Exposing Students to the Idea that Theories Can Change

Chance Hoellwarth and Matthew J. Moelter, California Polytechnic State University, San Luis Obispo,

Rhe scientific method is arguably the most reliable way to understand the physical world, yet this aspect of science is rarely addressed in introductory science courses. Students typically learn about the theory in its final, refined form, and seldom experience the experiment-to-theory cycle that goes into producing the theory. One exception to this is the Powerful Ideas in Physical Science curriculum (PIPS) developed by the American Association of Physics Teachers.[1] In this curriculum students develop theories based on experiments. The "Heat and Conservation of Energy" unit illustrates the experiment-to-theory cycle in a set of experiments introducing the conservation of energy. The idea of conservation of energy is developed early in the unit; however, students must expand their idea of energy in order to incorporate new phenomenon, namely the specific heat and phase transitions. Yet even with these experiments, the ideas of energy and of a theory remain abstract. In order to address the abstractness of energy, many authors have introduced energy diagrams.[2-5] In these energy diagrams, the height of a bar graph represents the amount of different types of energy, nicely illustrating how energy transfers from one form to another. The PIPS curriculum took this one step further and used area to represent thermal energy when mixing different amounts of water. Thus, the conservation of area illustrates the idea of conservation of energy. Using this as a starting point, we have extended the energy/area diagram so that it includes other aspects of thermal energy, making the idea of a theory more concrete. Every new experiment requires a change in the theory and hence a change in the corresponding energy diagram. In this paper we develop this enhanced energy diagram through a series of experiments taken from the PIPS curriculum. While PIPS is designed for nonscience majors, this sequence of events as a lab or as demonstrations would work for any introductory course. The sequence involves four experiments. We will describe each of the experiments the students perform and the typical results. Then we describe the theory building that subsequently adapts the energy diagram to explain new data. This will demonstrate how the theory building takes place and how the energy diagram is developed based on experimental results.

Experiment #1 – Identifying the important parameters

Students are asked to melt some ice using water. They perform experiments and determine how the temperature and the amount of water affect the amount of ice that the water can melt. This is not as straightforward as it sounds. Students usually begin by measuring the time it takes to melt one ice cube, which at best is related to the "melting power." But after some thought and work, they determine that more water melts more ice if the temperature remains the same and that higher temperature water melts more ice if the amount of water remains the same. The importance of this activity is that it identifies the important parameters, temperature and mass, and it will allow for a "definition" of energy as the ability to melt ice.

Experiment #2 – Mixing

The students are asked to determine a rule for determining the final temperature when mixing water with different initial temperatures and amounts. After the experiments, the students find the final temperature for mixing equal amounts of water at different initial temperatures is the average

$$T_\mathrm{f} = \frac{T_\mathrm{A} + T_\mathrm{B}}{2} \tag{1}$$

and the final temperature for mixing different amounts of water at different initial temperatures is the weighted average

$$T_\mathrm{f} = \frac{m_\mathrm{A} T_\mathrm{A} + m_\mathrm{B} T_\mathrm{B}}{(m_\mathrm{A} + m_\mathrm{B})} \ . \tag{2}$$

The students will resist figuring this out on their own, but we've found that if you wait, with encouragement they will come up with something equivalent to the weighted average result.

Theory Building A – The basic energy diagram

The students tend to be very happy with their algebraic equation; however, we now introduce a different way to represent their equation using a picture (energy diagram). We rewrite the weighted average result, Eq. (2), using algebra to get

$$m_\mathrm{A} T_\mathrm{A} + m_\mathrm{B} T_\mathrm{B} = (m_\mathrm{A} + m_\mathrm{B})\ T_\mathrm{f}. \tag{3}$$

The left side of the equation represents the initial states of the two water samples (before mixing); the right side represents the final states of the waters together (after complete mixing). This rewritten equation can be represented with a diagram. The mass is plotted on the horizontal axis and the temperature is plotted along the vertical axis. A situation where we mixed 2 g of water at 4°C with 1 g of water at 1°C, leaving 3 g of water at 3°C, would look like Fig. 1

This is the basic energy diagram. We have students practice constructing energy diagrams for a variety of situations. They use their equation to determine the final temperature; then they draw the energy diagram. We have chosen the examples to cover the basic possibilities: larger mass–higher tempera-

