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Realizing the educational promise of technology

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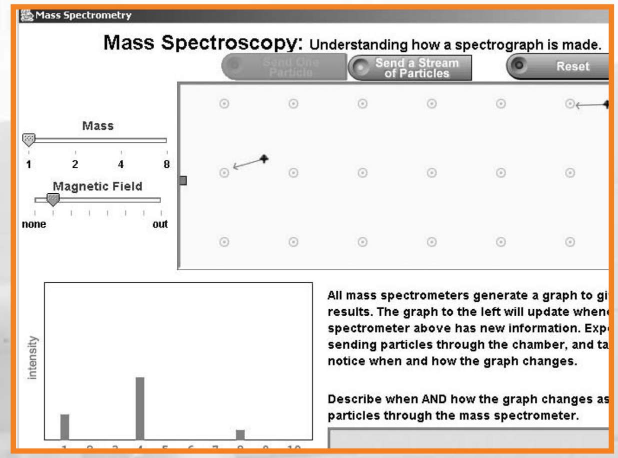
A Tale of Two Revolutions



By Boris Berenfeld, Dan Damelin, Amy Pallant, Barbara Tinker, Robert Tinker and Qian Xie

Two revolutions are on the horizon. Every era seems to be associated with a revolutionary technology that reshapes society. In the process, each technology attracts massive investments, demands new infrastructures, and creates vast new employment opportunities. Each also requires education to focus on new skills and understandings. In the 19th century it was steam and railroads. Then came electricity, the automobile, telephones, airplanes, and chemistry. While in the 20th century digital electronics were ascendant, two coming revolutions – biotechnology and nanotechnology – promise to dominate the 21st century.

Biotechnology and nanotechnology are close cousins. These two revolutions are related across the organic-inorganic divide, operate at the same scale, and are both based on the capacity of molecular machinery to provide the answers to practical challenges. Both revolutions demand that students learn more about the world of molecules and their interactions.

Biotechnology has already become an enormous enterprise. Where only several decades ago, just a handful of companies were based on this technology, now at least 1,500 firms are employing drug-related researchers. In fact, the number of employees doubled between 1993 and 1999, rising to 115,000 (see note 1). Work in this sector promises to deliver more and better food crops for the poor, more effective and economic medicine, and improved detection of disease.

Nanotechnology has the potential of becoming as important as biotechnology. The field focuses on making tiny, useful things that are as large as a tenth of a micron (100 nanometers) or as small as ten Angstroms (one nanometer, or roughly ten carbon atoms). Understanding the behavior of atoms and molecules on the nano-scale allows the creation of materials and devices from the "bottom up" by placing the right atoms in the right places.

To illustrate how nanotechnology differs from today's manufacturing, Dr. Ralph C. Merkle, one of the pioneers of nanotechnology, explains: "Casting, grinding, milling and even lithography move atoms in great thun-

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A researcher and student use a mass spectrometer. With the Molecular Workbench modeling software, which simulates atomic-scale interactions, students can practice a simulated laboratory procedure, such as mass spectroscopy.

Perspective

Technology to the Rescue

Robert Tinker

Nationwide, student achievement in technical fields – mathematics, science, and technology – is unacceptably low, highly inequitable, and headed downward. Scores of students in the class of 2003 on the ACT test provide the latest indications of the problem. Only a quarter of students taking the test reach a level that predicts a satisfactory grade in college science, and this figure is down from previous years. The scores for under-represented minorities are unacceptable, with only one in twenty African-Americans reaching this level. Only college-bound students take these tests, so national averages are certain to paint a more depressing picture.

Educational technologies are part of the solution

Although technologies are increasingly available in schools, mathematics, science, and technical (MST) educators make insufficient use of technology, one of one of the few new resources at their disposal. Information and computer technologies (ICT) should be an integral part of MST teaching. Better use of ICT is urgently needed because technology can be used to greatly improve learning and it is an essential part of modern science. ICT is called for in teaching standards and numerous reports from government, business, universities, and academics.

