Extending the Use of Collaborative Virtual Environments for Instruction to K-12 Schools[†]

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Abstract:

Research on the development of virtual environments has been limited to date to universities due to the high cost of equipment and high-speed internet access. Applications of virtual environments using CAVE technology are numerous in medicine, architecture, military weapons systems, medicine, science research and business training. However, the cost of this emerging technology has prevented the exploration for using it to enhance learning in the K-12 classroom. Virginia Tech's University Visualization and Animation Group (UVAG) of the Advanced Communications Information Technology Center (ATITC), successfully developed the CAVE™ Collaborative Console (CCC), an overlay of the Electronic Visualization Laboratory (EVL) CAVE-simulator and Limbo. CCC allows users at remote sites to interact in real time with each other at their desktop computers and with users in the Virginia Tech CAVE. This paper describes the features of CCC software, what was learned from a pilot project using the software to deliver a collaborative virtual learning environment to K-12 students in remote locations across Virginia and a perspective on future development of collaborative virtual environments for instruction in K-12 schools.

1.0 CAVE™ Collaborative Console: networked shared virtual environment

The CAVE ™ Collaborative Console (CCC) is a software application that enhances collaboration by networking desktop computers into a shared virtual environment (VE) running a CAVE-simulator. This collaboration can include, but is not limited to, the fully immersive VE of a CAVE.

The CCC was created to work with a CAVE. The CAVE is a multi-person, room-sized, high-resolution, 3D video and audio environment, which is shown schematically in Figure 1. In the current configuration, graphics are rear projected in stereo onto three

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 ™ CAVE is a trademark name of the electronic Visualization Laboratory of the University of Illinois

walls and the floor, and viewed with stereo glasses. As a viewer wearing a position sensor and stereo glasses moves within its display boundaries, the correct perspective and stereo projections of the environment are updated by a supercomputer, and the images move with and surround the viewer, which creates the experience of "immersion". Hence, stereo projections on the walls and floor create 3D images that appear to have a presence both inside and outside the projection-room continuously; while the walls and floor surface effectively disappear. To the viewer with stereo glasses this 3D image space appears to extend to infinity. For example, a tile pattern can be projected onto the projection-room floor and walls such that the viewer sees a continuous floor extending well outside the boundaries of the projection-room. Three-dimensional objects such as tables and chairs would appear to be present both inside and outside this projection-room. To the viewer, these objects are really there until they try to touch them or walk beyond the boundaries of the projection-room walls that have disappeared.
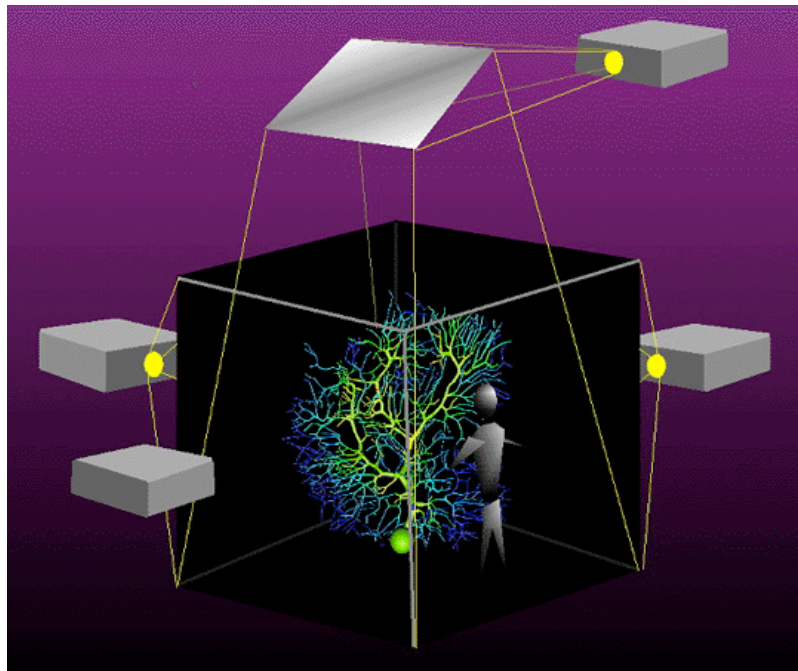

Figure 1. Schematic shows the minimal configuration of a CAVE projection-room showing the location of projectors.

