Physics-PHY101-Lecture#04

FORCE AND NEWTON'S LAWS

Till now in this course of physics, we have looked at kinematics which includes basic concepts such as displacement, velocity, and acceleration. We talked about one dimension that if the body can move only on one dimension i.e., on a straight line then how do we define velocity and acceleration? We talked about derivatives, then we generalized it into two and three dimensions. Then some interesting problems were also solved. But this question remains to be raised why do bodies/objects move like this, where do they get this acceleration from? We will look at these issues in today's lecture.

The theme of today's lecture is dynamics. By dynamics, we mean the force which acts on the body and gives it acceleration. In this context, we will talk about Newton's three laws of Motion. So, the real question arises where does acceleration come from? For this, we will need a new concept which we will call Force. Dynamics means it is the study of forces and the resulting motion. So how does a body get motion and what is the effect of force on it will be discussed in this lecture? Before Newton's time, it was believed that the natural state of everything is to come to a standstill, which means that everything wants to come to a standstill or stop, so for example: if we roll a ball then the ball stops after some time or if you throw any other thing then it moves forward for a while and then stops as if it is a natural state that is the of rest and if something moves then there must be some force acting on it, hence this idea was common before Newton's time that some force behind moving body.

For this reason, it was believed that the sun, the moon and all the other planets are moving then there must be some force behind them. For example: if mars rotates in its orbit like this then there must be something pushing it. This was an old idea but after Newton a great revolution took place. Newton said that the natural state of everything is that it wants to continue its movement. The modern view is that objects tend to remain in their initial state, that is they want to remain in the same state in which they were and unless some force acts on it will maintain their condition. Isaac Newton was probably the world's greatest scientist and thinker. He wrote a book called Principia Mathematica about 350 years ago in which he proposed three laws of motion.

Newton's First Law of Motion:

It states that everything either remains at rest or moves with constant speed unless some force acts on it. This means that the body moving will keep moving on its own without the application of external force and can be considered as a free body.

Frame of reference:

If we measure the movement of a body and someone else measures the motion of the same body then there can be differences between the two, so here we have to talk to you about reference frames as shown in figure 4.1. These are two frames of reference, one we can call S, and the other can be called S'. Imagine that you are at rest and standing on land and exist in frame S. There is another person who exists in frame S' and it is moving away from us at velocity V. Let's assume a point P having distance x from our frame of reference. Now the person who is moving will say that I measured this distance as x'.

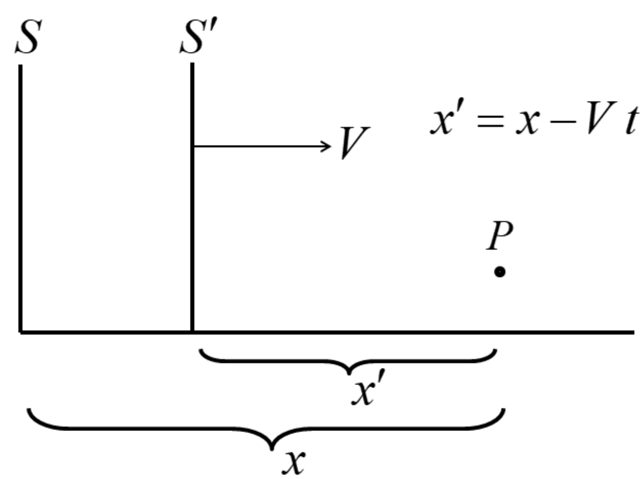

Figure 4.1: Frames of references S and S'.

The relation between these two distances is given by

$$x' = x - V\,t$$

and at $t = 0$

$$x' = x$$

So initially ($t = 0$) both distances are measured to be the same, but as the second observer moved forward, there was a difference between x and x' which is called a frame of reference. According to this, two different observers will have different sets of coordinates for the same point and whatever measurements we make will depend on these coordinates. Now the question arises of whose measurements are more accurate.

Inertial and non- Inertial Frame of Reference:

Newton's first law applies in every frame which is moving with constant velocity and such frames are called **inertial frames.** Newton's law is valid in all inertial frames and all non-accelerating frames are called inertial frames.

For example: Imagine that you are sitting in the car and there is a hydrogen or helium balloon in that car, and it is suspended inside the car. Now when the car accelerates, we will observe that the balloon starts moving backwards. It seems like some force is acting on the balloon. But in reality there is no force acting on it, but we feel it as if it's moving backwards. And that is because you are not in the same inertial frame. The frame which accelerates is a **non-inertial frame** and apparently, a force acts in it sometimes called a fictitious force. It appears to be force but in reality, it is only observable because we have chosen the wrong frame of reference. So, Newton's first law is true only in inertial frames.

