Ten Steps to Developing Virtual Reality Applications for Engineering Education

John T. Bell
H. Scott Fogler
Department of Chemical Engineering
University of Michigan
Ann Arbor, MI 48109-2136
(313) 763-4814, Fax 763-0459
http://www.engin.umich.edu/dept/cheme/bell.html

Introduction

Work has been conducted in the Department of Chemical Engineering at the University of Michigan for several years to develop a series of virtual reality (VR) based computer modules for use in undergraduate engineering education. The goals of this work have been 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 outlines our findings to date regarding the second goal, which encompasses not only how to produce effective VR applications, but also the identification of which students and topics will most benefit from VR, and how best to incorporate educational VR into the engineering curriculum. The modules themselves (Vicher1, Vicher2, and Safety) have been described in previous papers. [1-6]

Background

Bloom's Taxonomy of Educational Objectives

In the early 1950's Benjamin Bloom [7], in conjunction with other educators, developed a taxonomy of educational objectives ranging from simple memorization to complex evaluation, as outlined in Figure 1. Traditional teaching and testing methods tend to stress primarily the three lowest levels of Bloom's taxonomy -- knowledge, comprehension, and application. These levels are easy to teach, comprehend, and evaluate, because problems based upon these levels tend to have a specific concrete answer that is either right or wrong.

The higher levels of Bloom's taxonomy begin with analysis and include synthesis and evaluation. Bloom ranked evaluation as the highest level in his taxonomy on the grounds that a thorough evaluation requires the use of all five of the lower levels. These upper levels are more difficult to teach and evaluate than the lower levels, and as a result are not implemented as extensively in most curriculums (with the obvious exception of capstone design courses which operate almost entirely at the upper levels of Bloom's taxonomy.)

Level 1, Knowledge: The basic ability to recall information, without requiring any understanding of the material being recalled.

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.

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.

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.

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.

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.

Figure 1: The Six Main Categories of Bloom's Taxonomy

Learning Styles

We all learn through a wide variety of different methods, including but not limited to reading, attending lectures, video / multimedia presentations, laboratory experimentation, and participation in heated discussions. However for any given individual there are certain modes of learning and thinking that are more natural and effective than the other learning methods. Many educational researchers have studied the different styles of learning and teaching that occur in our classrooms, and as a result, several different classification schemes have emerged [8]. These learning style models include the Meyer-Briggs Type Indicator [9], the Kolb Learning Style Model [10], the Herrmann Brain Dominance Instrument [11], and the Felder-Silverman Learning Style Model [12], the last of which is outlined in Figure 2. All the researchers in this field tend to agree that it is important to teach to all types of learners using all teaching methods, but that unfortunately there is usually a mismatch between the predominant teaching styles and many students' learning styles.

Educational Simulators

Edgar Dale found in 1969 that two weeks after learning new information we remember no more than 20% of what we hear and read, but up to 90% of what we say and do [13]. In general Dale found that the more active and participatory a learning activity, the longer the material remained in memory. This agrees with the work of Kolb [10], who found that experience is one of the most powerful learning activities available. This fact is well known in engineering education, which is why laboratories, plant trips, summer internships, and co-operative education programs are all valued as highly desirable educational opportunities. Unfortunately, however, there are many experiences that cannot be easily provided to all students, due to economic, logistical, safety, or other constraints. As a result we are seeing an increasing number of educational computer simulators being developed for use in undergraduate engineering courses [14-22]. This is still a growing field of research, and one that should continue to progress as student computing capabilities steadily increase.

<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.

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

Virtual Reality

Virtual reality is a special kind of simulation, designed to convince users to the greatest extent possible that they are actually within the computer generated simulation environment. This environment is portrayed using complex three dimensional graphics that are re-calculated and re-displayed many times per second in response to users' actions. The critical feature of VR is believability, which is attained through high degrees of immersion and interaction. An effective VR simulation can cause a willing suspension of disbelief in many participants, such that they forget, if only for a short while, that it is only a simulation. The level of immersion (and hence believability) is often enhanced through the use of special hardware, such as head-mounted displays (HMDs) and wired gloves. Other techniques used to enhance VR simulations include 3D spatialized sound, stereoscopic vision, tricks of human perception and psychology, and even more specialized devices such as haptic feedback and olfactory displays. Further information can be found in many good books on the subject of virtual reality [23-26].

