Chapter 37: Temperature and Heat

Temperature

Over the course of the next three chapters, we will conduct an investigation of heat and thermodynamics. Thermodynamics is the study of matter and heat energy and how heat behaves in systems. This first chapter is devoted to the differences between heat and temperature and how heat is transferred from one object to another. The other two chapters focus on how heat energy in a system can be analyzed and used to produce work.

We begin this chapter by discussing and defining the concept of temperature. Most students believe they have a very good grasp on what temperature means, and in fact they are correct. Temperature, in the vulgar sense, is a measure of how hot or cold an object is. In reality, since cold is an absence of heat, temperature is a measure of how hot something really is. While this vulgar definition is fine, the student should beware not to use their senses to make measurements. The human body is notoriously a bad thermometer. Consider waking up one winter morning and jumping out of bed directly onto a stone or ceramic tile floor. Now consider the same event, but landing on a nice soft carpet. Both the carpet and the floor are actually the same temperature, but one feels colder. The point here is that there are other factors (like heat transfers) that often make the human body think that objects are hotter or colder than they really are. Leave the measurements to the instruments!

A more precise definition of temperature is that it is a measure of the average kinetic and potential energy of the particles in an object. It is important to keep this in mind. Temperature measures the average energy of the particles in an object. Thus, two objects at the same temperature have the same average energy. If they are made up of different particles, with different masses, they will necessarily have different speeds to achieve the same temperature. Also notice that it is an average. In actuality, in any object, the particles do not all have the same speed. Some are moving very fast and others very slowly. They collide and switch speeds often. In fact, the speeds of particles in an object represent a bell curve and the temperature is a measure of where the middle of that curve falls. This will be discussed in detail later, all that is necessary for the student to be aware of right now is that there are many different speeds in any object.

Once we know what temperate is, it remains to begin to assign units and a scale to the phenomena. To do this, scientists had to pick out one natural event with a specific temperature and assign it a number. They chose to use the triple point of water. The triple point of water is the point at which liquid, solid and gas can all coexist together. This only occurs at one set of temperatures and pressures for water. That set is called the triple point. Scientists defined this temperature to be 273.16 K. After that, they set the scale such that each Kelvin would be 1/273.16 of the difference between the triple point and the absolute lowest temperature possible, called absolute zero. This is the Kelvin scale, the scale used in science.

There are other scales used in everyday life and the student should be aware of them and how they are used. They are the Fahrenheit scale and the Celsius scale and they both use units of degrees, unlike the Kelvin scale (for example a temperature would be 45^o C, or 45 K, not 45^o K). The table below shows the conversion factors among the three scales as well as listing a number of common temperatures and their readings in the three different scales.

Fahrenheit = (Celsius)(9/5) + 32

Kelvin = Celsius + 273.15

	Celsius	Fahrenheit	Kelvin
Water Freezes	0^o	32^o	273
Water Boils	100^o	212^o	373
Body Temperature	37^o	98.6^o	310
Room Temperature	26^o	78^o	299
Absolute Zero	-273.15^o	-459.4^o	0

While the Fahrenheit scale tends to be a little more "human based" (by putting the temperatures we are most used to dealing with in the high double digits and having finer gradiations than the Celsius scale), the Celsius and Kelvin scales are the two used in science. Both have equal gradiations while having different starting points. It should be noted that the Kelvin scale is the one we really need to focus on while studying thermodynamics. This is important because for the mathematics to work out properly, Kelvin temperatures must be used. Consider the case of having an object with a temperature of 35^o C. If you wished to double its temperature, the answer would not be 70^o C, but instead it would be 616^o C. The astute student should be able to figure out why this is. Also, it should be noted that doubling the temperature of an object does not necessarily mean doubling the average energy of its particles. Temperature is a measure of the average kinetic energy, but the relation is not a simple, direct relationship.

In the previous paragraphs, we have often mentioned "absolute zero" without ever really saying what it is. When different gases were first being experiment on, some interesting results occurred. If a certain quantity of gas was cooled, its pressure decreased. In fact, a certain pattern was noticed, the relationship was linear. For every one degree a gas was cooled, its pressure decreased by 1/273. As it turned out, it doesn't matter what type of gas we use, we always get the same result for all different gases. If this were plotted on a graph, it would result in a line with an x-intercept of -273. What did this mean? It meant that at -273^o C, the gas would have zero pressure and thus zero volume. Obviously, this was physically impossible. The gas could not vanish (it was impossible for another reason, can you figure it out before reading ahead? An astute student could!) This temperature was taken to be "absolute zero." The physical interpretation of these phenomena was taken to be that this was the lower boundary of physically possible temperatures of an object. No matter how hard you try, you cannot cool an object below absolute zero. The more you try, the closer (asymptotically) the temperature gets without ever reaching it. It should be noted that objects even at absolute zero have some energy (called the zero point energy) which is explained through quantum mechanics. Now, to return to the second reason why our above explanation was impossible. Think about the graph we discussed. It involved cooling a gas to colder and colder temperatures. At some point, the gas would liquify and the graph would change dramatically. Although this problem seemed to hinder the concept of absolute zero, instead, we simply accept the fact that this would be the case and say that we are defining this idea conceptually, not based on experiments.

