



In this section of Resonance, we invite readers to pose questions likely to be raised in a classroom situation. We may suggest strategies for dealing with them, or invite responses, or both. "Classroom" is equally a forum for raising broader issues and sharing personal experiences and viewpoints on matters related to teaching and learning science.

Pitfalls In Elementary Physics

1. Velocity, Acceleration and Force

Introduction

Elementary physics – the physics that one learns at the senior secondary or introductory college stage – is not really elementary. Even the best can make silly mistakes in its domain, not by oversight alone but because of serious misconceptions. Among the average students, misconceptions about the basic terms, notions and laws of physics are, of course, widespread and deep-rooted. Some of these probably arise from spontaneous cognitive frameworks that everyone develops from childhood through physical interaction with the environment and the language. These alternative frameworks are robust and do not easily yield to the correct conceptions of physics despite much instruction. Perhaps the only pedagogic strategy to remedy them is to develop a heightened awareness of their conflict with the standard conceptions of physics through examples and problems. In this and subsequent articles, we shall describe and illustrate a few of the universal misconceptions that students reveal in elementary physics.

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Instantaneous Velocity and Acceleration

Consider a particle in motion. Its position vector is a function of time. The velocity of the particle is the time-derivative of this vector:

$$\mathbf{v} = d\mathbf{r}/dt$$

and acceleration is the time-derivative of the velocity vector:

$$\mathbf{a} = d\mathbf{v}/dt = d^2\mathbf{r}/dt^2$$

For simplicity, let us consider one-dimensional motion only with a function (position of the particle on a line) defined at every instant and its derivatives defined at every instant (if the motion is smooth). The notions of instantaneous position, instantaneous velocity and instantaneous acceleration thus appear to be straightforward. But are they really so? Try this example the simplest one can imagine in kinematics - on a class of undergraduates. A ball thrown vertically reaches its uppermost point. What is its speed at that point? Students will readily give the correct answer : zero. What is the acceleration of the ball at the uppermost point? A good many are likely to say: zero. Some of these students might (correctly) answer the following question in the negative: if $f(t)$ is zero at say $t = 0$, must its derivative be zero at $t = 0$?

Why do so many students falter when it comes to translating the idea of derivative in mathematics to the idea of instantaneous speed in physics? It is difficult to be sure of the reason, but our experience is that student's intuitive notion of speed is the notion of average speed over an interval. Similarly, acceleration intuitively means the average acceleration i.e. the change in velocity divided by the time interval. This is the notion used in everyday life. Speed makes sense over some interval, however small. The meaning of speed at a point in space or time when no distance is covered and no time has elapsed is intriguing. It takes some effort before a student internalises the notion of



instantaneous velocity/acceleration as the limit of average velocity/acceleration when the time interval tends to zero.

This example has become hackneyed - it is quoted at many places and many informed students would answer it correctly. But the intuitive notions, as said earlier, are robust - they may lie hidden in familiar problems of physics but will show up in unfamiliar contexts. Try another simple example on a class of undergraduates. A train starts from a station at 5.00 p.m. and reaches another station (a distance of 180 km) at 8.00 p.m. What is the average speed of the train? (Assume the path to be a straight line). What is the average acceleration? What is the speed of the train at 5.00 p.m.? Is the acceleration of the train zero at 5.00 p.m.? Is it zero at 8.00 p.m.? Students are unlikely to handle the latter parts of the question (earlier parts are trivial) correctly thus: the speed of the train at 5.00 p.m. and at 8.00 p.m. is zero. The acceleration at 5.00 p.m. and at 8.00 p.m. is not necessarily zero. Note, we have not said that the acceleration of the train must be non-zero at the starting and end points. A particle may have zero velocity and also zero acceleration at an instant, and yet may not remain at rest. For example, with position-time dependence of the type $x(t) = t^3$, both velocity and acceleration are zero at $t = 0$. A constant force cannot, of course, produce a dependence of this type but that is another matter.

The syndrome 'a particle momentarily at rest has zero acceleration there' may show up in the following example also. Consider a point on the rim of a wheel that is rolling perfectly (i.e. without slipping) on a horizontal surface with uniform velocity. What are its velocity and acceleration when it comes in contact with the ground? If a student answers that the velocity is zero at the instant of contact but not the acceleration, he is hopefully free from the syndrome.

