The Potential of 3D Virtual Learning Environments: A Constructivist Analysis

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Introduction

In recent years, tertiary educators have seen a rapidly increasing demand for flexibility in the way that learning experiences are delivered or facilitated (Dean, 2002). One of the key implications of this demand is the need for innovation in the design of learning resources as an alternative to face-to-face classes. Alongside this change has been the widespread acceptance of constructivist theories of learning, which emphasise the importance of learners "actively interpreting and constructing individual knowledge representations" (Jonassen, 1991, p.5). Information and communication technologies can be important in the process of adapting to the new demands, as they have the potential to make learning resources more accessible, to allow a greater degree of individualisation and to make the learning process a more active one. Two important technological advances in this context have been the widespread adoption of the Internet and increases in desktop computer graphics and processing capability. Three-dimensional (3D) environments, which have become almost ubiquitous within the computer games industry, have the potential to harness these technological developments and facilitate new levels of learner-learner and learner-computer interaction.

This paper addresses the theoretical potential of 3D learning environments - with a particular focus on their use in tertiary chemistry education at a distance. The focus on the theoretical potential (rather than the actual potential) should be emphasised. Although there has been an increasing number of published papers describing 3D learning environments, there have been few evaluations of their educational effectiveness. By drawing on educational theory and linking this to the capabilities of 3D environments, it is hoped that educational designers and developers will have a better basis for making decisions about whether or not to incorporate 3D environments into the resources they develop. A description of the Charles Sturt University (CSU) virtual chemistry laboratory, along with a design rationale in terms of chemistry pedagogy, should help the reader to see how the ideas derived from the theoretical analysis can be applied to a specific learning situation.

The paper begins with a discussion of constructivist theories of learning, drawing on an earlier analysis of the consequences for computer assisted learning of various interpretations of constructivism (Dalgarno, 2001). Background information about 3D virtual learning environments is then presented, followed by a constructivist analysis of their potential, leading to a list of 3D environment design elements consistent with each interpretation of constructivism. Next is a discussion of chemistry education from a constructivist perspective, followed by a description of the CSU virtual chemistry laboratory that is currently under development. The design elements used in the virtual laboratory are described in terms of the general 3D environment design elements identified earlier. The paper concludes with a discussion of some of the wider implications of the use of virtual laboratories in tertiary education.

Constructivist Theories of Learning

The constructivist view of learning can be explained in terms of three broad principles. The fundamental principle is that each person forms their own representation of knowledge and consequently that there is no single ‘correct’ representation of knowledge. This principle was originally articulated by Kant and was later adopted by Dewey (Von Glaserfeld, 1984). The second principle is that learning occurs when, during active exploration of the knowledge domain, the learner uncovers a deficiency in their knowledge or an inconsistency between their current knowledge representation and their experience. This principle is normally attributed to Piaget (McInerney and McInerney; 1994; Slavin, 1994). The third principle, normally attributed to Vygotsky, is that learning occurs within a social context, and that interaction between learners and their peers is a necessary part of the learning process (Vygotsky, 1978).

A large number of different approaches to the teaching and learning process have been articulated, based on these broad principles - including Wittrock’s *generative learning* (1974), Bruner's *discovery learning* (1962), Ausubel's *expository learning* (McInerney & McInerney, 1994) and Brown, Collins and Duguid’s *situated cognition* (1989). Moshman (1982) identifies three distinct interpretations of constructivism which these approaches draw on to varying degrees. He labels these *endogenous*, *exogenous* and *dialectical.* These can be summarised as follows:

- Endogenous constructivism emphasises the individual nature of each learner’s knowledge construction process, and suggests that the role of the teacher should be to act as a facilitator in providing experiences that are likely to result in challenges to learners' existing models.

- Exogenous constructivism is the view that formal instruction, in conjunction with exercises requiring learners to be cognitively active, can help learners to form and refine their knowledge representations.

- Dialectical constructivism is the view that learning occurs through realistic experience, but that learners require *scaffolding* provided by teachers or experts as well as collaboration with peers.

These interpretations of constructivism will be used throughout this paper as a way of breaking down the threads of constructivist learning theory so that the consequences for the design of 3D learning environments can be analysed. It is important to emphasise that rather than subscribing wholly to one of these interpretations, many educators will draw on elements of each, depending on the learning situation. Consequently, the learning resource design elements derived from the analysis should not be seen as mutually exclusive, but as a superset of elements available for use, depending on the knowledge domain and learning context.

The following section provides some background on 3D learning environments, leading into the analysis of the implications of these three interpretations of constructivism for the design of such environments.

3D Learning Environments

The choice of term for the learning environments discussed in this paper was a difficult one. Two candidates, Virtual Reality and Virtual Learning Environment have become increasingly ambiguous terms. For example, Moore (1995, p.91) states that "virtual reality falls into three major categories: text-based, desktop and sensory-immersive VR". These categories incorporate a very wide range of technologies - each with quite distinct pedagogical issues. Similarly, the term Virtual Learning Environment is now used to encompass any Internet or Web-based learning resource, with associated discussion tools. Consequently, the term 3D Learning Environment has been chosen to focus on a particular type of virtual environment that makes use of a 3D model.

