Visual Learning for Science and Engineering

Michael B. McGrath and Judith R. Brown

***Visual Learning** is the use of graphics, images and animations to enable and enhance learning.*

Executive Summary

This White Paper examines the emergence of Visual Learning in Science and Engineering, an important methodology for learning and understanding scientific principles. It highlights successful activities in classrooms throughout the world and points out some areas where more work is needed.

Scientists and engineers are grappling with increasingly difficult problems, such as efficient use of world resources, care of a growing population, and global warming, increasing the need for students in STEM (science, technology, engineering, and math) fields. Moreover, through current technology, we can now provide educational opportunities that take advantage of all the senses, that allow non-linear, individual exploration, and that allow students to be totally immersed in individual or collaborative environments. Such activities were impossible, technically and financially, only a short time ago. Educators and students are now limited only by the extent of their abilities to take advantage of these technologies, with visual learning being a key strategy that is used in increasingly effective ways.

As the number of students choosing to pursue science and engineering has declined, we look at visual techniques for showing students how important and fascinating science and engineering careers can be. Although this specific project focuses on undergraduate STEM education, we need to be aware of the entire educational pipeline and the importance of getting children interested in science at a young age. Because the number of students in the field of science diminishes as the students grow older, it is vital that we have a large number of potential scientists in this pipeline at an early age. As graphics, images, and animation have become easier to use, a visual approach offers opportunities to more fully engage young students and keep the pipeline of future scientists filled.

The goal of this White Paper is to encourage faculty in STEM disciplines to use visual methods to communicate about science and engineering. By exploiting the visual senses of students, teachers can engage students' interests and enhance learning. This methodology has the potential to increase the number of students in STEM fields, especially women and minority students.

Why visual learning is essential

Visual learning methods:

- open up new ways of problem solving,
- provide new ways to think about science and engineering, and
- enhance the education and practice of science and engineering.

This paper discusses the opportunities provided through visual learning, how these visual methods are being used, why the use of images is important for learning, and what future work should be done.

An important benefit from a visual approach to science and engineering is better communication. Visual approaches let scientists and engineers communicate more complex and more subtle concepts to each other and to students, and visual approaches to learning can engage the student more fully in the ideas. A revolutionary change to scientists' way of thinking is evidenced by the fact that they now say they cannot do scientific research or communication without visualization. This "visualization revolution" showed that letting scientists engage the higher cognitive parts of the brain by thinking and communicating visually improved how they performed their research [1]. Similarly, educators can use visuals to engage students in active learning, support traditional lessons, and strengthen learning experiences. Just as visualization techniques are now considered to be an integral part of scientific research, they have the potential to be equally important to science education, and students must be able to think visually and communicate effectively using visuals. Also, with new opportunities for learning and enhanced understanding, this "visualization revolution" can expand from research to education.

Early activities

The current efforts arose from numerous discussions at SIGGRAPH conferences exploring the potential of visual techniques for teaching science and engineering. The first organized effort was a three day workshop, a "Campfire" on Visual Learning, at Snowbird, Utah, June 1-4, 2002, sponsored by ACM SIGGRAPH (the Special Interest Group on Computer Graphics and Interactive Techniques of the Association for Computing Machinery) and Eurographics (the European Association for Computer Graphics) [2]. This three-day workshop brought together 26 researchers and practitioners from eight countries. Participants were from engineering, science, mathematics, psychology, computer science, art, design, photojournalism, and other areas where images play an important role in communicating ideas and enabling education.

A second, follow-up workshop on visual learning in science and engineering was held as part of the ACM SIGGRAPH and Eurographics Computer Graphics Education Workshop (CGE 2004), in Hangzhou, China, June 2-5, 2004 [3, 4]. This workshop had support from the U.S. National Science Foundation (DUE 0407830), Zhejiang University, State Key Laboratory for CAD (Computer-Aided Design) and Computer Graphics, National Natural Science Foundation of China, and Ministry of Education of China. This was a global endeavor to understand how people communicate visually worldwide, and participants had backgrounds in engineering, computer science, information science, web design, instructional design, and fine arts.

This White Paper is a compilation of the results of these two workshops and other discussions that followed, and it is intended to encourage the development and use of visual learning techniques in STEM fields. Parts of this White Paper appeared in IEEE Computer Graphics and Applications [5] and were presented in the Eurographics 2005 Educators Programme [6].

Technology advancement

Some visual learning activities have been around in the sciences for a long time. For example, fifty years ago there were stick-and-ball models of molecules to show chemistry students how simple molecules were assembled. However, the amount of visual learning in the sciences has increased with the advent of high-powered, low-cost computing, and all the sciences can now offer strong visual approaches. In geology, applications such as those developed by Steve Reynolds [7], let students visually examine both abstract and actual geological structures. In chemistry, many tools, including the Chime system [8.], are available for presenting and manipulating both simple and complex molecular models, and students can work with online databases of molecular models. Mathematics systems such as Maple [9], Matlab [10], and Mathematica [11] let students define models either symbolically or numerically and then visualize the model's output. In biology, in addition to molecular model, there are models of structure and function, such as the beating heart, blood flow through the circulation system, and neural and brain responses to stimuli.

Some tools cut across disciplines to let students and faculty use images in innovative and powerful ways to examine scientific principles and data. For example, the GeoWall [12] displays two registered polarized images that look fully 3-dimensional when viewed through polarized glasses. Scientists use this tool for both natural and synthetic images, ranging from molecular models to photographs from the Mars rovers. Users can assemble the system from off-the-shelf components, costing from $6,000 to $10,000. All it requires is a desktop PC with a fast graphics card, two projectors, and a screen.

Assessment of visual learning

The Audio-Visual (AV) Commission on Public Information published research in the late 1950s showing more learning in less time with AV [13, 14]. This "Gateway to Learning" publication was used as a selling point to establish AV centers all over the country, and it included testimony from Dwight D. Eisenhower that "use of films in WWII speeded and broadened training of troops beyond any precedent." Other visual techniques that were useful in both military and general applications at this time were semaphores and Morse code, the latter of which was both visual and auditory.

