VI. Heat and Temperature

Concept Review

Warm-Up Exercises

Conflicting Contentions

1. Galileo’s Thermometer
2. Fire Syringe
3. Pop Goes the Soda Bottle

Qualitative Reasoning

1. Heating curves
2. Hot pack / cold pack
3. Bimetallic strip
4. Specific heats of metals
5. Mechanical equivalent of heat
6. Frozen orange juice and grape juice

Can You Explain This?

1. Re-useable hot pack
2. Refrigerator cooling?
3. Exception to the Second Law?
4. Hypothermia
5. Match and ice cube
6. Heating water in a paper cup
7. Freezing ice cubes

CONCEPT REVIEW

1. Heat is a form of energy in transit from one object to another. Heat is not stored in an object.

2. Temperature is a property of an object. Temperature only has meaning for large aggregates of particles: individual particles (atoms, molecules) don't possess a temperature.

3. Temperature is related to the average kinetic energy of the particles of a system.

4. Heat flows from one object to another due to a difference in temperature.

5. Heat flow may result in a change in temperature of an object, or the energy flow may be used for other purposes, such as breaking chemical or physical bonds between the particles of a substance.

6. An early theory of heat, the caloric theory (from the Latin calor, meaning heat) assumed that heat was a fluid. The *calorie* was defined as the amount of heat needed to raise one gram of water one degree Celsius.

7. James Prescott Joule was able to demonstrate in the mid-1800's that heat was a form of energy. The SI unit of energy is the Joule, named in his honor. One calorie is equivalent to 4.814 Joules. This conversion is called the mechanical equivalent of heat, since the Joule is defined in the field of mechanics as the amount of energy resulting from one Newton of force acting through a distance of one meter.

8. On the microscopic level, heat always results from forces acting through distances, which is microscopic work. On the macroscopic level, heat is the result of randomly applied microscopic work. Macroscopic work is the result of microscopic work acting simultaneously in the same direction (i.e., a gas piston expanding).

9. Thermal energy can be transferred from one object to another by conduction, convection, or radiation. Conduction occurs when particles of matter collide with each other directly. Convection occurs when large collections of particles at the same temperature move through space together. Radiation is the transfer of energy through space by the electromagnetic spectrum instead of through particles with mass.

THE THREE LAWS OF THERMODYNAMICS

The first law of thermodynamics states that changes in internal energy of a system (U) can occur either as a transfer of heat (q) or as a transfer of work (w):

$$\Delta U = q + w$$

If heat is added to a system, then q is positive and energy is added to the system; if q is negative, then heat is flowing out of a system and energy is lost by the system.

If a gas expands, then it loses energy and work is negative; if a gas contracts then work is done on the system and it gains energy.

The first law implies that energy is conserved, since energy must come from somewhere and it must go somewhere: it can't be created or destroyed, only transferred from one object or system to another in the form of work or heat.

The second law of thermodynamics states that heat spontaneously flows from a hotter object to a colder object. It is possible to convert some of this heat into work (your car engine does this; so do turbines at a power plant) but the second law shows that there is a limit to how much heat can be converted to work. This limit, which is called the efficiency of a process, is based on the temperatures of the two objects.

Although heat spontaneously flows from a hotter object to a colder one, that doesn't mean that heat can't flow the other direction. However to do that, one must do First Law work to make it happen.

Scientists have defined a concept called *entropy* to help us understand the second law. Entropy is the heat flowing into or out of a system divided by the temperature of the system. Entropy is a property of a system, just as volume, mass, and temperature are properties of a system.

It can be shown that another way of stating the Second law is that *any* process, whether spontaneous or not, must increase the total entropy of the universe. Again, that doesn't mean that the entropy of a system can't decrease, only that the total entropy of all systems or objects involved in the process must be greater than zero, or at best equal zero.

The third law of thermodynamics states that the entropy of a perfect crystal at absolute zero is zero. The Third law will not be used in these exercises.

WARM-UPS

1. Why do many directions for baking a cake require a lower oven temperature if a glass pan is used instead of a metal pan?

2. On a cold wither's day, the living room feels cool if you walk into it from a hot kitchen, but warm if you walk into it from the outside. Why is that, since the temperature of the room is the same?

3. Why do sidewalks have lines in them, and why do bridges have expansion joints?

4. The carbon dioxide in a fire extinguisher is at air temperature. But when the carbon dioxide is expelled through the nozzle, it can get cold enough to chill the water vapor in the air to snow. How is that possible?

5. If we warm a volume of air, it expands. Does that mean that if we expand a volume of air, it warms?

6. Explain how perspiration is able to cool the body.

7. Rising smoke from a cigarette doesn't always reach the ceiling. Sometimes it rises to a certain height then stops; sometimes it sinks again. Why is that?

