PHYSICS 101

AN INTRODUCTION TO PHYSICS

This course of 45 video lectures, as well as accompanying notes, have been developed and presented by Dr. Pervez Amirali Hoodbhoy, professor of physics at Quaid-e-Azam University, Islamabad, for the Virtual University of Pakistan, Lahore.

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GENERAL INFORMATION

Purpose: This course aims at providing the student a good understanding of physics at the elementary level. Physics is essential for understanding the modern world, and is a definite part of its culture.

Background: It will be assumed that the student has taken physics and mathematics at the F.Sc level, i.e. the 12^{th} year of schooling. However, B.Sc students are also likely to find the course useful. Calculus is not assumed and some essential concepts will be developed as the course progresses. Algebra and trigonometry are essential. However, for physics, the more mathematics one knows the better.

Scope and Duration: The course has 45 lectures, each of somewhat less than one hour duration. All main fields of physics will be covered, together with several applications in each.

Language: For ease of communication, all lectures are in Urdu. However, English or Latin technical terms have been used where necessary. The student must remember that further study and research in science is possible only if he or she has an adequate grasp of English.

Textbook: There is no prescribed textbook. However, you are strongly recommended to read a book at the level of "College Physics" by Halliday and Resnick (any edition). There are many other such books too, such as "University Physics" by Young and Freedman. Study any book that you are comfortable with, preferably by a well-established foreign author. Avoid local authors because they usually copy. After listening to a lecture, go read the relevant chapter. Please remember that these notes cover only some things that you should know and are not meant to be complete.

Assignments: At the end of every lecture summary you will find a few questions that you should answer. The book you choose to consult will have many more. Those students who are seriously interested in the subject are advised to work out several of the questions posed there. In physics you cannot hope to gain mastery of the subject without extensive problem solving.

Examinations: Their schedules will be announced from time to time.

Tutors: Their duty is to help you, and they will respond to all genuine questions. However, please do not overload them as they have to deal with a large number of students. Happy studying!

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Summary of Lecture 1 – INTRODUCTION TO PHYSICS

1. Physics is a science. Science works according to the *scientific method*. The *scientific method* accepts only reason, logic, and experimental evidence to tell between what is scientifically correct and what is not. Scientists do not simply believe – they test, and keep testing until satisfied. Just because some "big scientist" says something is right, that thing does not become a fact of science. Unless a discovery is repeatedly established in different laboratories at different times by different people, or the same theoretical result is derived by clear use of established rules, we do not accept it as a scientific discovery. The real strength of science lies in the fact that it continually keeps challenging itself.

2. It is thought that the laws of physics do not change from place to place. This is why experiments carried out in different countries by different scientists – of any religion or race – have always led to the same results if the experiments have been done honestly and correctly. We also think that the laws of physics today are the same as they were in the past. Evidence, contained in the light that left distant stars billions of years ago, strongly indicates that the laws operating at that time were no different than those today. The spectra of different elements then and now are impossible to tell apart, even though physicists have looked very carefully.

3. This course will cover the following broad categories:
   a) *Classical Mechanics*, which deals with the motion of bodies under the action of forces. This is often called Newtonian mechanics as well.
   b) *Electromagnetism*, whose objective is to study how charges behave under the influence of electric and magnetic fields as well as understand how charges can create these fields.
   c) *Thermal Physics*, in which one studies the nature of heat and the changes that the addition of heat brings about in matter.
   d) *Quantum Mechanics*, which primarily deals with the physics of small objects such as atoms, nuclei, quarks, etc. However, Quantum Mechanics will be treated only briefly for lack of time.

4. Every physical quantity can be expressed in terms of three fundamental dimensions: Mass (M), Length (L), Time (T). Some examples:

Speed	LT^{-1}
Acceleration	LT^{-2}
Force	MLT^{-2}
Energy	ML^2T^{-2}
Pressure	$ML^{-1}T^{-2}$

You cannot add quantities that have different dimensions. So force can be added to force, but force can never be added to energy, etc. A formula is definitely wrong if the dimensions on the left and right sides of the equal sign are different.

5. Remember that any function $f(x)$ takes as input a dimensionless *number x* and outputs a quantity *f* (which may, or may not have a dimension). Take, for example, the function $f(\theta)=\sin\theta$. You know the expansion: $\sin\theta=\theta-\frac{\theta^3}{3!}+\frac{\theta^5}{5!}-\cdots$ If θ had a dimension then you would be adding up quantities of different dimensions, and that is not allowed.