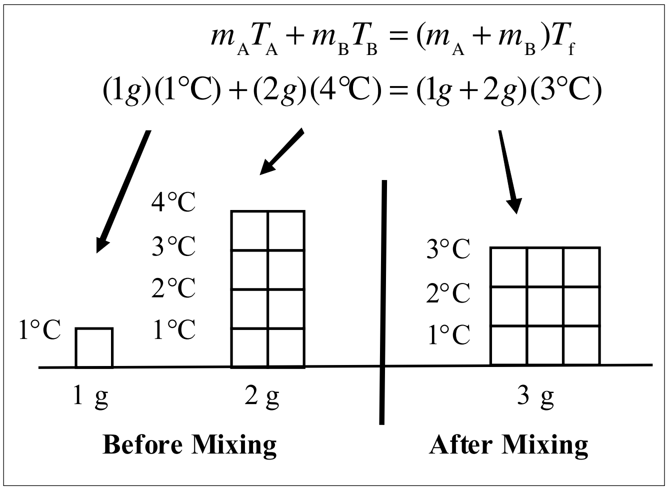

Fig. 1. Energy diagram representing the mixing of different amounts of water at different initial temperatures.

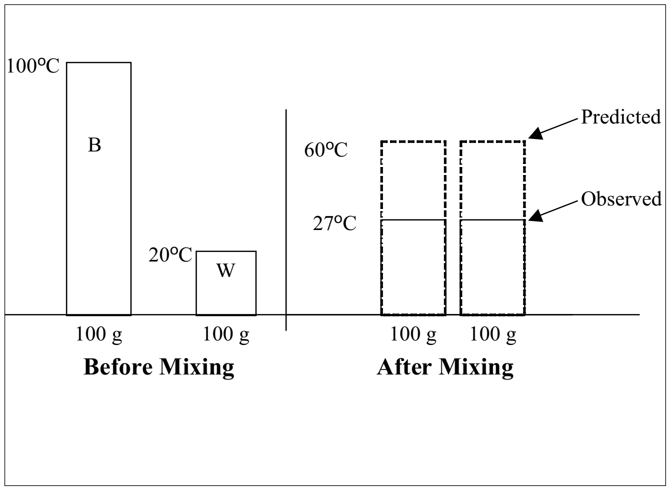

Fig. 2. Energy diagram for mixing hot brass and cool water. The dashed box is the result predicted from the weighted average equation. The solid line is what is observed.

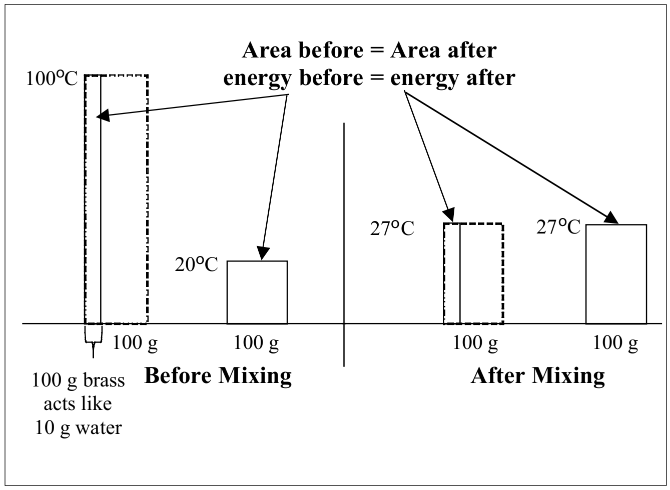

Fig. 3. Modified energy diagram for mixing hot brass and cool water with water equivalent of brass shown with the solid line and the dashed line the actual brass.

ture mixed with smaller mass–lower temperature, larger mass–lower temperature mixed with smaller mass–higher temperature, and any mass mixed with any other mass at 0°C. Then we have the students look at their diagram and answer the following questions:

1) What can you say about the number of boxes (amount of energy) before mixing compared to the number of boxes after mixing? What does this mean?
2) What does a box represent? Think back to Experiment #1.
3) Are there any trends in the energy flow? If so, what are they?

With this prompting, they discover that the number of boxes (the area) is the same before and after, that each box represents energy, and that energy appears to flow from the high-temperature object to low-temperature object. We declare that a 1 g by 1°C box has the energy of one calorie.[6]

Experiment #3 – "Mixing" brass and water

The students are asked to predict the final temperature when 200 g of brass at 100°C are immersed in 100 g of water at 20°C. They use the energy diagrams (or their equation) to determine that $T_f = 60°C$. They then do the experiment and find that $T_f = 27°C$. The students are then asked how much water at 100°C needs to be mixed with the 100 g of water at 20°C to produce the final temperature actually observed, 27°C in this case.