Specifically, the CAVE is a 10x10x9 feet projection-room, made up of three rear-projection screens for the front, right, and left walls, and the floor where images are projected through an open ceiling, see Figure 1. Electrohome Marquee 8500 projectors throw full-color workstation fields (1280x1024 stereo) at 96 Hz onto the screens, giving a 3,840 linear pixel resolution to the surrounding composite image. A computer-controlled quadra-phonic audio system provides a sonification capability to four speakers located in the upper corners of the projection-room. A viewer's head and hand are tracked with an Intersense IS900 acoustic-inertial system. Stereographics' LCD stereo shutter glasses are used to separate the alternate fields going to the eyes. Optical emitters surround the project-room and synchronize the shutter glasses in all directions. A Silicon Graphics

Inc. (SGI) Power Onyx computer with 8-R10K CPUs, 1.5 Gbyte memory, and three Infinite Reality "pipes" with two raster managers per pipe is used to create the stereo imagery that is projected onto the walls and floor. Very fast graphics are required to generate stereo images to four projectors, which must operate at 96 Hz (96 stereo frames per second). This high-speed graphics system is realized in the SGI pipes and raster managers, not in the speed of the eight CPUs. The cost of such a system can easily exceed $700,000, which requires that such a resource be shared. Hence, it is critically important that CAVE applications run on less expensive desktop computers. This was a requirement that educators and researchers at Virginia Tech stipulated in the NSF proposal to build a CAVE at Virginia Tech. This link to desktop computers was satisfied by the creation of the CAVE-simulator. The requirement of a link from the desktop to the CAVE also motivated the creation of shared VEs.
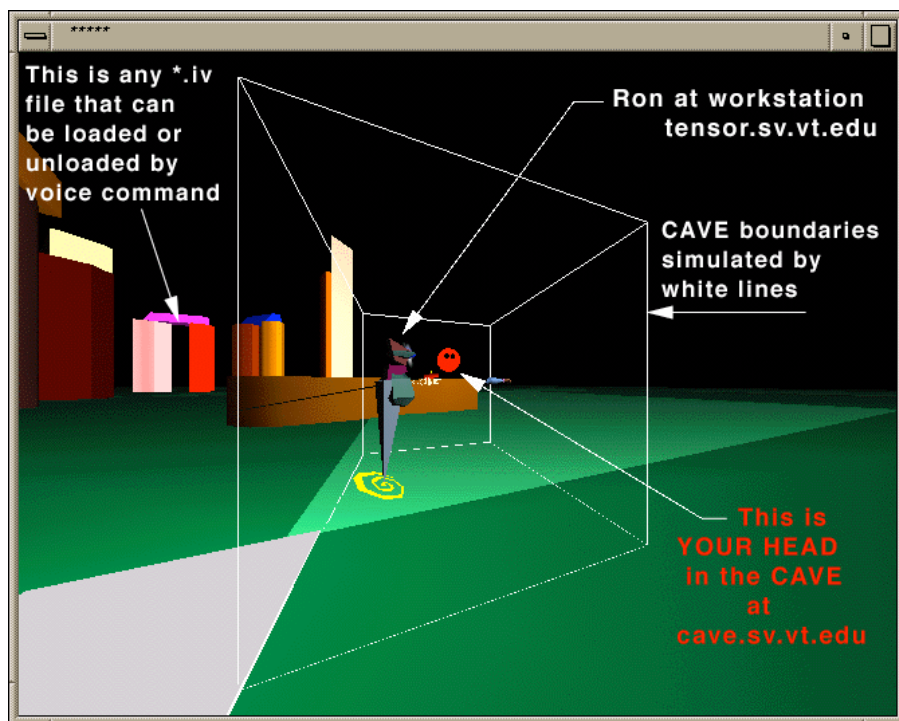

Figure 2. Screen capture of the CAVE-simulator running on a desktop SGI Octane computer. "Ron" is shown as an "avatar" working from a computer with an IP-name of "tensor.sv.vt.edu". The white lines simulate the boundaries of the CAVE projection-room and provide a 3D reference of participants who are working in a CAVE system.

