

The Investigation and Application of Virtual Reality as an Educational Tool

John T. Bell, H. Scott Fogler
Department of Chemical Engineering
University of Michigan, Ann Arbor, 48109-2136

Abstract

Many studies have shown that students learn best when a variety of teaching methods are used, and that different students respond best to different methods. To this end, computers are being used more and more as teaching tools, to provide students with a wider variety of learning experiences. These approaches include multimedia presentations, computerized question-and-answer sessions, and some quite realistic simulations of situations too complex, costly, or hazardous to bring into the classroom. This paper addresses the application of virtual reality as a new educational tool, designed to get students more deeply immersed in the computer simulations, and to present educational experiences not possible using other methods. Details of the virtual reality based educational program Vicher are presented, along with a discussion of our experiences using the program as part of an undergraduate chemical reaction engineering course.

Introduction

Educational Objectives

In order to teach most effectively, we must have clear objectives of the skills we wish our students to master after having received the benefit of our instruction. In the early 1950's, a group of educators put together an extensive, highly detailed, classification of educational objectives, known as Bloom's Taxonomy of Educational Objectives³, which is widely used by educators today to judge the depth and appropriateness of their coverage of course material. The general categories of Bloom's Taxonomy are shown in table 1, and range from knowledge (memorization) at the low end, to evaluation (judgment) at the high end. Most educators are disappointed to find that their traditional teaching methods rarely address more than the first three levels of this cognitive hierarchy, (knowledge, comprehension, and application.) Montgomery and Fogler, in their classification scheme for interactive

computer aided software¹⁴, have noted that in addition to using Bloom's Taxonomy to identify skills to be practiced, it is also necessary to identify the best methods to teach the students, according to their individual learning styles.

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| <p>Level 1, Knowledge: The basic ability to recall information, without requiring any understanding of the material being recalled.</p> <p>Level 2, Comprehension: The ability to understand and interpret material or situations, and to extrapolate that understanding to areas not covered by the original input.</p> <p>Level 3, Application: The ability to determine which knowledge is relevant to a particular situation, and to correctly apply that knowledge to produce a correct solution to the problem at hand.</p> <p>Level 4, Analysis: The ability to break a complex problem or situation into parts, and to recognize the relationships between the parts and the organization of the parts.</p> <p>Level 5, Synthesis: The ability to create a unique new entity, by drawing on different aspects of knowledge and understanding, such that the result is more than simply the sum of its component parts.</p> <p>Level 6, Evaluation: The ability to judge the value of ideas, solutions, methods, etc. This level is considered to be the top of the cognitive hierarchy because the student must employ all five of the lower levels, plus an appropriate evaluation criteria, in order to determine the overall value of the subject being examined.</p> |
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Table 1: The Six Main Categories of Bloom's Taxonomy

Styles of Learning and Teaching

We all learn through a variety of different mechanisms, where the particular methods which are most effective vary greatly from individual to individual. Several researchers^{7,9,10,11,12,14,17,19} have studied these different styles of learning, and have developed classification schemes for determining the preferred learning / teaching styles for individual students and instructors. For example, Felder and Silverman⁷ have developed a classification scheme which measures students preferred learning methods along five different scales, or dimensions, as

shown in table 2. They further conclude that the preferred teaching style of most engineering faculty, in general does not match the optimal learning style of most engineering students. (Most engineering students learn best from learning processes which are sensory, visual, inductive, and active, while most lectures tend to be intuitive, verbal, deductive, and passive in nature.) Further discussion of how Bloom's Taxonomy and Felder and Silverman's learning styles can be used conjunctively to guide the development of instructional software can be found in Montgomery and Fogler¹⁴.

<u>Sensory</u> / Intuitive:	Sensors prefer facts, data, and experimentation, are careful and patient with detail, but may be slow. Intuitors prefer concepts, principles, and theories, and may be quick but careless.
<u>Visual</u> / Verbal:	Visual learners prefer pictures, diagrams, charts, movies, demonstrations, and exhibitions. Verbal learners prefer words, discussions, explanations, formulas, and equations.
<u>Inductive</u> / Deductive:	Inductive learning develops principles and generalities from observations, the natural human learning approach. Deductive development starts with governing principles and then develops applications, the natural teaching approach.
Active / Reflective:	Active learners learn by doing and participating. Reflective learners learn by thinking or pondering introspectively. Unfortunately, most lectures provide opportunity for neither approach (passive).
Sequential / Global:	Sequential learners take things step by step, and will be partially effective with partial understanding. Global learners must see the whole picture for any of it to make sense, and are completely ineffective until they suddenly understand the entire subject.
<u>Underlined</u>:	Preferred by most engineering students.
Bold Face:	Preferred by most engineering professors.

