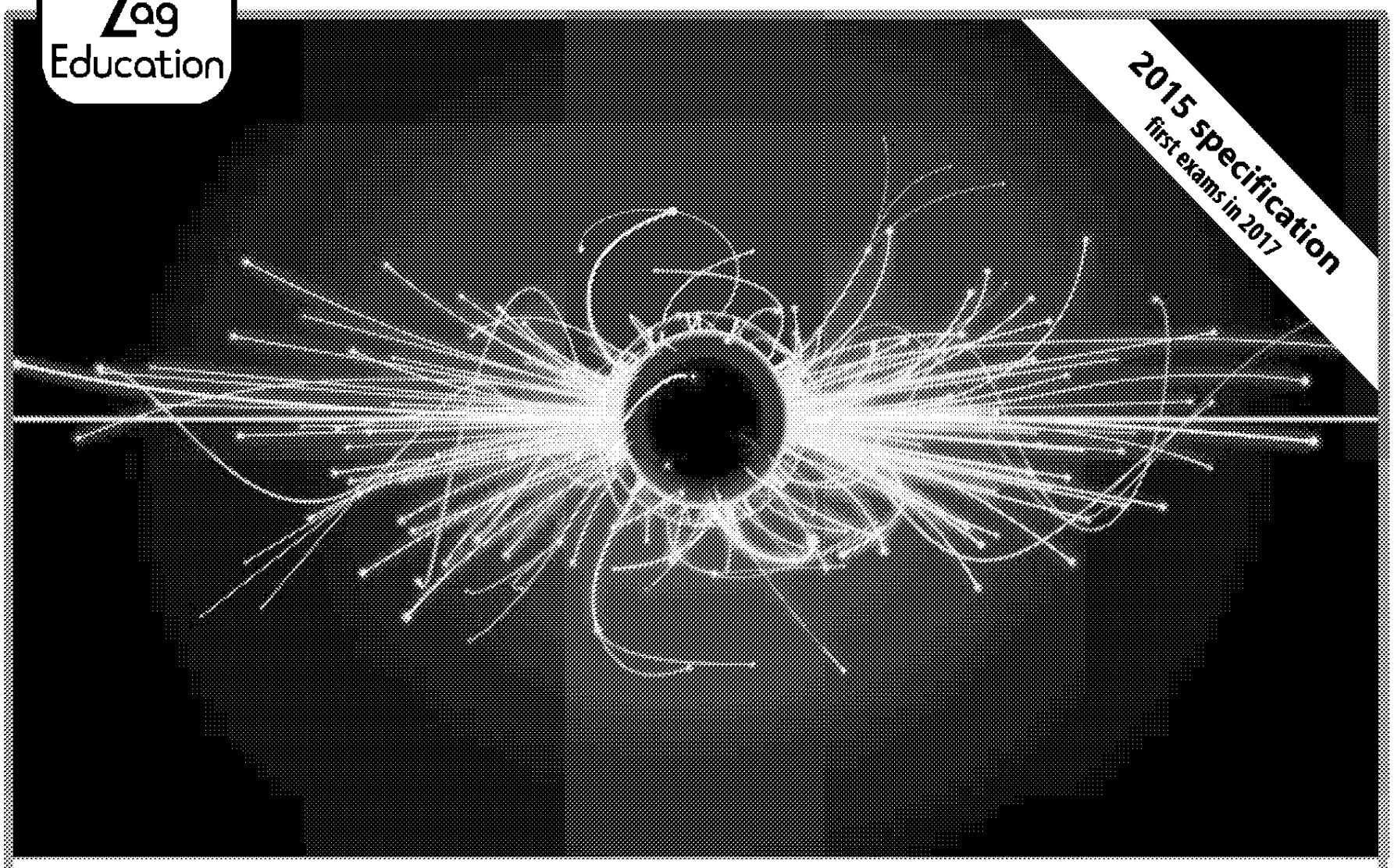
Zig Zag Education

Physics

A Level | AQA | 7408



Stretch and Challenge Articles

for A Level AQA Physics

Year 1 (Topics 1–5)

zigzageducation.co.uk

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Contents

Teacher's Introduction

These 'Stretch and Challenge' articles are designed to provide stimulation and new challenges for Physics AQA A Level students.

The pack contains 16 articles that cover areas of topical interest to physicists. The articles reach beyond the frontiers of the specification, although there are links to the AQA Physics A Level Year 1 content.

The aim of the resource is to challenge the most capable and engaged physics students. However, it should also be accessible to students of a range of ability levels as the articles add to the specification knowledge. However, the aim of the resource is to be challenging.

For each article, a mix of the following activities is included:

- comprehension questions to ensure understanding of the material and link ideas in the articles to core concepts in physics
- discussion questions to encourage debate on topical issues and wider scientific and ethical questions
- extension tasks that encourage students to conduct further research and support them to structure a written piece

Each article has a link to the specification, but also goes beyond the specification, including recent discoveries, case studies and applications of theories to the wider natural world.

Each article is between 1,000 and 2,000 words, and is expected to take a student approximately 30 minutes to read. The discussion questions can be whole-class activities, guided by the teacher, or small-group activities to encourage less-confident students to take part. The extension activities take a range of forms (individual and pair work), while the comprehension questions should be attempted individually.