Information and computer technologies can help more students achieve and surpass the current goals of MST learning.

Not all uses of ICT are equally important for improving MST learning. Multimedia, drill and practice, Internet searches, and student-generated reports are increasingly commonplace and do have some role in teaching and learning, but these applications skirt the periphery of education. The core of math and science is about investigating, exploring, asking questions, analyzing, and thinking – activities that ICT is uniquely able to facilitate and deepen. ICT can enhance this kind of learning through student investigations of real events with probes, investigations of highly interactive models, electronic communications about investigations, and assessments embedded in learning activities.

Achieving current MST goals

Information and computer technologies can help more students achieve and surpass the current goals of MST learning. To do this, we make extensive use of substitution units that can be used in place of other instructional materials and require about the same amount of classroom time. Teachers can, for example, substitute a unit on phase change based on exploring the Molecular Workbench for a comparable unit taught using traditional approaches. (See "A Tale of Two Revolutions" on page 1.)

Most of the really hard concepts in introductory science can be addressed with substitution units and there is strong evidence that doing so will increase student learning. Our research already has promising data for substitution units for kinematics and dynamics, genetics, physical science, and plate tectonics.

Policy makers rightly require more rigorous data, however. For example, a dean or district superintendent needs to know whether these materials are reliably better than other approaches, whether they will be effective in colleges or schools like their own, using technology and professional development that they can afford. They also need data on a complete range of content, because their decisions might involve technology purchases for an entire course, not for just a unit on one topic. The Education Accelerator that we recently launched is designed to

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The Concord Consortium

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provide applied research data that can answer these policy questions. (See “The Education Accelerator Becomes a Reality” on page 11.)

Transforming MST education

But we need to do more than simply get more students up to the present standards for MST education. The most exciting capacity of ICT goes beyond simply finding better ways to meet current educational goals. Technology can fundamentally change what is taught in introductory science. For instance, linking genetics and biomolecular models might permit a treatment that connects classical to modern genetics in middle school. Similarly, molecular modeling might give beginning students deep intuition for atomic explanations of the states of matter. New tools and models could allow nanotechnology to become a topic in introductory physical science, or genomics to be taught early in biology, or calculus concepts to be taught in physics. These advances would not be just for advanced students, because this kind of learning depends on explorations of the real world and models that any student can undertake. Unlike most MST teaching, these explorations avoid mathematical formalism, a barrier to most students.

This kind of curriculum change is difficult to justify to decision-makers, and extensive data will be required to convince skeptics of the value of making such changes. Any school willing to experiment with these approaches would need to find the courage to go well beyond the current standards. Careful research, of the kind planned by the Education Accelerator, will be needed to document the value of all the changes needed.

Ultimately, the kind of accelerated learning that we expect to document will give rise to a fundamental re-evaluation of the science education standards. Our long-term goal is to generate sufficient data to demonstrate that the science standards could profitably address a few core concepts more thoroughly, downplay the thicket of minor concepts that follow from a deep understanding of the core ideas, be more focused on cause-and-effect relationships, and include far more modern, interdisciplinary content.

As a nation, we are not protecting our technological lead by producing a technically literate population, nor are we training adequate numbers of MST leaders. We are squandering the contributions that could be made by large segments of our population, including women and under-represented minorities. The new capacities for learning that ICT creates could address these challenges by fundamentally changing what is taught and how learning takes place. @

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Interdisciplinary science

An example can help illustrate the possibilities. An introductory interdisciplinary science course could start with our molecular models of atoms (see http://workbench.concord.org). By exploring what happens to two elastic atoms that collide, students will learn about the energy conservation laws and, because the atoms have an attractive van der Waals force, potential energy. Extending this to many atoms gives rise to the idea of temperature, which is simply the average kinetic energy. At low temperatures these atoms condense into a liquid and a crystalline solid, releasing potential energy that can be measured and compared to the attractive forces between atoms. The atomic basis of diffusion, entropy, phase change, latent heats, the distinction between heat and temperature, conduction, crystal structure and faults, evaporative purification, and many other phenomena are immediately obvious and open to exploration.