Thermal Expansion

As the temperature of an object changes, its physical properties can change also. Some of the properties that can change with temperature are color, density, electrical and optical resistance, and length. If a property can change with temperature, that means it is possible to construct a thermometer and calibrate it according to those properties. Color thermometers are often used on aquariums, density thermometers are rarely used except for decorations (the floating bulb, Galileo type) and electrical thermometers are often used. I am unsure about the existence of optical thermometers, but they are probably out there somewhere. The last property, length, is the most commonly used property as far as thermometers are concerned.

When an object is heated, it expands. A short contemplation of what is occurring on the atomic level provides an explanation. As heat is added, the particles begin to acquire more kinetic energy, allowing them to move more freely and to extend the bonds between other particles. As each particles gets a little further from every other, the entire object expands. The forces involved in thermal expansion can be tremendous. If an object wants to expand, it will. If for some reason it can not do so freely, it will exert a force on its restraints. Either the restraints will break or something else might occur (if there is a very slight break in the objects symmetry, it will often crack or bend along this and release the strain in that way). For example, suppose you had a small, 10x10x10 cm block of steel and you left it outside from summer to winter (a change of about 30º C). If you wanted to pile enough weight on top of the block to stop it from expanding, you would need about 11,000 pounds. If something wants to expand, it will.

Although thermal expansion is an important theoretical concept, it also has tremendous applications and importance in the practical, everyday world. Below are a number of example of where the effects of thermal expansion are often seen.

Bridges, roads and railroad tracks expand greatly from winter to summer. If they were not allowed to expand freely, they would buckle and either break themselves or break what was holding them in. Bridges would expand into the roads at either end and break the pillars holding them up. The way engineers take care of this situation is to build in expansion joints in bridges. As you go over a large bridge, you might notice a zig-zag pattern in the road. This is an expansion joint. In the summer there is very little gap between the “teeth” and in the winter, the bridge contracts and the gap becomes larger. On smaller bridges, the ends are often not “fixed” to the end posts, meaning the bridge is simply laid across the gap. Since it is not fixed in place, it can expand a small amount without disturbing its function. Rail road tracks have gaps in between the rails where they are joined together. These allow for expansion and contraction. As you can see, thermal expansion is something that engineers must take into account whenever something will be exposed to the elements and undergo a temperature change. Imagine what would happen if the glass windows on a skyscraper did not expand as much as the metal around them! Also imagine how important thermal expansion was a consideration on a satellite that will go from day to night (about a XXXX degree temperature change in a matter of minutes).

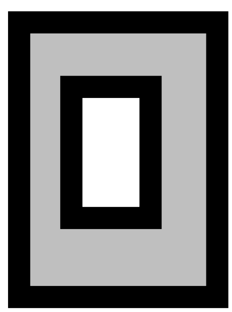
Another important, although not often considered, thermal expansion consideration come when the human body is helped or corrected by foreign objects. Imagine what would happen if the fillings in your teeth were made of a material that did not expand and contract at the same rate as your teeth. If you drank a large swallow of hot coffee, it could cause your fillings to simply crack your teeth apart.

Thermal expansion is also the property that many of our thermometers employ to read temperature. A thermometer is made with a glass tube and some liquid (it used to be mercury, but for health reasons mercury thermometers are rarely ever made any more, instead colored alcohol is used) that will expand more than the glass when heated. Thus as it expands, it rises up the tube. If it expanded the same as the glass, it would be always read the same number. An interesting fact about thermometers is that when you place them in a very hot liquid, the level actually drops quickly and briefly before rising to the correct temperature. An astute student should be able to figure out why this is.

Another fact about thermometers that is often forgotten is that they can never give an accurate reading of what the temperature of an object originally was. Suppose you wanted to measure the temperate of a cup of coffee. You drop your thermometer into the cup and read the temperature. However, since your thermometer was colder than the coffee originally, the temperature of the coffee will drop slightly to raise the temperature of the thermometer. You could mathematically figure out what the original temperature was, but in general the change is so small that it becomes unimportant. However, this does really need to be taken into account when samples are very small. **Thermometers in a lab should always be very, very small compared to the sample of the substance being measured.**

As a final example of thermal expansion, it is worthwhile to consider an object called a bi-metallic strip, consisting of two different types of metal, joined together one on top of the other to create a strip. Since the two metals do not expand at the same rate, it caused the strip to bend in a curve with the faster expanding metal on the outside of the curve. Since it bends a predictable and consistent amount at given temperatures, this device comes in very handy. It is often used as a thermostat, a device that turns things on or off at given temperatures. The metal strip can be used as an electrical connection that naturally "bends away" and breaks the circuit when it gets warm. A bi-metallic strip is also commonly used as a thermometer, since it will bend to different points at different degrees.