Although scientists and science instructors generally believe that visualization, including both visual presentations and visualization of experiments, can improve learning, empirical evidence that visualization really does help is lacking, and some evidence shows that it does not help if used incorrectly. Hegarty *et al* showed that both a printed presentation and a hypermedia presentation of a mechanical system gave the same learning results [15]. However, Kehoe *et al* suggest that visualizations are more valuable when used in homework or study settings [16]. Narayanan et al report a line of experimental results for both mechanical and computational systems, comparing multimedia to printed presentations [17]. They use these experiments to create a design process that incorporates a number of cognitive factors that lead to genuinely improved learning with the visualizations.

These examples lead to the conclusion that we need a study on how to assess the value of visual learning. Assessing learning is always difficult. Assessment is even more difficult in a visual learning environment because our usual means of assessment are verbal and written, methods that do not reflect visual learning. How do you test visual learning in science and engineering through written or multiple-choice exams? How do we expect students to be able to express verbally something they have understood through visual means?

According to Associate Professor Emeritus Lida Cochran [18], the educational media field was struggling in the late 1970s with this question of how to examine the effects of visual presentations on learning They believed visual abilities to be important even then, and they advocated using qualitative research to assess learning.

In 2002 and 2003, an ACM SIGCSE (Special Interest Group on Computer Science Education) working group in computer science studied the question of animations for teaching, focusing on computer science 19]. They examined the literature and polled instructors about their beliefs and practices in using animations for teaching. Rather than look at factors such as color, sound, and interactivity as reported by Khuri [20], they looked at a set of commonly-accepted best practices for using animated visualizations of algorithms to teach computer science. These are given here as a simple list, but are expanded in the working group report 19].

Best practices:

- provide resources that help learners interpret the graphical representation,
- adapt to the knowledge level of the user,
- provide multiple views,
- include performance information,
- include execution history,
- support flexible execution control,
- support learner-built visualizations,
- support custom input data sets,
- support dynamic questions,
- support dynamic feedback, and
- complement visualizations with explanations.

The designer of a visualization must weigh these practices carefully because there is no single visualization activity or system that is best for all learners. In this design, you should consider the level of engagement that the student is to have with the visualization. There are six levels of engagement you should consider:

1. no viewing,
2. viewing,
3. responding,
4. changing,
5. constructing, and
6. presenting.

This is not a simple hierarchical scale because any combination of these (except the first) can be used in the design of a visualization. While there is no hierarchy implied by the ordering, the working group formed a set of hypotheses about the learning value of these levels of engagement.

- Viewing vs. no viewing: several studies have shown that viewing results in equivalent learning outcomes to no visualization, though these studies were based on small sample populations.
- Responding vs. viewing: the hypothesis is that responding results in significantly better learning outcomes than viewing.
- Changing vs. responding: the hypothesis is that changing results in significantly better learning outcomes than responding.
- Constructing vs. changing: the hypothesis is that constructing results in significantly better learning outcomes than changing.
- Presenting vs. constructing: the hypothesis is that presenting results in significantly better learning outcomes than constructing.
- Multiple engagements: the hypothesis is that multiple engagements results in significantly better learning outcomes than a single engagement.

The working group is engaged in testing these hypotheses but no results have been reported yet.

An area where visual learning has been explored in some depth is algorithm visualization in computer science, which is the basic area studied by the working group [19], although they intended their hypotheses and approach to be more general. Algorithm visualization uses animations to explain algorithms to students. These have been used for a number of years and are received enthusiastically by students, but studies of their effectiveness have not produced convincing proof that they actually improve learning [21]. A research program to develop educationally-effective algorithm visualizations was reported in [22], based on the learner-centered design of [23] and using some key features that are of interest here:

- Animations are embedded within a hypermedia environment that also employs textual descriptions, static diagrams, and interactive examples to provide contextual information.
- An animated analogy is embedded in the very first view of the algorithm that a student sees.
- Three distinct kinds of animations are provided to illustrate qualitatively different views of algorithm behavior.
- Algorithm animations are provided in discrete segments accompanied by explanations of the specific actions being accomplished.
- Student participation is encouraged by allowing rich interactions with the animations and using probes or questions that stimulate thinking and foster self-explanations.

The algorithm visualizations developed in this project were compared with beginning lectures, advanced lectures, lecture and animation combination, and another respected algorithm visualization system, and the results were quite positive. The paper mentioned above has more details [22].

The conclusion, extrapolated from algorithm visualization to more general-process visualizations, is that the best practices and hypotheses about engagement levels make up a set of basic principles that we can apply to an educational visualization to improve learning [19]. Conversely, ignoring these principles can make the visualizations poor teaching and learning tools, even if the images are beautiful. Although visualizations other than that of algorithms might not have the same results, the principles above should lead to sound learning support generally.

Cross cultural challenges

The concept of “cross cultural” can mean across disciplines, such as biology and chemistry, or across nations. Making an effective image requires that you know your audience, so in some ways, communication may be easier between two chemists in different countries than, say, between a chemist and a biologist in the same university. However, a visual approach includes additional aspects, such as color, icons, body language, and gesture, that can interfere with communication between scientists from different geographic cultures.

Although some things are hard-wired in our brains, such as attention to contrast and noticing motion, we learn other things via societal interactions, according to Jacqueline Ford Morie, Associate Director of Creative Development at the University of Southern California's Institute for Creative Technologies (ICT). For example, Western cultures might use faster, MTV-style animation, while Eastern and Eastern European cultures might use a slower, more contemplative animation style. Similarly, other visual techniques may differ from one culture to another.

Projects undertaken without knowledge of cultural backgrounds can backfire. For example a 2003 Toyota advertisement [24]—"China's most hated Toyota ad," according to Xin Zhao, Ph.D. Candidate in Marketing at the University of Utah—evoked widespread anger among Chinese viewers. The ad showed a stone lion - a symbol of China and traditional Chinese culture - saluting a Toyota automobile, which is a Japanese product. The ad reads (in Chinese), "Prado, (a car that) you have to show your respect." Symbolically, the images presented China as being inferior to Japan. The ad ignored the history of Japan's invasion of China in the 1930s and the resulting animosity some Chinese consumers still felt toward Japanese products. Toyota quickly pulled the ad, and the advertiser publicly apologized for neglecting the cultural and social factors.