6. Do not confuse units and dimensions. We can use different units to measure the same physical quantity. So, for example, you can measure the mass in units of kilograms, pounds, or even in *sair* and *chatak!* In this course we shall always use the MKS or **M**etre-**K**ilogram-**S**econd system. When you want to convert from one hsystem to another, be methodical as in the example below:

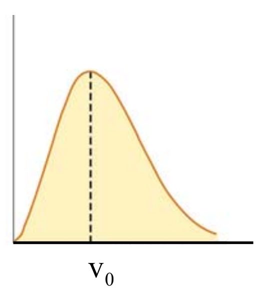
$$1\frac{mi}{hr} = 1\frac{mi}{hr}\times 5280\frac{ft}{mi}\times\frac{1}{3.28}\frac{m}{ft}\times\frac{1}{3600}\frac{hr}{s} = 0.447\frac{m}{s}$$

   When you write it out in this manner, note that various quantities cancel out cleanly in the numerator and denominator. So you never make a mistake!

7. A good scientist first thinks of the larger picture and then of the finer details. So, estimating *orders of magnitude* is extremely important. Students often make the mistake of trying to get the decimal points right instead of the first digit – which obviously matters the most! So if you are asked to calculate the height of some building using some data and you come up with 0.301219 metres or 4.01219×10^6 metres, then the answer is plain nonsense even though you may have miraculously got the last six digits right. Physics is commonsense first, so use your intelligence before submitting any answer.

8. Always check your equations to see if they have the same dimensions on the left side as on the right. So, for example, from this principle we can see the equation $\mathrm{v}^2=u^2+2at$ is clearly wrong, whereas $\mathrm{v}^2=u^2+13a^2t^2$ could <u>possibly</u> be a correct relation. (Here v and *u* are velocities, *a* is acceleration, and *t* is time.) Note here that I use the word *possibly* because the dimensions on both sides match up in this case.

9. Whenever you derive an equation that is a little complicated, see if you can find a special limit where it becomes simple and transparent. So, sometimes it is helpful to imagine that some quantity in it is very large or very small. Where possible, make a "mental graph" so that you can picture an equation. So, for example, a formula for the distribution of molecular speeds in a gas could look like $f(\mathrm{v})=\mathrm{v}e^{-(\mathrm{v}-\mathrm{v}_0)^2/a^2}$. Even without knowing the value of a you can immediately see that
   a) $f(\mathrm{v})$ goes to zero for large values of v, and v = 0.
   b) The maximum value of $f(\mathrm{v})$ occurs at v_0 and the function decreases on both side of this value.



QUESTIONS AND EXERCISES – 1

1. Scientists are told to doubt everything and not believe anything that is not provable. Is this a strength or weakness of science?

2. According to the philosopher of science, Sir Karl Popper, even the most well-established and popular scientific theory can never be proved – it can only be disproved. Discuss this strange sounding claim.

3. Suppose we measure time by using hour glasses filled with sand. Discuss the various errors that would exist if we tried to use this as a world standard for time. Give a rough estimate for the error over a 24 hour period.

4. Which of the following equations are definitely wrong:

   (a) $\mathrm{v} = at^2$

   $(b)\quad x = 3at^2 + \mathrm{v}t$

   $(c)\quad E = \dfrac{mc^2}{\sqrt{1 - \dfrac{\mathrm{v}^2}{c^2}}}$

   $(d)\quad P = \dfrac{E}{c\sqrt{1 - \dfrac{\mathrm{v}^2}{c^2}}}$

   In the above $x =$ distance, $t =$ time, c and $\mathrm{v} =$ velocity, $a =$ acceleration, $m =$ mass, $E =$ energy, and $P =$ pressure.

5. Find how much time is taken for a telephone signal to go from your mobile to your friend's mobile. Assume that the relevant satellite is orbiting the earth at a distance of 250 kilometres, and that the electronic circuits have a delay of 300 microseconds. Give your answer in microseconds.

Summary of Lecture 2 – KINEMATICS I

1. *x(t)* is called displacement and it denotes the position of a body at time. If the displacement is positive then that body is to the right of the chosen origin and if negative, then it is to the left.