Naturally, if objects expand in one direction when heated, they expand in all directions when heated. Area and volume expansion also occurs with heating. This leads us to an interesting question: Consider the object below, a rectangular piece of steel with a hole cut into it. What will happen to the hole when the object expands? Will it get larger, smaller or stay the same?



The correct answer might surprise you: it will get larger. At first, many students say it will get smaller, since the plate itself will increase in size, causing the hole to get smaller. However, when objects increase in size, they increase in every measurable direction. What this means is that the length of the circumference of the interior hole must increase also. To understand this more easily, break the object up into small rectangles. If every rectangle must increase in size, those that make up the sides of the hole must increase also.

Another interesting example of thermal expansion at work occurs with glass. This is an experiment you can try at home (but only with safety goggles and your parents permission, of course) but don't expect it to work every time. Take a glass jar, and put it in the freezer for a few hours. Then, bring a pot of hot water to a boil on the stove. Remove the jar and place it in the sink and then quickly pour the hot water over the bottom part of the jar. It might shatter, so stand back and don't drop or splash the hot water you are holding. What happens here can be easily explained by thermal expansion. When the hot water hit the cold glass, it caused it to expand quickly, but only the part that the hot water hit. The other, still cold, part of the glass remained the same size. If one part expands faster than another, the material must stretch to accommodate the change. Glass is a very brittle material that simply cannot stand the stresses. A small crack forms and then a chain reaction causes other sudden stresses to shatter the material. In labs, classrooms and kitchens can be found a special kind of glass, Pyrex, that is made to handle heat and heat changes better than ordinary glass (but it can't withstand all heat changes). The patented type of glass is made to have a very small coefficient of expansion (see below), thus its size changes very little and the stresses are greatly reduced.

The mathematics of thermal expansion is quite simple. When an object expands, it does so according to:

$$\Delta L = L\alpha\Delta T$$

Where ΔL is the change in length of the object, α is the coefficient of linear expansion and ΔT is the change in temperature (in Kelvins or degrees Celsius). The coefficient of linear expansion is simply a constant that is dependent on the material in question, there is a different coefficient for each different substance. The value depends on the structure and the bonds involved in the material and is usually derived experimentally, not theoretically.

EX JUH.) A steel ruler, exaclty 12 inches long at room temperature, is used to measure an icicle at -10º C. How long is the icicle if it is exactly as long as the ruler? The coefficient of linear expansion of steel is $1.1\times10^{-5}\ {}^{o}C^{-1}$.

When we begin to deal with thermal expansion for area and volume, we need to derive different coefficients, although the formulae are the same as for linear expansion.

$$\Delta A = A\delta\Delta T$$

$$\Delta V = V\beta\Delta T$$

The area and volume coefficients, δ and β, respectively, are related to the linear coefficient by the following:

$$\delta = 2\alpha \quad \text{and } \beta = 3\alpha$$

Of course, only the volume coefficient has any meaning in regards to liquids

An astute student, noticing the above equations, might notice a logical discrepancy between them. It is worth taking a look at this in more detail.

EX YCD.) Using the formula for linear expansion, derive an equation for area expansion and locate the discrepancies between the derived formula and the ones given.

The reason for these discrepancies lies in the fact that the formulae for area and volume expansion given ($\delta=2\alpha$ and $\beta=3\alpha$) are actually approximations. It is assumed that α is a very small number, much less than one, as it in fact is. Thus, squaring and cubing it lead to even smaller and smaller numbers. The formulae given are actually first order approximations in α, where the very tiny terms are discarded so that the mathematics can be more easily accomplished. Let us now do one final example.

EX GTF.) Imagine that one gallon of water is placed in a square metal container at the bottom of a mountain at 30° C and brought to the top where the temperature is 7° C. If the container is 15x15x30 cm (LxWxH), what is the volume of water at the top of the mountain? The coefficient of volume expansion for water is $2.07\text{x}10^{-4}$ $(\text{C}^{\text{o}})^{-1}$ and the metal has a linear expansion coefficient of $1.2\text{x}10^{-5}$ $(\text{C}^{\text{o}})^{-1}$. What has happened to the lost water? How much has the water level changed in the container?