It is fortunate that high-speed graphics are not needed on the desktop computer to simulate the same 3D scene-graph seen by a user in the CAVE projection-room. Hence, a desktop CAVE-simulator was created by the Electronic Visualization Laboratory (EVL) at the University of Illinois at Chicago that could run on a desktop computer. Although the graphics speed of an SGI pipe is not needed at the desktop, fast graphics are still needed for moving through 3D scene-graphs with a large number of polygons. Hence SGI ("UNIX") workstations provided the necessary speed for larger 3D scene-graphs. The CAVE-simulator shown in Figure 2, simulates the CAVE projection-room

boundaries with white lines, and the user's head is simulated with a red sphere that has two black eyes. Both the CAVE projection-room SGI Power Onyx computer and the CAVE-simulator desktop computer run the same executable software where the default is the CAVE projection-room format and the desktop CAVE-simulator runs when the "simulator" parameter is set to "on" in the ".caverc" configuration file.

Because the CAVE computer and the desktop computer are executing the same software, it is possible to link these two computers over the network into a shared collaborative space using the Limbo software developed at the Electronic Visualization Laboratory (EVL) at the University of Illinois at Chicago, Ref [1]. Using Limbo the shared VE is enhanced by transforming a participant's head (displayed as a red head icon) into a full-bodied "avatar", which is shown in Figure 2 as the "Ron" avatar. CCC participants running the CAVE-simulator see themselves as a red head and others as avatars with a head, torso and hand, not as a red head. Movement of a participant's head in the CAVE is tracked and displayed in the CAVE-simulator as a torso with a moving head. Movement of a participant's hand is also tracked in the CAVE and displayed in the CAVE-simulator as a torso with a moving arm. Each participant attaches a headset with an earphone and microphone so that participants can see and hear each other in the shared virtual space. If standing in the fully immersive environment of a CAVE, the CAVE user will actually experience the other participant's avatar standing next to them and carry on a conversation while pointing at and looking at objects in this shared space. To the user at the desktop computer running the CAVE-simulator, the CAVE user is seen moving through this shared space as a walking and talking avatar.

The CCC does not require the use of an expensive CAVE projection-room system. Participants can collaborate using only desktop computers running the CAVE-simulator and a low-bandwidth network. If participants setup a conference phone call using speaker-phones, it is possible to only use a modem to track the participant's heads and hands. Hence CCC does not depend on high-speed networks or connection to an expensive CAVE running high-speed graphics. CCC can be used for desktop-to-desktop collaboration without a CAVE.

The CAVE Collaborative Console (CCC) was first created by Kevin Curry and Kent Swartz to enhance the existing Limbo software with "collaborative-awareness" by including "participant lists", "two-dimensional (2D) radars", and "three-dimensional (3D) radars", etc. for each participant in the shared space. This project started as a project in the class on Computer-Supported Cooperative Work (CSCW) and continued with funding by the National Science Foundation (NSF) Partnership in Advanced Computational Infrastructure (PACI) project. Early development of collaborative-awareness in CCC was the basis of Kevin Curry's Master Thesis Ref [2]. As an NSF-PACI partner with University of Illinois, Virginia Tech's CAVE facility was used to develop the CCC as a collaborative tool for both the CAVE and the desktop CAVE-simulator as part of the NSF PACI Team-C on Enabling Technology: Data & Collaboration. The CCC was further developed by F. das Neves, John Kelso, and Ron Kriz at Virginia Tech as a generic collaborative workspace for research collaboration and educational distance learning, Ref [3]. CCC was combined with Atomview into

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CCC_atom which was designed to enhance research collaboration, where multiple users could view, interpret, and analyze physics based simulation models of atomic structures, Ref [4]. The remainder of this article will describe how CCC was used for education and distance learning.

