Heat and Temperature

A learning-by-doing module for secondary schools

Bhas Bapat
and the Eklavya Team

an eklavya publication

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Typeset by the author using LaTeX

September 2013 / 2000 copies
Paper: 100 gsm maplitho and 220 gsm paper board (cover)
ISBN: 978-93-81300-67-1
Price: ₹ 130

Developed with financial assistance from the Sir Dorabji Tata Trust
and the *Parag* initiative of
the Sir Ratan Tata Trust and the Navajbai Ratan Tata Trust, Mumbai.

Published by
Eklavya
E-10, BDA Colony Shankar Nagar,
Shivaji Nagar, Bhopal – 462 016 (M.P.)
www.eklavya.in books@eklavya.in
Printed at
Adarsh Pvt. Ltd., Bhopal, Phone 0755-2550291

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Preface

This module covers the topics heat and temperature at a level appropriate to the ending years of secondary school. It is mainly aimed at teachers, but students should be able to follow most of it.

Commonly observed effects of heat and transfer of heat are covered at the beginning. We then look into the equivalence of heat and work, and as a natural extension, look into pressure and expansion in the context of gases. We next come to the question of what causes heat and what is meant by temperature and arrive at the kinetic theory of heat and temperature. After this the applicability of the theory is discussed in the context of gases. Finally, we briefly look at a few heat-based devices that have had a significant impact on our lives.

The emphasis is on activity-based learning wherever possible. However, it has to be appreciated that physics requires a certain degree of abstraction based on observation, which then leads to building models to explain natural phenomena. This module accepts that approach, and an attempt is made to lead the reader from inferences drawn from classroom based activities to the modern theory of heat based on particulate nature of matter and random motion of the particles. While this is by no means the only viable or valid approach, we have attempted to make it self-contained and pedagogically consistent. Experiments that drive home the justification for the particulate model of heat and matter are suggested. We are aware that model building based on a small set of observations may have gaps and, in places, only loosely justified leaps. Where this is done, it is clearly stated. Strictly speaking, building a widely applicable model requires distillation of several diverse observations and is necessarily a long drawn activity that would be impractical in classroom teaching.

The module contains a large number of activities than can be done with ease in the classroom or school laboratory, with modest tools and equipment. Questions related to the observations are often left unanswered, or are left with a hint, to stimulate thinking. We have also made a conscious effort to dispel confusing notions, and to avoid confusing terminology.

The activities should be approached as follows. First the description should be read to understand the activity, without actually doing it. Wherever there are questions in the descriptions, an attempt should be made to estimate or predict the outcome of the experiment. If there are questions posed in the description, these should be thought over before the activity is done. After this the activity should be performed, and the observations noted down. Finally inferences should be drawn and the questions answered. Teasers based on feedback from various teachers, students and other resource persons, and perceived misconceptions, are presented at the end of the module.

We hope that this module is appreciated for the route it takes.

Notes for the Teacher

This module is based on performing many small activities. A single activity may need as little as a minute, but some may need as much as 15 minutes. A couple of activities suggested in the module may not be possible in school laboratories, but are needed for the development of the subject. These are available as a video film. We have intentionally desisted from preparing video films of all activities since they are likely to deter students from performing the activities and learning the skill of experimentation.

Like any scientific experiment, these experiments have to be done carefully. This implies not just doing them with accuracy, but also realising the shortcomings, and identifying the potential sources of errors and work-arounds. We hope that the spirit of these activities is recognised, and with these comes the realisation that it is not always necessary to have sophisticated experimental set-ups to understand basic principles.

We have listed below some points to ease the performance of the activities and some practical hints and pointers.

1. Activities in this module often require a source of heat. Common sources of heat that can be recommended are a candle, a spirit lamp, a stove, a small (250 W) electrical immersion heater. Gas-filled lighters with a metal body could also be used for small tasks. Their suitability for a particular activity has to be judged on a case-by-case basis.

2. Many experiments will need water and suitable containers. Containers could be beakers, or steel tumblers or kitchen utensils. Students should be made aware that while heating or cooling water or other liquids, the containers also likewise get heated and cooled, although we do not make an explicit mention of this.

3. All laboratory thermometers do not respond identically. They may show different readings for the same object (e.g. for the same sample of water)! This is due to manufacturing shortcomings. For the experiments to be done here, it is necessary to make sets of 3–4 thermometers which have similar responses. This can be done as follows. Keep beakers of cold

water and very hot water at hand. Dip thermometers pairwise in the two beakers one after the other, and keep together thermometers that show nearly the same readings, both at the low temperature and at the high temperature.

4. In all activities that involve mixing and objects in contact, there are factors such as heat transfer to the surroundings, which affect the observations. Hence the results of these experiments are approximate.

5. In the activities on liquids in contact, they are actually separated by the wall of the container. Heat is transferred to the container also and the temperature of the container changes during the experiment. The second activity in this context suggests a way around this hitch.

6. Certain activities are best done using a thermos flask. Since a thermos flask is expensive, it is impractical to spare a few for these activities every time. Two improvised alternatives to the thermos flask are suggested. (a) Use two disposable type thermocol cups, one placed inside the other (b) Make an insulated beaker by wrapping a thin sheet of packing foam a few times around a glass beaker, place a thick circular disk of the same material under the beaker, and secure the wrapping with packing tape.

7. Some activities require the use of equal masses of more than one liquid (e.g. water and kerosene). It is much easier to use a volume measure for liquids than a weight measure. Wherever a fixed mass of a liquid is needed, we may use a volume measure. In doing so, it is useful to know that the density of water is 1 g/mL and that 10 g of kerosene and water have volumes 12 mL and 10 mL, respectively. The use of vegetable oils is not recommended, because they are viscous and heat does not spread quickly enough in them. There are greater variations in their densities than in kerosene.

Chapter 1

Hot and Cold

1.1 Common experience of hot and cold

Two words that are frequently used in our day-to-day life are *hot* and *cold*. We sometimes remark "Isn't it hot today?" or "It's cold today!". If it is very cold, we cover ourselves up with a shawl or we wear a sweater. On wintry days the floor of the house feels cold. On the other hand, on a hot summer day it becomes impossible to sit upon a bicycle or a scooter left standing in the sun.

If we reflect a bit on the manner in which we use the words hot and cold, it will become clear that in our everyday use, the terms can be quite imprecise, even confusing. Consider the following examples.

- If given a cup of lukewarm water and another cup of lukewarm tea, we are likely to say that the water is too hot (*to drink*) while the tea is too cold (*to drink*). So, here the sense of something being hot or cold is related to the *purpose*.
- Oddly enough, it might happen that another person finds the same cup of tea *hot enough*. Another similar example is that of warm water for a bath. One person might declare a bucket of water to be too hot to have a bath with, but someone else might find it just right for a bath. So here, the perception or sense of hotness depends on the *person*.
- When a pan of just boiled milk is taken off the stove and left standing, we say after some time that the milk has cooled down, although it may not be as cool as another pan of milk that has not been placed on the stove at all. In fact the first pan will be declared to be even more cool after some more time has elapsed. To add to the confusion, somebody might declare it to be *less hot* than it was earlier. In this case we are using the term cool (or hot) in a *relative sense*.

Our idea of hot and cold (in common usage) is usually based on the sense of touch, that is, on our skin acting as

Figure 1.1: Comparison of sensation of hotness by palms dipped earlier in cold or hot water.

a sensor. Our sense of touch is not very reliable, and there can be conflicting interpretations of the terms hot and cold even for the same person. This can be easily seen by a simple experiment.

A 1.1 *Hot or Cold?*

Take three identical containers (large tumblers or pans would be fine). Fill the first with water from a water cooler, or a refrigerator, or an earthen pot. Fill the second with tap water, and the third with tap water that has been heated for a few minutes. Dip one of your palms first in cold water for 15 s, and the other palm in warm water for 15 s. Then dip both palms simultaneously in tap water (See Fig. 1.1). On the basis of the sensation in your palms in the two cases, can you say whether the tap water is hot or cold?

In common practice, the use and the meaning of the terms hot and cold is often subjective, i.e., it depends on the context or purpose, it may be relative to something, it depends on the person, and also on the conditioning of the sense of touch. The examples and the activity above indicate that the sense of hot and cold is relative, not absolute. How can we then meaningfully say that one object is hot while another object is cold?

Let us examine the pan of boiled milk once again. To begin with, we declared it to be hot but some time after it was left standing, we declared it to be cooler or less hot. As time passes, we find that the hotness of the milk is *continuously* reducing, or the coolness is *continuously* increasing. The process of reduction of its hotness, or increase in coolness is a continuous one. In a contrasting situation a tumbler containing chilled water becomes less cool or becomes warmer as time goes by; here too, the reduction of its coolness or, equivalently, the increase in its hotness, is continuous.

The inferences from our observations could be stated as follows:

- We could equally well say that all objects are cold, but some are colder than others, or that all objects are hot, but some are hotter than others.
- Hotness and coldness are not compartments or distinct categories. They merge into each other, or change continuously from one to another. Hotness and coldness are like two values on the same scale, one large and one small.

1.2 Temperature

The degree of hotness is given the name *temperature* and its value changes in a continuous manner. A 'hotter' body has a higher temperature while a 'colder' body has a lower temperature. One of the earliest successful attempts at establishing a method of measuring the degree of hotness was that of Galileo (around 1610 CE). He constructed a device called a *gas thermoscope*, which can be considered as the forerunner of the thermometer. A thermoscope is based on the expansion of a gas due to change in the degree of hotness. We will construct a thermometer later.

Thermometers are now commonly used devices. We come across various thermometers: in the laboratory, in a doctor's clinic, or in a weather bureau. We frequently come across reports of temperatures, such as in a weather report, or the body temperature of a patient, or the temperature of a solution in the laboratory. These temperatures are variously reported as "so many degrees Celsius", or "so many degrees Fahrenheit". We will use the Celsius scale for all our work, and treat the number indicated by the alcohol or mercury column as the *degree of hotness, or temperature*.

A 1.2 *Examine a thermometer*

A laboratory thermometer is a long glass tube sealed at both ends, inside which there is another very fine tube with a fat bulb at one end, partly filled with a liquid. The liquid could be mercury (a shiny substance) or alcohol (mixed with a red or blue dye). Observe the mercury column. There is a scale along the tube which shows markings in °C, or degrees Celsius. Take a look at its initial reading. What is it showing the temperature of? Hold it in a tumbler of water. Note the reading. Next put the bulb of the thermometer in cold water or in crushed ice and watch what happens to the mercury column. Then hold the thermometer in a saucepan containing water and placed

Galileo Galilei (1564–1642)

Galileo was very versatile and did seminal work in many areas, and he is best known for championing the heliocentric theory proposed by Copernicus. He also laid the foundations of kinematics (the study of motion) by recognising that under ideal conditions an object would continue in its state of rest or uniform motion till an unbalanced force acts on it. This, along with his work on the pendulum and falling bodies, was a strong challenge to the views proposed by Aristotle which had been accepted for almost two thousand years. What did he contribute to our understanding of heat and temperature? He not only invented the thermoscope (in which the expansion or contraction of an enclosed volume of a gas indicated increasing or decreasing temperatures respectively), but also proposed that a higher temperature might be attributed to the constituent particles of that object moving faster. But since this came before the particulate nature of matter came to be widely accepted, it was largely ignored.

over a flame. Find out the temperature at which water boils.

A 1.3 *Temperatures of objects around us*

You will need a beaker with tap water, a small pile of dry sand which has been kept in the room for a long time and a few thermometers[1]*. Take one of the thermometers and place it in a beaker containing tap water. Take another thermometer and place it in a pile of sand. Leave one thermometer in contact with air. Note down the reading in all three thermometers after approximately 5 min. Are the temperatures noted in the three thermometers identical? If not, why?*

You might wonder about questions such as: is there a limit on how cold or how hot something can be? What is the highest possible temperature? Can the temperature be negative? How low can it get? We will try to answer these questions in due course.

A 1.4 *Hot or cold re-visited*

Take two identical thermometers. Mark them as A and B. Now repeat the palm-dipping activity with three beakers of water using the thermometers A and B, instead of your left and right palms. What reading do you expect on the thermometers in each case? In what way has the use of a thermometer helped our investigation, compared to the case when we used our palms to gauge the degree of hotness?

It should be clear from this activity why a thermometer is a more precise and

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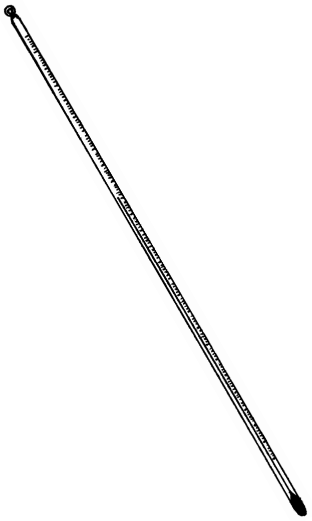
[1] See 'Notes for the Teacher' at the beginning.

Two temperature scales

Our laboratory thermometer has a Celsius scale, but there is another scale of temperature, called the Fahrenheit scale. It is commonly used by doctors to measure the body temperature. The normal temperature of the human body is around 98 °F or 37 °C, and it varies from person to person. The freezing point and boiling points of pure water are 0 °C and 100 °C, respectively, when the surrounding air pressure is 1 atmosphere. On the Fahrenheit scale these points are 32 °F and 212 °F, respectively. (The previous activity might have led to different values. Try to reason out why.) Thus 100 degrees on the Celsius scale equal $212-32$, or 180 degrees on the Fahrenheit scale. Hence 1 degree on the Celsius scale equals 1.8 degree on the Fahrenheit scale. 0 °C equals 32 °F, 1 °C would be [32 + 1.8] °F, 2 °C would be [32 + (2×1.8)] °F, and so on. If C and F denote the temperatures on the two scales, we can write the general relationship, $F = 1.8 \times C + 32$. Can you find out at what temperature the Fahrenheit and Celsius scales read the same? To find out more about the interesting history of thermometers, see the article *'taapmaapii mein paaraa kyon?'* by Sushil Joshi, *Sandarbh, Issue 67, p 7–18*.



reliable indicator of the degree of hotness than touch.

Temperature of Parts

We often use warm water for a bath, and we take the water out of the bucket mug-by-mug. That is, we take water part-by-part. Is the temperature of each part of the water that we take the same as the temperature of the water in the bucket? Would it matter, as far as temperature is concerned, which part of the bucket we take the water from? Instead of the example above, consider a situation in which we take two half-filled mugs of hot water at the same temperature and pour the contents of one into the other. The amount of water is *equal to the addition* of the amounts of water in the separated portions. Does the temperature of the water also add up in a similar manner?

If we imagine a substance to have

been divided into equal or unequal parts, each part will have the same temperature. It does not matter whether you consider the whole substance or part of it. If you combine two parts of water, the temperature of the sum of parts is not equal to the sum of the temperatures. We say that temperature is an *intensive* property[2]. By contrast, if we combine two parts of water, the volume of the combination is equal to the sum of the volumes of the parts. The same is true of the mass of the substance. These are examples of *extensive* quantities. Can you say whether the density of a substance is an extensive or an intensive quantity? Recall, that density is mass per unit volume.

1.3 Temperature of objects in mutual contact

We know from common experience, as for example, the pan of hot milk left standing, that hot objects gradually cool down. Likewise a cold object, say chilled water in a glass, left standing, becomes warm. Now examine the following activity, which is a variation of a commonplace kitchen trick for cooling down a pan of hot milk.

A 1.5 ***A water bath***

Take a boiling tube partly filled with very hot water. Close the boiling tube with a stopper or a thermocol cap, which has a hole for a thermometer. Stand the boiling tube in a large beaker that contains tap water. Suspend a thermometer each in the boiling tube and the beaker (Fig. 1.2). How do you expect the thermometer readings to change as time elapses? Repeat the above activity with the hot water in the boiling tube replaced by the same amount of chilled water. Make a simultaneous note of the readings shown by the two thermometers at intervals of 30 seconds. How far do you expect the thermometer readings to

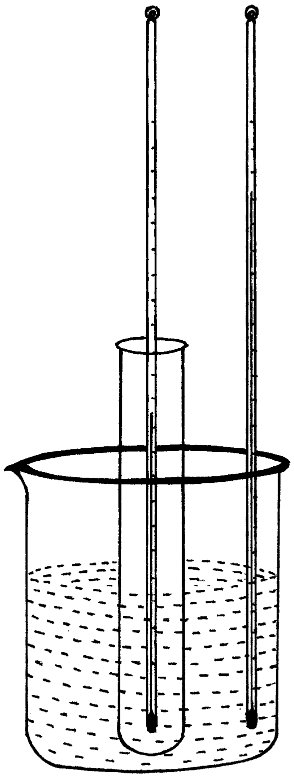


Figure 1.2: A boiling tube containing hot water in a cold water bath.

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[2] There may be a real confusion among students on this point. If so, the activity with parts of water should be done and analysed properly.

go? Note the readings of the two thermometers as before. Compare the changes in temperature with the previous activity. What happens after a long time, say 1 h later? How far do you expect the thermometer readings to go? It would be instructive to plot graphs of temperature versus time. You will have four plots in the same graph.

Is cooling of one object accompanied by warming up of something else? What was warming up as the hot water in the boiling tube cooled down? Assess the following statement in the context of chilled water in a glass: *air is cooling down while the water is warming up,* and then perform the next activity.[3]

A 1.6 *Liquid in contact with gas*

Take a thermos flask, or improvise one.[4] *Leave aside the lid. Make a tight-fitting lid of thermocol or packing foam with a hole to insert a thermometer to fit whichever thermos you use. Take some chilled water and determine its temperature. Fill approximately three-quarters of the thermos with chilled water and shut the lid with the same thermometer inserted in it. Ensure that the thermometer does not touch the water (See Fig. 1.3). Note the thermometer reading as time lapses. What does the thermometer show the temperature of? After approximately half an hour, push the thermometer gradually inwards so that its bulb dips in water. What do you expect the temperature of the water to be?*

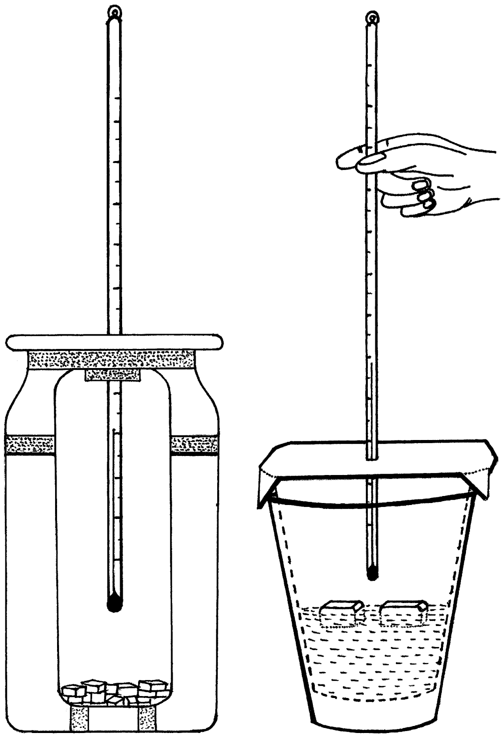

Figure 1.3: Cold water and air in contact with each other and isolated from the surroundings.

A 1.7 *Temperature of liquids in mutual contact*

Fill a beaker to about half with water at about 60 °C. It would be good if you can use a beaker with a jacket as in the previous case. Suspend a thermometer in it. Note the temperature. Keep another thermometer ready. Very gently pour kerosene at room temperature over the

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[3] It should be noted that when we say liquids are in contact in this activity, they are actually separated by the wall of the container. Heat is transferred to the container also and the temperature of the container changes during the experiment. The activity on the next page eliminates this hitch.

[4] See 'Notes for the Teacher' at the beginning.

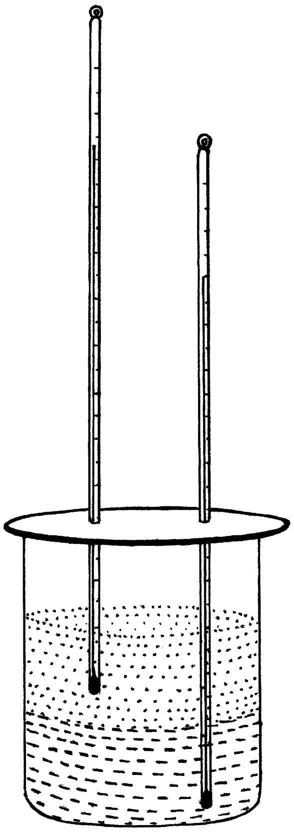

Figure 1.4: Two liquids, kerosene (above) and water (below), at different temperatures and in contact with each other.

water in the beaker. Pour gradually along the wall; do not splash. You will have kerosene at room temperature floating on top of hot water (See Fig. 1.4). Make sure that the volume of kerosene is sufficient for a thermometer bulb to be completely immersed in kerosene alone. Suspend the second thermometer in the beaker such that its bulb is entirely in kerosene, and does not touch the water. Predict the temperatures shown by the two thermometers as time elapses. What do you conclude?

