Under Development
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UNIT NINE

Temperature and Heat

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Hands-On Physics Activities with Real-Life Applications
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9.1 Temperature

The temperature of a body is often confused its internal energy by introductory physics students. Yes, the internal energy of a body is related to its temperature, but also to its mass. Consider the following relationship for a monatomic gas:

$$U = \frac{3}{2}kT$$

where temperature is expressed in Kelvins and the constant, *k,* is Boltzmann's constant. This equation for internal energy is per atom. The greater the number of atoms that are contained within a volume of gas, the greater the internal energy so long as the temperature remains the same. More atoms means more mass; thus, internal energy is related to both temperature and mass.

9.2 Thermal Expansion

Thermal expansion is most often directly related to change in temperature. Thermal expansion often – but not always – occurs with increasing temperature. Can you think of a situation where it does not? (One answer is water; as water cools below a certain temperature close to freezing, it actually begins to expand as hexagonal crystalline rings form that require more space than do unbound water molecules.) As the energy of particles increase with rising temperature, they bounce off one another with increasing speed thus requiring more space. As a gas is heated, for instance, its atoms or molecules pick up increasing speed and hit the walls of the container with increased speeds. The net effect is to increase the pressure on the walls of the container. If the container's walls are movable, the gas expands. If the walls are immovable, the pressure within the container merely increases. Both of the following laws describe the relationships for thermal expansion: $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$ (for an ideal gas) and $\Delta\ell = \alpha\ell\Delta T$ (for linear expansion; similar expressions also exist for area and volume expansion).

9. 3 Specific and Latent Heats

Specific and latent heats are sometimes confused, but they should not be. The words "specific heat" is sometimes used interchangeable with the phrase "heat capacity", but heat capacity is sometimes confused with internal energy. "Heat capacity" is therefore a deprecated term; use specific heat to avoid this confusion.

9.3.1 Specific Heat

Specific heat (of a solid) relates the capability of a substance to absorb a certain amount of heat (hence heat capacity) for a given change of temperature. For instance, one material can absorb a certain amount of heat and have only a small rise in temperature. Another mother can absorb the same amount of heat, but it can have a high temperature change as a result. Specific heat is closely related to the molecular structure of a substance; the more degrees of freedom of movement there are in a substance, the less will be the temperature rise for a given infusion of heat. This is so because the energy might appear as vibrational, rotational, or translational. Only the translational is manifest in the rising temperature of a body. So, which the internal energy might go up dramatically, the temperature will rise only a limited amount. Hence, different substances will have different specific heat values depending mostly upon their internal structures.

9.3.2 Latent Heat

Latent heat describes the amount of heat associated with phase change (say from liquid to a gas or from a liquid to a solid). The latent heat of vaporization associated with water turning to steam (or even the mere evaporation of water!) and visa versa is 540 kilocalories per kilogram (deprecated units) or $22.6\text{x}10^5$ Joules per kilogram (preferred units). The latent heat of fusion associated with water turning to ice and visa versa is 80 kilocalories per kilogram (deprecated units) or $3.33\text{x}10^5$ Joules per kilogram (preferred units). That is, these numbers represent the amount of energy required or given off to change the internal structures of a substance. The amount of heat required to make the phase change is independent of the direction of that phase change, but it does depend upon the nature of the matter. The total amount of heat required in a phase change, Q, is equal to a product of the mass and latent heat value for the specific matter and phase change in question. In algebraic form we have $Q = mL$.