8. Why does a weather balloon expand as it rises into the atmosphere?

CONFLICTING CONTENTIONS

1. Galileo’s Thermometer

The Situation

“Here’s something neat I wanted to show you,” Mr. Nicholls said one day at the start of class, “It’s called Galileo’s thermometer.”

In the front of the room was a tall glass cylinder. There was a clear liquid in the cylinder with what appeared to be five glass balls with different amounts of colored liquid in them and metal tags with numbers hanging from them. Three of the glass balls were floating on the top surface, the other two were resting at the bottom of the cylinder.

“Did you say that was a thermometer?”, asked Beth, “Does it really measure temperature?”

“Yes”, he said, “Let me show you.” The teacher turned on a blow dryer and began heating the outside of the cylinder with sweeping motions. After a short period of time, a glass ball with the number “76" attached to it sank to the bottom of the cylinder. “See how the sphere showing a temperature of 76 Fahrenheit just sank to the bottom? Since the lowest floating sphere is 80 Fahrenheit, that is the temperature of the thermometer – or, more precisely, the temperature of the liquid is between 76 and 80 degrees.”

“I’ve seen those before,” Daniel added, “They’re kind of neat.”

“So how do they work?”, Mr. Nicholls asked. “I knew that one what coming”, John remarked.

“I know this one!”, Frank exclaimed. “When the liquid gets hot, the heat pushes down on the balls, so they sink to the bottom.”

“So why don’t they all get pushed down together at the same time?”, Alonzo asked.

“Because it pushes down on the lowest ball first,” he said.

“Why?”, Cathy asked. “Because it’s lowest”, he explained.

“You realize that what you said doesn’t make any sense whatsoever and isn’t based on any real physics, don’t you?”, Mr. Nicholls replied. “Yeah,” Frank agreed, “But I wanted to be the first one to be wrong this time.”

Do you have an explanation for Galileo’s thermometer?

The Predictions

After some discussion, the class agreed that the thermometer had to be based on the properties of the liquid, or the properties of the spheres, or both. The class then split up into two groups, based on whether they thought it was the properties of the liquid or the properties of the spheres that was more important. Here are their best explanations:

Liquid:

> Heating a fluid, whether air or a liquid, creates convection currents when the hotter part of the liquid rises. Using Frank's idea as a starting point, the downward convection currents – not the heat – push the balls to the bottom of the cylinder. The lowest floating ball is pushed to the bottom first because it is at the front of the current.

Spheres:

> Heat causes matter to expand. That's why hot air rises, since it is less dense than the cooler air around it. When the spheres get warmer, they also expand, which changes their density. This group guessed that each sphere had a slightly different density, which what why they had different amount of colored liquid in them. When the density of the sphere changed compared to the liquid around it, the sphere sank.

"One of your explanations is so very close, but it's backwards," Mr. Nicholls acknowledged.

Can you figure out the flaw in each argument? Based on Mr. Nicholls statement, can you surmise the correct explanation of Galileo's thermometer?

The Solution

Convection currents cannot explain Galileo's thermometer. First, although the lowest floating ball would be the first to move to the bottom, the others should also demonstrate motion, which they don't. Second, there is not enough room in the cylinder to create convection currents that could circulate such large spheres. But the most important argument against this hypothesis is that if all of the spheres were that well balanced, then logically it would be just as likely that the highest sphere at the bottom of the cylinder would rise to the top with the upward moving convection current as the lowest sphere at the top would move downward with the descending convection current.

There are two problems with the second hypothesis. First, solids, such as the glass spheres, do not expand very much with an increase in temperature: certainly much less so than gases or liquids. Therefore, the density of the spheres should not change enough to cause the rising or sinking. Moreover, if the explanation was correct, then heating the spheres with the blow dryer should have caused the lowest one to rise, since it became less dense with heat, instead of causing the lowest floating ball to sink.

Galileo's thermometer is based on changes in density with temperature, but it isn't the spheres that change density, it is the liquid. Each of the spheres does have a slightly different density. As the warmer liquid becomes less dense, the sphere that use to float because its density was less than that of the liquid now sinks because its density is greater than that of the surrounding liquid.

Compare Galileo's thermometer to Cartesian Diver in Chapter 5.

2. Fire Syringe

Mr. Nicholls place a small wad of cotton in the bottom of a cylinder with a tight-fitting piston. To everyone's amazement, when he pushed down quickly on the piston, the cotton burst into flame.

"How did you do that?", Frank asked.

"That's what I was going to ask you," he said.