In the activities above, we noticed that a hot object cools down if the surroundings are cooler than the object, and a cold object heats up if the surroundings are hotter than the object. Objects in contact gradually come to the same temperature if their temperatures are different to begin with. The change in temperature is continuous, till the temperatures of the two objects become equal. The temperature of the hotter body falls, while that of the cooler body rises. While one body cools down, bodies in contact with it heat up. Even when something happens to cool down (e.g. a pan of just boiled milk left standing) or warms up (e.g. chilled water in a glass left standing) by 'itself', the surrounding air is getting warmer or cooler, respectively. It is only that we do not generally notice this change in the temperature of air. Why do we not? Can you describe a situation where you actually feel it?

The first conclusive experiments to determine what happens to hot or cold objects when kept in contact with each other were done by Joseph Black, who, using a thermometer, came to the conclusion that objects which are in contact with each other acquire the same temperature. This is true whether the bodies are solids, liquids or gases, and irrespective of what temperatures they are at to begin with. Of course, it has to be stressed that there should be no external factors hindering the contact between the bodies for this to happen. The ideal situation of no external hindrance is not

Joseph Black (1728–1799)

Black studied ice-water mixtures and observed that the application of heat does not always cause a rise in the temperature. He also found that continued supply of heat to boiling water only increases the amount of steam produced, and does not lead to an increase in the temperature of the water-steam mixture. Thus, he was the first to recognise the latent heat during change of state. He also showed that different substances have different specific heats. Black's work led to the development of efficient steam engines, and he is also credited with the discovery of carbon dioxide.

generally attained in practice, so normal observations might appear to not conform to this conclusion. Contact between two bodies may not be exclusive, there may be a third body, such as the surrounding air. This observation is significant in the development of our understanding of heat and temperature. So significant, that the state of achievement of the same temperature by two bodies is given a special name; the bodies are said to have reached a *thermal equilibrium*. The term *equilibrium* indicates that no further change in temperature can take place. In fact, if a body A is in thermal equilibrium with a body B, and body B is in thermal equilibrium with a body C, then the bodies A and C are also in thermal equilibrium.

1.4 Does equal heating make things equally hot?

When we heat a substance, do we find that the rates of rise of temperature of all substances are the same? Are they the same for different quantities of the same substance? We know from our day-to-day experience, that a small amount of water in a pan becomes hot quickly, as compared to a large amount of water in the same pan, when heated on the same stove. If we take the same quantity of oil and water, would heating them for the same time under same conditions increase their temperature identically? Let us perform a few activities to check and quantify these ideas.

A 1.8 *Rate of change of temperature in different substances*

Fill a large beaker or saucepan with water and heat to around 60 °C (pan can be left on the stove). In the meantime prepare two identical test-tubes with corks, containing 10 g each of water and kerosene, respectively. Also set aside two thermometers having identical responses. Make an arrangement to immerse the test-tubes with the thermometers in the

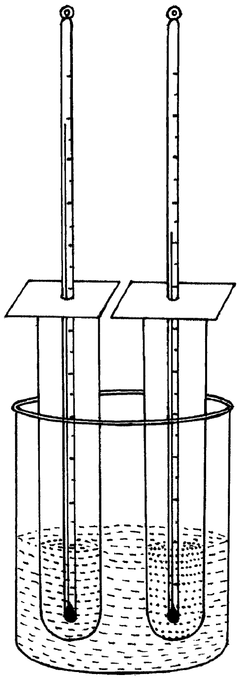

Figure 1.5: Testing the rate of change of temperature in different liquids.

pan of hot water as shown in Fig. 1.5. Take care that the level of the test-tubes is such that the liquid inside is fully immersed. Note the temperature of the two liquids in the test-tubes every 30 seconds. Compare their rates of change of temperature.

A 1.9 *Rate of change of temperature for different amounts of a substance*

Similar to the previous activity, but instead of different liquids, take different amounts of water: 10 g in one test-tube, 20 g in the second and 40 g in the third. Dip them in the pan of hot water for the same period of time. Do not stir. Observe the change in temperatures in the three samples of water. Repeat the experiment with three samples of kerosene instead of water.

Does the same amount of heat supplied to different substances of the same mass lead to the same rise in temperature, or is the rise different for different substances? If a fixed amount of heat is supplied to different masses of the same substance, is the change in the temperature of the samples the same, or does it depend on the quantity of the substance? *The amount of heat required to increase the temperature of 1 g of a substance through 1 °C is called its specific heat, and is denoted by the symbol s.* The amount of heat required to raise the temperature of 1 g of water through 1 °C is called a calorie (cal), i.e., the specific heat of water is 1 cal/g/ °C. If the specific heat of a substance is s, we can determine how much heat (Q) is needed to raise the temperature of a substance (whose mass is m) by a certain amount (say the change is ΔT). These quantities are related by

$$Q = ms\Delta T.$$

Water has a high specific heat among commonly occurring substances. Table 1.1 gives the values of specific heat of some substances.

With the help of the concept of specific heat and rate of change of temperature that we just discussed, can you predict the temperature of the mixture when two different quantities of water at two different temperatures are mixed? Read the next activity, but perform it after making the prediction.

Table 1.1: Specific heat of some common substances

Materials	Specific Heat [cal/g/ °C]
Silver	0.06
Copper	0.09
Glass	0.21
Granite	0.19
Air	0.24

A 1.10 *Temperature of mixtures*

Take two beakers of the same size and heat 200 mL of water in each of them to the same temperature. If you pour the two into a larger beaker, what do you expect the temperature of the mixture to be? Suppose now that you heat the water in one beaker to 80 °C and the other to 60 °C. What will be the temperature of the mixture? Test it out. Now take 100 mL of water at 80 °C and 200 mL of water at 60 °C and mix the two. What is the temperature of the mixture?

Check your prediction as follows.[5] Let the initial temperatures of the samples of masses m_1 and m_2 be T_1 and T_2 (the higher of the two temperatures is called T_1, the lower is called T_2). Let T be the final temperature of the mixture. The temperature of the mixture is lower than the temperature of the hotter sample, but higher than the temperature of the colder sample. This means that the hot sample has lost heat, and the cold sample has gained heat. The amount of heat lost by the hotter sample Q_1 is $m_1 s(T_1 - T)$. The amount of heat gained by the cooler sample, Q_2, is $m_2 s(T - T_2)$. Since heat lost by the first sample is equal to the heat gained by the other sample, $Q_1 = Q_2$, which can be written as

$$m_1 s(T_1 - T) = m_2 s(T - T_2)$$

and can be simplified to

$$T = \frac{m_1 T_1 + m_2 T_2}{m_1 + m_2}$$

Repeat the experiment with different masses and temperatures of the samples. How close are the experimental values and the predicted values of T? If there is a difference, try to explain why.

Using the above analysis, solve the following problem: You have two beakers containing identical masses of water and oil. Both are at the same temperature and well insulated from the surroundings. Two identical blocks of the same metal at the same temperature (which is lower than the oil/water temperature) are lowered into the oil and the water, respectively. Will the temperatures of the oil and water be the same after some time?

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[5] Do keep in mind that this exercise is approximate, because there is heat loss to the surroundings and containers, not just between the water samples.

1.5 What flows, heat or cold?

A commonly asked question, when we wish to keep something cold (e.g. to prevent ice from melting), is: Do we wish to prevent cold from escaping, or prevent heat from entering? In a contrasting situation, we might wish to keep tea warm in cold weather, and ask the question, do we wish to prevent the cold from entering or the heat from escaping? Consider also the following: A tumbler of cold water does not become colder and thereby heat the surroundings, nor does hot oil left standing become hotter while cooling the surrounding air.

In our common usage, saying that an object is hot merely means that it is hotter than some reference object, such as our body, and when we say that an object is cold, it is colder than the reference object. It is possible to say that all bodies are cold, but some are colder than others, just as it is possible to say that all bodies are hot, but some are hotter than others.

We can summarise all the above observations by saying that *in all cases, heat is transferred from a body at higher temperature to a body at a lower temperature*. What we really wish (in the previous examples) is to prevent transfer of heat from the surroundings to the object if the object of interest is [to be kept] colder than the surroundings, and we wish to prevent transfer of heat from the object to the surroundings if the object of interest is [to be kept] hotter than the surroundings. Heat moves towards colder objects, not coldness towards hotter objects.

Henceforth, we will avoid using the terms hot and cold in an absolute sense. When we use them, we will remember that they are relative, and imply *higher and lower temperatures*, respectively. We will also abandon the term *flow* that causes much confusion in the context of keeping heat in/cold out etc. Instead, we shall uniformly use the term *transfer of heat*, which is the next topic of discussion.

Summary

- *The terms* hot *and* cold *in daily use are relative terms. Temperature is the quantity used to describe how hot a body is, and a thermometer is a device used to measure temperature. Hotter the body, higher is its temperature.*
- *Objects in contact with each other, and initially at different temperatures, gradually reach a common temperature due to transfer of heat from the body that has the higher initial temperature to the one that has the lower initial temperature. This is true of solids, liquids and gases.*

Chapter 2

Transfer of Heat

In the activities in the last chapter, we observed that objects initially at different temperatures when kept in contact, gradually come to a common temperature. It takes some time for this to happen, or for *thermal equilibrium* to be established. When we heat a substance, it takes some time for it to become warm. Does the entire object become warm all at once? Does heat take time to get transferred from one point to another? Let us do some experiments to find answers to these questions. We will look separately at the transfer of heat in solids, in liquids, and in gases.

2.1 Transfer of heat in solids

A 2.1 *Heat transfer along a strip*

Take a metal strip roughly 15 cm long and 2 cm wide. You may use a metal ruler or even a cycle spoke, instead. Using wax stick several paper pins along a straight line at equal distances (approximately 3 cm apart) on it as shown in Fig. 2.1. With the pins hanging down, hold one end of the strip to a candle flame. Note the order in which the pins fall. Why do the pins fall?

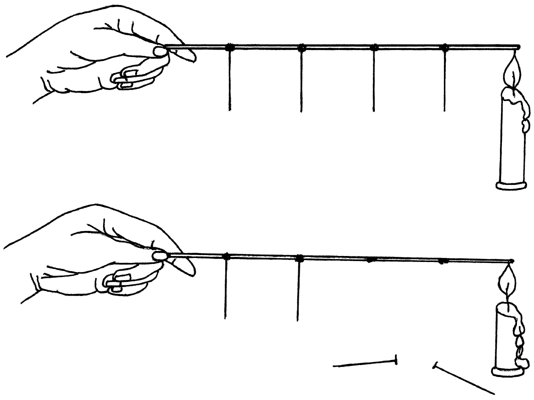

Figure 2.1: Transfer of heat from one end of a solid to the other.

Once again fix pins to the metal strip. This time leave the central spot empty and heat the strip at the centre, as shown in Fig. 2.2. What is the order in which the pins fall?

What is the explanation for the order in which they fall? Heat is transferred equally in all directions from the source. That is why in the first case the pin closest to the candle falls first, while in the second case, pins at equal distances from the candle fall at almost the same time. In which direction is heat transferred

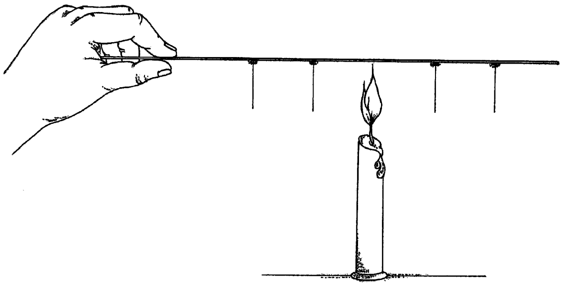

Figure 2.2: Transfer of heat in different directions in a solid, away from the source.

more rapidly? Does it make a difference whether the strip is horizontal or vertical? Try out the above activity with strips held in different orientations.[1]

Does the rate at which heat is transferred in a solid body depend on its size and shape? Let us find out.

A 2.2 *Factors affecting heat transfer in a solid*

Take a saucepan or a beaker. Take three pipes of aluminium of the same length (length of the pipes should be about twice the depth of the pan), same wall thickness, but different diameters. Make an arrangement using a cardboard lid with three holes of the right size, to suspend the three pipes in the pan as shown in Fig. 2.3. You may use a couple of tight turns of a rubber band around each pipe to prevent it from slipping. Ensure that the lengths of the pipes in the water are the same, and that they do not touch the bottom. Place a small drop of wax close to the upper end of the pipes. Make sure that the drops are identical in size. Heat the water. After some time drop some wax in the water. Continue heating for a few minutes after the wax melts, while you stir the water gently. Stop heating and stirring. Let the water become still. Quickly place the pipes with the lid in the water and start a stop watch. Note the times at which each drop of wax starts melting. Repeat your experiment, but with the wax drops now placed closer to the hot water (i.e. closer to the lid) than before. Compare the time needed for the wax drops to melt in the two cases.

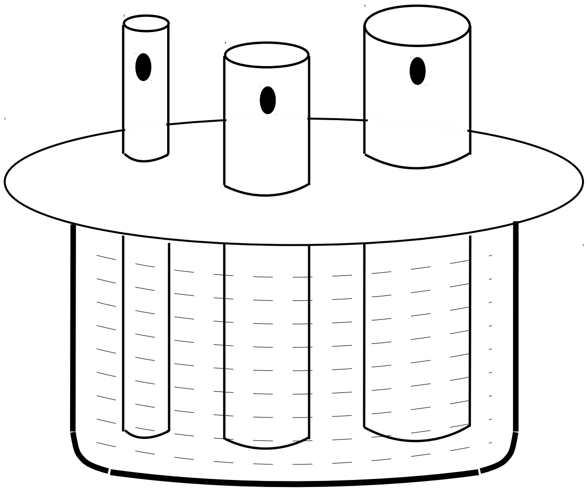

Figure 2.3: Transfer of heat through solids and the effect of size and shape.

Let us put together our observations. Does the time taken to melt increase as the distance of the wax blob from the surface of the water is increased? How does the time taken to melt change with the change in the diameter of the strip? If the time

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[1] While turning the metal strip to point in different directions, make sure that the flame of the candle does not spread out. Also ensure that the point at which the strip is being heated does not change.

Proportionality

We often come across situations where one quantity depends on another. An example might be that the volume of paint (x) required to cover a wall depends on the desired thickness of the layer of paint (y); if the thickness is doubled, the volume of paint required also doubles. Or, if a tank is being filled with water, the mass of the water in the tank (x) increases as the height of the water column (y) increases; if the tank is being emptied, the mass decreases as the height of the water column decreases. In both these examples, the quantities in question were directly varying with respect to the other. The amount of paint doubles if the thickness doubles, the mass of the water doubles as the height of the water doubles, etc. We say that the first quantity is directly proportional to the second ($x \propto y$). On the other hand, if you were to fill a fixed amount of water in a cylinder, the height of the water column (x) in the cylinder would be large if the cross-section area of the cylinder (y) were small, and vice-versa. Doubling the cross-section area of the cylinder would halve the height of the water column, and so on. This is an example where the first quantity is inversely proportional to the second ($x \propto 1/y$). For direct as well as inverse proportions, we can specify a (fixed) number which will convert the proportionality relation to an equation. This number is called the constant of proportionality. In the first example, the constant of proportionality is the area of the wall, in the second it is the cross-section area of the tank, in the third, it is the volume of water given to you.

to melt is shorter, then we say that heat is conducted well.

It has been found after repeated experiments of the type we just performed, that the amount of heat transferred per unit time (q) between two points with a temperature difference ΔT is directly proportional to the cross-sectional area (A) of the strip and the temperature difference (ΔT), and inversely proportional to the length of the strip. Note the distinction between the heat transferred per unit time and the total heat transferred, for which we had used the symbol Q earlier. We can thus write three relationships

$$q \propto \Delta T, \quad q \propto A, \quad q \propto 1/l.$$

If the above experiment were repeated with pipes of different materials, but of the same diameter and length, would you expect the time taken for melting to be the same for all materials? What would have happened had we chosen glass instead of a metal as the material of the strip? Recall, that you feel the heat due to the hot tea faster when the tea is in a metal container, as compared to a glass container. All other factors, namely $\Delta T, A, l$ remaining the same, the heat transferred varies from material to material. This variation is specified by the constant of proportionality in the above equation. Heat transfer through solids is called conduction, and the constant of proportionality is called the *thermal conductivity* of the material and denoted by σ. Thus,

$$q = \sigma \,\Delta T\, A/l.$$

Materials with small values of conductivity are commonly called insulators while those with large values of conductivity are called conductors. The units of σ are cal·cm/s/ °C. It is generally seen that good conductors also have small values of specific heat.

2.2 Transfer of heat in liquids and gases

In solids heat is transferred in all directions. Does that happens in liquids?

A 2.3 *Heat transfer in a liquid*

Take a boiling tube and fill it 3/4th *with water. Hold it inclined to a flame such that only the upper part of the water gets heated as shown in Fig. 2.4. Once the water starts boiling, touch the bottom of the tube. Surprised? Why does the water at the bottom remain cool, even when the upper half is boiling away?*

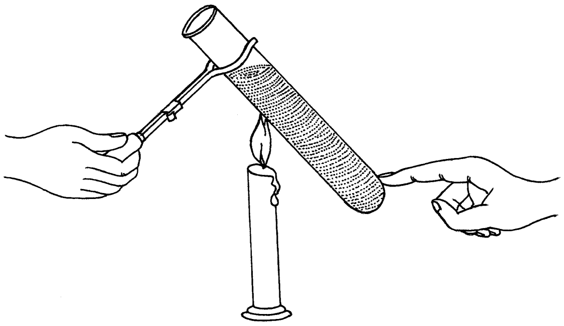

Figure 2.4: Transfer of heat in a liquid.

Consider a situation where we heat a beaker of water using a small electrical immersion heater as shown in Fig. 2.5. Notice that the bulb of one thermometer is above the lower end of the heater and the bulb of the other is below it. Predict the temperatures that would be measured by the two thermometers after the heater is turned on and then perform the activity.

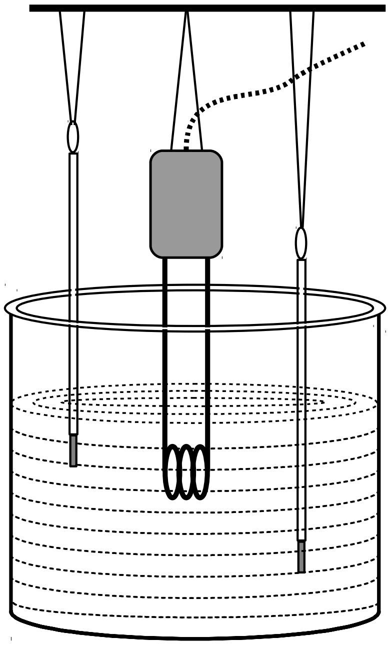

Figure 2.5: Temperature of water above and below the source of heat.

A 2.4 *Heat transfer in a liquid*

Make an arrangement as shown in Fig. 2.5. Ensure that the immersion heater is well dipped and not touching the beaker or the thermometer bulb. Then turn the heater on. Observe the change in temperature indicated by the two thermometers at 30 s intervals and explain the readings.

When heating water to make tea, we generally heat the pot only from the bottom. Yet, the water at the top (and everywhere within the pot) also becomes hot in a short time. What is the process by which the entire mass of water becomes hot, even though heat is supplied only from the bottom? Will the water become hot everywhere if we heat it only near the top as it would in a solid? Let us revisit the 'normal' water heating process, as in water being boiled for tea, but with some aids for observation.

A 2.5 *Movement within a liquid due to heating*

Let us place a beaker filled with cold water on a hot plate or over a spirit lamp. Drop a crystal of potassium permanganate in the water. Switch on the hot plate or light the lamp and observe the motion within the liquid. The motion will be indicated by the movement of the solution of potassium permanganate. Observe carefully the motion of the liquid, with particular attention to the pattern of its flow.

Find out, or reason out, what might happen when the shape of the container is changed. Heat transfer in a liquid occurs by the movement of the liquid itself. Portions of the liquids closest to the source of heat get hot first. Portions of the liquid that become hot rise to the surface and their place is taken by portions of the liquid from the top, thereby heating the liquid all through. This movement of portions of the liquid in a loop pattern is called convection, and thus we say that heat transfer in a liquid is due to convection. Contrast this mode of heat transfer, with that in a solid. In a solid we discerned no net movement of the matter constituting the solid.

What might be the mechanism for transfer of heat in gases? Is it similar to the case of solids, or the case of liquids? Or something else? We cannot see air. But if the lighting is appropriate, we can see smoke or dust moving and mixing in air. We will utilise the motion of smoke from an incense stick as a tracer for the movement of air in our experiments.

A 2.6 *Convection in gases*

A broken test tube can teach us something interesting. Take a broken test tube and two lighted incense sticks. Hold the test tube inclined, while a friend holds two incense sticks close to the two ends of the test tube as shown in Fig. 2.6. Watch the incense sticks carefully as you heat the test tube at its centre.

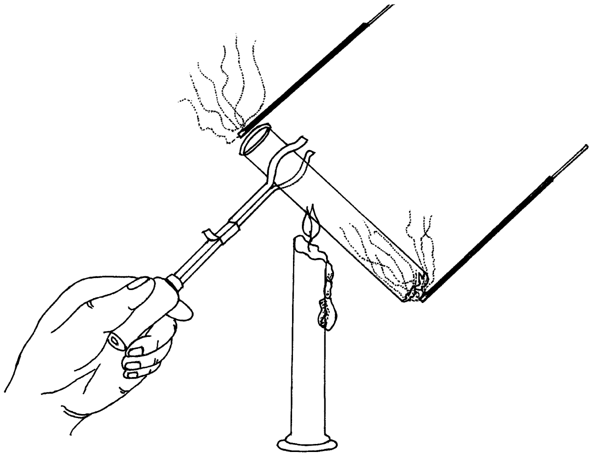

Figure 2.6: Transfer of heat in air.

