Heat

1. Introduction:

You all have a gut feeling about heat: Rubbing produces heat, burning produces heat, sun radiates heat, electric current produces heat. Hotter objects have a higher temperature. Heat flows from hot to cold objects. Heat can be used to change phase, say melting a solid. Heat can be used to move things. It is a form of energy, generally called Q. The question is what differentiates heat energy from other kinds of energy.

We have studied motion of individual objects and of large aggregates of individual objects (atom and molecules as gases, liquids and solids).

In discussing mechanics we followed the following reasoning. First, motion of individual objects was considered under the action of a well defined force or torque of a force. We discussed for instance motion under gravity or elastic force. We discussed translational motion as well as rotational motion. Energy was shown to be an important concept. An object can possess energy because of its location in the force field and because it is moving or rotating. The first is called potential energy (PE) and the second is called kinetic energy (KE). Conservation of energy was expressed as

$$\text{PE} + (\text{KE})_{\text{translation}} + (\text{KE})_{\text{rotation}} = \text{constant}.$$ 

Potential energy changes when mechanical work is done by the system or mechanical work is done on the system by forces. Energy is expressed in Joules, 1 Joule = Newton-meter.
In discussing properties of matter we had to think about how to describe the average behaviour of a large collection of basic units. In a gas the basic units move around in straight paths until they collide with other units or with the walls of the container. The pressure exerted by these units of gas is also due to this motion. Temperature of the gas is also related to this motion. This motion is chaotic or random. To define pressure or temperature or density we have to find the average properties of these aggregates. Ideal gas law

\[ p = \rho_{\text{particle}} k T \]  

(1)

is a relation between these average properties of basic units. This is called kinetic theory of matter. The reason we must take averages is that the motion of elementary units, gas particles, is random and it is not possible to know precisely the velocity of all the \(10^{23}\) particles at each instant of time, but it is possible to determine their averages. So we find relations between these averages - average density, average pressure, average kinetic energy (T), average flow velocity in the case of liquids etc. Such relations describe macroscopic (or large scale) behaviour of matter.

So you have some idea of what is temperature - it is related to the average kinetic energy (translational) of the fundamental units. What is heat? What can heat energy do to a system? These are the questions we will address in the next sections.

2. **Ordered versus disordered energy**

When a ball is falling from a height it acquires kinetic energy of downward motion. Its gravitational potential energy is being
converted into its kinetic energy of motion. This is an example of well ordered motion. Gravity pulls, ball accelerates and gains kinetic energy as an ordered whole body. Potential energy is also ordered form of energy which has a specific value at each position.

If it falls on the ground and breaks into pieces where does the energy of motion go? It goes into many disordered parts and also into vibrating atoms in the ground.

When you heat a piece of metal a different kind of motion is imparted to the atoms in the metal. The atoms are made to vibrate about their equilibrium positions but in a totally uncoordinated, disordered or random manner. Each of these vibrations have kinetic energy, but some have more than others. This energy is internal to the piece of metal. It is its thermal energy.

3. Heat and Temperature

- Definitions:

  (1) Heat or thermal energy is the net disordered kinetic energy (KE) possessed by a group of particles, usually the atoms of bulk matter.

  (2) Temperature (at values greater than 0° K) is a measure of the ability of moving particles, usually atoms, to directly impart thermal energy to a thermometer or any other object. It reflects not the net amount of random KE, but its average value - which is like the concentration of its thermal energy.

- Observations:
Temperature of a substance is independent of the total number of atoms present. It only depends on the average kinetic energy of atoms of the substance.

A large object and a small object can be at the same temperature if they are in thermal equilibrium, however, the large object contains more heat as compared to the small object. This is because in contrast to temperature, thermal energy depends on both the total number of atoms present and their average random KE (which depends on temperature).

It is reasonable and quite accurate to define the average KE of random motion of atoms in a macroscopic object because in a macroscopic object there are very large number of atoms in it and an average can be precisely defined and the fluctuations in the average are very small.

An object that is moving can have a net momentum with all of its constituents are moving and also a well defined temperature which measures the average KE of random motion. You can alter its temperature without effecting its net momentum because random motions do not have a net motion.

When you apply a force to move two bodies in contact with friction present, the frictional force distorts the atoms from their equilibrium positions creating vibrational motion that rapidly spreads thru the material increasing the random energy of the atoms and this appears as heating the material and raising its temperature.

When radiant heat falls on a material, the atoms of this material are put into vibrations about their equilibrium position by the electrical fields present in the radiation. These
vibrations quickly spread throughout the material producing random motion which is heat.

4. **Measuring temperature**

Any physical property which depends on temperature can be used to define temperature. For instance we saw that ideal gas law, \( PV = NkT \), says that if pressure is constant then changing temperature changes volume. This is also true for mercury. So most thermometers we commonly use have a mercury column enclosed in a narrow tube with a bulb at the bottom. When the bulb is placed in contact with object whose temperature you wish to measure the mercury column changes length until temperature of the bulb equilibrates with temperature of the substance. Column length is a measure of temperature. Any other temperature dependent property can be used - for instance electrical resistance of a wire.

5. **Measuring Heat**

This is more subtle. Rise in temperature of an object by heating it depends on its mass and its atomic (electrical) properties. A standard amount of heat is defined as that which is needed to raise the temperature of 1 gm of water thru 1\(^0\) C. This is called a calorie. So to raise 10 gms of water thru 1 degree would need 10 calories. To raise 100 gms of water thru 5 degrees would require 500 calories. This dependence can be written as an equation

\[
Q = cm(T_f - T_i) \text{ calories}
\]  

(2)

The constant \( c \) is called specific heat of a substance. For water is exactly unity. It is calories per gm per degree. For water it is by
definition 1. Most other substances have values of specific heat which are smaller than that of water. Suppose a piece of metal has specific heat of 0.1 calories per gm per degree. Take 1 gm of metal and 1 gm of water and supply both the same amount of heat. The metal’s temperature will rise 10 times more than rise of temperature of water. If you want to store heat water is an excellent substance. Large specific heat of water is also the reason why oceans do not heat up as much as land - this leads to sea breezes.

