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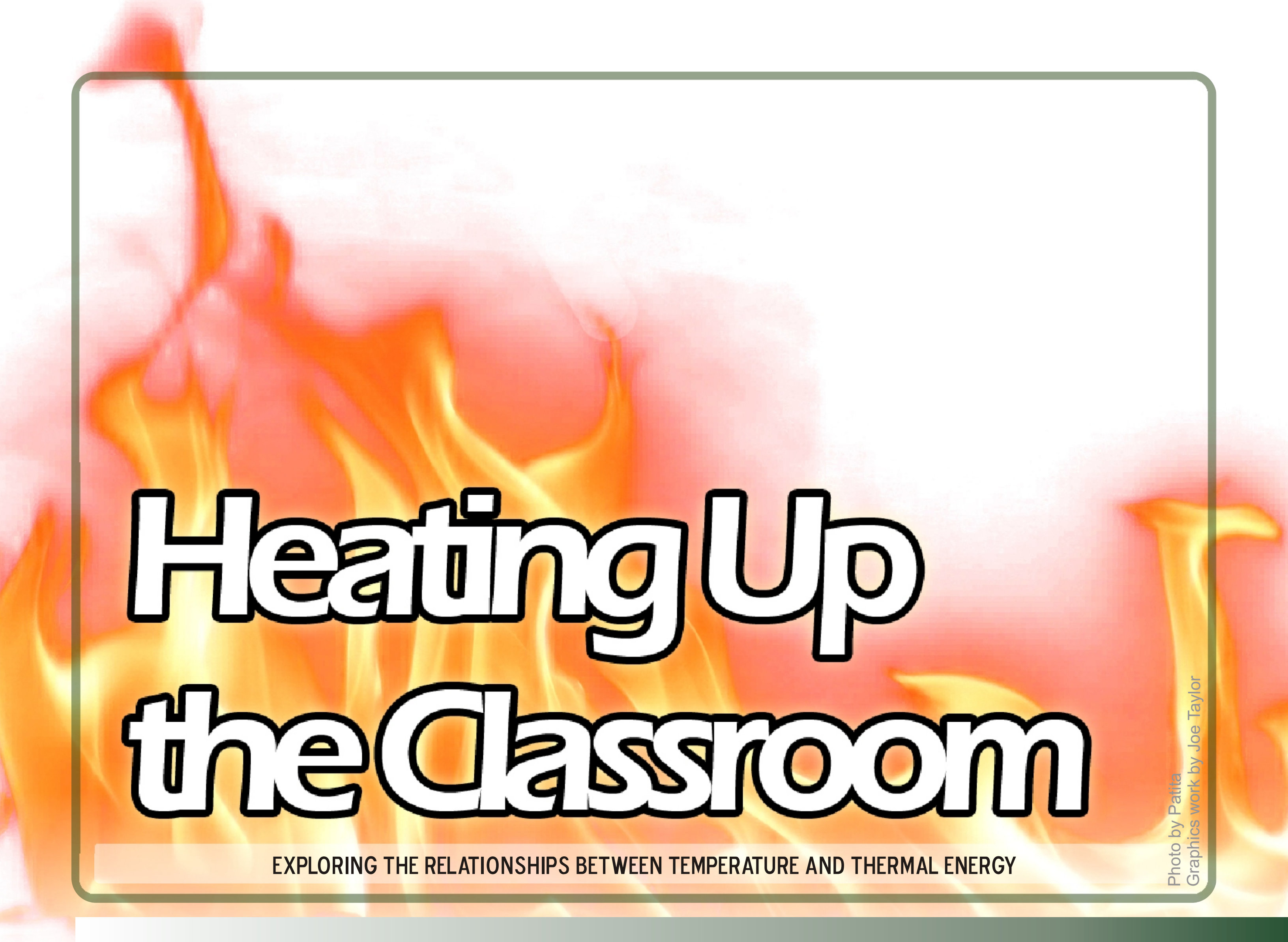
Heating Up the Classroom: Exploring Relationships between Temperature and Thermal Energy