Developers of the virtual environments of cultural heritage sites at Fraunhofer Institute, Germany, are concerned with meaning and storytelling. Because the viewer's cultural background and knowledge affects an image's meaning, each person will have his or her own story of the image. The Fraunhofer group is working on how to compose the models and tell the stories. They have found that it is important to have a good visual storyboard before building the models and animations. Then they carefully define how to navigate in the virtual environment to determine what kind of an experience it will be. One method used in the virtual reality (VR) exhibit of the Dunhuang Caves site in Northwest China is to allow each user a real flashlight to lighten and explore the simulated cave as he or she wishes. Augmented reality, adding information to the historic or scientific site, can also change the experience dramatically. Figure 1 shows virtual Dunhuang Cave art.

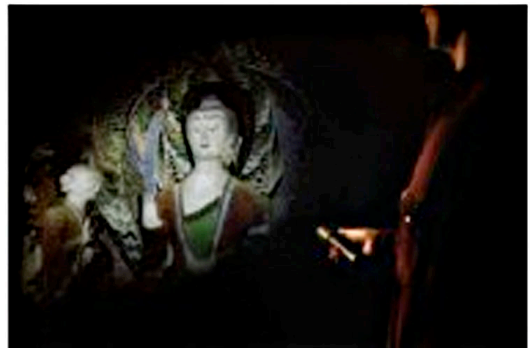


Figure 1. A virtual environment, presenting one of the caves at Dunhuang, China. Courtesy of Bernd Lutz, Fraunhofer Institute, Germany.

What students must learn

The skills needed to produce visuals depend on what you want to accomplish in your design. You need to know the audience for *this* visual. You need to know when to refine and simplify. In the business world, the customer will have the final say as to when the visual is right. For example, researchers developed ship simulation virtual reality systems at Dalian Maritime University (details later), for commercial use, in addition to their use for student training. One major customer, the Dalian Ocean Shipping Company, is a state-owned shipping enterprise with specific requirements for its system.

Designers must also keep in mind each student's experience and readiness, which contributes to his or her visual understanding. For example, students must learn to read maps and charts in the control room before they can benefit from this virtual reality ship simulation and learn to navigate.

Realism versus abstraction

Because the cost for VR technology has dropped so much in recent years, cultural and scientific institutions can use this technology to present endangered or fragile objects to the public while still preserving the objects. VR technology lets viewers observe ancient people and sites, as well as things that could not be seen in real life, as shown in the Dunhuang Cave example above. Viewers can also freely explore and interact with these virtual people, sites, and object, as shown in both the Dunhuang Cave example and in the South African HIV/AIDS health training virtual environment below. Bernd Lutz, the Dunhuang Cave developer, believes it is sometimes preferable to present objects in an abstract form. In architectural blueprints, for example, special symbols represent objects such as windows and doors. In a three dimensional world, we use 3D objects. Because archeologists don't always know what ancient objects looked like, a realistic presentation of a cultural object in an animation or virtual environment can be misleading. In this case, an abstract form is preferable.

Drawing and sketching

The importance of drawing and sketching has been a hot topic of conversation at the ACM SIGGRAPH Educators' discussions for several years. Many educators feel that drawing is essential and are requiring this skill in their courses.

Drawing and sketching play a major role in engineering education because they help develop a student's creative side. However current curricula have neglected these skills.

For many years, engineering education has sought to give students a foundation in good design and problem solving. The increasing complexity of the modern world and global competition requires that students be much more than technically proficient. They must also be well versed in written and oral communication, work effectively in teams, and be creative problem solvers. The modern engineering curriculum has embraced these goals and has made good progress by including work on communication, teamwork, and design. However, there is little active course work on developing the students' creative abilities.

Students are typically given design projects early in their careers so they can experience the design process while working in teams. An early design phase is the exploration of alternative approaches to meeting the problem criteria. Although this is important, industry is looking for students who can "think outside of the box," that is, be creative. But how do you teach students to explore and be creative? How do you show students that there are many solutions, and the first one is not always the best? Course work is needed to develop the students' creative abilities.

A proven method for developing creativity is to exercise what is commonly referred to as the "right side" or visual and spatial side, of the brain. Tom West's book, "The Mind's Eye" [25], cites many examples of Nobel Prize winners who give credit to visual thinking for enabling them to make discoveries. Visual thinking is not an alternative to the analytical and verbal modes of thought, but a complementary method.

To foster creative problem solving, engineering schools should offer formal courses in sketching and drawing in support of design projects. Sketching and drawing cause a shift in thinking that seems to stimulate the mind to creativity. Kathryn Moore [26] suggests that we use drawing imaginatively, as Leonardo da Vinci proposes, "as a way of enhancing and arousing the mind to various inventions." The art field uses this approach in educating students.

In the 1960s, Robert H. McKim developed a popular and successful course at Stanford that incorporated this approach in support of design. His book, "Experiences in Visual Thinking" [27], and the course's success are evidence of the value of visual thinking. Stanford's present day course, entitled Ambidextrous Thinking, course number ME313, is a successor to this course. The course description cites it as having a "focus on right mode or visual, spatial, kinesthetic, and intuitive skills that will foster a balanced or whole-person approach to problem solving."

A recent study [28] using a Thinking Styles Assessment instrument on engineering students showed that the students and the staff had a strong preference for visual thinking. Such research makes a case for fundamentally rethinking and revising our educational system to include visual literacy to balance our overdependence on analytical approaches.

Picturing to learn

Some science and engineering faculty feel that learning happens when a person draws or creates an image. Felice Frankel, Massachusetts Institute of Technology, has devoted years to aspects of imagery for learning science. She describes how drawings and other means of visual communication help students to understand scientific concepts [29]. A student's drawing tells the teacher whether the student's thinking is correct. At the same time, the process of creating the drawing, including making mistakes, clarifies the idea for the student who is making the drawing. Figure 2 shows frames from a student's storyboard.

