Physics for Backbenchers

Sharad B Nalawade

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About the Author

Sharad B Nalawade writes out of his passion for science. He enjoys communicating the most intricate concepts of science to general readers. His first book, *The Speed of Time*, on the mysteries of our universe was a bestseller. Sharad spent over 25 years in the IT industry before taking up to writing. His love for Physics and Maths combined with his passion for making these subjects popular among the students and the curious minded readers continues to motivate him.

Sharad lives with his wife Shashi, son Akarsh and daughter Yashaswi in Bangalore.

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Preface

Being a backbencher in a classroom is so much fun. The other day, I went to lecture at one of the institutes and as soon as I entered the classroom, I found most of the front rows empty with the back benches completely full! It was a fairly big classroom and if you are sitting at the back bench, your intentions are quite clear. So I decided to have a bit fun. I went to the opposite end of the room and started teaching! All the backbenchers were now closest to me with their backs facing me! I was a backbencher myself and I know all their tricks. Anyway, the experience was quite enjoyable.

By backbencher, I don't mean the mischievous, noisy, bored, distracting, least engaged and pretentious types. These qualities come and go in most of us. A backbencher means someone who has lost interest in the subject and so the opportunity to learn it the first time in the classroom has been wasted, but later realized that they wanted just one more chance. The reason to be a backbencher may be many. Some feel the class room to be an intimidating place for learning or the reason could be that the teacher is either boring or bossy or there simply is no motivation to learn. Whatever may be the reason, many of us miss the chance to learn in a serious classroom setup and later struggle to catch up with others. By the way, Backbenchers are smart folks!

So, the phrase backbencher here is not used negatively, but more circumstantially and metaphorically. In any case, the whole idea of this book is to present physics to students and generally curious minded readers. If you are not a student anymore but always felt that you missed the whole point about physics then this book is equally good for you. Students studying from high school all the way to post graduation can use this book as a supplement to enhance their understanding of physics concepts. This book can be a good companion to guide you throughout your learning and can be read along with your other text books. Although the book starts with very simple concepts, it takes you far into advanced concepts and prepares you well for solving advanced problems!

Physics is a non-intuitive subject. Many times, it does not appear to be a common experience. You need a fair amount of visualization and thinking to understand a concept. Of course, not all concepts are hard. The other aspect of physics is that it is intimately related to mathematics. If you like physics but not math, then there is very little you can do about it. Math itself is a highly non-intuitive subject and when combined with physics, the challenge may look quite daunting. Many students feel the heat not because they don't like physics but because there is so much of math in it! You will learn in this book that math is as beautiful as physics! Many times while reading this book, you will wonder if you are learning more math than physics! But this much math is required to build a solid foundation in physics.

The structure of the book and the sequence of concepts presented are not very rigid and don't compare with a standard text book! I have tried to cover most of the basic concepts as fully as possible. But it is never enough.

I have tried to make the whole experience of learning physics easy and enjoyable. The book is narrative in its style and uses examples from our daily life as much as possible. Remember, the whole idea of the book is to drive away the fear in you about ones inability to learn hard concepts in physics. Obviously, this book is not a replacement for a good interactive teacher and if you are lucky to have one, keep this book as a supplement. As a student of physics a long time ago, I was always in search of an unconventional and ridiculously simple book and I did find one in *Physics can be fun* by Y. Perelman. I must also admit that this book is highly influenced by the immortal *Feynman Series of Lectures on Physics* by one of most brilliant physicists of all time: Richard Feynman.

Physics for Backbenchers focuses on the fundamental concepts in physics such as *Newton's laws of motion, Friction, Rotational motion, Wave nature, Thermodynamics, Einstein's Theory of Relativity – both Special and General Theory of Relativity, some math concepts like Calculus, Vectors, Trigonometry, e and Logarithm,*. What about other topics like *Field Theory, Optics, Light, Electricity & Magnetism, Atoms, Quantum Mechanics, etc.*? Well, most of these topics are extensions of the basic concepts being covered in this book.