Table 2: The Five Dimensions of Felder and Silverman's Learning Styles

Virtual Reality

Virtual Reality, VR, is a newly emerging computer interface characterized by high degrees of immersion, believability, and interaction, with the goal of making the user believe, as much as possible, that s/he is actually *within* the computer generated environment, as opposed to being an external observer looking in. In an ideal virtual world, a user would be completely unable to determine whether they were experiencing a computer simulation or "the real thing." Virtual reality implementations typically use high speed, high quality three dimensional graphics, 3-D audio, and specialized hardware such as head-mounted displays and wired clothing to achieve high degrees of realism and believability.

Although the concept of VR has been around for over thirty years, it has taken recent advances in hardware and software to bring this technology to within the budgetary reach of ordinary users and researchers. There is, of

course, a wide range of solutions available, with higher quality implementations providing a greater degree of realism, immersion, and believability at a correspondingly higher cost. At this point, high-quality solutions are not yet affordable, and affordable solutions are not yet high-quality; However we feel it prudent to begin developing virtual reality based educational applications today, so that we will be prepared for the advances in equipment and software which will become available tomorrow, as the burgeoning popularity of this new technology drives prices down and quality up. Further discussion of low cost virtual reality and its application to chemical engineering can be found in Bell and Fogler².

How can Virtual Reality Address Educational Objectives and Learning Styles?

When developing instructional software, it is important to keep in mind the specific skill levels (Bloom³) and learning styles (Felder and Silverman⁷) which one is

attempting to address, to ensure that the software is fulfilling a need which could not be met using simpler, less costly methods. As described above, students learn through a variety of different mechanisms, many of which are not utilized adequately in traditional educational methods. In addition to not addressing a particular student's "preferred" learning style, we all learn more and retain more when information is presented to us multiple times, preferably through multiple channels. Virtual reality stands poised to not only add to the variety of educational delivery mechanisms, but to specifically address those areas where traditional methods are weakest. Addressing each of the five dimensions of Felder and Silverman's learning styles in turn:

1. On the sensory / intuitive scale, most lectures stress concepts and theories, where students are looking for concrete facts, data, experimentation, and a way to relate the material to a "real" situation. Virtual reality can provide a tangible representation of abstract concepts, such as a mathematical surface that students can walk on, or a world where "efficiency" takes on physical properties.
2. On the visual / verbal scale, virtual reality is highly visual, (although audible narration is also a valuable component.) There is also another dimension to this scale, which is rarely even mentioned because traditional educational techniques have no place for it: non-verbal auditory stimulus. In virtual reality, auditory cues, (such as the sound of a door closing), provide very important contributions to the realism of the overall experience, and this component can easily be expanded to provide educational sound cues, such as the sound of bonds breaking as molecules react, or the changing "pitch" of entropy.
3. On the inductive / deductive scale, virtual reality is a natural medium for free-format explorations and learning by observational experience.
4. On the active / reflective scale, virtual reality is highly active and immersive. The whole raison d'être of virtual reality is to pull the user inside the simulation and make him/her an active participant.
5. On the sequential / global scale, virtual reality can help address the needs of the global learners, who must see the big picture, by showing the inter-relationships of the mathematical and abstract concepts with the physical realities described by those concepts.

The need for student activities and involvement other than simple lectures has long been known, of course, and for that reason educators have long used homework, films, and where possible laboratory or "field trip" assignments as educational supplements to traditional books and lectures.

More recently, advances in computer technology have led to many high-quality computer based educational tools, including interactive computer modules, multimedia presentations, and process simulators^{5,8,14,16,18}. Most of these computer programs, however, still leave the student as an external observer being presented with information, with only limited active participation. Virtual reality, on the other hand, promises to pull students *inside* the simulations, to immerse them totally in educational experiences not otherwise possible. There are also certain experiences and viewpoints which only virtual reality can provide.

For example, homework gives students practice working out the mathematics, and various math packages can display plots, some even as 3-D surfaces. But only VR can let the student walk around on that math surface, climbing the peaks and valleys to see how the variables inter-relate. Photographs and movies, possibly delivered through multimedia, can show students what industrial equipment looks like, but only from the viewpoint(s) chosen by the photographer. Work experience or plant trips would allow students to see the outside of the equipment from any angle, but this is not always feasible, and still would not allow students to enter inside the equipment, which can be easily done using virtual reality. Laboratory courses give students hands-on experience, but the kinds of experiments and equipment involved are limited by size, cost, and safety constraints, whereas VR can model a thousand foot tower full of acetylene as easily as a two foot column full of water. Virtual reality can present both the concrete and the abstract side by side, and the relationships between the two indicated through various means.

