

5. Mass, Weight and Orbits

Mass

This recaps some the ideas in Newton's second Law. What do we mean by "mass". In simple terms it is the amount of "stuff" in an object. We measure it in kilograms (kg). This is not the sort of definition that is very satisfying so let's make it more precise. "Mass is a measure of the inertia of an object". You might say this is passing the buck, as what do we mean by inertia. Here is an example. Two couples are driving along and both break down at the same time occupying much of the road. The cars need to be shifted. Fortunately the road is flat, but one car is a mini and has a mass of about 1000 kg, while the other is larger and has a mass of 2000 kg. They get together and push the mini off the road – an effort but not too bad. The other car is more difficult to get going (and harder to stop when it does). It has more "inertia" – 2000 kg rather than 1000 kg.

A more homely example is provided by toilet rolls. Snatching off a sheet when the roll is full with a larger inertia is easy. Try this when the roll is nearly empty when there is less inertia and you end up with an "Andrex advert" situation with toilet paper all over the floor.

The mass of an object tells you how difficult it is to get it moving. And how difficult it is to stop it when it is moving. The mass of an object does not change wherever you are in the universe. If you take a 10 kg mass to the moon it will certainly be easier to hold it above the ground. But that is holding it still. If you wanted to throw it sideways with a certain speed it would need the same effort to do this on the moon as on the Earth. Its reluctance to get moving, its inertia, is the same.

We have met this before and is summarised in $F = ma$, but we repeat it here because we want to make clear the distinction between mass and weight.

Weight

When you stand on a pair of scales you want to know your "weight". You will get an answer in kg. (I am avoiding old English units like stones and pounds, sorry). So are weight and mass are the same thing? NO. From the point of view of understanding it would be much better if the scales gave an answer in different units. So all this needs some explanation. It is convenient that humans have been to the Moon, as comparing Earth and the Moon helps with the explanation.

Weight is the pull of gravity on a mass. On Earth the pull of gravity on a 1 kg mass is 9.8 newtons. A newton (N) is the standard scientific unit of force used in $F = ma$. For simplicity we can say roughly a 1 kg mass weighs 10 newtons. So on Earth a person of mass 66 kg would weigh 660 N. The person would weigh 660 N in Paris, or in China, or in Australia. So for most purposes we don't need to bother with the distinction between mass and weight and just say the person weighs 66 kg. Bad scientifically, but there it is. If you want to understand what comes next you need to stick to the idea that mass measures inertia. Weight measures the pull of gravity on a mass. *Totally different.*

Now this same person happens to be an astronaut and goes to the Moon with the same pair of bathroom scales. When they stand on them they would read about 11 kg. Just one sixth of the reading on Earth. So while their mass is the same on the Moon, they have the same amount of stuff in them – they are just as difficult to push around on the flat – their weight is different. The pull of gravity on them is just one sixth. The scales should, therefore, be set in newtons. Then on the Earth they would say 660 N and on the moon 110 N. If you want the scales to tell you 'mass' then the scales need changing to match the pull of gravity - different scales for different places in the universe.

How far does Gravity extend.

Many people will say “up to the end of atmosphere”. The last chapter gives the rule between objects attracting under gravity. In Newton’s equation:

$$F = G \frac{m_1 m_2}{r^2}$$

If you make r twice as big r^2 gets four times bigger. If you make r three times bigger r^2 gets nine times bigger (3×3). Make r four times bigger and r^2 gets sixteen times bigger. But to get the force you have to divide by r^2 . So the force is a quarter when r is doubled, it is a ninth when r is 3 times bigger, it is one sixteenth when r is 4 times bigger and so on. So the force of gravity goes on for ever but getting rapidly weaker. It obeys an *inverse square law*.

Distances are measured between centres of objects. So just above the atmosphere the distance from the centre of the Earth is not that much different from at the surface. Gravity is only slightly weaker. So why do people think gravity stops at the end of the atmosphere?

It seems that this idea comes about because astronauts orbiting the Earth beyond the atmosphere seem weightless. But if that were the case then the Earth’s gravity would not extend to the Moon and the Moon would fly off into deepest space. So here we are back to the essay on circular motion. It is the pull of gravity towards the centre of the Earth that provides the force keeping the satellites like the ISS in orbit.