"I took chemistry last year in high school," Beth said, "So I know that you need oxygen to make something burn. So I bet that when you push down on the handle, the concentration of the oxygen increases suddenly and that causes the reaction to start."

"Yes, it's true that oxygen is needed for the cotton to burn", he replied, "and yes, the concentration of oxygen increases when the volume gets smaller, but that isn't why the cotton catches fire. You left something out in your explanation of combustion."

What did Beth forget from her chemistry class?

"I think I know," said Daniel, "If I want to start a burn pile on fire, I need a match. And a lawn mower or car uses a spark plug to ignite the gasoline. Did the piston make a spark when you pushed down hard? I didn't see one."

"No, I didn't create a spark" the instructor replied, "but it is true that to start a fire you do need a source of energy. However, a lot of materials, like gasoline also have a flash point. The flash point is a temperature where a material can ignite without a spark because enough thermal energy is already present in the surroundings to start the reaction."

"So are you saying that you reached the flash point of the cotton when you pushed down on the plunger?" Mary asked. "Yes, I am," the teacher replied.

"So how did you do that, just by pushing on a plunger?" Frank asked.

"That's my question to you. But here are two hints. First, it's either based on the first law or the second law of thermodynamics. And second, it's important that I push down on the plunger quickly, or the cotton won't combust."

So is it the first law or the second law that is the key to the fire to the fire syringe?

And why must the plunger be pushed quickly? Try to come up with your own reasoning before reading the final hints.

Here are the last set of hints for the explanation of the fire syringe. The law of thermodynamics that applies the most in this case is the first law, which states that energy is transferred into or out of a system either in the form of work or heat. Second, by pushing on the plunger quickly, there is not enough time for energy to be absorbed from or released into the air surrounding the piston.

The scientific name for this condition is ‘adiabatic’, meaning no heat exchanged between the system (in this case, the piston and its contents) and its surroundings. That means the change in the internal energy of the system – air plus cotton – during the process must be zero.

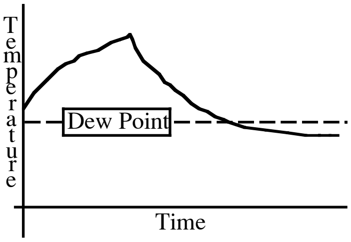
Heat, work, no change in total energy, increase in temperature of the system. Can you finish putting these ideas together into a clear and plausible written explanation of the fire syringe?

3. Pop goes the Soda Bottle

“Have you ever noticed the fog that forms sometimes when you pop the cap off a bottle of soda? Let me show you what is happening to produce that. But before I do, here is the key concept: the dew point of a liquid is a temperature where fog will form spontaneously. The dew point depends, in part, on the amount of vapor in the air about the liquid. In the case of water, we call that the humidity in the air.”

Mr. Nicholls then produced an apparatus consisting of a glass bottle with a rubber stopper pushed tightly into the neck and some water in the bottom. The stopper had been drilled and sealed with a bicycle pump hose so that air could also be pumped into the bottle. Finally, Mr. Nicholls had a thermistor, which is an electronic thermometer, sealed inside the bottle as well.

Mr. Nicholls then began pumping air into the bottle. The curve shows how the temperature of the air changed as he pumped, the sudden change occurred when the stopper popped out of the bottle. And, sure enough, at that point, fog formed inside the bottle.



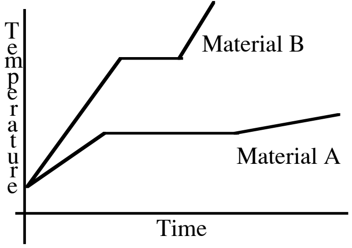
The explanation for this demonstration is either very similar to that of Galileo’s thermometer or the explanation of the fire syringe. Can you figure out which one?

Also, can you explain why the temperature rises when air is pumped into the bottle, and why it suddenly drops when the stopper pops off?

QUALITATIVE REASONING

1. Heating curves

One hundred grams of two solids with melting points between 30 and 60 Celsius were melted and poured into two separate beakers then allowed to re-solidify. The beakers were then placed side by side on the same hot plate, which produced heat at a constant rate.



Based on the two heating curves shown on the graph:

Which material has the higher melting point, and how do you know?

Which material has the larger enthalpy of fusion, and how do you know? (Enthalpy of fusion is the amount of thermal energy per gram it takes to melt a solid).

Which liquid has the higher specific heat, and how do you know?

2. Hot pack / cold pack

It is possible to buy a certain type of ‘chemical’ hot pack (or cold pack) which increases (or decreases) in temperature when a seal between two liquids is broken. Suppose a certain hot pack increases by 15 Celsius when used, whereas a certain cold pack decreases by 10 Celsius when used.

