2. Newton's Laws

Newton (1643-1727) was the scientist who first brought some unity and clarity to the ideas of Physics. His work was the first great unification of many ideas about the way things move – the science of dynamics. He also did work in other branches of science – for example he invented the first reflecting telescope. His "Newtonian" design is still used by amateur astronomers today – almost without modification.

But his three laws of dynamics, together with his law of gravity are key ideas which form the backbone of his work. This essay tries to explain the three laws.

The First Law

Every object continues in a state of rest or in uniform motion in a straight line unless acted upon by a force.

What does this mean? Take a book and push it along a table. Stop pushing and it stops. How does this make sense with the first law which says things will just keep going without a force to keep them going. Suppose you have a platform with wheels, maybe a skate board, or a truck with Meccano. If you put the book or some other object on that, then when you push it will keep going much further.

Now think of a skater on ice. When they stop skating they will carry on for some distance and generally have to make an effort to stop. The slowing down in all these cases is caused by "friction" – a force that acts between surfaces that resists the motion of one over the other. The friction is large in the first case, reduced in the second and much further reduced on the ice. Air resistance is another force of friction that resists the motion of objects moving through the air.

You should be able to imagine that if all friction were removed then the object would carry on in a straight line forever without pushing. This is the First Law. In space there is a vacuum and so no air resistance. Spaceships will then carry on without their rockets being fired. In the lunar landings the bulk of the journey was made without the engines firing. (Gravity is still acting and we shall talk about that later).

Speed and Velocity

Before talking about the second law we need to distinguish between *speed* and *velocity*. In everyday parlance they are the same. In science they are not. Speed is a measure of how fast something is going irrespective of which way it is moving. Velocity says how fast, but also it need a statement of direction.

For example a car moving south on the M1 at 60 mph will have a speed of 60 mph. A car moving north of the M1 at 60 mph also has a speed of 60 mph. The speedometers will read the same value. But one car will end up in London and the other in Leeds. Velocity takes account of direction. One car has a velocity of **60 mph south**, whilst the other has a velocity of **60 mph north**. The velocities are different. Velocity has a size and a direction. Such quantities are example of *vectors*.

A satellite orbiting the Earth may have a near enough constant speed, but its velocity is continuouslychanging because its direction is continuously changing. When moving in a curve the distinction between speed and velocity is very important and will be taken up in more detail in the next chapter.

So to restate the First Law:
Every object continues in a state of rest or in uniform motion in a straight line unless acted upon by a force.

This could equally be stated:
Every object continues in a state of rest with uniform velocity unless acted upon by a force.

A constant velocity implies constant speed *and* constant direction.

The Second Law

Newton's own words for the second law would be easily misunderstood as the words he used at that time have somewhat different meanings today. So we will use modern terms.

The acceleration produced by a force acting on an object is directly proportional to the force and inversely proportional to the mass of the object.

OK! This requires some explanation. We have some new words, "acceleration", "proportional" and "mass".

Acceleration is easy to understand if the object is moving in a straight line. (Moving in curved paths comes in the next essay). This is because acceleration is the rate at which velocity changes, not simply speed. So here to get the idea we will just think of moving in a straight line.

Suppose something is already moving with a velocity of 2 metres per second in a straight line from A to B. The speed is written as 2 m/s. Suppose that 3 seconds (3 s) later it is moving at 14 m/s. So it has increased by 12 m/s in 3 s. We say that the value of the acceleration is 4 m/s per second. If it went on speeding up at the same rate after a total of 10 seconds it would have speeded up by 4 x 10 = 40 m/s and so the final speed would be 42 m/s.

In the above case we say the value of the acceleration is 4 m/s every second which is written, for short as 4 m/s^2. The little 2 indicates we giving the increase of the speed in m/s each extra second.

(Note: All of this is OK because we are talking about motion in a straight line. How this works when the acceleration is not in the same direction as the velocity is the subject of the next chapter. But we deal with one thing at a time!)

Proportional. What does this mean? In this case it says the acceleration is proportional to the force. This simply means double the force and you get double the acceleration, three times the force gives three times the acceleration and so on.