Similar experiments can be done with molecules that can break apart at sufficiently high temperatures. Experiments with these lead to a deep understanding of chemical reactions, equilibrium, reaction constants, and that mysterious free energy. The atoms in these molecules can be charged, enabling learning experiments with ions, polar molecules, and solvents. Finally, with smart surfaces and some other constructs, molecular biology concepts such as conformation, surface binding, and self-assembly can be subjects of inquiry.

A course with this structure is a blend of physics, chemistry, and biology. It would give students unprecedented ability to understand the fundamental ideas of all three subjects. It could be taught without a single equation to beginning or liberal arts students, or it could be used as the conceptual core of a highly mathematical treatment. By treating topics such as the physical basis of latent heat and giving students rich mental models of sophisticated topics like thermodynamics, such an interdisciplinary course would enable students to learn a few ideas more deeply and be able to apply these ideas to a very wide range of situations. Science would appear less as a miscellaneous collection of facts and more as a coherent set of powerful concepts.

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dering statistical herds. It's like trying to make things out of LEGO blocks with boxing gloves on your hands. Yes, you can push the LEGO blocks into great heaps and pile them up, but you can't really snap them together the way you'd like. Nanotechnology promises to let us inexpensively arrange atoms in most of the ways permitted by physical law, getting essentially every atom in the right place" (see note 2). As we develop better techniques for creating objects this small, there will be many applications, from the ability to manufacture sub-microscopic robots traveling through our body, detecting illnesses and killing viruses, bacteria or cancer cells, to making new generations of super powerful and inexpensive computers that can store all the information of the Library of Congress into a memory the size of a sugar cube!

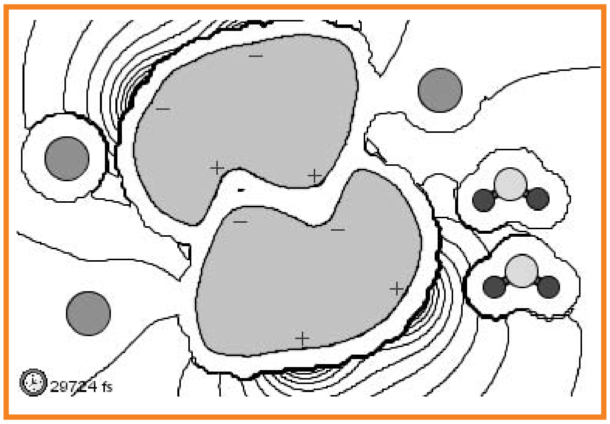

Figure 1. Smart surfaces. This is a model of molecular recognition between polymers. Each bead represents an amino acid. By changing the properties of amino acids, students can alter the effectiveness of the recognition.

Biomimicry

An important strategy in nanotechnology is to learn from biology and to mimic the design of cellular machines. For example, researchers try to mimic the way living cells assemble their protein-based machines one amino acid at a time in the sequence dictated by the genetic code. This "bottom up" manufacturing allows cells to obtain materials of an exact desired shape, using simple principles of self-assembly and help from molecular "chaperones." As scientists understand biology better at the molecular level, they are emboldened to take further, and we hope, careful, steps to make new molecular products.

The challenge to education

William James described the world of a newborn infant as a "blooming, buzzing confusion." The molecular world, that universe in which large and small molecules jostle each other randomly and continuously, exchanging energy and undergoing dynamic changes in three-dimensional conformation, can appear much the same to our students – and to us! Yet this vibrating universe underpins the incredible stability of living beings, the regularity of crystals, and the functionality of modern electronics.

