Students' misconceptions about heat transfer mechanisms and elementary kinetic theory

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Abstract
Heat and thermodynamics is a conceptually rich area of undergraduate physics. In the Indian context in particular there has been little work done in this area from the point of view of misconceptions. This prompted us to undertake a study in this area. We present a study of students' misconceptions about heat transfer mechanisms, i.e. conduction, convection and radiation, and about elementary kinetic theory.

Introduction

The study of heat and thermodynamics is an important part of a physics students' education. It is a conceptually rich area and also one which gives rise to a large number of misconceptions. The identification and study of misconceptions is important because it leads to new ideas for teaching physics at the secondary as well as undergraduate levels. There has not been much work done, especially in the Indian context, on misconceptions in the area of heat and thermodynamics. This prompted us to undertake a study in this area. In an earlier study (Pathare and Pradhan 2005) we explored students' misconceptions with respect to some of their basic ideas about heat, temperature and pressure. In the present study we investigate their ideas about heat transfer mechanisms (such as conduction, convection and radiation), the particulate nature of matter and elementary kinetic theory.

One aspect of misconceptions is that they are part of a student's line of reasoning (Maier 2004). A misconception is more than having a fact incorrectly memorized. Misconceptions are often referred to as alternative conceptions because they point to the existence of students' own models or cognitive frameworks which are different from ('alternative' to) the accepted scientific theories. Extensive studies in the field of misconceptions have revealed some common likely causes.

- *Presumed ideas*. Students have some presumed models formed even before they encounter a scientific notion; e.g., force is needed to keep an object in motion.
- *Language and metaphor*. Daily conversation with peers gives rise to many alternative models. A word/phrase which means one thing in daily parlance may mean something else in scientific terminology; e.g., weight lifters have a lot of power in their arms.
- *Conceptual difficulties*. The difficulties arise because concepts like acceleration are not directly amenable to experience. They are constructs and therefore non-intuitive. Students fail to understand the limitations of the applicability of a concept or a law and hence they over-generalize.

- *Teacher driven*. In a typical Indian classroom, the teacher is viewed as an ultimate authority. The explanation of a concept delivered by a teacher is accepted by the student as it is. One of the important reasons for this is the examination driven system which depends heavily on skills of memory and recall and underemphasizes understanding. Teachers often fail to give students an overview of the topic necessary for understanding it. This may lead to the formation of alternative models which are different from the relevant scientifically accepted models; e.g., any two equal and opposite forces make an action–reaction pair.

With physics being a very conceptual subject, misconceptions in physics get developed at the very basic levels. It is well understood in the physics community that misconceptions must be addressed if they are to be overcome. If not confronted at the right time, they keep floating in the students' conceptual framework all the way up to their undergraduate period.

Ironically, at the root of the development of a misconception lies its remedy. In Piaget's model of intelligence, what is required for a sound understanding of a concept is accommodation following a state of disequilibrium. If the student experiences are skillfully guided at this stage, the misconceptions which may develop by way of unchecked accommodation may be avoided or disentangled. In other words, according to this model the way to prevent or resolve misconceptions is to have the student herself confront the misconception directly with an experience that causes disequilibrium followed by sound accommodation (Maier 2004).

Previous studies have documented some of the ideas of secondary students about conduction of heat. Students often consider heat as a substance (Clough and Driver 1985). The concept of convection is not well understood by them (Erickson 1985). A report prepared for the Royal Society of Chemistry investigated students' ideas regarding elementary kinetic theory (Barker 2000). Novick and Nussbaum (1978, 1981) investigated the notion of the particulate nature of matter among various age groups of students. Séré (1986) investigated the ideas 11-year olds have about gases prior to teaching. Expressions such as 'hot air rises' were commonplace. Our study confirms these observations.