How is it possible to produced either ‘heat’ or ‘cold’ from a chemical reaction?

What general conclusions can you draw from this information concerning the operation of these two chemical hot packs and cold packs concerning the flow of thermal energy and the amount of thermal energy absorbed or released?

What assumptions do you have to make about the hot and cold packs in order to draw any useful conclusions concerning the relative change in temperature of each one when used?

3. Bimetallic Strip

A bimetallic strip consists of two different metal strips bonded together along one surface. This type of strip is often used in thermostats to control the temperature of a room. As the strip is heated, it tends to curve in one direction because of the different thermal expansion coefficients of the two metals.

If a flat, bimetallic strip laying on a table top tends to curl upward with increasing temperature, which metal, the one on the top or the one on the bottom next to the table, has the larger coefficient of thermal expansion? That is, which metal expands more on heating?

What would happen to the strip if the temperature in the room decreased instead of increased, and why?

How could you make a bimetallic strip that curled by a larger amount with the same change in temperature compared to the one you currently have?

4. Specific heats of metals

Equal masses of aluminum, copper, and lead ‘shot’ are heated in containers placed in boiling water. Each sample is poured into separate containers of water, with each container having the same mass of water. The temperature of the water with the aluminum added to it rises 15 Celsius; the water with copper rises 6 Celsius, and the water with lead rises 4 Celsius.

How do the specific heats of aluminum, copper and lead compare?

One can readily observe that the volume of aluminum is much greater than that of copper or lead, with lead occupying the smallest volume. What does this observation mean, and why doesn’t it have any impact on the other observations made in this demonstration?

5. Mechanical Equivalent of Heat

500 grams of lead shot at room temperature (23 Celsius) is placed in a 2 meter long cardboard tube. The tube is turned end-over-end 40 times. The lead shot is immediately poured into a Styrofoam cup containing 50 grams of water. The temperature rises from 23 Celsius to 25 Celsius.

How does this experiment demonstrate the mechanical equivalent of heat?
Can this data be used to calculate the mechanical equivalent of heat?

Hint: Why did the temperature of the water increase?

6. Frozen orange juice and grape juice

I have often noticed that a can of frozen orange juice is more likely to develop frost on the outside of the can compared to a can of frozen grape juice. I have also noticed that the grape juice is more likely to come out slushy when opened, and takes much less time to dissolve in water when reconstituted compared to orange juice.

Based on these observations, what conclusions can you make concerning the thermal properties of orange juice and grape juice, assuming the two concentrates have approximately the same mass?

BONUS: Is the assumption that the two concentrates have the same mass important? Is the assumption valid?

CAN YOU EXPLAIN THIS?

1. Re-useable hot pack

There is a certain type of re-usable hot pack available on the market. To activate it, the user presses on a ‘button’, and the liquid pack gets warm and also feels more ‘slushy’. To reactivate the hot pack, place it in very warm water until it is all liquid again, then take it out and don't disturb it while it cools.

Can you explain how the re-usable hot pack works?

2. Refrigerator cooling?

If the kitchen is cold on a winter's day, you can warm it up by turning on the stove and leaving the door open. But if the kitchen is hot on a summer's day, you can't cool it off by leaving the freezer door open. Can you explain why not? Which principle of thermodynamics applies in this situation?

3. Exception to the Second Law?

"Wait a minute, Mr. Nicholls," Frank says. "You told us that, according to the Second Law, hot things always get cooler and cold things always get hotter. Then how do you explain an air conditioner? They make the inside of a room cooler and dump the heat outside the house, where it is warmer."

Do you have an answer for Frank?

4. Match and Ice Cube

There is more thermal energy is a 10 kg block of ice than in a burning match head.

Can you explain this statement?

5. Hypothermia

Although certainly a tragedy, most of the passengers of the Titanic must have died from hypothermia in the icy waters of the North Atlantic rather than from drowning. Hypothermia is the dangerous lowering of a person's body temperature. It can occur on land even under 'mild' temperature conditions, such as air temperatures in the 50's. One of the early symptoms of hypothermia is confusion or a loss of judgment.

Why is hypothermia so much more likely to occur in water than on land?

One way to counteract hypothermia is to give warm liquids, but a better remedy is direct skin-to-skin contact. Why is that?

6. Heating water in a paper cup

Try this yourself. Fill a paper cup with water and set it on a ring stand. Light a bunsen burner under the cup and the cup won't burn. In fact, you can even boil the water in the cup.

Can you explain this strange behavior?

7. Freezing ice cubes

It is true that a tray of ice cubes prepared with warm water will freeze more quickly than a tray of ice cubes prepared with cold water. Can you explain why?