PHYSICS

Bridging Work

The purpose of this bridging work is twofold:

- It will allow your two class teachers to get to understand you as a student and give us an idea of the support and structure you will need as an individual to progress and succeed right from the start of the course.
- It introduces the key ideas of A-Level Physics. The reading will primarily start with a core concept from your previous learning and push it beyond the level of GCSE study, as well as give you an idea on how to investigate the concepts further if this is an area of interest for you.

The attached article is about Mass. Read the article thoroughly. I suggest taking notes to organise your thoughts before attempting the questions. A recommended method of note taking which has been successful for many of our A-Level students is the Cornell Method (link).

When you are prepared, answer the questions in the Form (link). We expect answers in full sentences in clear English. Bullet points are a good way of breaking up your key points and have no issue with you using them, if the points are in full sentences.

Further Preparation

If you are looking to make a head start and prepare yourself for the course, here are a few ideas for how you could spend your time.

Books to read:

- Why does $E= mc^2$? , Brian Cox and Jeff Forshaw
- Six Easy Pieces , Richard Feynman
- The Big Bang , Simon Singh
- Galileo's Finger , Peter Atkins
- The Universe: A Biography , John Gribbin
- A Brief History of Time , Stephen Hawking

Documentaries:

- Cosmos, Neil DeGrasse Tyson (Disney+)
- Shock and Awe, Jim Al-Khalili
- Forces of Nature, Brian Cox
- Particle Fever

The Mysteries of Mass

Thinking about mass

If you kick it, it hurts your foot. The more there is of it the harder it is to get it moving. It was Sir Isaac Newton who first put into a logical and clear form these vague ideas about what everything seems to be made of. At least, everything that is anything: stones, people, water, the Moon and the Earth, and so on. When he did this, sometime in the late seventeenth century, he couldn't do it by giving a simple independent definition of what he was talking about. He named the 'stuff' of the Universe mass. He could only define it in terms of what it did. It did two things, one of which is where this paragraph starts. Mass has the property that it will not change how it is moving (or not) unless pushed. To be as precise as Newton, the mass we are talking about is what you get when you divide a force by the acceleration it produces. So, we can't really understand what mass 'is' unless we also understand what a force is and what acceleration is. We can then tell how much mass an object has by working it out from the equation ***m* = *F* / *a***.

We'll come to the second property that mass has later.

Don't push me around

This first property of mass, a kind of unwillingness to be pushed around, is called inertia. So if you read about inertial mass it isn't a special new kind of mass, it's just the ordinary kind, but the writer wants you think about the unwillingness-to-change-movement aspect of it.

This may all seem very reasonable, but think about it. How do you know how much force there is, say, acting on an object? Well, you measure the acceleration and multiply it by the mass, obviously. But we don't know what the mass is unless we already know what the force is (see the end of the first paragraph). We seem to be going round in circles here. The only way we can break out of the circle is to get a lump of something and say 'This is what I mean by mass. Here is 1 kilogram of it. Hang on to it for dear life'. So there exists a lump of platinum–indium alloy, carefully isolated from the common herd in an air-conditioned cellar in Sèvres, France. This is the actual and only basic international standard of mass.

Newton was aware of the problem, and called mass simply 'quantity of matter'. But what is matter? We now know, as Newton didn't, that matter is made up of atoms, which in turn are made up of a small number of elementary particles: electrons and quarks are enough to make everyday materials. The simplest substance, hydrogen, has a nucleus (with three quarks) and a single electron. One way of defining mass would be to say that this atom represents one unit, two represents two units and so on. The mass of a bag of sugar would be represented by an astronomical number, of course, so it isn't a very practical unit. But we could call a number of hydrogen atoms, say for the sake of argument 6.0×10^{26}, a kilogram, and the everyday world wouldn't be any the wiser, or sorrier.