I have carefully selected 20 problems and put them in the appendix that will make you feel confident! Once you are done with these problems, you are ready to take on more challenges in physics! After reading this book, if readers and students get motivated to pursue physics as their course at higher levels, then my purpose is met. Fundamental and pure science subjects like Physics, Biology, Chemistry and Math will remain with us forever. If we don't reveal their inner beauty in the early stage of student life, it would be a great loss to the society and the world as a whole.

Alright, without much ado, let's get cracking!

Sharad Nalawade 19th May, 2014

Chapter 1 Archimedes versus Newton

Albert Einstein reportedly once said "*Education is what remains after one has forgotten everything he learned in school*". How true! As a playful child, I bet your first encounter with physics was not in the school. Remember, your first ride on the swing in your backyard? What about aiming a stone at a mango from your neighbor's tree? And your first bicycle ride? And that great feeling of playing on the seesaw at a nearby park? The one that I enjoyed the most was admiring the breathtaking view of the night sky flooded with twinkling stars with an occasional streak of a falling meteor. While poets expressed this beauty in the form of a poem, the budding scientists wondered and questioned with an agitated mind. If you choose to ignore and move on, you would probably be a tax consultant!

When you translate the above mentioned fun activities into a structured one hour physics class in a school environment, all the thrill seems to fade away. How nice would it be to have your teacher take you all to a nearby park and play with you all and explain in simple words the laws of physics? Or even better, get a seesaw or a slide or a swing into the class room for a demo and I bet the backbenchers will fight for a seat at the front!

Let's get back to the swing and play for a while. What is the first thing you notice? Well, it goes back and forth just like a pendulum on your grandpa's clock. A Pendulum starts from the rest position, goes to the left and then comes back to the rest position only to swing to the right side before returning to the rest position again. This is one oscillation. Thus the pendulum keeps oscillating for a very long time. Let's call one oscillation as one cycle. For a pendulum in the clock this cycle takes exactly one second. The pendulum goes on making 60 cycles in one minute and 3600 cycles in 1 hour and 86400 cycles in one day and 3,15,36,000 cycles in one year and so on! Of course, you will need to wind your clock constantly for the pendulum to keep going. Your backyard swing also behaves exactly in the same manner. But the fun part is that your swing always takes *same time* to complete one cycle *irrespective* of how wide or narrow it swings! You may give it a harder push and let it make a wider swing but even then it takes the same time to complete one cycle. You may like to check this out next time you play with it. Same is the case with the pendulum. Galileo first observed this property when sitting quietly in the cathedral of Pisa watching the chandelier swinging overhead. But strangely enough, he also observed one more property of the pendulum. If you now change the *length* of the string that carries the bob or the chandelier, the time to complete one cycle changes! So, one can adjust the time period of the cycle by adjusting the length of the string of the pendulum. In fact, manufacturers of the pendulum clocks adjust the length of the pendulum so that it takes exactly one second for it to make one cycle.

Let's now move to a seesaw in the park. When you play on a seesaw, you will observe that even if your friend is heavier than you, you can still make him go up easily by yourself sitting close to the edge of the seesaw at the opposite end. A seesaw has a wooden plank whose center is fixed to a fulcrum or a pivot. The length of the plank on either side of the pivot is same. That means, when no one is playing on it, it should balance perfectly and stay horizontal. When you and your friend sit on the opposite sides of the seesaw, depending upon where you sit, you will create a turning or a lifting force. The farther away you sit from the center or pivot, the greater is the lifting force you will produce! This is exactly what the great Archimedes said. He went on to further challenge by saying famously, "*Give me a long rod, a fulcrum and some place to stand, I will move the earth!*". Simple ideas of the great minds!