When we burn an incense stick, the smoke does not immediately spread everywhere. Which way does it preferentially move? Try to see it! Does this observation have a link to the commonly made statement, that warm air is light, and hence rises upward?

In gases, as in liquids, transfer of heat takes place through the movement of the matter itself. Why does the movement of the liquid or the gas start off mostly only in the upward direction? Why does the liquid or the gas that has moved up return towards the bottom? What would happen to transfer of heat in liquids had there been no gravity?

In the examples and discussions here, we looked into heat transfer in solids, which we called conduction, and then in liquids and gases, which we called convection. The distinguishing feature between the two was that in convection, there is movement of the medium as a whole, which is not the case in a solid. It is found from rather difficult and carefully performed experiments[2] that a small amount of heat does get transferred by conduction in liquids, similar to that in a solid, but for most purposes, we can assume that convection is the dominant mode of heat transfer in gases and liquids.

2.3 Heat transfer in the absence of a medium

In the discussions so far, we have always had a medium through which heat is transferred. Is a medium always needed to transfer heat? When you stand beside a bonfire (Fig. 2.7), you feel hot. A similar effect is observed if you place (without touching) your palm *below* a hot pan kept on a stand. Recall that convection only transfers heat upwards, neither sideways, nor downwards. This implies that, when you are standing level with a fire, or below a hot body, there must be some means other than convection that transfers heat to you.

On a winter day when the sky is clear and the sun is shining, if you step out of shade into the sun, you immediately feel warm. This is due to the heat from the sun. Now if the heat from the sun were being transferred via air as the medium, there

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[2] See, for example, the internet resource, `http://fluidproperties.nist.gov/thermal.html`

Figure 2.7: Heat may be transferred in all directions, as we notice around a bonfire.

could not have been a dramatic difference in the temperature of air in a distance as short as a step. Since air is in constant motion, the temperatures of two portions of air should be nearly equal. Moreover, the air around you feels cool, but if you stay in the sun long enough, your skin gets quite hot. This means that your body is absorbing heat from the sun more rapidly than the air surrounding you. Heat from the sun is reaching you without the air in between getting hot.

A 2.7 *Temperature in sun-n-shade*

Make an arrangement to suspend a thermometer from a portable stand. Make two such arrangements, and place one of them in the shade of a building or a tree, and the other in direct sunlight. Keep a watch on the thermometer left in direct sunlight. If its reading increases rapidly, bring it back into shade quickly, otherwise it may break! Are the two readings different? If the thermometers are left in place for a long time, how do the temperature readings shown by the two change? Why?

The examples that we just saw suggest that in addition to convection, there is another way of transferring heat, which transfers heat in all directions. In fact, in all these cases heat can be transferred even in the absence of a medium. This mode is called transfer by radiation. Radiation, like light, can be reflected, in particular from shiny metallic surfaces, as we will see next.

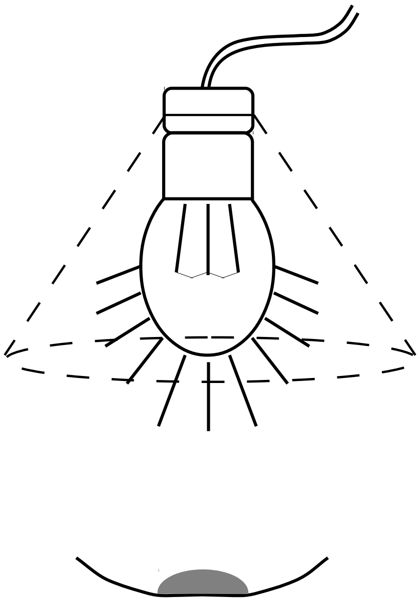

Figure 2.8: Using a canopy to reflect heat from a light bulb.

A 2.8 *Reflecting Heat*

Take a 100 W light bulb with a reflector canopy. If it does not have a canopy, you can improvise one using thick aluminium foil, but do make sure that the foil does not touch the wires or other electrical contacts. Take a small amount of solid ghee and place it in a spoon under the lamp as shown in Fig. 2.8. Switch on the light bulb and record the time it takes for the ghee to melt. Next, put the canopy on the bulb and again record the time it takes to melt the ghee. Compare the two readings. What role would you say the aluminium canopy has played in warming up the ghee?

When placed in the sun, black or dark objects get hotter quickly, as compared to an object that has a shiny, white surface. A dull or rough surface gets hotter more easily than a shiny surface of the same material. This is because a smooth surface reflects heat from the sun better than a rough surface. To get an idea of how startling the difference in the ability of different bodies to absorb heat in the absence of convection or conduction is, let us perform a small experiment.

A 2.9 *Dull and Shiny, Black and White*

Take tinfoil, or thick aluminium foil. Make two cups out of it, either using origami ideas or some of your own. The cups should be almost identical, and approximately 50 mL in volume. It is preferable if the mouth of the cup is smaller than the overall diameter. Hold one of them with tweezers over a candle or kerosene flame, such that the flame does not touch the cup but the soot from the flame gets deposited on the outside of the cup. Now place a small blob of wax in each cup, and place the cups in the sun. Watch what happens, and explain your observations.

2.4 Conductors and insulators

We always use a metal saucepan for cooking. We do not use a glass bowl. However, when we drink tea, we usually use a glass or a ceramic cup, not a metal cup. What is the reason for that? Can you think of more cases where we use to our benefit the ability of certain materials to resist transfer of heat? Such materials are called insulators.

Table 2.1: Thermal conductivity of some common substances

Materials	Conductivity [cal/cm/s/ °C]
Silver	1.01
Copper	0.99
Steel	0.012
Glass	0.0025
Polyethylene	0.00006

Being able to prevent conduction of heat is vital in many cases. When we go out on a cold day, we wear a sweater. In cold regions of the world people wear several layers of warm clothes. Very often, it is necessary to prevent loss of heat in factories, to conserve fuel. With experience we have been able to devise many insulating materials. Table 2.1 gives the values of conductivity of some substances.

The data in the table might suggest that we use polyethylene tongs instead of metal tongs. But we do not find such tongs in use. However, pans or pressure cookers often have plastic covered handles. Why is this so? What would happen if the tongs were short, or if we had to hold a pan on a stove using a pair of tongs for a long time? The usefulness of a substance, or design of devices is based on multiple considerations. Reason out the case of tongs by taking into account conductivity and melting point of the material of the tongs, distance of the hot object from the user, ease of use and robustness.

Touch sensation of cold and hot

From our earlier experiments, we know that objects in a room gradually reach the same temperature. However, you must have noticed, even when objects have been left in the same surroundings or conditions for a long time, we do not sense them as being equally cold or hot. A metal pan, for instance, feels colder than a plastic container. A polished floor tile feels colder than a floor mat, but a rough stone tile feels less cold. A metal bench left in the sun feels hotter than a wooden bench left in the same place.

These common observations result from several factors coming into play. We will first note these factors and then apply them to the situations above. (*a*) We find something hot to touch when heat is transferred to our skin, and cold to touch when heat is transferred from our skin to the object. (*b*) Metals are good conductors of heat and have smaller values of specific heat than non-metals. (*c*) The rise in temperature depends on the specific heat of the substance. (*d*) Rough, hard surfaces make poor contact with our skin in comparison to smooth, hard surfaces.

A rough tile feels less cold than a polished tile because the roughness reduces the area of contact with the skin so less heat is transferred from the skin. A mat feels less cold than a floor tile because it is a poor conductor and hence there is less heat transfer from the skin. A metal pan feels colder than a plastic container because heat gets transferred very quickly to it from our skin, not because of a temperature difference – the temperature of the two objects is almost the same – but because of the higher conductivity of the metal. In the case of benches kept in the sun, apart from the differences in sensation due to conductivity, there can be a difference in the temperature itself. A metal bench could in fact have a higher temperature than a wooden bench. When placed in sun they heat up by radiation. The temperature of the metal may increase more than that of the wooden bench, owing to the lower specific heat of the metal, even though it absorbs less radiation than wood.

2.5 Prevention of heat transfer

We wear woollen clothes in winter to keep ourselves warm. Ice is covered in a gunny bag or covered in saw dust or straw to prolong its melting. What is the role of the covering material? Suppose you take two identical blocks of ice and place them in two saucers, and cover one of them up by sawdust, or woollen strands or coconut husk powder. Which cube will melt faster? Why?

In the examples above, we are preventing heat from being transferred to or from the object of interest, as the case may be, by covering it with a poor conductor of heat. Since heat can be transferred by conduction, convection and radiation, a scheme for prevention of heat transfer, or insulation, must minimise all three modes of transfer.

Let us examine the choice of woollen clothes in winter to keep ourselves warm. Air is a poor conductor, but convects easily – so one can achieve heat insulation using air, provided the air is still or trapped! This happens very effectively in the so-called warm clothes. Wool has many minute pores which trap air. Cotton too is porous, but less so, and is usually densely spun and woven, leaving very little trapped volume. Moreover, cotton fibres have fewer empty spaces than wool fibres. So for a given thickness wool insulates better than cotton. A woollen pullover is therefore more effective than a cotton pullover of the same thickness in keeping the body warm, and two thin blankets (one over the other) more effective than a single blanket of double thickness. Bird feathers form another superb system of insulation based on trapped air and porous non-conducting natural polymer (keratin) to protect themselves from cold. It might appear surprising, but certain communities use blankets made of animal fur to insulate themselves from the harsh sun. In colder climes, it is very important to protect oneself from the wind, as wind can carry away a lot of heat from an exposed body. Whatever clothing we wear has to allow sweat to evaporate, otherwise we will end up being clammy! Wool scores well in this respect too.

There are several cases at home, in the industry, and so on, where it is important to be able to conserve heat, or prevent transfer of heat. Pipelines carrying cold water in the industry, or even those in large air-conditioning plants, have an insulated casing made of a porous or spongy material with a reflective outer layer. This prevents heat transfer from the outside to the cold water in the pipe. Even a simple thing like covering the saucepan when boiling water for tea prevents loss of heat by convection of air above the water surface. List a few situations where you find various means of preventing heat loss being employed!

A Thermos Flask

A thermos flask is used to keep things cool or warm for a long time. It is commonly used for food, but in the laboratory it is used for storing other substances too. How should an ideal thermos be? A thermos has to prevent transfer of heat from either inside to the environment, or the other way round. This implies that its design should prevent conduction, convection, and radiation. Conduction can be reduced by choosing an insulating material, and reducing the area of contact between the inside and the outside. Convection can be reduced by preventing a contact between the container and the surrounding air. This suggests that a thermos should ideally consist of two containers, one inside the other, with the air in the gap removed. To reduce radiation loss, the surfaces of the container should be made smooth and highly reflecting. A practical and close to perfect thermos took time to develop, and the thermos flask, as is known today, is credited to James Dewar. A Dewar flask consists of a double walled glass container, the top rims being fused to each other. The inner surface of the outer wall and the outer surface of the inner wall are silvered, the air in the gap is removed, and the evacuated gap is sealed off. The

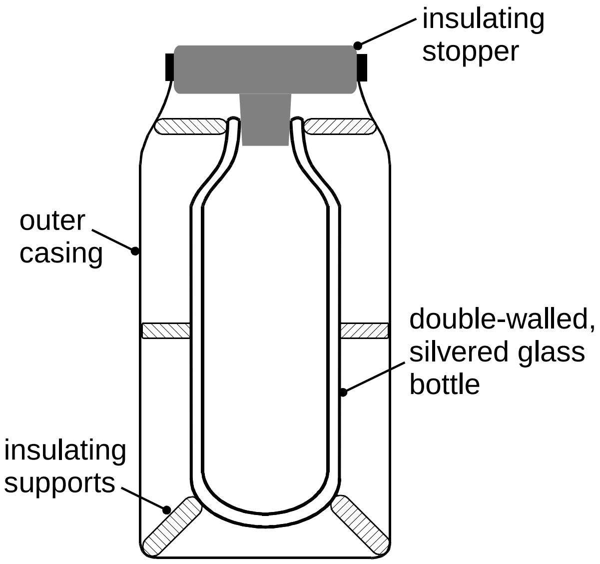

Figure 2.9: The construction of a thermos flask.

glass container has a stopper lid made of an insulating material. The glass is then placed in a larger plastic container, leaving an air gap. Small supports hold the glass in place, while minimising the area of contact. Figure 2.9 shows a sketch of such a flask. Thermos flasks of the Dewar type are being replaced by containers that are double walled (usually stainless steel inside, and plastic outside), with a thick layer of an insulating, porous polymer in between. These are more robust and useful from a practical point of view, but are less effective than a Dewar flask.

Summary

- *Heat is transferred within a body from a region of higher temperature to the one at lower temperature.*
- *The mode of transfer of heat in solids is called conduction. While conduction can occur in liquids and gases too, the dominant mode of transferring heat in these is convection, which involves an overall movement of the matter in the medium.*
- *Heat can also be transferred in the absence of a medium. Such heat transfer is called transfer by radiation. Light coloured and shiny objects mostly reflect the heat falling on them while dark coloured and dull or rough surfaces tend to absorb most of the heat falling on them.*
- *Certain substances prevent heat from being transferred quickly through them as compared to others, and they are called insulators. Metals conduct heat effectively, and also reflect radiation effectively.*

Chapter 3

Effects of Heat

In this chapter we will look at the physical effects heat has on a substance. From our day-to-day experience, we are aware of changes such as expansion of an object or the change in the state of an object, e.g. ice changing to water or water changing to steam. We will look at these in detail.

3.1 Heat and expansion

Let us begin by looking at the effect of heat on gases.

A 3.1 *Expansion of gases*

Take an empty ball-pen refill and an empty injection bottle with a tight stopper. Remove the refill tip. Pierce a hole in the stopper using a thick needle and push the refill through it. Slide in a drop of coloured water into the refill. You may use a pin to 'guide' the drop. If you quickly open and shut the stopper, the water drop will slide in easily. Make sure that the drop does not fall into the bottle. Now rub your palms together vigorously and hold the bottle tightly between your palms (See Fig. 3.1). Observe what happens to the water drop and explain your observations. What is the change in the volume of the air inside?

Some fun is in order. Take a used PET water bottle. Remove the cap and add a little water to it. Press a coin on its mouth and invert the bottle to wet the coin sufficiently. Verify that no water leaks out. Now place the bottle in an upright position without disturbing the coin. Warm up your palms by rubbing and then hold the bottle gently, but firmly in your palms, so that there is adequate contact between the palms and the bottle, ensuring that the bottle is not compressed.

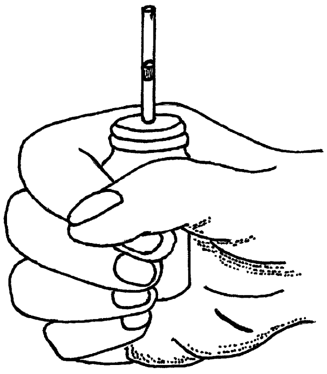

Figure 3.1: Expansion of air in a bottle by the warmth of a palm.

Watch what happens! Explain what you saw. Explain the role of water in the experiment.

Do liquids behave in the same manner as a gas when heated?

A 3.2 *Expansion of liquids*

Let us now do a similar experiment, but with water. Simply fill the previously used injection bottle fully with the coloured water that was used earlier for blocking the refill. Make sure that there is no air left in the bottle, and that the liquid level is clearly seen in the refill. Now warm your palms by rubbing and hold the bottle in your warm palms for some time. Watch what happens. Do you see any change like you did in the case of air? Next, hold the bottle with a pair of tongs and hold it over a candle (See Fig. 3.2). Does the level of the ink in the refill change? Find the reason for the difference seen between warming up using your palms and using a flame.

In both activities, you would have observed that the level of water in the small tube rises. Why does it rise? Why did it not rise in case of water, when the bottle was held between warm palms? What happened to the volume of the air or water in the bottle when it was heated? What happened after you stopped heating?

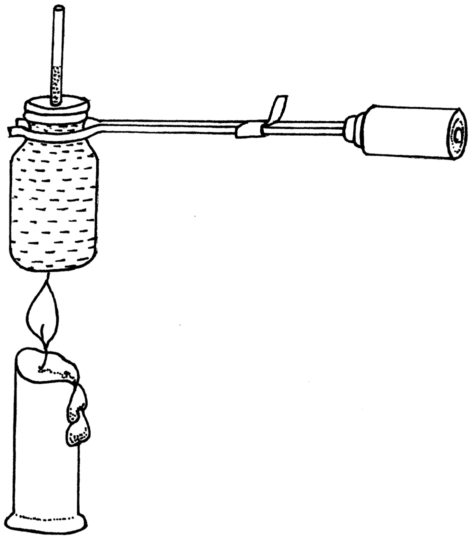

Figure 3.2: Expansion of water on heating by a candle.

A 3.3 *Expansion of a solid*

Let us now see what happens to a solid when it is heated. Collect a few items: a bicycle spoke, few short wires, a battery and a bulb, a candle and matches, a square piece of aluminium or tinfoil wrapped over a small rectangular piece of wood, and a couple of stones or paper weights. Build an electrical circuit with the spoke as one of the components as shown in Fig. 3.3. In the beginning let the spoke touch the coin and check that the circuit is complete and the bulb glows. If it does not, check all contacts and clean them using sand paper or a blunt blade. Now create a small gap between the coin and the spoke by slipping a strip of paper in between. Does the bulb go off? Remove the paper gently, taking care not to disturb the arrangement. Heat the spoke and watch what happens. Does the bulb glow again?

Can you explain why the bulb glows again after the spoke is heated? What

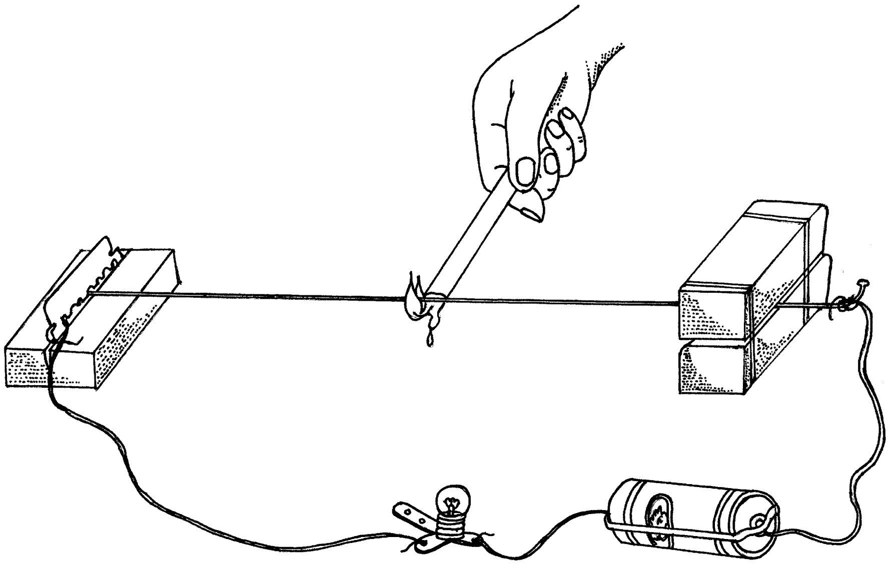

Figure 3.3: Increase in length of a solid on heating.

change in the spoke caused the circuit to be completed? What happens a short while after you stop heating?

In the experiment with a spoke and a bulb, you saw that the spoke expands when heated. Let us repeat the experiment after increasing the gap very slightly. You may set the gap first by slipping a strip of paper, and in the second stage, set the gap by inserting two strips, or a thicker strip. Does the gap get bridged by the heating with the same candle for the same time? What if you heat for a longer time? Can we increase the gap indefinitely, as we heat the spoke ever longer?

Suppose you heat the spoke using two candles instead of one. How do you expect the observations to change? Repeat the experiment with two candles to test your prediction. The length of the spoke increased when heated. What happened to its thickness (diameter)? Had you replaced the spoke by a shorter, but thicker rod (both made of steel, and of the same mass), and repeated the experiment exactly in the same manner, would the electrical contact be re-established upon heating for the same time?