All resources can be photocopied in black and white. We hope you enjoy reading and using these resources.

June 2019

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When Particles Collide

3.2.1 Particles

Particle accelerators are used to probe the nature of the universe: to [illegible] and the art and other objects; to carry out research into (and are used in [illegible] medical treatment) food products before being sold. But how do they work?

Keywords

Charge	The intrinsic property of a particle that causes the particle to interact
Hadron	A type of subatomic particle that interacts with the strong force
[illegible]	[illegible] similar to an electron but with a much greater mass

Constructing a particle accelerator

Like any object, a particle will accelerate if a resultant force acts upon the particle. This is just Newton's second law. But the kinds of particle that particle accelerators deal with are subatomic, so are too small to simply give them a shove. Instead, these particles are accelerated using the force exerted by electric fields. Of course, this means our particle accelerator can only accelerate charged particles, but until we can manipulate gravity it's the best we've got.

LINACs

Consider the simple circuit of a battery connected to two plates, i.e. a capacitor. An electric field will be set up between these plates. A charged particle entering this electric field will, therefore, experience a force given by the equation:

$$F = \frac{qV}{d}$$

A linear accelerator, or LINAC, consists of many of these 'capacitor' set-ups in a row, negative to positive. A particle, like an electron, passes through one capacitor, [illegible]

[illegible] the electron reaches the next gap between capacitors, it's moving from a positive plate to a negative plate – it starts to decelerate. To stop this happening, a LINAC uses an alternating current to reverse the polarity of the charged plates as the electron passes through, so the electron carries on accelerating to the next plate, which is now positive.

To make an electron continually accelerate, the frequency of this polarity switch must [illegible] controlling the frequency manually, the LINAC is built so that the electron has just [illegible] of one section before the polarity switches. This means that each section is longer [illegible] gets faster, it covers more space in less time. This means LINACs are typically very [illegible] higher energies.

LINACs are commonly used in industry and in medicine. There are around 10,000 [illegible] 99 % are used in industry or medicine. LINACs are used because they are relatively [illegible] maintain (compared to particle accelerators used for research). These applications [illegible] energies, so the LINACs aren't as likely to [illegible]

Cyclotrons

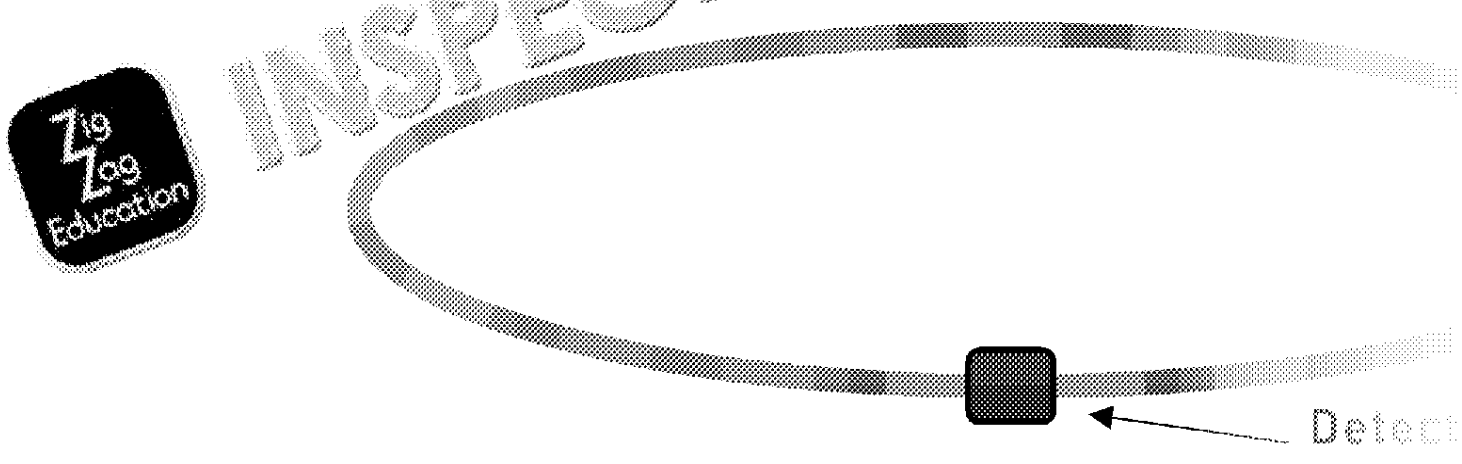
The particle accelerators used in scientific research tend to be circular accelerators. The particle continually accelerates around the ring, reaching much higher energies before colliding with its target.

The cyclotron was the first type of circular particle accelerator developed. A charged particle moving in the presence of a magnetic field will experience a force. This force will act perpendicular to the motion of the charged particle (from Fleming's left-hand rule), causing a centripetal force, turning the direction of motion of the particle. By cleverly positioning where the charged particle is in a magnetic field, the particle can be kept travelling in a circular path, continually accelerating due to an external electric field, in the same way as a LINAC.

However, these cyclotrons do have a limit. As the particle reaches relativistic speeds, its mass increases, causing its radius of circular motion to increase. Eventually, the particle collides with the cyclotron. Therefore, cyclotrons can only accelerate protons to around 15 MeV, or 10 % of the speed of light.