Mass. The mass of an object, (measured in kilograms, kg) measures how difficult it is to get an object moving and how difficult it is to stop it once it is going. So here Newton Second law, saying the acceleration is *inversely* proportional to the mass, means that when the same force acts on twice the mass, the mass is twice as difficult to get going and so the acceleration is *halved*. Three times the mass and the same force would only produce one *third* of the acceleration. The scientific way of saying that mass measures how difficult it is to get something going, is to say that mass is a measure of *inertia*. Inertia here, therefore, has a precise scientific meaning.

Let's put this all together. First, Force – a push or a pull. This is measures in units called newtons (N). A newton is the force that when it pushes on a 1 kg mass will give it an acceleration of 1 m/s^2, so an increase in speed on 1 m/s every second. So 10 N would accelerate the 1 kg mass at a rate of 10 m/s^2, because the acceleration is proportional to the Force. If we have the same force and double the mass to 2 kg, the acceleration would reduce to half, i.e. 5 m/s^2, as the acceleration is inversely proportional to the mass.

All these figures are consistent with the famous way of stating the Second Law as an equation:

Force = mass x acceleration

$$F = ma$$

(In algebra the x sign is not written). You can see this fits with numbers above. For example the force of 10 N gives a 2 kg mass an acceleration of 5 m/s^2. 10 = 2 x 5.

Way back in the 1970s when the "Star Wars" movies came out students at school would remember the formula:

"May (ma) the force (F) be with you."

The Third Law

This law is frequently misunderstood. In Newton's own words:
To every action, there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

This is usually stated now as:

To every action there is an equal and opposite reaction.

Here action and reaction refer to forces. The law is often misunderstood thought can go like this. "Well if to every force there is an equal and opposite force, then these forces should cancel and nothing should ever move!". Newton's own statement explains why this is wrong as he says the action and reaction are **directed to contrary parts***.* What he means is that the action force and the reaction force **act on different objects**.

Here is a simple example. I am sitting at my desk writing this essay. I am exerting a force on the chair because gravity is pulling me downwards – my weight. The cushioning on the chair is squashed because of this. But I am not falling down, the chair is pushing me up.

*****BOB INTERUPTS*****

Bob: I don't see how the chair is doing any pushing. It is just a chair.

Me: Look this is an interruption – you are wrecking my argument. I will get Alice to explain and put your chat in italics, then can carry on when you have finished.

Alice: Hi Bob. I heard your question but just to be sure you agree that gravity is still pulling you down?

Bob: Yes as otherwise I would float off. But the chair stops me falling to the ground.

Alice: Yes it does by exerting an upward force on you to balance the force of gravity on you. Think about a rather odd chair - let's say a hard wooden topped stool, but instead of legs the top is supported by three vertical strong springs.

{necessary to insert picture of the stool here??}

Alice continued: What happens when you sit on that?

Bob: Well the springs will squash a bit I guess.

Allice: But when you squash a spring it is pushing back. Think of just a small short spring squashed between your thumb and forefinger. You can feel the spring resisting and pushing back as you try to squash it. So when you sit on the stool the springs squash and give an upward force on you to balance gravity so that you don't fall.

Bob: But a chair doesn't have springs.

Alice: Doesn't it? Your bed mattress has springs – or some material that has a similar effect and that is not so different from a chair. If you push your hand down on the chair it will give a bit and then "bounce" springlike when you let go.

Bob: How about a chair with a wooden top, or if you sit on a brick wall. They aren't like springs.

Alice: Actually they are! All materials are springy. It is just that in some materials the spring behaviour is very stiff.

Bob: I think you are having me on.

Alice: So here is an example. Steel is hard, you may say not springy. But springs are made from steel. Piano strings can be made from steel and they stretch and act like springs when the tuner stretches them to keep the piano in tune.

Bob: You will tell me next the floor is a bouncy as well.

Alice: Yes. Hard materials are very stiff. It takes a lot of force to squash them so when you sit on a hard surface it squashes only a little to oppose your weight. This means the force is concentrated over the small area where the surface "gives" and so the force on your rear end is high over that same small area. It is uncomfortable. A cushion – which is less stiff allows the forces to act over a large area, so the force on any place is less. So it is more comfortable.