Thus, one could probably learn and wonder at the fun rides in the park and try to figure out if they can be explained using simple laws of physics. You can explain for example, why the bicycle you are riding on, does not fall sideways when it is moving or for that matter, why the moon does not fall on the earth. Further why a stone thrown up with a sufficiently large force never returns to the earth, or why large ships float on the water, why you see colors in a rainbow, why electrons don't fall into the atomic nucleus, why our universe is expanding, why one does not age when moving at the speed of light, why a single electron exists in two places at the same time and so on.

Archimedes did dazzle the world by his challenge. He knew he was right and he had faith in the laws of physics that they would never ditch him. Even though he was one of the greatest thinkers of all time, he had no idea about the concept of gravitation. It took over 1900 years and a genius like Isaac Newton to discover gravity that somehow never occurred to his predecessors. All Newton said was that there is always a force of attraction between two masses. For example, sun and earth are pulling at each other with some force. As of today no one (not even Einstein) knows how exactly this force of gravitation attracts objects at such vast distances. Newton gave a formula to express this force of attraction between any two massive bodies. Assume that, you and your friend are the only two people in the entire universe and that you are floating in the vast continuum of empty space with no earth or sun or stars, nothing but absolute void. The only force that now exists in the entire universe is the force between you and your friend. Since you are the only two massive bodies next to each other, the force of attraction between you two will keep you both close to each other. How much is that force of attraction? Well, Newton said, the attractive force between you two depends on how far away you are from each other and also how large are your masses. If you are too close, this force of attraction is greater. Likewise, if you are away from each other, this force reduces. Okay, but by what factor? Well, assume you and your friend are one meter apart and the force of attraction between you two is X. Now when you move farther apart by say one meter more (you are now two meters apart) the force will reduce by 75%. That is, it is only 25% of the original force X. If you move farther apart, say by three meters, the force will now reduce to only 10% of the original force X. So, you will observe that, as you move away from each other, the force reduces rapidly. So, don't go too far from each other or else you will never ever be able to shake hands again! What happens to the force of attraction if we increase the masses of the bodies but keep the distance between them the same? Say, you weigh 75 kilograms and your friend is 100 kilograms. The force of attraction is now proportional to 75 multiplied by 100 which is 7500 units of force! Well *almost*. We will see why almost later. But I am sure this will give us some idea about how the force of attraction depends on the masses of the bodies and the distance between them. Thus, more massive the bodies the greater is the force of attraction between them and farther away they are from each other, the lesser is the force of attraction.

I said earlier that the force of attraction (that we call force of gravitation) between any two or more bodies depends upon their masses and the distance between them. More precisely, the force of attraction between any two masses depends *directly* upon the *product* of the two masses (i.e. $m_1 x\ m_2$) and *inversely* proportional to the *square of the distance* between the them.

($1/\mathrm{d}^2$, if 'd' is the distance between the masses). This is universally true. This is *Newton's law of gravitation*. You take any two masses anywhere in the universe and measure the force between them, the above law always holds well. One thing you must observe is that the gravitational force is always attractive and never repulsive. Unlike in the case of magnets where you have both the types viz. 'Like poles' repel each other and 'Unlike poles' attract each other, there is no polarity for gravity. If you keep the two masses and keep the distance between them fixed and take the setup to any corner of the universe, the magnitude of the force between them is always the same. This means that there is something unique about this force of gravitation.

We used the terms like mass, force, etc. quite casually in the previous paragraph but in physics they have a well defined meaning and we will study them as we go along. One thing that always troubles the curious minded is the exact difference between *mass* and *weight*. When you measure your weight on a weighing machine at home you may say for example, it is 70 kilograms. If you now take the weighing machine to the moon and weigh yourself again, it will now show your weight as only 11.5 kilograms! So the best way to lose weight is to visit moon! But if you weigh yourself on the surface of Jupiter, you will weigh as much as 165 kilograms! Is there a difference between mass and weight? Yes there is, and the difference is that, while the mass always remains the same the weight depends upon how much gravitational force is acting on you. Hence, mass is something that is much more fundamental. It is something intrinsic in you. This applies to every matter be it a human being or a piece of stone. If you lose mass, it gets converted into energy which is what Einstein's famous equation $\mathrm{e=m}c^2$ says. Even while you were on the moon, your mass remained the same but your weight got reduced. Since the gravitational force on earth is more than that on moon, you will weigh more on the earth than on the moon. Likewise, you will weigh more on the Jupiter than on the earth because, Jupiter is much more massive than earth and hence it will have a greater gravitational force. To recap, mass is the amount of matter and its weight is decided by the gravitational force acting on it. Mass is always the same wherever you go in the universe but not the weight. Lifting heavy objects on the earth is more difficult than on the moon. Whenever you lift something you have to overcome the force of gravity. Try lifting a heavy table and the gravitation force will pull it down with stronger force. You can lift the same table easily on the surface of the moon.