Shannon McLaughlin
Simpson College

Mahima Bajpai
Iowa State University



Heating Up the Classroom

EXPLORING THE RELATIONSHIPS BETWEEN TEMPERATURE AND THERMAL ENERGY

Photo by Patita
Graphics work by Joe Taylor

Shannon McLaughlin & Mahima Bajpai

ABSTRACT: Thermal energy, internal energy, temperature, and heat are words that carry very specific meanings. However, common usage and the lack of consistent usage from texts and teachers can interfere with students' abilities to develop a strong conceptual foundation of thermal energy (Westphal, 2003). Stiles (2006) suggests that using experiences to investigate relationships is an integral part of moving students from simple knowledge to deep understanding. Understanding, higher-order thinking skills, the ability to work and think collaboratively, effective communication skills, and the ability to make informed decisions are all important goals teachers should support through their instruction. Smith (1996), Freedman (1997), and Mao and Chang (1998) suggest that using inquiry methods result in significantly improved mastery of science content, content retention, enhanced critical thinking skills, laboratory skills, and attitudes when compared with traditional teaching methods. Yet, we as teachers have important roles to play in making inquiry-based instruction work. This article articulates how inquiry oriented instruction can consistently promote the goals stated above while developing an understanding of thermal energy through basic science concepts.. *This article promotes National Science Education Standards A and B, and Iowa Teaching Standards 1,2, 3, and 5.*

Thermal energy or energy thermal (E_Q) refers to a unique energy storage category. We use the phrase "energy thermal" with our students for a specific purpose: to carefully suggest that this energy *category* is not inherently different than any other energy as is often suggested with phrases like a "different kind" or "different form" of energy (Swackhamer, 2005). Understanding energy thermal requires a deep knowledge of specific underlying concepts that are often assumed, disguised in equations, or shadowed by complex procedures.

Prior to completing the activities described here, students should have many successive experiences with the concepts of mass and particle motion. Students should have experienced a wide variety of activities to develop the idea that mass is a measure of the amount of substance and that mass is proportional to the number of particles for a given substance. Secondly, students should be familiar with the ideas that all substances are made of particles too small to be visible, those particles are in motion, and temperature is a measure of the average particle motion. Furthermore, students must recognize that energy thermal transfers are spontaneous from a region of high temperature to low temperature, and energy thermal transfers cease when equilibrium is reached. Students must realize that heat describes an energy transfer through particle motion and heat is not a "thing" that flows when there is a temperature gradient.

Detailing the development of students' background knowledge lies beyond the scope of this article. However, we must stress that simply telling students about the relationships between temperature and particle motion will not likely result in authentic or lasting learning. Instead, students must be encouraged to think about phenomena they observe, and then guided toward the notion of particle movement.

As a brief example, we have had students observe different states of water (solid, liquid, gas) and draw out their ideas concerning how the particles in each state compare. The resulting discussion enables us to draw students' attention to how increased energy results in increased motion that can be measured by temperature. We also ask students to speculate what happens if a fast moving particle and a slow moving particle run into each other (we might even use billiard balls for a quick demo).

Mixing Hot and Cold Water

One traditional activity is to mix two equal amounts of water at different temperatures and predict an equilibrium temperature. This activity can be expanded by mixing unequal amounts of water at different temperatures, or even exploring with other substances. These activities are often sold as high interest and "hands-on" inquiry activities because students are making predictions about the final temperatures and the results may come into conflict with some of their predictions. While students may be predicting and actively participating, blind faith in the activity, without careful orchestration by a competent teacher, will usurp important connections to fundamental science concepts.

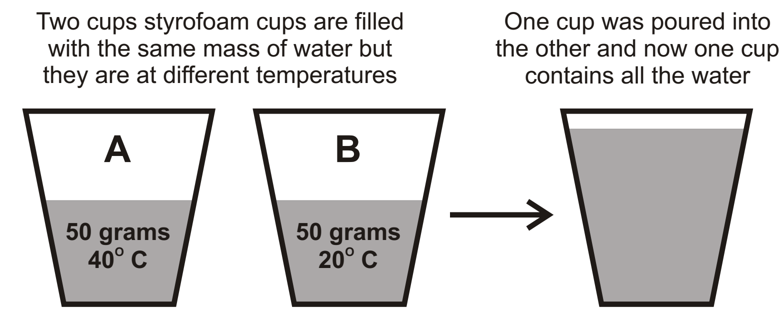
These types of activities rarely require students to integrate particle theory or the energy concept into explanations. Phrases suggested in teacher notes like "heat lost by hot water and heat gained by cold water" only reinforce deeply rooted misconceptions about energy. Often, teachers quickly progress to complex mathematical relationships like $E_Q = mc\Delta T$ and have students complete calculations for a wide variety of decontextualized problems. This "plug and chug" problem solving promotes seeking answers rather than strong conceptual explanations. Without careful guidance by the teacher, the activities contribute to weak conceptual understanding and obscure the relationship between math and science with respect to identifying relationships, mathematically modeling variables, and developing the intuition required for interpreting natural phenomena (Hestenes, 1987).