An approach to solve this problem is to increase the strength of the magnetic field as the particle moves around the cyclotron. Therefore, as the relativistic mass of the particle increases, the particle moves further around the cyclotron, experiencing a stronger magnetic field and, therefore, a stronger centripetal force, curving towards its original circular path. This cyclotron is called an isochronous cyclotron.

The energies reached by particle accelerators can be further increased by instead using magnetic fields present only over the path of the particles, and not over an entire region. This means that it is the path of the particles rather than the strength of the overseeing magnetic field, that keeps the particles in a circular path. The radius of the particles can be made to be much larger, as less equipment is needed to guide the particles. These accelerators are called synchrotrons. The smallest synchrotron ever built had a diameter of 1 km, whereas the largest synchrotron ever built, the Large Hadron Collider, has a diameter of 10 km.



These synchrotrons tend to come in groups, each a different size. A LINAC will first accelerate particles into the smallest synchrotron. The speed of the particles increases until the synchrotron can no longer accelerate them. They are then fed into the next largest synchrotron to continue accelerating. The Large Hadron Collider is the last ring in this chain, where particles are accelerated to energies of 6.5 TeV.

The particles collide with other particles, resulting in a particle interaction of huge energy. These usually occur in high-energy cosmic rays, and can also be present shortly after the Big Bang. Collisions that occur in the detectors release a large number of particles that undergo decay in fractions of a second.

Particle physicists use the tracks left in the detectors to piece together what happened in the collision, like a jigsaw. From this mass of different particles and their kinetic energies, the particle physicists can work out which particles were initially created after the collision. This is how the Higgs boson was discovered. The Higgs boson's lifetime before decaying is estimated to be $\sim 10^{-22}$ s.

ISIS neutron and muon source

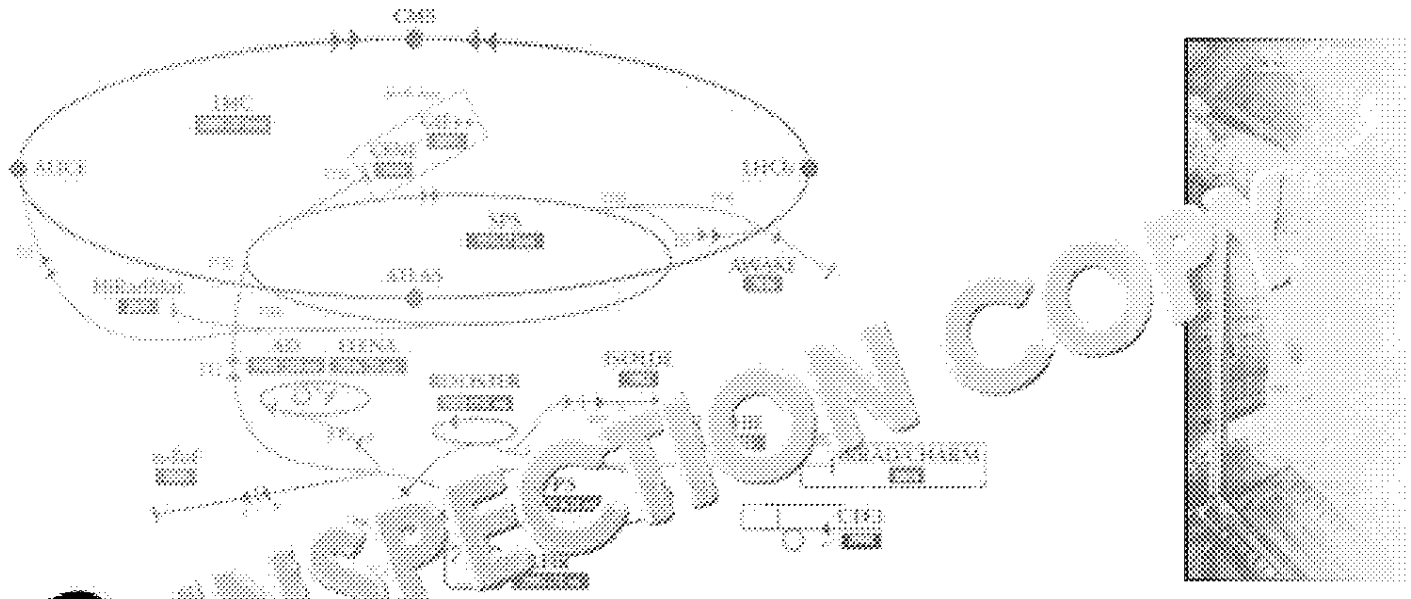
Situated in the Rutherford Appleton Labs in Oxford in the UK, the ISIS Neutron and accelerator that accelerates neutrons and muons to probe the structure of condens

The neutrons are produced by using a standard particle a[illegible]tor to produce high aimed at a tungsten target. The collision of the p[illegible]ns with the tungsten atoms re pass through the sample to be detected. The same proton beam is also used to pro beam at a graphite target. This produces pions which quickly decay into muons.

Over 600 experim[illegible] are conducted at the ISIS Neutron and Muon Source each ye st[illegible] mi[illegible]ic structure of turbine blades and gas pipelines. By analysing th [illegible]ic le[illegible], the design of these objects can be catered to ensure that the risk

Large Hadron Collider

The Large Hadron Collider (LHC) is the largest ring of the particle accelerators at CE Switzerland. CERN is a collaboration between 22 countries and was first built in 19 not the only experiments being performed at CERN, but they are the most famous.



