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Virtual Chemical Engineering: Guidelines for E-Learning in Engineering Education

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Abstract

Advanced three-dimensional virtual environment technology, similar to that used by the film and computer games industry can allow educational developers to rapidly create realistic three-dimensional, virtual environments. This technology has been used to generate a range of interactive learning environments across a broad spectrum of industries.

The paper will discuss the implementation of these systems and extrapolate the lessons learnt into general guidelines to be considered for the development of a range of educational learning resources. These guidelines will then be discussed in the context of the development of ViRILE (Virtual Reality Interactive Learning Environment), software which simulates the configuration and operation of a polymerisation plant. This software package has been developed for use by undergraduate chemical engineers at the University of Nottingham.

Keywords: engineering education, visual tools, process engineering, virtual reality, chemical plant

Background

The modern world expects high levels of industrial safety. In general there has been continuous improvement in the safety performance of the developed industrial nations over recent decades. This has been due to a combination of factors including changes in management culture, enhanced design and planning, technological improvements and legislation. All of these factors have tended to reduce the chances of accidents and incidents and led to improved safety performance, however it is measured. Accidents still happen however and in many ways the improved safety performance makes it now even harder to improve such performance any further. This particularly applies to the decreasing ability to 'engineer out' obvious problems. The law of diminishing returns starts to play a role, incremental improvements in any of the above factors ends up only improving safety performance marginally.

It is accepted that some industries are more hazardous than others. Chemical engineering is generally seen can be a hazardous profession with higher-than-average rates of injury and fatality and there are many reasons for this and again there is clearly no single solution to the problem. Closer investigation of the situation points to the important role that training can play in creating a motivated and safe workforce. Training techniques have benefited from advances in technology but fundamentally in most industrial settings there has been no major change in training methodology in recent years (Allison, 1992, Halff et al, 1996, Imache et al, 1995, Thurman, 1992, Wilson et al, 1996, Schofield, 2005).

This paper will demonstrate that there are alternative training methodologies now becoming available based on rapid advances in computing technology that have taken place over the last decade. With careful integration into a planned training strategy this offers the potential for further improvements in safety performance. Advances in Virtual Reality (VR) technology mean that it is now both feasible and cost effective to consider mass training of workforces using simulated computer representations of the workplace. The ability to safely expose workers to hazardous situations, both routine and unusual, and to test their knowledge of safety procedures is key to this new methodology.

Downes (2003) summarised a key finding regarding the use of virtual environments for training:

> *"So few people have grasped what it means to live and learn in the information age. However, many people who, for example, are only just now coming to grips with the internet find virtual environments a natural training mechanism as they mirror reality.*
>
> *"The very technology that makes self-directed (and self-motivated) learning possible, also makes it necessary. You don't get the benefits of becoming an agricultural society without also having to live on farms; you don't get the benefits of learning in an information society without also having to live with large amounts of information."*

However the integration of such advanced technology into existing work systems and practices is not a trivial issue. A number of complex human factors and organisational processes interact and can create barriers to the successful development and implementation of such training systems (Silvester et al, 2001, Schofield et al, 2002, Schofield, 2005). Acceptance by the workforce is a crucial issue, and implementation strategies must be considered carefully. The paper will describe the development of the ViRILE system, a polymerisation plant simulator used by undergraduate students at the University of Nottingham.

Chemical Engineering Education

Early attempts at 'virtual' engineering teaching laboratories and training simulations have often consisted of little more than online calculators or interactive diagrams (Ponton, 2003, Karweit, 2003) and those that have ventured into applying three-dimensional computer graphics based technology have been constrained by lack of realism detail in their graphical interfaces and level of simulation (Parker et al, 2000, Bell & Fogler, 1996). However, it has been also noted that even given these limitations, these virtual environments have the potential to allow users to experience situations which would not readily exist within the real world, e.g. to see 'into' a chemical reaction or to cause a major catastrophe through their actions (Schofield et al 2001, Nasios, 2002).

Recent advances in computer graphics and virtual reality technology, driven by the film and games industry, allow developers to rapidly create realistic three-dimensional, virtual environments. Research work at the University of Nottingham, and previous work by the authors building, interactive, virtual reality based engineering experiments have shown the enormous benefits of using this type of learning in a University environment, and also highlighted a few of the potential problems (Schofield et al 2003, Tromp & Schofield, 2004).