Theory Building B – Water equivalent or specific heat

The students predicted that if 100 g of brass at 100°C were mixed with 100 g of water at 20°C, the final temperature of the mixture would be about 60°C. In reality they find that the final temperature was closer to 27°C. Looking at the energy diagram in Fig. 2, it appears that the system ended up with less energy than it started with.

This seems to imply that the energy before mixing does not equal the energy after mixing, or, in other words, energy is not conserved. At this point there are two choices. The students can conclude that energy is not conserved when we mix different substances (a perfectly reasonable viewpoint) or they can conclude that there is more to the story and that they need to modify their understanding of energy somehow. With the appropriate incentives they choose to modify their understanding of energy.

Energy diagrams have successfully predicted water temperatures, so the energy of the water should be correct. The new addition was the brass. Brass is not water; perhaps one gram of brass does not act the same as one gram of water. In other words, maybe one gram of brass at 100°C does not contain the same amount of energy as 1 g of water at 100°C.

In order to find out how much energy the brass started with, students solve the following equivalent problem: How much water at 100°C (the initial temperature of the brass) needs to be mixed with 100 g of 20°C water in order to produce the observed final temperature of 27°C? They find that it takes about 10 g of 100°C water. This means that 10 g of water at 100°C has the same thermal effect as 100 g of brass at 100°C.

The energy diagram needs to be modified so that energy is conserved (area is conserved) when mixing different substances. The energy diagram for materials that are not water will use a dashed box to represent the actual mass of the material and a solid box to represent the equivalent mass (i.e., how much water would contain the same amount of energy as the other substance). The solid box represents the amount of energy the object contains. The dashed box is just used as a reference to show how much material is actually there. If this is done, then the area, and thus the energy, is conserved. This new extended energy diagram will look like Fig. 3.

Experiment #4 – Phase changes

The students are asked to predict the final temperature when 100 g of water at 20°C are mixed with 10 g of ice at 0°C. They use energy diagrams (or their equation) to determine that T_f = 18°C. They then do the experiment and find that T_f = 11°C. Something is not right. We ask them to calculate how much energy is needed to melt one gram of ice. Students do this by calculating the energy before mixing and the energy after mixing. The missing energy must have melted the ice. Students usually determine that it takes 70-80 calories to melt one gram of ice.

Theory Building C – Phase changes, melting

In Experiment #4 students found that approximately 80 calories must be added to 1 g of 0°C ice in order to change it into 0°C liquid water. For example: They could have mixed 1 g of 0°C ice with 10 g of 20°C water. The final temperature would have been around 11°C.

In the example in Fig. 4, 80 calories are missing. That is why "energy to melt 1 g of ice" is -80 calories. This was the energy needed to melt (change from a solid to a liquid) 1 g of ice at 0°C. This "missing" energy needs to be incorporated into our energy diagrams. How best to accomplish this takes some class discussion. With some guidance, the students can see that this can be represented by an energy hole associated with a solid. If 80 calories are added to 1 g of the solid at the melting point (the hole is filled), then the solid (ice) becomes a liquid (water). If 80 calories are removed from 1 g of liquid water at the freezing point (the hole is dug), then the liquid (water) becomes a solid (ice). Therefore, the energy diagram of a solid will include an energy hole (see Fig. 5).[7]

It appears that the mass of the solid has changed. It looks like there are 2 g in the solid phase and 1 g in the liquid phase, but this is not really true. The 1 g of ice really has two components to its energy. There is the thermal energy, which is the same as the energy diagram from before, and the phase energy, which is the energy associated with the phase transition. Once a sample has two different types of energy, the horizontal axis no longer represents the mass of the sample. When the energy diagram is drawn, the thermal energy and the phase energy can be bracketed together to indicate that both energies are associated with the same amount of material. As a practical concern, the hole is difficult to draw so the horizontal line will represent zero energy, indicated with a zero to the left of the line. Area above this line is positive energy; area below this line is negative energy. This new form of energy diagram is shown in Fig. 6.

The liquid-gas phase change can be treated in the same manner. Students are asked to predict the final temperature when 3 g of steam are added to 100 g of water at 20°C. They

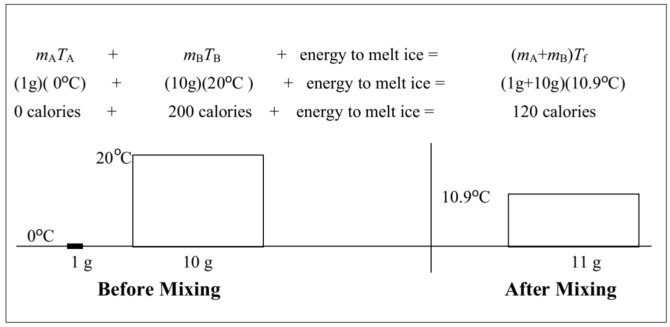

Fig. 4. Determination of the amount of energy needed to melt ice.