Now the next question is: *Can I measure my mass if I know my weight?* Yes, you can. Mass and its corresponding weight are related through the force of gravity! More is the gravitational force on a body for a given mass, more is its weight. Before we proceed, let's first try and understand what is force. In physics, force is considered as something that brings about a change in the body on which it is acting. What change? Well, force makes body move or *accelerate*. If you want to move a body faster, you will need to apply more force. Likewise, if the body is heavier, you will need more force to move it. So, somehow force is related to two things: how *fast* you want to move a body and how *heavy* is its mass. It does not matter if the force is ordinary force of pushing or if it is a force of gravitation. If something is falling under the influence of the gravity, it accelerates while falling down. What is acceleration? We will learn about it shortly, but for now, let's consider acceleration as speed that keeps changing. If a body is moving at some constant speed and we apply some force to it, then it will start moving faster. Thus force induces acceleration in a body. In the case of a falling body, the gravitational force is inducing acceleration and it is called 'g' in physics.

Can you consider weight as force? Yes! If you are standing on earth, you are being pulled down by the force of gravity all the time. This is because you have mass. Although, we are standing still on the ground, we are under the influence of the force of gravity and thus undergoing acceleration 'g'! But we had said earlier that acceleration is something that makes an object move faster! Then how come we are standing still? Well, this is because our movement downward is blocked by the earth itself! We are stuck to earth so to say. By chance, if the land below us slides, we fall down with acceleration g! So what we call weight is nothing but a force that is acting on us all the time due to gravity. When I say, my weight is more than my friend's weight, what I mean by that is, the force acting on me is higher than the force acting on my friend. This is because I am more *massive* than my friend. Let's not worry at this stage, if it does not make sense but we will soon get there.

As said, force say F is related to the mass of a body and the acceleration it induces in it. In math, it is expressed as $F=ma$ or $F=mg$ depending upon whether it is an ordinary force or gravitational force. What's F=mg really? How did we get this? A force in physics is something that causes some change in the body or an object. We use force to push a chair, or lift a bag, kick a ball and so on. We all know that, the amount of force that we will need to do some activity depends upon what change we want to bring about. For example, if we want to kick a ball, we decide to apply some force on the ball so it starts rolling on the floor. Compare this to the force that one needs to lift a bucket of water. In either case, the force we used has resulted in some change. In the case of a ball, it actually moved from one point to another with some speed. In the case of a bucket, the force helped us in lifting it against the force of the gravity. When we kick a ball or lift the bucket of water, we need different amounts of force. The amount of force that we need really depends upon the mass of the object. So in plain English, we could say, force is something that brings about a change in the *state* of an object on which force is being applied. Smaller the mass, lesser the force we need to move it from one point to another. We can also express this in math as *force = mass* x *acceleration*. All it means is that, the amount of force we apply on an object depends upon its mass and how fast we want it to move. If you are given two footballs of equal mass and you kick them with different amounts of force, you will see that the two balls roll with different accelerations. Any object that moves from its resting position has some *acceleration*. Acceleration is nothing but the rate of change of *velocity* and velocity is the rate of change of position. Wow! Too many terms in such a short time! Don't worry, we will shortly study both velocity and acceleration in more detail, but it will help us to know at this stage that, different amounts of force induce different amounts of acceleration in an object. If the force is greater, so is the acceleration. In short force is something that makes an object go faster and it changes its position from one place to another.