These problems can arise from the expectations of younger users who naturally compare commercial game software to educational software. The former tends to be a high end multi-million pound development whereas the latter is severely budget restricted. This inevitably results in harsh comparisons is the interface is not sufficiently well developed. The chemical engineering virtual environments developed at the University of Nottingham replicate both 'laboratory' experiments and 'real' industrial processes. The latter allows undergraduate students to experiment with large-scale equipment to which they would not normally be able to access. The authors were aware during the developmental stages that the front end (interface and appearance) should not be neglected whilst striving to create realistic chemical simulation data. e.g. from previous work the authors found that the level of enthusiasm of younger subjects was higher, but all the subjects were impressed with the visual representation of the virtual experiments. This reaction of the subjects overrules any suggestion of a reluctance to accept new technology. Factors such as age and experience do not appear to affect the choice of a virtual reality based training system but these factors may influence the way in which people learn. Through appropriate programming, the complexity of the virtual world and the level of content can be varied and designed to meet the diverse needs of students and the different laboratory and 'real' work situations in which they may operate.

The previous exposure to a computer medium was quite high with 48 % of subjects having experience of playing computer games. All the subjects had computing experience and used computers everyday (mainly word processing, internet and e-mail software).

The chemical engineering virtual environments developed at the University of Nottingham replicate both 'laboratory' experiments and 'real' industrial processes. The latter allows undergraduate students to experiment with large-scale equipment to which they would not normally be able to access.

There is already substantial research which supports the case for using virtual environments for teaching and demonstrates marked improvements in student learning and retention (Hollands et al, 1999, Wilson et al, 1996, Hussin et al, 2004). However, there has been little, relevant work on the mechanisms by which students learn when faced with interactive systems of this nature, although such work is starting to be undertaken (in collaboration with cognitive psychologists) by the authors at the University of Nottingham.

University chemical engineering laboratories present a significant challenge to health and safety personnel due to the many types of hazards that are present. Laboratory safety is extremely important, particularly in those laboratories where students first develop practices and habits that they may carry with them throughout their careers. Because this importance is widely agreed upon, most undergraduate engineering laboratory experiments include some amount of equipment familiarisation and safety training, encompassing at a minimum a long list of safety rules (Jenkate et al, 2001). These rules are often handed out on the first day of laboratory work, along with the assessment policy, exam schedule, and instructor's e-mail, office location etc.

In spite of these precautions, however, accidents can still occur. Two major causes for these are forgetfulness and complacency, the latter of which can be considered as forgetfulness of the importance and significance of the rules, as opposed to forgetfulness of the rules themselves. The important feature is that equipment operation procedures and safe practices are not always retained in students' memory (Bell & Fogler, 1999).

Those persons who have ever been involved in an accident, however, tend to remember their experience much longer and more vividly than any set of written rules. As a result, they tend to follow safe practice guidelines much more rigorously, in order to ensure that such experiences never happen again. Theoretically, if all students could experience simulated laboratory and industrial accidents, then they should become more safety conscious (Bell & Fogler, 1999). Proving this theory would make an interesting study in itself.

Chemical Engineering Training Systems

Two virtual chemical engineering simulations developed at the University of Nottingham are described in this paper:

- An absorption column (where two packed columns absorb ammonia from an air stream).
- A three-stage distillation process (where a feed process supplies a reactor which feeds the product into distillation columns).

For the absorption column a real time dynamic simulation of the process needed to be created to allow interaction with the processing equipment. For the distillation process a large amount of process data was generated using commercially available, steady state chemical flowsheet simulation software called HYSIS.

The authors undertook a series of tests and experiments to generate feedback on these virtual learning environments. A number of further tests are currently underway aimed at understanding the way students learn in this virtual world and how they improve their understanding of chemical processes using these systems. The results of this evaluation have been previously reported (Schofield et al, 2005).

Figure 1: The 'Real' and 'Virtual' Absorption Column.

The Virtual Absorption Column

Packed columns are used extensively in distillation, liquid-liquid extraction and especially gas absorption and gas scrubbing operations (Coulson &

Richardson, 1998). Fluid flow through packed beds is therefore something that chemical engineering students need to learn, in order to understand the significance of phenomena like pressure drop and adsorption kinetics.

One University of Nottingham pilot plant consists of two packed columns (Figure 1), which share the same ammonia, air and sulphuric acid supplies. This equipment processes these substances at concentrations high enough to present a serious hazard to an individual exposed to them, and health and safety is therefore always an issue.

The operation between the two columns is switched by changing four valves on the plant. Dilute sulphuric acid flows down each column from the tank above and is metered. Ammonia is supplied at 1 bar and is metered as it leaves the liquid cylinder. Air is supplied at 2 bar pressure and mixed with ammonia before it reaches the columns. A rotameter measures the flow and a kerosene manometer measures the pressure of the combined air and ammonia stream, which enters the column at the bottom and exits at the top. A sampling point is provided at the top of each column, so that ammonia concentration in the gas outlet can be measured. Any ammonia present is then scrubbed out downstream to ensure that only air is released into the atmosphere. Indicators detect excess ammonia in the outlet stream.