How can students get a sense of the influence of random motions and fluctuations that are a manifestation of temperature? How can they discover the order that emerges from it?

Over the last half-century biology has employed a progression of metaphors, drawings, and microphotographs to provide students with a glimpse of the molecular world. Although microphotographs present a realistic view of molecules, they do not permit students to gain a feeling for the dynamic nature of colliding and interacting molecules. Computer-based dynamic molecular modeling, previously the province of academics using supercomputers, now can be made available to them.

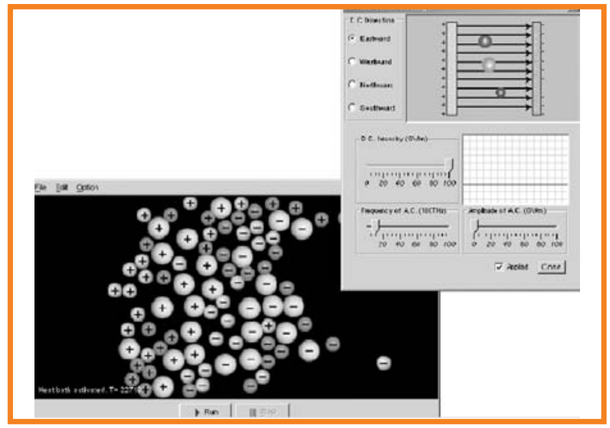

Figure 2. Simulated electrophoresis. Using a control panel, students can change the direction and strength of the electric field, the temperature of the system and properties of the particles.

Expanding our models to accommodate the new revolutions

Several National Science Foundation grants have allowed us to develop the Molecular Workbench, software for creating molecular simulations that we use in high school and college science and technology courses. At the heart of the Molecular Workbench is a simulation that models the motion of atoms that results from forces that act on atoms: mutual repulsion and attraction, bonds, and charge. These models all show random thermal motions and, therefore, help students gain a deep understanding of thermodynamics. The basic models can help explain phase change, diffusion, thermal conduction, solutions, crystal structure, and many other properties of materials.

In order to expand the utility of the Molecular Workbench into chemistry, biology, biotechnology, and

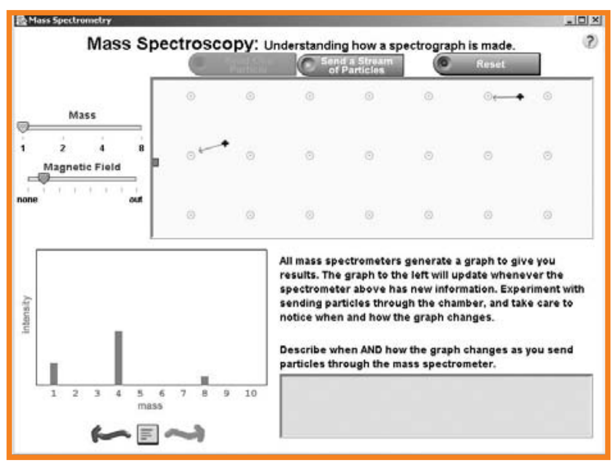

Figure 3. Fragment of the simulated mass spectrometer activity. Students explore how the mass of particles and the strength of the magnetic field affects the deflection angle of moving particles. Their task here is to manipulate the magnetic field so that the particles hit the detector.