It is now clear that, both acceleration and mass tell us how much force one needs to apply to an object in order to bring about a change in its state. We can say, *force* α *mass and acceleration*. Here, the symbol α is a *proportionality* symbol. In the language of mathematics, we say force α mass x acceleration. If you take an object of mass 1 kg and apply force on it so it starts accelerating with say 10 kilometers per second every second, we say, the force we applied is equal to 1 kg x 10 km/sec/sec. So, in reality, force, F is nothing but the product of mass and acceleration. Hence, F = ma is our natural conclusion!

Now let's come to our earlier question of why force (F=ma) and weight are one and the same. As said earlier, every matter or object in the universe has some intrinsic mass. This mass is always under the influence of some force. For example, our own body mass is being dragged down continuously by the force of gravity. Even though we are being pulled by the gravity, we try to overcome it by exerting some force of our own. If we don't do this, we fall flat on the floor and remain stuck to the earth! To live and move around, we will need to counterbalance this force of gravity all the time. And the force that our bodies use to counterbalance the effects of gravity is nothing but our weight! So, there is no harm in saying that weight is one type of force. Hence, we have F=ma=mg. Why 'g' and not 'a'? Well, 'g' is the acceleration due to gravity so we replace 'a' with 'g'. We use 'g' in the case of gravity and 'a' in normal cases such as driving a car, etc. Even though you are standing still on the floor your body is under a constant force of gravity by the earth. If you were at some height instead and if you choose to fall, you will fall with an acceleration 'g' due to gravity. When you apply some force to move an object of mass 'm' with some acceleration say, 'a' then we say, the force = ma. But when the same object is falling down due to the force of gravity acting on it, the object gets an acceleration 'g', so we say, the force of gravity = mg. Thus F=mg is just a special case of more general F=ma. In physics, we take 'mg' as weight (W), so we have F=W=mg. If you know the value of F or W and 'g', you can find the value of mass 'm'.

As an example, if your weight is 75 kg and if you want to know your mass, all you have to do is divide this weight by 'g' as F=W=mg. Obviously, your mass is lesser than your weight by an amount proportional to 'g'. The 'g' on earth is more than the 'g' on the moon and hence, your weight reduces on the moon even though your mass is the same.

Gifting mankind with the law of gravitation was one of greatest contributions of Newton. But he also discovered equally great laws called the *laws of motion*. There are three laws of motion and they seem to be a bit non-intuitive in nature. Let's see in simple terms what these laws of motion are and later we can try and develop a better understanding of these laws with some examples.