2.0 Overview of CCC: features developed for educational distance learning.

With funding from the Institute for Connecting Research and Science to the Classroom (ICRSC) and an equipment grant from Silicon Graphics Inc. (SGI), CCC was developed for an educational project in collaboration with the Central Virginia Governors School and Central Shenandoah Valley Regional Governor's School.

The CCC was developed on top of EVL's Limbo. While Limbo provided a shared space where participants could view each other as avatars, there was no provision to make participants aware of each other's position, when avatars are no longer in the field of view, and Limbo did not have any capabilities to coordinate actions among participating avatars.
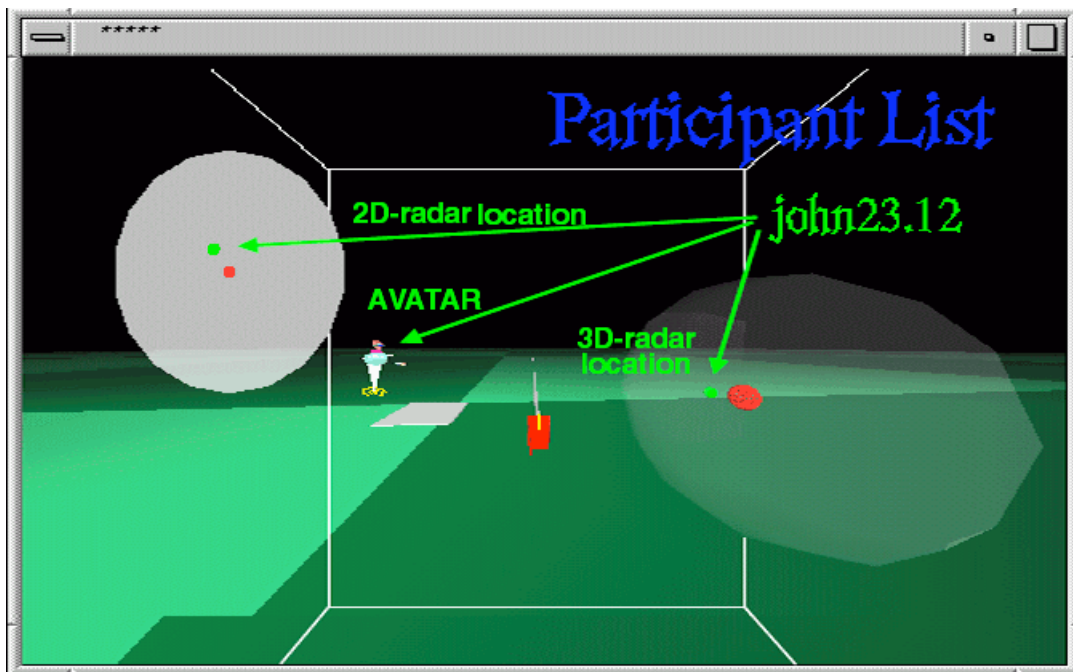

Figure 3. CCC session showing avatar location in participant list, 2D radar, and 3D radar.

The need to know one's position in the world and relative to others became evident after a Collaborative VE session at Supercomputing'98, where researchers at different sites met in a shared, virtual space. Due to the extension of that space, it was often the case that an incoming participant couldn't see avatars either because avatars were beyond the horizon, or occluded by walls and constructions. As a result of this experience and because of the lack of other tools, participants had to rely on verbal communication to discover common

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landmarks and describe their relative position to each other. Needless to say, this procedure was time-consuming and frustrating.

CCC adds three tools to support awareness: The Participant List, the 3D radar and the 2D radar shown in Figure 3.