The main characteristics of a 3D environment are as follows:

- The environment is modelled using 3D vector geometry, meaning that objects are represented using x, y and z coordinates describing their shape and position in 3D space.

- The user's view of the environment is rendered dynamically according to their current position in 3D space, that is, the user has the ability to move freely through the environment and their view is updated as they move.

- At least some of the objects within the environment respond to user action, for example, doors might open when approached and information may be displayed when an object is selected with a mouse.

- Some environments include 3D audio, that is, audio that appears to be emitted from a source at a particular location within the environment. The volume of sound played from each speaker depends on the position and orientation of the user within the environment.

This paper focuses on the "desktop" category of 3D environments (using Moore's terminology), which require standard computer hardware. Much of the early 3D environment research focussed on "sensory-immersive" environments, which require expensive hardware such as head-mounted displays. Recent advances in the capabilities of standard desktop computers allow highly complex 3D models along with 3D audio to be delivered at realistic frame rates and with very high response times (Kelty, Beckett and Zalcman, 1999). Additionally, Robertson, Card and MacKinlay (1993) argue that desktop 3D environments can be easier to use than immersive environments because people are already familiar with the desktop computer, and do not subject the user to the physical and psychological stress often associated with immersive environments. Lastly, the development and proliferation of the Internet has made possible distributed 3D environments which can be explored by multiple learners together, from their own desktop computers, at separate locations.

A Constructivist Analysis of 3D Learning Environments

This section discusses the theoretical potential of 3D learning environments from a constructivist standpoint, drawing on Moshman's three interpretations of constructivism. The discussion focuses particularly on aspects of 3D environments that make them different to other types of interactive multimedia or online learning environments. Example applications of 3D learning environments are used to illuminate this discussion. Finally, the discussion is summarised in the form of a table listing the 3D environment design elements consistent with each interpretation of constructivism.

3D Learning Environments and Endogenous Constructivism

The endogenous interpretation of constructivism emphasises the discovery of knowledge through the learner engaging in an active exploration process. There are two ways in which a 3D environment can be designed that are consistent with this interpretation. The first is as a simulation, which includes simulations of the observable world and simulations of abstract concepts. The second is as an interface to a complex information space, as an alternative to a standard web or hypermedia interface. These are each explained, with reference to examples, in the following paragraphs.

The use of simulations, including 3D simulations is very consistent with the endogenous interpretation of constructivism, which emphasises learner discovery of knowledge through their interaction with the environment rather than from direct instruction. Such simulations can provide a realistic context in which learners can explore and experiment, with these explorations allowing the learner to construct their own mental model of the environment. The interactivity inherent within them allows learners to see immediate results, as they create models or try out their theories about the concepts modelled (Rieber, 1992).

There are a number of circumstances where the use of simulations may be preferable to exploration of real environments. One such circumstance is the exploration of places that cannot be visited, such as historical places, outer space or the ocean floor. For example Alberti, Marini and Trapani (1998) describe a 3D environment modelled on a historical theatre in Italy. Another is the exploration of microscopic environments, such as molecular structures (see, for example, Tsernoglou, Petsko, McQueen and Hermans, 1977, cited in Wann and Mo-Williams, 1996). A 3D simulation of environments such as these can provide a greater sense of realism than other types of simulations based on 2D animations or photographic material, due to the fact that the learner can move freely through the environment and view it from any position.

The most important benefits of simulations, particularly from an endogenous constructivist perspective, occur through the learner interacting with objects within the environment. Any knowledge domains where the learner is expected to develop an understanding of entities exhibiting dynamic behaviours may be suited to simulations with this greater level of interactivity. For example, in the discipline of physics, students are expected to understand how objects will respond to forces. By exploring an environment that allows for specific forces to be applied to objects and for the resultant object behaviours to be observed and measured, a learner can improve their conceptual understanding. 3D technologies are well-suited to such physical simulations because they allow for the modelling of the full physical behaviour of objects rather than restricting the motion and behaviour to two dimensions.

As well as facilitating the development of a conceptual understanding of the dynamic behaviour of entities within an environment, simulations can also allow the learner to practise skills. The use of simulated environments for practising skills can be particularly appropriate where the tasks to be learned are expensive or dangerous to undertake in the real world. For example, 3D environments have been used to train nuclear power plant workers in Japan (Akiyoshi, Miwa and Nishida, 1996 cited in Winn and Jackson, 1999) and to train astronauts in how to repair a space telescope (Psotka, 1994 cited in Moore, 1995). However, simulations may be of value for any tasks that cannot be conveniently carried out by learners as often as they need to.