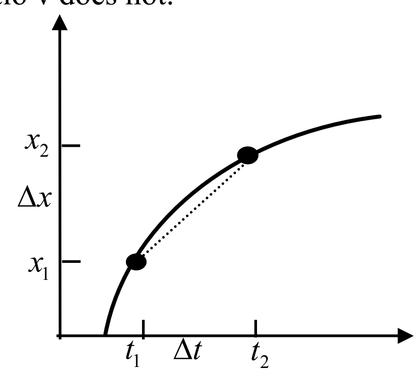
2. If a body is moving with average speed v then in time t it will cover a distance d=vt. But, in fact, the speed of a car changes from time to time and so one should limit the use of this formula to small time differences only. So, more accurately, one defines an average speed over the small time interval Δt as:

$$\text{average speed } = \frac{\text{distance travelled in time } \Delta t}{\Delta t}$$

3. We define *instantaneous velocity* at any time t as:

$$\mathrm{v} = \frac{x(t_2) - x(t_1)}{t_2 - t_1} \equiv \frac{\Delta x}{\Delta t} \quad .$$

Here Δx and Δt are both very small quantities that tend to zero but their ratio v does not.



4. Just as we have defined velocity as the rate of change of distance, similarly we can define *instantaneous acceleration* at any time t as:

$$a = \frac{\mathrm{v}(t_2) - \mathrm{v}(t_1)}{t_2 - t_1} \equiv \frac{\Delta \mathrm{v}}{\Delta t} \quad .$$

Here Δv and Δt are both very small quantities that tend to zero but their ratio a is not zero, in general. Negative acceleration is called deceleration. The speed of a decelerating body decreases with time.

5. Some students are puzzled by the fact that a body can have a very large acceleration but can be standing still at a given time. In fact, it can be moving in the opposite direction to its acceleration. There is actually nothing strange here because position, velocity, and acceleration are independent quantities. This means that specifying one does not specify the other.

6. For constant speed and a body that is at $x=0$ at time $t=0$, x increases linearly with time, $x \propto t$ (or $x = \mathrm{v}t$). If the body is at position x_0 at time $t = 0$, then at time t, $x = x_0 + \mathrm{v}t$.

7. For constant acceleration and a body that starts from rest at $t = 0$, v increases linearly with time, $\mathrm{v} \propto t$ (or $\mathrm{v} = at$). If the body has speed v_0 at $t = 0$, then at time t, $\mathrm{v} = at + \mathrm{v}_0$.

8. We know in (6) above how far a body moving at constant speed moves in time t. But what if the body is changing its speed? If the speed is increasing linearly (i.e. constant acceleration), then the answer is particularly simple: just use the same formula as in (6) but use the average speed: $(\mathrm{v}_0 + \mathrm{v}_0 + at)/2$. So we get $x = x_0 + (\mathrm{v}_0 + \mathrm{v}_0 + at)t/2 = x_0 + \mathrm{v}_0 t + \frac{1}{2}at^2$. This formula tells you how far a body moves in time t if it moves with constant acceleration a, and if started at position x_0 at $t=0$ with speed v_0.

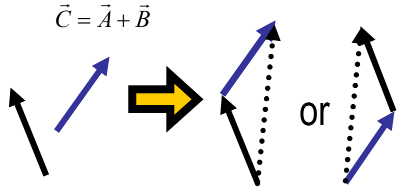
9. We can eliminate the time using (7), and arrive at another useful formula that tells us what the final speed will be after the body has traveled a distance equal to $x - x_0$ after time t, $\mathrm{v}^2 = \mathrm{v}_0^2 + 2a(x - x_0)$.

10. Vectors: a quantity that has a size as well as direction is called a *vector*. So, for example, the wind blows with some speed and in some direction. So the *wind velocity* is a vector.

11. If we choose axes, then a vector is fixed by its components along those axes. In one dimension, a vector has only one component (call it the x-component). In two dimensions, a vector has both x and y components. In three dimensions, the components are along the x,y,z axes.

12. If we denote a vector $\vec{r} = (x, y)$ then, $r_x = x = r\cos\theta$, and $r_y = y = r\sin\theta$. Note that $x^2 + y^2 = r^2$. Also, that $\tan\theta = y/x$.

13. Two vectors can be added together geometrically. We take any one vector, move it without changing its direction so that both vectors start from the same point, and then make a parallelogram. The diagonal of the parallelogram is the resultant.