As for addressing the educational objectives of Bloom's Taxonomy, that will depend on the specific applications developed. Virtual reality does provide the capabilities, however, to develop applications which will address the higher skill levels of Bloom's Taxonomy, such as level 4, analysis, (Explore an operating chemical plant, to determine how all the components interrelate, or perhaps troubleshoot a non-functioning process), level 5, synthesis, (Given a storeroom full of equipment, chemicals, unit operations, and theories, put together a working process to produce a desired product), and level 6, evaluation, (Explore two processes for producing the same product, and compare and contrast the benefits of each system; Then propose a third system taking advantage of what you have learned from the first two and the material covered in class.)

Exactly how well virtual reality will be able to fulfill its potential as an educational tool is yet to be determined, as are the as yet unforeseen benefits of this new technology. However before those benefits can be analyzed, the first virtual reality based educational simulator must be brought into existence.

Vicher - Virtual Chemical Reaction Module

In order to explore the potential of this new educational tool, a virtual reality based simulator, Vicher, is currently being developed at the University of Michigan Chemical Engineering Department, aimed at undergraduate students in the chemical reaction engineering course. While virtual reality has been recently employed in a few educational applications, (grade school and high school levels)⁴, and for advanced operator training, (virtual surgery¹⁵, flight simulation), the program presented here is the first known application of virtual reality to chemical engineering education. The goals in producing Vicher are threefold:

Objectives for Developing Vicher

1. To enhance undergraduate chemical engineering education by addressing educational objectives and various learning styles, particularly in those areas which are not addressed well by alternative teaching tools.
2. To build a knowledge base of virtual reality techniques, tools, and expertise which can then be applied to other problems at a later date.
3. To study virtual reality as an educational tool, in order to determine which aspects of virtual reality provide the most effective educational benefits, and to learn the strengths and weaknesses of this new technology in an educational setting.

General Information

Vicher, (**V**irtual **C**hemical **R**eaction module), is an educational application of virtual reality designed to aid in the instruction of undergraduate chemical reaction engineering. Much of this program has been described previously in Bell and Fogler¹, however the program is still under development, and much has changed since that earlier paper. Therefore a brief review is provided here of those areas which have not changed substantially, with more complete coverage of the new areas.

In order to put Vicher into the hands of as many students as possible as quickly as possible, the program is being developed on two IBM PC compatible computers, one of which is equipped with common hardware available to student budgets today, and the other of which incorporates hardware which should become more commonly available within the next year or two. This choice of hardware has been verified by several students who have bought comparable systems for personal use. The program can also be easily ported to other environments, such as Silicon Graphics, HP, or Sun workstations.

Users interface with Vicher using a joystick for movement, a mouse for "activating" objects and requesting information, and a keyboard for various other tasks, where "activate" takes on a meaning appropriate to the object, such as turning on the television or increasing the reactor feed temperature. When using the head-mounted display, the user may simply look where they want to go and push the joystick forward to move in that direction. This has been found to be the simplest and most effective navigation technique. Another strong benefit of the head-mounted display is the sensory-deprivation effect - When users are unable to see the "real" world, they become much more immersed in the virtual one.

The virtual environment being modeled in Vicher consists of a small portion of a modern chemical plant, plus some microscopic exploration areas. The rooms consist of a welcome center, in which users learn how to use the program and receive other pertinent information, a transport reactor room where students can study the effects of catalyst fouling, and a non-isothermal packed bed reactor area for the study of energy effects on reaction kinetics and reactor design. All of the reaction equipment may be operated by the students at different operating conditions to observe the effects of changing feed rates, inlet temperatures, etc. on reaction conditions. The microscopic areas are the inside and the outside of a catalyst pellet, and a highly magnified section of a catalyst surface.

The Welcome Center

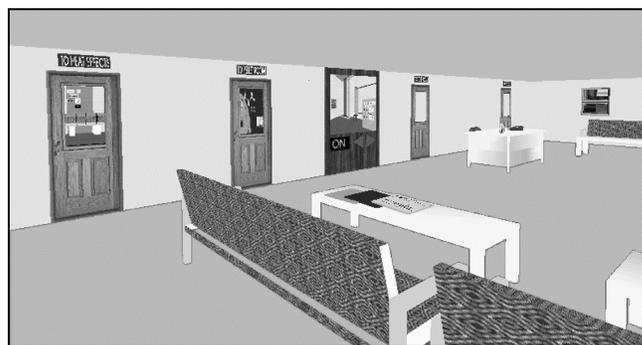


Figure 1: The welcome center, where users become accustomed to virtual reality and learn to navigate.