A map of the particle accelerators and their detectors at CERN.

- A proton is first created by stripping the electrons away from hydrogen atoms.
- These protons are injected through LINAC2 and into the PS booster (PSB) at an
- They are accelerated by the booster to 1.4 GeV before being injected into the
- They are further accelerated to 25 GeV before being injected into the super
- The SPS accelerates these protons to 450 GeV before, finally, they are injected
- After 20 minutes inside the LHC, these protons have an energy of 6.5 TeV, read
- The LHC can accelerate heavy nuclei up to lead – this requires much higher en can achieve.

The detectors

The two main detectors situated along the LHC are ATLAS and CMS. These both ex situated deep underground along the partic[illegible]. Having two detectors allows cross-confirmed. The other two d[illegible]ors on the LHC are ALICE and LHCb. The on certain areas of physics to study specific phenomena.

What's the Higgs idea?

One of the LHC's most famous discoveries was that of the Higgs boson and its asso
primary reasons for building such a high-energy particle accelerator.

The Higgs boson has a number of effects in particle physi
- It contributes to the mass of leptons, quarks an th ler ns that mediate the
- It is essential for electroweak symm r orc . The electromagnetic and we
  one force at high enough e gie r energies, these two interactions b
  the Higgs boson. Wi ect weak symmetry breaking, atoms wouldn't be
- The Higgs fie av been responsible for the period of inflation shortly af
  e th gest that a non-zero Higgs field might actually be responsib
  rse a whole, with the universe just being a vacuum fluctuation in the H
  ggs field might be the grand unification of the fundamental forces of the
  important and sought after aspects of particle physics.

This was one of the last missing pieces of the standard model which physicists use t
and if it wasn't found, it would have had profound effects on what we know about t
particles that make up the universe.

Discovering a new particle in a particle accelerator isn't as simple as finding eviden
interaction, though. Scientists at CERN don't declare the discovery of a new partic
points are collected, and the discovery achieves a 5σ value – essentially meaning th
collected that physicists are sure that there's only a probability of 0.00006, or 1 in 1
a fluke.

This might seem extreme, but occasionally news sites wil epo 4 iscoveries (0.0
the 'discovery' to turn out to be a false signal once more data is collected. This is b
happen so quickly that it's difficult to know of anything.

Comprehension questions

1. A proton ($q = 1.60 \times 10^{-19}$C, $m_p = 1.67 \times 10^{-27}$ kg) is accelerated through two p
   mm apart. The potential difference between the plates is 4.5 V. Calculate t
   between the plates.
2. Why are LINACs used in industry and medicine?
3. Explain how a cyclotron causes a charged particle to move in a circular motion
4. Describe the increase in energy of a proton as it's accelerated around the num
   CERN to get it up to 6.5 TeV.

Discussion

The LHC is a collaboration between many nations involving thousands of scientists
Discuss the advantages and disadvantages of performing large-scale experiments in

Extension

The Diamond facility located at the Ruth rf d . n Labs in Oxford is another l
accelerator but has a different pu st fo s Neutron and Muon Source. Rese
write up your findings as t eet.

The origin of antimatter

3.2.1.3: Particles, antiparticles and photons

Keywords

Antiparticle ...ld equal to a particle but with opposite charge

The Big Bang ...the theory that the universe started out as a hot, dense re...

Particle accelerator A device that can accelerate particles to speeds close to th...

...e beginning of the twentieth century physicists began to observe the we... **mechanics**. Quantum mechanics deals with the very smallest scale of matter, where... existence, teleport through solid barriers, and don't even really exist until someone l... of the universe had to be altered to accommodate this new and strange physics.

Around this time, Albert Einstein published his paper on **special relativity**, outlining... universal constant and that space and time vary around this constant for observers i... Einstein's theory of special relativity explained numerous observations and reconcile... different aspects of physics, so it was quickly widely accepted by the scientific comm...

A consequence of Einstein's theory was that energy and mass are closely related, an... – two sides of the same coin. The exact connection is shown in Einstein's famous re...

$$E^2 = m^2 \quad + p^2$$

Which for a stationary object (no momentum) reduces to:

$$E = mc^2$$

Around twenty years later Paul Dirac was working on deriving an equation that mer... relativity. He was successful and published his work with his **Dirac equation**:

$$(\beta mc^2 + c(\sum_{n=1}^{3} \alpha_n p_n))\psi(x,t) = i\hbar \frac{\partial \psi(x,t)}{\partial t}$$