Bob: So when I walk on the floor it is pushing up on me because I squash the floor a tiny bit and it pushes back holding me up?

Alice: Exactly. That is why softer flooring is placed near workbenches where someone may be standing all day. The upward forces are spread and so less strain on the feet.

Bob: So all materials are squashy to some extent – when you push them the material gives a bit and pushes back. So I guess this applies to all objects in contact. They "give" a little bit and so like a spring they push back.

Alice: That's exactly right. And it applies whether things in contact are still, or whether they are moving. (Oops I see he is going to make that point in a moment). The springiness of materials can be measured as a value. It is called Young's modulus. But we won't go there! Better take off the italics and let him get on.

As I was saying there is a downward action force on the chair and upward reaction force holding me up. These forces cannot cancel as they act on different objects, me and the chair.

Objects do not have to be still for the law to work. It works always. Fig 2.1 shows a heavy marble rolling towards a lighter one. The lighter one is at rest. When they collide there is an action force to the right on the lighter ball that sets it into motion, and there is an equal reaction force on the heavier one acting to the left that slows it down. The detail of what happens as a result depends on the mass of the balls and how bouncy they are. The speeds here are just examples.

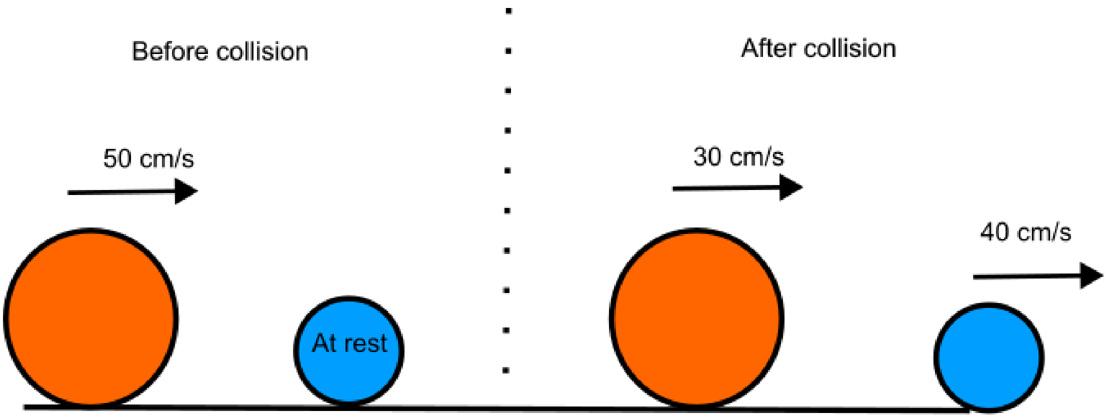

Fig 2.1

Another example would be two snooker balls moving with the same speed colliding directly head on. Snooker balls are bouncy so each would bounce back in the reverse direction. The third law says the forces when they strike are equal but opposite in direction on each ball. Since the balls have the same mass, they would bounce away with equal speeds. If the balls were sticky and stuck together both would stop. The force to stop the ball moving to the left is equal and opposite to the force on the ball moving to the right. So, as they are of the same mass that would stop also.

A final example – discussed more in a later essay. There is a gravitational force between the Earth and the Moon. This force on the Moon holds the Moon in orbit. The reaction to this force on the Earth is what causes the tides.

Summary

First Law. Things keep going in a straight line unless a force acts.
A force may slow the object down, speed it up, or make it deviate from a straight line if the force is not directed along the line.

Second Law. F = ma
This relates the force producing an acceleration to the mass on which the force acts and the acceleration produced. Units are F in newtons (N), m in kilograms (kg) and acceleration in m/s^2.

Third Law. To every force there is an equal and opposite force. These forces always act on different objects

Speed. Velocity and Acceleration
Speed is just a value e.g. 20 m/s or 1000 mph. Velocity and Acceleration are vectors. Their direction must be stated as well as their size.