Ten Steps to Developing Virtual Reality Applications
for Engineering Education

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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 problem with the lower levels of Bloom's taxonomy is that although they are useful for teaching students how to solve classic traditional problems, our students still have difficulties applying their engineering education to the practical problems they encounter in industry. Many students can "solve" the homework without being able to explain what it means in terms of real-world phenomena.

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.)
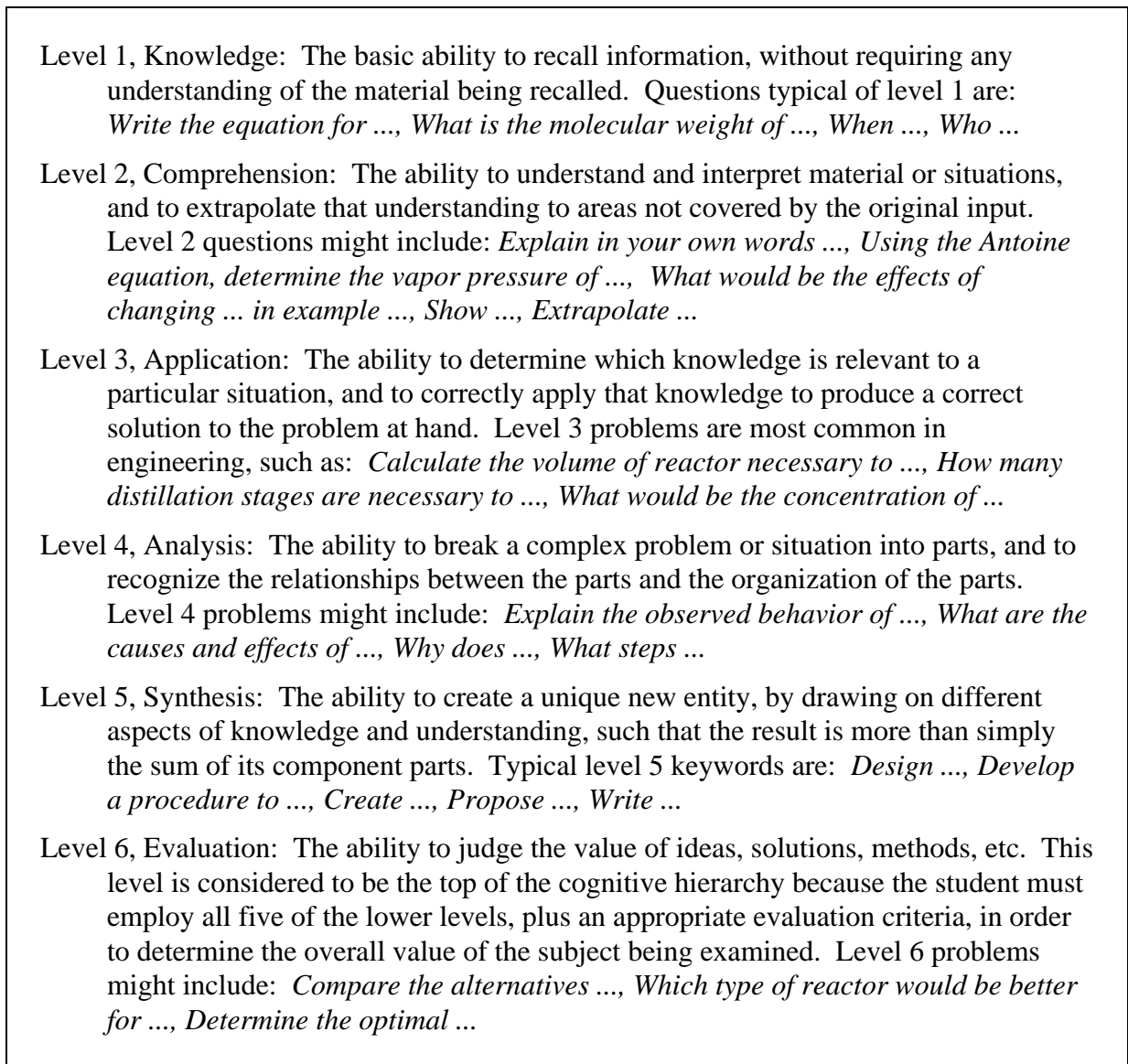
Level 1, Knowledge: The basic ability to recall information, without requiring any understanding of the material being recalled. Questions typical of level 1 are: *Write the equation for ..., What is the molecular weight of ..., When ..., Who ...*