The Abnormal Behavior of Water

Before we leave this section regarding the thermal expansion, it is important to take a few minutes and discuss a material that does not behave exactly as we have explained in the above explanation. That material is water. When water forms a solid, it is held together by hydrogen bonds. As these bonds form, it actually begins by pushing the particles further apart and then retracting them back together. Thus there is a stage when water expands as it is cooled, then begins to contract again. This is very important and well worth discussing in detail. Water, in its liquid state, contracts normally as it is cooled, until it reaches 4° C. At this point, the bonds begin to push the particles apart as they are forming, causing the water to expand until zero degrees. When the water is completely solid, it once again begins to contract with further cooling. This phenomena leads to a number of interesting (and important) conclusions.

Firstly, this means that water is most dense at 4° C. Any further cooling makes it less dense, until it is below zero and even then it has a long way to go to catch up to the 4° mark, since the coefficients are not equal between its solid and liquid state. Thus, ice cubes float in water. They could only float if indeed they were less dense than the liquid. Besides that, it also means that lakes freeze from the top down. Imagine a lake cooling off in the winter. The coldest water would begin at the top and then sink to the bottom as it cooled (since it would become more dense than the water below it). Thus the coldest water is always at the bottom of a lake. However, once the entire lake gets to be around 4° C, when the top layer cools off, it is now less dense than the water below it. It stays at the top and continues to cool until it reaches a solid state. Once a lake is frozen, you can bet that all the water under the ice is 4° C. In fact, in many deep lakes, the water at the bottom remains at that temperature all year round, since they are too deep to heat up completely in the summer. It should be mentioned that this is one of the reasons that life is possible on earth. If lakes froze from the bottom up, as other materials do, then they would freeze solid in the winter. Fish could not survive and water for animals on land would be very difficult to obtain.

Secondly, this explains why sodas burst when frozen (if in glass) and how some potholes form. Since water expands when frozen, the container can no longer hold the solid. Something must give, and indeed it is the glass. As was mentioned before, these forces cannot be easily held back. There is an demonstration where a cast iron bottle is filled with water and placed in a freezer. The force of the expanding water is enough to shatter the cast iron bottle. Now imagine what happens if a small crack develops in a road. Water might seep into the crack and freeze. When it does, the crack expands. If this happens multiple times, it could get very large (but please consider, this only happens if there is no easy escape for the water, perhaps the opening was blocked after the water entered.). This explains why sometimes potholes form. Some students might be asking "But if this is true, why doesn't a soda can explode in the freezer?" I leave that to the astute student to answer.

EX WATER.) Explain, precisely, what happens to the water level in a glass of water as the ice cubes in it melt and the glass heats up to room temperature.

Heat Energy and Internal Energy

We have learned that temperature is a measure of the average kinetic energy in an object. It remains now to examine the idea of heat and see exactly to what that refers. What is often called heat energy is actually not heat energy at all. Heat energy is a transfer of internal energy from one object to another. Notice how this is worded: heat is energy in motion. Thus it is incorrect to say that some hot object contains a large amount of heat energy. Objects cannot "have" heat energy, they can only transfer it from one object to another. Thus it is correct to say that a certain amount of heat energy is needed to change the temperature of an object, since energy must be transferred for this to be accomplished.

However, objects can have Internal Energy. Internal energy is the total amount of energy in an object. Particles inside an object can have energy in a multitude of forms: translational, rotational, vibrational, etc. All of these different forms of energy combine together to make up the objects internal energy. When an object transfers heat energy, its internal energy either goes up or down. It is important for the student to know and understand the differences between temperature, heat and internal energy.

Methods of Heat Transfer

We now know what heat is, but the question arises regarding how it is transferred from one object to another. We know that objects heat up and cool down, but how does that happen? The answer is that there are three methods of heat transfer: conduction, convection, and radiation.

Conduction occurs when two objects of differing temperatures are brought in direct contact with each other. In such a situation, heat will flow from the hotter object to the colder object by direct interaction between the particles. If very energetic particles are in contact with less energetic ones, they will transfer some of their energy to the less energetic particles while themselves becoming less energetic in the process.