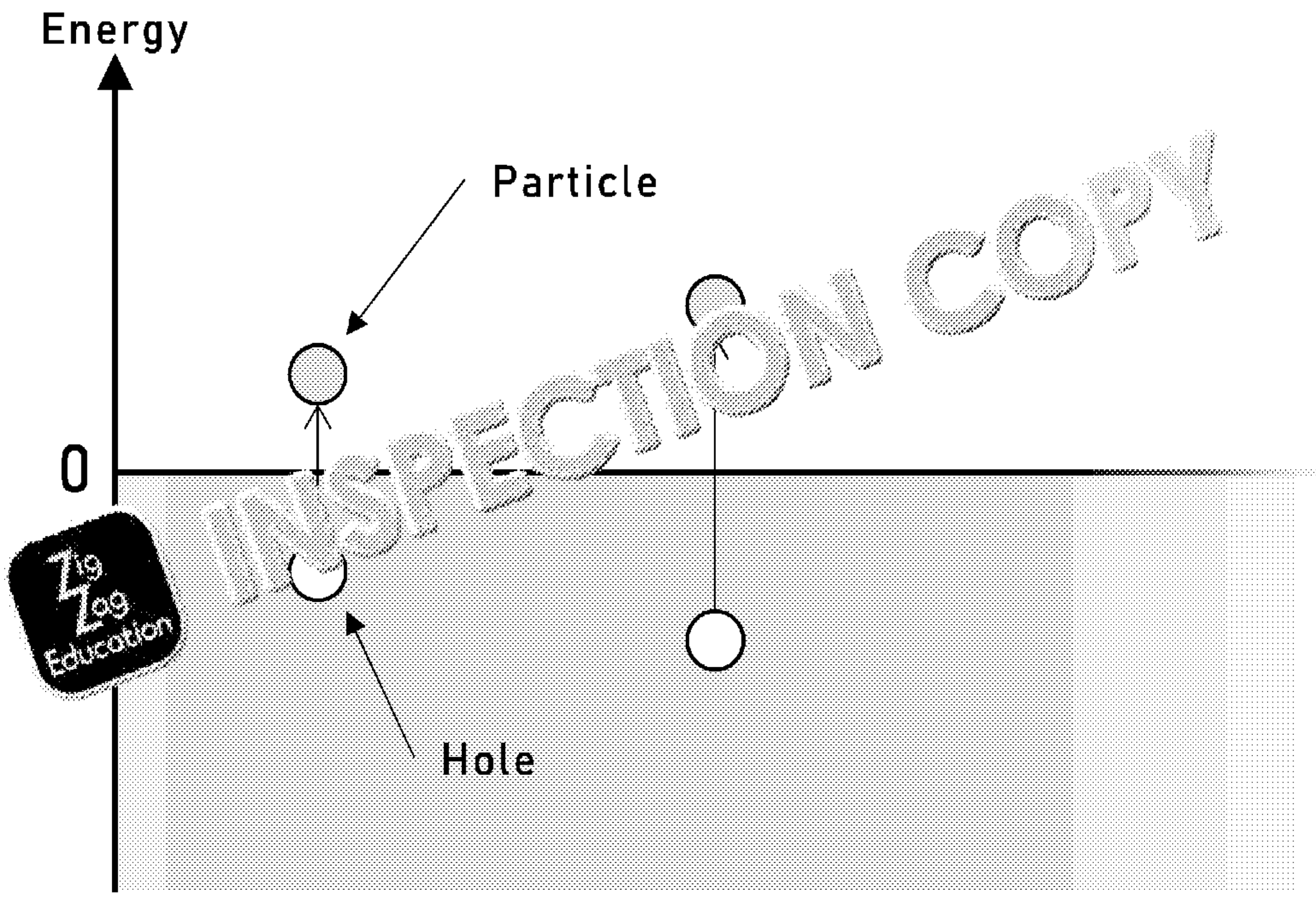
The solutions of this equation to find the energy of a particle don't have a lower bound, and the equation describes particles with negative energy just as well as it describes particles with positive energy.

This is hinted at by taking the square root of the Einstein relation:

$$E = \pm\sqrt{m^2c^4 + p^2c^2}$$

Which (like all square roots) can have a positive and negative solution. Only potential energies can be negative in physics, so this becomes a problem.

To solve the problem Dirac hypothesised **hole theory**. The principle of hole theory states that the vacuum of space is an infinite 'sea' of particles with negative energy. When a particle (which all have positive energy) is cre... a hole in the corresponding negative energy state in the



These holes have the same magnitude of energy (and, therefore, the same mass via $E = mc^2$) as their counterparts.

Say the particle created is an electron; the corresponding hole has the same mass as an electron, and therefore acts like a particle with the mass of an electron. However, its other intrinsic properties, such as charge and quantum numbers like spin are opposite to an electron. This means that particles can be created without violating conservation of properties like charge or lepton number.

In 1932, this theoretical antielectron was discovered, proving Dirac's theory to be correct. The antielectron is known as a **positron** and was the first antiparticle to be experimentally discovered. Since then it's been proven that all particles – protons, neutrons and even the weird ones like pions and kaons – have antiparticle equivalents.

Antiparticles are formed in a process called **pair production** – if a photon has energy equal to or greater than the mass of two particles (by $E = mc^2$), it can spontaneously turn into a particle-antiparticle pair, with any leftover energy being carried away by the particle and antiparticle.

The opposite of pair production can also occur. If an antiparticle was to collide with its particle counterpart, the two would **annihilate**, releasing energy in the form of two gamma photons. The energy of the photons would equal the energy equivalent of the total mass of the particles and their kinetic energy.

The majority of mass in the universe is normal matter; therefore, any antimatter that is created has a high chance of finding its normal matter counterpart and annihilating, resulting in a very short lifetime.

Where is the antimatter?

Laws of symmetry in physics arise quite frequently. Symmetry in physics is the idea of particles fitting neat hierarchies – if one particle has an antiparticle, all other particles must as well.