Research design

The target group for the study was undergraduate students studying physics. The concepts under the present study are introduced to the students in their senior secondary schools. Much before this formal introduction, the students come across these concepts in their childhood through daily experience or through conversation with friends, family members etc. As a result, the students develop their own intuitive ideas about these concepts. These ideas may conflict with their formal training in physics at the senior secondary school stage. We have chosen a sample of second-year undergraduate students who are pursuing physics as one of their subjects of study.

We conducted preliminary discussions with some undergraduate students from colleges in Mumbai. This was supplemented by discussions with some college teachers about their students' knowledge in this area. The study gave us clues to the difficulties that the students have in the topics under consideration. On the basis of the study, we framed a free response test consisting of short answer questions.

This free response test was administered to a sample of 57 undergraduate students. Their responses to this test were analysed. On the basis of the written responses, we decided to interview a few students to gain greater insight into their line of thinking. This exercise of free response tests and interviews brought out problem areas and helped us to identify misconceptions in a broad sense.

Findings

We present in each case a situation that was described to the students and a typical 'explanation' given by them embodying a misconception about the situation.

Conduction

Situation 1. When a metal rod is heated at one end, the other end becomes hot.

In metals at normal temperatures the contribution to thermal conductivity by free electrons is much more dominant than the contribution of lattice vibrations. Some students feel that electrons are released at the heated end and travel to the other end, transferring in the process their energy. For some students, heat travels from one end to the other in the form of a single longitudinal progressive wave. Some of them also regard heat as a fluid. According to them the conduction corresponds to the expansion of the fluid from the hot end.

A response by a student: '... *if we heat the metal at one end, the hotness of one end of the metal expands as there is space on the other side of the rod*...'

Situation 2. A steel and a wooden rod are kept in an air-conditioned room for a long time. When touched the steel rod feels colder than the wooden rod.

Most of the students respond to this situation by saying that steel radiates heat more than wood. Some also say that steel absorbs more 'cold' than wood.

Situation 3. Mercury in a clinical thermometer rises when kept in contact with the armpit of a person who has a fever.

A response by a student: '... *mercury at the lower end of the thermometer is in solid form. It 'catches' heat of the body, melts and its level rises*.'

Convection

Situation 1. A beaker containing water is put on a burner. After some time water at the top also becomes hot.

This is an example of natural convection. The density difference between the hotter water at the bottom and the cooler water at the top sets up convection currents in the water. Some students consider water as a good conductor of heat like metals. Some feel that the water carries electrons which transfer heat from the lower end to the upper end. Most of the students say that 'cooler water molecules' are heated by 'warmer water molecules', and thereby attribute hotness to a single molecule.

Situation 2. Drying hands by a hot air blower.

The hot air blower is an example of forced convection (Cengel Yunus 2004) in which air blown from the blower passes over a heater coil thereby giving rise to hot air. Most students do not realize this fact and report this phenomenon as conduction. For them hot air is an inherent property of the air blower, exhibiting unawareness of the actual process of hot air production. They fail to understand the idea of convection as the combined effect of conduction and fluid motion. Since the hot air cannot be seen by the eyes and the hands at a distance are dried by the hot air blower, some students relate this phenomenon to radiation emanating from the blower.

Radiation

Situation. We receive from the Sun not only light but also heat.

Some students feel that heat attributed to the Sun originates terrestrially due to the interaction between the electromagnetic waves coming from the Sun and the matter on the surface of the Earth. Some students think that heat energy arises due to friction between air molecules and the electromagnetic radiation from the Sun. Some students say that there is some medium between the Earth and the Sun and heat is conducted by the molecules of this medium from the Sun to the Earth.

Elementary kinetic theory and the particulate nature of matter

Students are aware that a gas consists of molecules and the molecules are in motion. However, when the motion is to be described in terms of velocities, many feel that the velocities of all the molecules are the same in magnitude; a few students also say that the velocities are the same in magnitude as well as in direction.

Prominent among the students' conceptions are the following.