A 3.4 *A simple thermometer*

Take the bottle and refill as was done in earlier activities. Fill the bottle completely with kerosene and shut it tight with the stopper in which the refill is fixed. Do it gently, so the kerosene will not spill, instead it will rise into the refill (see Fig. 3.4). Our thermometer is ready! Compare our thermometer with the laboratory thermometer. What are the similarities and differences? Hold both thermometers in hot water. Does

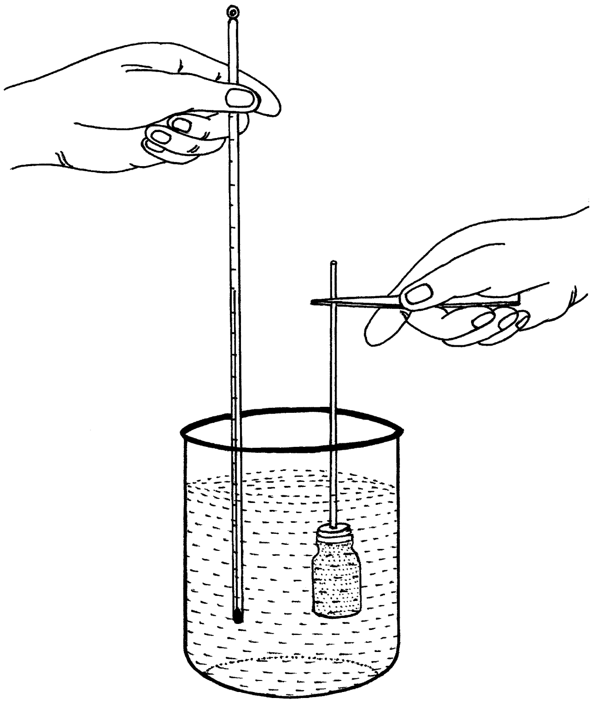

Figure 3.4: An improvised oil-based thermometer compared with a laboratory thermometer.

our kerosene thermometer take longer to reach the maximum height, or the laboratory thermometer? What could be the reason for this? What properties should a substance have to be suitable as a thermometric medium?

Let us compare our results concerning expansion of solids, liquids and gases. Recall that the tiny amount of heat supplied by rubbing the palms was enough to appreciably expand air, but not water, even though the volume of the air and the water was the same. That is, a small change in temperature led to a noticeable change in volume in case of gases. Also note, that the mass of air is much smaller than the mass of water for the same volume. Solids need to undergo a much larger change in temperature than liquids for a noticeable expansion. We can summarise our observations by saying that for a given rise in temperature, solids expand less than liquids, while liquids expand less than gases, the volumes being equal in all cases. Can we now say that expansion is a measure of how hot the substance is?

3.2 Change of state

What happens when we heat a solid such as wax or *ghee* long enough? Try it out. You will find that it melts, but would it have melted had it not been heated? What happens to a block of ice if you leave it in a saucepan? It turns into water, so, we say that ice is the solid form of water. Where did the heat that converted ice to water come from? Would the ice have melted in a shorter, or in a longer time had it been heated as in the case of wax?

Take some soldering wire or a small piece of tin (which you can obtain from a tinsmith), and hold it to a flame. Observe what happens. Does it turn from solid to liquid? Does the saucepan in which you heat the water also melt?

Take a small saucepan of water and cover it with a dry lid. Make sure that the lid sits firmly, but is not too tight. Heat the pan on a stove and pay attention. Do you hear a faint sound which goes

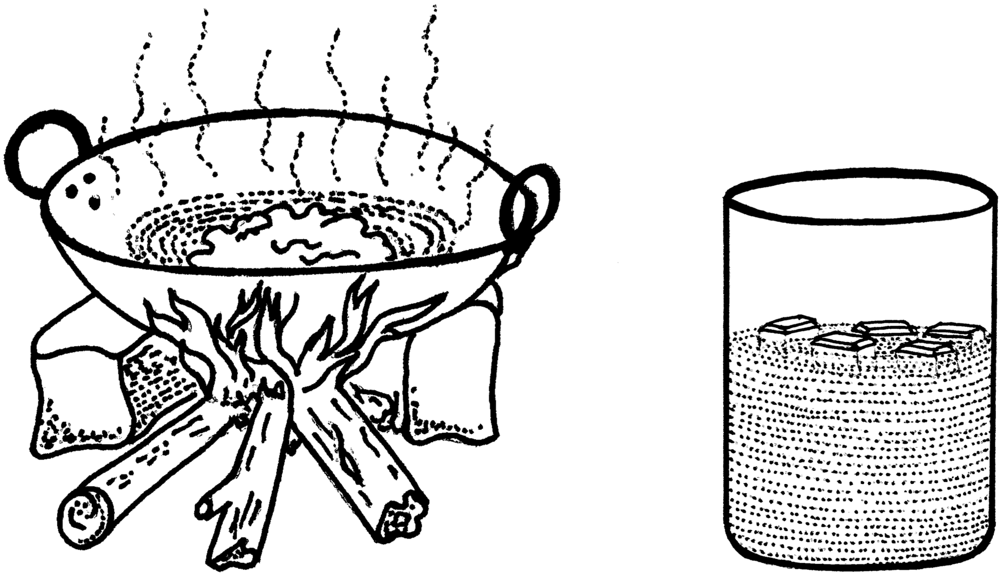

Figure 3.5: Some examples of change of state from solid to liquid.

on increasing? When this happens, stop heating and carefully lift the lid. What do you see on the underside of the lid? Where did the water come from? What happens when you heat longer?

In the examples above, we saw that substances changed their state – solid to liquid, or liquid to gas – when heated, or when left in a surrounding with a different temperature. Let us note some contrasting issues in what we saw. The metal pan in which water was being heated did not melt, but tin, which too is a metal, did melt. Wax melted only when heat was supplied, but ice, apparently, melted without any additional supply of heat! Can you assess the situation, not in terms of the heat supplied, but in terms of the temperature of the substance when the change took place?

It is found that most materials change state when heated. However, they do so at vastly differing temperatures. Water [liquid], for example, turns into ice [solid] at 0 °C and into steam [gas] at 100 °C. Aluminium [solid] turns into liquid at 570 °C, while nitrogen [gas] turns into liquid at $-196\,^{\circ}\mathrm{C}$. The temperature at which a solid turns to liquid is called its melting point, while the temperature at which a liquid turns to a gas is called its boiling point.

Densities of solids and liquids

What happens to the density of a solid when it melts? When we melt *ghee* (at home) or wax (as in the activity in the previous chapter), we find that the solid stays at the bottom of the container. This implies that the liquid has a lower density than its corresponding solid.

The thermometer re-visited

We have seen that when exposed to hot surroundings, the mercury or alcohol column in a thermometer becomes longer, i.e., the substance expands. Expansion is taken as a measure of the degree of hotness. An ideal thermometer based on expansion should have the following properties:

- It should expand or contract significantly for small changes in temperature, so that temperatures can be precisely measured.
- The substance should take up little heat from the object of interest to come to the same temperature as the object of interest, otherwise the thermometer will show a lower temperature than what it was before inserting the thermometer.
- The expansion should be uniform over a wide range of temperatures.
- If the thermometer can be made compact and reusable and provides accurate measurements each time, it is ideal.

Thus, the ideal thermometric substance has a high expansion coefficient which remains the same at all temperatures of interest, and should have a low specific heat. It should not change its state over the temperature range of interest. A gas based thermometer, or a thermoscope, satisfies most of these criteria, but it is voluminous, and cumbersome to use. A mercury thermometer satisfies most of these criteria, while also permitting a compact and robust construction. However the more commonly used substance is alcohol rather than mercury. The reason is *not* because it is superior based on the ideal criteria, but because mercury is a poisonous substance, while alcohol is not, and also because mercury is very expensive compared to alcohol. An alcohol thermometer is useful over the temperature range $-70\,^\circ$C to $110\,^\circ$C, while a mercury thermometer is useful over the temperature range $-20\,^\circ$C to $300\,^\circ$C. A dye is added to alcohol to improve readability.

The strange case of water

Have you noticed that when ice melts it floats on the water resulting from the melting? What do you conclude about the density of water compared to the density of ice? The case of water is a rare case of a solid having a lower density than the corresponding liquid. In most substances, the liquid has a lower density than the corresponding solid.

Solids that have a smaller density than the corresponding liquids exhibit another anomalous phenomenon, namely that their melting point is lowered under the application of pressure. A nice illustration of this is the gradual splitting

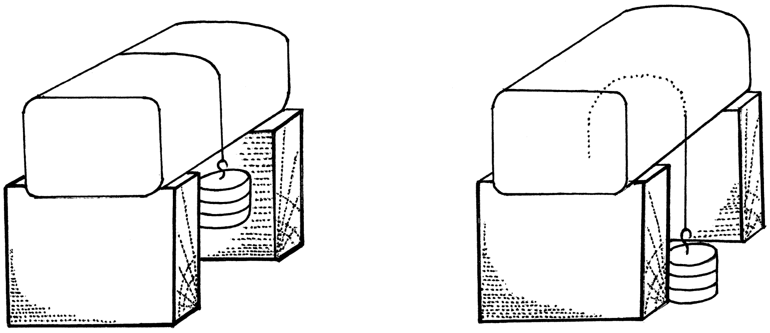

Figure 3.6: Melting of ice under pressure.

and re-joining of ice along the track of a wire exerting a force on the ice. This can be easily effected by hanging weights by a wire as shown in Fig. 3.6. A corollary of this effect is that two blocks of ice pressed together for a while will stick together when the pressure is released.

3.3 Vaporisation

If an open pan of water is left standing, the water level keeps falling, and ultimately the water disappears completely. Where does this water go? Observe this under different conditions – at different times of the day, at different times of the year or at different locations. If you were to leave a covered pan of water with a lid standing for a long time, you will notice fine droplets of water sticking to the underside of the lid. A similar, and a more dramatic effect is seen when water is heated with a lid on the pan.

What happens is that some of the water leaves the bulk liquid and having transformed to the gaseous state mixes with the air around. This process is called vaporisation. How do changes in the surrounding conditions affect vaporisation?

In most cases, the liquid and vapour phases exist together. Some liquids, such as alcohols and ethers evaporate readily, compared to water or oils. The reason why you smell alcohol when a bottle is left open is because the alcohol evaporates in copious quantities (even at room temperature) and reaches your nose. Air contains some water vapour, whose amount varies with temperature and the presence of large water bodies, such as lakes or rivers. Have you not noticed that the air feels moist in the vicinity of a lake or a river? A term called humidity is usually used to denote the amount of water vapour in the air.

Humidity is a significant factor in determining the weather. As the vapour content in the air keeps on increasing, there comes a point when the vapour condenses and forms droplets of water. The formation of droplets depends on both, the amount of water and the temperature of the surrounding air. The process of evaporation followed by condensation, when the water vapour and air temperature conditions are right, is responsible for phenomena such as the formation of dew and rain.

The effect of a fall in temperature on humid air can be seen easily. When a bottle of chilled water or a container from a refrigerator is left in the open, we find water collecting on the outer surface of the bottle or the container. This effect is more when the air is humid, and is due to the vapour in the air condensing on the cold surface.

Sublimation

Some solids undergo significant vaporisation. Two examples are naphthalene and camphor – we smell their presence by their vapours. All solids do vaporise to some extent, but the effect is very small. Ammonium chloride is a peculiar solid that does not vaporise significantly at room temperature, but when heated sufficiently, it gets completely converted to vapour, without undergoing a change to the liquid state. This process is called sublimation. ***Vapours of ammonium chloride can be dangerous, so do not try to sublimate it unless there is plenty of ventilation. Children should not do it without adult supervision.***

3.4 Does heating always lead to increase in temperature?

In the activities above and in the previous chapters we found that heating generally leads to a change in temperature, although the change may differ from substance to substance. But, is it always true that heating leads to change of temperature? Let us check it out.

A 3.5 *Latent heat of evaporation*

You will need two laboratory thermometers, a saucepan full of water, and a stove. Keep the saucepan on a stove and suspend the thermometers through slightly over-sized holes in a lid as shown in Fig. 3.7. Make sure that one of the two thermometer bulbs is well under water, but does not touch the pan, while the other is above the water. Now light the flame and note the temperature of the water every few minutes, until well past the time the water starts boiling. Record the temperature of the water vapour rising from the pan.

What is the most striking point in your observations? Can you explain the observed patterns of the readings in the two thermometers? Let us try out a similar activity, but with a solid.

A 3.6 *Latent heat of melting*

You will need: a laboratory thermometer, some ice and a small bowl or cup. Take some ice and crush or grate it. Fill up the cup

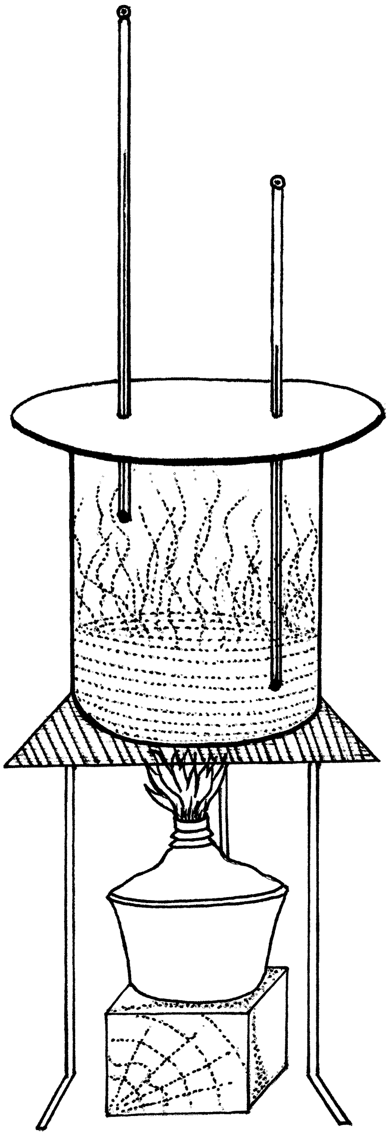

Figure 3.7: Change in temperature of water as it turns into steam.

completely with the crushed ice and stand the thermometer in it such that the bulb is completely enclosed by ice but does not touch the cup. Note the temperature shown by the ice. Now leave the cup in the sun or heat it gently. Keep a record of the temperature while you watch the ice melt. Does the temperature of the water formed rise continuously?

In both the above cases, heat was being supplied continuously, but the temperature did not rise continuously. It rose for a while, and then for some time it remained unchanged. At this juncture the *entire* substance was undergoing a change of state, from liquid to gas (or from solid to liquid). This change of state is different from the case of vaporisation, where only the liquid (or solid) from the surface was changing to gas. In other words heat was used for effecting a change of state, without increasing its temperature. Like specific heat, the amount of heat required to effect a change of state varies from substance to substance. The amount of heat per unit mass needed for the change is called latent heat of melting [solid–liquid change] or latent heat of evaporation [liquid–vapour change].

Summary

- *Heat causes expansion in all states of matter. For a given substance, expansion is a measure of how hot that substance is.*
- *Heat can transform matter from one state to another: solid to liquid to gas.*
- *Some substances may be directly transformed from the solid to the gas phase. This phenomenon is called sublimation.*
- *Change of state requires heat, but that does not lead to a change of temperature.*
- *Most substances contract upon cooling and expand upon heating, and the density of the solid is greater than that of the corresponding liquid.*
- *Water shows anomalous behaviour, in that it expands upon freezing, unlike other solids, and the melting point of solid water (ice) is reduced by the application of pressure.*

Chapter 4

Heat and Work

4.1 Some observations

We have already seen a connection between heat and expansion – supplying heat leads to an increase in volume. In the experiment on expansion of air in an injection bottle, we found that the drop of ink in the stopper moved outwards. In the experiment with the PET bottle with a coin as a lid, we found that the coin moved when the air in the bottle became warm.

Such movement from a state of rest implies that there is a force acting on the ink drop or the coin. Since pressure is force per unit area, we can say that the lid, or the ink drop, moved due to an increase in the pressure exerted by the air inside the bottle, which in turn was a consequence of heating of the air. In other words, heating, or change in temperature, not only led to an increase in volume of the gas, but also an increase in the pressure of the gas. Can it happen the other way round? Will an increase in pressure of a gas lead to an increase in its temperature?

A 4.1 *Compressing Air*

Find a bicycle pump, and push the piston back and forth a few times. Feel the barrel for change in temperature. Next, close the nozzle (or ask someone to press a finger against the nozzle) and pump again as shown in Fig. 4.1. Feel the barrel for change in temperature. Compare the two cases. Note that in the latter case air is not escaping the barrel, and its volume is reducing.

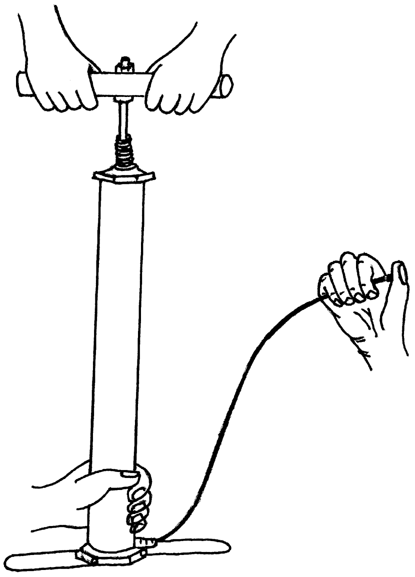

Figure 4.1: Increase in temperature of air upon compression.

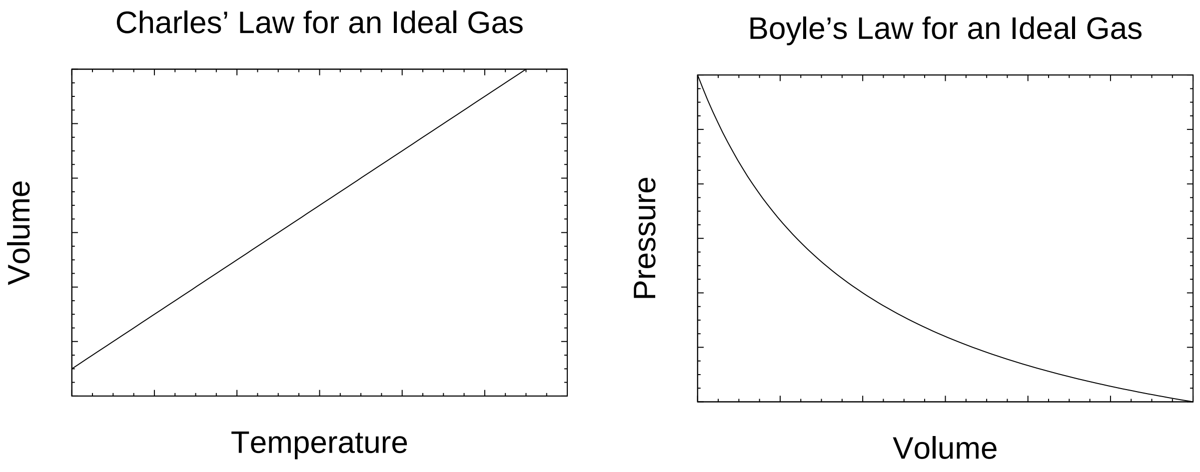

Figure 4.2: Graphs depicting Charles' and Boyle's laws for gases.

In the above experiment, with the nozzle closed, you exerted force on the air inside the barrel causing its pressure to increase, as a result of which its temperature increased and its volume decreased. Pressure, Temperature and Volume of a gas are related. The relationships between the three were studied by the scientists Charles, Boyle and Gay-Lussac, as early as in the 17th and 18th centuries. The inferences from their investigations are summarised in two important laws.

Charles' Law: At constant pressure, the change in the volume of a given mass of an ideal gas changes in proportion to the change in its temperature.

Boyle's Law: For a fixed mass of an ideal gas kept at a fixed temperature, pressure and volume are inversely proportional to each other.

The laws are depicted as graphs in Fig. 4.2. These laws are idealisations, or approximations, and all gases show some deviation from this behaviour. The behaviour of helium is closest to ideal gas behaviour.[1] Many gases come close to ideal gas behaviour at low pressures and high temperatures.

4.2 Expansion and mechanical energy

In the air expansion experiment using the injection bottle, the force that pushed the ink drop outwards does not cause it to move for ever. Explain why. What does the distance moved by the ink drop depend on?

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[1] An ideal gas is one whose molecules have zero size, and no internal structure, and scatter from each other without loss of energy. The significance of the concept of an ideal gas will be clear in the next two chapters.

Robert Boyle (1627–1691) and
Jacques Alexandre Cesar Charles (1746–1823)

Boyle got to know of the vacuum pump invented by Otto von Guericke and worked on improving its design with the help of Robert Hooke. He was able to conduct many studies using this pump, which led to the enunciation of the law which states that the volume of a gas varies inversely with its pressure. In addition, he was also able to discover the role of air in the propagation of sound. He also laid the foundation for modern chemistry by giving the first modern definition of an element and differentiating between compounds and mixtures. Charles was lucky to have a law named after him. The law which states that the volume of gases is proportional to the absolute temperature under constant pressure was in fact formulated by Gay-Lussac, who credited it to unpublished work by Charles. Charles had carried out an experiment in which he filled the same volume of different gases in five balloons. When he raised the temperature of all the five balloons to 80 °C, he found that the increase in volume was the same in all cases. Charles was also the first to use hydrogen in balloons where previously only hot air had been used. The first balloon managed to lift a weight of approximately 9 kg.

Recall from mechanics, that energy is spent when an object is displaced against a force. Mechanical *Work* is defined as the product of the displacement of a body along the direction of the applied force and the magnitude of applied force. *In the situation described above, heating of air leads to work being done on the ink drop.* In the case of the PET bottle, work is done on the coin.

Let us look more closely at the work done when a gas expands with the aid of an example.