9.4 Heat Transfer

Heat transfer, that is the movement of thermal energy, can take place in any of three forms: conduction, convection, and radiation. Conduction results from contact. A warmer object in direct contact with a cooler object will result in the transfer internal energy from the warmer object to the cooler object. Heat, the thermal vibration associated with dynamic motion of atoms and molecules (vibration, translation, rotation) is given up by the warmer body to the cooler body in this process. Heat should never be thought of as a substance; rather, the word is used to describe the transfer of energy. Convection is heat transfer that results from the motion of matter such as rising warm air. Radiation is heat transfer that results from the transfer of radiation resulting from thermal processes. The medium of exchange is not matter; in this case it is electromagnetic radiation – most often sensed as infrared radiation. Radiation from warm bodies is described by Stefan's law:

$$P = \frac{\Delta Q}{\Delta t} = \sigma A e T^4$$

9.5 Thermodynamics

It's hard to address all of thermodynamics in a small review such as this, but probably the most important law of thermodynamics (corresponding in importance to Newton's second law of motion, $F=ma$) is the first law:

$$\Delta U = Q - W$$

That is, between any equilibrium states the change of internal energy is equal to the difference of the heat transferred INTO the system, *Q,* and the work done BY the system. In other words, energy is conserved! Recall that work, *W,* can be written as $P\Delta V$ - pressure times the change in volume (for constant pressure). Thermodynamic processes are typically of four types: isothermal (constant temperature), isobaric (constant pressure), isometric (constant volume), and adiabatic (no heat transfer). Change in entropy (for a constant temperature) and thermal efficiency are also central ideas of thermodynamics. They are readily described with the following relationships respectively:

$$\Delta S = \frac{Q}{T} \quad \text{and} \quad \varepsilon = \frac{W_{net}}{Q_{in}} = 1 - \frac{T_{out}}{T_{in}}$$

FOR THE TEACHER

Thermodynamics is an incredibly important field for teachers to address. While it is sometimes characterized as a "dead" field (essentially exhausted as far as research is concerned), its study can pay tremendous dividends due to the vast number of practical applications in the everyday world.

9.1.1 Temperature Scales

Discussion: Temperature scales come in three well-known forms, but there others as well. Celsius, Kelvin, and Fahrenheit are the most famous, and Rankin comes in a close fourth. Because students are most familiar with Fahrenheit, it is a good graphing exercise to give students corresponding values of temperatures in two scales and ask them to find the relationship. The standard formulas for conversion between Celsius and Fahrenheit are given by the following forms:

$$C = \frac{5}{9}(F - 32^\circ) \quad \text{and} \quad F = \frac{9}{5}C + 32^\circ$$

Many students appear to have a mental block when it comes to remembering whether to add or subtract the 32^o before multiplying by the 5/9 or 9/5 factor. There are two approaches to dealing with this difficulty – either have the students make mental calculations for 212^oF (to convert 212^oF to 100^oC

requires that 32° be removed before multiplying by 5/9) or have them adopt a different "symmetrical" formula based on the concept that both F and C scales correspond precisely at –40°.

$$C = \frac{5}{9}(F + 40^\circ) - 40^\circ \quad \text{and similarly} \quad F = \frac{9}{5}(C + 40^\circ) - 40^\circ$$

Note the symmetry of the relationships; also note that any one of the above equations can be, through algebraic manipulation, be converted into any other of the remaining thee equations. The general rule for use of this second set of equations is simple, "Always add 40° before multiplying by 5/9 or 9/5 before subtracting 40°." The only thing students have to remember then is that Fahrenheit units are smaller than Celsius units and to apply the 5/9 or 9/5 correspondingly.

9.2.1 Thermal Expansion

Discussion: There are lots of examples of thermal expansion, and many can be readily demonstrated before a class. On way of doing it is with a bimetallic strip – a unit with two bonded strips of metal each with a different coefficient of linear expansion. By putting the metallic strip into a flame, the strip will curl one way; but putting it into a cold substance such as ice water, it will been the other direction.

A loop and ball demonstration is also quite nice. A metallic ball will pass easily through a "tight fitting" metal hoop. When the ball is heated, it will no longer pass through the metal hoop. It's always interesting to ask the students what will happen when the ring is heated instead. Some will argue that the hole will get bigger and other will argue that it will get smaller. It will get bigger. Can you see why?