In some knowledge domains the concepts to be learned are abstract and do not correspond directly to material objects. There can still be a role for 3D environments in these domains, if the formation by the learner of a 3D mental model of the concepts will improve their understanding. Winn and Jackson (1999, p.7) suggest that virtual environments “are most useful when they embody concepts and principles that are not normally accessible to the senses”. For example, they discuss the modelling of concepts such as justice. They use the term “reification” to describe the representation of phenomena that have no natural form. An example is the 3D environment for developing learner’s understandings of geometry described by Kaufmann, Schmalstieg and Wagner (2000). The term “microworld” is often used to describe simulations of abstract environments designed for concept formation (Rieber, 1992).

It would seem appropriate to use 3D simulations (as distinct from 2D simulations) in any situation where the concepts being modelled (whether concrete or abstract) are three-dimensional. However, this hinges on the assumption that a 3D computer representation explored through a 2D screen will help the learner to form a 3D mental model. A number of studies have found that learners can develop spatial knowledge through exploring a virtual environment (see, for example, Witmer, Bailey and Knerr, 1996 and Arthur, Hancock and Chrysler, 1997). However, studies comparing exploration of a 3D environment with alternatives such as viewing static images of the same environment, have been inconclusive (see, for example, Christou and Heinrich, 1999; Peruch, Vercher and Gauthier, 1995). It is well-established that the form of presentation of information affects the way that it is cognitively encoded (Baddeley, 1993; Salomon, 1994); however further research is required to investigate the cognitive encoding resulting from the exploration of a 3D environment.

Aside from simulations, the other approach to the design of 3D learning environments, consistent with an endogenous interpretation of constructivism is to use the environment as an interface to a complex information space. Traditionally, hypertext or hypermedia environments have been used in this way to allow the learner to discover information through their own free exploration rather than through a prescribed sequence of instruction. However, the provision of an interface that allows easy navigation through the information - while maintaining a sense for the overall structure of the resources and the connections between ideas - is problematic. 3D environments have been advocated as an alternative interface for navigating through such information spaces (Card, Robertson and York, 1996).

3D Environments and Exogenous Constructivism

The exogenous interpretation of constructivism emphasises the role of direct instruction to help the learner to form their own mental model of the ideas to be learned, supported by activities that allow the learner to test and further tailor their knowledge representation. These activities could be carried out using a 3D environment that simulates part of the knowledge domain. The important difference between 3D environments used in this way and 3D environments consistent with an endogenous interpretation is that in this case they would be supported by conventional learning resources, typically with a greater degree of system control over the selection and sequence of activities. For example, the 3D environment could be embedded within a tutorial resource, where the learner is expected to work their way through various instructional materials (which may include text, graphics, audio and video) and then periodically carry out activities within the virtual environment, before continuing with the next section of the materials. Alternatively, a set of instructional materials may include a number of smaller 3D environments or even discrete 3D models of objects, which are made available to the learner to explore or manipulate, when appropriate, as they work their way through the resources.

An alternative to embedding the 3D environment within a set of instructional resources is to use the 3D environment as an interface to the instructional resources. If the 3D environment is modelled on the context in which the knowledge is expected to be applied, it can be argued that there will be better transfer of learning. Specifically, because a 3D environment can provide a level of visual realism and interactivity consistent with the real-world, ideas learned within the environment should be more readily recalled and applied within the corresponding real-world environment. This is a logical corollary to the idea that knowledge can be internally anchored to experience. This idea is supported by research carried out by Baddeley (1993) suggesting that facts learned by divers under water are better recalled while diving than facts learnt on land. This is very consistent with theories of situated learning, such as Brown, Collins and Duguid’s theory of Situated Cognition (1989) and the Cognition and Technology Group at Vanderbilt’s theory of Anchored Instruction (1992).

Exogenous interpretations of constructivism also emphasise the use of cognitive tools, which help the learner to develop an understanding of concepts. Categories of such tools include concept mapping and graphing tools. There is scope for the development of 3D versions of these tools. If the concepts being explored or articulated (whether concrete or abstract) are more clearly understood with a 3D mental model, or if the data to be visualised has three components, then 3D concept mapping or 3D graphing tools may be more appropriate than their 2D alternatives.

3D Environments and Dialectical Constructivism

The dialectical interpretation of constructivism emphasises the undertaking of authentic activities by the learner but with support, or *scaffolding*, provided by peers, experts or teachers. Groups of learners working together and developing their understanding of concepts through a social learning process is also important. The use of computer-supported collaborative learning (CSCL) environments to allow learners to communicate and, ideally, work together on tasks is very consistent with this interpretation, and very important for distance education students, who otherwise may not get the opportunity to work with other students. Multi-user 3D environments with embedded communication tools have potential as CSCL tools for a number of reasons. Firstly, communication within a simulated environment relevant to the ideas being discussed can provide a greater 'sense of place' than other text-based alternatives such as MUDs or MOOs - and consequently a greater closeness within the group and richer communication. Most importantly, the distributed 3D environment can allow learners to undertake tasks together, rather than just communicate. Additionally, distributed 3D environments can allow for a teacher or domain expert to provide support to the learners as they undertake tasks.