Heating by conduction is the method that most stove tops employ to heat the bottom of a pan and it is also the method that causes burns when you are in contact with a hot object. However, conduction can also be deceiving. At the beginning of this chapter an example was mentioned regarding jumping out of bed on a cold day and landing on a stone floor compared to landing on a wooden floor or a carpeted floor. In this case, all three floors are the same temperature, but the stone allows a very rapid rate of conduction, while the carpet has a very slow rate of conduction. In essence, stone allows heat to leave your body quickly, causing a cold sensation. You may have also noticed this during the winter if you have ever sat on a stone or metal bench. You get a cold "seat" very quickly, while a wooden bench is more comfortable. Once again, it is the rate of conduction that affects this, not the temperature. Air itself is a very poor conductor of heat. You can notice this when you get into a pool. The water and the air may be the exact same temperature, but the pool will feel cooler. This is because your body is accustomed to a certain loss of heat that is continually occurring. Since water is a better conductor of heat, your body loses heat more quickly in the water, thus feeling cooler. One final example of conduction is the practice of firewalking or walking on burning coals. In this masochistic practice, a person walks barefoot over burning hot coals, often as far as 20 or 30 feet. This is supposed to show great mental ability to overcome pain. In fact, all it shows is the slow conductive nature of wood and the effect of sweaty feet. If the person is nervous, they sweat and the heat that does go to their feet boils away the sweat before it can ever reach their feet to cause skin damage (This is also a wonderful example of how high the specific heat of water truly is. Even that little bit of water requires a great amount of heat to boil, leaving very little left over to reach the skin).

Mathematically, conduction can be very tricky to work with. There are so many factors that go into the rate of conduction that in order to deal with it at all, a few approximations and assumptions should be made. First, conduction can only be approximated for a uniform slab of thickness L, secondly either side of the slab must be a heat reservoir (meaning it can absorb or give off heat with out affecting its own temperature appreciably) that is maintained at some temperatures T_H and T_C. Thirdly, remember that this is only for heat conduction, it does not account for the heat losses through the other two means.

The formula for conduction (heat per unit time) in such a situation is:

$$H = kA(T_H - T_C)/L$$

Where k is called the thermal conductivity and is a constant that is dependent on the material involved. Let us first do some problems and then discuss the significance of the equation above.

EX FGTN.) Suppose your house is maintained at a temperature of 28° C and the outside is 15° C. How much heat is lost through one wall of your house (area = 40 m^2) in six hours? Assume the wall to be made of plaster, insulation and wood, giving an approximate value of k/L = 0.00927 W/m^2K. How much would this cost at 10 cents per kilowatt hour?

The one thing to notice about the above equation is its dependence on ΔT. This is tremendously important and has far reaching consequences. What this means is that the rate of heat loss depends on the difference between the two objects. It is not a constant. Things heat and cool faster when they are farther apart. Two examples should show you how this works:

EX RFDR.) To minimize the time it takes for your coffee to cool down to a drinkable temperature, should you add the cold cream right away or wait until it is almost drinkable and then put the cream in?

EX CDGFE.) Suppose you are going to leave the house for four hours. Is it cheaper to leave the heat (or air conditioning) on for that time, or simply turn it off and then heat the house back up to a comfortable temperature when you get home?

It is hard to over stress the importance of the idea that the **rate** of heat transfer depends on the difference between the two objects. Thus the primary amount of cooling (or heating) between the two objects occurs when the two begin to exchange heat. Be sure you understand this idea.

EX NMU.) Make a rough sketch of the graph of an object cooling by conduction (temperature versus time).

Remember this idea when we discuss Newton's Law of Cooling at the end of this chapter.

The second method of heat transfer involves convection. Convection is when heat is brought from one object to another by means of a cycle of fluid. In a sense, convection is like conduction carried out by a third agent. Something heats the fluid, the fluid rises and then passes the heat on to something else (usually by conduction). Convection cycles are found often in nature, there are cycles in the ocean, bringing heat from the sea floor to the sky and there are convection currents in the atmosphere as well. It is also presently believed that there are convection currents inside the earth, bringing heat from the molten core to the surface and perhaps even causing the continental plates to shift. Convection can only occur, however, if two circumstances are met: a fluid must be present and so must gravity. Convection currents work because the hot fluid rises, a situation that only occurs in the presence of gravity. For our purposes, convection is not as important a factor in heat loss as are the other two and there is not much that can be done mathematically. Although it is essential in understanding such topics as meteorology, we will not discuss it further here.

The final method of heat transfer is radiation. Radiative heating and cooling is by far the most important of the three methods and is in fact the main method of heat transfer in everyday life. However, since it is not readily noticeable, it is often forgotten. To begin to understand this idea, we must make a simple statement: All objects absorb, reflect and emit radiation or light. We can easily understand that objects absorb light and reflect light, but often it is forgotten that objects also emit light. All objects emit light according to the temperature of the object. Most of the time this light is emitted in the infrared range and thus we cannot easily see it. However, when objects get hot enough, they begin to emit visible light, as is the case of red-hot melted steel or a burning coal. Most of the time, however, the light is invisible to our eyes. Some other principles of radiative heating are outlined below:

1.) An objects ability to emit light is directly related to its ability to absorb light. Good absorbers are good emitters.
2.) An objects ability to absorb light is inversely proportional to its ability to reflect light. Good

reflectors are poor absorbers.

3.) Light energy that comes into an object raises its temperature and light that leaves the object lowers its temperature. If an object remains at the same temperature, it is in equilibrium between absorption and emission.