Making Predictions

We use the following question and diagram (Figure 1) to engage the students with fundamental concepts prior to completing the actual water mixing activity.

- "What will happen if equal amounts of water at different temperatures are mixed?"

FIGURE 1
Title of figure



We also ask probing questions to help students integrate their prior knowledge with the new situation. We ask questions like:

- "How would the mass of water in cups A and B compare with the mass of water in the cup containing the mixed water?"
- "How could you test your ideas?"
- "How could you explain your thinking using the idea of particles?"
- "How might the behavior of the particles in cup A compare to the behavior of the particles in cup B?"

Questions alone rarely result in deep class discussions. We work to encourage student input by providing extensive wait time after questions and after student responses, by looking around the room with positive facial expressions and moving around the room. Rather than confirm or reject student ideas, we explicitly ask students to consider what their classmates are saying and make comments or add other ideas.

Once students have discussed the questions above, we ask:

- "What predictions do you have about the temperature of the mixed liquids?"

We ask students to submit their group's options on a hand held white board so that they can be shared with other students. Usually we provide about 3-5 minutes for groups to discuss and note their predictions. We encourage students to put any possible options on their board so that students have a range of possibilities from which to choose. During the group work, we circulate around the room asking groups questions to push student thinking and to gain insight as to what rationale they are using for their predictions.

Many students will reason appropriately that the temperature should be in-between the original two temperatures. However, when we ask how they could calculate the final temperature, their ideas typically include:

- Add the temperatures and divide by two or find the average.
- Count up and down until you reach the middle temperature (often these students don't realize this is the same as the first procedure listed)
- Subtract the lower from the higher temperature
- Add the temperatures together (the logic to this one is apparent in an energy analysis)

When students present their ideas, we do not indicate which are correct but ask students to explain why they think their strategy for calculating their prediction temperature is valid. So that students might test each of the different ideas, we ask

- "How might we find out which prediction method is most accurate?"

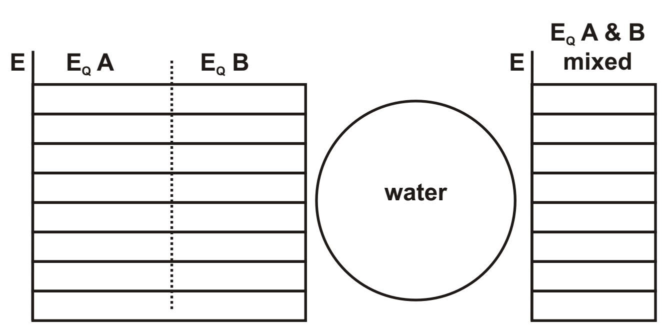
Simply telling the students which one to use does not require the students to make a decision. Ultimately, the students will remain more engaged if they are required to make the decision for themselves.

Visualizing predictions

The final pre-activity assessment we make is to have students complete an energy analysis for the water. The methods used for the energy analysis are described by Swackhamer (2005). The representations described below target qualitative understanding and help unravel important considerations relating to the energy thermal concept. Each teacher should determine whether the representations are appropriate depending on the developmental level of students engaged in the activity.

We ask students to complete the following energy bar graphs (Figure 2) for the initial and final conditions of the system. Remind students that the initial system includes only the water in cups A and B at their respective temperatures, and both amounts of water in the one-cup final state. Students may need to be reminded that temperature and energy could be related but are not the same idea. Typical student responses and justifications are illustrated and explained in Figure 3.

FIGURE 2
Energy bar graph for student use.



Students place their thoughts on a white board and present their energy analysis to the rest of the class while justifying their position. Students have previously learned that energy is conserved, but the unfamiliar situation will challenge their beliefs. The notion that thermal energy is dependent only on temperature typically permeates the discussion. We refrain from indicating which approaches, if any, are correct at this time and carefully control non-verbal behaviors that could sway students from their original positions. The remainder of this article describes how we engage students with investigating the water mixing to achieve greater understanding of the energy thermal concept.