Difference between inertial and non-inertial frames of reference:

Inertial frame	• The frame of reference which is moving with uniform velocity and does not accelerate (a=0). • Obeys Newton's law of motion. • Example, a train moving with uniform velocity is an inertial frame of reference.
Non-inertial frame	• The frame of reference which is accelerating (a≠0) is called non-inertial frame of reference. • Does not obey Newton's law of motion. • Example, a freely falling elevator is taken as non-inertial frame of reference.

Law of inertia:

Now the question arises when you want to change the state of motion of a body, you feel some resistance. How much does a body resist when you try to change its state of motion? It depends on its mass. The heavier the body, the more it will resist change in its state of motion. There are many examples of this.

For example: If you push a light body (like a shopping cart), it moves easily. If you push a heavy body (like a car or bus) it is possible that you may not even be able to move it. We define this resistance as **"inertia"**. So, inertia is the resistance to change in motion in other words resistance to acceleration and mass quantifies it. The greater the mass, inertia will be more accordingly. Now the question arises whether mass means size? to which the answer is no. Sometimes smaller bodies offer more resistance. It is related to density. To which the answer is also no. Is this related to weight? Is mass the same as weight? This is also not the answer. Mass and weight are not equal.

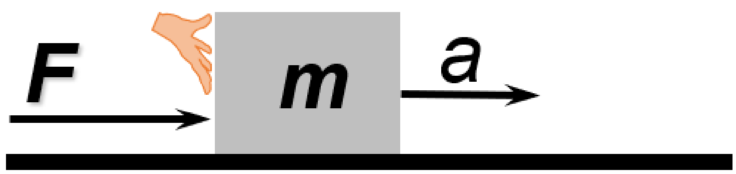

Figure 4.2: Force *F* acting on a body having Mass *m* and causing acceleration *a*.

Now look at Figure 4.2. Force F is acting on a mass whose value is m. Now the more force applied to it the acceleration 'a' will be greater accordingly. So mathematically it is written as

$$a \propto F$$

More force leads to more acceleration. But on the other hand, if we consider a body having more mass then the acceleration will be less.

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

Hence

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

$$F = kma \ (k=1)$$

Increasing the force increases the acceleration but increasing mass reduces acceleration.

Newton’s second law of motion:

Newton's second law of motion states that the product of mass and acceleration is equal to the total external force acting upon mass. Now there can be many forces (shown by subscripts) applied simultaneously in different directions. The total net force will produce acceleration.

$$F = ma \rightarrow a = \frac{F}{m}$$

Where

$$F = F_1 + F +_2 + F_3 + ...$$

By this, we can also define mass as:

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

So, how to rightly write this equation? There is an equation and there are three variables. Here you can measure the acceleration separately because acceleration is the rate of change of velocity and velocity is the rate of change of position. As position can be measured as a function of time so, velocity and consequently time-dependent acceleration can be measured. There is a need to measure force and how do we do this? We can give you many simple examples of this.

Example: We can consider a spring balance. In spring balance, we can place some mass and there is a spring. The more mass we place, the more spring will extend. Similarly, if we pull something with a spring balance, there is a scale on the spring balance showing the magnitude pulling force. If we pull a rubber band, this rubber band exerts a force on our hand and the more it is pulled, the greater the force. So, a rubber band can measure force.

Introduction to force:

Force is the vector and hence it has a magnitude and also a direction. The direction of force is also the direction of acceleration. There are many types of forces.

Let us consider **contact forces**. When two bodies come in contact with each other, one body exerts a force on another body that is a force acts on it, i.e., when we push a box, a force acts on the box, air exerts pressure on a moving car which is called **air resistance**. Consider a rope with a weight tied at one end that results in **tension** which is also a type of force.

Just like other physical quantities force also has dimensions given by,

$$[Force] = [Mass]\times[Acceleration] = [M]\times\left[\frac{L}{T^2}\right] = \left[\frac{ML}{T^2}\right] = \left[MLT^{-2}\right]$$

Units for force in the MKS system is Newton. Newton is defined as, if we apply 1 Newton force on 1 kilogram of mass then its acceleration becomes 1 m/s^2.

$$1N = 1kg.1\frac{m}{s^2}$$

Force F means external forces only. Consider a body made up of atoms (as all matter is made up of atoms), every atom attracts or repels the other atom. These interactions are internal forces so they cancel out each other. When we say that the acceleration of a body is *F/m*, then that F refers to external force only.