A 4.2 *Expansion and work done*

Take an injection syringe with its needle removed. Press the plunger nearly half way in and seal the tip by an airtight plug, or your thumb, or by using a sealant or an adhesive (See Fig. 4.3). Draw the plunger out. What happens when you stop drawing? Why does

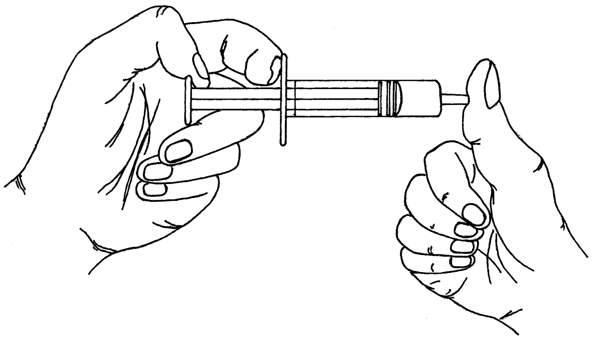

Figure 4.3: Pulling a piston (i.e. a syringe plunger) atmospheric pressure.

Joseph Louis Gay-Lussac (1778-1850)

Gay-Lussac did important work in both Physics and Chemistry. But we generally hear of him in connection to the law named after him which states that under constant pressure, the volume of a gas is directly proportional to its temperature. Gay-Lussac improved the design of common laboratory equipment like the burette and pipette along with playing a part in the discovery of boron and recognising iodine as a separate element. He also went up in hot-air balloons to study the composition of the atmosphere at different altitudes.

the plunger move into the barrel? It moves in because the air outside exerts pressure on the plunger. In drawing out the plunger of the syringe, the air inside expanded to occupy the increased volume, and the pressure inside is lowered in comparison to the pressure of the air outside. In pulling the plunger out work has been done by you against atmospheric pressure. When you release the plunger, the air outside does work on the plunger – and in turn on the gas inside it. Repeat the above exercise, but instead of drawing out the plunger by hand, stand the syringe in a hot water bath after sealing the tip. What do you expect?

In mechanics, the work done equals the amount of energy spent by the agent applying the force. Thus, if you push a block, you are doing work on the block, and spending energy. When you lift something, you apply a force. You need to spend more energy to lift a heavy object than a light one. In other words, you need to do more work.

How much is the work done when the barrel moves out? Let us find out. The force on the piston is $P \times A$, where P is the air pressure and A is the area of the plunger. If the plunger moves a distance d, the work done is

$$W = P \times A \times d$$

Since $A \times d$ is the change in the volume, ΔV, of the gas, the work done is $P \times \Delta V$. This is true whether the barrel moves out by your pulling on it, or because the air inside is heated. When the gas expands, it loses heat, which is converted into work.[2] That means energy is expended. This suggests a relationship between heat, work and energy. Indeed, heat is often called thermal energy, a term we shall discuss in the next chapter.

Recall the activity with blocked bicycle pump at the beginning of this chapter. There it was found that *compression leads to heating*, which is the exact opposite of *heating leads to expansion*. To reduce the volume of the gas, you had to perform work on it, whereas, when

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[2] The relation between the heat supplied and work done forms the basis of the steam engine!

a gas expands due to heating, the gas does work on the stopper. As another example, consider an empty, stoppered injection bottle held over a candle flame. In a short time the stopper flies off the bottle – try it out! Once again, heating of a gas is causing displacement of an object in contact with the gas. Thus heat performs work, or heat can be converted to mechanical energy. A common example of this conversion is when water is boiled in a saucepan, and the lid of the saucepan gets lifted.

A 4.3 *Displacing objects using heat*

Take a test-tube filled partly with water and close it with a cover-slip and set it on a flame. Note how long you have to heat until the cover-slip moves up and down. Record this time and throw away the hot water. Let the test-tube cool down completely. Add exactly the same amount of fresh water as before. Cover the test-tube, and place a small weight on the cover-slip, such as a few coins, as shown in Fig. 4.4. Heat once again. Note the time it takes for the cover-slip and coins to show some movement, and compare it with the previous experiment. This experiment could also be done with a saucepan having a close fitting lid.

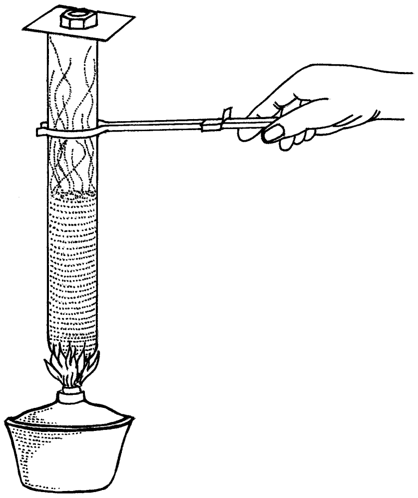

Figure 4.4: Work done by supplying heat to a gas.

What is the relationship between the weight displaced by the steam and the time for which heat is supplied? Since the steam arising from boiling water exerts force on the lid, and displaces it, it is doing work against gravitational force. Thus heat performs work.

4.3 Mechanical equivalent of heat

The equivalence of heat and mechanical work was demonstrated and established by the efforts of Joule. He spun a tight-fitting paddle in a cylinder containing water by applying a weight to a string wound over the axle of the paddle as shown in Fig. 4.5. Since the container is made water-tight, water cannot escape when the paddle turns. The spinning paddle churns the water and the kinetic energy of the spinning paddle is transferred to the water. The effect of constant churning of the water trapped in the water-tight container is to make the motion of water quicker and more irregular. Eventually, the

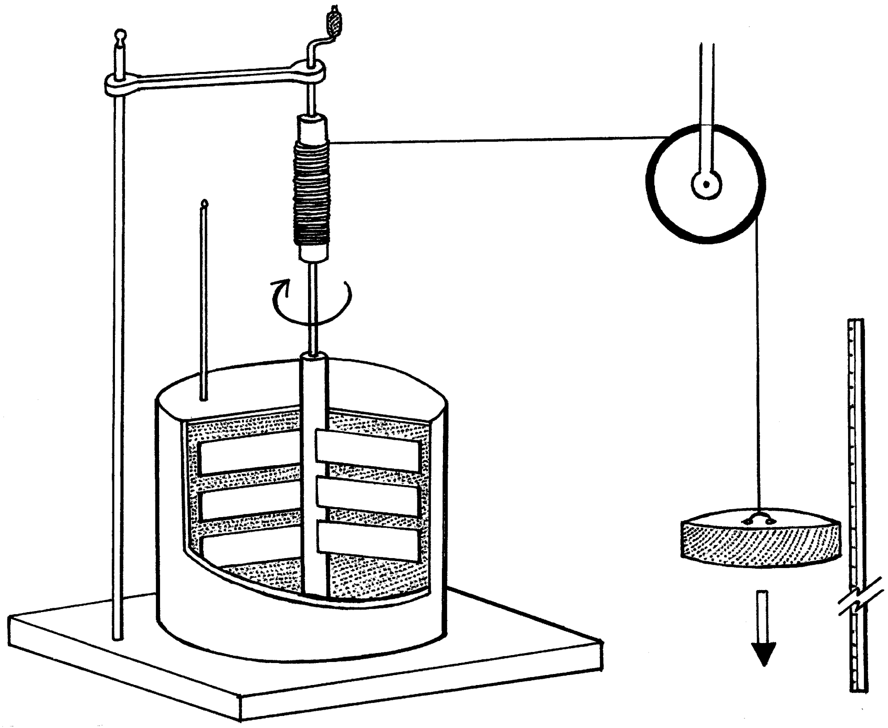

Figure 4.5: Joule's apparatus for demonstrating the equivalence of heat and (mechanical) work.

kinetic energy imparted by the paddles is distributed throughout the water, thereby increasing the thermal energy, and hence the temperature, of water.

If we measure the change, ΔT, in temperature of the water, then knowing the mass of the water m_w, and the specific heat of water s, we can calculate the heat transferred to the water Q:

$$Q = m_w \times s \times \Delta T$$

As the block accelerates under gravity, its kinetic energy increases. However, the acceleration of the block is less than g, the gravitational acceleration of a free-falling object, because the paddle in the water is resisting the motion of the block. If the acceleration of the block is a, m_b is the mass of the block, and d is its displacement, then $m_b \times a \times d$ is the work done by gravity on the paddle.

Having measured the rise in the temperature of water and the acceleration of the block, Joule could show that the heat generated Q was proportional to the work done, or,

$$Q \propto m_b \times a \times d$$

The constant of proportionality in SI units is 4.184 joule/calorie, and is called the mechanical equivalent of heat. You would remember, that 1 J is the work done when a body of mass 1 kg is accelerated by 1 $\mathrm{m/s^2}$ and is displaced through 1 m.

James Prescott Joule (1818-1889)

Joule was one of Dalton's pupils, and that might explain his ready rejection of the calorific theory which was widely accepted at that time. He was convinced that temperature was a measure of the motion of the constituent particles and made three different measurements of the mechanical equivalent of heat. Though his work was not immediately accepted (maybe because of the precision with which he claimed to have made the measurements), the SI unit of energy is now named after him. In addition to this work, he also found the relationship between the resistance and the amount of heat dissipated in a circuit.

4.4 Cooling by expansion

So far we have concerned ourselves with developing a relationship between an increase in temperature of a gas and work, by way of expansion. Let us now look at how expansion can lead to *cooling*.

A 4.4 *Cooling trick*

Take a bicycle tyre-tube. Pump it up hard.[3] *Now rapidly pull out the valve. Compare the temperature of the air rushing out, relative to the air outside. To do this you could place your finger on the neck of the valve as shown in Fig. 4.6, or even better, place the bulb of a thermometer in the air jet.*

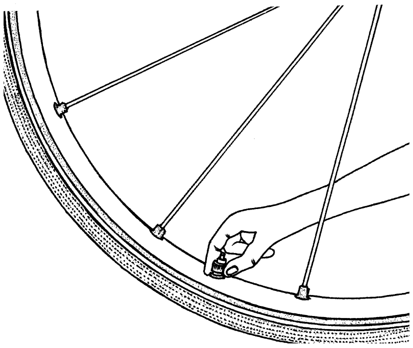

Figure 4.6: Expanding air cools when it does work against atmospheric pressure.

The air rushing out does *Work* against the atmospheric pressure. Part of the thermal energy of the air inside is converted to work, thereby reducing its thermal energy and hence the temperature[4].

The air inside the tube and the air outside have the same temperature since the tube is in contact with the outside air. So, cooling by expansion appears to be a case of transferring heat from a body at a certain temperature, to another similar body at the same temperature. Is this consistent with our inferences from earlier chapters?

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[3] If you wish to pump up the tube very hard, it is safer to have a tyre encasing the tube in this activity. Explain the role played by the tyre.

[4] This cooling effect is called the Joule-Thomson effect, or the throttling effect, and is useful for liquefying gases and for refrigeration and air-conditioning.

Julius Robert von Mayer (1814-1878)

Mayer took an indirect route to Physics, he studied and practised medicine and got interested in Mathematics and Physics only later. In spite of this, he made valuable contributions to the field of thermodynamics which were not immediately accepted. He was the first to state that energy can neither be created nor destroyed. Not only this, he described oxidation as the source of energy for living things and proposed that plants converted light into chemical energy.

Now suppose, instead of letting out the high pressure air from the tube to atmosphere, we had placed an airtight, evacuated container snugly on the nozzle, as shown in Fig. 4.7, and then opened the valve. Would there be a change in the temperature of the rushing air? Why or why not?

It is found that when a gas expands freely, there is no change in its temperature. This can be understood in terms of the work done – since the pressure in the evacuated container is zero, there is no force opposing the motion of the air particles rushing into it. So, at the beginning of the expansion no work is done and no heat is lost by the gas. As the gas starts filling the evacuated chamber, the pressure in the evacuated chamber starts building up and work is done as time goes by. In the earlier example, work was done by the expanding air against the surrounding air, causing it to lose heat and consequently the temperature of the expanding air was reduced.

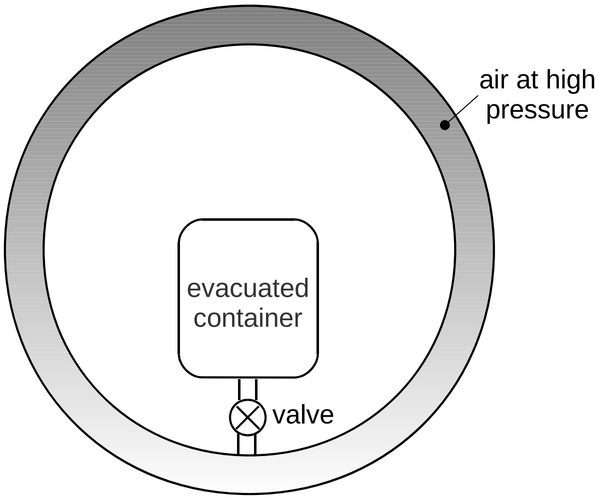

Figure 4.7: Expansion of air at high pressure into an evacuated container.

Heat transfer between bodies at the same temperature

As we have seen in the earlier chapters, objects at different initial temperatures, when kept in contact, gradually come to a common temperature, and heat is transferred from the object at a higher temperature to the object at a lower temperature. But, in the preceding example we found that heat was lost from the gas! Transferring heat from an object at a lower temperature to an object at a higher temperature, or between two objects that are initially at the same temperature, is impossible unless some energy is spent by *an external agent*. The phenomenon of cooling by expansion that we saw is an instance where energy is spent in reducing the temperature of an object (a gas) whose temperature is initially equal to the temperature of the surroundings.

Summary

- *Heat and work are related, and they can be transformed into each other; thus heat is a form of energy.*
- *Pressure, volume and temperature of an isolated gas are related to each other. Pressure is directly proportional to temperature, and inversely proportional to volume for a fixed amount of gas.*
- *When a gas expands, it performs work and loses heat.*

Chapter 5

What Makes Things Hot

In the previous chapters we accepted the notion that temperature is a measure of how hot a substance is. We observed that objects which have different temperatures come to the same temperature when they are in contact with each other, as the body with higher temperature loses heat. We also looked at some effects of heat, and at how heat is transferred. We have not yet answered the question *What is it that makes things hot*? Of course in our daily lives, we use a gas stove or a coal stove, or an electric heater to generate heat for our daily needs, while in our experiments we used candles or Bunsen burners, but these are merely means of heating a substance. *We still do not have an idea of what is it in a body that makes it hot, and what determines the temperature of a body*.

5.1 Early ideas

The question 'What is heat?' kept scientists of the past centuries busy. One of the prominent beliefs of the scientists until the middle of the nineteenth century was that heat is an invisible substance (called the caloric) that is present inside all matter. Joseph Black, an English scientist, was a proponent of this idea. He could explain many phenomena based on the caloric model. The plausibility of the caloric probably arose from phenomena related to the transfer of heat. As we have seen, heat is not transferred instantaneously across an object. Moreover, it is always transferred from a hot object to a cold object. Thus arose the notion, that hot objects have *something* in excess over a cold body. By postulating that when this excess is transferred, the deficit in the cold body is balanced, one could explain the observation that equality of temperatures is achieved between hot and cold bodies in contact.

The idea of a caloric was also useful in explaining expansion of an object upon heating. Expansion is explained by the spreading of the caloric between the particles of the material the object is made of, thereby increasing the gaps between the particles. This model of heat is able to explain phenomena such as transfer of heat and expansion due to heat, but it fails in certain respects.

There was one phenomenon concerning heat where the caloric theory failed spectacularly. It was a matter of common observation that rubbing objects against each other (such as one's palms), creates heat, and increases the temperature of the objects being rubbed. Explaining this effect satisfactorily was a challenge for the caloric theory. If the caloric theory were true, then the amount of caloric in each of the palms would remain unchanged unless some heat were explicitly supplied from outside (we leave aside the issue of what would happen to a person's palms if held over a flame). Merely moving them back and forth against each other should not have increased the amount of caloric within them. Experience tells us that heat can be generated by rubbing almost any pair of objects against each other, and the amount of heat generated depends not so much on the objects themselves, as on the force with which they are rubbed against each other.

A 5.1 *Heat by friction*

Take a flat iron strip (such as a hacksaw blade or a knife) and rub it against a rough surface (such as a large stone or the underside of a tawa). Another option is a marble rubbed against the floor. Is heat generated by rubbing? Does only one of the two surfaces in contact become hot? What happens when you rub for a longer time, without changing how rapidly you rub? Compare the temperatures of the heated surfaces when the rubbing is rapid and when it is slow, but for the same duration of time. Several commonplace examples of generation of heat by friction can be cited: the tyre of a vehicle gets hot while in motion, a stone or a piece of metal being cut by a saw-wheel or a cutting disc gets hot.

Is there a limit on how much heat you can generate by rubbing as in the above experiment? Suppose we keep rubbing for a minute, cool the object by dipping it in water and start rubbing it once again. In principle, you could repeat this process as many times as you want. So, there is no limit on how much heat you can generate by this means. If the caloric theory were correct, and the heat generated was due to the caloric being released, then at some time all the caloric would flow out, and it would be impossible to generate any more heat in that object by further rubbing.

Rumford's experiments

Very elaborate experiments concerning the generation of heat by friction were done by Benjamin Thompson (later known as Count Rumford), who was a supervisor in a gun factory. He observed that a great amount of heat is generated when the barrel of a gun is bored. So

Sir Benjamin Thompson, Count Rumford (1753-1814)

Rumford tried his hand at many things during his life – served in the army, invented the coffee percolator and recognised that heat generated by friction was a refutation of the calorific theory. He was also the first to appreciate the role of convection in the heating and cooling of fluids and that air and water were poor conductors of heat.

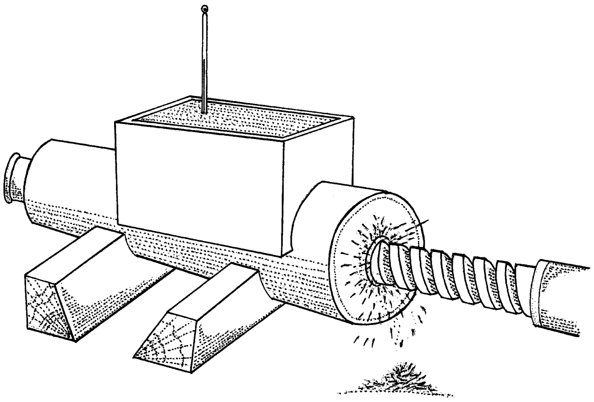

Figure 5.1: Heat generated by cannon boring in the experiment done by Rumford.

much, in fact, that the boring of a gun immersed in water could lead to the boiling of water, as demonstrated using a specially built apparatus, shown in Fig. 5.1. He noticed that heat was only generated when the borer was moving, and when boring was stopped the gun barrel gradually returned to normal temperature. He found that the pieces of metal that were expelled in the boring process were quite hot. This meant, if the caloric model were true, that caloric was being lost from the barrel, and that the barrel should never again become hot. This was not true, for when the boring process was resumed the barrel became hot once again; the supply of heat was apparently endless. Rumford confirmed that no physical change had taken place in the material of the gun barrel by comparing the specific heats of the material removed by boring and the material that remained. He measured the mass of the metal filings emerging from the boring while they were still hot, and after they had cooled down, in order to examine whether the loss of caloric appeared as a change in mass. His observations did not show a change in mass due to heating. This was a strong point against the caloric theory, for if the caloric were a substance, it ought to have a mass, but none of the carefully repeated measurements showed that it did.

He examined these observations very carefully and came to the conclusion that the concept of the caloric must be wrong. The most significant point emerging from his experiments was that *motion* is necessary for heat to be generated by friction. He therefore asserted that the root cause of heat was related to motion. But what kind of motion could be associated with heat? Clearly not any kind of motion, for two identical objects, one left stationary and the other moving around, do not show a difference in temperature! To stress the point that not any arbitrary motion can be linked to heat, let us do this thought experiment.

A 5.2 *A Thought experiment*

What if in Rumford's experiments at the gun factory, the borer were left in the barrel and the entire assembly were moved, instead of the borer moving within the barrel? Would such motion lead to heating of the barrel?

Although Rumford was convinced that motion was the only tenable source of heat, he could not say decisively which kind of motion was responsible for the observed heat. It was clear that ordinary motion, (such as movement of the cannon as a whole) could not be linked to heat. Moreover, heat was only being generated when objects were rubbed against each other. The nature of the surfaces in contact and the rapidity of the relative motion were two significant factors that had an influence on the amount of heat generated. The hypothesis of motion and heat being related needed investigation as to *which kind of motion* was responsible for heat.

With Rumford's hypothesis in mind, let us perform some experiments and see whether they give us any clue about the kind of motion that can be linked to heat.

5.2 Is everything within a substance static?

A 5.3 *Mixing in liquids*

Take two identical beakers and fill one of them with water at room temperature. Fill the other with the same amount of water, but at approximately 60 °C. The hot water used here should be pre-heated, stirred and allowed to become still. Add to the two beakers one drop each of ink that has already been diluted. A drop of red fountain pen ink diluted by about 10 drops of water at room temperature is suitable. Make sure that your dropper dispenses drops of the same size at all times. Watch how the ink spreads gradually (Fig. 5.2). Compare the rate at which the ink spreads throughout the water in the two beakers.

Figure 5.2: Spreading of ink in water.

We know from our day-to-day experience that salt or sugar dissolve in water more quickly when the water is hot, compared to the case when it is cold. To confirm this, let us do a small experiment.

A 5.4 *Mixing salt in water*

Measure out one spoonful of salt each in two identical beakers with insulation (or use insulated cups), containing the same amount of water, but one chilled (say at about 10 °C) and the other hot (say around 80 °C). Do not stir the mixture. Cover the cups and leave them standing for 2 min. Without stirring or shaking the solutions, check how salty the water at the top of the two beakers is, by gently scooping a little water and tasting it.