Locality of Newtonian Force

According to Newton's second law of motion, acceleration is

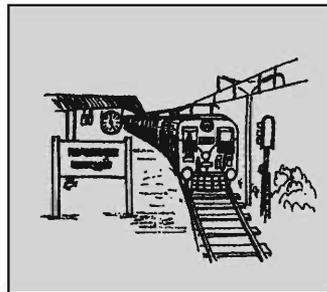


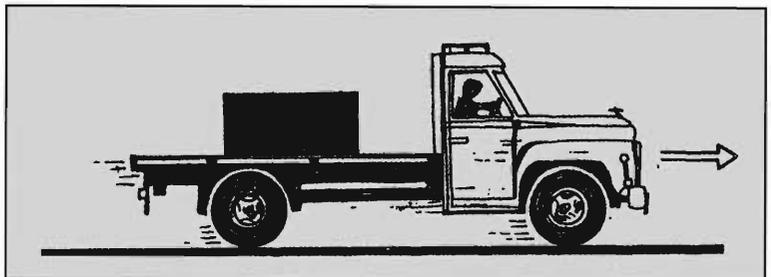
Figure 1 A train starts from a station at 5.00 p.m. Is its acceleration zero at 5.00p.m.? The 'zero speed implies zero acceleration' syndrome prevents most students from handling this question properly.



proportional to the impressed force. Though always implicit, we rarely emphasize the locality of the relation: acceleration of a particle *at a given position and time* is proportional to the force on the particle *at the same position and time*. The result is that students readily relate acceleration now to the force applied earlier, as the following example reveals. *A stone is dropped from a uniformly moving train. What is the acceleration of the stone just after it is dropped?* This is a familiar question. Most students know that to an outsider the trajectory of the stone is a parabola. Some might confuse acceleration with the changing velocity vector on the parabola but many would know that acceleration is simply that due to gravity : $g \text{ ms}^{-2}$ vertically downwards. A slightly modified question, however, puts most students in difficulty. *A stone is dropped from a train that is accelerating in the horizontal direction at $g \text{ ms}^{-2}$. What is the net acceleration of the stone after it is dropped? What is its trajectory as seen by a person on the ground?* If you try this on an undergraduate class, many are likely to confidently answer (wrongly) the first part $2g \text{ ms}^{-2}$ at 45° to the vertical, but would feel unsure about the trajectory. The response shows lack of awareness of the locality of the second law. We are referring to awareness of not the word (which is unimportant), but the notion (which is crucial). The correct response is : acceleration remains $g \text{ ms}^{-2}$ vertically down; the trajectory is a parabola with the constant horizontal velocity equal to the instantaneous velocity of the train at the moment the stone is dropped, neglecting effects of air resistance, wind, etc.

The ignorance about locality of the second law is widespread. Thus, while many students would correctly solve sums on kinematics of motion, their qualitative picture of the motion of

Figure 2 A box is lying stationary relative to the floor of an accelerated truck. What force is accelerating the box? Most students regard the truck's engine to be the agency of these forces.



say a ball thrown vertically upward can be something like this: *During the upward journey, the ball has two sources of acceleration, one due to gravity and the other due to the force by the hand that threw it up initially. The second dominates in the upward journey. At the uppermost point, the initial force has spent itself out and the ball then falls freely under gravity.* It is not fair to regard such responses as incorrect. The correct notion of force due to Newton was a supremely non-trivial discovery which superseded earlier incarnations of the notion due to Aristotle and later by 'impetus' theorists. Students' intuitive notions often show interesting parallels with pre-Newtonian concepts that now lie buried in history.

The preceding examples related to locality in time. A situation that relates to locality in space is the following. *A box of mass 100kg is lying on the floor of a truck that is accelerating at 1ms^{-2} . What is the force on the box?* The answer is straight: 100N. *What is the agency of this force i.e. what is pulling the box forward at an acceleration, of 1ms^{-2} ?* The most frequent answer would be: the engine, of course. In a layman's way of thinking, the answer is not wrong; but it is unacceptable in physics. Locality requires that acceleration of the box must be explained by a force on the box. In mechanics, there are only two kinds of forces: gravitational and contact forces. (Assume neutral, non-magnetic bodies, so that there are no electromagnetic forces. Also the fact that contact forces are electromagnetic in origin is irrelevant. In mechanics, contact forces such as friction, reaction, tension, etc are treated as independent macroscopic forces). The box can thus have only two agencies of forces on it – the earth that provides the gravitational force and the floor beneath that provides the contact force. We cannot say much about the contact forces a priori. But from the 'given' situation and using the second law, the contact force must be at an angle to the vertical. Its vertical component balances the weight of the box because the box is 'given' not to be sinking into the floor. The component parallel to the surfaces in contact called *frictional force* is what causes the horizontal acceleration of the box. Friction causing motion or acceleration goes against our



stereotype of friction as something against motion. But, of course, there is no problem: friction always prevents or impedes relative motion between surfaces in contact. Without it, the box would not move with the floor and there would be relative motion between the box and the floor. Friction acts to prevent that relative motion and the box moves with the floor.