Symmetry can be used to predict undiscovered particles, such as the third generation of quarks, the top and bottom quarks, hypothesised to solve symmetry breaking observations of colliders, and to match up with the three generations of leptons (electron, muon and tau).

Symmetry would suggest that there should be an equal number of matter and antimatter particles in the universe. This is also suggested by pair-production – antiparticles are always created with their particle equivalent. But the vast majority of the matter we observe is ordinary matter, with antimatter only being formed in high-energy particle interactions in particle accelerators and cosmic rays. So where is all the antimatter?

It's suggested that shortly after the Big Bang, the amounts of matter and antimatter weren't quite equal, there was a slight imbalance. This imbalance breaks charge symmetry (given the letter C), which states that each particle has an equal but opposite charge counterpart, i.e. an antiparticle. Whether charge symmetry breaking exists is a current hot topic in scientific research.

There are a few theories about why there might be so much more matter than antimatter, with the leading theories being:

- The Big Bang initially created unequal amounts of matter and antimatter, with all the antimatter created quickly annihilating with matter, and the left over small imbalance is the matter we see today.
- Some particle decays don't exactly favour the production of matter over antimatter. This is to do with how the particles' charge (C) and spin (P) interact, called **CP conjugation**. If even a small number of particle interactions produce matter without producing antimatter, the amount of matter in the universe would increase over time. Most of this imbalance would have been created in the high energies of the Big Bang, giving a potential cause for the initial imbalance of matter and antimatter in the universe.
- Matter and antimatter may have been created in equal amounts, but kept localised and separated from each other, so they couldn't annihilate. This could mean that somewhere out there are entire galaxies made from antimatter. Just think what would happen if two galaxies annihilated with each other!

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Important experiments

The Bevatron

The Bevatron was a particle accelerator situated at the Lawrence Berkeley National L
operating in 1954, and after a year of operation the antiproton was discovered. It h
but had negative charge. Then a year later, another team at Bevatron discovered th
subatomic particles that make up atoms had a new one the antiparticles discovered.
physicists' minds was 'Is it possible to create an entire atom?'

CERN

CERN is another particle accelerator that began operating in 1959. Unlike the Bevatron, which closed down in 1993, CERN is still active with many experiments currently in operation. It's situated in Geneva and stretches across the border between Switzerland and France.

From this point on, CERN became a hub of antimatter research. In 1978 CERN announced they had held several hundred antiprotons circling around their proton synchrotron for over 85 hours. Previous experiments had only contained antimatter for several hundred microseconds.

Then in 1981 the first proton-antiproton collision was performed at CERN's super proton synchrotron. Finally in 1995, a team led by Walter Oelert announced they had created atoms of antihydrogen at CERN's Low Energy Antiproton Ring. Only nine atoms were produced over the course of three weeks, and each only existed for 40 ns before annihilating.

One of the big challenges in antimatter science is containing the antimatter without it coming in contact with the abundance of normal matter. The trick is to slow the particles down, reducing the risk of collision with normal matter, and hold the antiparticles in place using magnetic fields. Do this in a near-perfect vacuum and the rate of annihilation is greatly reduced. In June 2011, ALPHA (an experiment at CERN) reported that it had held antimatter atoms for over 16 minutes!

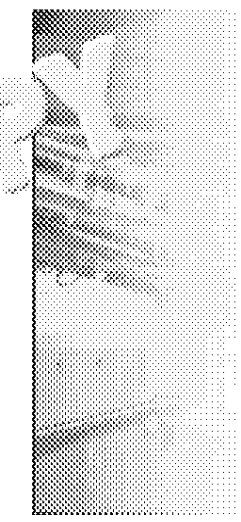
CERN currently has five active antimatter experiments based at its antiproton decelerator (which slows down antiprotons so they can be studied in depth):

- **ATRAP** and **ALPHA** compare and study hydrogen and antihydrogen atoms by slowing down and holding the antihydrogen atoms using electron gases and strong magnetic fields.
- **ASACUSA** studies the detailed structure of electron orbits around the nucleus of antiprotonic helium (an antiproton orbits a helium nucleus with an electron) and antihydrogen and compares this to the normal matter counterparts.
- **AEgIS** measures the Earth's gravitational acceleration on antihydrogen and compares acceleration of antimatter to precision within 1 %.
- **ACE** studies the medical effects of antiprotons, primarily its application as a cancer treatment, destroying cancerous cells, destroying cancerous tumours.

Several experiments have found that antimatter acts the same as ordinary matter (mass, charge and spin) to one part in a billion. This measure of precision means for every billion tests performed, one result (on average) will suggest that matter and antimatter don't act the same. This precision gives us a lot of confidence in our understanding of antimatter, but we still

Did you know?

In 1965 at the proton synchrotron, the first antinucleus was produced antideuterium, one antiproton and one antineutron. At the same time, a team at the Alternating Gradient Synchrotron in New York also observed



ATRAP

ASACUSA

Applications of antimatter

Positron emission tomography (PET)

A positron-emitting radioactive tracer is injected into the body. Like other radioacti
to be imaged. The positrons emitted annihilate with electrons in surrounding atoms,
two gamma photons. Because the positrons and electrons are moving relatively slo
are produced at 180° from each other. Detectors placed around the body will detect
their origin. A computer can then build a 3D image of the body from these detected

Antimatter engines

Although still in the realm of science fiction, antimatter could be used to fuel spacec
and all the mass is entirely converted into energy during annihilation. This m
of energy gives a higher energy per unit mass than chemical, fission or fus
engines to direct the gamma photons released to result in some sort of thrust.