Virtual Reality Addresses Bloom's Taxonomy and Alternate Learning Styles

Virtual reality provides an environment in which students can exercise the higher levels of Bloom's taxonomy in a manner totally unique from other educational methods. Within a VR simulation, students are free to explore, and to examine their environment from any vantage point they desire. This includes hazardous and inaccessible locations, such as the interior of an operating reactor or the microscopic pores of a catalyst pellet. With this newfound freedom to explore, students can analyze their problems and evaluate possible alternatives in ways never before possible.

In terms of learning styles, VR appeals particularly to visual and active learners in the Felder and Silverman classification scheme. Global learners can also benefit, from the opportunity to see the big picture and how their current studies relate to the larger whole. Of course experience, the main feature of VR, is of great benefit to all learning styles.

The Ten Steps

Through our development work we have identified ten key steps in the development and implementation of VR based educational modules. The following will describe each of the steps and what we have learned about that stage of the process.

Step 0: *Plan for the future; Never underestimate how fast technology will change during your development process.* Experienced professional VR developers working full time can put together a complete polished VR simulation in about six months. Educators and student researchers who must balance their development efforts with the pressures of classes, meetings, writing papers and seeking funding should plan on at least two years for their first simulation, possibly longer depending on the participants' backgrounds and resources available. During this time VR hardware and software will change dramatically. It is therefore our recommendation to A) Start with the most advanced equipment you can afford, in the hopes that it will not become obsolete before the project is completed, and B) be prepared to upgrade or even completely change development platforms during the course of the project.

Step 1: *Understand the strengths and weakness of educational VR.* VR is designed to model a space, an environment, or an experience. It is a graphical environment best suited to images, concepts, and illustrative examples. It is NOT an appropriate venue for displaying text or mathematical formulas for several reasons:

1. Low cost VR display devices (HMDs) have very poor resolution, making it nearly impossible to read any but the largest fonts. (Most such devices render the user legally blind.)

2. VR appeals primarily to visual learners, who perceive information much better through imagery than through words. Many of these students will choose to read as little as possible, even when a textual description is available.

3. Textbooks already do an excellent job of presenting text and formulas in a compact, easily portable form. It would be a huge waste for VR to attempt to duplicate that which is already adequately presented by other media. (Placing a book on a computer screen does not improve its educational effectiveness.)

Another important limitation in educational VR is the tradeoff between level of detail, realism, execution speed and required hardware. In order for a VR simulation to be believable, it is critical that the screen image be updated as quickly as possible, with minimal lag between a user's actions and the simulation's response. Ideally the frame update rate should be kept between 20 and 30 frames per second. Contrary to most computer games, however, VR graphics are completely re-calculated from a geometrical database for each screen update, which requires extensive computational power for all but the simplest graphical environments. Any additional details or behaviors that are added to the simulation will increase the realism of the experience, but will also either slow it down or else increase the minimum hardware requirements to run the simulation at a reasonable speed. Before adding any details or calculations the developer should always ask: A) Will the difference be noticeable? (Remember the resolution problem.), and B) Will the effect be worth the cost in performance?

Step 2: *Identify the intended audience and the end users' probable equipment.* Very realistic simulations can be achieved using high-end graphics supercomputers and million dollar display devices. However the number of undergraduate students nationwide who would have access to such equipment is fairly low. On the other hand, it would be inappropriate to base a complex surgical simulator on a cheap personal computer that does not have sufficient power to do an effective job. Remember: You need to predict what equipment your audience will have when your project is completed. In our case we began development under Microsoft Windows 3.1 and standard VGA graphics cards in order to reach a wide student audience, and now find ourselves switching to Windows NT, Windows 95, and Silicon Graphics (SGI) platforms in order to take full advantage of emerging graphics capabilities that did not exist at the start of our project.