Into the Lab: Investigating the relationship between energy thermal and temperature

Before students start investigating the original question concerning mixing different temperatures of water, they must first investigate how the amount of energy thermal and temperature are related. Students are easily convinced a hot plate is a thermal energy transferring device. We begin with the question,

- "How might you go about conducting an experiment for determining the relationship between energy thermal and temperature?"

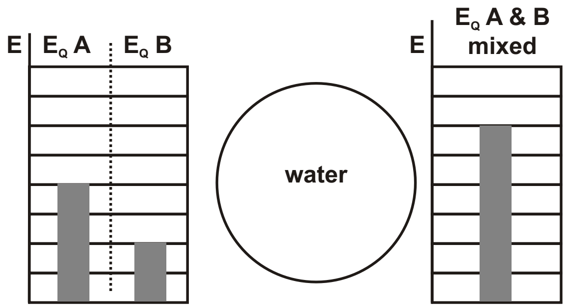
Students will typically respond by suggesting one of the following experimental procedures:

- Vary the energy thermal added with the numbered dial on the hot plate and take an equilibrium temperature reading at each.
- Vary the time a beaker spends on the hot plate and take the temperature every 30 seconds.
- Place the beaker on the hot plate until it reaches a set temperature and record the time on the hot plate.

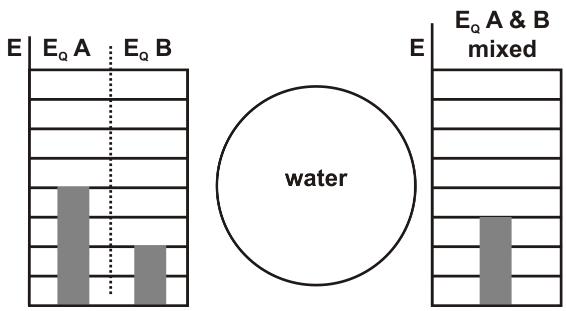
Any of these procedures would work although you may want to have the students discuss the pros and cons for each procedure. We should also note that during this discussion students should be asked how they might achieve a numerical value for the amount of energy thermal added to the system. Students usually respond that they can use the increments on the dial or students may suggest that every 30s could be counted as a unit of energy thermal added. Ideally students see that putting the beaker on the hot plate and reading the temperature every 30s is the most efficient procedure. Once a procedure is decided on, we have them indicate which variables are the independent, dependent, and control variables. Students then carry out the experiment.

FIGURE 3

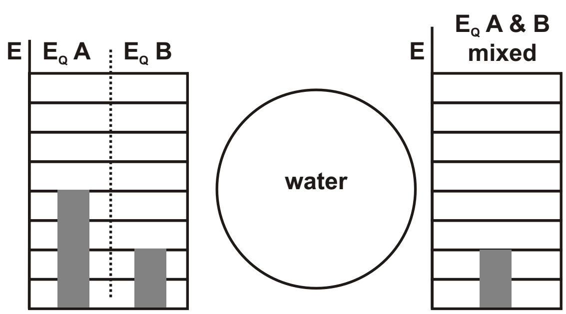
Typical student predictions of the energy conditions resulting from the mixing of cups of water of two different temperatures.



The students added the two initial temperatures together for their prediction, therefore they are assuming the energy thermal is additive. These students have a hard time explaining how predicted mid-temperatures could be less than the initial temperature of cup A. Another possibility might be students' application of energy conservation principles overriding preconceived notions about temperature and thermal energy storage. These students will have difficulty providing reasoning for a predicted mid-temperature of water.



These students have assumed that temperature is the measure of energy thermal stored and have simply replicated their temperature reasoning when applying the energy thermal concept. The primary challenge these students will face is explaining how their ideas work in relation to energy conservation rules. For example the instructor could ask students to compare the initial energy stored in the system to the final energy stored in the system.



These students are also replicating their reasoning with predicting a final temperature with the energy thermal concept. They are also assuming that temperature is a direct measure of energy thermal. These students will be challenged to explain how they only have two units of energy and many students will question why suggesting that the final temperature would be the same as the cup B's initial temperature, further indicating their notion that temperature is the measure of energy thermal.