The welcome center provides two main functions in Vicher. First, it provides a familiar, comfortable environment in which the user can become accustomed to the virtual reality experience and equipment and learn how to navigate. We have found that this goes a long way to combat the disorientation effects which some users experience when first encountering virtual reality. Secondly, it provides a convenient base of operations from which to branch out and explore the other areas of Vicher. A large-screen virtual television in this room provides a preview of the other areas

of the simulation. The other areas of Vicher will also have televisions, providing engineering information and other instructions appropriate to each area in the plant.

The Transport Reactor Room

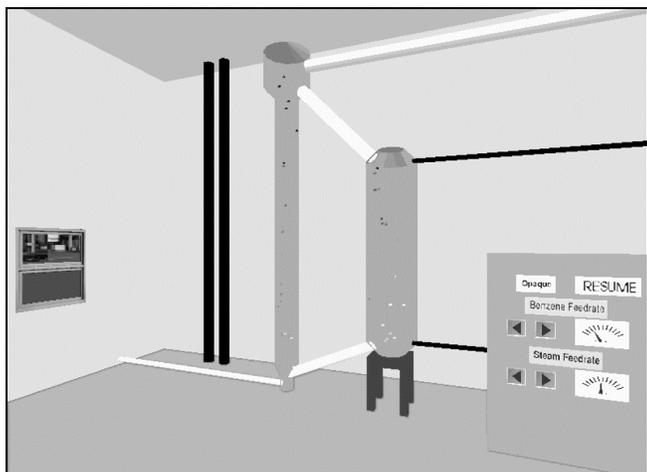


Figure 2: The transport reactor room, for the study of catalyst deactivation processes.

The transport reactor room contains a vertical straight-through transport reactor, (STTR), and its associated catalyst regenerator and control panel. The engineering principles being illustrated in this room are: 1) What does an industrial reactor really look like, and how does it operate, 2) The effects of flowrates on coking and decoking of catalyst pellets, and 3) the shrinking-core model of catalyst decay and regeneration. By turning the equipment transparent, (or by simply stepping inside), students can observe the coking and de-coking of the catalyst pellets as they move through the equipment, and how the process changes as various flowrates are adjusted. Gauges on the control panel indicate current operating conditions, and students can teleport into the microscopic worlds described below, either by "activating" or by stepping into the pellets within the reaction equipment.

The latest addition to this room is a three-foot diameter model of a catalyst pellet, sliced in half and linked to one of the pellets in the reactor. The purpose of this pellet is to illustrate the concept of the shrinking core model of catalyst de-activation. As the linked pellet travels through the reactor, the large pellet becomes more and more heavily coated with coke particles, working from the outer edges in towards the center of the pellet, in accordance with the model. As the linked pellet travels through the regenerator, the large pellet "cleans up", once again from the outside edges in towards the center according to the model. Changing the flowrates of either the reactant feed to the reactor or oxygen feed to the regenerator affect the coking and decoking behaviour appropriately.

Microscopic Areas

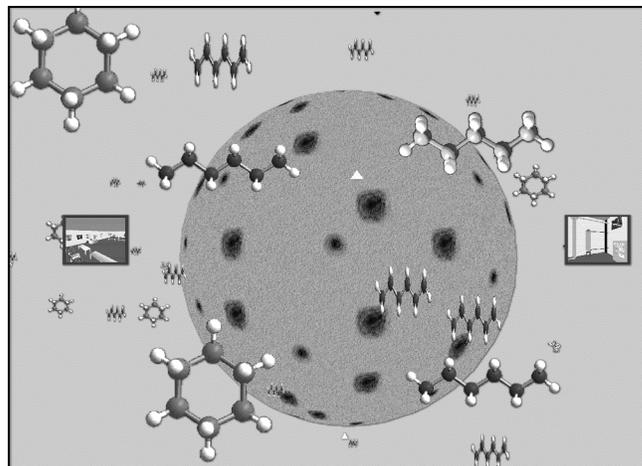


Figure 3: Students observe diffusional effects surrounding a porous catalyst pellet.

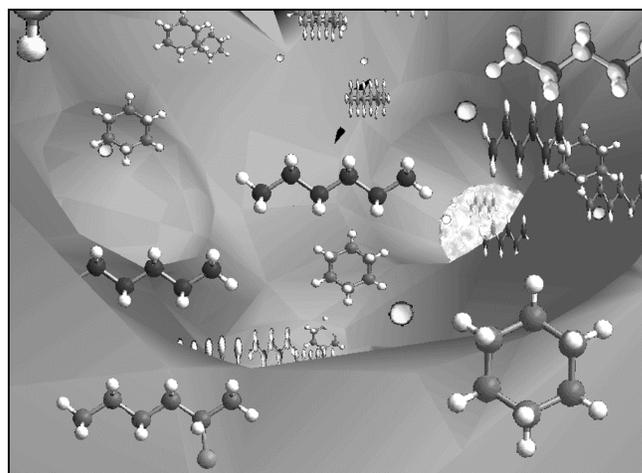


Figure 4: Catalytic reactions occurring inside a catalyst pore.