The Participant List displays a list of names of the participants that are present in the world, plus the distance to each avatar from one's current position. Every participant's name is colored differently, and the same color is used in the radars to represent the same user.

The 3D radar is an egocentric representation of the avatars in a shared VE, where each participant is at the center of their radar, and each blip represent other participants in the shared VE. Color of each blip is the same as the color of the participant's name in the Participant List. Position of the avatar representations in the radar is continuously updated as avatars move around the shared VE in any direction.

The 2D radar is a flat representation of the 3D radar, corresponding to a projection on a horizontal plane of all the avatar positions. We added the 2D radar because many people found it easier to understand than the 3D radar, especially because being a flat view, perspective does not distort the representation of distance as avatars move farther away from the user.
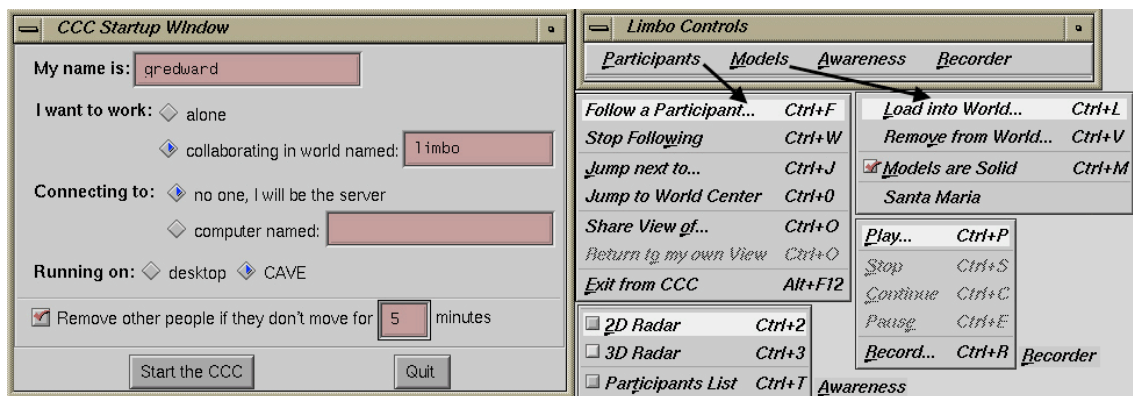

Figure 4. CCC GUI: Startup, menu: Participants, Models, Awareness, and Recorder

CCC capabilities evolved beyond the awareness tools to support avatar coordination. We allow a participant to:

jump next to another participant, so a group with a common activity can quickly gather around the activity organizer.

tether to another participant, so a more knowledgeable participant can lead a tour through the shared VE and show the most prominent landmarks. While a participant

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is tethered to a leader, he or she will follow the leader wherever he goes, although it is free to detach at any point in time or to look around while being lead on a tour.

   see through another participant's eyes ("shared view"). We discovered the need for this capability while testing a distributed class, where the teacher was describing a feature in a small spot and it was difficult for many avatars to gather around the teacher without interfering with each other. Instead, we allow all the students to virtually see through the teacher's eyes. When a student requests to see through the teacher's eyes, he or she sees at the eye level whatever the teacher is looking at. He or she cannot walk or grab objects in this mode to avoid conflicts, although they can look around from the position of the head of the participant he is connected to. All participants that are now seeing through another participant's eyes remain in the place they were before the participant started to share a view, and until the participant returns to their original avatar. A sign on the participant's avatar indicates the participant is not currently available for interaction.

Although the CCC has not yet formally been tested, it had an iterative development cycle where software developers invoked the principles of "user-centered-design". New features were evaluated by two groups: architects and Virginia Governor's School instructors. The latter were particularly involved in the design, since the CCC was distributed to a chemistry class with K-12 students. Both groups expressed the need to be able to collaborate with the CAVE using desktop computers. We supported this by designing CCC decoupling input from input interpretation. While in the CAVE input is performed by using the wand and voice commands, while in desktop machines input is performed with the mouse, keyboard and a floating menu bar. All options are available via voice and menu, and are coherent in naming and results.