It's also quite easy to show thermal expansion when heating rods of metal or liquids. Liquids such as those contained within a thermometer show this clearly. A metal rod expands much less than most liquids for the same change of temperature, so a bit more ingenuity is required to demonstrate it. Place a metal rod over a horizontal nail. Attach to the head of the nail a paper pointer. Heat the rod. As it expands one end remains fixed and the other rolls over the top of the nail causing the pointer to turn correspondingly. An ingenious physics teacher will know how to change the perceived rotation into linear distance.

9.1.3 Particle Speed in Relation to Temperature

The dispersion of ink droplets in water can be used to find the relationship between absolute temperature and thermal propagation of particles according to the following relationship:

$$\frac{1}{2}mv^2 \propto kT$$

Starting with two beakers that contain water at different temperatures, ask the students to notice the relative rates of propagation and explore way speed of the droplets are different in the two beakers. During the activities student should be able to develop the question "How does temperature effect speed of molecules?" and then developed a way of testing this. For example, they place a drop of ink in a beaker containing water at 70°C and, using a stopwatch and a small scale, they calculate the speed of the ink's dispersion. They then can perform this observation at different temperatures. Finally the students can plot a graph between *absolute temperature* and speed of molecules and find the relationship between them. Caution: While v^2 is proportional to T, students might generate a straight line if the variation in temperature is too small.

9.3.1.1 Specific Heat

Discussion: It's an easy thing to conceptually develop the need for the term specific heat. Take a given mass of pennies and the same mass of aluminum or steel washers and put them in hot water. Quickly transfer them from the hot water to separate Styrofoam cups filled with cool water and let them come to equilibrium. Then, measure the temperature change. Students will see a specific amount of heat has been transferred from the hot water to the cool water. Some metal have a greater "heat capacity" than do others. Here is a series of steps that might be used:

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1. Place three different objects of the same mass into boiling water and let them come to equilibrium.
2. At this time also prepare three identical cups of room-temperature water and place a thermometer in each to ensure that they have the same temperature. Be certain to determine the mass of the water before pouring it out. Put just enough water in each cup so that it will cover the object to be placed in it. If possible, use styrofoam cups as shown in the attached picture. These cups are excellent insulators and will not absorb a significant amount of heat from the water, and they can be ignored in future calculations.
3. Ask students to predict what will happen to the temperatures of the cups of room-temperature water if they would move each of the objects from the boiling water to its own cup of the room-temperature water. (The temperature will go up.)
4. Ask students if the temperature rise will be the same in all cases. (You will probably get a variety of answers.)
5. Have the students transfer the objects, each into its own cup of room-temperature water and note the rise in temperature. The students will see that each object causes the temperature to rise different amounts.
6. Have students explain why the water temperature rose by different amounts (e.g., 1.3^{o}C, 2.1^{o}C, 3.8^{o}C). They will probably note that each material has a different capacity to carry heat (hence, the phrase "heat capacity" has a natural meaning – and they have developed the concept before the term is applied which is important in a constructivist approach using any lesson cycle).
7. Note that "specific heat", c, "specific" to various materials and is applied to a "specified" quantity of mass, 1g or 1kg. You should note that just like with the measurement of mass, it is based on a definition. That is mass is a fundamental quantity. Similarly, specific heat of water is defined a 1 calorie per gram (or the equivalent number of Joules which came about later once the mechanical equivalent of heat was worked out).
8. If the students are made familiar with the definition $Q=mc\Delta T$, then they can work out the specific heat of the various objects if the mass of the water, the mass of the object, and the temperature change is known.

9.3.1.2 Latent Heat

Discussion: It will amaze students if they are asked to heat a volume of ice water, keeping it stirred and periodically measuring the temperature. Some students will be amazed that the temperature of the water won't begin to rise until all the ice has melted. "Where has all the heat gone?" they wonder. It has gone not into heating the water, but into breaking down the molecular bonds of the ice. A certain amount of heat per unit mass is required to do this. Similarly, when cooling water down, water at 0^{o}C must release an identical amount of "latent heat" before it can become ice.