Instead of heating water with a flame, you could stir the water until its temperature rose by 1 degree. Stirring requires mechanical work which can be measured. (For instance, place paddles in a pail of water and rotate them with known torque). We can find the relation between heat energy, calorie, and mechanical energy which is Joules. The relation is

\[ 1\text{cal} = 4.186\text{Joules} \] (3)

This is called the mechanical equivalent of heat. One food calorie is defined to be 1000 ordinary calories.

6. Different forms of Energy

- Kinetic energy of ordered motion: translational and rotational
- Potential energy :
  1. Gravitational
  2. Electrical
  3. Chemical (electrical on microscopic scale)
  4. Nuclear
• Heat: Energy in random motion of macroscopic systems
• Radiant: This is energy in Electro-Magnetic Waves
• Mass: Energy thru the use of $E=mc^2$

Energy in an isolated system can be transformed from one form into another but it cannot be destroyed or created. This is really the basis of first law of Thermodynamics. It relates the changes in work, internal energy and heat. Internal energy is due to random motions of atomic units. Internal energy of a gas or liquid has, at reasonable temperatures, three components: translational, rotational and vibrational energies of molecules. In a solid atoms can only really vibrate about their equilibrium positions, so their internal energy is vibrational.

If you allow a compressed gas to expand. As the gas expands work is done by the gas molecules and they loose kinetic energy of random motion which means its temperature will drop.

If you do work on a system, say for example you compress a gas contained in a cylinder - like when you pump up a bicycle or a car tire the system is not isolated. Energy conservation now must include the work you have done on the system. You know that the bicycle tire heats up, which is the same as saying that the random KE of the gas molecules in the tire increases upon compression.

If you heat a system, say a can containing gas, its temperature goes up but as long as the gas is confined in the vessel of constant volume no work is done by the gas. If the can is elastic, like a close balloon, it will expand. Gas will do work against the forces
of tension in the balloon. Some of the heat energy will go towards heating the gas in the balloon.

All these statements can be summarized by a simple statement:

$$\Delta U + W = Q$$  \hspace{1cm} (4)

where $\Delta U$ is the change in internal energy of random motion (can be positive if it increases and negative if it decreases), $W$ is the work done by the system or on the system (positive if its by and negative if its on the system) and $Q$ is the heat supplied (positive) or removed (negative). This is a statement of conservation of energy and is called the First Law of Thermodynamics.

7. **Producing and transferring heat:**

- **Methods of producing heat.**

  Oldest method of producing heat is fire. Producing a fire involves two steps: activating fire by friction and then fire continuing thru chemical reactions. Fire is produced by a chemical reaction where a hydrocarbon molecule is split apart and then carbon and hydrogen recombine with oxygen in the atmosphere to form carbon dioxide and water. The process has to be started or activated - generally done by lighting a match. In lighting a match energy is supplied by friction on its tip. Once it starts burning energy released in formation of $\text{CO}_2$ and water is sufficient to split apart other hydrocarbons and keep the process going. Here chemical energy associated with chemical reactions is converted into random energy of motion of atoms of the material that is burning - heat. Here
I point out that chemical energy has its origins in electrical energy of electrons in molecules and atoms. Another method is to pass an electrical current thru a very thin wire, usually tungsten filament. The electrical energy in current flow is converted into random motion of tungsten atoms producing heat and even light. The energy which keeps the sun shining is provided by fusion of four protons to form one helium atom in the core regions of the sun. Here nuclear binding energy provides the energy which is converted into random motion of atoms in the sun.

- **Methods of transferring heat:**

There three methods of transferring heat from one point to another: (1) **Conduction**, (2) **Convection** and (3) **Radiation**.

**Conduction:** Heat flow thru stationary materials. When heat is applied to one end of a metal bar very soon the other end also becomes hot. This happens because random vibrations of atoms at the hot end are systematically transferred to other parts of the rod. A temperature gradient is established throughout the metal rod. Heat conduction is accomplished by electrons which are free to move. Substances in which there are electrons which are free to move are good electrical conductors, they are also good thermal conductors. **No atoms move, just heat moves!**

**Convection:** Heat transfer occurs because moving fluid, liquid or gas moves from hotter region to a colder region. Consider air, when air is hot it is slightly less dense than
cold air, so it rises due to buoyancy. When hot air comes in contact with material which is colder it transfers some of its random energy upon contact to heat up the material. If upper layers of the atmosphere above the surface become hotter than at the surface, this convection does not occur - we have an inversion layer and the air below it is trapped and can become very polluted.

**Radiation:** Heat moving as 'light'. The atoms of a hot material are moving randomly, they are being continuously oscillated. When atoms oscillate their electrical charges are accelerated. This acceleration leads to emission of electromagnetic(EM) radiation or waves which contains EM energy. These EM waves travel thru space at the speed of light. Radio waves, microwaves, infrared light, visible light, ultra-violet light, X-rays and gamma rays are all EM waves of different wavelengths and frequencies. The nature of EM waves that are emitted from a heated substance depends on its temperature. A burning wood fire emits both light and infrared waves. A radio antenna emits radio waves. The sun emits most of its radiation in visible light although it emits both infrared and ultraviolet waves. You can heat up a substance by shining EM radiation upon it - particularly infra-red radiation whose frequencies are similar to the vibrational frequencies of atoms in a solid.