From these facts, we can begin to understand radiative heating effects. The rate of heat loss by radiation is proportional to the temperature to the fourth power:

$$\text{Heat loss} \propto T^4$$

As an example, consider an object heating up by absorbing radiation. It is doing so because more light is entering the object than is leaving it. But as the temperature rises, so will its emission rate, since they are proportional. Thus it will quickly balance out at an equilibrium temperature.

Most people have, by this stage in their school career, learned that black objects are black because they reflect no light and absorb it all. Conversely, white objects appear that way because they absorb very little light. With these concepts, we can understand why black objects are often hotter than white objects in the same situation. Consider a black parking lot with white stripes. Both receive an equal amount of light energy, but the white stripes reflect more of it. The black absorbs most of it, thus its temperature rises. The temperature of the white stripes also rises, but since it is absorbing less, it does not rise as high as the black before reaching equilibrium. It is interesting to note that without radiative heating and cooling, the only method available would be conduction with the air, and they would both be the same temperature. It is also interesting to note that without radiative heating, we would all be dead (why?)

The spectrum that is emitted from an object as it heats or cools is often very complicated. It does not emit a single wavelength of light, but instead emits a broad spectrum of wavelengths. While the spectrum is different for every object, Physicists often talk about the “black body radiation” spectrum. This is the spectrum for an object that reflects no light at all, and thus absorbs everything incident upon it and reradiates this energy according to something called a black body spectrum. There is no such thing as a true black body, except perhaps a hole. Often an example is given of taking a box and painting the inside black. Then a hole is cut in one side. The hole is almost a true black body, since all the light that hits it goes into the object. Notice, however, that it is the hole, not the box, that is a black body.

Nevertheless, even though they don’t really exist, physicists often use the spectrum of a black body as an approximation for the spectrum that an object truly emits. A black body spectrum is shown below:

Notice that this is only appropriate for one temperature. At other temperatures, the spectrum changes its peak and its shape, while maintaining a rough bell curve. Some of the light that is emitted is very high above the main peak (wavelength wise) and some is far below.

Now that we understand how objects transfer heat energy though the three methods, let us look at a number of everyday examples and see how these things apply. We will do so in the form of common questions along with their answers:

Why is Styrofoam used for insulated cups? There are two reasons Styrofoam is such a good insulator. First, the material is made with a large quantity of air pockets built into the foam. Since air is poor conductor of heat, this reduces conduction. Secondly, it is white. White is a good reflector and thus a poor emitter of heat. This cuts down losses to radiative transfer. This is also the reason that most coffee mugs are white.

Why are silver tea sets the "best"? At first consideration, it might seem that silver would be a poor material to use on a tea set, since it conducts heat very well and would make the tea cold quickly. However, since most of the loss is by radiation, the reflective nature of the material far outweighs its conductiveness, making a shiny metal teapot the best choice for keeping the water warm.

How does a thermos work? A thermos uses methods to reduce all three types of heat transfer so that the material inside is kept warm for as long as possible. Conduction and convection are kept down because the inside of the thermos (in between the outer and inner wall) is a vacuum. The inside wall might be hot, but it cannot travel to the outside wall because there is nothing for it to travel through. Thermoses are also made out of shiny metals, thus reducing emission. However, since a perfect vacuum cannot be created and even shiny metals have some emission, the material inside cannot be kept warm indefinitely.

Why does the wind at the beach always blow into the shore in the daytime and out to sea at night? During the day, the sun heats both the sand and the water through radiative transport. However, since the water is partially reflective and the sand is not a good conductor, two things happen: 1.) The sand heats to a high temperature more quickly and 2.) The water absorbs more heat. Although the sand is a higher temperature, only the surface gets heated. The water absorbs more heat energy, but the energy is used to raise a lot of water only a small temperature change. This creates a convection cycle: The hot air over the sand rises and the air over the sea rushes in to take its place. Thus the wind comes from the ocean to the land. At night, the sand cools off very quickly in the absence of sunlight, while the water retains its higher temperature for a longer time. This causes a convection cell in the other direction: hot air over the water rises and air from over the land rushes in to take its place.

Why does snow take so long to melt, even on warm days? Once again, radiation is the culprit. Snow gets most of its energy to melt from radiation from the sun. It cannot get much energy from the ground, since the ground is a poor conductor of heat. However, since snow is white, it is not a good absorber and thus takes long to melt. Notice that snow, once it is sullied (i.e. slush) melts very quickly.

How does a campfire make you warm? Most of the heat you receive from a campfire comes from, you guessed it, radiation. Since air is not a good conductor, very little is conducted to your body in that way. This explains why you get the most warmth from the fire when it is blazing and not when the embers are simply smouldering.