External force actually is a total force so if various forces are acting such as F_1, F_2 and F_3 till F_N then we have to add all these, given by:

$$F = F_1 + F_2 + F_3 + ... + F_N = \sum_{i=1}^{N} F_i$$

here we see a new symbol which is called the Greek symbol "Sigma $\sum$" or symbol of summation. So, this summation means we add F_1, and F_2 till F_N and this makes the total force.

As force is a vector quantity it can be added by two methods. One method is already discussed (the Parallelogram method) earlier. This can also be done and the other way is through vectors addition by components. The following sample problem (figure 4.3) can help us better understand the addition of two forces by components method. We are given two forces (F_1 whose value is 4 N along the negative y-axis) and F_2 whose value is 5 N at an angle of 36.9° with the x-axis (angle not mentioned on PPT slide).

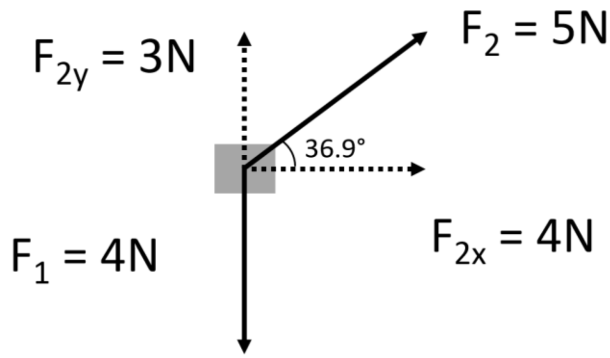

Figure 4.3: Sample problem.

Components of F_1:

$F_{1x} = 0$ (as no component along x-axis)

$F_{1y} = -4N$ (as it is along negative y-axis)

Components of F_2:

$$F_{2x} = F_2 \cos(36.9) \simeq 5*0.8 = 4N$$

$$F_{2y} = F_2 \sin(36.9) \simeq 5*0.6 = 3N$$

The sum of components along the x-axis,

$$\sum F_x = F_{1x} + F_{2x} = 0 + 4 = 4N$$

$$\sum F_y = F_{1y} + F_{2y} = -4 + 3 = -1N$$

So, the **magnitude of resultant force F** can be calculated by,

$$|F| = \sqrt{\sum F_x^2 + \sum F_y^2} = \sqrt{(4)^2 + (-1)^2} = \sqrt{17}N = 4.12N$$

Exercise for student: Determine the direction of resultant force F.

Mass and Weight:

Now we will discuss the difference between weight W and mass m. Weight actually is a force, the force due to gravity. If I have a kilogram of matter it will have a specific weight on earth's surface, but if I take it to the moon's surface, its weight will be different. The mass will be the same but its weight is different on both (earth and moon). Let's look at it in the formula, the weight is the force of gravity and if you apply the following equation.

$$F = ma$$

Where F becomes the weight W, mass m remains tha same, and acceleration a is replaced by acceleration due to gravity g.

$$W = mg$$

Like forces, weight is also a vector and is measured in Newton. If we measure the weight of the same body on earths and moon's surface, we will observe that the weight on earth will be seven times as compared to weight on moon although mass is same. If we go out into space where there is no celestial body, then our weight will be zero there as there will be no acceleration due to gravity, although mass will be non-zero and remain the same.

Difference between mass and weight:

Mass	**Weight**
Mass is a property of matter. The mass of an object is the same everywhere.	Weight depends on the effect of gravity. Weight increases or decreases with higher or lower gravity.
Mass can never be zero.	Weight can be zero if no gravity acts upon an object, as in space.
Mass does not change according to location.	Weight varies according to location.
Mass is a scalar quantity. It has magnitude.	Weight is a vector quantity. It has magnitude and is directed toward the center of the Earth or other gravity well.
Mass may be measured using an ordinary balance.	Weight is measured using a spring balance.
Mass usually is measured in grams and kilograms.	Weight often is measured in newtons, a unit of force.

Newton's third law of motion:

Newtown's third law says that the action of every force produces a negative force. The magnitude of these two forces is the same and direction is opposites (antiparallel).