The Federation in Star Trek uses antimatter to provide most of its energy, and Trisol
Problem collect antimatter from the space they travel through to power their engine

Weapons

A weapon that combines antimatter with matter on detonation would also release h
1 kg of antimatter annihilating with 1 kg of matter would produce 1.8×10^{17} J, only
bomba, the largest thermonuclear weapon ever detonated. Luckily, it's very expens
fact, it's the most expensive material in the world, at an estimated $25 billion to pro
therefore wouldn't be feasible to use in weapons or as fuel in the near future.

Comprehension questions

1. Describe how Einstein's relation allows for positive and negative energies for p
2. What is meant by annihilation?
3. What is one of the challenges in antimatter research?
4. Why do measurements from the antimatter experiments at CERN mean we can be
   sure that matter and antimatter act the same (apart from their opposite characteristics)?

Discussion

A team of scientists has invented a way to drastically reduce the cost of producing a
the costs by 99.9 %. Discuss whether this team of scientists should publish their res
precautions should be put in place.

Extension

The imbalance of matter and antimatter in the universe breaks charge symmetry, gi
Research the other types of symmetry and examples of where or when in physics/ch
been broken. Present your findings as a mind map, where each primary branch is a

3.2.1.5 Classification of particles

Keywords	
Cherenkov radiation	Emitted when light tr… fas… t… the propagation … similar to a … oo… …ound waves propagating th…
Standard model	The t…y … …bes three of the four fundamental …
Muon	…ier …sion of an electron

– a…s…ous and elusive fundamental particle. We can't see neutrinos… neutrinos passing through you – in fact, **65 billion** neutrinos pass throug… …ery second.

Neutrinos:

- have masses so low that they can't be measured
- are leptons
- are neutrally charged

Because of these properties, all particle interactions involving neutrinos are mediated by the **weak nuclear force**. This means that neutrinos rarely interact – for an interaction mediated by the weak nuclear force, the two particles have to come within an area of 10^{-42} m^2. Of the hundreds of trillions of neutrinos that pass thro…h your body, only 5000 neutrinos are likely to interact with t…ms that make up your body over your lifetime (abou… a …ee…).

Did yo…
The mass… despite th… passing t… neutrinos… the bodie… lived over…

Seeing the invisi…

If neutrinos int…ely, …ow were they ever even discovered? The first indica… …ly th… …as something we knew we couldn't see.

…us decay, a neutron turns into a proton, giving off an electron and an el…

$n \rightarrow p + e^- + \bar{\nu}_e$

When beta decay was first discovered, the electrons produced were found to have a… made no sense – for energy to be conserved, the kinetic energy of the electron had… binding energy in the nucleus, which would be a fixed amount. A new particle was … would need to have neutral charge and a very low mass, so that it couldn't ionise o… These two properties give the neutrino its name – literally meaning 'the little neutra…

This is how the paths of neutrinos are still calculated to this day, in particle accelera… Collider at CERN – they can't detect the neutrinos produced in an intera…, but by… momenta of the particles they can detect, they can determine t… …ce of neut… clearer picture of the interactions occurring.

Neutrinos can be detected indirectly, ho…e…. …teraction that's a lot like bet… with an electron antineutrino to …du… …on and a positron:

$p + \bar{\nu}_e \rightarrow n + e^+$

…t de…c…or neutrinos, this interaction occurred in a solution of cadmium… …o with an energy greater than 108 MeV would interact with the hydroge… p…to a neutron. This neutron wouldn't be bound to the water in any way, so… solution, until it was absorbed by a cadmium nucleus, which would then release an… ray would then be easily detected by scintillators around the solution.

Other detectors, such as the Super-Kamiokande detector in Japan, detect neutrinos. When a high-energy neutrino interacts with a hydrogen electron or nucleus in water positron which moves faster than the speed of light in water. This produces Cherenkov is produced when a particle moves through a medium faster than light can move th similar principle to a sonic boom, but with light instead of sound. Light can then around the outside of the detector.

Neutrinos interact with matter so rarely that neutrino detectors need to be enormous detecting a neutrino. This often takes the form of a giant tank of water or another has a height and diameter and holds 50,000 tons of water. Even so, detecti

The interaction of neutrino reactors are so rare that the noise from other types of ear ors are looking for. Because of this, neutrino reactors must be very unused mines, and others are deep beneath the ice in the Arctic. For the the detector need to be ultrapure, as any impurities could produce an unwa detection of a neutrino.

The Sun'll go out, tomorrow

Once neutrino detectors became sensitive enough, they were a useful asset to invest

In the centre of the Sun, protons fuse to form helium, giving out positrons, neutrino gamma photons almost immediately interact with another particle in the dense con promptly interact with another particle. The gamma photons bounce between part over 100,000 years for a photon produced in the core of the Sun to reach the surfac

Neutrinos, however, have no such problem with leaving the Sun. Neutrinos are pro pass straight through the Sun, and stream to Earth. Thus, neutrinos can give i interior than photons.

