The Science of Atoms and Molecules

BY ROBERT TINKER

"A dramatic revision of the science curriculum can generate a truly revolutionary way of teaching science in U.S. high schools." **—Leon Lederman, Nobel Laureate in physics**

"You mean there are air molecules hitting my arm all the time?" **—9th grader after having worked with a Molecular Workbench model**

If you could shrink by a factor of a billion (think "Honey, We Shrunk Ourselves"), you would enter a very hostile environment. Since gravity is negligible compared to other forces, you would feel like you were floating in space—until something hit you. The instant you arrived, you'd be knocked unconscious by a speeding atom. In fact, millions of atoms and molecules would be slamming into you at the speed of jet planes every second!

Here, everything is in violent, random motion and when things heat up, everything moves faster. Atoms and molecules constantly flex, vibrate, and crash into one another too quickly to comprehend. If you brought along a stop-action camera that slows time down a billion-fold, you would see that collisions are perfectly elastic, so atoms bounce off one another without losing even the tiniest fraction of their energy. The dominant force is electrostatics—if two atoms carry as little as one electron's charge, they exert huge forces on each other. Even uncharged atoms exert some electrostatic forces on each other. Without these forces between neutral atoms, there would be no liquids or solids, no life, no planets.

While contemplating that amazing fact—boom!—you hear a small explosion. That's the energy released when a chemical bond is formed. Sometimes this is accompanied by the release of a packet of light; other times the resulting molecule careens off a nearby molecule like a rocket. The reverse happens, too—a light packet or a high-speed collision can break up a molecule. Mostly, however, the molecules are strong, rigid blobs. Water molecules and many others of these objects have charges on their surface. You don't want to be between two molecules with these surface charges because they slam together and hold fast. Time to reenter the macroscopic world—fast!

Adventures in the atomic world

The atomic world is very different from our macroscopic world. Indeed, many of the instincts you have developed about the way things work do not apply at the atomic scale.

It is critically important to understand the science of atoms and molecules because it is at the heart of modern science and technology. "A concise summary of the last 100 years of science is that atoms and molecules are 85% of physics, 100% of chemistry, and 90% of modern molecular biology," claims Concord Consortium board member Leon Lederman.

> The science of atoms and molecules is the **fundamental basis of biology.** Atoms and molecules are also central to modern chemistry, earth science, electronics, nanoscience, forensics, and **all the interdisciplinary fields** like biochemistry, space weather, and plasma dynamics.

For instance, biology increasingly depends on the science of atoms and molecules. Many biological processes are understood in terms of molecules and their physical interactions, such as biomolecular synthesis, energy pathways, evolution, and ecosystems. We know precisely the mechanics of muscle contraction, how one errant molecule causes sickle cell anemia, and which molecular errors cause some cancers. The science of atoms and molecules is the fundamental basis of biology, and the future of understanding disease and developing new treatments. Atoms and molecules are also central to modern chemistry, earth science, electronics, nanoscience, forensics, and all the interdisciplinary fields like biochemistry, space weather, and plasma dynamics.

Incorporating atoms and molecules

The critical missing content in most introductory science curricula is a solid set of materials that addresses atomic-scale science. The basic physics of atoms and molecules needs to be introduced early so that chemistry can take advantage of these concepts. Similarly, biology needs to leverage student understanding of atomic-scale physics and chemistry to address key introductory molecular biology concepts.

The logic of this approach explains why Leon Lederman and many others have been advocating "Physics First"—a reordering of the introductory secondary science sequence that places physics before chemistry, which is then followed by biology. But this new sequence solves nothing if it doesn't incorporate the science of atoms and molecules.

Too often schools that have tried Physics First simply rearrange the sequence of topics without changing them. Without addressing atoms and molecules and exploiting the connections among the courses, this reordering will not significantly improve the science curriculum and can result in a net decrease in understanding.

The "Science of Atoms and Molecules" Provides the Answers

Since the atomic world is seldom taught well, we are developing the *Science of Atoms and Molecules*, a new project that has four strands of atomic-scale materials and professional development resources that unify the secondary curriculum sequence of physics, chemistry, and biology.

As part of this project, we are creating a *Molecular Concepts Inventory* to measure student understanding of the science of atoms and molecules. Answer these true/false questions, then find your score online (sam.concord.org/mci).

TRUE	FALSE	
❑	❑	Solids melt because the forces between atoms get weaker as the temperature increases.
❑	❑	All atoms attract one another with a short-range force.
❑	❑	ATP is an energy source because the high-energy phosphate bond releases a lot of energy when it is broken.
❑	❑	The temperature of a group of atoms or molecules is determined by their average kinetic energy and nothing else.
❑	❑	Atoms in solids are held in place so they do not move as fast as liquid and gas atoms at the same temperature.
❑	❑	Heat energy in a material consists of the disordered motion of its atoms or molecules.
❑	❑	Creating a chemical bond lowers the potential energy.
❑	❑	Evaporation causes a liquid to cool because evaporating atoms are, on average, hotter than the liquid they leave.
❑	❑	Ions dissolved in room-temperature water are surrounded by ice.
❑	❑	Oil and water don't mix because the oil molecules repel water molecules.

Molecular Workbench to the rescue

Our *Molecular Workbench* software simulates the basic properties of atoms, molecules, ions, photons, chemical bonds, biological molecules, and a wide range of forces. All sorts of phenomena emerge from these properties, such as phase change, evaporation, diffusion, latent heats, chemical reactions, black body radiation, and self-assembly. Students can play around with Molecular Workbench models and get a feel for the strange world of atoms. However, just as in the macroscopic world, without some guidance, students miss much of the value of the Molecular Workbench experience. To help, we created a sequence of activities for biology students. Other activities are designed for technical colleges and high schools as a bridge between science and technology courses.

When we studied student learning with Molecular Workbench in middle school through college, we found that students learned content while also getting better at using models. Students appeared able to use their understanding of the atomic-scale world to reason their way to correct explanations of new situations. There is some indication that students retained their model-based learning for a long time. By going deeper, it appears that students gained insights that persisted and helped them understand new problems.

LINKS *The Science of Atoms and Molecules*

- **Molecular Workbench**
  http://mw.concord.org/modeler
- **Science of Atoms and Molecules**
  http://sam.concord.org
- **Molecular Concepts Inventory**
  http://sam.concord.org/mci

Creating a better introduction to science

We are currently developing activities for high school Physics First curricula that start with the physics of atoms—how they are constructed and the relationship between their average kinetic energy and temperature. We introduce the all-important forces between atoms, which give rise to a potential energy, and the central idea that the sum of kinetic and potential energies is conserved. Chemical bonds are explored, along with the idea of electronegativity, which causes charge separation and explains the strong attraction of polar molecules. Color, fluorescence, spectra, and many other phenomena are explained by discussing how light can interact with atoms and molecules while conserving energy. These ideas provide a firm physical basis for many biology topics. As a result, the entire treatment of physics, chemistry, and biology is more logical and, therefore, a better introduction to the conduct of science.

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