The three-dimensional environment of the ammonia absorption column was constructed using commercially available modelling and animation software. The total number of polygons in the environment was optimised as this has an impact on the rendering speed of each frame. Objects needed to be constructed with appropriate detail in order to be easily recognisable. A number of texture maps were strategically used and a suitable portion of carefully chosen digital photographs were utilised in order to bring a sense of reality to the virtual environment (Figure 1).

A substantial amount of time was spent programming the dynamic features of the absorption column simulation to give high levels of realism in the virtual environment. The authors believe that this helps the students to gain a deep understating of the chemical engineering principles that govern this mass transfer process. The virtual plant operates in real time, using the Shockwave 3D graphics engine, allowing the students have to monitor instrumentation and wait until the equipment reaches its steady state condition.

The Virtual Absorption Column: The experimental task

Students control three valves which open and close in stages, controlling the air, ammonia and liquid flows that enter to the packed column, three rotameters measure the flowrate of these streams. Calibration graphs are provided for air and ammonia rotameters in order to convert their measured units to litres per minute. The liquid rotameter is pre-calibrated and measures litres per hour liquid flow.

During the 'real' experiment the students measure the output ammonia concentration as they optimise the system parameters using a Dräger tube instrument. In the virtual environment a gas analyser is connected to the output pipeline of the packed column. There is a monitor screen on a 'virtual' gas analyser where a graph is displayed that indicates the values of output ammonia concentration in parts per million (ppm). The graph is drawn dynamically and updated every second allowing students to monitor output ammonia concentration over a long period.

One of the main purposes of the virtual reality system is to help the trainees to identify the chemical process equipment on the rig and to become familiar with its operation. This operation of chemical engineering instruments and the knowledge of this laboratory rig layout (gained by using the virtual reality system) helps students to know exactly what tasks they should follow and what precautions they should take before they implement the experiment in the real laboratory. Students are able to set experimental tasks in the virtual world, and if they make any mistakes they will learn what went wrong without damaging the equipment or themselves (Nasios, 2002).

An online version of the virtual absorption column learning environment was created and distributed to the students. This slightly cut down version is made up of three modules related to component identification, hazard identification and procedural operation respectively.

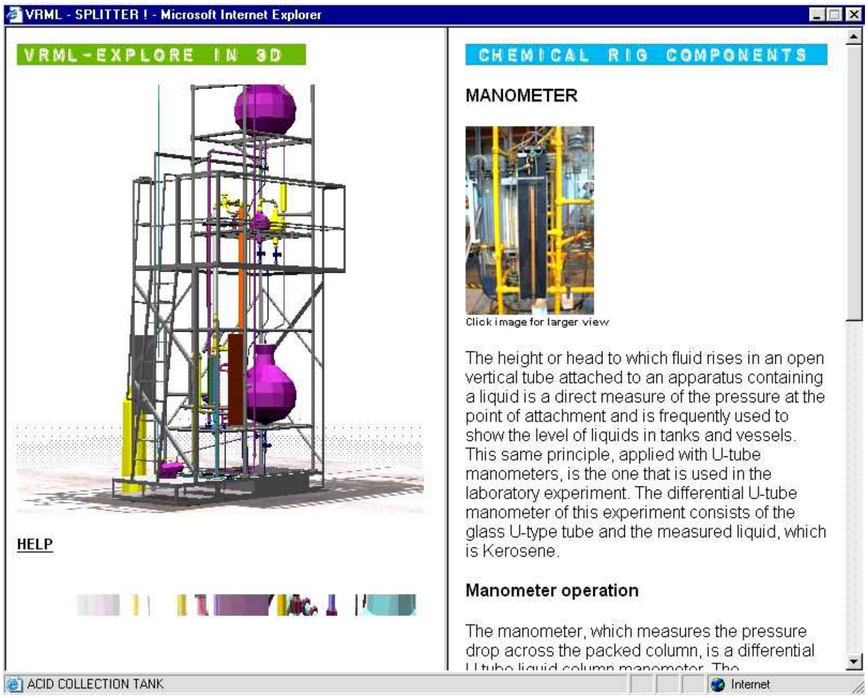

Figure 2: The 'Online' Absorption Column

The virtual laboratory rig is distributed in VRM[1] and allows students to navigate easily within the virtual world identifying and operating the process equipment. A number of detailed, linked, web pages with text and information on all the components of this equipment have also been provided. These enhance understanding of the rig's layout and along with the linked technical documentation provide a useful Internet resource for students writing up their 'real' experiments. By selecting any object in the three-dimensional virtual environment, the student can gain access to a plethora of relevant information (Figure 2).