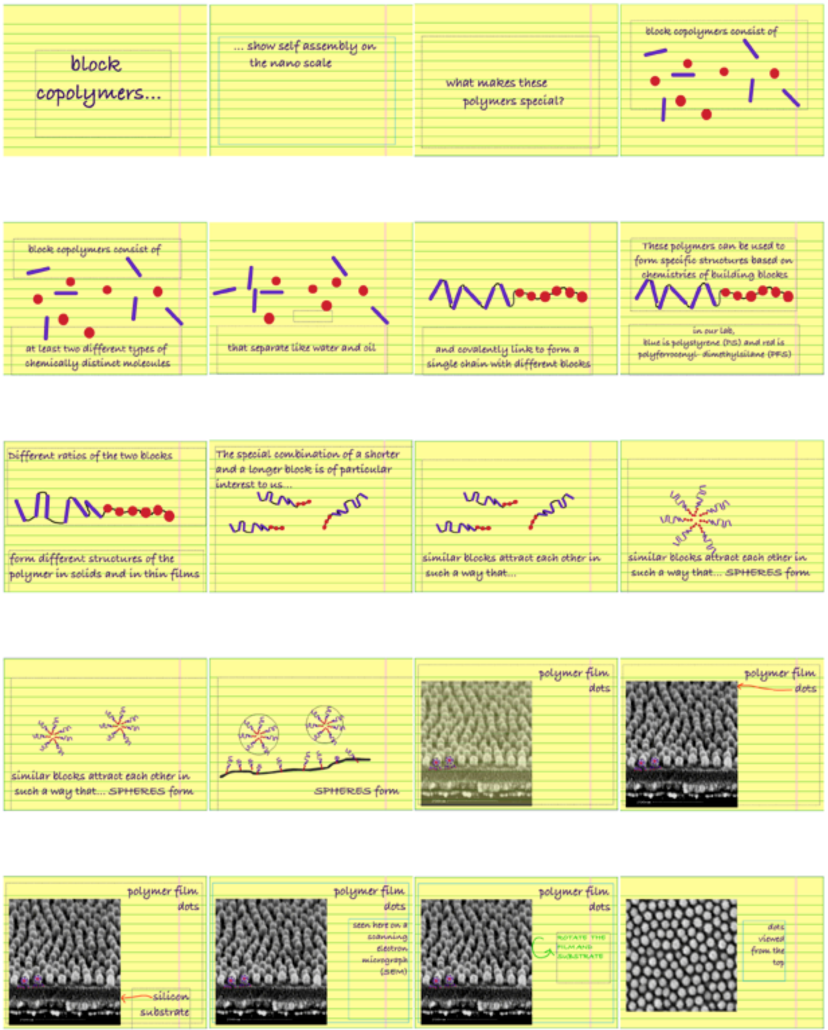


Figure 2. Frames from an animation illustrating block copolymers by Marianna Shnayderman, an undergraduate student at MIT. Courtesy of Felice Frankel.

In her U. S. National Science Foundation-funded project, "Picturing to Learn: Making Visual Representations by and for Undergraduates – A New Approach to Teach Science and Engineering," Professor Frankel is developing and testing her approach to teaching science and engineering in three courses The study and its results should be very interesting.

Felice Frankel also organized two major national events on the topic of images and meaning, one in 2001 at Massachusetts Institute of Technology (MIT) and the second in 2005 at the Getty Museum, Los Angeles, as part of the Envisioning Science Project in the School of Science at MIT. A description of this initiative and the programs states that the Image and Meaning events are intended to "help scientists, writers, and visual communicators develop and share improved methods of communicating scientific concepts and technical information through images and visual representations linked to appropriate text" [30].

Image effectiveness

Images can be effective for learning, or they can be irrelevant, or even misleading. By understanding what makes one image more effective than another, we can examine images critically and apply design principles to the creation process.

An early method of implementing scientific visualization, accredited to Tom DeFanti, University of Illinois at Chicago, described the level of polish needed for a visualization in terms of personal, peer, and presentation, depending on the intended audience. For example, a student engineer designing a new car might make a few quick sketches and a wire frame model for her own understanding. This is personal visualization – only the designer needs to understand the visual. To present these ideas to the instructor or classmates, the student makes a simple 3-D model that can be rotated and viewed from different viewpoints. This is peer visualization – the designer's engineering peers need to understand the visual. Finally, if the student is a working engineer who wants to sell the idea of her car to company management or the buying public, she would add color, lighting, and highlights to show off the car's best features. She might add some people to show scale and animate the car. This is presentation graphics –to explain or sell a scientific idea to people in other fields.

James Foley, Professor at Georgia Tech, suggests that the biggest grand challenge in computer graphics research is determining how we know when an image is “good enough.” How realistic must an image be? According to Foley, one way to measure “good enough” is to look at the results of the image used in a given application. It is good enough if it produces the desired effect. For example, if a virtual reality simulation for helping overcome phobias like fear of flying or fear of heights works, we know it was “good enough.” However, we often have no way to measure this quality.

Sometimes we must simplify scientific images for maximal understanding. Drew Berry, of the Walter and Eliza Hall Institute of Medical Research, Melbourne, Australia, develops animations representing the science of biomedical discovery [31]. These animations are founded on scientific accuracy but simplified to enable understanding and learning, and many of them are used on public television. Equally important, the imagery is high quality and visually engaging. Berry’s biggest area of focus is determining the amount of detail required to communicate the science visually. Some internal rules that he follows in the creation of these animations are:

1. Each animation communicates only one message or concept. Any extra environmental detail must not be distracting or confusing.
2. Follow film's tradition and grammar. These have developed over many years and include rules of framing, lighting, camera technique, and colour.
3. Images must include a lot of scientific detail, such as the molecular surface of a stem cell.

Figure 3 illustrates one of Drew Berry's biomedical science animations.

