Acceleration, Velocity and Speed

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Part I: (Happy accelerating!)

Acceleration is a fundamental concept of Kinematics that appears at middle school level and continues until you yourself decide to leave it aside. Most of us with some basic science background can easily iterate what is the acceleration. It is *the rate of change of velocity*, which means how much change in velocity occurred in a given time. However, beyond memorizing this standard definition of acceleration, we do not go ahead to actually grasp ourselves or to make our students understand this theoretical concept.

Most of the concepts of Mechanics, which generally covers the causes of motions, further base on the understanding of acceleration though it is sometimes confused with speed or velocity itself, not in terms of its literal meaning but how we mean it. The article here is an attempt to make a handhold on this concept qualitatively as well as quantitatively.

Let us go back to the very definition of acceleration, the rate of change of velocity. This phrase has three major terms: rate, change and velocity. *Rate* is something, which you must have confronted at several other places as well in your daily life e.g. run rate in cricket, call rate for mobiles, electricity rate, price rate etc. Rate of something means its measurement with respect to some other unit. Your run rate gives you runs *per* over or electricity rate gives you electricity charges *per* electric unit, call rate gives you call charges *per* minute. In the similar fashion, rate in the definition of acceleration stands for change in velocity *per* time. Therefore, how much change occurred in velocity in given time, would give you the rate, which we anticipate as acceleration.

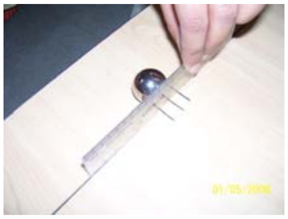
Let us explore the concept of velocity now and then we will look for its change. Distinct from speed, *velocity* carries information of speed, how much distance has been travelled in given time, and its direction both. Talking of speed need not to mention of its direction. However, velocity comprises of two physical quantities, the speed and the direction. A change in either of the two or in both will result in change in velocity. Therefore, *change in velocity can come from change in speed as well as change in direction*. The change can be positive as well as negative, which means speed can increase or decrease, in both the cases it will be considered as a change.

For example- when you apply brakes in your cycle, its speed reduces which means its speed has changed and so there has been a change in velocity as well. On a slope, the speed of the cycle keeps on increasing, so there is also a change in velocity. What about a turn! At a turn, a driver turns the vehicle and its direction is changed even if somehow its speed is maintained the same. You take your own case of the journey from school to home. Do you ever go with constant speed or without changing your direction? In almost all the motions in our daily lives, velocity changes. [Think of a counter-example here.]

Now going back to our definition of acceleration we can say wherever there is a change in velocity, there will be acceleration. Please make it clear that *acceleration is not the change in velocity* rather the rate of this change. Thus as we identified in almost all the motions in our vicinity, velocity changes, the motions are some or the other type of accelerated motions. Can you suggest some non-accelerated motion from your neighborhood? Is it the same question as the previous one?

You will agree with me that still this is not so obvious to make our children observe and get them a handhold on it. So here, we are suggesting an experiment, which demonstrates accelerated motion either in your classroom or in lab settings. You can try that out at your place and send your feedback to us.

Take a wooden plank, smooth tabletops of plywood with sun mica surface, of sizes 4’ x 2’ and available at any furniture shop will be perfect for this experiment. Make sure that the top surface is even and has no dents or scratches on it. Take some rubber blocks or some rigid support to lift this plank from one side. We will roll a ball on this inclined plank and will see whether there is any change in its velocity during its travel. The spherical balls of steel / rubber of roughly 1” diameter and without any seam can be taken up for this. Leave some space of around 8-10 cm from one edge and divide this plank into three or four segments of length 30 cm as shown in the figure 1. Less than this length will be too short to note the time from a stopwatch. Draw a starting line at 5 cm from the edge. Every time the ball is to be released from this line with the help of a ruler. A 6” ruler scale can be used to support the ball to keep it at rest at the start and later on the scale can be pulled outwards to release the ball.



We should be ready with at least two segments of 30 cm. If you take a longer plank, you can mark more than two segments. We also tried this with an aluminium channel of 12’. The only problem with Aluminium channel is that Aluminium being a soft material, the channel needs to be handled very carefully and there are huge possibilities of distortions in its shape.

Try to roll the ball from the starting line and see whether it is going straight. You might need to adjust your supporting block to make it going straight. Now you need people to note the timings for the different segments. Simple stopwatches or mobile stopwatches are good enough for this. While noting the timings from stopwatches, you should make sure that one-person notes time only for one segment. Taking longer segments would also result in parallax error.