(1) A gas has no mass. For some students negligible mass means no mass.
(2) If the gas is in a closed container it has mass, but if it is in an open container it has no mass.
(3) An ideal gas is that gas which obeys all of the gas laws. A real gas does not obey gas laws.
(4) The molecules of an ideal gas exert no interactive forces whatsoever. As a result, they do not exert any pressure on the walls of the container.
(5) A real gas is a mixture and an ideal gas is not.
(6) The change in volume from the liquid state to the vapour state is due to
    (a) change in the size of molecules,
    (b) breaking of molecules.
(7) The smoke due to a burning incense stick rises as the molecules of the smoke are warm and hence lighter than air. According to some students, the cause of the movement of the air

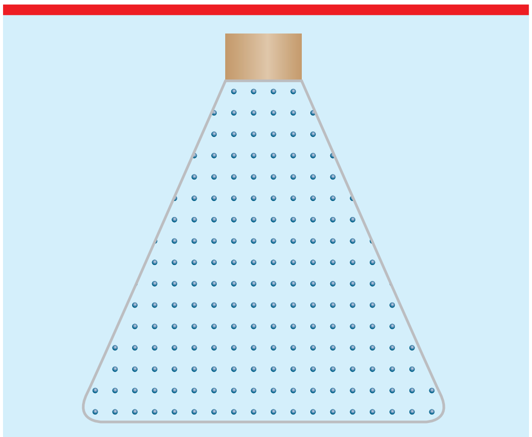

Figure 1. Spatial arrangement of air molecules.

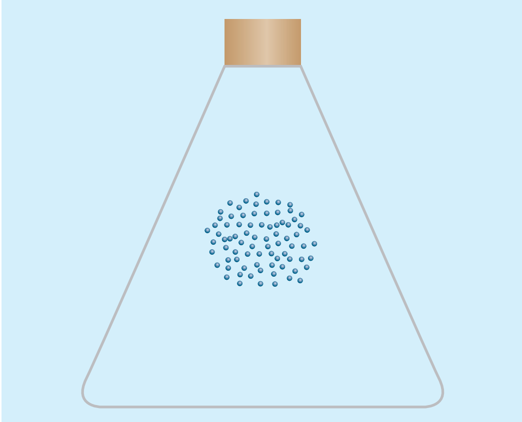

Figure 3. Molecules crowding at the centre.

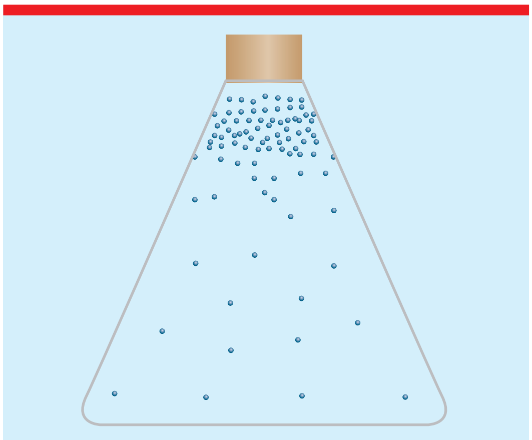

Figure 2. Molecules crowding at the mouth of the container.

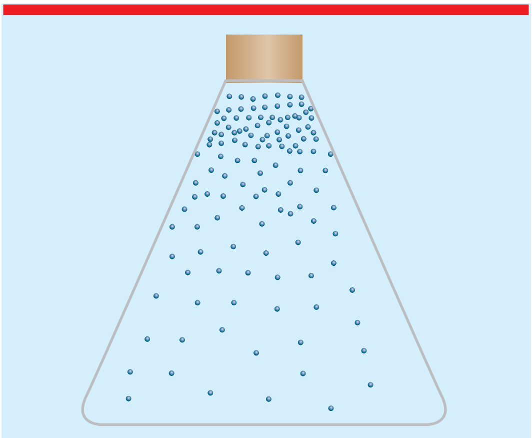

Figure 4. Molecules are denser at the mouth of the container.

towards the roof which carries the smoke with it is that the density of air is less towards the roof.