Step 3: *Identify an application that is suitable for VR.* First of all, there is no point in duplicating in VR an experience that is widely available in the real world. Ideal VR environments are those that are either

restricted, inaccessible, or completely non-existent in the real world. Examples would include electronics manufacturing clean rooms, the core of an operating nuclear reactor, or a futuristic Martian colony. (Abstract environments in which concepts rather than concrete objects are portrayed are also appropriate, but are generally better suited to liberal arts topics than technical education.)

Secondly, a VR application should be one in which the features of VR, such as 3D visualization, interactive feedback, and a sense of presence provide a tangible benefit. Examples might include a training simulator for space station assembly procedures or emergency response drills in a chemical plant. For low-cost student applications, the lack of detail dictates applications where overall trends are more important than specific results. (I.e. use VR to illustrate concepts, not to calculate useful numbers.)

Step 4: *Choose an appropriate development platform (computer hardware and software.)* While this sounds somewhat redundant of step 2, note the difference between development platform and end-users' platform. You may choose to develop on more (or less) advanced hardware than your users will eventually be using, or you may choose hardware available today that best approximates your prediction of your users' equipment of the future. In our case we deliberately chose a software development system that supported a wide range of hardware platforms [27], so that we could develop our modules under one system and then easily port the finished product to other platforms at a later date. In practice the porting process has not been as simple as we had hoped, but we are still happy with our choice and are currently porting to multiple environments.

Step 5: *Consider carefully the trade-offs of simulation realism versus performance, and plan out the simulation carefully.* If you were modeling a railroad locomotive that would only be seen from a distance, it would be a waste of effort and unnecessarily slow down the simulation to include every pipe, button, bell, and rivet. Depending on the distance, a simple (painted) box and some smoke and noise would be sufficient for the user to comprehend and visualize an entire train. (Human perception has a remarkable ability to fill-in "known" details even when they are not visible or even present.) Likewise it is pointless to burden your simulation with complex differential equations if the user cannot discern the difference from simple linear interpolation.

In terms of graphics imagery, the speed of the simulation varies roughly with the square of the number of polygons present. This yields a "polygon budget", which must be spent wisely in order to get the most effective simulation from limited resources. In this respect the VR developer becomes part magician, part psychologist, and part theatrical set designer. One trick often used is to have multiple versions of an object, having differing levels of detail, and to alternate which version is visible depending on the distance from the user to the object.

Step 6: *Start with a simple framework, and then gradually add details.* Your initial simulation should be very simple, with just enough geometry (e.g. boxes) to define the space and provide a general feel for the environment. Then you can gradually add more detail and functionality while striving to maintain acceptable execution speeds.

Step 7: *Provide for student evaluation early and often; Develop the simulation based upon user feedback.* A good VR simulation should be intuitive and easy to understand and use. (Recall the goal of VR to create a simulation so realistic that the computer interface is transparent to the user.) However it is not always easy for the developer to predict what will be intuitive and natural for the end users. In addition to questionnaires on which we ask participants to record their difficulties, comments, and requests for features, we also employ direct observation of student participants. As an example of the latter, we once noticed a student clicking on an exit sign in an attempt to get out of the program. It did not work, because we had not thought of that, but as soon as she was finished we edited the code, so when the next student tried the program there were several signs that were "clickable". On our evaluation forms we have occasionally had students requesting features that were already present, which indicated a need to improve our instructions / documentation.

Step 8: *Prepare instructions suitable for students, faculty, and systems administrators.* Each of these audiences needs different information. For students it is critical that the written instructions be as brief as possible, lest they get skipped entirely. (Recall that VR appeals most to visual learners, who prefer

images to words.) We make every effort to keep our student instructions to a single page for each program, plus a separate page for site-specific startup instructions. Instructors need information regarding the topics covered by each module, the goals to be accomplished by the students, and references to relevant material in the major textbooks on the subject. Sample homework / exam questions (with answers) are also appreciated. Systems administrators need installation instructions and information regarding required video modes, disk space, RAM, etc.

