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Introducing Molecular Visualization to Primary Schools in California: The STArt! *teaching* Science Through Art Program

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Our society is increasingly dependent on science and technology. Despite this reliance, there has been a decline in science proficiency in the United States since the 1960s *(1, 2)*. The state of California is a particularly striking example. In the 1960s California was at the forefront of American education. By the year 2000, the state's science scores were at the bottom of the national list *(3–5)*. The national emphasis on reading and math scores is commendable, but is often at the expense of subjects such as science and art.

Substandard science education is not just an academic problem. California's economy depends heavily on foreign workers to staff positions in fields ranging from the high-tech and animation industries, to teaching and nursing *(6)*. Many private companies and public facilities are concerned about replacing their technical workforce once current employees retire. The quality of basic services, from oil refinery to water treatment, may be affected. These so-called "gold collar" jobs are well-paying, and few of today's young people are ready to move into them. Additionally, today's health care depends on patients' taking a more active role in nutrition, prevention, and treatment. This is difficult, however, without a minimal understanding of the underlying biomedicine. Furthermore, nonscientists regularly make decisions in grocery stores, jury boxes, and voting booths concerning genetically modified foods, DNA fingerprinting, and cloning. In short, science literacy has become an essential component of modern life.

In response to this crisis, California revised its *Science Content Standards* in 2000 to introduce fundamental concepts at earlier grades. To take on this ambitious challenge, it adopted a "spiral approach". For example, physical science concepts such as atoms and the periodic table are first introduced in third grade, and again in fifth and eighth grades,

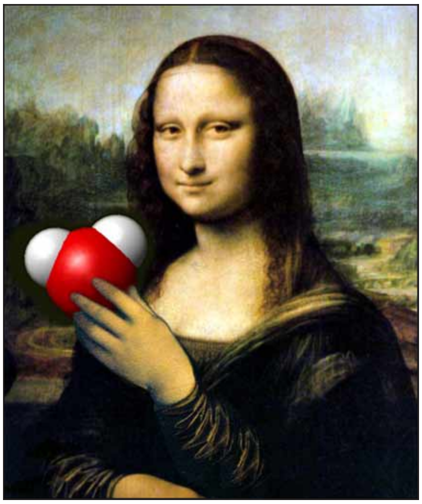

Figure 1. The STArt! logo pays tribute to Leonardo da Vinci, a scientist and an artist who "visualized" concepts and processes in his notebooks (2001 © S. M. Halpine).

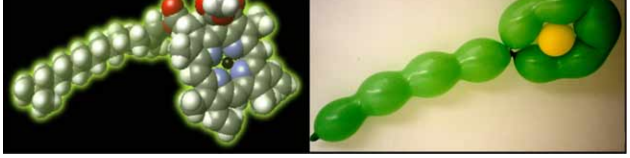

Figure 2. Models of chlorophyll molecules: (A) digital model of chlorophyll A, rendered using WebLab Viewer Lite software and (B) balloon model of chlorophyll molecule. The model is simplified to clearly define the ring with the central magnesium ion and tail structures (2001 © S. M. Halpine).

instead of in high school as the national standards recommend. This places the burden on primary school teachers, who might be very good at teaching reading and math but often lack training in science *(1, 2)*.

The STArt! *teaching* Science Through Art program was developed to help both students and teachers address the new California Science Content Standards *(7)* (Figure 1). The program began in 2001 with demonstration classes at Tulita School in Redondo Beach. In 2002, the City of Los Angeles Cultural Affairs Department funded a pilot program at the Coeur d'Alene Avenue Elementary School in Venice. This public school reflects the city's rich diversity: 35% European–American, 35% Latino, 20% African–American, and 10% Asian–American and other groups. Additionally, it has one of the highest homeless populations of the city (approximately 15%). If these students could learn about molecules using visualization, the program was likely to succeed elsewhere.

Using an artist-in-residence format, inservice classroom presentations have been developed for grades one through twelve, based on content standards and teacher input. An initial presentation introduces molecular visualization using narrative discussions, handheld models, visualization software, and art workshops (Figure 2). The program emphasizes low-cost materials, and freeware programs such as WebLab Viewer Lite *(8)*. Assessment tests indicate that, on average, 88% of third-grade students give a grade-appropriate description of the term "molecule" after a single one-hour presentation. Most important, boys and girls alike respond with overwhelming enthusiasm. Young students sense they are learning something valuable and important. As one third-grade boy stated, "So that's what H-2-O means!"