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 2 questions might include: *Explain in your own words ..., Using the Antoine equation, determine the vapor pressure of ..., What would be the effects of changing ... in example ..., Show ..., Extrapolate ...*

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 3 problems are most common in engineering, such as: *Calculate the volume of reactor necessary to ..., How many distillation stages are necessary to ..., What would be the concentration of ...*

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 4 problems might include: *Explain the observed behavior of ..., What are the causes and effects of ..., Why does ..., What steps ...*

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. Typical level 5 keywords are: *Design ..., Develop a procedure to ..., Create ..., Propose ..., Write ...*

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. Level 6 problems might include: *Compare the alternatives ..., Which type of reactor would be better for ..., Determine the optimal ...*

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, 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 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

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.

Sensory / **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.

Visual / **Verbal**: Visual learners prefer pictures, diagrams, charts, movies, demonstrations, and exhibitions.
Verbal learners prefer words, discussions, explanations, formulas, and equations.

Inductive / **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.

Underlined: Preferred by most engineering students.

Bold Face: Preferred by most engineering professors.

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

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 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 <u>NOT </u>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 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 choose to read as little as possible, even when a textual description is available.

3. It would be a huge waste for VR to duplicate tasks that are already handled by textbooks. (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. For a VR simulation to be believable, the screen image must be updated as quickly as possible, with minimal lag between a user's actions and the simulation's response, ideally 20 to 30 frames per second. Because VR graphics are completely re-calculated for each screen update, extensive computational power is required for all but the simplest graphical environments. (As opposed to most computer games which pre-calculate their graphics at the factory.) Any details or behaviors 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.), B) Will the effect be worth the cost in performance?, and C) What fraction of my intended audience can afford the equipment required to appreciate the addition?

Step 2: *Identify an application that is suitable for VR.* 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 futurist 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 3: *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 <u>when your project is completed</u>. In our case we began development under Microsoft Windows 3.1 on 90 MHz Pentium based computers with 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 4: *Choose an appropriate development platform (computer hardware and software.)* While this sounds somewhat redundant of step 3, 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.

Step 5: *Consider carefully the trade-offs of simulation realism versus performance, and plan out the simulation carefully.* Because execution speed is so critical to effective VR, you must squeeze the most effect out of every available CPU cycle. In terms of graphics imagery, the speed of the simulation varies 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. The VR developer becomes part magician, part psychologist, and part theatrical set designer.

For example, if you were modeling a railroad locomotive that would only be seen from a distance, it would be a waste of effort and CPU cycles 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.) As the train approaches, the crude representation can be replaced with successively more detailed models. Likewise it is pointless to burden your simulation with complex differential equations if the user cannot discern the difference from simple linear interpolation. (Remember, the goal of VR is to <u>convince the user</u>, not the calculation of precise results.)

Although you can't expect low-cost computers to perform rigorous engineering calculations and drive a VR simulation at the same time, it is perfectly acceptable to use VR to interact with results that have been pre-calculated by other programs, other computers, or even non-computer based methods. This is actually a standard procedure for presenting computational fluid dynamics and finite element analysis results in VR, even when supercomputers are available. When done properly the user often can't tell that the calculations were not done on the fly, so once again, what's the difference? Two other approaches are to freeze the simulation momentarily when engineering values must be updated, and to use two separate computers connected over a network to simultaneously perform engineering and VR calculations.

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 written 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[28], 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.
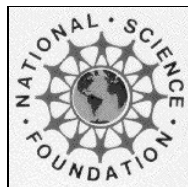
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