In the two activities that we just performed, try to assess the factor(s) that might have led to the observed differences in the mixing of the added substance (ink or salt) in the solutions while also making a note of the temperatures. Pay attention to the observation that at the beginning of both activities the substances that were added to water were present in one place (or close to one point within the liquid), but as time passed, they were no longer confined close to that point. *The substance had moved to different locations within the liquid.* Examine your inference in the light of Rumford's assertion about heat being related to motion. Assess the following statements.

- Ink spreads in water randomly, until there is equal amount of ink everywhere, i.e. it is spread out uniformly and mixed with water.
- Uniformity is achieved faster if the water is warmer.
- The above observations suggest divisibility of the ink drop or salt grains, and not mere expansion, or spreading out, of the drop or the grain as a whole.
- We call the divided units *particles*.
- Warmer the water, more rapid is the motion of the *particles*.
- Heat influences the motion of the *particles*.

Let us turn to gases. Do we observe any internal motion in gases? We usually do not, since many gases, and in particular the air surrounding us, are transparent. But there are cases when we do get a hint of internal motion in air. For example, when we see light streaming into a room through a gap or a hole in the wall or a window, we see dust suspended in air illuminated by the light. These particles are generally seen to move in random directions. What causes this motion? We know that dust particles often settle on the floor and other surfaces, and exhibit no motion, in contrast to the situation when they are in air. Could the air have some role in their motion?

Figure 5.3: Difference in the diffusion of two gases.

Have you noticed that when you enter a freshly painted room, you smell the paint? Why is that so? If you leave a petri-dish filled with alcohol in a closed room, does the air in the room start smelling of alcohol after a while? Does the quantity of alcohol in the petri-dish reduce after a while? Does this suggest that alcohol is spreading throughout the air?

Is there motion *within* a gas? Do gases spread and mix with each other? Let us find out.

A 5.5 *Diffusion in gases*

Take a long glass tube. Hold it horizontally and insert wads of cotton dipped in hydrochloric acid and ammonium hydroxide solutions into the two ends respectively as shown in Fig. 5.3. ***Be careful here, both chemicals are harmful to the skin, so it is recommended that you wear gloves or use tongs to handle the wads.*** *A white cloud starts appearing at a definite position within the tube which is due to the formation of ammonium chloride. Mark the position at which the white cloud begins to form. Repeat the experiment with the tube held vertically, taking care that the ends corresponding to the hydrochloric acid and ammonium chloride wads are not interchanged. Relative to the mark made in the first case, where does the cloud form in the second case? Do the experiment yet again, with the tube vertical, but upside down. If a long glass tube is not available, one could use a stiff transparent plastic sheet, rolled up and kept rolled by sticking a sellotape along its length.*

The white cloud of ammonium chloride was formed at some distance from either wad. This implies that ammonia from ammonium hydroxide and hydrogen chloride from the hydrochloric acid solution have *moved* away from the wads and spread through the air to react with each other. Does the ammonium chloride cloud have a regular shape? Can you describe where it is formed, how it grows, how it spreads?

Consider the assessments made in the context of mixing of liquids once again, but now in the context of paint, alcohol, hydrogen chloride and ammonia spreading in air. Would the motion of the *particles* of these substances be different, if they were to spread in empty space, i.e. if the surrounding air were removed?

Let us now do an experiment in which we try to compare the spreading of a substance in air, and in empty space.[1]

A 5.6 *Smoke in Vacuum*

Take a bell jar with an airtight baseplate which has a provision for a stopcock or a valve. Place a petri-dish on the base plate in which a matchstick is stuck vertically in a blob of wax and cover the baseplate with the bell jar. Place the bell jar in direct sunlight. Take a large convex lens and burn the matchstick by focusing sunlight on it (See Fig. 5.4). How does the smoke from the matchstick travel? Open the bell jar and replace the burnt matchstick with a new one. Cover again and pump out the air. The matchstick will burn even when the jar has been evacuated because the mixture on the match head contains potassium chlorate that releases oxygen. Repeat the burning activity using the same convex lens. How do you expect the smoke from the matchstick to travel now?

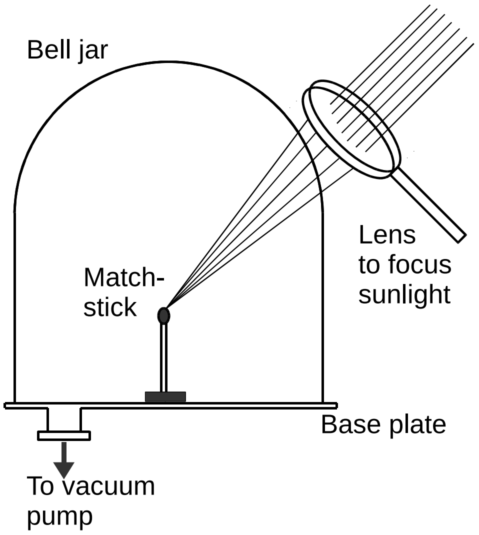

Figure 5.4: Experiment to observe the unhindered motion of smoke in partial vacuum.

In the experiment above, it is seen that when smoke is formed with air still in the bell jar, the smoke rises up and then gradually spreads all through the bell jar. When the bell jar is evacuated, however, the smoke travels in all directions more or less equally, and directly away from the matchstick. Compare the two cases with two situations in the game of carrom. If you place the *queen coin* at the centre, pack six coins around it, and strike them, they mostly move directly away from the centre. If, on the other hand, a large number of coins are spread randomly on the board, then a randomly struck coin will scatter here and there. Does the difference in the motion of smoke particles in the air-filled and the evacuated bell jar suggest what influence air particles have on the motion of smoke particles?

With the above observations in mind, examine the following statements.

- Smoke particles move around randomly in the presence of air because they collide with air particles.
- When the air particles are removed, the smoke particles emerging from the matchstick move in straight lines, without any collisions.

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[1] This activity may not be possible in schools. A video recording of this activity is available from `http://www.eklavya.in/616`

John Dalton (1766-1844)

To Dalton goes the credit of creating a theoretical framework which could explain all the empirical laws explaining the behaviour of gases and also the laws of chemical combination. He was drawn into chemistry because of his interest in meteorology – he was studying the amount and distribution of various gases in air (which led to his law of partial pressures) and he was led to conclude that the particulate nature of matter best explained the observations. Though this idea had been proposed more than two thousand years earlier by Democritus and periodically resurrected by Lucretius, Galileo and Boyle amongst others; Dalton was able to make it a fruitful scientific idea by linking the concept of weight to each atom, thus measurements could be linked to theory. With some simple assumptions, he was able to calculate the atomic weights of various elements. Of course, his work had to undergo further refinements before being finally accepted, but he deserves the credit for postulating the modern atomic theory.

5.3 Modern model of matter and heat

In all experiments that we have discussed in this chapter, we found that some kind of motion constantly occurs within liquids and gases. When some other liquid or solid material is introduced in the liquid, the foreign material tends to spread about in all directions randomly, and over time mixes completely in the liquid or gas. We also found that mixing is more rapid in a hot liquid or gas, as compared to a cold one.

A word of caution is necessary here. In all our discussions concerning the motion within a substance, whether it was mixing or diffusion, the *scale* of the motion, i.e. the *amount* of liquid that appeared to be moving, or the *distances* over which the motion was observed, was large enough to be perceived by our senses. That scale is, however, far larger than the scale of motion giving rise to heat. Nonetheless, it reflects to some extent the motion on a smaller scale that is the cause of heat. We shall see in the next chapter how tiny the ‘particles’ are and how densely packed they are in a substance. It will also give us some idea of how tiny the scale of the motion of the particles is.

Based on various experiments and observations – some of which we have discussed – scientists have put forth the hypothesis, that *all matter is made up of tiny particles that are in persistent random motion*. By *postulating* that matter is made of tiny, identical, indivisible particles, it is possible to explain the phenomenon

Brown, Einstein and Brownian Motion

Robert Brown (1773–1858) was a botanist who gave one of the earliest descriptions of the nucleus and cytoplasmic streaming. He finds a place in this module because the continuous jittery motion of suspended microscopic particles is called Brownian motion even though it was first reported by Jan Ingenhousz in 1784–85. Ingenhousz observed this using charcoal particles while Brown was observing tiny particles released by ruptured pollen grains which are suspended in water. The pollen particles in Brown's experiment moved about due to collisions with the water molecules, as they are light but large enough to be seen under a microscope. Brown later observed this with the particles of non-living matter too, leaving him to conclude that life was not generating this motion.

The explanation of this motion had to wait about three-quarters of a century, and it came from Albert Einstein (1879–1955), who is easily the most famous and easily identified scientist and is almost synonymous with genius. He is best known for his work on special and general relativity, but he got the Nobel Prize for his work on the photoelectric effect. His work on the problems of statistical mechanics led to the explanation of Brownian motion as evidence for the existence of particles, and this forms the basis of the modern kinetic theory.

of heat as being related to the *motion of the constituent particles in random directions* accompanied by collisions amongst the particles, which leads to motion not only in all directions, but also with varying speeds. An approximate idea of the motion of particles in a gas can be had from Fig. 5.5. The critical points are randomness of the motion, and collisions between particles – to be contrasted with directed motion, such as that when a particle moves along a well-defined path without colliding with other particles, or motion of the object as a whole.

This hypothesis explains most of the observations regarding heat, temperature,

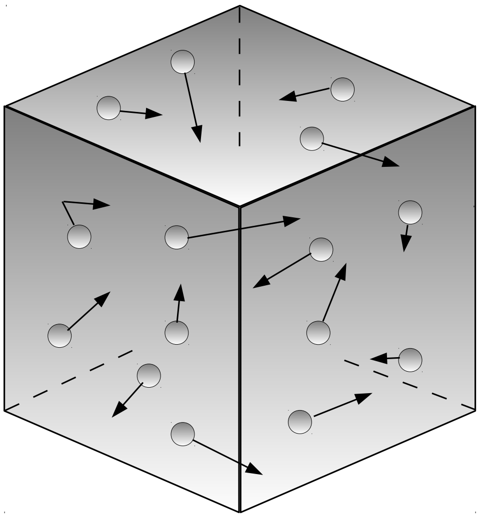

Figure 5.5: A representation of random motion of gas particles. The size of the molecules is greatly exaggerated in comparison to their separation.

pressure and diffusion. As a substance is heated, particles in the substance move more rapidly. In a liquid or a gas the motion is completely random, but in solids the constituent particles move back and forth, like the bob of a pendulum, or a weight attached to a spring. In other words, they *oscillate* about a point in random directions. They do not leave the solid, unless the temperature is very high. The hotter a substance becomes, the more rapidly its constituent particles move. When the substance cools down, the motion of its constituent particles becomes less rapid. Left in a particular surrounding, a solid, liquid or gas will achieve an equilibrium with the surroundings by exchange of energy between its particles and the particles of the surrounding medium. In the next chapter we will build on the idea that heat is nothing but motion of these particles and see how we can understand temperature in terms of the particulate model of matter and the motion of the particles.

Summary

- *Modern model of matter postulates tiny particles oscillating back and forth in solids, and moving randomly in liquids and gases.*
- *Heat is related to persistent random motion of the particles. The hotter a substance is, the faster is the random motion of the particles it is made of.*
- *Heat is not related to the motion of a substance as a whole.*

Chapter 6

Temperature and the Particulate Nature of Matter

Our model of matter and heat comprises tiny particles which are in constant motion, in random directions or in an oscillating manner. We have seen examples in which heating a medium makes the motion faster. Thus, the sense of an object being hot or cold must be related to how rapid the motion of the constituent particles is. In other words *temperature* should be related to the motion of the particles. How do we define a single quantity (temperature) that will represent the motion of all particles?

6.1 How large are particles of matter?

To begin with, let us make an estimate of how many particles we have to deal with. As a first step, let us estimate how small these particles might be and from that make an estimate of how many particles we have in 1 mL of a liquid. We assume, for simplicity, that particles are cubes.

A 6.1 ***Number of particles in a given volume***

The idea in this activity is to determine the thickness and volume of an oily film on water and use that information to determine the size of a single particle and the number of particles forming the layer, assuming, that the film is formed of a single layer of oil particles. It works best with oleic acid dissolved in hexane or benzene, but other oil–solvent combinations may also work.

Dissolve 0.2 mL of oleic acid in 20 mL of an organic solvent such as hexane or benzene. Select a graduated syringe (2 mL volume) and a fine needle (gauge 28 or finer) and confirm that it dispenses drops of uniform size. Establish conditions under which you can dispense a single drop at a time. Next determine the volume of one drop of the solution by finding out how many (say m) drops are formed from 0.2 mL of the solution. The volume of the drop is therefore $0.2/m$ *mL, and the volume of oleic acid in the drop (V) is* $(0.2/20) \times (1/m)$, *or* $1/(100m)$ *mL.*

As shown in Fig. 6.1, fill a large flat plate (approximately 50 cm in diameter) with water and sprinkle ordinary talcum powder on the surface. The talcum powder will aid in demarcating the area of the oil film.

***Precautions:** Fans should be turned off and the talcum powder should be sprinkled on the water surface only when it is still and just before adding the oil drop. If done in advance, the powder becomes wet and is not useful for demarcating the oil film.*

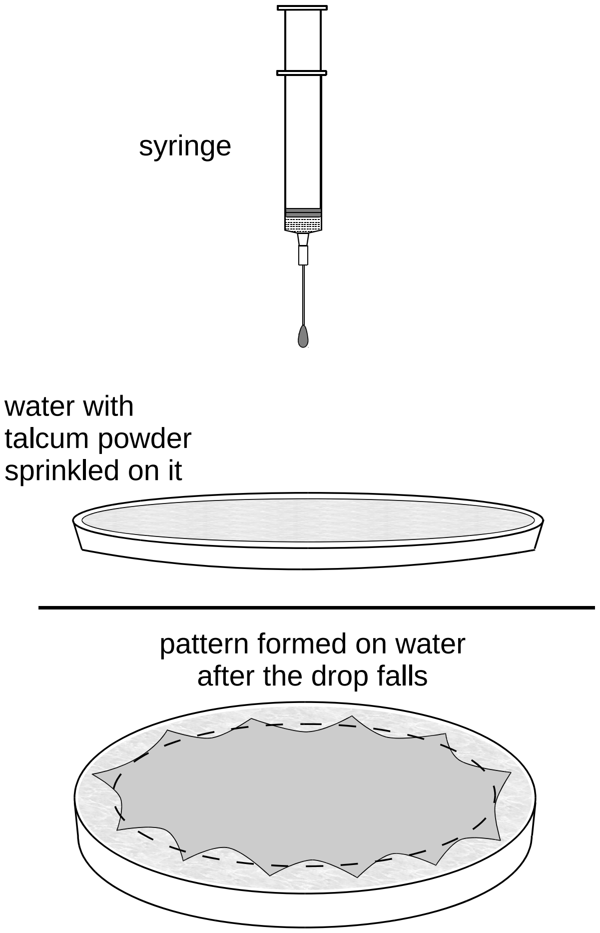

Figure 6.1: [Top] Creating a thin film of a measured amount of oil over a still water surface. [Bottom] Oil film formed on water, demarcated by the talcum powder. The boundary may not be very smooth, but we approximate it by an inscribed circle.

Add a drop of the oleic acid solution gently on the surface of the water using the previously established technique. The solvent evaporates as soon as the drop spreads over the water surface, leaving behind a film of oleic acid of a near circular shape. Measure the diameter (d, in cm) of the film and determine its area ($A = \pi d^2/4$).

Let us now calculate the size of the oleic acid particles.

- If the particles are cubes of side s, then the thickness of the film, assuming it is formed by a single layer of particles, will also be s. The volume of the layer will be $V = sA$. V and A are measured in the experiment, so we can calculate s.
- The volume of each particle is s^3, so the number of particles (N) in the oil film will be given by $N = V/s^3$.
- Hence the number of particles in 1 mL of oleic acid is mN.

In general liquids have more closely packed molecules than gases, while solids are slightly more densely packed than liquids. Typical numbers per mL are 10^{19} for gases, and roughly 10^{22} for liquids and solids. Thus, any quantity of matter that we can perceive with our senses contains a very large number of molecules.

Avogadro and his number

Lorenzo Romano Amedeo Carlo Avogadro di Quaregna e di Cerreto (1776–1856) was another scientist whose work was not appreciated in his own life-time. Based on Gay-Lussac's work on the volumes of combining gases, Avogadro recognised that the relationship between the masses of the same volume of different gases (under identical conditions of temperature and pressure) is the same as their respective molecular weights. He was the first to appreciate the difference between the atoms and molecules of elements, or that atoms of the same element could be combined to form molecules. He proposed, around 1821, that all gases contain roughly the same number of molecules in a given volume (the temperature being the same). This proposal was verified in due course, and generalised. The number of particles (atoms or molecules) present in one mole of any substance has been named the Avogadro number in his honour. A mole is that amount of a substance that corresponds to its atomic or molecular weight in grams. If, for example, you take M grams of a pure substance, where M is its molecular weight, then it contains the same number of molecules, no matter what the compound is. That means, 2 grams of H_2, 18 grams of H_2O or 63.5 grams of Cu all contain the same number of molecules or atoms. That number is approximately 6×10^{23}. A *mole* is often used as a unit to simply specify Avogadro number of particles.

6.2 Representative properties of a large group

In building further our model of heat being related to the motion of particles within a substance, we are now faced with an immediate problem. The problem is that we need to take into account the simultaneous motion of a collection of a very large number of particles. How do we describe the simultaneous, collective motion of such a large number of particles in a simple manner?

To sort this out, let us ask whether we need the exact motion of each one of the particles. How important is the behaviour of individual particles when describing the property of the collection of particles? Is it possible to derive a single number, or a single parameter that can be considered as representative of a property of a group consisting of several members?

Let us consider the following situation. A factory has a large number of workers, who are to be given a shirt and trousers as uniforms. Clearly not all of them have the same measurements. Some may be tall and thin, some short and thin, some tall and fat etc. Can we (more precisely, a tailor) make an estimate of how much cloth will be needed to clothe all workers, without really measuring each person up? Since clothes have been made for several generations, and by several people by now, tailors have a very good idea of how much cloth is needed, by and large, for a person. That estimate of size is behind the fact that cut pieces of cloth ready to be stitched usually have the same size. For convenience of storing, transporting and pricing, a commonly accepted size of cut pieces has been estimated and accepted by traders, and suits most people. Of course there might be some individuals who are either too tall or too fat to be accommodated in the standard size, but such cases are rare, and by-and-large the cut-piece system seems to work well.

The reason for this can be found in the fact that if we survey a large population and tabulate the heights (or girth, or any measurement of the body) of the individuals, we will, by and large, find that although there is a range of heights, within this range the heights of a large number of people lie close to a certain value. This value lies approximately mid-way between the extreme values of the heights in the population. If we were to add up the heights of all individuals and divide it by the number of individuals, we get a rather useful value that can be considered to be a representative height of the population. This value is called the *mean*, in the present case the mean height, and takes into account, to some extent, the variation in individual heights. In some sense it represents the characteristics of the entire population and can help in making useful estimates, as seen in the preceding example.

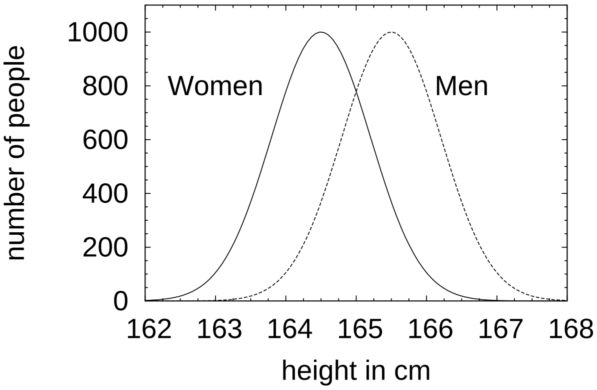

Figure 6.2: Distribution of heights of men and women in a population. The graphs show that on the average women are shorter than men, but not all men are taller than all women.

See the graph in Fig. 6.2 and say whether it tells you something about the cloth requirements for women in comparison to that for men (assuming similar dresses). Does the estimate match your intuition about the difference in the cloth requirement for men and women?

A single value, the mean height in this example, does not tell us how widely spread the heights in the population are. It can happen that the mean heights of two populations are the same, but in one population the heights are close together as compared to the other population. In this case another measure, called the

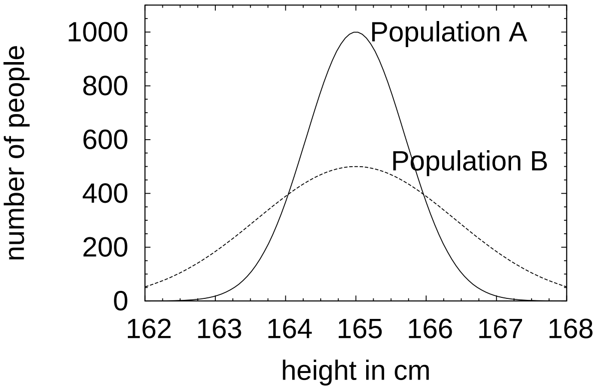

Figure 6.3: The distribution of heights of members of two populations. Although the mean heights are the same, the spreads of heights is different in the two populations.

variance is useful. The variance is a measure of the spread of values about the mean. In the graph in Fig. 6.3, you will notice, that values in population B are more widely spread out than in population A, although the mean values are the same. We then say that the variance of B is greater than that of A, and this single value brings out the fact, that the two population distributions are not quite the same, even though their means are identical.[1].