The Potential of Computers: Molecular Visualization

The development of high-performance computing and communication is creating a new media...

–Chris Dede, Harvard Graduate School of Education *(9)*

The computer's multimedia capabilities now comprise a unique synthesis of text, sound, motion-graphics, and interactivity. Computer literacy relies on spatial abilities and visual-motor skills as much as language proficiency, a boon to visual and tactile learners *(10)*. A powerful example of educational technology is molecular visualization software, which allows users to display and manipulate molecular models in real time (Figure 2A). Molecular visualization has become indispensable in fields such as biochemistry and cellular biology. The visual aspects are more than simple enhancements: text alone is often inadequate for describing complex molecular reactions such as hormones "docking" on a cell membrane *(11, 12)*.

Educational software was first developed in the 1980s. Yet, according to the National Center for Educational Statistics, multimedia content has not affected science scores nationwide *(3, 13)*. To be effective, educational media must be used in the classroom and must be tied to students' grades. If it is not on the test, students will not study it. It is also difficult to learn in one mode and be tested with another. By definition multimedia cannot be translated to a sheet of paper. Additionally, teachers may not have the time to become familiar with relevant technology *(14, 15)*. The STArt! program addresses this problem by helping teachers integrate appropriate technology. The program adapts to the school's current computer equipment. Software, selected for cost and ease of use, is installed before presentations. Molecular visualization software engages young students and helps them grasp complex concepts, thereby laying the foundation for high school and college chemistry courses.

STArt! Inspiring Concepts

We do not teach the introductory courses appropriately. Right now, we just teach all the basic facts... We should break the pyramid. We should begin with the most exciting ideas in chemistry...

–Shirley Tilghman, Princeton University *(16)*

The primary goal of the STArt! program is to inspire students with amazing conceptual theories. Once students develop an interest and understanding of concepts, they will seek out the requisite "measure and observe" methodology. Young students can begin to integrate the fundamental concepts into their knowledge of their world *(15)* (Figure 3). Similarly, STArt! often sidesteps introductory chemistry's usual inorganic approach to focus on familiar and grade-appropriate bioorganic topics.

Third-Grade Workshops: From Chlorophyll to Fuel-Cells

Several third-grade workshops were developed in response to the science standards as well as teacher requests. These include an initial presentation, "Green Chlorophyll and the Food Chain", that introduces atoms, molecules, and the periodic table using familiar materials with tangible properties. After the workshop, students are conversant in basic chemistry terms. While creating their "solar system t-shirts designs" in a subsequent workshop, for example, students included elements hydrogen and helium in their description of jovian or "gas" planets. In a workshop on "Hydrogen Fuel-Cell Cars" students discussed the basic workings of a fuel cell and then designed their own "car of the future" (Figure 4). The vehicle designs, including "flyers", submarines, and dolphin-mobiles, were exhibited at the Venice Branch Library. In response to the exhibit the Los Angeles Deputy Mayor of Transportation, Brian Williams, sent the Honda FCX on loan to the city to Coeur d'Alene School's assembly. The entire school community was able to experience the latest in vehicle technology.

Each workshop begins with narrative discussion involving the students, handheld models, and art workshops. Computer lab is also included in the introductory workshop, and accessed for digital art projects like "solar system t-shirts designs".

Figure 3. Many young students quickly integrate the concepts of atoms and molecules into their understanding of the world around them. This third-grade student drew a deer drinking from a river and indicated, "each drop of water has billions of molecules".

Figure 4. During a third-grade workshop on hydrogen fuel cells, students designed future vehicle concepts, including "The H2O Car".

Narrative Discussion

New concepts are introduced using narrative tools such as analogy and metaphor, and comparison and contrast *(15).* Group discussions also assess prior knowledge and understanding. The introductory presentation addresses third-grade standards such as: "All matter is made up of small particles called atoms, too small to see with the eyes"; the periodic table; basic color perception; and energy conversion and storage. Additionally, Art Standards require that students integrate visual arts with other subject areas *(17).* Topics based on the physical science standards are related to the students' day-to-day experiences. In the workshop, the color green is used to connect art and color perception, as well as chlorophyll and its importance in the food web.