A consequence of the dialectical constructivist emphasis on scaffolding, as the learner undertakes tasks, may be the provision of various forms of system-generated support within a 3D environment. At a simple level, this may just be a system-based help facility activated by the learner, possibly sensitive to the context of the task being undertaken. Alternatively it may take the form of an intelligent agent with a visual representation within the environment, acting as a guide to the learner. Another type of scaffolding can be the provision of support tools to help the learner undertake tasks, such as calculators, graphing tools or language translators. These could either be shown alongside the 3D environment or embedded realistically within it.

Summary of Constructivist Design Elements

The previous three sections have analysed the consequences of Moshman's three interpretations of constructivism for the design of 3D learning environments. The results of this analysis can be expressed as a series of 3D learning environment design elements consistent with each interpretation. Table 1 synthesises the ideas developed in this analysis into discrete design elements.

Table 1
Constructivist 3D Learning Environment Design Elements

Endogenous Constructivist Elements	
Design Element	**Explanation**
Place simulation	Simulation of hard-to-visit places
Microscopic simulation	Simulation of microscopic environments
Dynamic behavior simulation	Simulation of physical environments containing entities with dynamic behaviours
Skill practice	Simulations of dangerous or expensive environments for skill practice
Modelling abstract concepts	Visual modelling of abstract concepts in 3D
Information interface	3D interface to complex information structures

Exogenous Constructivist Elements	
Design Element	**Explanation**
Practice modules	3D models or small 3D environments embedded within instructional resources
Situated instructional resources	Instructional resources situated within a 3D environment
Cognitive tools	3D cognitive tools
Dialectical Constructivist Elements	
Design Element	**Explanation**
Situated remote communication	3D environment providing a 'sense of place' as part of computer-mediated communication
Remote task collaboration	Distributed 3D environment allowing learners to collaborate on tasks at a distance
Remote task support	Distributed 3D environments allowing teachers or experts to provide support as learners undertake tasks
Scaffolding tools	Tools to provide support or scaffolding as the learner undertakes tasks in a 3D environment

Constructivism and Chemistry Education

According to Johnstone (1991, cited in Tasker, 1998) there are three levels to an understanding of chemistry - the macro level, which relates to what one sees and measures within the laboratory, the sub-micro level which refers to what is happening on a molecular scale, and the symbolic level which refers to the representation of reactions using equations. According to Tasker (1998, p.12), a "rich understanding of chemistry involves being able to link what one sees substances doing in the laboratory to what one imagines is happening within these substances at the invisible molecular/ionic level."

Moshman's three interpretations of constructivism have implications for the educational approach and the type of educational resources appropriate to help facilitate the development of this rich understanding. The endogenous interpretation suggests that the most important learning occurs when the learner’s exploration uncovers a deficiency in the leartner’s current knowledge representation (Vander Zanden and Pace, 1984). In the context of chemistry education, the laboratory experiments fill an important role in providing an opportunity for the learner to subject their sub-micro level knowledge representation to empirical testing

However, the student is not likely to develop a consistent model of molecular behaviour purely through undertaking experiments. Consequently, there is an important role for direct instruction, to introduce learners to the models accepted by the scientific community, in addition to the associated symbol systems. This direct instruction is more consistent with the exogenous interpretation of constructivism.

A dialectical interpretation of constructivism would suggest the importance of collaboration between learners and their peers as they grapple with concepts. Specifically, according to this interpretation, the processes of phrasing a question to a peer or explaining a concept to a peer are very likely to help with the learning process. Additionally, the provision of support in the form of well-organised learning resources, along with direct support from demonstrators during laboratory sessions, is very consistent with a dialectical interpretation of constructivism.