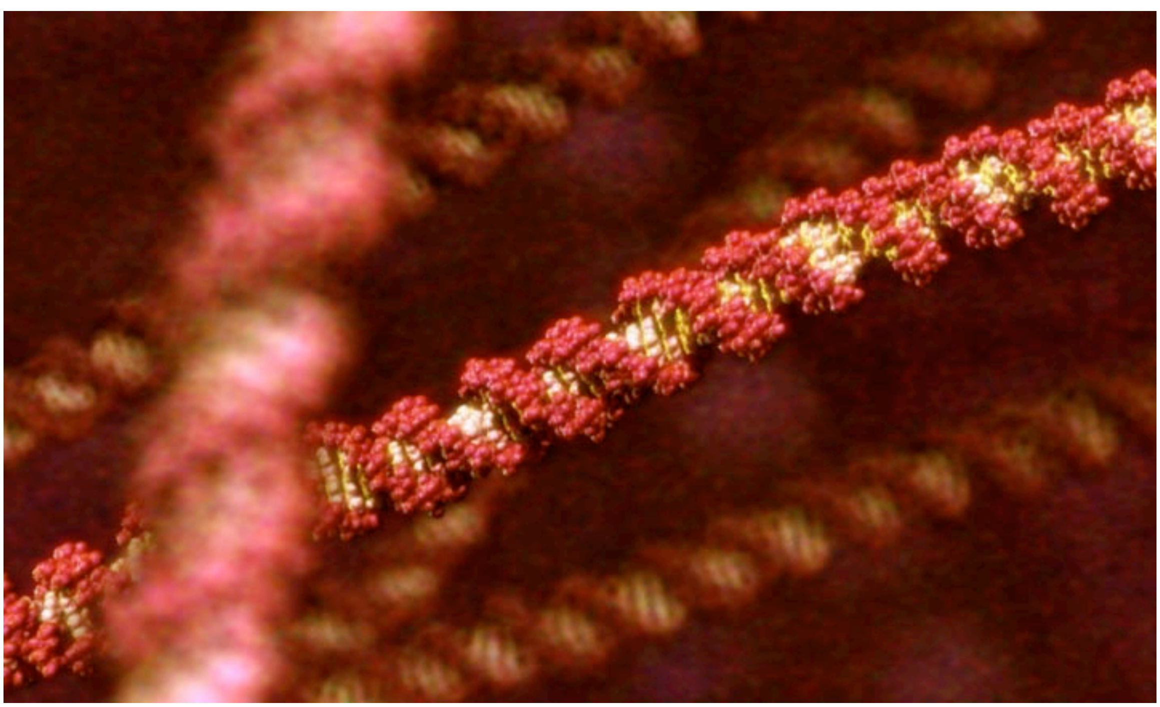
Strategies and implementations

Different sizes, levels, and types of educational institutions exist, as do different cultures. So, the nature of a course varies among countries and educational institutions. It probably is not feasible to put skills for visual learning in a required general education class. Consequently, traditional curricular approaches are to:

- make an existing visual learning elective course into a required course,
- modify an existing course to include visual content,
- create a new required course, or
- create a new elective course

Courses need not be credit-bearing. A student’s goal may be to acquire competency rather than complete graduation requirements.

Figure 3. A frame from an educational animation of DNA, courtesy of Drew Berry.



Educators have implemented various successful approaches using visual learning strategies and technologies, as described in the following sections.

Visual Scholars Program

In 1975, The University of Iowa College of Education established a Visual Scholars Program through a grant from Eastman Kodak. The goal of this program was to determine if there was such a thing as "visual literacy." The charge was to prove that students learn via a visual language. Participating students came to the program from a variety of disciplines, and each had a mentor in his or her own discipline. Students were to develop and demonstrate competence in the following:

1. visual perception
2. human learning and development
3. visual communication
4. visual technology as a research tool

Several students graduated successfully from this program, but few colleges or universities had programs teaching visual literacy, so graduates found positions in other fields. The University of Iowa did not continue the program after the funding ended.

Associate Professor Emeritus Lida Cochran, one of the program's co-founders, cites the speed of current technology as one of the most important changes in allowing academics to teach using visual materials. The amount of time it took for faculty to prepare visuals for classroom use 25 to 30 years ago was inhibiting, but this task takes a reasonable amount of time now. Just as researchers have accepted visualization as an important aspect of the research process, faculty are beginning to understand the use of visual techniques in teaching and are now able to apply them.

Digital entertainment courses

There is a growing demand for computer science students to learn techniques for digital entertainment. The global games industry alone is expected to have a value of $52 billion by 2007, up from $33.2 billion in 2003 [32]. Xubo Yang, Shanghai Jiao Tong University, China, teaches a digital entertainment education program that aims to build the knowledge and skills that digital animation and computer games developers need. Such computer science classes have become more common as the game industry has grown.

Visual learning technologies programme

Some universities are expanding visual techniques coursework into entire programmes, such as the Visual Learning Technologies programme at the University of Coimbra, Portugal. This was started by Professor José Teixeira in 2003, following the Campfire on Visual Learning in Snowbird, Utah. The programme is technologically oriented, with a strong scientific component, and does not compete with art or design courses. Its goal is to teach students to be productive in modelling, visualisation, and visual information acquisition and processing. It will be a four-year program organized around four scientific areas: mathematics, computer science, computer graphics and image processing, and design. Visual thinking and visual communication are essential for generating and processing geometric models and digital visual information.

Visual thinking course

Brown University offers a course called Visual Thinking/Visual Computing that aims to help students create, use, and understand computer-generated images [33]. The goal is for students to be able to create effective visual materials and to understand how image meaning can be created as well as how it can be interpreted. This multidisciplinary class combines concepts from cultural studies, cognitive science, computer science, art, and design. It makes use of the Graphics Teaching Tool (GTT), a Java-based image-creation environment developed at Brown University for non-computer science majors, and Exploratories, Java applets developed at Brown University for teaching technical topics in computer science. Both the GTT and the Exploratories can be found at the web site above and downloaded. The course was developed by Ann Spalter and Andy van Dam.

Visuals as a check on other processes

Visuals can inform students as to whether or not they have solved a problem correctly. Clemson University has a unique approach to teaching computer science concepts through the use of a problem-based, computer graphics approach. Τεχνι (pronounced "techni"), the name of this course, is the Greek word for art and shares its root with the Greek word for technology. Clemson established a graduate degree program in 1999, the Master of Fine Arts in Digital

Production Arts (DPA), that bridges arts and sciences. The goal of Τεχνι is a redesign of the B.A. program in computer science that incorporates DPA and computer graphics research results into all required computing courses.