The dual framed web page with integrated VRML sections provides a highly interactive interface for the student because they can easily move within the virtual rig in the left frame and in the same time they can view the descriptive, photographic, diagrammatic and mathematical information that is available for the ammonia rig components in the right frame as shown in Figure 2.

ViRILE: The Virtual Polymerisation Plant

One frequently identified problem in chemical engineering education is the student cohort's lack of awareness about 'real' process equipment. Question and answer sessions indicated that the undergraduates are often not only unfamiliar with full-scale industrial plant, but are also unable to identify some of the main components (Schofield et al, 2003, Schofield et al, 2005).

Figure 3: The Virtual Polymerisation Plant

Figure 4: The Realism of the Virtual Plant

To address this issue it was decided that the next virtual environment to be developed should replicate a 'real' industrial process rather than a 'laboratory' experiment. This would allow the students to experiment with large-scale equipment to which they would not normally have access. It was decided to build a far larger scale virtual simulation where students are able to design and build a particular chemical plant and then operate the major equipment. Key features of this project will include the design-orientated nature of the task facilitated by the interactive character of the technology.

A continuous polymerisation plant was modelled, consisting of a pump and preheater section, a reactor section followed by a second heat exchanger system (cooling) and three distillation columns (Figure 3). It is important not to underestimate the work involved in developing commercial quality, virtual reality software tools to a professional standard (Figure 4). To a generation weaned on animated movies and computer games, the level of expectation of our student cohort is high. Previous virtual learning environments developed have provided experience of the quality of the software required to gain a level of acceptance among the students.

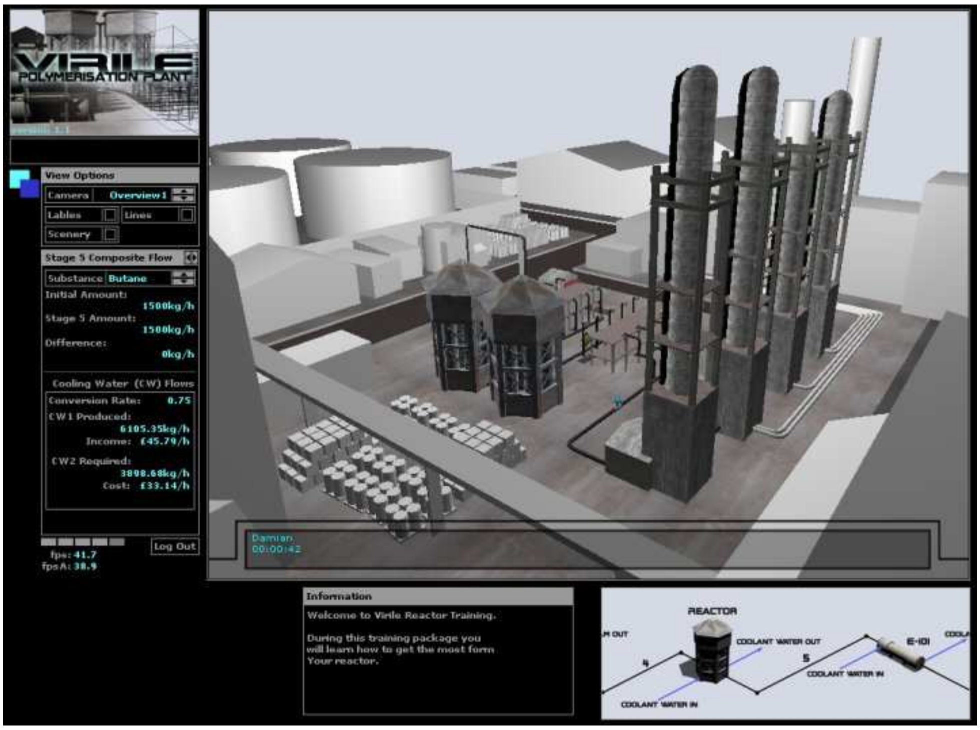

Figure 5: The Simulation Engine

Massive amounts of simulation data was generated using HYSIS (steady state chemical flowsheet simulation software). A complex real-time, mathematical model was programmed to reference the data generated (Figure 5).

The final learning environment contains over a billion discrete configurable states, allowing the students unlimited scope for experimentation and configuration. This also allows academics to set individual tasks within the learning environment for particular students. A full economics and costing model has also been integrated into the simulation, giving students an insight into the constraints facing engineers in the real world (Schofield et al, 2005).

ViRILE: The Experimental Task

ViRILE can be used at school level (year 12) upto final year undergraduate chemical engineering level. The complexity of the tasks can be adjusted to suit the user. For example with younger users and first year undergraduate chemical engineers, the following text is provided:

> **What is ViRILE?**
>
> *ViRILE is a virtual reality interactive learning environment*
>
> *This ViRILE is a chemical plant that makes hydrocarbons that are useful to the chemical industry. The process is relatively straightforward – small hydrocarbons (with less than 5 carbons) are pumped through a reactor packed with catalyst and the unsaturated molecules polymerise with each other to form larger molecules (with 6 to 10 carbons). These products are considerably more valuable to the chemical industry and can therefore be sold at*

a higher price.