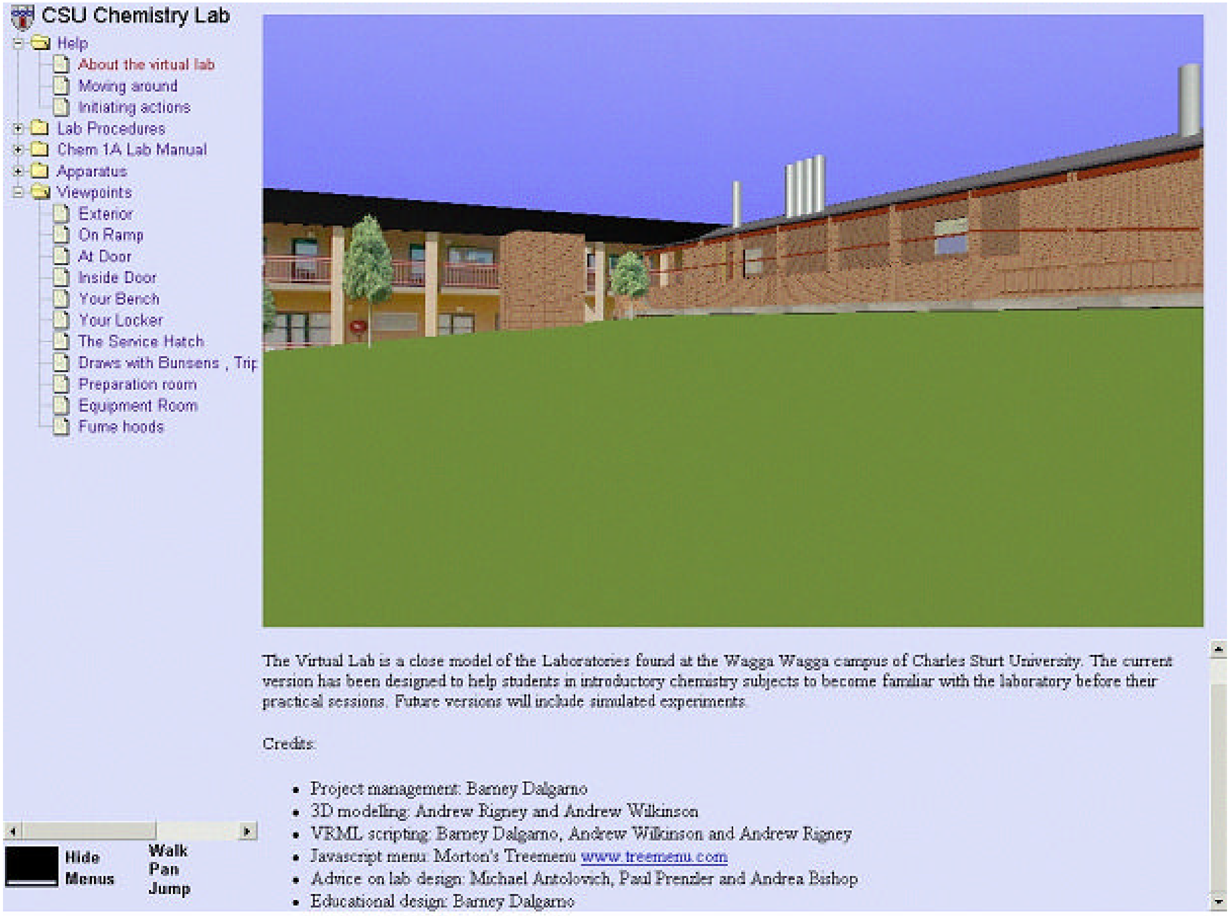
The importance of the learner developing a consistent understanding of the three levels of chemistry knowledge would suggest that the more closely the laboratory work is integrated with the theory the better. However, there are logistical barriers to this integration within distance education courses. A typical approach (and the approach used at Charles Sturt University) is to require students to attend a residential school once during the semester, during which all laboratory experiments are undertaken. Obviously this results in a separation of the theoretical learning from the practical experiments, thus reducing the pedagogical benefits of these experiments. This is one of the key justifications for the development of a 3D virtual chemistry laboratory; this is discussed in the next section.

The Charles Sturt University Virtual Chemistry Laboratory

The Charles Sturt University virtual chemistry laboratory is an accurate model of a chemistry laboratory used in undergraduate teaching. The initial version has been designed to allow learners to become familiar with the layout of the actual laboratory, as well as to find out information about procedures to follow in using the laboratory. It has been developed using the Virtual Reality Modelling Language (VRML) and is accessed through a web interface. Learners can explore and manipulate items of apparatus within the laboratory and by selecting an item can view information about its use. The contents of the introductory chemistry laboratory manual are also accessible from within the virtual laboratory.

Figure 1 shows the virtual laboratory screen layout with a view from outside the laboratory. The menus at the left allow the learner to access information about the laboratory, apparatus and procedures, to move to specific positions within the environment and to carry out actions - such as moving an item of apparatus. Laboratory procedures, information about apparatus and messages advising the learner on actions available are displayed in the text area below the environment view window. The options at the bottom left of the screen allow the learner to hide the menus and to switch between the three movement modes, Walk, Pan and Jump. When the menus are hidden, the environment window is expanded to fill the screen (as shown in Figure 2). The full range of movement and object manipulation is possible from this view. In this way the virtual laboratory caters for endogenous learning (through free exploration) and exogenous learning (through exploration within the context of the use of instructional resources)

Figure 2 shows the virtual laboratory with menus hidden. The area to the bottom left of the view window shows a Bunsen burner that has been picked up by the learner and can be carried around and placed elsewhere in the laboratory. Figure 3 shows a view across the laboratory. Figure 4 shows a learner's locker (students are allocated a locker with common items of glassware in their first laboratory session) along with a bench with various items of apparatus.