These concepts about the mean value of a property and the spread of the values among the members of a population will be useful to us in describing the motion of the large number of particles of matter that are in persistent random motion. Our goal is to relate the motion of all particles within a substance to the degree of hotness.

6.3 A measure of the random motion of a collection of particles

The property relevant to us at the level of the individual particle in the context of heat is how rapid its motion is. Taking that as the basis, we will assign a representative quantity for the rapidness of the *motion of all particles taken together*.

For a single particle, the motion is completely described by its velocity. For a collection of particles in a substance the velocities of the particles are random, so the average velocity of the entire collection will be zero, irrespective of how small or large the individual velocities are. To see how the average velocity is zero, consider any direction you like. Some particles will be moving approximately in this direction. But, you could have chosen exactly the opposite direction and seen an equal number of particles moving in *the newly chosen* direction. If you take the velocities along the first direction to be positive, the velocities along the opposite direction will be negative. So the sum, and hence the average of the velocities for the chosen pair of directions is zero. This argument can be repeated for any pair of opposite directions. So

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[1] The *mean* is defined as the sum of all values divided by the number of values; $\mu = \sum_i x_i/N$. The *variance* is defined as the sum of the squares of the difference of values from the mean, divided by the number of values; $\sigma^2 = \sum_i (x_i - \mu)^2/N$

the average velocity of a large collection of particles is zero, no matter how rapidly the molecules may be moving. Thus, the average velocity does not tell us anything about how rapidly the individual particles are moving. In other words, no useful link can be made between the average velocity of the particle and the degree of hotness.

Let us trace the motion of a particle. It moves, collides with some other particle, as a result of which the direction and speed of both particles may change. Had there been no collisions, the particle would keep moving along a straight line, and finally escape from the substance. This is not what most particles do (although in the case of evaporation some particles do escape). When a substance becomes hotter, as seen in the examples of mixing in the previous chapter, the motion within the substance becomes more rapid. But higher speeds alone are not a characteristic of a hot substance. A necessary consequence of the more rapid motion is that the time between successive collisions reduces, or in other words, the number of collisions in a given time, i.e., the rate of collisions, must increase. Thus, something becoming hotter implies two consequences at the level of the particle motion: increase in velocity and increase in frequency of collisions. A quantity that is used to define temperature must take into account both factors, the speed of the particle and the frequency of collisions. In other words, the quantity that we could consider as representative of the degree of hotness must necessarily depend on the product of two factors, speed of the particles and the frequency of their collisions. But, as a little reflection shows, the frequency of collisions itself depends directly on the speeds of the particles involved: the more rapidly particle moves, the greater is the rate at which it encounters other particles.

Hence the quantity that represents the degree of hotness must be proportional to $v \times v$. Notice that if we add the quantity v^2, particle after particle, the sum will not be zero, because v^2 is always positive, and is unaffected by the direction in which an individual particle is moving, while simultaneously reflecting the fact that the motion has become more rapid. Hence the average value of v^2, rather than the average of the velocity, is the appropriate quantity for conveying the degree of hotness within the model of heat that we are building.

The quantity v^2 is closely related to kinetic energy. The kinetic energy of an object of mass m moving with a velocity v is given by $mv^2/2$. The average kinetic energy of N number of particles is:

$$\mathrm{KE}_{ave} = \frac{1}{N}\left[\frac{m_1 v_1^2}{2} + \frac{m_2 v_2^2}{2} + \ldots + \frac{m_N v_N^2}{2}\right]$$

The average kinetic energy is a non-zero quantity that takes into account the change in the rate of collisions and the change in the velocity of the particles

Ludwig Eduard Boltzmann (1844–1906) and James Clerk Maxwell (1831–1879)

Boltzmann was also a firm supporter of the particulate nature of matter and his suggestion that the energy levels of a physical system are discrete could be considered the foundation of quantum mechanics. He worked extensively on heat and temperature, or what is more generally called thermodynamics. His major contribution was in providing a statistical description of the motion of particles in gases. Together with James Clerk Maxwell, he formulated a description of the speeds of these particles, upon which the modern idea of temperature is based.

Maxwell is best known for his equations of classical electromagnetic theory which brought together the fields of electricity, magnetism and optics. But he also worked on what is now known as the Maxwell–Boltzmann distribution. This explained the observations and laws of classical thermodynamics and is a statistical method of understanding the distribution of particles moving with different velocities.

simultaneously. Hence it is chosen for defining temperature.

The temperature T of a collection of molecules is defined to be a quantity directly proportional to the average kinetic energy of the collection of molecules. The constant of proportionality, k_B, is called the Boltzmann's constant. The temperature thus defined is called the absolute temperature, *defined* by the expression:

$$T = \frac{1}{k_B}\mathrm{KE}_{ave}$$

6.4 Absolute temperature

The absolute temperature defined in terms of $\mathrm{KE}_{\mathrm{ave}}$ has units of Kelvin (K). Absolute zero, or zero on the Kelvin scale, is the temperature where all *internal or particulate motion within a substance* stops. The above equation suggests that temperature can never be negative (since the kinetic energy is always positive). How is it then that we hear of negative temperatures in cold regions of the world? For historical reasons, there exist other scales of temperature which are commonly used, and are different from the Kelvin scale of temperature. It is on such scales that negative temperatures exist. We are familiar with the Celsius scale of temperature, on which temperatures below the freezing point of water are negative.

The magnitudes of a unit on the Celsius and Kelvin scales are the same.

William Thomson, or Lord Kelvin (1824-1907)

Kelvin can be counted amongst the few scientists who made immense contributions in both theory and practical applications. His work on the relation of heat and work (with Joule) led to the first and second laws of thermodynamics and the recognition of the absolute zero temperature – the Kelvin scale being named after him. But he also did important work in telegraphy and in improving the compass to make it more reliable.

The zeros of the two scales are different. Temperature on the Kelvin scale equals the temperature on the Celsius scale *plus* 273.15. The Kelvin unit is written *without* the customary ° for temperature. A comparison of the two scales can be made from the hypothetical thermometers shown in Fig. 6.4.

Temperature lower than absolute zero does not exist, as all motion stops at this temperature. Most substances solidify at temperatures much higher than absolute zero. Helium is an exception, it remains gas until 4.2 K and is expected to solidify only at absolute zero. Temperatures as low as a few 10^{-6} K have been reached under controlled conditions for a small collection of atoms, while temperatures as high as 10^4–10^5 K are routinely achieved in plasmas. Room temperature is close to 300 K, while human body temperature is approximately 310 K.

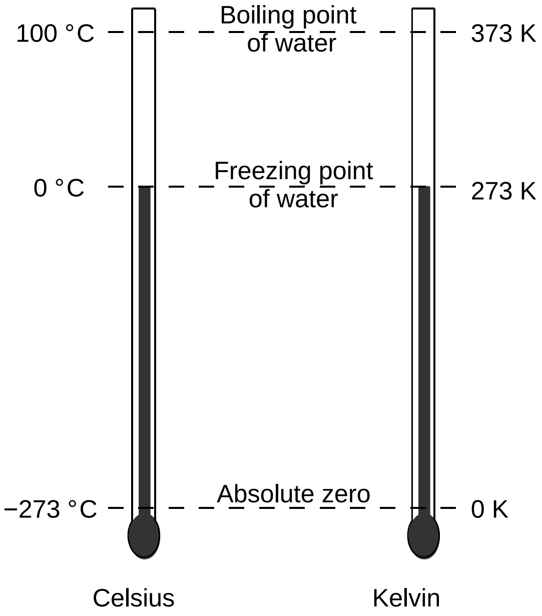

Figure 6.4: Comparison of Celsius and Kelvin scales of temperature.

6.5 Thermal energy and heat

We now understand heat and temperature as being related to the kinetic energy of the particles constituting the substance. We have seen above how temperature is defined. In defining temperature, we summed the kinetic energies due to the internal motion of all particles. This sum is given a special name, *Thermal Energy*, and is denoted by the symbol U. What is heat, then? Recall various *uses of the term heat*. In all uses the term heat is used in a *relative context* – i.e., when there is a temperature difference, or when we speak of hot and cold objects. We do not use it in the sense of being a property of an object or a substance itself.

A 6.2 *Addition of thermal energies*

You have a cupful (180 g) of nearly boiling water and a bucketful (18 kg) of nearly freezing water. (18 g of water contains Avogadro number of molecules!) Compare the absolute temperatures and the thermal energies of the two samples. If you mix the two, what will be the thermal energy of the mixture? What will be the temperature of the mixture?

Consistent with our particulate model of matter, *we understand heat as thermal energy that is being transferred* due to difference in temperatures. Thus, the particulate model of matter yields the following fundamental concepts:

1. All matter is composed of tiny particles that are in constant random motion within the substance. The kinetic energy of the particles due to this random motion is not the same for all particles.
2. The *sum* of the kinetic energies of all particles is called the *thermal energy* of the object or the system.
3. Thermal energy is due to *random motion* of particles *within a substance*, and is not influenced by directed motion, such as when the object moves as a whole.
4. Temperature is proportional to the *average* kinetic energy of particles moving in random directions within a substance. As in the case of thermal energy explained above, it is *not* influenced by directed motion.
5. Thermal energy *in transfer* from an object to another, due to the differences in temperature, is called heat.

The last point needs some elaboration with respect to terminology: since thermal energy in transfer is understood as heat, strictly speaking the expression *transfer of heat* is improper, as transfer (of thermal energy) is implied in the term heat.

In our model of matter and heat, particles are constantly in motion and collide with each other, and transfer of heat is to be understood in terms of energy exchange in these collisions. As an example, let us consider the case of hot water brought in contact with cold water. The molecules in the cold water have a lower average kinetic energy than the molecules in the hot water. When the two samples are brought in contact, molecules in a sample not only continue to collide with each other, but also start colliding with molecules from the other sample. During collisions the kinetic energy of a given molecule may change, but the sum of the kinetic energies of all molecules together remain constant. The result of several collisions is that the average kinetic energy of a collection of molecules in any part of the entire liquid is the same, no matter which part of the liquid you choose. As was the case before the samples were brought in contact, not all molecules have the same kinetic energy, but the average kinetic energy is the same all throughout. At this point, the temperature of the liquid is the same throughout and heat transfer is complete. We can understand in a similar manner heat transfer within a solid (the difference being that the particles of the solid do not move randomly, only back and forth about a mean position), or within a gas or between a solid and a gas or a solid and a liquid.

A 6.3 ***Temperature of a mixture***

You can work out whether the temperature of two water samples in the previous activity, which are initially at temperatures T_1 *and* T_2 *and are mixed together, will eventually become steady at a value less than both values, greater than both values or some intermediate value. All you need to remember is that the net thermal energy is number of particles times the absolute temperature. The thermal energy of the first sample,* U_1*, is* $N_1 k_B T_1$*, while that of the second sample* U_2*, is* $N_2 k_B T_2$*, where* N_1, N_2 *are the numbers of particles in the two samples respectively. The combined thermal energy is* $U_1 + U_2$*. Upon mixing, this thermal energy is shared by all particles. So, when mixing is complete, the temperature of the mixture is* $(U_1 + U_2)/(N_1 + N_2)$.

Transfer of thermal energy from one object to the other is determined by the temperature, not the total thermal energy of the objects. Our model does not entirely explain why, when two bodies at different temperatures are in contact, thermal energy does not get transferred from the colder body to the hotter one. Based on various studies, this phenomenon is formulated as a law: *there cannot be a process whose sole result is the transfer of thermal energy from a cold body to a hot body.*

Let us try to see how the relation between pressure, temperature and volume of a gas can be explained within the particulate model of heat and matter.

6.6 Particulate model and pressure

Our model of matter has particles moving about continuously, in random directions, and colliding with one another. In the course of this random motion, they will collide not only with one another but also with the walls of the container. Let us see how the model explains the relationship between pressure, temperature and volume of a gas.

A 6.4 ***An imaginary game***

Suppose many of you stand near a wall and throw balls at it. What happens to the wall? Not much, but every time the ball hits it, and rebounds, the momentum of the ball changes,

Figure 6.5: Balls striking a wall or any membrane exert pressure on it. The effect is more readily seen if the membrane is flexible, as seen in the second picture. Molecules exert pressure on the walls of a container in a similar manner.

i.e., a force is exerted on it. If you now double the rate at which balls are thrown, will the force be greater? What if you throw the same number of balls, but with greater speed? In both these situations, the force on the wall increases. We know that pressure on the wall is simply the force exerted (by the balls on the wall in this case) divided by the area. Thus, increasing the number of balls colliding with the wall in a given time, or increasing the speed of the balls striking the wall, results in an increase in the pressure on the wall. The effect on a surface by the striking of particles on it is more obvious if the surface is not rigid. Compare the two situations shown in Fig. 6.5.

The situation with molecules of a gas and the wall of the container is very similar. Let us consider a fixed number of molecules of a gas. If the molecules collide with greater kinetic energy, on the average, the force on the wall, and hence the pressure, increases; if the frequency (rate) of collisions increases, that too increases the pressure. Thus increase in pressure is a consequence of increase in the average kinetic energy and rate of collisions of the molecules. In the particulate model, an increase in average kinetic energy and increase in the rate of collisions are identified with an increase in the temperature of the gas, so we conclude that increase in temperature leads to an increase in pressure. This is in conformity with the gas laws stated earlier, and were based purely on observations.

Let us think of what will happen

if we increase the number of molecules in our container, without increasing the volume of the container? As in the case of balls being thrown at the wall, an increase in the number of molecules will increase the force on the walls of the container, which implies an increase in pressure. What should be done to keep the rate of collisions the same as before? A straightforward solution is to increase the volume of the container. Thus, increasing the volume occupied by a gas reduces its pressure, while reducing its volume will increase its pressure, again in conformity with the laws stated earlier.

A 6.5 ***A Thought experiment***

In the previous case, we increased pressure by increasing the number of molecules. The key point was that the number of collisions went up. What if we had increased the temperature of the gas, while keeping the number of molecules constant? How would that have affected the number of collisions? What would have been the effect of the increased number of collisions on pressure?

6.7 Particulate model and expansion

Having seen evidence for the dependence of the volume of a gas on its temperature, let us see how it fits in within the particulate model. When heated, the particles in a gas or a liquid gain kinetic energy, while simultaneously the rate of collisions between the particles also increases. Since particles in a liquid or a gas are in continuous random motion, the (geometrical) extents of a gas are not fixed, as we know from common experience. The extents are determined by the surroundings – i.e., the shape and the size of the container, or the pressure of the surrounding air. So the phenomenon of expansion is related to the interaction between the molecules of our sample gas with the surroundings. In particular, if the surrounding is a solid container, then the molecules continue to collide with the walls ever more frequently and with greater kinetic energy on the average, as the temperature increases.

If the force due to collisions is not large enough to damage or break the wall, the net effect is to transfer thermal energy to the walls of the container, leading to an increase in the temperature of the container itself. Of course, as we have seen in our activities earlier, heating of the solid leads to its expansion, so the container itself expands in the process. Of course, this expansion is relatively small. On the other hand, if the container is not very rigid, or some part of it is a flexible/movable partition, then the flexible part of the container is pushed out, so we very clearly see the volume increasing. An example of this might be a balloon that is inflated and then kept in contact with warm water, or a hot air balloon, in which a gas burner heats the air inside to create a lift. As discussed earlier, the air outside also exerts a pressure on the 'partition', so the expansion is in fact due to the pressure of the gas inside becoming greater than that of the surrounding air. In this case, the phenomenon of expansion cannot be seen in isolation, we have to take into account simultaneous changes in pressure, temperature, volume and the work being done against the boundary.

The situation with expansion of liquids is very similar to the case of gases, and the arguments based on the particulate model are identical. Particles in a solid do not move randomly, but only back and forth about a mean position. An increase in temperature implies an increase in the extent of their oscillation on the average, so the effective spacing between any pair of particles increases. This in turn implies that the volume of the solid increases.

6.8 Particulate model and convection

We have seen that heating of a liquid or a gas happens mostly by convection. Let us examine convection in view of the particulate model of heat and matter. When a liquid is heated at the bottom, the kinetic energy of the molecules close to the base increases rapidly. Some of the molecules that move in the upward direction now have sufficient kinetic energy that they can transfer to the molecules above them, in turn enabling some of the molecules above to overcome the gravitational force, and move further upward. No single molecule is likely to make a trip all the way up to the surface, but because of the heat supplied from below, an ever larger number of molecules is gradually able to rise upwards, against gravity, and towards the surface of the liquid.

As the collection of these molecules moves further upward, their kinetic energies decrease (similar to a ball losing its upward velocity when thrown against gravity). A small number of them reach the surface with excess kinetic energy and may leave the surface. This is consistent with the observation that heating leads to greater evaporation. The collection of molecules that move upwards is replaced by molecules with lower kinetic energy that tend to move downward due to gravity, constantly colliding with other molecules, and a loop pattern of motion is set up. The shape of the loop can be quite complex. The shape of the container, the extent of the source of heat and the nature of the liquid come into play. If gravity were absent, there would be no convection. However, the random, persistent motion of molecules will still be there and heating a gas will increase the kinetic energy of molecules in the vicinity of the source of heat, thereby increasing the probability of their collisions with other molecules, and enhance their transport to other regions of the container. The mode of heat transfer in a gas or a liquid in zero gravity would be a mix of diffusion and conduction.

Summary

- *The average kinetic energy of the molecules due to the random motion is a measure of the temperature of the substance. The temperature scale based on the average kinetic energy, called the absolute scale, or Kelvin scale, is always positive.*

- *When two objects are brought into contact, thermal energy flows from the object at higher temperature to the object at lower temperature. The thermal energy keeps flowing till the two bodies are at the same temperature, that is, till thermal equilibrium is achieved.*

- *Pressure of a gas is due to collisions between the particles and the walls of the container. Increase in temperature increases the average kinetic energy of the particles and the rate at which they strike the walls, thereby increasing the pressure of the gas.*

- *The conversion of heat into mechanical work can be understood in terms of the kinetic energy transfer from the randomly moving particles to the surroundings, and is readily observed in case of expanding gases.*

- *Transfer of heat within liquids and gases is by a combination of random and directed motion of particles within the substance, and is influenced by gravity.*

Chapter 7

Some Remarkable Devices

We use heat for many of our day-to-day activities. The commonest example is that of cooking; we can hardly imagine cooking without a source of heat. We use a variety of heating devices for this. Stoves based on the burning of a fuel such as petroleum gas or kerosene, electrical heaters, microwave ovens are examples of such devices. Devices based on the use of heat are also employed for a variety of purposes outside home. Many of the effects of heat that we studied in the earlier chapters are exploited in the construction of different devices.

Perhaps the most significant of devices using heat are based on the equivalence of heat and work, and their relationship with pressure and temperature in the context of gases. Examples are the steam engine – used in the past for a whole lot of tasks in factories, in shipping and railways, and for generating electricity by driving a generator, and the internal combustion engine – now the overwhelmingly common engine for powering vehicles of all descriptions from the scooter to trains, ships and aeroplanes. Odd as it may seem first, even cooling needs heat, as in refrigeration and air-conditioning. These devices have had a major impact on the society. They are remarkable because of the way they exploit our understanding of heat, and perform useful and contrasting tasks. The steam engine and the internal combustion engines exploit the increase in thermal energy of a substance to do work, whereas a refrigerator exploits work to reduce the thermal energy of a substance. We shall look at these devices in detail in a while, but first we will look at a simpler device that is just as significant, because it is directly connected to the most basic of human needs – food.

7.1 The pressure cooker

There are many methods or techniques of cooking such as boiling, roasting, frying. Of these, boiling occupies a major place in routine cooking – for cooking rice, daal, etc. Boiling is the process of

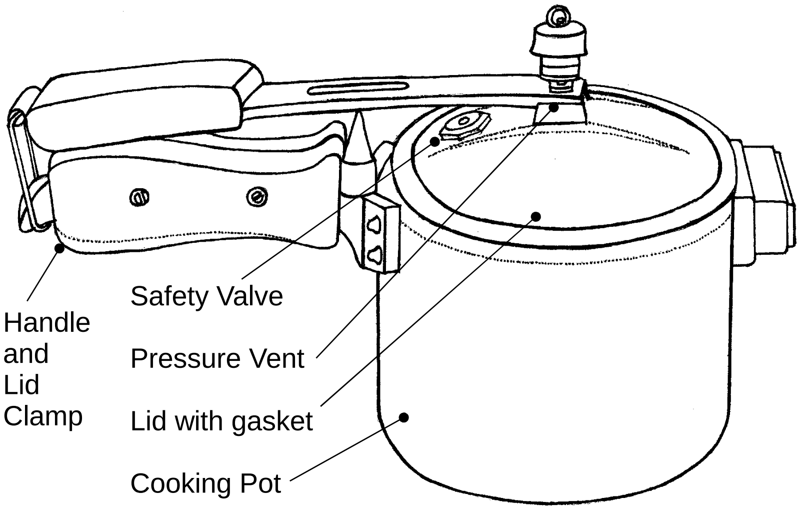

Figure 7.1: Structure of a pressure cooker.

immersing in water the substance to be cooked, followed by heating the water, bringing it to boil, and leaving it on the boil until food is cooked. The boiling point of water is approximately 100 °C, so food immersed in water cooks at that temperature. All cooking cannot be accomplished at 100 °C; different substances need different temperatures for cooking well. Moreover, most cooking can, at least in principle, be accomplished faster at a higher temperature. If a substance needs a higher temperature for cooking, this cannot be achieved by boiling, since no matter how much heat you provide to the water in a saucepan, its temperature will not rise beyond the boiling point.