A trial course in the new program, Tools and Techniques for Software Development, has been completed. This course focuses on programming methodology and is taught through the large-scale problem of constructing a ray-tracing system to render synthetic images. Students can tell immediately if the image is accurate and can easily correct their mistakes because the image points back to the underlying problem. Both correct images and mistakes facilitate learning. According to Tim Davis, Assistant Professor of Computer Science at Clemson University, the course results in students:

- showing increased motivation, working far beyond the course's requirements.
- engaging in projects more effectively, as evidenced by their work and evaluations; and
- stating they were excited about the class.

The course organizers hope this type of class will draw more women and minorities, as has been the case in the DPA program in which about 30% of the students are women and 15% are African American. Figure 4 is an example of student work from this course.

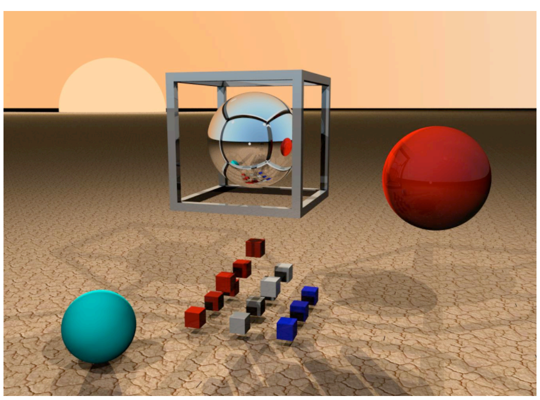


Figure 4. Produced by Scott Duckworth, a sophomore student at Clemson University. Courtesy of Scott Duckworth and Tim Davis.

Studio Courses

Studio courses focus on student activities rather than lectures or traditional laboratories and are examples of active learning in the sciences. In studio courses, the instructor might give a short demonstration or discussion to set up the day. The students then work individually or in small groups, with the instructor answering questions or giving advice as needed. This emphasis on student activities puts students more in control of their learning. The course activities can also include critiques of student work by the instructor or other students.

Studio classes can be organized in several ways. In the sciences, courses usually involve active exploratory work. In the "Studio Physics" model, students use computation and visualization tools in their explorations. For example, MIT's Electricity and Magnetism course, developed by John Belcher uses Technology Enabled Active Learning (TEAL) [34]. The course is taught in a room with tables set up for three groups of three students, each group having one computer to work with. Many of the explorations for the course use visualizations that are quite compelling [35]. Figure 5 shows one image from a course activity that is part of a desktop experiment in electrostatic forces.

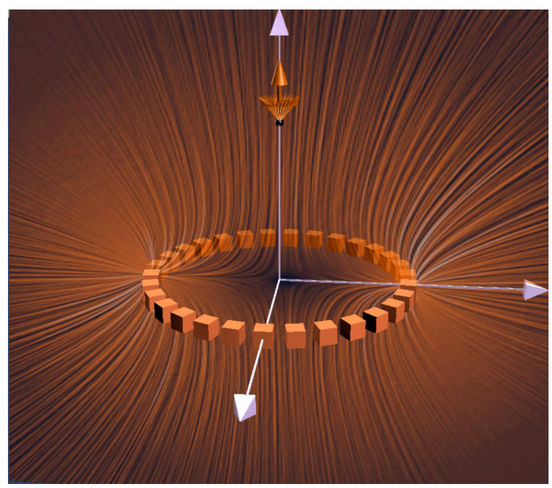


Figure 5: An electrostatic field that has a ring of charges, with forces on a moving particle above the ring. Courtesy of John Belcher.

At Rochester Institute of Technology, Marla Schweppe has developed a more traditional studio-based class for teaching visualization to science and engineering students. This "Visualization in Science and Engineering," course uses a set of modules so instructors can adapt it to various situations. Science and engineering students and professionals must be able to communicate with images and animations, because, as Professor Schweppe notes, "words are not enough." The ability to communicate about the images and to distinguish between good and bad representations of information is critical. The class emphasizes the more basic design principles, but it takes most examples from science; and basic drawing techniques relate specifically to communicating ideas about science and engineering. This differs from traditional life drawing courses in art and design. In this critique-based class, students discuss how well (how accurately and clearly) the design communicates the intended content, rather than whether it is good art. Not only do students learn to analyze how well information is communicated, they learn not to be offended by criticism of their work. Questions from the visualization's audience indicate how well viewers understood its content. Figure 6 illustrates student work in this course by James Hauenstein.

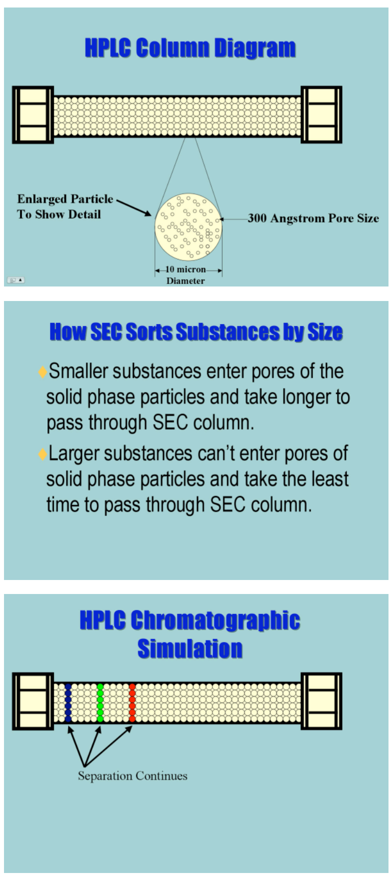


Figure 6: Three frames from a PowerPoint presentation by James Hauenstein. Courtesy of James Hauenstein.

Visual approaches to programming

Some educators are introducing strongly visual approaches to programming courses in computer science. Several computer science faculty, such as Steve Cooper at St. Joseph's College and Wanda Dann at Ithaca College, use the Alice programming environment in their beginning programming courses [36]. In this environment, students use standard programming constructs to control the behaviors of virtual humans in a 3D space. This puts the student in a familiar environment and makes programming a human process, rather than an abstract process.