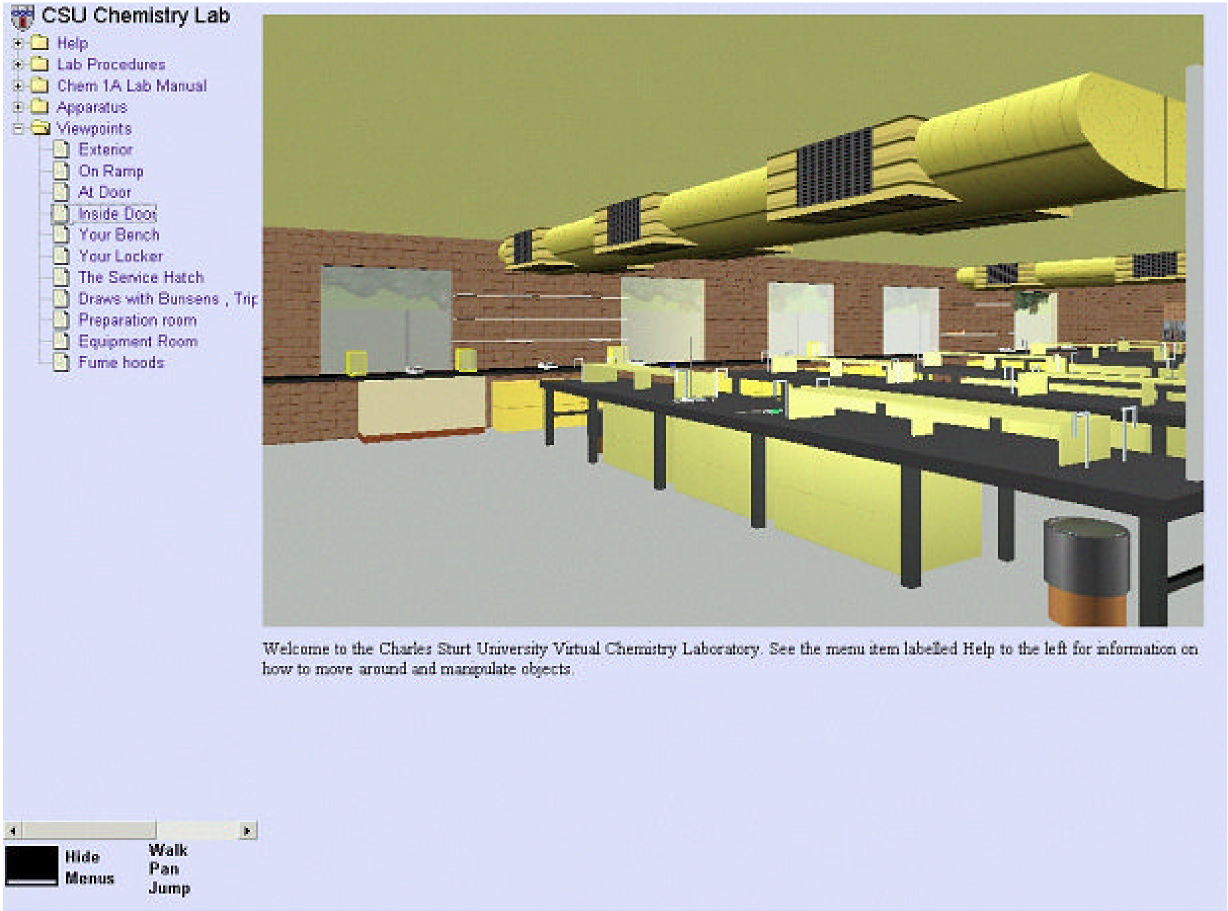
The Virtual Lab is a close model of the Laboratories found at the Wagga Wagga campus of Charles Sturt University. The current version has been designed to help students in introductory chemistry subjects to become familiar with the laboratory before their practical sessions. Future versions will include simulated experiments.

Credits:

- Project management: Barney Dalgarno
- 3D modelling: Andrew Rigney and Andrew Wilkinson
- VRML scripting: Barney Dalgarno, Andrew Wilkinson and Andrew Rigney
- Javascript menu: Morton's Treemenu www.treemenu.com
- Advice on lab design: Michael Antolovich, Paul Prenzler and Andrea Bishop
- Educational design: Barney Dalgarno