Although time did not permit a formal usability evaluation, it was observed that very little training was required to teach the Governors School instructors how to use the CCC CAVE-simulator from a computer keyboard. Development of CCC also benefited from the fact that users in the CAVE and users at desktop computers can work with two separate input modes: CCC works with either pull down menus or voice-activated commands. Because these two separate input modes work coherently, training instructors to move from the CAVE to the desktop CAVE-simulator was facilitated as a consequence. As a result, we have a community of CCC users with a range of preferences and settings that work in different environments, which includes: full immersion of a CAVE, stereo displays projected on walls, and standard monitors.

3.0 Developing CCC for K-12 distance learning project with Virginia Governors School.

   A commitment of the Virginia Tech ACITC is to explore how collaborative virtual environments can be used to solve problems associated with distance learning, outreach and research across the state of Virginia. This commitment lead to a pilot project to demonstrate that users at the Virginia Tech CAVE could deliver a collaborative virtual learning environment to K-12 students in remote locations across Virginia. The project was a joint venture between the ACITC, the Virginia Tech Institute for Connecting

Science Research to the Classroom, the Virginia Governor's Schools and SGI. The *objectives of the project* were:

1) to connect K-12 students at two remote locations via the Internet to the Virginia Tech CAVE.
2) to provide K-12 students the opportunity to learn about and experience virtual environments.
3) to allow K-12 students to actively collaborate with professors who are using the CAVE for their research.
4) to create and deliver a content specific lesson to K-12 students using a virtual environment that allows the students at remote sites to actively collaborate with each other as they investigate the subject matter.

   The project succeeded in connecting students at two remote locations in Virginia and researchers at the Virginia Tech CAVE via a collaborative virtual environment. The path to success was certainly more challenging than expected! However, information gleaned from the endeavor will be useful in extending collaborative virtual environments in the future to the K-12 education community. An summary of obstacles encountered and progress made, is organized below by project objectives.

1) **To connect K-12 students at two remote locations via the Internet to the Virginia Tech CAVE.**

   The two schools connected to the Virginia Tech CAVE were the Central Virginia Governor's School for Science and Technology in Lynchburg and the Central Shenandoah Valley Regional Governor's School for Science and Technology in Fishersville. Connectivity was a larger obstacle than expected. The CCC did not work going through a proxy server. Opening the ports on the proxy server the CCC uses to communicate did not work. Eventually, all SGI traffic was routed around the proxy server. Under this arrangement, the CCC was used to connect the two schools with the CAVE at Virginia Tech. The T1 lines available at each school provided enough bandwidth to utilize the CCC technology. Two recommendations were derived from this experience. First, work needs to be done on making the CCC work with networks using proxy servers. Secondly, for this to happen, a programmer with extensive network expertise needs to work with the CCC programmers to solve connectivity related problems at remote sites. The level of expertise available out in the field is not sufficient to deal with the problems encountered.

   In order to attempt a collaborative CCC session, a conference call had to be set up since the verbal communication is handled via a normal phone connection. Conference calls were always initiated from CVGS which tied up the school's two phone lines for as long as the session lasted. Hence, extensive use of the CCC dictates that the sites have at least two phone lines that can be dedicated to the CCC for the duration of the sessions.   Speaker phones did not work well in the K-12 classroom environment. Talking on the handset meant only one person in communication at a time. No easy solution was apparent for this problem.

2) To provide K-12 students the opportunity to learn about and experience virtual environments.