We carefully monitor students during lab time, move around the room, and engage the students with questions like

- "How will you be able to communicate what you are doing today in our lab discussion tomorrow?"
- "What patterns are you noticing in your data?"
- "How might you represent your data in a different way?"
- "What conclusions have you made and how do your data support those conclusions?"

We encourage students to present their data graphically and most will determine a direct relationship between relative energy thermal added and the temperature of the substance. It is important to note that some students may use a change in temperature and others may record actual temperatures. Those using change in temperature will have a y-intercept on their graph of approximately zero, while those recording actual temperatures will have a y-intercept close to their average starting temperature. A slope value could be calculated and interpreted as the change in temperature for each unit of energy thermal added. We require students to generate questions for further study and to work out differences in data. **Ultimately students must note that the temperature increases proportionally with the amount of thermal energy added to the water**. (Note: For a freshman science class evidence that temperature and EQ are related is the first step in the process of developing the concept of energy thermal. Unfortunately it does re-enforce the naïve belief that temperature is the only variable that determines the thermal energy of a substance but careful scaffolding can get them past that point at a later time.)

Back to the Beginning - Mixing water at different temperatures

Now that a relationship between temperature and energy thermal has been determined, we have students explore the original question. We remind the students that they have discussed several ways to predict the final temperature and suggest that they do so before completing trials. So that students don't become too stressed about exact amounts/temperatures, we indicate that the initial set up was simply to start the discussion and students can use any equal mass in cups A and B and initial temperatures can vary as well.

To carry out the mixing experiment, students will need a balance, Styrofoam cups, and hot and cold tap water. Students are provided time to conduct the experiment several times in order to be satisfied with their results. While experimenting, the instructor can keep students engaged by asking questions like:

- "How will you know when to record a temperature reading for the mixed amounts?"
- "What have you noticed between your predictions and the results you are obtaining?"
- "What adjustments might be made to achieve more consistent results?"

These questions allow the instructor to evaluate procedural knowledge of taking a temperature and assess student's ideas of equilibrium. The questions also encourage the students to modify their procedures and reflect on their results while still carrying out the activity.

To improve upon their procedures, students often suggest making sure they measure the temperature after massing their amounts, mix the water quickly after recording temperatures, cover the top of the mixed container with the other cup, and pour the cooler water into the warmer because it is closer to the temperature of the surroundings. After some experimenting, students should present the results of their trials and discuss general trends in the data. Students should recognize that predictions using the mid-temperature or averaging the temperatures were the most accurate. For the most part, students will recognize that they can obtain results within a degree or two of the mid-temp prediction. To draw out student thinking and encourage reflection on their investigations we ask

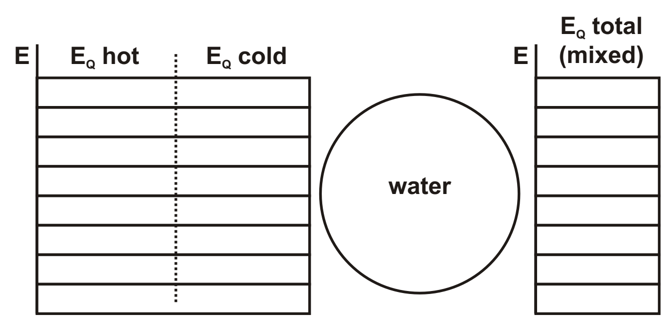
- "How did your results change as you completed more trials and adjusted your procedure?"

Now that students have investigated the mixing water, we work to draw connections between the predominant science concepts involved. We use questions like the following to help students draw relationships between particle theory, equilibrium, and energy thermal. The questions encourage students to revisit temperature as an average measure of particle motion, and use the relationship between temperature and energy thermal to make some decisions about the energy analysis they completed earlier.

- "How might the change in temperature of each amount of water compare?"
- "How could we explain an increase in temperature of the cold water?"
- "How could we explain a decrease in temperature of the hot water?"
- "How are temperature and energy thermal related?"
- "If the cold water got warmer, how can we explain this in terms of change in energy for the cold water particles?"
- "If the warm water got colder, how can we explain this in terms of the change in energy for the hot water particles?"
- "How might adding the two **changes** in temperature help us understand the change in energy thermal for the whole system before mixing to after mixing?"
- "After mixing, the cold water temperature goes up while the hot water temp goes down. What might this indicate about the total change in energy thermal of the system (both amounts of water)?"