In addition to the macroscopic worlds, students can also observe catalyst activity on a microscopic scale, in the form of a single highly detailed catalyst pellet. From the outside of this pellet, students observe external diffusion; On the inside, students witness internal diffusion and the mechanism of catalytic reaction on a molecular level, including undesired side reactions and coke production. A recent refinement to this areas is to reduce the light levels inside the pore as the pellet cokes up, thereby making the world progressively darker. Conversely while the user rides the pellet through the regenerator, the light levels increase as the pellet cleans up.

Two new features are being added to this world as of this writing, and should be in place in time for student trials next week. The first is the addition of two "staged" reaction sites. Most of the molecules inside the catalyst pore diffuse randomly, and reactions either occur or do not occur according to kinetic equilibrium. This random behaviour can make it sometimes difficult to observe the

reactions, since the observer must be looking at the right place at the right time. The new staged reaction sites, on the other hand, will have reactions repeatedly and predictably occurring for easier viewing. These sites will be clearly marked for easy identification.

The second new feature allows users to fly through the stage areas to a new world, where the magnification has been increased to the point where the surface appears nearly flat. In this world, a single reaction occurs repeatedly, along with side reactions and coking. Each step of the reaction is clearly labeled, and as the catalyst surface cokes up, the rate of reaction declines, as the reactants bounce off the coked surface rather than adsorbing.

Non-Isothermal Reaction Area

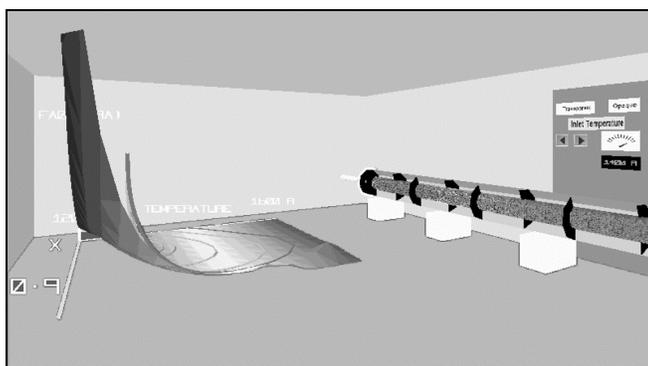


Figure 5: The kinetics surface and the reactor internals are color coded to indicate temperature.

The most recently developed room in Vicher is the non-isothermal packed bed reactor exploration area. In this area, students examine an exothermic reaction occurring in a packed bed reactor surrounded by a cooling jacket. In addition to the reactor itself and the associated control panel, this room also contains a mathematical surface, which describes the reaction kinetics as a function of temperature and fractional conversion. Overlaid on top of the surface are a number of lines, indicating reactor conditions along the length of the reactor, with different lines corresponding to different reactor operating conditions.

This room makes extensive use of color to convey temperature information. First of all on the kinetics surface, the high temperature area is indicated by varying shades of red, and the low temperatures are indicated by varying shades of blue, with intermediate temperatures colored white. Secondly, this color coding is carried over to the reactor, with high temperature areas again represented by red and low temperatures by blue. (As in the transport reactor area, the equipment may be made transparent to observe internal conditions.) This temperature indication mechanism allows students to quickly and easily determine where the hot spots are within the reactor, and to observe how those hot spots change in

both intensity and location as reactor operating conditions are varied. The interaction between the kinetics surface and the physical reality of the reactor goes a long way to bring "meaning" to the mathematics, by showing students a tangible link between the equations, formulas, and mathematics and the physical situations being modeled by those equations.

Two other points which users explore in this area are rather subtle: Why do the reactor path lines diverge from the kinetics surface? And why is one corner of the kinetics surface so bumpy? The answer to the first question is that the surface is isobaric, at the reactor inlet pressure conditions, whereas the lines follow actual reactor conditions, including pressure drop. Therefore the lines are at a significantly lower pressure than the surface at the reactor exit conditions, and have a substantially lower reaction rate. The answer to the second question centers around the fact that the reaction is reversible and equilibrium limited. The corner of the surface which is bumpy represents a set of conditions which are physically impossible to attain from the given inlet conditions, thereby yielding erratic and invalid results from the mathematical model.

Preliminary Results

Recall that Vicher is being developed with three major goals in mind: Enhancing undergraduate chemical engineering education, building up a knowledge base of virtual reality techniques and expertise, and determining the strengths, weaknesses, and general usefulness of virtual reality as an educational tool. Each of these three goals will be addressed in turn.