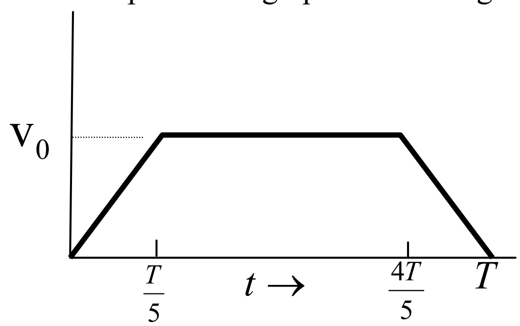
14. Two vectors can also be added algebraically. In this case, we simply add the components of the two vectors along each axis separately. So, for example, Two vectors can be put together as $(1.5, 2.4) + (1, -1) = (2.5, 1.4)$.

QUESTIONS AND EXERCISES – 2

1. A train starts at rest, accelerates with constant acceleration a for 5 minutes, then travels at constant speed for another 5 minutes, and then decelerates with $-a$. Suppose it travels a distance of 10km in all. Find a.

2. A ball is dropped from a height of 10 m. At the same time, another ball is thrown vertically upwards at an initial speed of 10 m/sec. How high above the ground will the two balls collide?

3. A train follows the speed-time graph as in the figure below:



a) Find the total distance travelled during its journey.

b) Find the average speed.

4. Find the resultant of the two velocity vectors $v_1 = (3,2)$ and $v_2 = (4,6)$ and the angle that the resultant makes with the first vector.

5. a) Is it always true that the resultant of two vectors is bigger than either one of the vectors?

   b) Is it possible to define a function of two vectors that is a scalar? Give an example.

   c) Is it possible to define a function of two vectors that is a vector? Give an example.

6. Show that the magnitude of the resultant of two vectors is always less than or equal to the sum of the magnitudes of the two vectors. In what situation are the two equal?

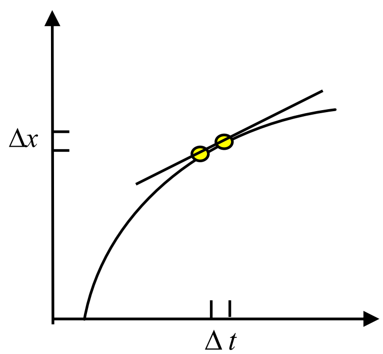
Summary of Lecture 3 – KINEMATICS II

1. The concept of the derivative of a function is exceedingly important. The derivative shows how fast a function changes when its argument is changed. (Remember that for $f(x)$ we say that f is a function that depends upon the argument x. You should think of f as a machine that gives you the value f when you input x.)

2. Functions do not always have to be written as $f(x)$. $x(t)$ is also a function. It tells us where a body is at different times t.

3. The derivative of $x(t)$ at time t is defined as:

$$\begin{aligned}\frac{dx}{dt} &\equiv \lim_{\Delta t\to 0}\frac{\Delta x}{\Delta t}\\ &= \lim_{\Delta t\to 0}\frac{x(t+\Delta t)-x(t)}{\Delta t}.\end{aligned}$$



4. Let's see how to calculate the derivative of a simple function like $x(t)=t^2$. We must first calculate the difference in x at two slightly different values, t and $t+\Delta t$, while remembering that we choose Δt to be extremely small:

$$\begin{aligned}\Delta x &= \left(t+\Delta t\right)^2 - t^2\\ &= t^2 + \left(\Delta t\right)^2 + 2t\Delta t - t^2\end{aligned}$$

$$\frac{\Delta x}{\Delta t} = \Delta t + 2t \Rightarrow \lim_{\Delta t\to 0}\frac{\Delta x}{\Delta t} = \frac{dx}{dt} = 2$$

5. In exactly the same way you can show that if $x(t)=t^n$ then:

$$\frac{dx}{dt} \equiv \lim_{\Delta t\to 0}\frac{\Delta x}{\Delta t} = nt^{n-1}$$

This is an extremely useful result.

6. Let us apply the above to the function $x(t)$ which represents the distance moved by a body with constant acceleration (see lecture 2):

$$x(t) = x_0 + \mathrm{v}_0 t + \frac{1}{2}at^2$$

$$\frac{dx}{dt} = 0 + \mathrm{v}_0 + \frac{1}{2}a(2t) = \mathrm{v}_0 + at$$

This clearly shows that $\frac{d\mathrm{v}}{dt} = 0 + a = a$ (acceleration is constant)

7. A stone dropped from rest increases its speed in the downward direction according to $\frac{d\mathrm{v}}{dt} = g \approx 9.8$ m/sec. This is true provided we are fairly close to the earth, otherwise the value of g decreases as we go further away from the earth. Also, note that if we measured distances from the ground up, then the acceleration would be negative.

