Understanding Heat and Temperature: Can Atoms Help?

BY ROBERT TINKER AND AMY PALLANT

A fundamental tenet of our work is that a deeper conceptual understanding can simplify learning. If students understand deep, unifying ideas, they don't have to memorize apparently disconnected effects. This fits with the recent recommendation from the National Academy of Sciences for "revising standards to focus on core ideas."[1]

Our *Science of Atoms and Molecules* (SAM) project is developing activities for a Physics First curriculum, which permits high school freshmen to apply the concepts they learn in physics in later courses in chemistry and biology; their understanding of all sciences is improved because they can go deeper and make connections. Using the *Molecular Workbench* (MW) modeling environment, students gain an understanding of what is happening at the atomic scale, which helps to explain multiple macroscopic phenomena across the sciences.

The idea of reaching for fundamentals sounds great in theory, but how does it work in practice? The concepts involved with heat and temperature challenged our theory of teaching deeper concepts to simplify a collection of phenomena. We believed that if students understood the atomic nature of heat and temperature, they would have a profound foundation for building an understanding of phenomena related to phase change, gas laws, van der Waals attractions, and chemical reactions, plus protein folding, diffusion, and osmosis. While agreeing on the concepts, we were challenged to articulate what could be taught at this level and how to approach the topic conceptually.

Challenge 1: Temperature and kinetic energy

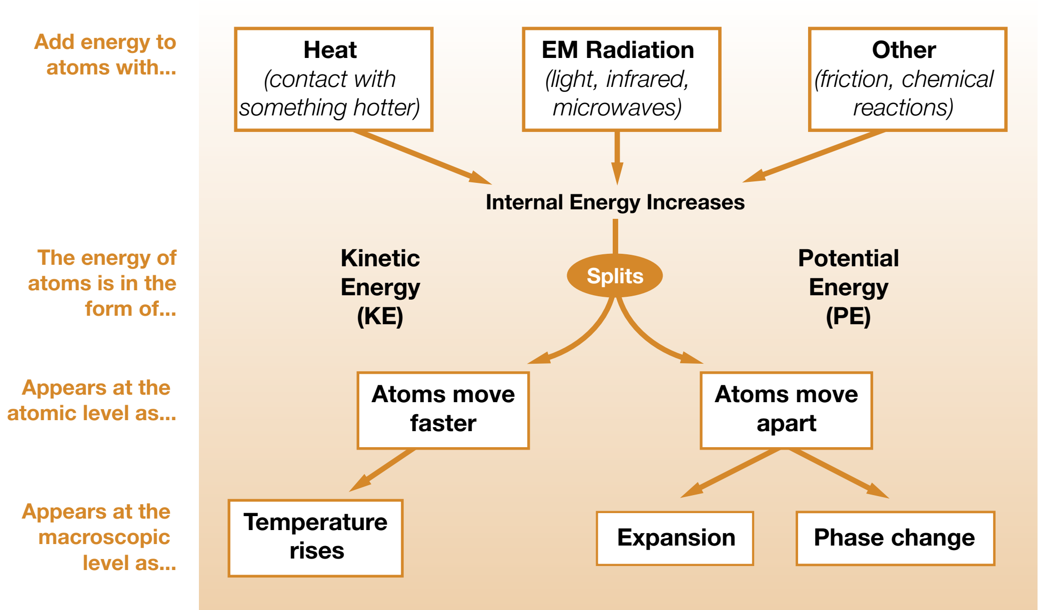
We defined the following learning goals for our *Heat and Temperature activity* in the SAM project:

- Heat flows from hot to cold through collisions of atoms and molecules.
- A temperature scale is a measure of the average kinetic energy of atoms and molecules.
- At equilibrium all particles have the same average kinetic energy over time regardless of size, shape, or mass.

One of the most documented areas in science educational research is students' understanding and misconceptions about heat and temperature. So it came as a great surprise that when we began to develop our models and curriculum on this topic, we uncovered nuances to teaching and learning we had not expected.

The definition of temperature is usually not addressed in science curricula until the ideal gas laws are encountered. Then, at some point the kinetic-molecular theory is introduced, often as a set of assumptions without any explanation of how these relate to the gas laws. We wanted to know whether it is helpful to define temperature as the average kinetic energy of atoms. But as you look closely at this, questions arise. Are we using the average kinetic energy over time? Or the average per atom? Is temperature the average kinetic energy of the atoms or the molecules? Why exactly is temperature related to kinetic energy and not the average speed or mass times speed or some other quantity? Will students confuse macroscopic kinetic energy—like that of a falling rock, for example—with temperature?