Educational Enhancement

This is the first semester that reaction engineering has been taught at the University of Michigan since the development of Vicher began, and no examinations have been given since the students have had access to Vicher. Therefore no firm numeric data are available at this time. We will, however, be examining the test scores of those students who have chosen to explore Vicher prior to the oral presentation of this paper, and those results will be presented at that time. In order to account for the natural bias in the test group, all exam scores will be divided by the scores from the first exam, (given before any students had access to Vicher), and the ratios will be used for comparison.

We have measured initial student response to Vicher, in the form of (anonymous) questionnaires filled out by student volunteers. Participants were first asked to respond to several engineering questions prior to entering the simulation, and were then given the opportunity to modify their responses after having experienced the virtual

exploration. Students were also asked to respond to general questions regarding their virtual experience. For this initial trial, students were only allowed access to the welcome center and the non-isothermal reaction area, because the class had not yet covered catalysis. Further trials will be conducted next week.

Overall, response was very good. Slightly over 25% of one section of the reactor design course chose to participate, which is high for a voluntary activity having no effect on course grades. User responses after the simulation were in general more accurate, more complete, and showed a better understanding of the engineering concepts than the same students' responses prior to entering Vicher. (Of course it is understood that the students most likely to voluntarily participate in this activity are those who are highly visual and active oriented, which is exactly the target audience that Vicher was designed to reach.) In addition, over 80% responded affirmatively to the question asking if they felt they had learned anything from the experience, with the remainder being primarily students who had already completed the course during previous years, and felt that they understood the material to begin with (TAs).

In response to the more open-ended free format questions, some of the students had this to say:

The color schemes were helpful in seeing trends. The visualization will stay with me."

"This experience will stay in memory much longer than any notes or lectures." (Several similar responses from different students.)

"Very good form of learning, a good complimentary device", "Very good, a lot of potential."

"It's easier to understand things when you can visualize them."

"I think its great! The graph really aided on actual vs. mathematical"

"Gives a clearer picture of the concepts."

"More, more! - Entire plant, separations, design, heat transfer, etc."

"Especially good for 3-D graphs."

"Awesome", "Neat", "cool", "wow", "fun", etc.

One feature which most students seemed to really appreciate was the three-dimensional colored graph of the reaction kinetics and its relationship to the packed bed reactor. They generally reported that this gave them a much more tangible grasp on the meaning behind the formulas and equations. As one student put it, "When I work on an engineering problem for an hour, all I have to show for my efforts is a number, which doesn't always mean anything to me. But when I spend an hour sweeping

the streets, (in a summer job at an amusement park), I can see a tangible difference between the street I've cleaned and the part I haven't gotten to yet. This program gave me a chance to *see* kinetics for the first time." One of the values of virtual reality is its ability to give tangible, corporeal substance to otherwise abstract ideas and concepts.

Technical Knowledge Base

We feel that we have acquired a good deal of VR technical expertise, and are ready to apply that knowledge to future applications. This is evidenced by the fact that the most recent areas have been developed very quickly, on the order of one week from concept to first student trials. We have also put together a number of less intensive side projects, on the order of a week or two from start to finish.

An example of the technical issues which have been mastered is how to move multiple complex objects in a realistic manner at reasonable speeds. (For virtual reality to be effective, the graphics images must be re-calculated and re-displayed several times per second, ideally 20 to 30 frames per second.) This technique has been implemented both in moving the catalyst pellets through the reaction equipment and also in moving the molecules within the catalyst pores. Note that in both these situations the objects in question also change form as the chemical reactions progress. Other features which have been developed and will be incorporated in future expansions include the implementation of a functional television set with both pictures and sound, and the control panels with functional buttons and gauges. We are currently exploring additional techniques, such as more extensive use of sound as a reaction rate indication mechanism.

Strengths and Weaknesses of Virtual Reality as an Educational Tool

During the course of our program development we have discovered several areas where virtual reality is quite effective, and also certain weaknesses. In addition, we have learned some things regarding human factors which are neither strengths nor weaknesses of virtual reality, but do indicate how this technology can best be applied as an educational tool.

The main strength which we have found in virtual reality is, not surprisingly, the ability to visualize situations and concepts which could not be otherwise seen, and to immerse the student within that visualization. For example, a photo or movie could show students the internal geometry of a reactor, but only VR will allow them to step inside and watch it operate from whatever angle or viewpoint they desire. An animation could illustrate the mechanism of catalytic reaction, but VR provides students with a much stronger sense of "being there". As mentioned above, students reported a much better understanding for

the mathematics behind non-isothermal reactions after having explored the 3-D kinetics surface and its relationship to the physical characteristics of the reactor.