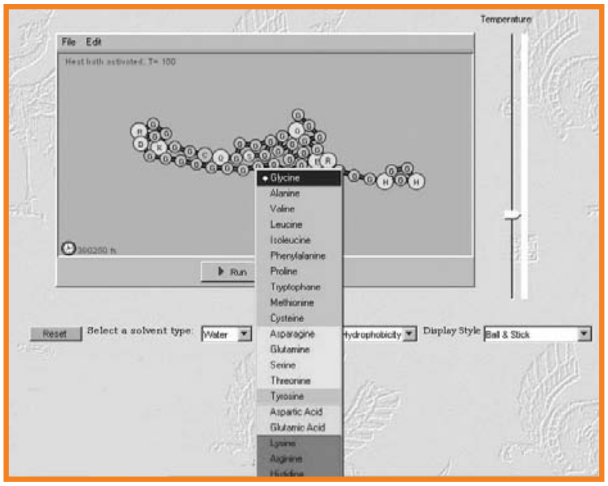

Figure 4. Exploring protein conformation. Students work with a model protein made of 46 amino acids. Each amino acid can be replaced by another of the 20 different amino acids. They can then observe the effect of polar and non-polar amino acids on the resulting protein shape. Students also can test the stability of the structure by increasing the temperature.

nanotechnology, we have added some unique innovations. By introducing effective hydrophobic and hydrophilic forces, we can illustrate protein conformation in solution without having to explicitly put in numerous solvent molecules. By combining the collision theory of chemical reactions and molecular dynamics, we can model chemical equilibria and reaction energetics. By supporting "smart surfaces" and "splines" (see Figure 1), we enable student investigation of the interactions of larger biomolecules, in which their molecular surfaces play a decisive role. We are now exploring educational applications of these expanded models in nano- and biotechnology.

Sample explorations

Several key investigations can give students a "hands-on" feeling for molecular manipulation. For example, students can compare the subatomic structure of charged, polar and neutral molecules and then practice a simulated laboratory procedure of molecular separation, such as electrophoresis (Figure 2) or mass spectroscopy (Figure 3), in which these concepts are used. Students are then in a good position to understand the role of polar and non-polar amino acids in shaping protein structures (Figure 4) and continue on to discover the effects of temperature on protein folding.

"DNA to protein" (Figure 5) allows students to experiment with changing codons in DNA responsible for the primary structure of a protein, and explore mutations that change the shape (and possibly the function) of a protein. "Smart surfaces" (Figure 1) permits students to design simple 2D approximations of proteins shaped as antibodies, receptors or pore components. They can then go on to explore interactions between "smart surfaces" or between them and a small molecule, thus modeling receptor-ligand interaction and other aspects of molecular recognition.

These illustrations cannot do justice to the models, which are in continual motion due to the effect of temperature. Because our models are based on molecular dynamics, they automatically incorporate an accurate model of thermal motion and they exhibit temperature effects. Unlike software that might simply allow students to assemble molecular designs, the Molecular Workbench incorporates thermal motions, which must be considered in any nano-scale design.

Dynamic molecular modeling is a simple, yet central tool

What challenges will the bio- and nanotechnology revolutions pose for educators? It is impossible to know in detail the educational needs of specific bio- and nanotechnologies, but it is easy to know on what science they will depend. Students will need to know about atoms and molecules, the forces that act on them, and the properties that emerge from collections of them. Experiences like those illustrated above could lead to a better understanding of both natural and designed "molecular engineering." Simulations like the Molecular Workbench that model these systems will be central to any instructional strategies, because of the technical difficulty of doing actual experiments, and the mathematical difficulty of understanding these systems analytically.

We are looking for high school and community college science teachers interested in testing our software. We offer a small stipend, as well as community support. Please contact Amy Pallant (apallant@concord.org). @

Figure 5. DNA to protein. Students can substitute or delete any nucleotide in the model gene that codes for the protein above, and explore how this mutation affects the resulting shape of the protein.

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ARTICLE LINKS & NOTES

Note 1. http://www.gene.com/gene/features/25years/biotech-backgrounder/employment.jsp

Note 2. Silicon Valley Chemist. American Chemical Society. Vol. 23, No 5.

See examples of biomimicry. – http://www.biomimicry.org

National Science Foundation – http://www.nsf.gov

Molecular Workbench – http://workbench.concord.org

Download the Molecular Workbench. It runs under Windows and OSX. – http://xeon.concord.org:8080/modeler/webstart/index.html