Chemical engineering processes can be broadly placed into three stages

Preparation *– Heating, grinding, cooling, pressurising, mixing are basic preparation stages*

Reaction *– chemical and physical reactions.*

Separation *– distillation, condensation, centrifuge, drying, spraying, adsorption, absorption, density separation are all basic separation technologies.*

In the ViRILE chemical plant:

Preparation – the hydrocarbon feed is being pumped from a ship 2 miles away which requires some pressure to bring it on site. However, the reaction won't take place at these conditions. The feed must be further pressurised and heated to increase the rate at which these reactions will occur.

Reaction – once the feed stream is sufficiently hot and pressurised, it is pumped through reactor vessels (large tubes packed full of catalyst material). Reactors and the design of reactors is vital in ensuring good yields of product and also in operating safely. Sometimes reactions can be exothermic and this can mean that the feed stream heats up during the reaction stage as a result of chemical bonds being formed or broken. Since the temperature of reaction can effect the rate at which these reactions occurs, uncontrolled heating inside the reactor can lead to an increase in the rate of reactions (which in turn yields further heat) until there is a run away reaction which is not at all desirable. Controlling this is of paramount importance.

Separation – Normally the product stream is a mixture of products and unreacted feed compounds. These have to be separated since the value of the product is often dictated by its purity. The feed stream into the polymerisation plant contains several different compounds anyway, some of which don't react, and this means that you have to separate them out at the end. In this case you have four distillation columns and must capitalise on the different chemical and physical properties of the chemicals in the product stream to separate them out.

Familiarisation with the controls

View Options
This section enables you to move around the plant or simply view the plant from fixed locations. You can toggle between various GROUND locations and then move around in the plant. Use your mouse to do this. If you press CTRL and drag up, you will lift upwards. If you press SHFT and drag your mouse around, you can alter the angle of view. You cannot alter the view from the 4 static OVERVIEW cameras.

You can walk through objects which become wire frames.
Reset
You can press RESET if you want to return to a GROUND view looking straight ahead.

Lines
If you activate this feature you'll see a red numbered object appear around the plant. Right clicking on these diamond shaped objects brings up a summary of current conditions at that position in the system (temperatures and pressures). Until the whole plant is configured some of these labels will appear blank.

Spend a few minutes familiarising yourself with the controls. Perhaps follow the pipework round to see if you can work out where the plant starts and ends.

Year One, Task One: General Familiarisation

Draw the structure of the following compounds – Butane, 1 Hexene, 1 Octene, i-Butane, 1 Heptene, Propene, 1 Butene, Propane.

- *Use the control panel to find out what the feed stream is composed of?*
- *Why is there a mixture being fed into the system?*
- *What is the molar and weight fraction of each for the feed stream?*
- *Which of these are unsaturated and what does that mean?*
- *What does propene become if it reacts with another propene molecule?*
- *What happens if propene reacts with two other propene molecules?*
- *Rank them in order of perceived value?*
- *How much do you think each one is worth per Kg?*
- *Sketch out the plant layout as seen in the simulation showing the position of the various units and the pipework*
- *Using the following symbols for each unit, draw a simple flowsheet to describe the whole process. You will need to pay careful attention to the pipework on the floor to work out the sequence of units*

Student Evaluation

As part of a larger evaluation exercise, all first year chemical engineering students (55 in total) were asked to use the ViRILE software alongside 2 other software packages. One was a well known 3D spatial awareness test that is normally presented as a paper exercise – This was called Cube Test and a screenshot is given in Figure 6. The other package was a real-time physics engine game that allows the user to alter parameters such as friction and speed to play a target hitting game (Figure 7).

The reason for comparing these other games in the evaluation exercise is to bring some perspective to the responses and feedback gained from the students. The tasks the students undertake in the ViRILE environment do not all involve chemical engineering theory, knowledge and application. The students also have to be able to spatially understand, model and map the three dimensional equipment. They also have to understand how changes made to a simulation model affect the behaviour of objects in the virtual environment. Hence, ViRILE uses spatial skills (like Cubetest) and is an interactive package with multiple parameters (like Blingball) but also brings in an educational angle where the students are now bringing in knowledge from other disciplines into their interaction with the simulation.

Figure 6: Cube Test. The user has to identify the two most likely matches.

Figure 7: Blingball. The user must hit the puck onto the target using by hitting it with a ball moving at the appropriate speed and direction.