At the end of the workshop, an assortment of library science books are presented. Books help answer the students' many questions, address alternate learning styles, and tie in with Language Arts projects. Some students have subsequently incorporated chlorophyll molecules into their writing assignments. Questions during the discussion can also serve as the basis for scientific-inquiry projects.

Models

A great deal of emphasis is put on understanding the concept of models. This is not difficult, since children often play with dolls or toy vehicles in place of "real" things. Students have little trouble listing dental, architectural, and human models, as well as pointing to globes and geographic models located within the classroom. Models also demonstrate the importance of creativity in science: students are encouraged to explore both submicroscopic atoms and immense planets using their imagination.

A toy car is held up to demonstrate how its shape—or form—affects its function. For example, if the wheels were removed and glued onto the roof of the car, it would still have four wheels but would no longer roll (e.g., structural isomers). Similarly, balloons are fashioned to represent the primary structures on a chlorophyll molecule: the ring structure with a central magnesium ion and the tail (Figure 2B).

Computer Lab

Once molecules are introduced with large handheld models, students recognize structures within digital molecular models. As they explore the chlorophyll model, they answer questions on a worksheet or Molecular "Baseball Card". Using WebLab Viewer's software interface, students first select the entire molecule, then the tail and ring structures, followed by individual atoms. They count the atoms, learn that molecules are composed of atoms, and relate the molecule to familiar objects such as green leaves. Models can be rotated to show structural complexity, and represented in different formats such as "ball-and-stick" or "CPK". Ideally, a class will collect a series of "molecule cards" for several color-, smell-, and taste-producing substances.

Art Workshop

Students illustrate the role of chlorophyll molecule in the food chain during the art workshop, which requires an additional class period. Students paint colorful landscapes and storyboards (Figure 5). For their solar system t-shirts, they researched information and images on the Internet and composed the iron-on printout within Microsoft Word.

Program Assessment and Results

An assessment test is administered before and after the presentation and is deliberately kept simple to not overburden teachers. We ask two basic questions: "Tell me about a molecule. Tell me about a atom or an element. Can you think of examples of each?" Students can answer using words or drawings, a practice borrowed from college-level biochemistry *(18)* (Figure 6). A typical grade-appropriate answer might be: "Molecules are made up of atoms. Molecules make up everything."

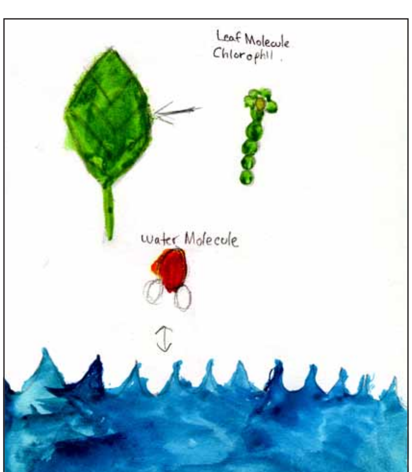

Figure 5. Third-grade students were asked to include references to molecules in their paintings. This student painted molecular models of water and chlorophyll and indicated that they were found in the ocean and in leaves, respectively.

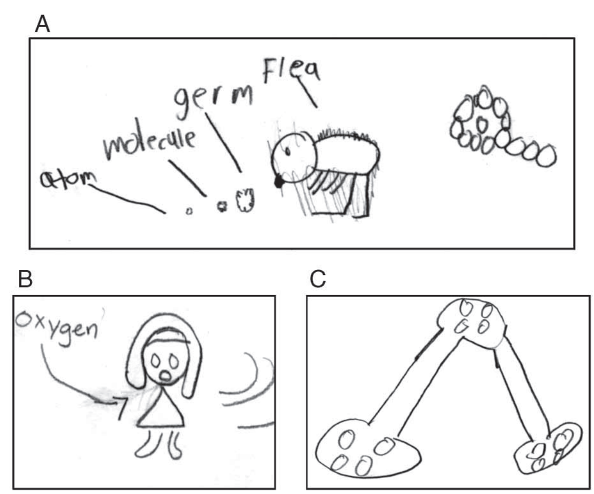

Figure 6. Third-grade students used drawings to describe molecules for post-workshop assessment test: (A) This whimsical drawing shows the relative sizes of an atom, a molecule, a germ, and a flea. A chlorophyll model is also included on the right. (B) Another student illustrated oxygen as a component of the air we breathe. (C) Several students drew "Tinker Toy" models of a water molecule. Tinker Toys were used in the STArt! presentation to demonstrate the formation of H_2O from H_2 and O_2.