Note the two timings for two segments and repeat the whole exercise from ball releasing to actual measurement of time, several times. For this experiment, taking around 10 readings will be good enough to reduce human error. After taking the averages of these readings, you will converge to two final time readings for these segments. In which segment does the ball take more time to cross? If you do this experiment, you find that time to cross first segment is more than the time to cross second segment, which implies that the ball has been faster in later segment.

You can also do actual calculations to estimate average speeds for these segments. Average speed is defined as the total distance travelled in the given time. So average speed for the first segment would be the length of that segment divided by the time taken to cross this segment and similarly for the second segment. Which segment's average speed is more?

If you increase the number of segments by taking a longer plank, you would notice that the average speed in the first segment is least among all the average speeds and the bottommost segment would have the highest average speed. Where does this information lead us? It hints that the average speed is continuously increasing during the journey of the ball. Even if you take smaller and smaller sections, you would find the same pattern. Continuous change in the speed implies that there is a continuous change in velocity and that the balls' motion is accelerated.

You can also use glass marbles instead of steel balls. You just need to ensure that the sphericity of the marbles is even.

Once established that the motion of the ball on inclined plank is accelerated, we can go for its quantification. Have you ever thought of how we can measure it? What information do you need to measure acceleration? This we will cover in the next article.

But wait! Story does not end here only. Why have we so much talked of acceleration? Where do you find application of it? Is it just in your textbooks? Alternatively, does it have any daily life usage? Except that it makes a base to understand the concept of force, we also apply this concept while driving our two-wheelers; remember the pickup and the accelerator of your two-wheeler. Think of some other examples on your own.

Part II: (Estimate the pickup of your bike!)

Once established the qualitative notion of acceleration, we can go even deeper to explore this abstract concept. We keep hearing of gravitational acceleration as 9.8 m/s^2. We also talk of pickups of different bikes; however, we hardly have any idea of the pickup value of our own vehicle. What is pickup? Pickup is nothing but the attribute of being capable of rapid acceleration. In fact, in routine life, we are never asked such a question how much is the acceleration unlike we ask what is speed or how much is the distance travelled. Here we are asking you another important question how you will estimate the acceleration in a motion. Can you estimate the acceleration for the motions in your neighborhood?

For the present purpose to learn estimation of acceleration, we will restrict ourselves to rectilinear motions only. It will keep our calculations simple. Later on, this estimation method can be modified to work for any general motion.

Few months back, we were also struggling with the same problem until recently we arrived at a method by using some idealizations and some approximations to estimate the acceleration for straight-line motions. We used the same wooden plank, same 1” diameter steel ball and same markings as we did in the observation of acceleration experiment to avoid any extra stuff.

Before going to the actual method, let us revise our definition of acceleration, which states that the acceleration is the rate of change of velocity. It means we will have to note the change in velocity and the time taken to occur this change. In addition, since we are dealing with only rectilinear motions, we need not to bother about the direction of velocities. Thus, we reduce the problem to look for the change in speed and the time taken for this change in speed.

We observed that the speed of a ball keeps on increasing when it is rolled from the top of a plank. So we just have to take two speeds at two different instances and measure the time between the two going by the very definition of acceleration. But here the question arises how you will measure the speed at a particular instant as the speed has been defined so far as the distance travelled in a given time and at any particular instant, neither the distance is travelled nor is any time consumed. So this is our first bottleneck.

However, the speed at an instant has never been an easy concept to understand. This problem is pursued by taking a small neighborhood of that instant and taking measurement for that small segment. Neighborhood of an instant means two distinct instances in the immediate vicinity of that particular instant. We further assume that the average speed for this small segment will give us the speed at that instant. This is our first approximation. How small this segment would be, is decided by the least count of the measuring instrument. If you take a stopwatch with the least count of 1 second, the neighborhood can be taken of 2 seconds and if it is 1 minute, the neighborhood can be taken as 2 minutes. The least count of measuring instrument of distance will also matter and will magnify the complexity of the problem.

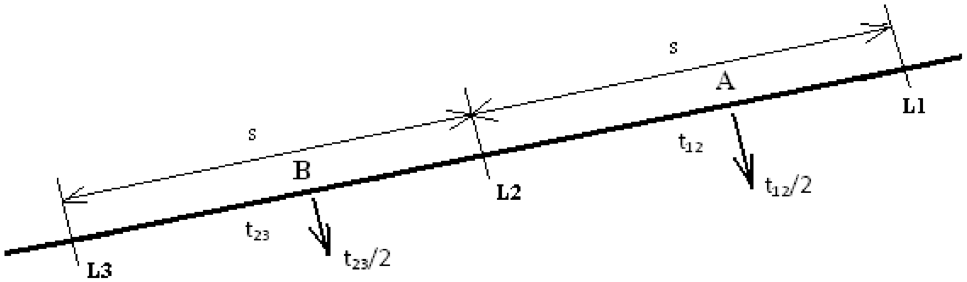
Least count of an instrument is the least value, which can be measured from that instrument. For e.g. least count of a feet-scale is 1 milimeter and for a normal wrist watch is 1 second.