8. A useful notation: write $\frac{d\mathrm{v}}{dt} = \frac{d}{dt}\left(\frac{dx}{dt}\right) = \frac{d^2x}{dt^2}$. We call $\frac{d^2x}{dt^2}$ the second derivative of x with respect to t, or the rate of rate of change of x with respect to t.

9. It is easy to extend these ideas to a body moving in both the x and y directions. The position and velocity in 2 dimensions are:

$$\vec{r} = x(t)\hat{i} + y(t)\hat{j}$$

$$\vec{\mathrm{v}} = \frac{d\vec{r}}{dt} = \frac{dx}{dt}\hat{i} + \frac{dy}{dt}\hat{j}$$

$$= \mathrm{v}_x\hat{i} + \mathrm{v}_y\hat{j}$$

Here the unit vectors $\hat{i}$ and $\hat{j}$ are fixed, meaning that they do not depend upon time.

10. The scalar product of two vectors $\vec{A}$ and $\vec{B}$ is defined as:

$$\vec{A}\cdot\vec{B} = AB\cos\theta$$

You can think of:

$$\vec{A}\cdot\vec{B} = (A)(B\cos\theta)$$

$$= (\text{length of } \vec{A}) \times (\text{projection of } \vec{B} \text{ on } \vec{A})$$

OR,

$$\vec{A}\cdot\vec{B} = (B)(A\cos\theta)$$

$$= (\text{length of } \vec{B}) \times (\text{projection of } \vec{A} \text{ on } \vec{B}).$$

Remember that for unit vectors $\hat{i}\cdot\hat{i} = \hat{j}\cdot\hat{j} = 1$ and $\hat{i}\cdot\hat{j} = 0$.

QUESTIONS AND EXERCISES – 3

1. Apply the definition of derivative (see point 3 above) to calculate:

a) $\frac{d}{dt}\frac{1}{t^2+1}$

b) $\frac{d}{dt}\frac{1}{t^3+2}$

c) Show that $\frac{d}{dt}\sin t = \cos t$

d) Show that $\frac{d}{dt}\cos t = -\sin t$

To do this, carefully study the example worked out in point 4 above.

2. Suppose the position of a particle changes with respect to time according to the relation

$$x(t) = a_0 + a_1 t + a_2 t^2 + \frac{b_0 + b_1 t^3}{t} + c\sin dt$$

a) What are the dimensions of $a_0, a_1, a_2, b_0, b_1, c, d$?

b) Find $\frac{d}{dt}x(t)$.

c) Find $\frac{d^2}{dt^2}x(t)$.

3. We shall find the derivative of a product of two functions in this problem. Suppose that $f(t) = g(t)h(t)$. Start from the definition, $\frac{df}{dt} = \lim_{\Delta t \to 0}\frac{g(t+\Delta t)h(t+\Delta t) - g(t)h(t)}{\Delta t}$. Now write $g(t+\Delta t) = g(t) + \frac{dg}{dt}\Delta t$ and a similar equation for $f(t+\Delta t)$. Hence show that:

a) $\frac{df}{dt} = \frac{dg}{dt}h + g\frac{dh}{dt}$

b) $\frac{d(1/g)}{dt} = -\frac{1}{g^2}\frac{dg}{dt}$

c) $\frac{d(f/g)}{dt} = -\frac{f}{g^2}\frac{dg}{dt} + \frac{1}{g}\frac{df}{dt}$

Summary of Lecture 4 – FORCE AND NEWTON'S LAWS

1. Ancient view: objects tend to stop if they are in motion; force is required to keep something moving. This was a natural thing to believe in because we see objects stop moving after some time; frictionless motion is possible to see only in rather special circumstances.

2. Modern view: objects tend to remain in their initial state; force is required to *change* motion. Resistance to changes in motion is called *inertia*. More inertia means it is harder to make a body accelerate or decelerate.

3. Newton's First Law: An object will remain at rest or move with constant velocity unless acted upon by a net external force. (A non-accelerating reference frame is called an inertial frame; Newton's First Law holds only in inertial frames.)