An appeal to gravity

But we still don't know what mass actually is. Why should a hydrogen atom – or anything else – have this unwillingness to change how it moves? Perhaps the other property of mass will give us a clue. This property was also identified by Newton. He realised that the Moon went around the Earth because the two bodies attracted each other with a force he named as gravity. He used this idea, and the inertia property, to calculate with good accuracy how long the Moon should take in travelling around its orbit. He used the idea that the force between the two masses depended on how far apart they were – and how much mass each had. This seemed to be the same kind of 'mass' as the inertial kind. He could cancel the mass out in his calculations and still get the right answers. But gravitational mass is linked to force by a different relationship than inertial mass is. The gravitational relationship is

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

Here *M* and *m* are the two masses (each with its own inertia), *r* is the distance between them and *G* is a constant needed to get all the numbers to work out right. This relationship defines gravitational mass: the property of mass that allows it to attract another mass across empty space (and non-empty space, come to think of it – you can't escape from gravity).

Maths will keep creeping in to physics, often making things simpler – but often also hiding the genuine underlying mystery of it all. Now for Newton the really big mystery was how a force from the Earth could actually get to the Moon. There was nothing to carry it. 'I just give up' he said (in Latin 'Hypothese non fingo'). But he decided to accept it – that is just how things actually were.

Are the two 'kinds' of mass really the same?

But are inertial mass and gravitational mass 'the same'? Inertia and gravity are such different things that on the face of it, it would seem to be very unlikely if they were. But physicists have checked and rechecked the idea that inertial mass and gravitational mass can be described by the same numbers. The question is 'Is a kilogram of inertial mass the same as a kilogram of gravitational mass?'. The answer is 'yes', to as high an accuracy as we can measure anything. Could this be a coincidence, or is it a sign that there is something deeper underlying all this?

Well, thank you, Sir Isaac. Now let's give a warm welcome to Albert!

Albert Einstein came to thinking about gravity via a deep study of time and space. He got to thinking about time and space because he thought that there was something odd about physicists' ideas about light. So, what has light got to do with space and time? That's another story, but we can remind ourselves that nowadays distance (as measured by surveyors planning roads and railways) is defined in terms of how long light takes to travel the distance being measured. There used to be a standard distance (another expensive bit of platinum in the Sèvres cellar, next to the standard kilogram), but that has become an obsolete museum exhibit. To cut a rather a long story short, Einstein has managed to convince physicists that mass has a deeper and more fundamental property: it curves space–time. The Moon doesn't move in a circle through space. It moves in a straight line through space–time. But the space–time is curved. Its orbit is a kind of optical illusion because we humans haven't evolved a sense of seeing space–time as it really is. Which may be just as well for ordinary existence. In Einstein's theory, called General Relativity, he showed that there was no way to tell the difference between an acceleration and a uniform gravitational field. This had to mean that inertial mass and gravitational mass were indistinguishable – and so identical.

Einstein's work also revealed something else. He showed that there is a deep connection between energy and mass. In General Relativity, it is energy that gravitates, and has inertia. What we call mass is just a part of the total energy - a part we usually forget about, despite its being enormous. The mass of an object can be understood as just the so-called 'rest energy' - the energy the object has when not travelling past us.

Now we get somewhere on what mass 'really is'. The mass of an object is just the energy $\mathbf{E_{rest} = mc^2}$ it has when it is not moving past us: $\mathbf{m = E_{rest} / c^2}$. Does it help? Now the problem is what energy 'really is'. But at least two difficult questions have become one difficult question.

And we get something new; travelling at high speed past us the energy of an object starts to have noticeable inertia of its own. That is the reason why things can't go past us faster than light.

Gravitons

If you have read this far you should have realised that the property of matter we call mass is not at all a simple thing to understand. And this is where it gets even worse. Again.

The small particles that everyday matter is made of, electrons and quarks, not to mention the fairly rare particles like mesons and muons, behave and interact in very strange ways that Newton – or even Einstein – never dreamt of. Particles of matter like this are held together or pushed apart by forces and can be accelerated and slowed down like cars and aeroplanes. But on their tiny scale the modern theory is that the forces are carried by special force-carrying particles. The particles are called bosons, and the most well-known of these is called a photon. This particle is not just 'a little bit of light', but also carries the electromagnetic force between the particles. For example, electrons repel each other because they swap photons, which transfer momentum between the particles. Or in simple language, they give each other a rapid succession of little pushes. Protons also repel each other like this. These force-carrying swapped particles exist for a short time only. They only exist at all because, for a very short time, they are allowed to break the law of conservation of mass–energy. They aren't real particles in the ordinary sense and so are called virtual particles.