So how do we explain that astronauts in the International Space Station (ISS) seem weightless. You could reasonably comment that I have just said weight is the pull of gravity, so no weight means no gravity. Clearly some explanation is needed and it is based around the fact that they are NOT weightless, but just appear so. Here is another way of looking at it.

Imagine what happens in circumstances that are a bit far-fetched. (Although we shall see later that it is not so far-fetched.) Someone at the top of a tall tower has a canon that can fire a ball horizontally. Fig 5.1 shows the path of the ball fired at a slow medium and fast speed.

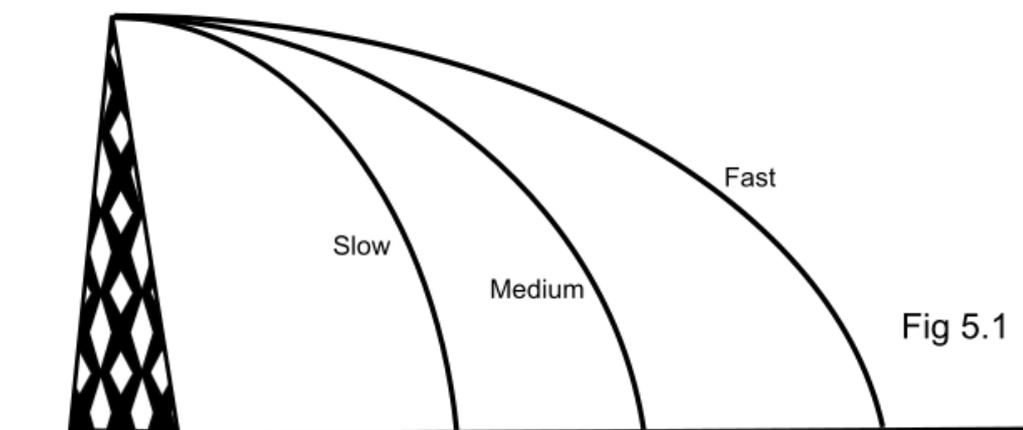
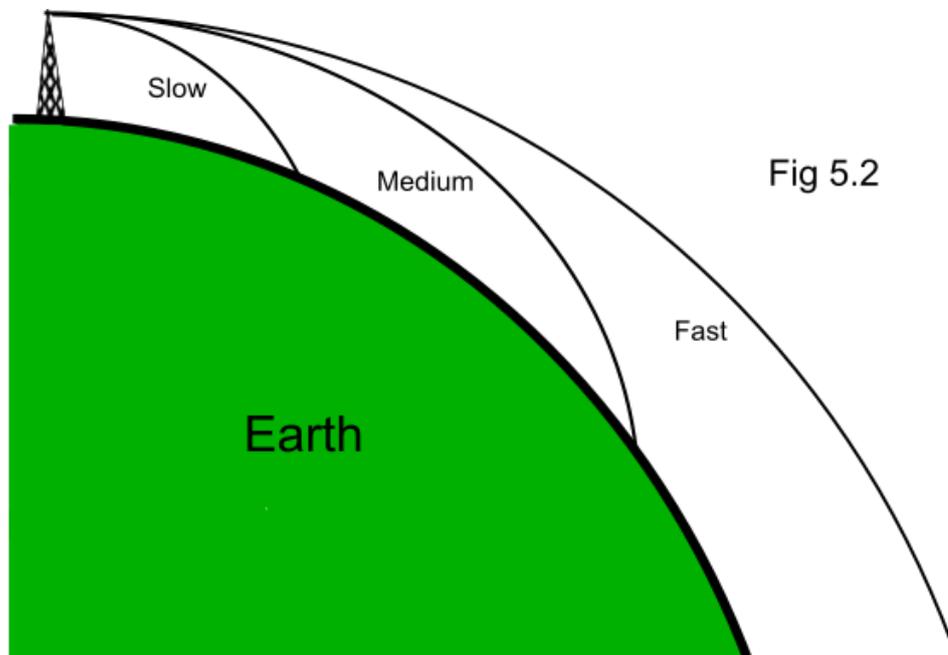


Fig 5.1

Now suppose we make the tower taller and zoom out to the point where we notice that the Earth is not flat but a sphere. Here are the pictures again.



In the fast case, the speed is such that as the ball falls down in a curve, the curvature of the Earth also becomes important. At a certain speed the Earth curves away at just the same rate as the ball curves downwards as in Fig 5.2. We have launched a satellite into orbit! The ball still has weight, but the weight is all “used up” in keeping the ball falling – the weight is providing the inward acceleration of circular motion. If you like you can think of it as none is left to get it to move closer to the Earth.