4. More force leads to more acceleration: $\Rightarrow \quad a \propto F$

5. The greater the mass of a body, the harder it is to change its state of motion. More mass means more inertia. In other words, more mass leads to less acceleration:

$$\Rightarrow \quad a \propto \frac{1}{m}$$

Combine both the above observations to conclude that:

$$a \propto \frac{F}{m}$$

6. Newton's Second Law: $a = \dfrac{F}{m}$ (or, if you prefer, write as $F = ma$).

7. $F = ma$ is one relation between three independent quantities (m, a, F). For it to be useful, we must have separate ways of measuring mass, acceleration, and force. Acceleration is measured from observing the rate of change of velocity; mass is a measure of the amount of matter in a body (e.g. two identical cars have twice the mass of a single one). Forces (due to gravity, a stretched spring, repulsion of two like charges, etc) will be discussed later.

8. Force has dimensions of $[\text{mass}] \times [\text{acceleration}] = MLT^{-2}$. In the MKS system the unit of force is the Newton. It has the symbol N where:
1 Newton = 1 kilogram.metre/second^2.

9. Forces can be internal or external. For example the mutual attraction of atoms within a block of wood are called internal forces. Something pushing the wood

is an external force. In the application of $F = ma$, remember that F stands for the total external force upon the body.

10. Forces are vectors, and so they must be added vectorially:

$$\vec{F} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \cdots$$

This means that the components in the $\hat{x}$ direction must be added separately, those in the $\hat{y}$ direction separately, etc.

11. Gravity acts directly on the mass of a body - this is a very important experimental observation due to Newton and does not follow from $F = ma$. So a body of mass m_1 experiences a force $F_1 = m_1 g$ while a body of mass m_2 experiences a force $F_2 = m_2 g$, where g is the acceleration with which any body (big or small) falls under the influence of gravity. (Galileo had established this important fact when he dropped different masses from the famous leaning tower of Pisa!)

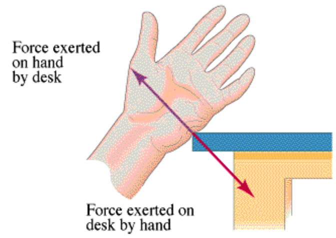
12. The weight of a body W is the force which gravity exerts upon it, $W = mg$. Mass and weight are two completely different quantities. So, for example, if you used a spring balance to weigh a kilo of grapes on earth, the same grapes would weigh only 1/7 kilo on the moon.

13. Newton's Third Law: for every action there is an equal and opposite reaction. More precisely, $F_{AB} = -F_{BA}$, where F_{AB} is the force exerted by body B upon A whereas F_{BA} is the force exerted by body A upon B. Ask yourself what would happen if this was not true. In that case, a system of two bodies, even if it is completely isolated from the surroundings, would have a net force acting upon it because the net force acting upon both bodies would be $F_{AB} + F_{BA} \neq 0$.

14. If action and reaction are always equal, then why does a body accelerate at all? Students are often confused by this. The answer: in considering the acceleration of a body you must consider only the (net) force acting upon that body. So, for example, the earth pulls a stone towards it and causes it to accelerate because there is a net force acting upon the stone. On the other hand, by the Third Law, the stone also pulls the earth towards it and this causes the earth to accelerate towards the stone. However, because the mass of the earth is so large, we are only able to see the acceleration of the stone and not that of the earth.

QUESTIONS AND EXERCISES – 4

Q.1 The picture shown here makes the fairly obvious statement that action and reaction forces in this situation are equal. However, why do you feel pain if there is no net force acting upon your hand?



Q.2 Two astronauts are in outer space connected with a rope in a state of complete weightlessness. Each pulls one end of a rope with his hands. Describe what will happen as time goes on.

Q.3 Add together the forces $\vec{F}_1 = 3\hat{x} + 5\hat{y} - \hat{z}$ and $F_2 = -2\hat{x} - 3\hat{y} + 2\hat{z}$ and obtain the magnitude of the resultant force.

Q.4 A cube of constant density ρ is pushed with a pressure P from one side. The cube is place on a smooth level surface. Find the acceleration of the cube, and the distance covered after time t.

Q.5 Describe all the forces acting upon a ladder that is leaning against a wall. Both the floor and the wall are rough.

Q.6 In the above situation, suppose the floor and wall suddenly become perfectly smooth. What will the net force on the ladder become, and what will be the acceleration in the horizontal and vertical directions?