The stopwatches, which we used had 1 centi-second as their least count. However, the minimum time, which one could note from those stopwatches, was on average 15-16 centi-seconds because it takes time in pressing buttons of stopwatches to start and then to stop. It meant we can not take any measurement of less than that time. This puts constraints on our segment length also because if the ball takes time less than this time or of the time of this order, the results will be highly erroneous. After some manipulations, we found that if the plank of ~120 cm length is lifted by 5-10 cm from one end, the ball takes sufficient large time to cross a segment of 30 cm length and that is why we asked you to take at least 30 cm length segments.

In the case of plank and steel ball, the ball is assumed to roll with a uniform acceleration. (Second approximation) Though it can be experimentally verified later, we can also ascertain that it happens to be uniformly accelerated motion from other theoretical reasons as well, the discussion of which is beyond the scope of this article.

Once we have understood the meaning of the speed at a point, we will proceed further to measure the acceleration of the ball in the plank-ball setup.

Here we have two segments of 30 cm length and to start with the calculations, we need two speeds at two different instances. Now extending our argument of the speed at a point, which are also called ‘instantaneous speeds’, let us see what happens if the segment size is significantly large as it is in this case. At which instant does the average speed of the segment can be assumed to occur? Refer Box 1 for these calculations. The calculations imply that the average speed can be assumed the instantaneous speed at half of the time. If the time taken for the first segment is t_1 , the average speed for this segment will be s / t_1 (say v_1), where ‘s’ is the length of the segment. Similarly, the average speed for the next consecutive segment will be s / t_2 (say v_2).



First average speed is the instantaneous speed at $t_1/2^{th}$ instant and similarly the second average speed is the instantaneous speed at $t_2/2^{th}$ instant. So the time difference between these two instances will be $(t_1/2 + t_2/2)$.

BOX 1

Let there be a uniformly accelerated motion with acceleration ‘a’. Suppose the initial instantaneous speed of the body is ‘u’ and after time ‘t’, the instantaneous speed becomes ‘v’.

So,

Change in instantaneous speed = (v-u)
Time taken to change the speed = t
=> Rate of change of speed = (v-u) / t

By very definition of the acceleration, this rate of change of speed is the acceleration ‘a’.

=> $(v-u) / t = a$
Some basic algebraic transformations imply that:
$v - u = a\,t$
$v = u + a\,t$
……………………… (1)

Also, Average speed for a uniformly accelerated motion
= (Initial instantaneous speed + Final instantaneous speed) /2
$= (u + v)/2$
$= (u + u + a\,t)/2$
(from equation 1)
$= u + a\,(t/2)$
……………………… (2)

This average speed has a value in between initial and final speeds. Therefore, it has to occur somewhere in between the observed motion. Let this speed occurs at time ‘T’ taking starting point as reference.

Using equation (1): Speed after time‘T’ = Average Speed
$= u + a\,T$
& from equation (2): Average Speed $= u + a\,(t/2)$
=> $u + a\,T = u + a\,(t/2)$
=> $a\,T = a\,(t/2)$
=> $t = (T/2)$
, given $a \neq 0$

Now we have all the values, two instantaneous speeds and the time difference between those two instants. Thus, acceleration can be estimated as per following manner:

Acceleration = rate of change of velocity
= rate of change of speed (for rectilinear motions)
= change in speed / time taken for this change
= difference between any two instantaneous speeds / time difference between these instants

$$= \frac{(v_2 - v_1)}{(t_1/2 + t_2/2)}$$

$$= \frac{(s/t_2 - s/t_1)}{(t_1/2 + t_2/2)}$$

$$= \frac{(s/t_2 - s/t_1)}{(t_1+t_2) / 2}$$

You should take your own readings and estimate the acceleration for your parameters. Taking average of more than one reading minimizes the possibility of random errors. The experiment can also be tried with different balls of different material or different sizes or for different heights, though there are certain limitations also. While choosing different balls, you should make sure that the balls of other material have no seam and the lift of the plank is such that there is no sliding of the ball while rolling.

To bring further precision to the experiment, we replaced stopwatches with electronic LDR sensors to minimize the human error component. The sensors were mounted on the plank and were interfaced with a computer through a microprocessor. But keeping in mind the classroom constraints, we are not elaborating it further.

Finally, we hope that the experiments would have thrown a light on the complexity of the measurement of acceleration. Do write back to us if at all, helps you to understand the concept of acceleration and its measurement. If you face any problems in either setting it up or in conducting it in your classroom, please get in touch. Happy accelerating!