Newton's Law of Cooling

Although heating and cooling by the three methods of heat transfer are rather sophisticated in terms of solving the equations mathematically, we can make some approximations. One of the earliest scientists to do just that was Isaac Newton. What he did was come up with a simple formula for determining the rate of cooling of an object. While the law works well in most everyday circumstances, our experiments now and our mathematical understanding of conduction, convection and radiation show us that it is only an approximation that holds well as long as the temperature of the object and the surroundings are not too far apart.

Newton's Law of Cooling is as follows:

the rate of temperature loss = $-A(\Delta T)$ Or

$$dT/dt = -A(\Delta T)$$

Where A is a constant based on the set up of the situation (What are its units?). The second equation is a calculus based equation. Remember when we discussed the rate of heat loss for conduction, we discussed how the rate was based on the difference and not the temperature. This law states the same thing mathematically, however it is very difficult to solve explicitly (without calculus) since the rate is based on the temperature, which is itself changing. However, with calculus, we can get a different equation from the one above:

$$\Delta T = \Delta T_o e^{-At}$$

Where ΔT_o is the original difference in temperature between the object and its surroundings when the time begins. This version of Newton's Law of Cooling makes it easier for us to manipulate it and get answers. However, there is one very important warning: **the first ΔT in the equation is the the difference in temperature between the final temperature and the temperature of the surroundings - it is not the difference between the initial and final temperatures of the object.**

EX HFR.) Draw an accurate graph of Newton's Law of Cooling (temperature versus time). With $\Delta T_o = 40^o$ C and $A = 0.1\ s^{-1}$.

EX OIJU.) If you are poured a hot cup of coffee at 95^o C and you don't like to drink it unless it is only luke warm (say 40º C), how long will you have to wait if the cup/coffee combination has an A value of 0.0012 s^{-1}? (Use room temperature as the outside temperature.)

<u>Assignment #37</u>

(Note: coefficients given are all linear, unless it is a liquid, which is volumetric)

1.) Suppose you took a person and doubled the average kinetic energy in all of their particles. What would their temperature be? Give the answer in Fahrenheit, Celsius, and Kelvin.

2.) If the flagpole in front of the school is made of steel, ($k=1.1x10^{-5}$ ºC^{-1}) and is 12.5 m high in the summer (at 100º F), how high is it in winter (at 25º)?

3.) If a spoon is 15 cm long at room temperature and is made of silver ($k=1.9x10^{-5}$), how long is it after sitting in a hot (85º C) cup of coffee? Assume it is in there long enough to completely acquire the same temperature.

4.) A submarine leave port in sunny Florida, where the surface water temperature is 30º C, submerges and heads for the North Atlantic where the water temperature is about 4º C. By how much does its length change if it is made of steel and is about 200 m long?

5.) A 5 cm length of steel is placed next to a 5 cm length of another material at 25º C and then heated to 80º C. At this point, the steel piece is 0.04 cm shorter than the other metal. What is the thermal expansion coefficient of the other material?

6.) Imagine that a cookie sheet is used to bake cookies in a 400º F oven. What is the ratio of the area available for cookies when the sheet is hot to when it is cool (room temperature)? Consider the sheet to be made of steel.

7.) If you fill your car's radiator when it is cool (30º C) with antifreeze, how much will spill out when the car heats up to operating temperature (100º)? Use the coefficient of the antifreeze to be $7.00x10^{-4}$ C^{o-1} and the coefficient of the radiator to be $1.5x10^{-5}$ C^{o-1} and the capacity to be 12 quarts.

8.) Imagine that a refrigerator had the following characteristics: surface area of 8 m^2, and a coefficient of 0.028 W/mºC. If it is 3º C on the inside and 28º C on the outside, how much heat was absorbed through the walls (3 cm thick)? If the refrigerator had an electrical rating of 500 W, how efficient is it?

9.) If you placed one end of a 40 cm steel spoon into a large pot of boiling soup (100º C), how long would it take until 100 J of energy was absorbed into your hand? Steel has a coefficient of 13 W/mK. Make the following assumptions: the cross sectional area of the spoon is about 1.5 cm^2 and no heat is lost through the shaft of the spoon.

10.) Find the coefficient of a hiker's clothing if the following is true: the clothing is 1 cm thick, the air inside the clothing is body temperature, the outside temperature is 8º C and there is an average of 1 m^2 surface area on the hiker. Their heat loss in this situation is about $4x10^2$ W. After a rain storm, their coefficient changes to that of water: 0.60 W/mK. What is their heat loss at this time?

11.) If a cup of coffee begins at 100º C in room temperature air and cools to 80º C in six minutes, how long will it take to reach 60ºC? Use Newton's Law of Cooling.