Table 1. STArt! Program Assessment: Percent of Correct Answers for Grade-Appropriate Descriptions of the Terms "Molecule" and "Atom"

Grade and School (assessed participants)	Molecule		Atom	
	Pretest (%)	Posttest (%)	Pretest (%)	Posttest (%)
3rd Grade, Average (115)	11	88	6	70
3rd Grade, Coeur d'Alene (59)	11	82	5	68
3rd Grade, Tulita (56)	10	94	6	72
4th Grade, Tulita (51)	34	84	16	70

NOTE: These results do not reflect overall science achievement in classrooms or of schools.

The effectiveness of the STArt! approach is striking. For example, 88% of third-grade students at Tulita and Coeur d'Alene schools combined gave an accurate description of a molecule, compared to only 11% before the one-hour presentation (Table 1). Many students drew molecular models, some showing different styles such as "line" and "ball-and-stick".

Fourth-Grade Pretest Misconceptions

Preliminary results underscore the importance of early introduction of basic chemistry. The science standards had just been released before the 2001 demonstration classes, and both third and fourth-grade students had not yet covered atoms in class. One might expect that fourth-grade students would grasp abstract chemistry concepts at least as well, if not better, than third-grade students. Yet at Tulita School third-grade classes scored higher, on average, than fourth-grade classes. (Fourth-grade workshops were not held at Coeur d'Alene School.) Ninety-four percent of third-grade students gave appropriate answers, up from 10% before the presentation. However, 84% of fourth-grade students gave appropriate answers, compared to 34% before the presentation. There were approximately 60 students at each grade level, three third-grade classes with 20 students each, and two fourth-grade classes with 30 students each.

Most disturbing, many fourth-grade students had serious misconceptions about the terms. On the pretest, most third-grade students simply stated, "I don't know what a molecule is"—an acceptable answer. On the other hand, 34% of fourth-grade students gave correct answers, and about 10% said they had heard about molecules but had not yet learned them in school. Another 10% had formed misconceptions and described molecules as germs, small bugs, or something eating inside them—perhaps confusing the term with "microbes". Students even drew pictures of the molecule as germ–bugs (Figure 7). One student said a molecule was "maybe a mouse exercising", possibly an indirect association with a lab rat. Elements were described as "wind, rain, and fire"—perhaps based on the expression "exposed to the elements". Furthermore, most associations were negative. In addition to the examples just mentioned, the atom was often associated with the destructive power of the atomic bomb. Overall, there seemed to be an age-dependent predisposition for understanding: if no definition is available, the student generates one.

The lower impact and assessment scores (10 → 94% for 3rd grade versus 34 → 84% for 4th grade) may reflect fourth-grade students struggling to overcome established misconceptions. These results may indicate systemic problems: if most students are taught about atoms and molecules in high school, teachers may be battling five years of negative misconceptions about basic chemistry terms. These preliminary results indicate that third grade may indeed be the appropriate time to introduce basic chemistry, as the California Science Standards suggest.

Informal Observations: Girls

"I used to not like science but now I do! My favorite part was the computer and knowing the different molecules and atoms..." The enthusiastic responses from girls were extremely encouraging. The STArt! program is designed for students who are curious, but do not learn by the traditional "measure and observe" approach to science. Girls seem to appreciate the narrative format. Additionally, artistic expression may be particularly appealing to girls. One girl spontaneously wrote a poem, called *Science Rocks!*, about her desire to be a scientist (Figure 8). To date, no boys have used poetry to express their scientific ambitions.

STArt! explores everyday experiences such as colors, food, and the human body, and girls seem to respond to this bioorganic approach. For example, during recess, third-grade girls hunted for leaves to rub green chlorophyll stains on paper. One fourth-grade student wrote that she immediately tried an experiment mentioned in the workshop: during lunch she kept chewing on a piece of bread to see if she could detect the sugars breaking down in the starch. Sugar hydrolysis is typically covered in college-level chemistry, but this young student could relate the concept to the physical experience. Overall, there was a sense that girls were delighted to be included in the science club usually dominated by boys.