The CCC proved to be a tool that has the potential of extending the collaborative virtual environment found in the Virginia Tech CAVE to K-12 schools and other remote sites at a very low cost. It is a tool in the formative stages of development and much of the actual work done during the project amounted to "alpha" testing of the software. This lead to many improvements that CCC programmers implemented such as:

> fixing numerous bugs which caused the CCC to crash when it was executing on SGI-O2 desktop computers at remote sites.
> a binary version that can be downloaded which avoids having to locate files in the appropriate locations and then actually compiling the CCC.
> a dialog box with list of loaded models that appears when you choose the "remove model" from the menu.
> the capability of "shared view"
> the capability to jump to the middle of the "world" if you get lost.
> the capability to return models back to their original orientation after moving them around.
> the capability to choose whether or not models are solid or whether models are allowed to pass through one another.

With each revision of the CCC software, a series of bugs were detected and corrected when the version was utilized on the remote SGI O2s. Although this type of work was not envisioned in the proposal, the team feels that a lot was accomplished from a "user-centered-design" viewpoint. The CCC is a lot more stable when it is used in remote locations than it was initially!

It took a lot of time for the high schools students who participated in the project to become familiar with using the controls to "fly around" the virtual CAVE. The controls were awkward and difficult to master, particularly, given the time constraints of K-12 classrooms. Revising the controls to make them more user friendly is needed but this level of programming was beyond the financial support provided by the grant. Another feature needed is the capability to load and remove multiple models at one time while retaining the capability to move them around individually in the virtual environment. Loading and removing multiple individual models during a lesson was a real time consuming task which often prevented completion of a lesson in the K-12 environment.

3) To allow K-12 students to actively collaborate with professors who are using the CAVE for their research.

The CCC provided the capability for K-12 students to **actively** collaborate with researchers in the VT CAVE. It is also apparent that the CCC can provide the means for students at remote sites to easily collaborate with each other on projects.

4) To create and deliver a content specific lesson to K-12 students using a virtual environment that allows the students at remote sites to actively collaborate with each other as they investigate the subject matter.

Four lesson plans related to molecular structure of organic chemistry molecules were developed. The team's experience suggests that development of programs for use in the CAVE and CCC is currently beyond the time constraints and expertise levels of K-12 teachers. The molecules utilized in the lesson where generated via the VMRL File Creator for Chemical Structures, Ref [4]. To use these chemical structures in the lesson, the following steps had to be accomplished.

> Since the CAVE only supports "vrml version 1" type files, all molecules used in the lessons, which began as vrml version 2 models, had to be converted to Performer Binary files (.pfb). The conversion process was done by importing these files into 3-D CAD software package and then exporting the files as .pfb. This software was too expensive for the Governor's Schools to purchase just to convert files. Therefore, all conversions had to be done by Virginia Tech staff/students.

> Since the lessons involved placing the molecules in specific places in the "CAVE", the original model's coordinates had to be translated using PF Transform. This special software was not available to the Governor's Schools except at significant cost. Therefore, all translations had to be done by Virginia Tech staff/students.

The team was successful in developing the lessons. However, it was apparent that to develop a more complex CAVE program requires full-time programmers. It was also evident that to utilize the CCC at a remote site, a staff member must have a basic knowledge of Unix administration.

4.0 Future development of CCC: CCC-DIVERSIFIED

Virginia Tech's VE software development team has been funded to develop collaborative VEs, with an emphasis on shared VE collaborative **design** environments by the Office of Naval Research (ONR).

Developing shared VEs to include a design environment philosophy required creating a new "shared-memory" architecture that would include *networked VE devices*. For example, a force-feed-back *device* allows participants (students and researchers) to manipulate objects in shared VEs with their hands and sense of touch. These objects can be 3D molecular structures, where users at the desk top, or in a CAVE, can feel six degrees-of-freedom (6-DOF) (3-forces and 3-moments) associated with docking a 3D-drug onto a 3D-protien. Another useful *networked VE devices* is a hand-held pocket-PC attached to a 6-DOF tracking device, with VELCRO of course, which could operate in either the CAVE or CAVE-simulator. The pocket-PC could be used to point to various

objects in the shared VE where participants could upload and download detailed information associated with these objects. Such a device would extend the collaboration after a shared VE session. The pocket-PC could be detached form the 6-DOF device and the information could be downloaded and post processed on other computers. Other devices used in VEs include 6-DOF motion platforms, remote-site real-time physics-based simulations and atomic force microscopes.