Example: Two boxing gloves A and B collide and come in contact with each other while punching. A Pushes on B and B pushes on A. So, these are action and reaction forces are in opposite direction but have same magnitude (negative sign on the right-hand side of equation in figure 4.4 shows opposite direction)

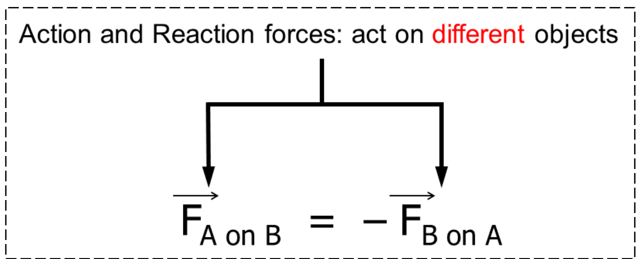

Figure 4.4: Action reaction forces.

Note that $F_{A\ on\ B}$ is equal to negative $F_{B\ on\ A}$, so the effect of A is on B & B is on A. A is not affecting C, D or anything else, nor is B on anything else. It is so that A is on B & B is on A.

Example: An apple is lying on the table, so this is the force of the earth on the apple. We will call it action, and this is due to gravity. Its reaction is not the force of the table on the earth, but the force of the apple on the earth. Earth pulls this apple down, and on the other hand this apple pulls the earth to itself. We assume earth is not pulled to apple which is wrong. Apple is light and very small in comparison to the earth, but the apple also pulls the earth toward itself. Now because the earth is so heavy its acceleration is very less. But apple definitely exerts a force on earth. Table also exerts as a force on apple and its reaction is that apple also exerts a force on table. Now you can ask how the table exerts a force on the apple. How does the force exerted by the table affect it? It's obvious that if there was no apple there would be no force. But if you keep the apple on the table there is a slight bend produced in the table as a result of which a force is produced in upward direction.

To make this discussion interesting we will narrate a story of a very educated horse. He studied Newton's law in his spare time and especially Newton's third law. One day, while he was studying, his owner got angry. His owner attached a cart to him and ordered horse to pull it. The horse said that there is no use of it because he has just read Newton's third law and according to that if he pulls the cart then the cart will also pull him back with same force. He will not move forward hence it is useless to pull the cart. The owner got angry, he gave a pat at the back and what happened? The cart started moving forward. Why did it happen? If the horse is right then the cart would not have moved but there is a mistake in it. So, let's see where the mistake is.

If we look at this student in figure 4.5 walking forward on the ground. Similar to the student depicted in figure we also push ground backwards with our feet. The ground pushes us forward as a reaction. Newton's third law says that if we push something back, it pushes us forward. In this way we move forward. So whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.

Figure 4.5: Person 'P' walking on ground 'G'. F_{GP} is a backward force exerted on ground by a person. F_{PG} is forward force exerted on a person by ground.

Now look at Figure 4.6 of assistant boy 'A' boy is moving forward on ground 'G' and at the same time he is also pulling a sledge 'S' forward. When he pushes ground backward (F_{GA}), the ground pushes him forward (F_{AG}). The tension in this rope (F_{AS}) also pulls this boy backwards. But if the total force produced in the forward direction is more than the backward pull, then this sledge will move forward.

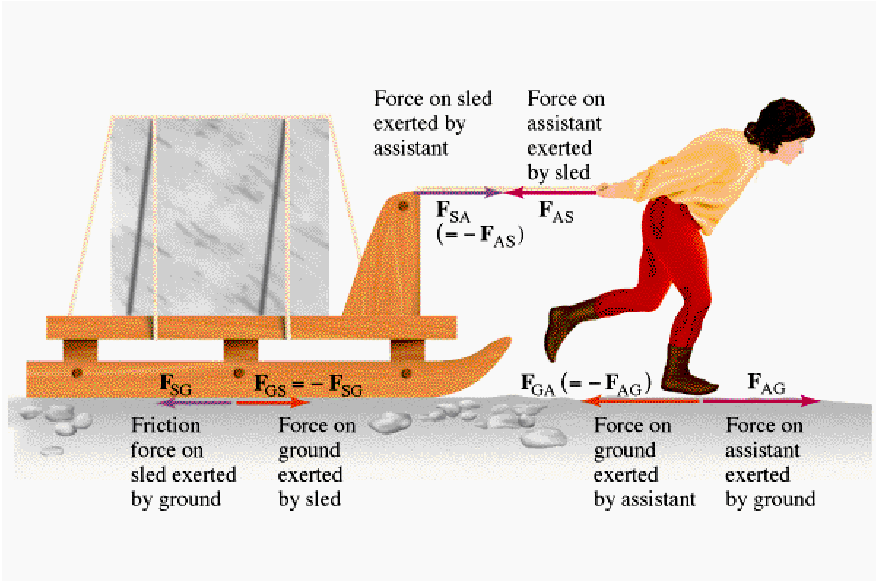

Figure 4.6. Assistant boy 'A' moving forward on ground 'G' and also pulling sledge 'S' forward.