9.4.1 Heat Transfer

Discussion: Heat can be transferred in any of three ways: conduction, convection, and radiation. Here is one way to inform and befuddle your students with regard to conduction. Point out a block of wood and a block of metal, both at room temperature. If they are at the same temperature, they ought to feel so, right? Wrong! When students pick up the metal it feels cool to the touch, and much cooler than the wood at presumable the same temperature. Can you explain why? The human body is a poor sensor of temperature, but it is a good sensor of heat flow. When one is in a room roughly equal (actually lower due to a regular heat flow from the body) to one's body temperature, one is unaware of the heat flow. When the heat flow increases above the norm, the body senses coldness due to the resulting loss of heat. When the heat flow decreases below the norm, they body senses heat due to the accumulating heat within the body. Heat flow is directly proportional to the temperature difference. The greater the temperature difference, the greater the heat flow and the more rapidly one becomes uncomfortable.

Convection is readily shown with two jars filled with hot water, the cold jar positioned above the hot jar. An index card is used to separate the fluids. The hot water might be colored read; the cold water blue. Removing the index card between them will show interchange and intermixing of the fluids.

Radiation is readily shown with the use of an infrared lamp and the human hand or with a thermometer.

9.5.1 Thermodynamics

Discussion: The concept of conservation of energy is most worthy of note in this law.

Applications to Everyday Life

Thermometers: Thermometers of differing types use the principle of thermal expansion to demonstrate changes in temperature. We are all familiar with the standard liquid thermometer; many are less familiar with the bimetallic strip that is used inside most temperature-regulating thermostats used in homes. Even the liquid Galilean thermometer with floating balls of different densities can be used to measure temperature given changes in density as the result of changing temperature.

Thermal Expansion Joins: Have you ever wondered why bridges have "disconnects" with the abutting road, or why sidewalks have horizontal rules shaped into their surfaces, or why large sheets of concrete have sections of mysterious black materials between their various sections? It's all because of thermal expansion. Such gaps are called expansion joints. When sunlight heats such surfaces, they warm and expand. Without a place to expand into, they will buckle and crack.

Thermal Insulators: Many kitchen experts use hot pads when transferring or moving hot objects. Hot pads are normally made out of materials that have very poor heat conductivity. That is, heat does not rapidly flow through them and they are, therefore, good insulators. Let a hot pad get wet, however, and the heat of an object will rapidly be transferred to the hand. Homes and hot water pipes are often surrounded by cocoons of thermal insulation to keep the heat from flowing outward to their surroundings.

Ice Cubes: Yes, ice cubes dilute the very drinks they are intended to cool (unless they are water!). Many people complain about this. If it weren't for the melting process, the drinks wouldn't cool. The conversion of ice into water "draws" heat out of the surrounding liquid thereby cooling it.

Blue Ice: This containerized material is often used to keep temperatures low in a ice chest or cooler. It is containerized so that when it melts, the liquid substance of the blue ice does not contaminate the very items it is intended to cool. Additionally, the blue ice material is often noxious if not toxic when ingested.

The material of the blue ice is chosen, however, for its high heat of fusion. It takes a lot more heat to melt the blue ice than it would an identical amount of water ice. This makes the blue ice a much more serviceable cooling substance, with the benefit that it can be used over and over merely by refreezing it.

Wind Chill: As noted in the example above with the wood and metal blocks, the body is a better sensor of heat flow than of temperature. As such, it is subject to "wind chill." Let's say its 30^o. If the wind isn't blowing, the coolness is bearable. However, if the wind starts blowing, it feels much colder than 30^o. This phenomenon is called wind chill. A person feels colder because with the motion of the wind heat is more rapidly carried away from the flesh, making one feel colder. Inert objects are not affected by wind chill. Feeling colder and being colder are two entirely different things. Even with gale force winds, an object will not cool below 30^o if that is the ambient air temperature. A hot engine, when turned off, will return to 30^o much more quickly with a wind, but it will never get below 30^o.