If the boiling point of water could be raised by some means, then it will become possible to heat the water to higher temperature, and achieve faster cooking. Of course, the source of heat must have a much higher temperature than 100 °C to achieve this, but this is hardly a problem, as the temperature of stove flames, although dependent on the fuel used, is much higher. How do we raise the boiling point of water? The trick is to increase the pressure of the air surrounding the water. This is done in a pressure cooker, which is a sealed vessel that does not permit air or other vapours from inside it to escape to the ambient air, unless the pressure inside exceeds a certain value. The idea of a pressure cooker dates to 1670 CE, the first commercial venture dates to 1864 CE, while the modern pressure cooker can be traced to the year 1938 CE. A sketch of the essential features of a modern pressure cooker is shown in Fig. 7.1.

When food is placed for boiling in a pressure cooker, the steam arising from water and the hot air inside it lead to a pressure build up within the cooker. This in turn suppresses further boiling of water. The heat from the stove now causes the temperature of water to rise beyond its normal boiling point and eventually start boiling at a higher temperature. The steam resulting from boiling is trapped in the cooker until the pressure exceeds the set value. This arrangement has two advantages. First, the food cooks at a higher temperature. Due to the increased temperature, the food cooks quickly with heat from the steam. Thus, much less water is needed than when boiling in an open saucepan. Cooking via steam also preserves nutrients which might be lost during prolonged cooking by immersion in boiling water in a pan. The net effect is savings on fuel and time. Most domestic pressure cookers are set to operate at a pressure twice the normal atmospheric pressure, which raises the boiling point to about 120 °C.

What is the ideal way to use a pressure cooker? First, one should use as little water as is possible – just enough to create an adequate amount of steam. Second, once the steam pressure has built up, the flame should be reduced – excess heating will only create more steam which will keep escaping periodically as the pressure increases beyond the set value. Escaping steam represents heat lost to conversion of excess water to steam and eventually to the surrounding air! So, the principle that so many *whistles* (i.e., pressure releases) are needed to cook a certain food item is a wasteful one. It is better to let the steam build up to the set pressure (just below escape), and then reduce the flame and cook for as long as is needed for the particular item. In fact, even after the flame is turned off, cooking continues due to the transfer of heat from the steam to the food item, until all steam condenses to water inside the cooker. A rule of thumb is that a correctly used pressure cooker will not give out a whistle.

7.2 The steam engine

The idea that steam, created by heating water, can be used to displace objects was cleverly exploited in the 17th century. A steam engine is a device that uses heat to create steam from water and uses the steam to perform mechanical work, usually by moving a piston back and forth. Steam engines have been used in locomotives and powering machines such as looms in factories. In fact, the association of the steam engine with a railway locomotive is so strong, that rather inappropriately, the steam locomotive is called a steam engine. The steam engine is considered to have been one of the most important industrial inventions, and the herald of the industrial era.

Figure 7.2 shows the essential parts

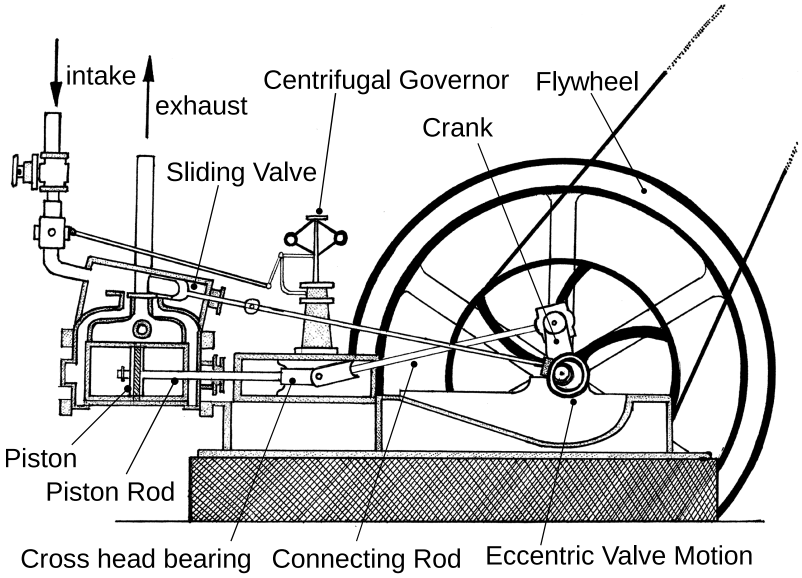

Figure 7.2: A steam engine, with the main parts labelled.

of a steam engine. Steam is generated at a very high pressure in a boiler by burning coal or some other fuel, such as petroleum oil or gas. When the steam pressure crosses a limit, it escapes into a cylindrical chamber inside which there is a tight fitting piston that can move along the axis of the cylinder. The high pressure, super-hot steam expands, pushing the piston out, or *working* the piston. The expanded steam has lost heat (it is converted into the motion of the piston) and is cooler, so will condense. The condensed steam can be recycled back to the boiler.

In the meanwhile the piston has been set into motion. Connected to the piston is a crankshaft (a shaft that moves back and forth synchronous with the movement of the piston) and a flywheel (a heavy, supplementary wheel that rotates as the piston moves). The crankshaft also converts linear motion of the piston into circular motion of the wheel of a locomotive or the propeller of a ship or the spindle of a loom. The rotary action of the flywheel ensures that the piston is pushed back into the expansion cylinder after the expanded steam has returned to the boiler.

The invention of the steam engine is often considered the starting point of the industrial era. The steam engine was the first device which enabled conversion of heat into mechanical work in a practical manner. Compared to the work that can be done using human or animal power, a steam engine can do much more work at a lower cost and in less time. This made steam engines very popular for all kinds of machines – from spinning and weaving machines to locomotives.

James Watt (1736-1819)

Most of us have heard of Watt in connection with the steam engine, and he is usually credited with inventing it when he only improved it enormously. The steam engine was actually invented by Newcomen, but the fuel efficiency attained by Watt's engines and their versatility (the Newcomen engine was only used for pumping water) led to the linking of Watt with the industrial revolution and the steam locomotive. Two of the innovations that he introduced were (*i*) a separate condenser so that energy was not wasted in repeatedly heating the cylinder and (*ii*) using the engine to generate rotatory motion. He introduced the concept of horsepower and the unit of power is named after him.

7.3 The internal combustion engine

In a steam engine fuel is used to create steam from water, which then works a piston. Burning of the fuel, or combustion, occurs outside the cylinder in which steam expands. In contrast to this arrangement, there are engines in which a mixture of a fuel (generally a fossil fuel such as petrol, diesel, kerosene or compressed natural gas) and air is ignited inside a cylinder, and the gases resulting from combustion (mainly oxides of carbon and water vapour) expand in the same cylinder, working a piston. Such engines are classified as internal combustion engines. IC engines deliver far more power for the same size of the engine compared to an external combustion engine. The piston can then be made to drive a crankshaft and a wheel as needed.

IC engines are of two kinds, two-stroke and four stroke. A two-stroke engine performs repeated compression and expansion strokes. Admission of the air-fuel mixture and its ignition occurs in the compression stroke, while expulsion of the combustion products occurs in the expansion stroke while the piston is being pushed out. In a four-stroke engine

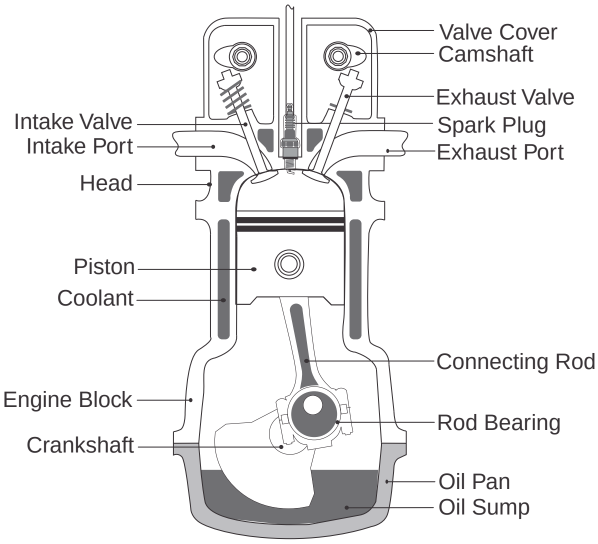

Figure 7.3: Structure of an internal combustion engine.

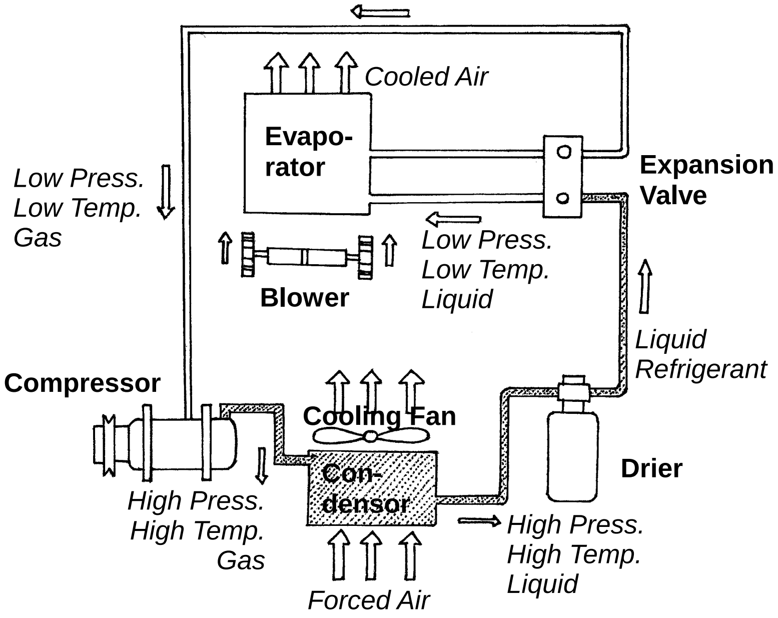

Figure 7.4: A schematic diagram of the refrigeration cycle based on expansion and compression of a gas.

the compression and ignition operations are sequential, such that ignition takes place after the mixture is completely compressed. Expulsion of the expanded gases takes place after the piston is fully pushed out. Not only is combustion more efficient in a four-stroke engine, but also the expansion of the combustion products is more efficiently converted to work. IC engines are usually configured with two or more (generally even) number of cylinders performing alternate strokes.

Due to their compact size, high power output and robustness, they are the engines of choice for vehicles of all descriptions, whether on land, or sea, or in air. In fact, heavier-than-air powered flight was possible only after IC engines came along.

7.4 Refrigerator

Recall the cooling effect of air escaping from a pressurised cycle tube. If one had means of compressing the air repeatedly and filling it in an enclosure, while alternating the compression by expansion, it would be possible to cool the air – and in turn cool the object in the region of expansion. This is the principle of refrigeration. It uses mechanical energy (during compression of the gas) to transfer heat from a region of interest to the surroundings, even when the temperature of the surroundings is not lower than the temperature of the region of interest.

In a refrigerator, a gas is circulated between two units, the condenser and the evaporator, by a compressor (Fig. 7.4).

Internet resources

Apart from the pressure cooker, we do not usually get an opportunity to see the internal workings of the devices described in this chapter. Computer animations are often useful in understanding such devices. Several resources are available on the internet. We mention some of them here.

For the steam engine see

`http://en.wikipedia.org/wiki/Steam_engine`

For the IC engine see

`http://www.howstuffworks.com/engine1.htm`

and

`http://en.wikipedia.org/wiki/Cylinder_(engine)`

See a picture explaining the refrigeration cycle at

`http://en.wikipedia.org/wiki/Heat_pump_and_refrigeration_cycle`

The compressor does work on the gas, for which it uses electrical energy. The refrigerant vapour is compressed, and in the process its pressure and temperature increase. This compressed vapour is passed on to the condenser, where it loses heat to the surrounding air and condenses to a liquid. The liquid is forced through a fine valve, which is the key element. It consists of a fine orifice, which opens and closes synchronously with the compression. As the liquefied gas is forced through the orifice into the evaporator, it expands rapidly (just as we saw in the case of the bicycle tube) thereby cooling the evaporator,which in turn cools the air around it. The hot and cold areas of the refrigerator are well insulated from each other, and the valve demarcates the two zones. In effect, heat is transferred from a cold region to a hot region, by means of a gas and a compressor.

Air conditioners work on the same principle as refrigerators. The compressor in an air conditioner is driven by an electrical motor (in buildings) or by an IC engine (in vehicles). The work that is needed to transfer heat is thus effected by a supplementary source of energy.

Can you explain why a refrigerator is sometimes called a *heat pump*?

Teasers

There are several situations in real life concerning heat and temperature which are not readily explained, and leave us confused. Here is a collection of teasers which we hope you will find stimulating, and will be able to solve based on the exposition in this book.

1. Does a warm blanket provide you with heat when you wrap yourself up in it? Can the blanket also be used to keep something cold?

2. When a window is accidentally left open on a wintry night, do you feel uncomfortable because the cold is getting in, or because the heat is escaping from the room?

3. When you are faced with a glass bottle with a metal lid that is very tight, it becomes easier to unscrew the lid if it is warmed up. Explain how this happens.

4. A thin-walled plastic bottle is filled to the brim with water and its cap is tightly closed. The bottle is left in a freezer. What is the likely outcome of the freezing?

5. What do you understand by the statement *warm air is lighter*?

6. If you wish to keep a block of ice for long in winter, would you choose to wrap it in a blanket, in an aluminium foil, or simply leave it in the open? What if you have to do the same in summer?

7. In winter a metal surface feels colder to touch than other surfaces. Explain why. How would the cold sensation change if the surface were rough? If the surface were smooth?

8. What difficulties might an astronaut face in boiling water to make tea?

9. Suppose your normal body temperature were lower than what it is. How would the sensations of hot and cold change?

10. In view of the activity *Reflecting Heat*, can you say why food (especially *chapati*) is wrapped in an aluminium foil if it is to be kept for some time before being served?

11. A room has a west-facing glass

window, and you wish to prevent the room from getting very hot on summer afternoons. Three methods are suggested below. Rate their effectiveness, giving reasons.

(a) covering the outside of the glass panes with an aluminium foil,

(b) covering the inside of the glass panes with a thick thermocol sheet,

(c) covering the inside of the glass panes with black chart paper or black curtains.

12. What is the reason for your shivering when you have a fever?

13. When you perspire and the wind blows, you feel cold. Why?

14. What is the difference between cooling a pan of hot milk by standing it in a pan of cold water, and by blowing on it or stirring it?

15. Does a refrigerator violate our conclusion that a body at a lower temperature cannot transfer heat to a body at a higher temperature? If it does, explain what will happen if the compressor is removed from the refrigeration cycle.

16. Can you cool a room by leaving a refrigerator in the room with its door open?

17. If you heat a circular disk with a hole, what change do you expect in the diameter of the hole? Remember that the effect of heating is to increase the separation between any pair of particles.

18. You have a glass full of water kept inside a large chamber. The air in the chamber is (suddenly) removed. Describe what will happen to the water.

19. A short plastic rod and another short metal rod of the same mass are left in a refrigerator for a long time. They are removed and given to you to grab in the fist. Which one feels colder? Which one feels colder for a longer time?

20. Why might clothes dry quicker in cold dry air than in hot humid air?

21. On the basis of the kinetic theory, explain the bursting of a tyre in summer.

22. What would you recommend as ideal clothing when going out in the sun? Black or white? Short clothes or covering up in loose clothes (e.g. *kurta-pyjama* or *salwar-kameez*)? Might it explain why people in desert countries usually cover themselves completely in white?

23. A raincoat is made of a non-woven, water-proof, insulating material. How would you rate it for use as a protective garment on a cold day? On a windy day?

24. On a rainy day, a dry glass is filled with ice, covered and left standing. As the ice melts, water collects on the outer surface of the glass. Where does this water come from?

25. Why is the water in mountain streams usually cooler than the surroundings?

26. If instead of the theory of *heat*, we construct a theory of *coldness*, i.e. instead of speaking in terms of *heat transferred*, Q, we talk of *coldness transferred*, $-Q$, what quantity might replace the absolute temperature T?

27. Why does M gram of any pure compound (M being the molecular weight of the compound) always contain Avogadro number of molecules?

    Hint: Avogadro number is roughly the reciprocal of proton mass (or the atomic mass of hydrogen) in grams.

A Note on Units

It is recommended that one uses SI units for all physical quantities. The two physical quantities central to this module are Heat and Temperature, while a few other quantities also find mention. We look at SI units for the quantities appearing in this module, and their relation to the units that have been mentioned, or used, in this module, or are often used in practice.

- Heat is a form of energy, and the SI unit for energy is *Joule* (**J**), so the SI unit of heat (thermal energy) is *Joule*.
- The SI unit of temperature is *Kelvin* (**K**).
- We used the unit calorie (more precisely, the thermochemical calorie) for heat earlier. A calorie is equal to 4.184 J.
- The unit of specific heat is defined in terms of the *amount of heat* required to raise the temperature of a *unit mass* of a substance *per* °C, so the SI unit of specific heat is **J/kg/K**. The commonly used unit cal/g/ °C is equal to 4.184×10^{-3} J/kg/K.
- Rate of transfer of heat is another quantity we encountered. Its unit is Joule per second, which is given a special name, *Watt* (**W**).
- Conductivity, which is defined as the rate of transfer of heat per unit difference in temperature per unit length, therefore, has the SI unit **W/m/K**. In terms of the practical units calorie and cm, it has the unit cal/s/cm/ °C, which is equal to 4.184×10^{-2} W/m/K.
- Pressure is force per unit area, and its SI unit is *Pascal* (**Pa**), or Newton/m^2. Non-SI units that are in common use are bar (1 bar = 10^5 Pa) and torr (1 torr = 133.32 Pa). The standard atmospheric pressure is 1.013×10^5 Pa.

The **Nutritional Calorie** is a frequently misunderstood unit of heat. One often hears, for example, that an adult needs 2500 Calories per day. Does this number sound right? To answer this, let us estimate how much energy is spent in a routine activity, such as walking. Walking speed is 5–6 kmph or 1.5 m/s. In walking work is primarily done against gravity, but the force is not vertical, it is at a small angle (say 10°) to the ground. So, the force applied by a person weighing

60 kg when taking a step is approximately 60 kg × 9.8 $\mathrm{m/s^2}$ × sin(10°), or 80 N. Hence the power expended is 80 N × 1.5 m/s, i.e. 120 W. In walking for a minute, this is an expenditure of 7200 J, or 1700 cal. Surely 2500 cal of nutrition is too little! This apparent contradiction arises because the nutritional Calorie is in fact 1000 standard (or thermo-chemical) calories (or 4184 J). Note the capital C in the nutritional Calorie, to distinguish it from the thermo-chemical calorie.

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Acknowledgements

The inspiration and the starting point for this module are chapters dealing with heat from Eklavya's earlier publication, *Bal Vaigyanik*. This module attempts to take qualitative ideas regarding heat and move towards the kinetic theory, while maintaining the level of abstraction accessible at the high school level. Considerable guidance and feedback was obtained in this endeavour from Eklavya's larger resource group including Vijaya S. Varma, Amitabha Mukherjee, Pramod Kumar Shrivastava, N. Panchapakesan, the late M. M. Kapoor, Sushil Joshi, Kamal Mahendroo, Patrick Dasgupta and Aamod Karkhanis. Past and present team members of Eklavya, Reva Yunus, Himanshu Shrivastava and Uma Sudhir helped in trying out various activities and refining them, as also in offering multiple points of view on the text. L. Mishra and R. Rangarajan gave critical inputs as the module was taking its final form.

The organisation of the concepts and activities was tried out in two teacher trainings organised by Eklavya in Indore and again with students in a workshop organised by the Vidya Bhawan Society in Udaipur. Once the entire structure of the module was finalised, Rama Chari and Urjit Yajnik went through it to check for conceptual correctness and clarity and made some valuable suggestions to improve the presentation of the ideas. Most of the illustrations were drawn by Bharat Jamra, and some by Nishith Mehta and Boski Jain. The Eklavya publications team looked into the finer details of the layout and look of the module, as well as the editorial aspects.

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– Bhas Bapat

Eklavya is a non-governmental registered society working in the fields of education and people's science since its inception in 1982. Its main aim is to develop educational practices and materials related to a child's environment that are based on play, activities and creative learning. In the past few years, Eklavya has extended its area of work to include publishing. We bring out three periodicals: *Chakmak* is a monthly science magazine for children, *Srote* is a weekly science and technology news feature, and *Sandarbh* is a bimonthly magazine on science and education for teachers. In addition to titles on education, popular science and creative activity books for children, we develop and publish books on the wider issues of development.

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