Mark Guzdial at Georgia Tech has developed a "Media Computation" course for students who are not computer science majors. In this course, students use standard programming techniques in the Python language to manipulate image, video, and sound data. The Python language is relatively easy to use, and it is exciting for the students to write programs using media data to achieve familiar media goals.

For both of these courses, visual content is critical to keeping students excited about their work and improving their success. Also, each course aims to interest students in computing enough that they will choose computing as a career goal. An increasing number of women are taking and completing these beginning computer science courses.

Visuals in Computer Graphics and Geometric Modeling

Co-ordinate transformation in 3D space is one of the main tasks in both computer graphics and geometric modeling. Understanding the rather simple formal background of transformations is generally not a problem for advanced students of Computing Science who have obtained a thorough mathematical foundation during their first semesters as undergraduates. However, it is often difficult for them to imagine or anticipate the result of a series of transformations. This is particularly true when rotations in combination with translations, or rotations about arbitrary axes are involved. Good imaginative abilities are also required when it comes to mastering illumination and colors, the effects of reflection and refraction, and the application of textures. Again, the basic concepts of simple shading algorithms or even ray tracing and radiosity can usually be well understood, but skills beyond pure mathematics are needed for the proper use of these techniques.

Graphical illustrations and animations form an integral part of the presentations in the introductory Computer Graphics course within Computing Science education at the University of Hamburg, as is certainly true for most Computer Graphics curricula. To complement these lectures, and allow the students to practise and enhance their imaginative skills, an optional lab assignment is also offered.

Working in teams of three, the students create animated sequences using POV-Ray for photorealistic rendering of the individual frames, and the constructive solid geometry (CSG) modeler contained within POV-Ray to model the objects of the scenes. They may freely choose the topics for their movies. At least one of the objects should feature moving extremities, and digital pictures are to be used as textures. As a scene description language, POV-Ray may be rather clumsy, but students of Computing Science can be expected to handle it well. Its advantage lies in the fact that they are obliged to formulate every CSG modeling step and every detail in their scene descriptions explicitly, thus proving that they understand the underlying concepts and mathematics.

At the end of the semester students submit a CD containing the completed movie, the POV-Ray script, and written documentation of their work. The movies are presented to the entire group of students who attended the course, and they act together as jury to assess the submissions. Figure 7 is an example of this work.

The creativity involved with this task and the immediate visual feedback result in very high motivation, even enthusiasm. This course also attracts students who take Computing Science as a minor field of study, although their mathematical background is not always as firm as that of the Computing Science students. Students are generally very excited about this course, so much that some of those students who are not required to carry out the assigned task do it anyway, and with very good results. With the addition of soundtracks and other effects, most of the submitted movies exceed the requirements.

Immersing students in an active learning experience

Immersion is an effective learning tool in Xie Cui's Maritime Visualization class at Dalian Maritime University, China, mentioned earlier. In a program funded by China's Ministry of Transportation, graduate students built a very sophisticated ship command simulation. The simulation includes a ship's bridge, engine, radar, and charts, as shown in Figure 8. Students learn to command a ship with the simulation program, which lets them plot routes and avoid other ships. The simulation includes a 3D rendered forward view showing 240 degrees in real-time (with several levels of detail), and 3D audio of ocean waves and the ship's engine sounds. Three to five people are required to operate the ship, and five simulated ships can run on the same ocean area.

Figure 7. "The AntHropoid," frame from a movie of an ant playing basketball, by Peer Stelldinger, graduate student at the University of Hamburg, Germany.

This class puts students in active control of the simulated ships and provides them a realistic learning environment that combines visual learning, collaborative learning, and virtual environment strategies to enhance navigation training. The main objective of navigation training is for students to master both navigation theory and technology. They must fully understand the scientific concepts of ship maneuvering, that can only be learned through personal experience. The collaborative learning environment consists of a portable desktop system and a larger, fully immersive system. This educational model is learner-centered, with the integrated and collaborative environment offering a variety of learning strategies and resources.

Learning results showed that students were actively engaged by the interactive visual learning experience and gained a good knowledge of navigation theory and technology.

The educators at Dalian Maritime University feel that visual learning, with particular connections to collaborative learning methodologies and virtual environments, is crucial to the future of learning.

Figure 8. An image of the view from the ship's bridge in the virtual environment. Courtesy of Xie Cui.

Continuing Education: HIV/AIDS Virtual Environment

Sarah Brown, a student pf Edwin Black at University of Cape Town, South Africa, created this virtual environment (VE) as a teaching tool for people living with HIV or AIDS. It is modelled on a typical South African home and contains four virtual actors. It begins with three of the actors meeting in a casual support group to discuss their HIV experiences. This short scene is observed and listened to by the user, and it provides some social support. Then the user can explore the kitchen with the fourth actor and learn about AIDS-related issues such as nutrition, vitamins, food safety, and hygiene. This VE is displayed on a typical desktop computer using the mouse for directional control and minimal keyboard usage, such as one key for virtual walking. The low keyboard usage and visuals are necessary due to the low level of literacy in South African communities. This particular VE is especially timely because of the high incidence of HIV/AIDS in South Africa. In figure 9, you see the actor "Sandi" explaining the concepts of food groups and vitamins as the user explores.

Student control of the visual environment

Letting students control and simplify the scientific image can help them to understand the science better. For example, Ruwei Yun, Educational Technology Department, News and Communications College, Nanjing Normal University, China, seeks to simplify the teaching of relative motion in physics classes. This subject is difficult to teach because, when observing moving objects, people can unconsciously include nearby objects that are relatively static (such as roads, trees, and houses) as reference objects. Thus, they don't clarify the relation between the two moving objects of interest.

Figure 9. A scene from the HIV/AIDS educational virtual environment.

Using the virtual reality modeling language (VRML) software and the internet, Professor Yun has developed an internet-based virtual physics lab that students can access and use to communicate with each other while they're working. This virtual world and "virtual process" shows how objects move relative to each other in a way that we can't see in the real world. To learn relative motion, students must be able to change the viewpoint from which they are observing the object. Yun's system also lets them conceal the surrounding objects that interfere with perception.