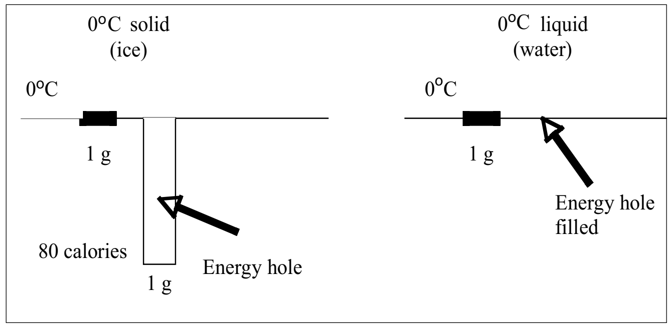

Fig. 5. Energy diagram for ice at 0°C changed to water at 0°C showing the filling of the energy hole.

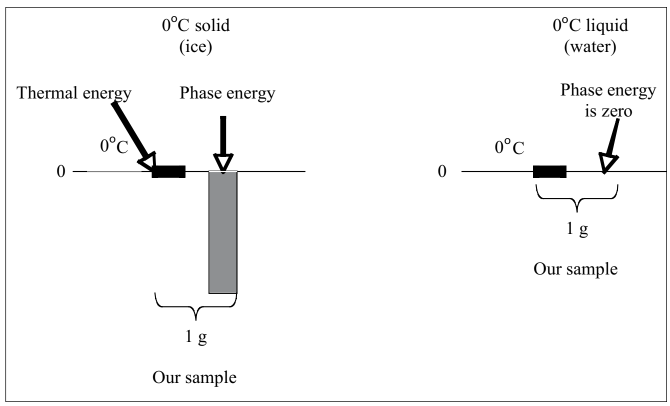

Fig. 6. Energy diagram on the left shows the ice at 0°C consisting of both thermal energy and phase energy. The right shows the corresponding situation when the ice has melted and is now water at 0°C. Notice that the brackets indicate the total mass of the sample.

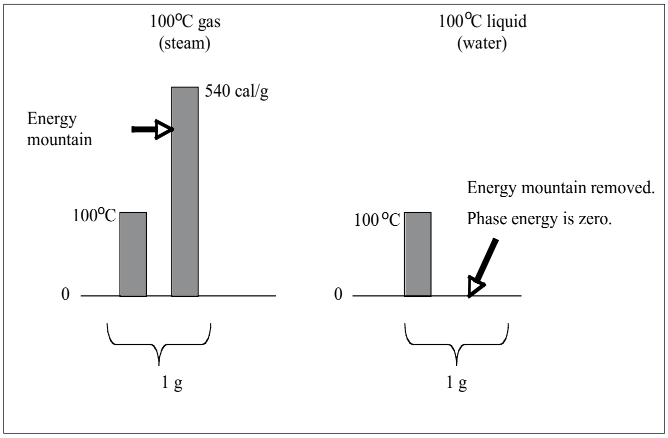

Fig. 7. Energy diagram for steam at 100°C changed to liquid water at 100°C showing the loss of the energy mountain.

predict $T_f = 22.3°C$ if they go back to the equation or $T_f = 24.6°C$ if they assume it takes 80 calories to turn one gram of liquid water into steam. They then do the measurement and find that $T_f = 36.9°C$. We then extend our energy diagram so that the gas phase has a corresponding energy mountain. An example is shown in Fig 7.[7]

Conclusions

We have introduced an enhanced energy diagram, one that addresses specific heat and phase changes, to accompany a series of experiments adapted from the PIPS curriculum. This dynamic development allows students to see the experiment-to-theory cycle that goes into producing a theory, something that is usually not addressed in the standard curriculum.

Acknowledgments

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6. While the joule is the standard unit of energy, numerical convenience and student experience from chemistry and biology make the calorie an easier and more familiar choice.
7. The energy hole and mountain are arbitrary. There could be a mountain associated with the liquid phase, or two holes associated with the solid phase. Because we mostly deal with liquid water, it makes it easier if there is only a hole or mountain with the least used solid and gas phases.