Newton's Third Law

Pitfalls concerning this law arise mainly from the use of the words *action and reaction* in its statement. The loaded connotation of these words in ordinary life together with the crisp easy-to-remember statement of the law (*To each action, there is an equal and opposite reaction*) have misled generations of students. Nowadays, books and also teachers often remind us that action and reaction are simultaneous (action does not precede reaction), that the words are interchangeable – any one of the pair of forces involved may be called action and the other reaction. But these reminders fail to convince students when they confront a situation in which there is a natural cause-effect relationship. I decide to press a wall with my hand; I move my hand towards the wall and hit it; the wall presses my hand in the opposite direction. Isn't there a causality involved? Has action (moving in my hand and pressing the wall) not preceded reaction (the wall pressing my hand)? How then can action and reaction be interchangeable? The confusion arises because we are equating the broad meaning of a word in ordinary language to its precise technical meaning in physics. In ordinary language, action does not always mean just one event – it could also mean a sequence of steps or events. In the third law, on the other hand, action means precisely a force at a given position and time. There is indeed a causality between the sequence of events (motion of the hand) and the wall pressing the hand back. But *action* in the third law is *not* a sequence of events leading to a force. In the example, action-reaction pair ensues at the instant of contact; the two forces (force on the wall by the hand and force on the hand by the wall) arise simultaneously and there is no cause-effect relationship



between them. The motion of the hand and my decision to move the hand are irrelevant to the application of third law to the pair of forces between the wall and the hand. The learning problems of the third law can thus be reduced if the words action and reaction are expunged out of the physics vocabulary and the law is simply stated in the following manner: Force on a body always arises due to some other body. According to the third law of Newton, force on A due to B at an instant is equal and opposite to the force on B due to A at the *same* instant. There is no harm in telling students at this stage that this simultaneity of action and reaction is strictly possible only for contact forces, according to relativity.

That brings us to a final remark on causality. The meaning of causality needs to be carefully explained in elementary physics teaching. It is not necessary to introduce this new word or its formal definition, but the notion is important. In ordinary life, two kinds of causality are familiar. One is the so-called final causality. I get up from my desk to have tea in the canteen. Here the goal, the final end (having tea) is the cause and my getting up is the effect. We need to emphasize to young students that this kind of teleological reasoning, so much a part of our life, has no place in a scientific explanation. Otherwise, students are apt to view (wrongly) the following statement in a teleological sense 'A particle in a field environment moves so that it reaches its minimum potential energy'. A better way is to say that the force on a particle at a point in a field is always in the direction of decreasing potential energy. But initial causality – the correct causality in science – wherein cause precedes effect can also generate misconceptions as seen already, namely that acceleration now is seen as the effect of force earlier. It all boils down to making the students internalise the local and instantaneous nature of the basic concepts in mechanics: velocity, acceleration, force and the relations between them.

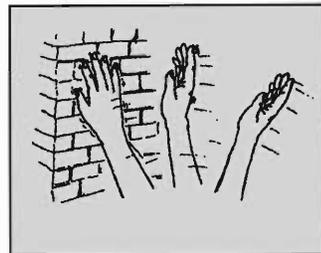


Figure 3 A hand moving to the wall, pressing it and experiencing a reaction force. Students often equate 'action' in this situation to the sequence of steps leading to the force on the wall by the hand. Reaction in this view is then naturally regarded as a causal consequence of action, in violation of Newton's third law.

Suggested Reading

- ◆ Arnold B Arons. *A Guide to Introductory Physics Teaching*. John Wiley, 1990.
- ◆ Arvind Kumar. *Cognitive Frame-works in Physics. Physics News*. Vol.25. p.76, 1994.
- ◆ Arvind Kumar and S Barve. *How and Why in Physics*. Vols. I to III. HBCSE, 1993,94.