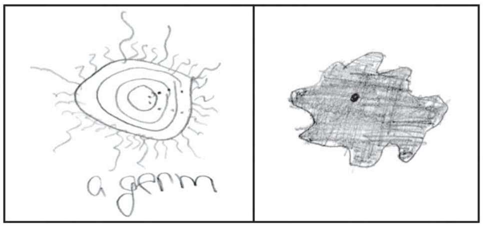

Figure 7. Fourth-grade pretest misconceptions. Students were asked to describe the term "molecule" on the pre-workshop assessment test. Several students drew germ or amoeba-looking "molecules", perhaps confusing the term with "microbes". Most third-grade students, on the other hand, usually responded "I don't know" on the pretest.

"Special Students" with Learning Disabilities

The STArt! program's multimedia approach seems to be effective in reaching students with different learning styles. At the end of one introductory presentation, Billy asked to see a model of "gas" because his father worked in an oil refinery. Not only had Billy grasped the concept of molecules forming materials, but he was relating the concept to his father's occupation. An instructor later told me she was surprised by his in-depth question because Billy is usually considered one of the "special students" with learning disabilities.

Labeling itself may be one problem. Anecdotally, many "science-phobic" adults are in fact very interested in science topics. At some time in their education, however, they were tagged as "not able to learn science", and thereafter avoided the subject.

Positive Teacher Response

The STArt! program is designed as a resource for teachers that want to learn more about science visualization programs within the context of their own classroom curriculum. Teachers demonstrated a range of positive responses. Some teachers gained renewed confidence in their own cross-disciplinary approach to science education. Others were grateful for visualization techniques that convey new material: "I would have done much better in biochemistry if I had seen these digital molecular models." Still other teachers expressed a deep fear of science, often stemming from a negative high school experience. These teachers either tried to avoid certain topics, or "crammed" to cover the material and were glad when it was over. For these teachers, the non-threatening approach to learning science was an eye-opening experience. In every case, teachers learned from the presentations, and often joined the discussions with questions of their own.

Science Rocks!

Science is cool.
Cool for school.
I enjoy learning about science and I hope you do, too.
Enjoy learning while you can.
Never give up on your dreams.
Can always count on learning.
Everybody is good at something and I'm good at science.

Really try hard.
Oh boy! I got an A in science.
Can you make a difference?
Keep trying.
Science Rocks!

Figure 8. The poem, *Science Rocks!*, written by a fourth-grade girl in response to a STArt! presentation on mineralogy, was included in a "thank-you" letter.

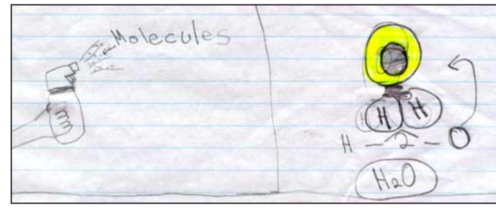

Figure 9. A fourth-grade student drew a model of a water molecule and pointed to a drop of water mist, thereby relating the molecule to a familiar substance and indicating the relative scale.

Encouraging Students' Interest in Science: Wonder, Observe, then Measure

> One of the challenges of schools is to build on children's motivation to explore, succeed, [and] understand...
>
> –From *How People Learn (15)*

The students' extremely positive response to the STArt! workshops was evident in their participation, interest in digital models, and in their artwork. Additionally, some wrote "thank you" letters that included colored drawings (Figure 9). For example, one fourth-grade student wrote, "...You made learning more fun and interesting, because you had all the material for us to actually look at. You also showed a good example on molecules & atoms so it was easier to understand."

If we hope to develop a science literate society we must broaden our teaching methods. We can no longer ignore populations that learn through nontraditional formats. The standard "measure and observe" approach to science is not for everyone. Early exposure to science through visualization motivates independent learning using a child's intrinsic curiosity, integrates science into a student's understanding of world, and may prevent "math–science fear" that begins before adolescence *(19)*.

Education professionals frequently ask the question, "how do we teach students to think visually about science?" The answer seems obvious. Start teaching science through art.

Acknowledgments

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WSupplemental Material

Information about the workshops is available in this issue of *JCE Online*. In addition, figures in this paper are presented in color in the PDF version of this article at *JCE Online.*

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