uninstallation, and help system if appropriate.

The SGI versions are easily unpacked using "`tar -xvf filename`" at a command line prompt. If the target directory is initially empty, then the programs can be easily removed by simply deleting the directory and any subdirectories created. The components of the SGI versions are identical to the Windows versions, except for the program groups and icons.

Integration of VR Modules into a Course Curriculum

Because the benefits of VR are unique to each individual, it is recommended that these modules be implemented as optional extra-credit activities. This approach allows students who already understand the class material well (e.g. verbal learners) to spend their time on other activities, while providing an additional perspective for those who most benefit from an active visual experience. It is also vital that the programs be installed where students can access them at their convenience. At the University of Michigan we have implemented this in a mixed fashion - The VR modules are available on ordinary monitors 24 hours/day, and special times are also set aside when students have access to special equipment such as the BOOM or the CAVE.

Assignments related to VR should be designed to make students think about the underlying concepts (and to provide impetus for exploration), rather than testing their abilities to solve problems. Questions that begin with "Explain the significance of ..." or "Discuss the trade-offs of ..." are particularly suitable. (I.e. the analysis level of Bloom's Taxonomy [16].) Groups of two or three students working together can use the VR modules as the basis for discussion of the class topics. When assigning "grades", credit should be given for participation and an honest effort at answering the questions, rather than a rigorous grading of right and wrong answers. The instructor's answers, (which will generally be more well developed and thought out than the students'), should be provided after the students have completed their assignments.

Instructor's guides for the Vicher modules (including sample questions and answers) are under development, and should be available by the time this paper is presented.

V. Conclusion

This paper has discussed the use of virtual reality in chemical engineering education, focusing on changes that have occurred since 1996 and on implementation guidelines. Information has been provided on how to download and install the software, and recommendations made for integration into a course curriculum. In particular, it is recommended that the modules be implemented as an optional extra-credit activity, available 24 hrs/day, with a suitable set of questions to encourage analysis and reflection of the topics covered.

VI. Acknowledgments

VII. Bibliographic Information

1. Pimentel, Ken and Teixeira, Kevin, "Virtual Reality: Through the New Looking Glass", second edition, Windcrest Books, 1995.
2. Bell, John T., and H. Scott Fogler, "Vicher: A Prototype Virtual Reality Based Educational Module for Chemical Reaction Engineering", *Computer Applications in Engineering Education*, **4**(4), October, 1996.
3. Bell, John T., and H. Scott Fogler, "Recent Developments in Virtual Reality Based Education", *Proceedings of the American Society for Engineering Education Annual Conference*, Washington, DC, June 1996.
4. Edgar, Dale, "Audio-Visual Methods in Teaching, 3rd Edition", Holt, Rinehart, and Winston, 1969.
5. Felder , R. M. and L. K. Silverman, "Learning and Teaching Styles in Engineering Education", *Journal of Engineering Education*, **78**(7), 674-681, April, 1988.
6. Bell, John T., and H. Scott Fogler, "Virtual Reality in Chemical Engineering Education", *Proceedings of the North-Central Section of the American Society for Engineering Education Annual Conference*, University of Detroit Mercy, Detroit, MI, April 3-4, 1998.
7. Sense8 Corporation, 100 Shoreline Highway Suite 282, Mill Valley, CA 94941, (415) 331-6318, http: // www.sense8.com.
8. Fakespace, Inc, 241 Polaris Ave. Mountain View, CA 94043, (415) 688-1940, http://www.fakespace.com.
9. Electronic Visualization Laboratory, University of Illinois at Chicago, 851 S. Morgan St., room 1120, Chicago, IL 60607-7053, (312)996-3002, http://www.evl.uic.edu.
10. Division Incorporated, 46500 Eleven Mile Road, Novi, MI 48374, (810) 348-1683, http://www.divnc.com.
11. StereoGraphics Corporation, 2171 East Francisco Boulevard, San Rafael, CA 94901, (415)459-4500, http://www.stereographics.com.
12. General Reality Company, 124 Race Street, San Jose, CA 95126, (408) 289-8340, http://www.genreality.com.
13. Ascension Technology Corporation, P.O. Box 527, Burlington, VT 05402, (802)860-6440.
14. Polhemus Incorporated, 1 Hercules Drive, PO Box 560, Colchester, VT 05446, (802) 655-3159, http://www.polhemus.com.
15. InstallShield Corporation, 900 National Parkway, Suite 125, Schaumburg, IL 60173-5108, (800) 374-4353, http: // www.installshield.com.
16. Bloom, Benjamin S., "Taxonomy of Educational objectives: The Classification of Educational Goals, Handbook I: Cognitive Domain", David McKay Company, New York, 1956.

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