Figure 1
The CSU virtual chemistry laboratory showing a view from outside

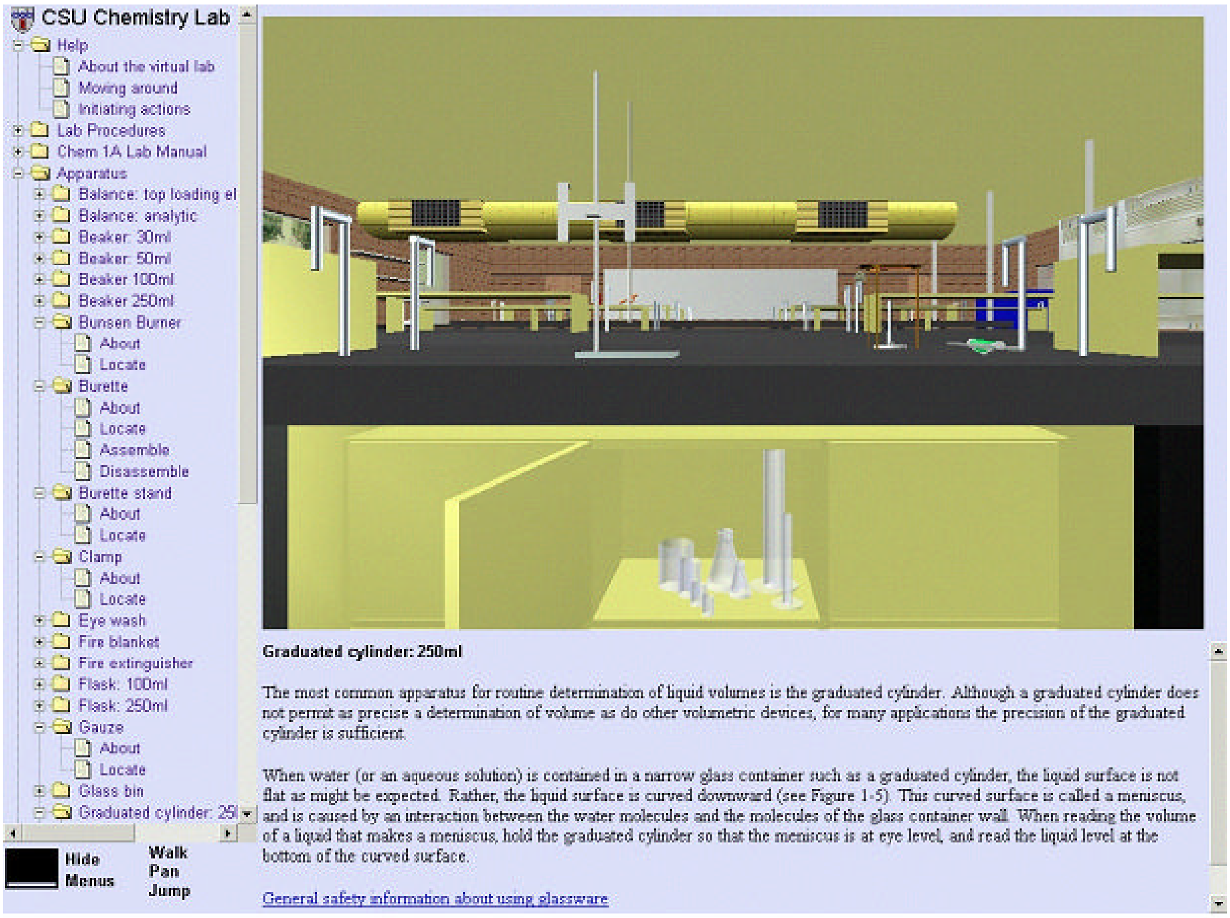
Figure 2
The CSU virtual chemistry laboratory showing the menus hidden and a Bunsen burner that has been picked up



Welcome to the Charles Sturt University Virtual Chemistry Laboratory. See the menu item labelled Help to the left for information on how to move around and manipulate objects.

Figure 3

The CSU virtual chemistry laboratory showing a view across the laboratory



Graduated cylinder: 250ml

The most common apparatus for routine determination of liquid volumes is the graduated cylinder. Although a graduated cylinder does not permit as precise a determination of volume as do other volumetric devices, for many applications the precision of the graduated cylinder is sufficient.

When water (or an aqueous solution) is contained in a narrow glass container such as a graduated cylinder, the liquid surface is not flat as might be expected. Rather, the liquid surface is curved downward (see Figure 1-5). This curved surface is called a meniscus, and is caused by an interaction between the water molecules and the molecules of the glass container wall. When reading the volume of a liquid that makes a meniscus, hold the graduated cylinder so that the meniscus is at eye level, and read the liquid level at the bottom of the curved surface.

General safety information about using glassware

Figure 4
The CSU virtual chemistry laboratory showing the learner's locker along with their bench with various items of apparatus

A formative evaluation of the virtual laboratory involving 10 chemistry students was undertaken early in 2002. Various changes were made to the design of the user interface as a result of this evaluation, and a summative evaluation involving 34 students was undertaken midway through 2002. This evaluation showed that, although not as effective as a tour of the real laboratory, the virtual laboratory is an effective tool for developing familiarity with the laboratory and its apparatus. The detailed results of this evaluation will be reported in an upcoming publication.

Current development work on the laboratory is focussed on allowing the learner to undertake virtual experiments. A feature of the simulated experiments will be an option allowing the learner to zoom in to the molecular level. Simulated experiments supplementing the real experiments undertaken at a residential school have the potential to make up for the lack of regular experiments supporting the theory. Their use has been advocated by a number of researchers. Gaddis (2000, p.8) notes that computer simulations of laboratory experiments "have the potential to address misconceptions, promote conceptual understanding of molecular processes, improve visualisation and effect conceptual change". Hollingworth and McLoughlin (2001, p.4) suggest that in addition to these benefits, computer simulations can "replace experiments that use hazardous materials; reduce cost; replace experiments that occur too quickly or too slowly to be done in a regular laboratory period; reduce cognitive noise so that students can concentrate on the concepts involved in the experiments; allow rapid data collection; serve as pre-laboratory preparation to aid understanding of the laboratory".

Future development will include client-server software allowing distributed learners to work collaboratively in the laboratory. Each learner present within the laboratory will be represented by a 3D model, or *avatar*, and learners will be able to communicate with each other and see the effects of each other's actions. This will allow, for example, learners to undertake virtual experiments together, as a group - under the supervision of laboratory demonstrators. Other related enhancements will include logging of activity and intelligent context-sensitive support and guidance.