Student interest and enthusiasm are also obvious benefits of virtual reality. While some of this can be attributed to the novelty of the experience and the general interest that some students have for anything computerized, virtual reality is designed to pull the user into the experience, and anything that we can do to get students more enthused and interested in our subject matter is a good thing, even if the effect is short lived.

In terms of learning styles, virtual reality is excellent for reaching the active, visual, inductive and global learners, who are not always served well through traditional teaching methods. As it stands now, Vicher targets primarily levels 2 and 4, comprehension and analysis, of Bloom's Taxonomy, although level 6, evaluation is also addressed in terms of choosing optimal reactor operating conditions.

There have also been some weaknesses discovered regarding virtual reality as an educational tool, the most significant of which being the presentation of textual information, such as equations, formulas, or definitions. This is due to the fact that virtual reality is very much a graphical environment, rather than a textual one. The problem is compounded by the fact that users may choose any viewpoint they wish, (often oblique angles), and the diminished resolution when using a head mounted display. We have tested several possible approaches to presenting text in a virtual world, with the following results:

1. Displaying text in an alternate window. This is actually quite effective under the MS Windows environment, and is used to provide hypertext based help information with the click of a mouse in the Windows version of Vicher. In the DOS version, however, this is not an acceptable method, as the "alternate window" is actually an alternate monitor, which is generally overlooked in any case and is completely impossible to see when the head-mounted display is in use. For either DOS or Windows this method detracts from the immersion of the experience, although the effect is less noticeable under Windows, as the user does not become as completely immersed to begin with.
2. Text as three dimensional objects. This method is effective for small labels, but is not practical for larger blocks of text, particularly where Greek letters, mathematical symbols, and super- and sub-scripts are involved.
3. Graphical "pictures of text". This method shows potential, and will probably be utilized to a greater extent in the final version of Vicher. In particular it is

desired to provide more engineering background information on the virtual television sets which are present in various areas. However there are some technical difficulties involved, including the large size of each image, some resolution constraints, and some difficulties in generating the appropriate images to begin with.

4. Supplemental paper-based workbooks and/or instruction sheets, and increased auditory feedback. This approach addresses the issue by letting virtual reality do what it does best, (present experiences), and not try to make it do something for which it is not well suited. By analogy, a student in a laboratory course would not expect the equipment to tell him/her what to do; That would be the job of the laboratory instructor and the laboratory workbook.

We have also experienced some difficulty modeling certain abstract areas, such as the interior of the catalyst pore structure. This is because 1) Never having been inside a catalyst pore, we don't really know what it should look like, and 2) In that no one else has ever been inside a catalyst pore either, no one will recognize that environment even if we model it perfectly! This area is definitely one in which adequate explanation is required in order for users to fully understand what they are experiencing.

Another difficulty in implementing VR on a student achievable budget is the level of detail which is attainable at a practical speed. Contrary to most computer applications and video games, virtual reality must re-calculate the user's view for each frame update, taking into account such considerations as (partially) hidden objects, oblique angles, light sources, textures of materials, shadings, distance from the user and others. To be effective, all this must be performed several times per second, (ideally 20 to 30, realistically 4 to 5 in our experience), in addition to any engineering calculations which must be performed. This necessarily limits the amount of detail and complexity which is practical within a given scene, although we have learned several techniques for making the most effect out of a limited number of polygons, and those hardware imposed limits will be pushed back as the next generation of PC graphics cards becomes available, (within 6 months.)

In terms of human factors, (a science in and of itself), one area which we have had to address is navigation. In early versions of Vicher, the different rooms were connected by hallways, designed to provide logical continuity between areas. What we discovered was that many users had difficulty negotiating the hallways, that they added little to the overall experience, and that when teleports were provided as alternatives, most users preferred to use the teleports, with little difficulty. Accordingly, all hallways have since been replaced by teleports, providing the additional benefit of much greater flexibility in terms of

interconnecting new areas. Students also get a kick out of some of the "hidden" teleports, such as stepping through a bookcase to get to a study, or through a fireplace to get to the non-isothermal reactor area. (Unfortunately, OSHA regulations have required the removal of all fireplaces from the vicinity of the chemical processing areas.)

Developing the proper computer-human interface is also crucial to an effective virtual world. In order to be most effective, a virtual reality implementation should have an interface which is as intuitive as possible, so that the user may more easily forget they are using a computer. The best interface found for Vicher is a combination of the joystick and the mouse. The keyboard has been found to be a poor interface for virtual worlds. This is especially true when using the head mounted display unit, as the user is unable to see the keyboard easily. The joystick, on the other hand, is especially effective in conjunction with the head-mounted display, as the user merely looks in the desired direction and pushes the stick forward. The only drawback to the joystick as an interface device, is that not all potential users have joysticks attached to their computers, and some environments (such as undergraduate computing labs) perceive them as toys and will therefore resist their implementation. There is also a small learning curve associated with using the joystick, with some users reporting difficulty initially. Of course it also takes some people a little while to get used to walking on the ceiling!