Cubetest simply presents a challenging spatial awareness game with a limited graphical interface and limited 'interactivity'. This test is used to assess the overall ability of a subject to use 3D information which some find straightforward whilst others struggle to rotate 3D objects in their heads. *Blingball* allows significantly more interactivity (students can select multiple parameters in order to play the game – e.g. surface friction, ball speed, elasticity, ball size, puck size) with a more developed interface but the package is a game rather than typical educational software.

Figure 8 shows that there is a spread of results for each package with Cubetest as the least straightforward. Averages show this to be the case (3.9, 3.2 and 2.9 for Blingball, ViRILE and Cubetest, respectively where 6 is a perfect 'Easy' and 1 is a perfect 'Hard'). As expected, the game like Blingball was deemed the easiest of the simulations to use. However, it is interesting to note that a specific, focussed, relatively trivial three-dimension spatial assessment task (Cubetest) is perceived as being harder than interacting with three-dimensional components of a complex chemical plant simulation (ViRILE). One possible explanation for this is that the sophisticated levels of realism in the ViRILE simulation, and application of the software to a real world, familiar problems make the task more engaging than the abstract nature of the Cubetest problem.

The fact that Blingball is a straightforward game shows through in terms of 'enjoyment'. Cubetest shows a Gaussian distribution for enjoyment (Figure 9) with ViRILE showing a more even spread of data.

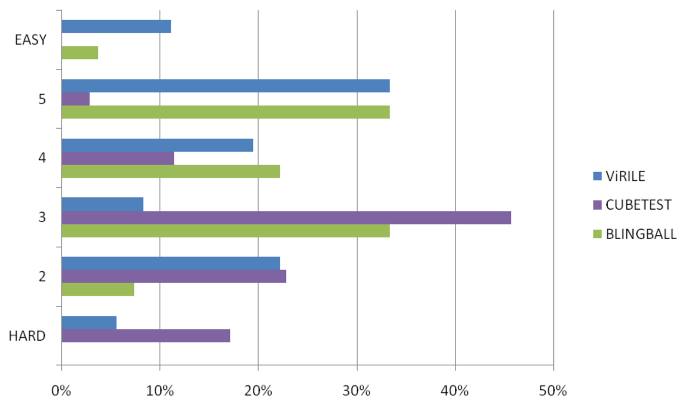

Figure 8: perceived difficulty of ViRILE, Cubetest and Blingball activities.

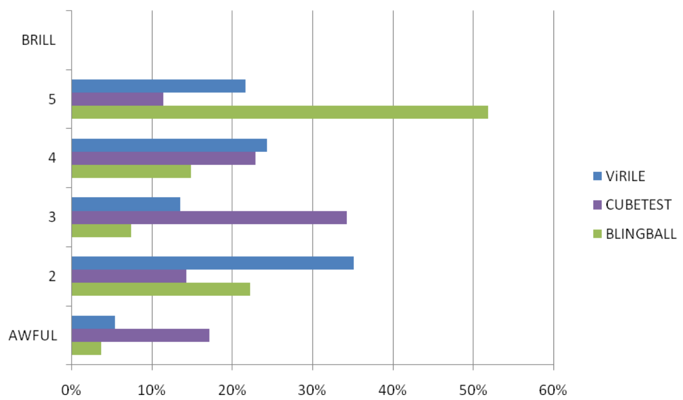

Figure 9: perceived enjoyment of ViRILE, Cubetest and Blingball activities.

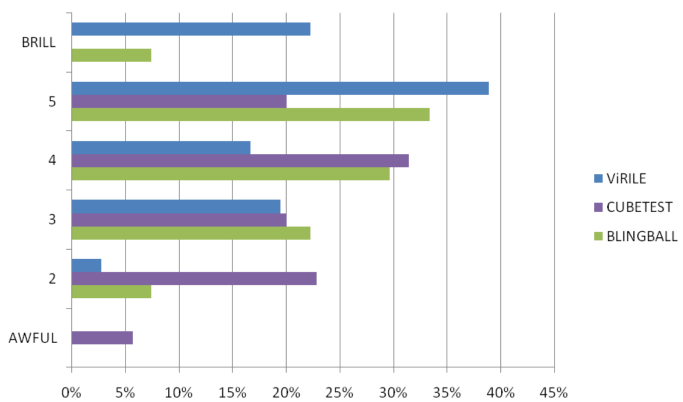

Figure 10: perceived graphical realism of ViRILE, Cubetest and Blingball software.

