Curricular Modules: 3D and Immersive Visualization Tools for Learning

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Many scientific principles are dynamic in nature but are commonly presented through static two-dimensional media such as textbooks and blackboards, leaving the student to make the connection between the two. In several science courses at Connecticut College, faculty experiment with the use of 3D animations to increase the students' understanding of these concepts.

Curricular Modules: 3D and Immersive Visualization Tools for Learning, a project funded by the National Science Foundation, provides innovative pedagogical tools for subjects in the sciences that have been traditionally challenging for students to master. The 3D and virtual reality tools represent groundbreaking advances in pedagogy in a wide variety of areas of science education.

Six science modules were created by cross-disciplinary teams comprised of faculty (fellows at the Center for Arts and Technology) and students from the science, computer science, and design departments. A benefit of this team approach is the mutual understanding gained from working with individuals with different expertise and backgrounds.

Specific subjects included human physiology, graph theory, introductory physics, organic chemistry and biochemistry, cell biology, and astronomy education. For example, users understand the production and propagation of an action potential through immersion in a 3D environment, experiencing how the ions flow back and forth. A multi-sensory approach is used in which some of the modules include audio and haptics (force feedback).

Interdisciplinary collaboration

This project represents a collaborative effort among faculty from a wide range of disciplines. The modules were developed by small teams of three students and three faculty members, each representing a different discipline — science, computer science, and design. The team approach provided a rich and focused learning environment, allowing students to collectively understand and solve visualization problems. All participants developed a greater respect both for the collaborating outside disciplines and their own specialties.

Students in the center's certificate program explore the symbiotic relationship between technology and the arts, developing an understanding of the meaning and role of technology within the larger context of the liberal arts. Students who are accepted into the center's certificate program must take an interdisciplinary course in the history of arts and technology as well as courses in the arts and computer science. Furthermore, they must complete a summer internship and subsequently spend two semesters working on an integrative project. Throughout the program, they are exposed to colloquia and symposia, and the students participate in exchanges emphasizing the connections between the arts and technology.

The modules that students worked on were complex and abstract in nature. Initially, all participants met for a discussion of the principle concepts of the modules. Students then began to sketch out the narratives of the scientific principles, brainstorming together to develop visually possible metaphors to describe the principles. The design of the scientific principles was explored on three levels: information design, interaction design, and sensorial design.

The computer science students began to test and modify the sketches, and to build them in different digital environments. At this stage, it was important to maintain clarity and the carefully crafted visual aesthetics. Once the direction and procedure was clear, work on the computers began in earnest. Design students explored components of information design by testing color, form, text, and shape on the computer screen, taking into consideration legibility and clarity of the narrative. The interactive components were also tested and modified, ensuring that links, input systems, and calculators worked effectively. The sensorial component (force feedback) tests involved applying varying stress to visual elements within the chemistry module, which added an enriching detail to the user experience. These design considerations all contributed to a virtual reality space that represented an information—complex-visual form, information source, transmission conditions, users, and their responses.

The technology used to develop each module enabled sophisticated graphics and clear information design through immersion in a virtual reality environment on a PC or UNIX platform and a 3D Web version (either VRML or ActiveX plugins). Most of the modules were developed on a PC/UNIX platform using C++ and Sense8's virtual reality libraries. Some of them used the Sense8 WorldUp software, and others were programmed specifically for the Web. Those that use haptics were programmed using SensAble's C++ Ghost toolkit libraries.

Examples

The modules examine six different concepts. The first is in human physiology and concerns the molecular events that take place during the production and propagation of an action potential. A second concept is the relationship between molecular configurations and mathematical equations. The third concept is in mathematical graph theory and calculates maximal flow through a network. Another concept, in cell biology, is the continuous flow of membrane during exocytosis. The fifth concept is the electric potential function in physics. The last concept is the idea of a galactic center in astronomy. The concepts were chosen because they are difficult to learn from a textbook situation and would benefit from visualization and interaction. For example, in the chemistry module, reading about the relationship between a mathematical formula and the forces on a molecule is not as clear as watching the relationship dynamically develop. Likewise, being able to walk through a graph algorithm, testing hypotheses along the way, makes the algorithm more vivid and the understanding of the mathematical proof more complete. Several of the modules are described in more detail below.