Now one more **example** is depicted in figure 4.7. Your hand is on the table in front of you, and with your hand, you are applying pressure on the table and pushing it downwards but table is pushing your hand upward in opposite direction.

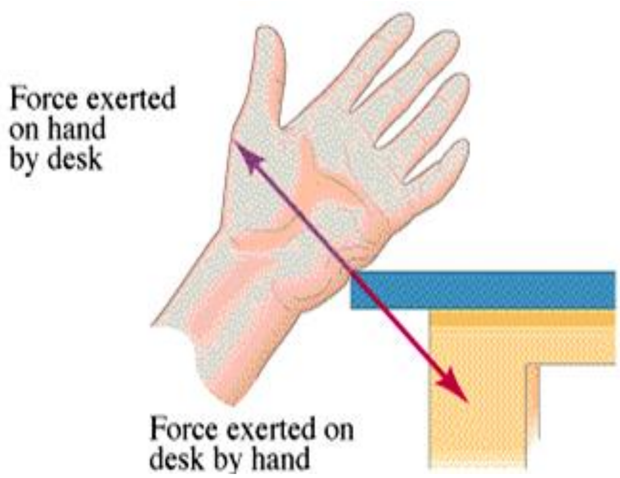

Figure 4.7: Action-reaction pair for hand and table.

Let's consider another **example** shown in figure 4.8. The person is standing and pushing against the wall and the wall pushes the person back with same force. If the action-reaction forces are equal and opposite in direction, why they do not cancel out each other?

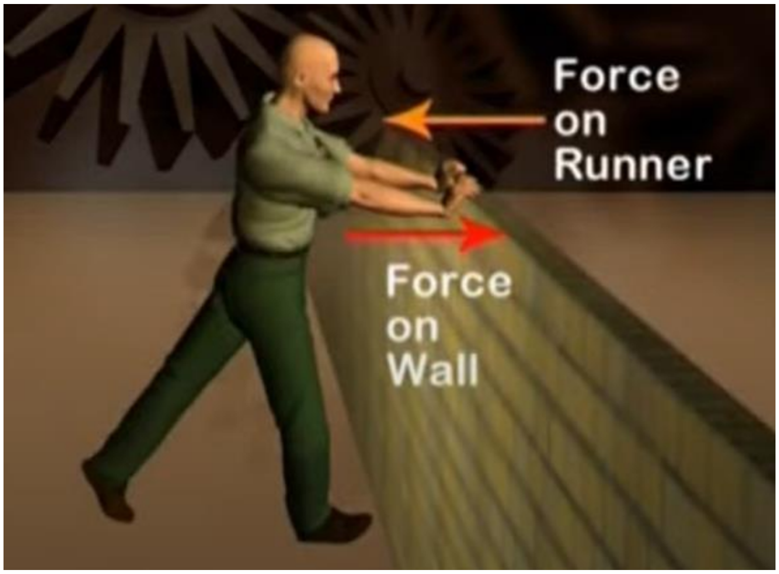

Figure 4.8: Action-reaction pair for person pushing wall.

Figure 4.9 elaborates forces involved with more details. A person is leaning against a wall. Two forces are acting on this person. One is his weight and written it as $F_{m\ on\ f}$ meaning the force of mass ‘m’ on the floor ‘f’. This force act in downward direction. Reaction to this force i.e., the force of floor on the man $F_{f\ on\ m}$ acts upward and cancel out each other. The force exerted on the left side is force of man on the wall $F_{m\ on\ w}$ and the force of wall on the man $F_{m\ on\ w}$ is on opposite direction. Both these forces are equal in magnitude and in opposite direction.