Step 9: *Incorporate the simulation into the curriculum.* Virtual reality cannot take the place of lectures, textbooks, or laboratories, nor should it try. The best use of VR is to supplement traditional educational methods, especially for those students who are not well served through traditional means (due to a mismatch in teaching and learning styles or for other reasons.) There will be some students in every class who understand the material perfectly based upon lectures and texts. In general it is a waste of everyone's time to force those students to use VR. Rather VR should be offered as an available resource for those students who did not fully grasp the material in class or from the text. The objective is to provide these students with another viewpoint that will cause them to better understand the material that was previously presented through traditional means. VR can also be used as the basis for an analysis of the simulated environment, in order to reach the higher levels of Bloom's taxonomy.
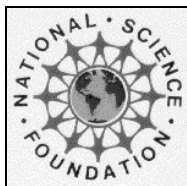
Step 10: *Share your results far and wide.* In order for an educational simulator to have the greatest impact, it is important to put it into the hands of as many students as possible. The program should be free (or as close to it as possible) to the students, and should run on hardware that is readily accessible to most students. Placing the program on the world wide web for free download is an excellent approach (if third-party licensing restrictions allow) but should also be accompanied by advertising that lets students and educators nationwide know where to find the files. Our own programs are planned for widespread distribution through the non-profit CACHE corporation [ref], and also through the world wide web depending on currently evolving not-for-profit licensing agreements.

Conclusions

This paper has outlined some of our key findings to date concerning the optimal applicability of virtual reality as an educational tool for undergraduate engineering. The unique characteristics of student affordable VR have been considered, and guidelines presented for taking those characteristics into account when choosing a topic for virtual simulation and for identifying the most likely audience to benefit from educational VR. Key steps in the development of an educational VR simulation have been outlined, and guidance provided for each of the listed steps. Based on our findings, we feel that VR has the potential to become a powerful tool in undergraduate engineering education, particularly as the capabilities of student affordable computing equipment continue to escalate.

Acknowledgments

References

1. 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), 1996.

2. Bell, John T., and H. Scott Fogler, "The Status and Prospects of Virtual Reality in Chemical Engineering", Presented at the *Annual Meeting of the American Institute of Chemical Engineers,* Chicago, IL, November 1996. Copies available from the author upon request.

3. Bell, John T., and H. Scott Fogler, "Recent Developments in Virtual Reality Based Education", *American Society for Engineering Education Annual Conference,* Washington, DC, June 1996.

4. Bell, John T., and H. Scott Fogler, "Preliminary Testing of a Virtual Reality Based Module for Safety and Hazard Evaluation", *Proceedings of the 1996 Illinois / Indiana ASEE Sectional Conference,* March, 1996, Bradley University, Peoria, IL.

5. Bell, John T., and H. Scott Fogler, "Virtual Reality in Chemical Engineering Education", *Proceedings of the 1995 Illinois / Indiana ASEE Sectional Conference,* March 16-18, 1995, Purdue University, West Lafayette, Indiana, http://fre.www.ecn.purdue.edu/fre/ asee/sect95/2A/2A3.html.

6. Bell, John T., and H. Scott Fogler, "The Investigation and Application of Virtual Reality as an Educational Tool", *Proceedings of the American* Society for Engineering Education Annual Conference, Anaheim, CA, June 1995, pp 1718-1728.

7. Bloom, Benjamin S., "Taxonomy of Educational objectives: The Classification of Educational Goals, Handbook I: Cognitive Domain", David McKay Company, New York, 1956.

8. Felder, Richard, "Matters of Style", *ASEE PRISM*, December 1996.

9. Lawrence, G., "People Types and Tiger Stripes: A Practical Guide to Learning Styles", Third edition, Center for Applications of Psychological Type, Gainseville, FL, 1994.