For example, a spinning top with a horizontal axis moves when it is on the North Pole, as shown in Figure 10. Without letting them first see the visualizations, the instructor asks students two questions:

1.) If you are viewing from straight over the North Pole, how are the top and the earth moving?
2.) If you are viewing from a given point on the earth's surface near the North Pole, how are the top and the earth moving?

A few students answered the first question correctly, but none answered the second question correctly. The instructor then asked them to use the VRML visualization. After viewing and controlling the simulation, all of the students answered the first question correctly, and 80 percent answered the second question correctly.

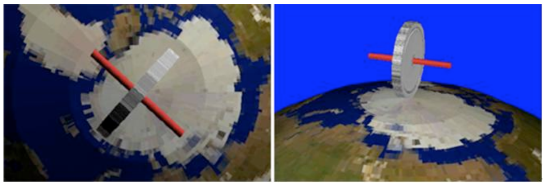


Figure 10. Views of an experiment using an image of a top and the earth. On the left, the top and earth are observed from a point directly above the North Pole. On the right, the top and earth are observed from a point on the earth near the North Pole, Courtesy of Ruwei Yun.

Understanding advanced geometry
Dr. Daina Taimina, mathematics researcher at Cornell University, uses everyday objects to explain mathematical theory. However, mathematics faculty have often found it difficult to find appropriate models to help students visualize hyperbolic space, and Dr. Taimina has found a unique way to visualize this kind of geometry [37, 38]. This advanced geometry has a constant negative curvature, as opposed to a ball that has constant positive curvature, or a flat surface that has zero curvature. William Thurston, now a professor at Cornell, first came up with the idea of using annuli (parts of rings having the same radii) to make a paper hyperbolic plane model. Dr. Taimina's husband, David Henderson, also teaches hyperbolic geometry at Cornell University, and although he created models from paper and tape as early as the 1970s, these models were too fragile to be useful for student exploration. Dr. Taimina creatively determined how to crochet the models, and they are used every year in Cornell math classes. Figure 11 shows one of the crocheted

Figure 11. A crocheted model of Hyperbolic Geometry created by Dr. Daina Taimina. An important factor in making these models mathematically correct is that they must be crocheted very tightly.

models. Although the different colors have no scientific or numeric meaning, having different colors helps the viewer see the curvatures.

Although no learning studies have been done, students say that they enjoy the models, and most students say that the models are helpful in understanding hyperbolic geometry.

Integrated learning experience
A group of participants at the 2002 Campfire on Visual Learning for Science and Engineering concluded, "To tap into the emotional learning systems, we must engage as many of the senses as possible." Jacquelyn Ford Morie, Associate Director of Creative Development at the University of Southern California's Institute for Creative Technologies (ICT) notes the increased importance of visual learning for understanding complex scientific and engineering concepts, with vision comprising much of the information received. However, this center's research looks at effective combinations of visual, auditory and other sensory functions to provide an integrated learning experience, taking advantage of the natural connectivity of the brain

The same part of the brain controls both emotional meaning and motivation, and scientists conjecture that these mental processes are closely related. The ICT prototype environment uses emotional cues within the participant's experience to increase retention of specific elements in the training situation. It blends sights, sounds, and visceral frequencies (infrasound) to present the information to be learned and to create emotional catalysts. The project's goal is longer-lasting memories of the experience. Its hypothesis is that emotional connectivity and holistic involvement through multiple-sensory stimulation significantly enhance the learning experience.

Conclusions
From these workshops and discussions with science and engineering educators, we have found some common views, as well as areas where more work is needed. We draw some conclusions from our discussions and classes.

Conclusion 1. Students need to create their own visuals for understanding and learning. All science and engineering students should have some exposure to creating visualizations. All science programs should include a firm grounding in visual theory and practice.

Conclusion 2. Technology advances and cost decreases have opened up new possibilities for visual learning. Technology now allows us to create and demonstrate images and animations easily. Visualization equipment (hardware and software) costs have dropped to where they are affordable for classroom use.

Conclusion 3. Engineering education must be fundamentally revised to include visual thinking throughout the curriculum. Drawing and sketching are important techniques to accomplish this and should be included in the student's experience.

Conclusion 4. We can build new "languages," or symbol systems, of visual communication. A visual language can communicate most effectively in some situations, just as verbal, mathematical, or musical "languages" communicate effectively in other situations.

Conclusion 5. Visual thinking is needed in order to create the collaborative learning methodologies and enhance the distance learning environments that are crucial to the future of learning.

Conclusion 6. Visuals must often be considered in context with text and other resources.

Future Directions

Our experiences have illuminated additional work needed to accomplish our goals. We encourage NSF and other funding agencies to support this continuing work towards better understanding and effective learning through the use of images and animations.

1. Visual thinking is crucial to the future of learning, with particular connections to collaborative learning methodologies, distance learning, and virtual learning environments. We need to find ways to articulate and interpret the nuances of visual worlds.

2. We need to collaborate across disciplines to articulate this visual methodology.

3. We need to perform more studies that assess the value of visual learning, including studies of how to assess visual learning itself. Can we assess visual learning accurately through traditional oral and written exams?

4. We need to be able to show academics that the use of imagery for teaching science and engineering is a respectable approach. In order for academics to embrace visual learning techniques, we must show the importance of this approach to learning.

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This work was supported by National Science Foundation under the grant DUE-0407830. All opinions, findings, conclusions and recommendations in any material resulting from this work are those of the principal investigators, and do not necessarily reflect the views of the National Science Foundation.

Parts of this White Paper appeared in *IEEE Computer Graphics and Applications*, Volume 25, No. 5, pp. 56-63 and were presented in the Eurographics 2005 Educators Programme.

Judith R. Brown's recent work has been in visualization, virtual reality, collaboration, and education. Retired from University of Iowa, she is ACM SIGGRAPH Past President, and a member of Eurographics Education Board, Academic Committee of the State Key Lab of CAD and Computer Graphics in China, and International Advisory Committee for the National Visualization Center in São Paulo, Brazil.

Michael B. McGrath is retired form the Colorado School of Mines, where he was a professor in the Engineering Department. He has a PhD in applied mechanics from the University of Colorado. He is a past Director for Education of ACM SIGGRAPH and a member of the International Federation for Information Processing, Technical Committee 5 Executive Committee.