First of all, it is a common experience that nothing moves unless pushed. A football on the ground remains stationary for ever unless someone moves it by kicking or a strong wind pushes it. This is intuitive. But what is not intuitive is that, if a football is moving, it does not stop unless someone or something stops it. But in reality, when you kick a ball, it rolls for a while and then stops on its own. Well, this is because there is *friction* on the ground that stops the moving ball. If there was no friction or air, the football would move forever! This is non-intuitive. Many of the celestial bodies like earth, moon, sun, stars, etc. keep moving in the space due to this property. The inability to stop from moving or moving without being pushed is termed as *inertia*. So, *Newton's first law of motion* states: "*An object is at rest or it moves at a constant velocity unless acted upon by an external force*". What this means is that, if something is at rest, it will continue to remain at rest until such time that someone moves it by applying some external force. Likewise, if some object is already moving at a *constant velocity*, it continues to move at that constant velocity unless someone applies some external force to slow it down or stop it or speed it up. Well, first of all, there is a technical term here called *constant velocity*. But first, what's *velocity*? In physics, velocity is the speed at which something moves. Velocity is the change in position of an object w.r.t. time. If you cover 50 km on your bike in one hour, we say your speed or velocity is 50 km/hour. Obviously, you cannot maintain the same speed of 50 km/hour throughout the journey of one hour (we will discuss the reason shortly). But for the sake of argument, let's assume that this is the case. We can then say that the biker is now moving with a constant velocity. If the road on which you are biking is smooth and straight without any curves, one can imagine the velocity to be constant. But we all know this is not possible. What are the conditions for your bike to be moving at a constant velocity? We just saw two conditions: the road should be smooth without any friction and it must be straight without any curves. Any other conditions? What if we accelerate the bike while going with a constant velocity? Obviously, we will not be able to maintain constant speed anymore. Another condition is that we should not apply the brakes. If we apply the brakes while moving with a constant velocity, our bike will slow down thus once again coming out of the constant velocity. So, if you accelerate or brake, you can break out of constant velocity. But to do these two (accelerating and braking), you will need some force. Any external force we apply to a bike moving at a constant velocity will result in a *non* constant velocity. In the absence of any external force or friction, a body keeps moving at a constant velocity *without* accelerating or slowing down. To accelerate something or to slow it down, one needs to apply a force. Newton's first law of motion is really all about the concept of a body at rest or a body moving at constant velocity. Supposing, something is moving at a constant velocity, do we need any external force to maintain it at that constant velocity forever? No! As long as there is no friction that stops the moving body and there are no curves, we just don't have to worry about any additional or external force at all. This is certainly very difficult to visualize this in the world we live in. Our world is full of frictional forces, curvy roads and pot holes! All that the first law of motion is saying is that, if a car is moving along a *straight* road at a constant velocity (same distance travelled in the same amount of time during the entire journey) and there is *zero* friction then the car will never stop. But the moment you decide to accelerate the car or to stop it, you will need to *apply* some external force.

If we kick the ball, it starts rolling on the ground with some acceleration. The acceleration with which the ball moves depends on how hard one kicks the ball, which is to say, how much *force* we apply. The more force we apply, the faster the ball rolls. This is obvious. But one must also notice that, while the acceleration depends upon the force one applies, what about the mass of the body? Instead of a leather ball, if we are pushing a steel ball that has much greater mass then the amount of force that we need to apply to make it accelerate as much as an ordinary football, it would be many times more! This means, the force we will need to apply to a body depends on its mass as well as the acceleration we want in it. As we saw, if F is the force we are applying on a body of mass 'm' and 'a' is the acceleration it induces, then we can safely say, $F = ma$. Whenever we have a product (multiplication) in the formula, it always means it depends on all the quantities in the product. So, force that we apply on a body depends on its mass *and* acceleration. What about the relationship between acceleration and mass if we assume force to be constant? This would mean that the acceleration is *inversely* proportional to the mass. That is, higher the mass, lesser is the acceleration for the same force applied. Also, lower is the mass, higher is the acceleration induced for the same force. This is *Newton's second law of motion*. Let's say it in technical terms: "*The acceleration of a body is directly proportional to, and in the same direction* *as, the net force acting on the body and inversely proportional to its mass*". As you noted, there is *direction* as well. The object always moves in the direction of the force being applied on it. We are assuming that there is no friction. The friction changes the direction of motion! This may not look obvious but it is true.

And then there is Newton's third law of motion. "*When one body exerts a force on a second body, the second body also exerts equal and opposite force on the first body*". This again is a bit non-intuitive. Push the wall hard and you will feel some pain in your shoulders. Why? Well, when you push the wall, the wall also pushes you back! Another example is, when you fire a bullet from a gun, you will be pushed back due to the recoil of the gun. The rocket that is fired into space is yet another example of 3rd law of motion in action. Simplest example is when you drop a tennis ball on the floor, it bounces back at you.

So, to sum up we have the three laws of motion and one law of gravitation. This is the work of a genius like Newton. No wonder we all adore him so much. With this, we are now more comfortable than ever to move on with more interesting aspects of nature. The study of motion is a part of what is called a *Classical or Newtonian Mechanics* as against *Relativistic Mechanics* introduced by Einstein that we will study later in the book.