*****BOB INTERRUPTS *****

Bob: I don't get it. I am still falling. You say as gravity is still pulling me down, but the ISS astronauts seem weightless. Better put Alice on again – she explains better than you.

Me: Thanks very much! ALICE!

Alice: Hi Bob. What's the problem?

Bob: It's this idea of the Astronauts being weightless in the ISS.

Alice: Have you followed the bit about if you get thrown fast enough horizontally from a great height then as you fall the Earth curves away under you. That way you don't get any nearer the Earth.

Bob: Yes, I think so, but that has to be very fast surely.

Alice: Yes it is. To get a satellite into orbit just outside the atmosphere the speed is about 7.8 kilometres per second (17,500 mph or 28,000 km/h) . And the important thing is that it is the same for all satellites, big one or small ones. I think he explains at the end of the essay that all objects fall at the same rate no matter how much mass they have – you do have to get rid of air resistance though.

Bob: Why is this last bit important?

Alice: Well the ISS itself is an object like any other. So in orbit it is falling at the same rate as all the bits inside it, including the astronauts. It would be like being in a tall lift where the cable is (hopefully temporarily) released. You and your shopping would seem weightless and all fall together. So there is nothing holding them to anything that could be called "ground". Astronauts appear weightless – their weight is being "used up" (unscientific) in keeping them in orbit, constantly falling towards an Earth which is constantly curving away at the same rate. A case of acceleration with constant speed that we have met before.

Bob: Ok, I'm happy now.

In fact gravity extends out forever, but it gets gradually weaker and weaker. Here are some of the things that gravity does:

- Gravity keeps our feet on the ground and everything else on Earth
- Gravity keeps the moon in orbit
- The effect of the pull of gravity from the Moon causes the tides
- The gravity between the Sun and each of the planets (including Earth) keeps them in orbit around the Sun
- The rings of Saturn are caused by a combination of Saturn's gravity and objects orbiting close to Saturn which causes the objects to break up into small lumps comprising the rings
- Gravity keeps all the artificial satellites orbiting the Earth including those that enable GPS.

Why Objects fall at the same rate

At the time of Galileo there was a dispute between those who thought all objects fall at the same rate and those who thought heavier objects fall faster. There is a story – probably apocryphal - that to solve this dispute Galileo dropped a heavy and light object from the top of the leaning tower of Pisa to show that they hit the ground at the same time. Simple experience, such as watching a feather falling, seems to support the view that heavy objects fall faster. This, however, ignores the effect of air resistance. In school science labs students these days will watch a demonstration with a coin and a feather both in a tall wide glass tube. When the tube is inverted the coin falls faster than the feather. The air is then removed from the tube with a vacuum pump. Now when the tube is inverted the feather and coin fall at the same rate. The feather is much more affected by air resistance and when this is removed the coin and the feather fall together.

So, irrespective of the weight, any object will fall to the ground at the same rate as any other object - when air resistance is small. There is a YouTube video of the astronaut David Scott showing this on the Moon by dropping a hammer and a feather. The moon has no atmosphere so the hammer and the feather hit the ground at the same time. The objects both fall slower than on the Earth as the Moon exerts a smaller gravitational force.

The explanation is not difficult. Think about a 1 kg mass and a 2 kg mass. The force of gravity on the 2 kg mass is double that on the 1 kg mass. But mass measures inertia. The 2 kg mass is twice as difficult to "get going". These two effects cancel, twice the force but twice the inertia, so the objects fall at the same rate.

Summary

Gravity is a force of attraction between any two objects.

The force depends on the masses of the objects.

Gravity gets gradually weaker the further the objects are apart.

Mass is the amount of stuff in an object and is a measure of its Inertia – how hard it is to get it going or to stop it.

Weight is the pull of gravity on an object it should be measured in newtons. We get away with using kg for weight as the pull of gravity is pretty much the same all over the Earth

Astronauts appear weightless, but their weight is just keeping them in orbit and all objects around them are falling at the same rate. The force of gravity is providing the force towards the centre needed for circular motion.

If air resistance is negligible all objects fall at the same rate. (This rate is different on the Earth and Moon or other places where the gravitational pull is different – like another planet).