Molecular Workbench is a wonderful tool for correlating random thermal motion to changes in temperature. Students can think about the properties of temperature and look for something at the atomic scale with the same properties. The simplest property of temperature can be seen by observing how changes in random kinetic energy of



Atoms and Energy Can Help. Thinking atomically helps connect added energy (top row) to observed changes (bottom row). All the ways of adding energy shown increase the internal energy. This increase is split between increases in kinetic and potential energy. The former is seen at the atomic level as faster atoms and at the macroscopic level as increased temperature. Increases in potential energy involve moving atoms farther apart, which can cause expansion and phase change.

1. Science education that makes sense. (2007). *Research Points: Essential Information for Education Policy,* 5(1). American Educational Research Association.

molecules are related to changes in the temperature. Some experimentation should convince students that atoms speed up when the temperature rises.

Another experiment has students isolate objects at different temperatures. Students put these objects in contact while they remain isolated from anything else and observe how they come to a single temperature between the starting temperatures. They can experiment with molecules of varying mass, phase, or composition while observing different properties, such as average speed and kinetic energy. In this dynamic and robust environment in which students have control of variables, they quickly grasp the relationship between temperature and the average kinetic energy due to random motion.

Challenge 2: What about heat?

Heat and temperature are easily confused. A lot of confusion is in the terminology. Textbooks that introduce heat offer different definitions: "heat is energy," says one; "heat is a form of energy," reports another; and "heat is internal energy." The term "heat energy" sounds a lot like temperature, which we are emphasizing is a form of energy, namely kinetic energy.

What is heat? At the atomic scale, heat is the total energy of atoms, that is, the kinetic energy plus the potential energy. That still sounds a lot like temperature, but with this new idea of potential energy. The potential of what? Where does potential energy come from?

How do we use an atomic view of heat as seen in MW in a way that might help clarify some of these confusions? Some of the issues we faced were:

1. **What do we call it?** Many authors use "heat energy," but that can be confused with "kinetic energy," which is temperature. "Thermal energy" is used, too, but doesn't seem any better. A strong case was made for "internal energy" because it is accurate and it isn't loaded with meaning or common terminology. But we did not want to introduce a new term that teachers and students might find intimidating. In the end, we decided the simple word "heat" was best.
2. **How exactly do you convey the difference between heat and temperature?** At the atomic scale, heat is the total internal energy—kinetic energy (KE) plus potential energy (PE)—and temperature is average KE. While this is simple and elegant, potential energy at the atomic scale takes some getting used to.
3. **Do we want to talk about heat per atom?** Temperature is KE per atom, an intensive quantity. Heat is the total KE plus PE for all atoms, an extensive quantity. To bring out the differences between heat and temperature, it is tempting to introduce the average heat per atom. Students have problems with intensive quantities, however, so it may be good to not talk about the heat per atom.

From classical mechanics students should learn that whenever there is a force, there is a potential energy (at least if it depends only on distance). The problem is that a full understanding of the relationship between force and potential energy involves calculus and few ninth graders have had calculus. We decided to make a qualitative case that energy is needed to tear atoms apart and this energy is called potential energy.

Potential energy at the atomic scale helped explain several common observations. An increase in PE for atoms means they get farther apart. And if students understand this, then they can observe models of evaporation, change of state, and even thermal expansion. At last, we began to see some payoffs from thinking atomically (see figure).

Challenge 3: How do we make it simple?

In the end, through simple steps in our Heat and Temperature activity, students are able to investigate the way the atomic scale uses energy concepts from physics to relate heat, heat flow, temperature, light, mechanical motion, phase change, evaporation, and thermal expansion.

By starting with a foundational atomic-scale understanding of heat and temperature, subsequent activities in the SAM project can build on this. For instance, the phase change activity relies on student understanding that energy is required to change states of matter, and to overcome attractive forces of atoms and molecules. In the chemical reaction activity, students are asked to explain the connection between temperature, collisions, and reaction rates. A biological application in SAM's protein folding activity relates how changes in temperatures might cause an increase in random thermal motion and denaturation of a protein.

LINKS *Heat and Temperature*

Science of Atoms and Molecules
http://sam.concord.org

The Molecular Workbench
http://mw.concord.org/modeler

Heat and Temperature
http://mw2.concord.org/tmp.jnlp?address=http://mw2.concord.org/public/part2/heat/index.cml

Developing this unit revealed a problem with our approach of teaching fundamental concepts that can relate many particular observations: you don't get fundamentals for free, even when a tool like MW appears to make them transparent. Teaching the fundamentals requires new concepts, vocabulary, and approaches. *Internal energy, heat per atom,* and *potential energy at the atomic scale* help unify many parts of science, but they also are part of a new and unfamiliar perspective.

We know that introducing atomic-scale concepts works, confirming what the American Educational Research Association reported: "students gain insights when they use visualizations to link situations, rather than using only text or static drawings. Such tools can help learners connect salient information to their existing ideas." Molecular Workbench allows students to go deeper and simplify many phenomena, including what might seem as basic as heat and temperature.

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