The current version of the virtual laboratory can be explored at **http://farrer.csu.edu.au/chemistry.**

Having described in general terms the features of the CSU virtual chemistry laboratory, it is appropriate to identify which of the design elements derived earlier and summarised in Table 1 are used. To this end, Table 2 lists an example of how each design element has been or will be used in the virtual laboratory. Given that the discussion of chemistry pedagogy concluded that all three of Moshman's interpretations of constructivism have merit in chemistry education, it should not be surprising that the virtual chemistry laboratory draws on design elements from each interpretation.

Table 2.
Constructivist design elements in the CSU virtual chemistry laboratory

Design Element	**Explanation**
Place simulation	Simulation of the layout of the laboratory, including the location of apparatus, to allow distance education students to have a level of familiarity prior to the residential school laboratory sessions.
Microscopic simulation	Simulation of experiments at the microscopic level.
Dynamic behavior simulation	Simulation of the behavior of chemicals at both a macro and microscopic level in response to actions initiated by the learner.
Skill practice	Use of virtual apparatus, such as burettes and pipettes, in preparation for laboratory sessions.
Modelling abstract concepts	Protons, neutrons and electrons are essentially abstract concepts to be simulated as part of virtual experiments.
Information interface	The information currently available in the students' laboratory manual will be accessible through the virtual laboratory within the context of relevant tasks.
Practice modules	The menus will provide sequences of instructional materials with suggested practice tasks to be undertaken within the virtual laboratory.
Situated instructional resources	Information from the laboratory manual and other learning resources currently available in printed form will be accessible within the 3D environment.
Cognitive tools	There is potential for the use of tools allowing the learner to either manipulate 3D representations of molecules and see the corresponding equations displayed or vice versa.
Situated remote communication	Communication between distributed learners within the laboratory.

Remote task collaboration	Group experiments carried out by distributed learners
Remote task support	Remote support by laboratory demonstrators, as learners undertake tasks within the laboratory.
Scaffolding tools	Virtual calculators and graphing tools to help learners with exercises undertaken as part of virtual laboratory experiments.

Conclusions and Wider Implications

This paper has discussed the theoretical potential of 3D virtual learning environments from a constructivist perspective. A series of approaches to the design of 3D learning environments consistent with three interpretations of constructivism have been derived. The derivation of these approaches or design elements was based on a theoretical analysis, rather than on the results of empirical studies. It should be noted that many more empirical studies of 3D learning environments are required before the propositions about the appropriateness of these approaches can be strengthened. Nevertheless, the results of this analysis should be very helpful to educational developers considering the use of 3D learning environments.

In order to illuminate further the design elements derived and how they might be used as part of the development of a 3D learning environment within a particular context, the features of a 3D virtual chemistry laboratory currently under development at Charles Sturt University have been described. A discussion of chemistry pedagogy concluded that the three interpretations of constructivism identified each had merit within the context of chemistry education. Consequently, the list of design elements in the virtual laboratory included all of the elements identified, that is, elements consistent with each interpretation.

Clearly there are good pedagogical grounds from a constructivist perspective for the use of 3D learning environments. However, there are a number of implications of the use of such environments that need further exploration.

In addition to the cost of development (which in the case of the CSU virtual chemistry lab has primarily been borne by research grants), an often-forgotten cost of the use of online and interactive multimedia learning resources is the cost of ongoing maintenance. In the case of the virtual laboratory, updates will be required whenever changes to the real laboratory occur, in order to keep the simulated environment accurate. This is important if the virtual laboratory is used to familiarise students with the real laboratory prior to their laboratory sessions. Additionally, changes to the information and instructional resources embedded within the virtual laboratory may be required each time the printed distance education materials on which they are based are changed. Over a longer period of time, changes to the versions of software available on learners' computers will necessitate additional technical changes to the virtual laboratory.

Clearly, if the use of 3D learning environments is to become more widespread, the cost of development and maintenance has to be justified - either in terms of learning benefits or savings elsewhere. In many cases, increased learning outcomes are not sufficient to secure funding; cost savings are the only argument that the 'bean counters' will hear. In the case of virtual laboratories the obvious potential for cost savings is in reducing the number of actual laboratories that students undertake. The cost of consumables and of employing technical staff to set up and support teaching laboratories is significant, and so there is real potential for sufficient savings to allow widespread use of virtual laboratories.

It is the view of this author, however, that the replacement of laboratory experiments with virtual experiments should only go so far. Learners who only do virtual experiments may well develop an understanding of concepts sufficient to pass written exams, but they will miss out on important learning outcomes that can only be achieved in the real laboratory. Additionally, it is unlikely that they will develop the "rich" knowledge of chemistry that Tasker advocates if they only ever subject their personal mental models to scrutiny within a virtual environment. Such learners are likely to always have reservations about whether the chemistry, (or physics or biology) that they encounter in the real world will really behave as they found it to in the virtual world.

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