10. Kolb, D. A., "Experiential Learning: Experience as the Source of Learning and Development", Prentice-Hall, Englewood Cliffs, N.J., 1984.

11. Herrmann, N., "The Creative Brain", Brain Books, Lake Lure, NC, 1990.

12. Felder , R. M. and L. K. Silverman, "Learning and Teaching Styles in Engineering Education", *Journal of Engineering Education*, **78**(7), 674-681, April, 1988.

13. Dale, Edgar, "Audio-Visual Methods in Teaching", Third edition, Holt, Rinehart, & Winston, 1969.

14. Cooper, Douglas J., "PICLES: A Simulator for Teaching the Real World of Process Control", *Chemical Engineering Education*, **27**(4), 1993.

15. Cooper, Douglas J., "PICLES: The Process Identification and Control Laboratory Experiments Simulator", *CACHE News*, 37, 6-12.

16. Fogler, H.S., S.M. Montgomery, and R.P. Zipp, "Interactive Computer Modules for Chemical Engineering Instruction", *Computer Applications in Engineering Education*, **1**(1), 11-24, 1992.

17. Jayakumar, S., R.G. Squires, G.V. Reklaitis, P.K. Andersen, and L.R. Partin, "Purdue-Industry Computer Simulation Modules: 2. The Eastman Chemical Reactive Distillation Process", *Chemical Engineering Education*, **27**(2), 1993.

18. Jayakumar, S., R.G. Squires, G.V. Reklaitis, P.K. Andersen, and B.K. Dietrich, "The Purdue-Dow Styrene-Butadiene Polymerization Simulation", *Journal of Engineering Education*, **84**(3), July 1995.

19. Montgomery, Susan and H. Scott Fogler, "Selecting Computer-Aided Instructional Software", *Journal of Engineering Education*, **85**(1), January, 1996.

20. Montgomery, Susan and H. Scott Fogler, in *The CACHE Monograph* , Brice Carnahan, editor, CACHE Corporation, Austin, TX, 1995.

21. Rosendall, B. and B. Finlayson, "The Chemical Reactor Design Tool", *Proceedings of 1994 ASEE meeting*, Edmonton, Alberta, 1994.

22. Squires, R.G., P.K. Andersen, G.V. Reklaitis, S. Jayakumar, and D.S. Carmichael, "Multimedia-Based Applications of Computer Simulations of Chemical Engineering Processes", *Computer Applications in Engineering Education*, **1**(1), 25-30.

23. Aukstakalnis, Steve and Blatner, David, "Silicon Mirage: The Art and Science of Virtual Reality", Peachpit Press, 1992.

24. Larijani, L. Casey, "The Virtual Reality Primer", McGraw Hill, 1994.

25. Pimental, Ken and Teixeira, Kevin, "Virtual Reality: Through the New Looking Glass", second edition, Windcrest Books, 1995.
26. Stampe, Dave, Bernie Roehl, and John Eagan, "Virtual Reality Creations", The Waite Group, 1993.
27. Sense8 Corporation, 100 Shoreline Highway Suite 282, Mill Valley, CA 94941, (415) 331-6318, http://www.sense8.com.

Author Biographies

JOHN T. BELL

(Lecturer, Department of Chemical Engineering, University of Michigan, 3074 H.H. Dow Building, Ann Arbor, MI 48109-2136, (313) 763-4814, JohnBell@umich.edu, http://www.engin.umich.edu/dept/cheme/bell.html) John holds a MS in computer science and a PhD in chemical engineering. His research interests involve the application of emerging computer technologies (e.g. virtual reality) to chemical engineering and education.

H. SCOTT FOGLER

(Vennema Professor of Chemical Engineering, same address, (313) 763-1361, H.Scott.Fogler@umich.edu) Scott has over 140 research publications, including "The Elements of Chemical Reaction Engineering" (the most used book on this subject in the world) and "Strategies for Creative Problem Solving." Scott was the 1995 Warren K. Lewis award recipient of the AIChE for contributions to chemical engineering education.