The graphics for each game showed quite interesting results as well (Figure 10). ViRILE had the best scores on average (4.6) with Blingball in second place (4.1) followed by Cubetest (3.4). This is not particularly surprising as the Cubetest is the least graphically appealing with no variation in appearance with minimal interaction or virtual content. As described earlier in this paper, the authors and developers spent a large amount of time ensuring that the ViRILE environment reflected a high level of graphical realism. Computer graphics technology advances rapidly and students, who regularly watch animated movies and play three-dimensional interactive games, expect to see their TV/movie/game experience duplicated in the software they use. Students expect professional visual representations illustrating complex processes, polished digital media displays demonstrating the location of spatially distributed objects and equipment and dynamic animated graphics showing event chronologies.

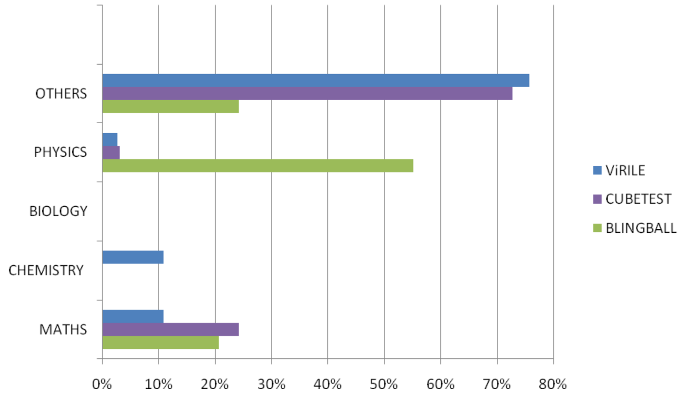

Figure 11: perceived discipline expertise required by ViRILE, Cubetest and Blingball activities.

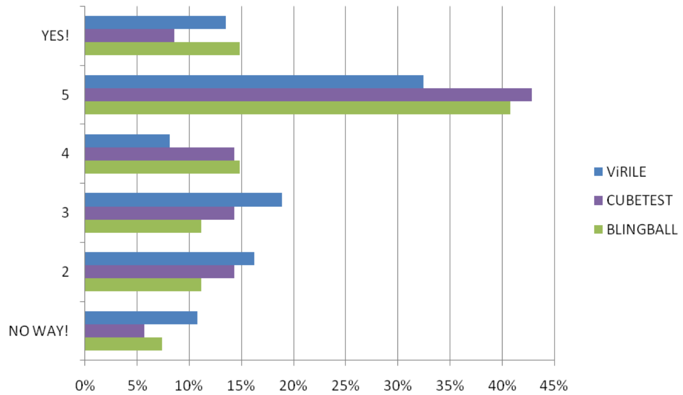

Figure 12: positive/negative response to the ViRILE, Cubetest and Blingball.

Figure 11 shows that the users acknowledged that the physics engine Blingball game was essentially maths and physics based whereas ViRILE (chemical engineering) and Cubetest (spatial awareness, psychology) were essentially outside standard science areas and did not require extensive ore knowledge in these areas to use these software products.

The final part of the questionnaire asked the students to feed back on whether software packages should be more prevalent in education as tools to teach principles. The response was fairly evenly spread with all three packages i.e. users appear to be in favour of the development and integration of similar 'tools' in education.

Applying the Guidelines

The authors have developed a number of virtual reality based applications in the chemical engineering field, including the two described above (Schofield et al, 2003, Tromp and Schofield, 2004 and Schofield et al, 2005). Experience has shown that the factors influencing the effectiveness of the industrial training software described in this paper are also relevant to chemical engineering educational software packages. Although not an exhaustive list, the key factors and guidelines followed can be summarised as follows:

Graphical Realism

- A sophisticated level of realism, containing a high level of detail is necessary since modern trainees have high levels of graphical literacy.
    - *Both the absorption column and the polymerisation plant utilised graphical interfaces that were developed to a professional standard by commercial three-dimensional modellers.*
- Combining abstract and realistic representations to enforce a training message can be effective, however, testing must be undertaken to ensure that the users are getting the correct message.
    - *In the ViRILE application a multi-modal display was utilised allowing the user to interact either in a three-dimensional environment or with a more abstract diagrammatic flowchart representing the plant layout.*
- A multi modal approach (combining high resolution, three-dimensional virtual environments with photographs, plans and textual information) can be successful.
    - *Both applications allowed the display of information in a variety of formats. In particular the absorption column simulation contained an identification task in which the learner navigates around the virtual absorption column viewing photographs of the real column to increase familiarisation with the spatial layout of the column's components and the connections between those components.*
- Limiting the three-dimensional modelling necessary will shorten the development time required.
    - *Although both of the systems described utilised free-roaming three-dimensional virtual environments, the worlds were limited in scope allowing the software to be rapidly developed.*