Complete a final energy bar analysis (Figure 4) for the results you obtained when using the change in temperature as a way of determining the change in thermal energy for the water.

FIGURE 2
Final energy bar analysis.



Using guiding questions to get the students to evaluate the experiment from the newly established relationship between energy thermal and temperature will help reinforce the relationship and help them more critically evaluate the energy bar charts. By getting the students to focus on the *change* in temperature and probing them to recall that temperature and energy thermal are directly related, the instructor can guide the students to the realization that the **total change in energy for the system can be determined as zero by summing the *change* in temperatures for each amount of water.** Students with negatives or positives close to zero should identify the possible role of the surroundings and their procedures as likely explanations for how energy transferred in or out of the system. Energy escape or entrance from the surroundings can be represented in the energy analysis with an arrow pointing in or out of the system circle with appropriate justification.

Many students will wonder why the energy thermal is not an average of the two original energies like the temperature is. These students may need to be reminded that while temperature and energy thermal are related, temperature is a measure of average particle motion, not a measure of the energy of a system. One way to draw their attention to maintained energy thermal is to repeat a demonstration of energy kinetic transfer conducted when energy was studied macroscopically.

Students can be led through evaluating the energy of a system of two spherical objects, one rolling the other standing still. In the initial state students will see the E_k of the system is accounted for by only one of the spheres. After a collision, students typically recognize the original moving sphere is capable of transferring some of its E_k to the other ball as a result of the collision, thus distributing the total E_k between both objects. This can be accompanied by a demo of two colliding billiard balls and ideally should be the scaffold students need to adequately explain the median temperature from a particle point of view.

Other students will notice that maintaining energy thermal while temperature changes is contradictory in regards to the idea that temperature and energy thermal are directly related. We encourage students to think critically about how this might happen by asking:

- "How might we explain how we have a median temperature but the same total amount of energy thermal?"
- "How might we explain why some changes in temperature for the system are negative but close to zero and others are positive and close to zero?"

Students can now adequately reason that the mass of water may be a factor contributing to the total energy thermal stored in the system. The students have the experience of using equipment and designing an experiment so the natural progression is to ask the question,

- "How might we go about determining if energy thermal is related to the mass of the system?"

Modifications for advanced physics

It is important to note that many physics students hold the same naive conceptions that 9th grade students have in regards to energy thermal. The lab activity described can be adjusted for physics students to mathematically model the energy thermal stored in the water quantitatively. This requires that the students have a grasp of the concept of power and the ability to reason energy transfers from electrical to thermal. Simply use the wattage rating on an immersion heater to get the rate of energy transfer, e.g., 200W at 30s = 6000 J of energy electrical transferred to energy thermal. Students can then plot energy thermal as a quantitative variable and place the heater in a cup of water for a set change in temperature. Graphing EQ versus a change in temperature should result in a slope of approximately (4.18 J/gºC) x (mass (g) of water used) and have units of Joules/degree C. For example if 100g of water were used, the slope would be 418 J/ºC. If compared with another substance, it will be evident that there is a factor, which we call the specific heat capacity to account for different temperature changes for the same mass of different substances when the same amount of E_Q is added.

Conclusion

This activity takes significant work on the part of the teacher. We must resist telling students answers and use our questioning and body language to elicit all student ideas and steer discussions. We could easily hand our students step-by-step instructions to complete this activity and supply accompanying problems. Yet, having students mindlessly input numbers into formulas rarely results in deep conceptual understanding of the science concepts. Furthermore, abstract mathematical representations are far more difficult for students to understand and rarely promote the goals evident in the lesson described. By working to provide students with appropriate experiences and encouraging them to reflect as well as make predictions, we set students up for the investigation – encouraging the students' minds to be engaged as well as their hands.

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Shannon McLaughlin teaches physics and physical science at Norwalk High School and Secondary Science Methods at Simpson College. Shannon previously published an article about circular motion in the Fall 2006 issue of the Iowa Science Teachers Journal. Mahima Bajpai is a graduate of Iowa State University. Questions for the authors of this article should be directed to Shannon at smclaughlin@norwalk.k12.ia.us.