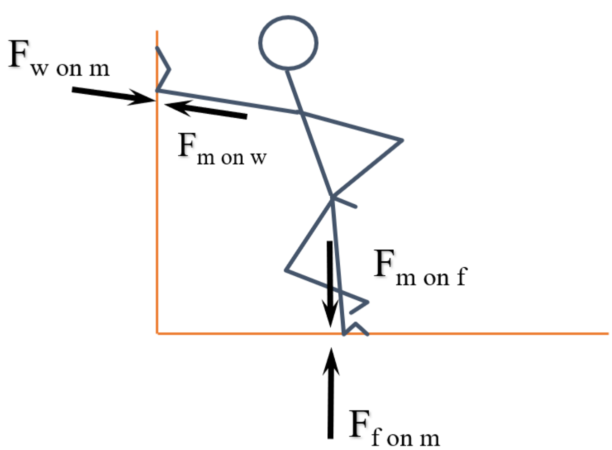

Figure 4.9: Forces involved for physical scenario of man ‘m’ leaning against wall ‘w’.

Now if we push a body with much greater force then there is possibility that it will start moving in the direction of applied force. Such **an example** is shown in figure 4.10. A block/box is on frictionless (ice) surface. Man pushes block/box to the left (negative x-axis) by a force $F_{m\ on\ b}$ (force of man on block). Reaction to this is force of block on man ($F_{b\ on\ m}$) is towards right side (positive x-axis). Although both forces ($F_{m\ on\ b}$ and $F_{b\ on\ m}$) are equal and opposite in direction but block moves to left side. So how is it possible? Why are these forces not cancelling each other?

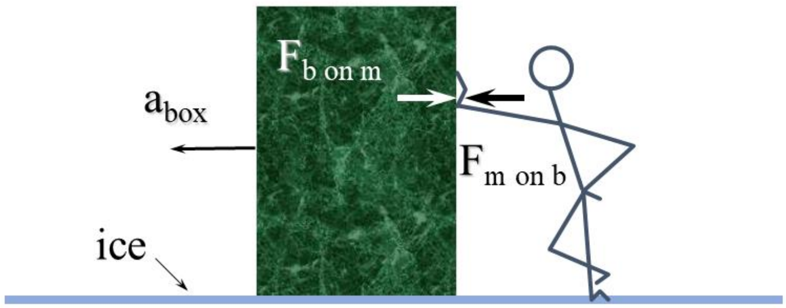

Figure 4.10: A block/box on frictionless (ice) surface being pushed by man.

The answer to why these forces is not cancelling each other out is that a body moves depending upon the total external force acting on that body (having mass m). The force that will act on a body will create acceleration in it. By considering ONLY the block/box as the whole system we can answer above mentioned questions. The force on block/box ($F_{on\ box}$) is equal to force of man on block/box ($F_{m\ on\ b}$) which by newton's second law is equal to product of mass m and acceleration of block/box (a_{box}). Mathematically it can be written as

$$F_{\text{on box}} = F_{\text{m on b}} = ma_{\text{box}}$$

Acceleration of block/box (a_{box}) will be,

$$a_{\text{box}} = \frac{F_{\text{m on b}}}{m}$$

<u>Misconception:</u>

Table 4.1: This table enlist few misconceptions related newton's laws

Sr. No.	Claim	True or False. Explanation
1.	If something is moving, there must be a net force on it.	This is a false claim. A body moving at constant velocity has no net force on it. An accelerating body must have a net force on it.

2.	All equal and opposite forces are action-reaction pairs.	This claim is false. The weight of a book sitting on a tabletop and the normal force of the table acting on the book are equal and opposite, but they are not an action-reaction pair!
3.	If there is a force on an object, it must be accelerating.	This claim is false. Only a net force on the object leads to acceleration.

In our daily lives, we observe the validation of Newton's law on many occasions, especially the first and second laws. There is a concept about these which we call inertia that a body tends to maintain its state of motion or rest and its speed doesn’t change. This resistance to change of state is proportional to its mass. An example involving glass and paper is discussed in the video lecture followed by the stretching of rubber band as a function of applied force (amount of water).

We will pay close attention to the applications of Newton’s law during the next few lectures. The application of Newton’s laws is not limited or localized. These laws are applicable in the whole universe (also termed as universal set of laws). Interestingly concepts at the base of Newton’s laws do not exist in the world. They only exist in our minds. For example, if we talk about free particles (as mentioned earlier that free particle is the one on which no force acts on it) but is there any free particle in reality? The answer is NO. There is no such thing as a free particle. If we even take a particle/body million and millions of miles away from Earth, there will be a minute force acting on it due to gravity. We have also talked about this earlier there is such a thing as a point mass or point body. Despite these facts, we are related to the abstract concept that Newton's laws related to things that do not exist yet this is the achievement of human thinking. We will discuss the application of these laws and how phenomenon are explained.