Students were asked to draw schematic drawings of air in a container at different pressures and temperatures. Following are some details of their drawings.

(1) Air at a temperature of 30 °C and pressure of 1 atm.

The students show the air molecules in the container properly spatially arranged (figure 1).

(2) Air at a temperature of 30 °C and a pressure of $1/10$ atm.

Since the pressure in the container is reduced, the students draw far fewer molecules in a substantially large part of the container below the mouth. Near the mouth from where the air has been sucked, they show crowding of the molecules (figure 2).

(3) Air at a temperature of 90 °C and a pressure of 1 atm.

Since the temperature is increased to 90 °C, the walls of the container become hot; air near them becomes much less dense. As a result there is a crowding at the centre of the container (figure 3).

Some students feel that since the temperature is increased the air becomes lighter and hence it rises to crowd at the top (figure 4).

(4) Different gases at the same temperature and pressure.

According to students, two identical containers filled with different gases, oxygen and hydrogen, at the same temperature and pressure should have the same weight. With hydrogen

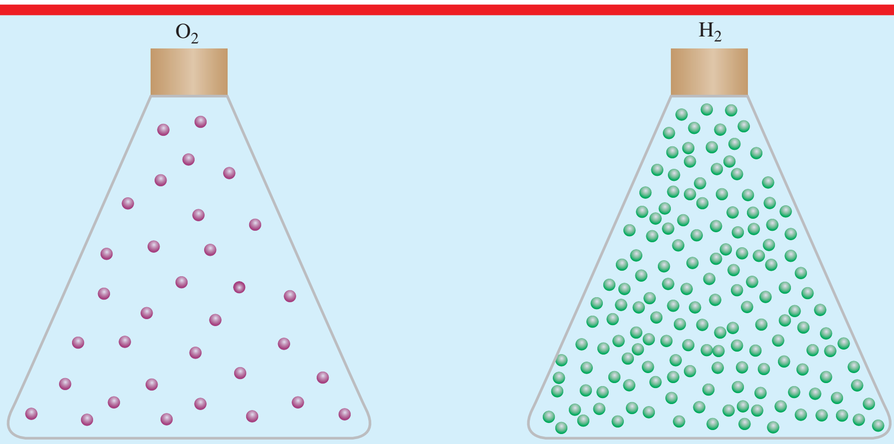

Figure 5. Containers with two different gases.

being lighter, this for them implies a higher number of hydrogen molecules (figure 5).

Discussion

Following this exercise of understanding the students' framework of heat transfer mechanisms and elementary kinetic theory, the next step was to plan remedial measures directed towards their misconceptions. We believe that measures arise from the discussion of each particular concept with the students. Their statements comprising their misconceptions are to be taken as the starting point of the discussion. For example, in figure 5, the students' reasoning about different numbers of molecules in the two containers was taken as the basis. The students were already exposed to the ideal gas equation $PV = nRT$ in their undergraduate physics curriculum. Hence, they were asked to think about each variable in the equation and relate it to the conditions imposed on these variables in the situation given to them. A point of confrontation occurred when they realized that pressure, volume and temperature have the same values for both gases. It is therefore necessary to have also the same n for both gases. At this point the students realized a discrepancy between the scientifically accepted framework and their framework.

In the case of an example of forced convection ('drying hands by a hot air blower'), the students considered the hot air to be an inherent property of the air blower. In this case, the students were exposed to two experiences, one in which the air blower was operated as it is and the other in which the heating element of the air blower was removed. They felt the temperature difference between the two cases, and thereby realized that when air flows over a heating element, heat is carried due to the motion of the air molecules.

While developing remedial measures in different situations, we have adopted approaches based on demonstrations and/or discussions. We are still working on these and hope to report on them later.

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