But is this how gravity works? If this model applies to gravitational forces, then we have to have a boson that carries the force. This is called a graviton. But the graviton has yet to be discovered. If it exists it would overcome Newton's objection to his own theory – how a force can be carried by empty space.

Higgs enters the field – and brings his own

Forces like electricity and magnetism have fields – regions where the forces exist and work. Think about electricity. Its field is caused by the fact that some particles have electric charge. This charge, amazingly, is the same for every free charged particle in the known universe. Quarks (which are always found trapped inside bigger particles) carry either one-third or two-third size lumps of this charge. So charge is a fundamental property of matter. It comes in two flavours: positive and negative. The only particle of matter that doesn't have a charge of some kind locked in it is the neutrino. This is a genuinely neutral particle. Other neutral particles like neutrons are neutral because the opposite charges carried by the quarks inside them just cancel each other out. They add up to zero.

The theories of fields and particles have become extremely mathematical in the last 40 years, but the mathematics has had the habit of producing equations which contain odd, awkward things which might be interpreted as particles. The earliest particle to be predicted in this way was the positive electron (positron). This happened in the early 1930s. The advanced theory – and the double-particle system – was needed to explain the very existence of these kind of particles and fields.

In the 1960s an even more advanced theory about fields and particles emerged. This was the Higgs field – and its particle the Higgs boson. Peter Higgs is a British physicist, educated in Birmingham and Bristol, formerly Professor of Theoretical Physics at Edinburgh University. But the Higgs field and boson were not about matter and its ability to have electric charge, but about matter and its ability to have mass. At last we are getting to a theory that might explain why matter has this mysterious but rather useful property.

There's not as much matter in mass as you might think

Now one of the basic objects that make up the universe, the quark, seems to have very little inertial mass. The three quarks that make up a proton, for example, are measured to have masses that add up to just a few per cent of the total mass of the proton. The rest of the mass is due to the internal energy of the proton – remember the Einstein equation: $\mathbf{m = E / c^2}$. The quarks are held by very strong fields (potential energy) and move around a lot (kinetic energy) and keep exchanging virtual particles (which have mass as long as they last). And it gets worse. The quantum theory of particles is one of the most successful physical theories of all time. It makes predictions to an extremely high degree of accuracy, for example. The most modern theory (well – so far) only works if electrons and quarks have zero mass.

As long ago as 1966 Peter Higgs thought of a way to get around this rather serious contradiction that mass does actually exist (try kicking a 10 kilogram lump of iron) with this splendid theory that it can't. The Higgs idea is like this: a truly massless particle such as a photon has to travel at the speed of light. A particle with mass can't ever travel at this speed. But what if all of space is filled with a 'something' that can grab hold of some particles and slow them down? This space-filling something would be a field (like the gravitational or electrical fields). It would grab hold of the particles with its force carrier and have the effect of slowing them down to sub-light speeds. The field is now called the Higgs field and the grabber particle is the Higgs boson. This means that the 'really' massless particles like electrons and quarks have an 'effective mass'. They have different effective masses insofar as they interact differently with the Higgs field.

As we said earlier, these force-carrier particles only exist for extremely short times. The only reason that they can exist at all is due to the indeterminacy principle which says that the universe doesn't mind if something impossible happens or exists just as long as the product of energy and time involved is less than a certain value (6.6×10^{-34} joule seconds). But as long as they obey this rule we can have as many of these particles as we like. If, however, we want to 'see' them they have to last long enough for our instruments to detect them. This means providing a lot of energy in the right place at the right time. This is what the big particle accelerators at places like CERN are for. The new collider at CERN – the LHC or Large Hadron Collider – should be able to provide enough energy for the Higgs boson to be observed. If it exists.

More to read

Bowdery C 1996 The origin of mass Physics Education 31 237–41. This is a good easy-to-read introduction to modern theories about mass.

Davies P and Gribbin J 1991 The Matter Myth: Towards 21st Century Science (Viking Penguin). A readable summary of modern physics: goes from the death of materialism via quantum physics, the origin of the universe and a little string theory to what is life?

Greene B 1999 The Elegant Universe (Jonathan Cape). All you want to know about practically everything; deals with string theory, which has been ignored in this reading. Take a week off to read the book and find out why.