Action Potential

The molecular events that take place during production and propagation of an action potential are important concepts for students in human physiology to understand. The operation of voltage-gated channels with the subsequent flow of ions in and out of the axon is a dynamic process that can best be visualized through animation. This module allows students to see the results of opening and closing the sodium and potassium voltage-gated channels during the production of an action potential. In the design of this module, students chose to emphasize a shape for the sodium ions that matches the shape of the corresponding gate, thus making clear that these gates only allow certain ions to pass through. The animation allows the students to choose the perspective from inside or outside the axon and is accompanied by audio. There are two versions of this module: one runs on the Web in VRML; and one uses a C++ environment and may be viewed in stereo.

Molecular Conformations

Another example comes from chemistry. It is very important for students in organic chemistry and biochemistry to understand why molecules adopt their particular geometry. Length, bond angle, dihedral deformations, and a variety of non-bonded interactions are responsible for specific conformations. In molecular mechanics, all of these contributions to the total strain energy are molded by mathematical formulas that are minimized to find the lowest-energy configuration. By using a force-feedback hardware device called the Phantom (from SensAble), this module actually allows students to feel the forces acting on an atom as they simultaneously view the corresponding graph. For example, as a carbon atom in an ethane molecule is moved away from the other carbon atom, the student feels the restoring force. The virtual environment allows students first to choose a particular mathematical equation, then they are able to pull the atom in the molecule, either stretching or compressing the bond, and simultaneously observe the mathematical graph generated. There is an audio explanation of the mathematical equations and how they model the chemical processes. This virtual environment uses a force-feedback device (the Phantom from SensAble), so users can actually feel the increase in forces acting on the atom.

Maximum Flow in a Network

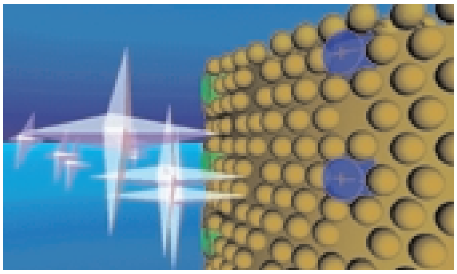
Another module, in graph theory, helps users understand how maximum flow through a network is produced. The mathematical justification for this algorithm lies in the relationship between minimum cuts and maximum flow. A cut is produced by dividing the vertices of the graph into two sets and then adding up flows on edges, joining vertices of the two sets. Cuts may be thought of as bottlenecks so, in some sense, the largest flow will be constrained by the narrowest bottleneck. As users pick out cuts and test them, they achieve a better grasp of the mathematics.

Electric Potential

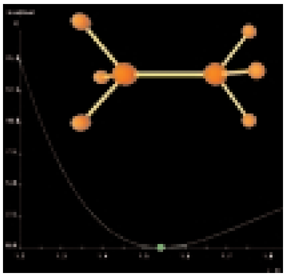
Another module deals with the electric potential function in physics. Students enter information (including location) about test charges, and then a 3D landscape is created where the altitude or depth at a location is the value of the electric potential. Values for this function depend on distance from the charges and the magnitude of the charges; these values may be positive or negative. Visualizing this function as a 3D landscape shows these relationships more clearly. By varying the magnitude of the charges, by making them positive or negative, and by changing their locations, users produce different landscapes. A test charge is also incorporated into the landscape, and this test charge moves according to the gradient of the potential. Additional modules deal with concepts in cell biology and astronomy.

Evaluation and Summary

The plan for evaluation is simple, but effective. The students exposed to the modules in the classroom were able to immediately evaluate the user experience and respond to the clarity of the information graphics. Tests were conducted this semester and there have not yet been any modifications.



Sodium ions (pink) outside the cell wall (brown), sodium-gated channels (blue), and potassium-gated channels (green).



As the student moves one of the carbon atoms away from or close to the other, the green ball traces the mathematical function.