12.) Suppose an object cools from 40º C to 38º C in twenty minutes and the air in the room is at 30º C. At what time will it have cooled down close enough to 30º C so that it will seem to be room temperature (it will never reach room temperature according to Newton's Law of Cooling, so use a very close temperature, such at 30.01º C).

13.) Decipher: "Missiles of ligneous or oterous consistency have the potential of fracturing my osseous structure, but appellations will eternally remain innocuous." DNCTHWG

Lab #26 - Heat Loss

In this lab, three containers of hot water will be monitored (by a computer interface) and their temperature will be recorded every 30 seconds as they cool to room temperature. The data will be plotted and compared to Newton's Law of cooling.

Procedure:

1.) Set up the computer interface to simultaneously record three temperatures. If this is not possible, have different groups do different containers and then share data.

2.) Pour 200 g of boiling water into three containers: one white, one black and one clear.

3.) Begin recording the temperature every 30 seconds until it levels off (the longer, the better).

4.) When all three are finished, graph each data set individually and find the best fitting exponential relation. Then select an area of the graph beginning at when the water reached 60^{o} C and ending at room temperature. Find the best fitting exponential relation in this case. Do the same for a range beginning at 40^{o} C.

5.) Compare these relations to Newton's Law of Cooling.

Conclusions:

Comment on how well (or poorly) your data matched Newton's Law of Cooling. What is the constant in each case? How and why is the constant different in each instance? Is it different in the way you would have expected? How does this show the limitations of Newton's Law of Cooling as an approximation?

Activity #20 - Fun With Heat and Temperature

In this activity, the student will perform a number of short, easy experiments that will demonstrate the concepts of heat and temperature. For each experiment, a short graph or equation or solution will need to be handed in.

For many of these activities, you will need a water bath. A water bath is one pan filled with water placed inside another pan filled with water. Bring both pans to boiling. This way objects can be placed inside the inner pan and will be heated without direct contact with the heating element. This ensures that the objects will be at 100º C. An alternative water bath is a large pan with a screen about 1 cm from the bottom. This ensures that the materials in the pan will not be in contact with the bottom where they could get heated by conduction from the element and not the water.

Procedure:

1.) Place a metal ruler in an oven set at 400º F, after tracing its outline onto a piece of wood. Take the ruler out with prongs and immediately place it on the wooden board alongside the outline. Determine the change in length and calculate the expansion coefficient. If possible, also measure its thickness before and after with a caliper.

2.) Take three weights from a water bath and place one on a wooden surface, one on a metal surface and one on a brick. Attach a thermometer to each (or even better, a sensor from a computer interface) and cover each with aluminum foil. Measure the temperature after a minute and after 5 minutes.

3.) Fill a graduated cylinder with water to a set mark. Set it in the freezer and find the volume after it has frozen. Find the ratio of the frozen to liquid volume.

4.) Take a washer that just barely does not fit on a hard, solid cylinder (a nail or bolt). Heat the cylinder and cool the bolt, then slip it on tightly. Let it cool and try to remove it.

5.) Take a white coffee cup and a black coffee cup and fill them with an equal amount of water. Put them both under equal wattage light bulbs, being careful that all other factors are equal (distance, ambient light, etc.). Measure their temperatures every two minutes.

6.) Fill one cup with very WARM water, another with cold and a third with middling. Place one hand in the warm and the other in the cold. Leave them there for three minutes and then place them both in the middle cup. Comment on how unreliable your senses are in determining temperature.

7.) Put a small paper cup on a ring stand and fill it with water. Using a bunsen burner, begin to directly heat the cup. Notice that the water will boil and the cup will not catch fire. Explain.

8.) Place a lighted candle on the desk and put an glass tube (open on both ends) over it. Observe. Now repeat by placing a divider (provided by your teacher) into the tube. Explain this result.

Activity #22 - Thermal Photography

In this activity, you will use a regular camera and infrared film to take “false color” images of objects, revealing their thermal patterns and their temperatures.

Procedure:

1.) Infrared, or thermal film can be purchased at many photography stores and even occasionally at supermarkets or “superstores”. It comes in regular 35 mm size and can be used in most regular cameras. Acquire the film and a camera.

2.) Design at least six different, interesting set ups to photograph. Try to design set ups that will illustrate the principles discussed in the previous chapter. Some ideas are: a glass of ice water, a white and a black coffee cup filled with hot water, a black and white object under a thermal lamp, a house at night and in the day time, a close up of a window at night, a refrigerator, etc.

3.) Take at least two pictures of each set up, keeping good notes as to what each one is. Make sure you will be able to tell from your notes, in case the pictures are hard to decipher. Remember to make notes about the environment as well.

4.) Develop the film and discuss the pictures after you have analyzed them. Try to explain why each area has the thermal emissions that it did. Discuss the idea of false color and how it applies to these images.