Current and Planned Developments

As mentioned above, we will be doing further student testing of Vicher next week, and will report the results of that testing at the oral presentation of this paper. We will also be enhancing Vicher based on feedback not only from current students, but also from past students and professional engineers who have experienced the simulator and provided us with their comments.

For example, one criticism of Vicher which we are addressing is that it requires further explanation before participants can fully understand what they are looking at and what they are supposed to do with it. We are addressing this issue with two responses. First of all, the audio component of Vicher is being greatly expanded, to provide more complete narration and verbal description of the contents and activities of Vicher. Some information is also being provided via wall-screen virtual television sets, which will provide detailed descriptions of each piece of equipment in each room, including how to utilize and observe it. Secondly, student instructional workbooks are being developed to provide more in-depth background and direction, as well as prompting students with questions to promote and test their participation. In many ways Vicher is very much like a laboratory experience. We would never set students loose in a real laboratory without some guidance and instructions, and it is appropriate that students

have instructions for their virtual laboratory as well. This will also help overcome a shortcoming of virtual reality - the difficulty of presenting text based material in a three dimensional graphical world. By restricting the virtual simulation to those aspects to which it is best suited, and providing paper based supplements to handle those aspects not handled well in a graphical environment, the whole can be more effective than the sum of its parts.

In terms of program developments, Vicher is beginning to reach a size where further expansion is no longer appropriate. Rather, the results of user feedback will be used to finalize and polish the areas which are currently developed, and prepare to distribute Vicher for testing at other sites. Related to this, we will be looking into porting Vicher to as many alternative platforms as is practical.

We will probably limit Vicher I to the catalytic study areas only, in order to minimize program disk and memory requirements, and use the non-isothermal study area as the cornerstone for Vicher II, dealing with non-isothermal effects. We are also interested in developing a series of very short, simple VR explorations, covering such topics as crystal structures, micro electronics manufacturing, laminar vs. turbulent flow, heat and mass transfer processes, and other topics where three dimensional visualization can be helpful. Interest has been expressed in the development of a training simulator for operators of chemical processing equipment, for the training and assessment of operator response to hazardous situations.

Summary and Conclusions

A virtual reality based educational simulation program, Vicher, is being developed in the Department of Chemical Engineering at the University of Michigan in order to achieve three main objectives, as outlined above:

1. To enhance undergraduate chemical engineering education by addressing educational objectives and various learning styles, particularly in those areas which are not addressed well by alternative teaching tools.
2. To build a knowledge base of virtual reality techniques, tools, and expertise which can then be applied to other problems at a later date.
3. To study virtual reality as an educational tool, in order to determine which aspects of virtual reality provide the most effective educational benefits, and to learn the strengths and weaknesses of this new technology in an educational setting.

Preliminary results indicate progress in all three areas. This paper has described Vicher and discussed how it is meeting each of these objectives. Future plans call for the

refinement and distribution of Vicher to all major chemical engineering departments, through the auspices of the CACHE corporation, and for the development of additional applications of virtual reality to chemical engineering, educationally and other wise.

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JOHN T. BELL

Dr. John T. Bell, Lecturer in the Chemical Engineering Department at The University of Michigan, received his BS in Chemical Engineering in 1984 from Georgia Institute of Technology, under the cooperative education program. He then did a year of graduate study at l'Institut du Génie Chimique, in Toulouse France, where he received a Diplôme des Études Approfondies, before moving on to the University of Wisconsin, Madison, where he received a MS in Chemical Engineering in 1987, a MS in Computer Science in 1988, and a Ph.D. in Chemical Engineering in 1990. Prior to coming to the University of Michigan, John spent four years teaching advanced computer courses at The Computer Classroom, a private computer training firm in Madison, Wisconsin.

H. SCOTT FOGLER

H. Scott Fogler, Vennema Professor of the Chemical Engineering Department at The University of Michigan, has over 120 research publications. In addition, he is author of two books, the most recent, "The Elements of Chemical Reaction Engineering" 2nd Edition, published by Prentice Hall in 1992 which is the most used book on this subject in the world.

In 1980, Professor Fogler was a first recipient of the newly instituted award for Outstanding Research from the University of Michigan College of Engineering, and also in 1980, received the Chemical Engineer of the Year Award from the Detroit section of the American Institute of Chemical Engineers. In 1987, he received the University of Colorado Distinguished Alumnus Award, and in 1988, he was elected President of the Computer Aids for Chemical Engineering (CACHE) Corporation.