Learning / Training

- The training method is not as important as navigation ability; the user may need to be 'guided' through the training scenarios.
    - *Both the absorption column and the polymerisation allowed the user to free-roam around the virtual environments – however this functionality was not a crucial to the material being learnt. The user had the option to utilise a number of buttons and hyperlinks which automatically navigated the viewpoint to appropriate locations within the virtual environments.*
- It is important to ensure that general workplace layouts in all the software packages described would be familiar enough to the users to allow them achieve their work tasks in the real workplace environments.
    - *The absorption column exactly mirrored an item of equipment in a chemical engineering laboratory at the University of Nottingham. This was necessary since the aim of this particular piece of software was to familiarise students with the operation of that single item of laboratory equipment. The polymerisation plant, on the other hand, was developed as a generic environment rather than a specific polymerisation unit which could potentially divulge commercially sensitive information.*
- The ability to allow learners to experience 'real' accidents within virtual environments can have an enormous impact since those persons who have ever been involved in an accident tend to remember

their experience much longer and more vividly than any set of written rules.

  - *Both of the virtual chemical engineering simulations described allow the learners to make mistakes and to cause accidents. By visualising the consequences of their actions and mistakes in a safe virtual environment the learners gain a deeper understanding of the potential dangers.*

- The average person retains far more information presented visually, than information presented orally.
  - *Both simulations make extensive use of visual information presented through the medium of three-dimensional virtual environments. A combination of visual and verbal is cited as the most effective* (web reference 1)
- It is envisaged that improving the training of workers in hazard recognition and correct remedial procedures can reduce the high incidence of workplace accidents and fatalities.
  - *Both simulations involve hazard identification and allow the learners to perform risk assessments of the tasks they are performing in the virtual worlds.*
- Interactive software resources inherently encourage their users to be active learners by forcing them to make decisions throughout the simulation.
  - *Both the absorption column and the virtual polymerisation plant are inherently interactive, requiring the user to make multiple choices and decisions regarding the operation of each particular item of equipment or plant component.*
- It is important that trainers do not underestimate the educational value of spending time providing feedback to the learners.
  - *In both simulations there exists the functionality to record every action taken by the learner. This allows a lecturer\trainer to provide extensive feedback to the learner and to even re-create the entire training session.*

Management

- There is a move towards Internet based software distribution which is the preferred distribution mode for many organisations.
  - *As described above, the absorption column is currently distributed online, utilising VRML to run in a web browser. The ViRILE software runs as a stand alone executable file. However, due to it's relatively small size, this can easily be web delivered.*
- With litigation by employees and victim's families becoming increasingly common, competency evaluations are more important than ever.
  - *The functionality to record every action taken by the learner allows the competency of the learner to be evaluated.*
- The monetary value of an accident can be considered as the most important factor when trying to motivate an organisation towards a safer working environment.
  - *Both the absorption column and the virtual polymerisation plant include full economic models of the processes being simulated.*

Conclusions

Interactive virtual laboratory environments can deliver highly realistic experiences through the medium of enhanced computer simulations. Virtual reality simulations are enhanced through high-speed interactive immersive three-dimensional computer graphics (Schofield et al, 2004). Graphical, interactive environments inherently contain many other attributes, these were re-enforced by the feedback collected by the authors during the studies reported in this paper. The attributes include

- Interactivity and visual appeal should mean that the learning experience is enjoyable.
- Environments may be augmented using data visualisation to enhance understanding.
- Aesthetic appeal and graphical quality will lead to high levels of acceptance.

Students can be provided with more than traditional training and teaching methods can offer. This results in an improvement in terms of retention of knowledge of subject content and an increase the depth of understanding. Students also receive an increased sense of ownership of the knowledge. They learn through active rather than passive actions and control the interaction and investigation of the knowledge contained within the world.

The authors believe that these virtual reality based learning systems provide ideal environments to facilitate student exploration and student-centred learning. The students must interact not only with the graphical objects, but also with the simulation behind the virtual environment to achieve specific aims and objectives. VR software can be effectively used as a familiarisation tool prior to real experiments e.g. the virtual absorption column exercise. VR exercises can augment the student experience with multiple benefits including safer operation in the lab.

These virtual experiments should not be considered as replacements for 'real' experiment but a new teaching method that can help students to execute and interpret 'real' experimental laboratory projects. However, this implementation is not straightforward, and it should be remembered that virtual reality is mainly used as a supplement to real experiences, or in situations where the real experience is inaccessible.

The assessments carried out and the feedback from students using the systems show that these professional software products improves the quality of engineering teaching provision at the University of Nottingham - creating graduates with broader experience, deeper understanding and an improved ability to actually perform the tasks they will be asked to undertake in their professional careers.

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[1] VRML: The Virtual Reality Modelling Language, a common protocol for creating and distributing navigable, hyper-linked three-dimensional environments over the internet