This idea of including network VE devices into a shared VE collaboration required a philosophical redesign of the underlying software Application Programming Interface (API) used in the CAVE or CAVE-simulator. At Virginia Tech the VE software development team created the Device Independent Virtual Environment: Reconfigurable, Scalable, and Extensible (DIVERSE), Ref [6]. To foster future development as well as VE research collaborations and educational VE distance learning collaborations, the DIVERSE API was licensed GNU-General Public License (GNU-GPL). GNU-GPL follows the same development philosophy of GNU/Linux, where over a significant period of time, significant software tools can evolve "freely" (as in free-speech not free-beer). DIVERSE 1.0 was released in January 2001 and currently runs on Linux and SGI-Irix operating systems. Future development of DIVERSE with an OpenGL interface will allow participants to collaborate on MS-Window, Mac-OS10, Sun Solaris, and HP-UX operating systems. With DIVERSE "freely" available accessible and running on a variety of operating systems, future development of CCC with the DIVERSE API will resolve many of the issues previously noted for this K12 project: 1) cost, 2) reduce complexity for user-development, and 3) running CCC on computers other than SGI.

5.0 VE applications in education distance learning: observations and future opportunities

The development of collaborative virtual environments for use in K-12 instruction is in its infancy. The project team believes it is an area that holds pedagogical promise in two main areas; applications allowing students at remote sites to share in the development of collaborative environments, and content specific applications providing students with a context for learning. In both types of applications, the virtual environment needs to be designed so it supports how students learn from a cognitive perspective. The environment needs to help students relate what they already know to new concepts they are learning and it needs to actively involve students in the learning process. In other words, the virtual environments need to be designed to assist students in assimilating new information into their cognitive schemas. In the first case, the team envisions a virtual "toolkit" that allows students in geographically remote schools to collaborate on creating a virtual environment. Could students create virtual robots designed to perform specific tasks in a virtual environment much like they might use Lego Logo kits to build a model robot in their classroom? This type of application is important for it provides students with the opportunity to use the emerging VE technologies like they are used in the professional world; to collaborate with colleagues with similar interests, to solve problems, and to create innovative designs in a cost efficient manner. In the second case, the virtual environment can introduce students to abstract concepts in a more concrete manner, thus providing a context for learning.

Development of contextual environments should focus on topics that are beyond the realm of the student's daily experience. For example, what if a virtual environment was created allowing students to pilot a spaceship they could accelerate in real time toward the speed of light. The program would allow students to experience visually in a virtual environment the effect of Lorenz contractions. Given that context, more students might understand the conceptual and mathematical tenants of relativity. Another example might be a virtual environment that allows students to investigate how weather phenomena like thunder storms form. Large databases containing pressure, temperature and wind velocity gradients related to thunderstorms are available. Virtual environments can provide students with visual access to this data. Students could then test their understanding of how the storms form by creating and testing hypotheses related to temperature, pressure and wind velocity values at different altitudes in the atmosphere. Finally, some science is beyond the realm of what students can imagine. How many high school chemistry students can imagine the dynamics associated with chemical bonding? A virtual "bonding toolkit", using haptic devices, could provide students with tactile feedback as they create bonds using different atoms and molecules. The experience might provide the context for understanding bonding energies and the role of molecular forces in the bonding process.

Based on our collective experiences and lessons learned from this project, the original CCC software development team at Virginia Tech together with the Governor School project participants are exploring opportunities for future funding to rebuild the CCC using the DIVERSE API. This project has been "a road less traveled", but it was rewarding and a lot of insight was gained. Now it is time to do it again! Using the knowledge we have gained, a new version of the CCC will be developed with DIVERSE. The new version will ensure that the process of extending the use of collaborative virtual environments to K-12 schools in the future, is a much easier task!

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