When the number of electron neutrinos from the Sun was measured in the 1960s, there were theories predicting that only a third of the predicted number of neutrinos were

Theories were put forward to try to explain the discrepancy. Could the standa interactions that produce the neutrinos, be wrong? Could it be that the predicted p the Sun's core had been miscalculated? Some people even put forward the idea tha Sun were changing, with solar neutrinos being the first indication, and the effect co effects, effectively turning off the Sun.

All of these theories had their own problems – if the standard model was incorrect, physics on its head, but have knock-on effects on the particle interactions observed with the standard model. **Helioseismology**, using waves in the Sun's corona to det confirmed the predicted pressures and temperatures at the Sun's core. And the ide science fiction – and there would surely be more signs than just fewer neutrinos.

Instead it was scientists' understanding of neutrinos themselves that was faulty. All fusion in the Sun are **electron neutrinos**, but two other types of neutrino exist – mu **neutrinos**. These neutrinos are heavier than the electron neutrino (although their m to be measured!) and are produced in particle interactions involving muons and tau

The neutrino detectors could then detect electron neutrinos – this should be fine, as neutrino produced in the Sun. However, what wasn't expected is that neutrinos can three types, and that they have enough energy to make up the mass deficit. This co ce as $E = mc^2$; because mass and energy are equivalent, neutrinos can be becoming higher or lower mass flavours of neutrinos.

So electron neutrinos are produced in the Sun but due to their high energy can chan neutrinos, as long as their energy at least meets the higher mass neutrinos' rest ene

change back to electron neutrinos, or the other type. By the time the neutrinos reac would be roughly evenly mixed.

This oscillation between types of neutrino actually proved that neutrinos have mass measured, so it was previously unknown whether they even had any mass, but different types of neutrinos, they must have mass.

	Lowest mass	
Charged leptons	Electron (e)	Muon (μ)
Neutrinos	Electron neutrino (ν_e)	Muon neutrino (ν_μ)

Confirming that neutrinos have mass also confirmed that neutrinos travelled speed of light in a vacuum, c, as only massless particles (like photons) can tr light.

In 2011, an experiment in Switzerland and Italy found something shocking. T measured neutrinos travelling faster than light! This contradicts all known ph scientists worked for months trying to determine what was happening.

In the end though, it turns out a loose fibre-optic cable was at fault, making neutrino source and detector out by a few nanoseconds from each other – w moving this fast, that's enough to make a big difference!

Majorana's mask

Neutrinos are so difficult to detect that there's still a lot we don't know about them still don't know what their antiparticles are. Neutrinos may be Majora the same properties as their antiparticles.

P being their own antiparticles isn't unheard of – gluons, which mediate the boson might both be Majorana particles. What makes neutrinos so interesting is th particle interactions.

When a neutron decays into a proton via beta decay it gives off an electron and an antineutrinos were identical, this would mean that lepton number would not be con

If neutrinos were Majorana particles, lepton number not being conserved would be there's so much more matter than antimatter in the universe.

Comprehension questions

1. What are two of the main methods of detecting neutrinos and what are their
2. Why are fewer neutrinos detected from the Sun than predicted?
3. What are the theoretical consequences of neutrinos being Majorana particles?

Discussion

Neutrino astronomy is the cutting edge of astrophysics. What are the advantage types that detect neutrinos from celestial sources?

Investigation

Do some research into sterile neutrinos, and write two or three paragraphs describi they might be so significant to physics.

3.2.2 Electromagnetic radiation and quantum phenomena

Keywords	
Black body	A body or object that absorbs all incident radiation
Photons	Quantised packets of electromagnetic radiation
Wave function	The description of the quantum mechanical state of a particle

Classical or Newtonian physics describes the physics developed before the twentieth century. It is based on Newton's three laws, his law of gravitation, the laws of thermodynamics, and Maxwell's equations on electromagnetism among others. Classical physics assumes that energy is continuous (i.e. allows for a system to have any value of energy), that time progresses at a constant rate, and that the mass of an object are the same for different observers, among other intuitive assumptions. Classical physics explained the world pretty well; however, there were a few discrepancies that needed to be resolved before a unified theory was formulated.

The quantisation of light (1900)

From studying black bodies, you know that all objects emit radiation, with the wavelength of the radiation depending on the object's temperature. Humans have a body temperature of 37 °C and emit infrared radiation. The hotter an object is, the shorter the wavelength of emitted radiation.

This was all well known in classical physics and is described by the Rayleigh-Jeans law for long wavelengths, but broke down at short wavelengths (high energy, high temperatures). Wien's law was used to describe the emitted radiation for short wavelengths, but deviated from experimental results for long wavelengths. Therefore, there was a need for these two models to be combined into one.

Max Planck proposed a law that could explain the experimentally observed radiation for all temperatures and wavelengths. The beginning of the derivation of the Planck law is as follows:

Consider a volume in a black body in the shape of a cube with sides L. If the black body is at the same temperature, T, then the inside and outside of the volume in question are in thermal equilibrium.

The electromagnetic radiation can take lots of different wavelengths, but must be a whole number of wavelengths, so can only take certain modes, shown by the diagram to the right. Think of it like stationary waves of a string – the wave can have an infinite number of wavelengths, but only certain wavelengths won't interfere destructively, so only certain wavelengths are seen.

In one dimension, x, the possible wavelengths of the modes are:

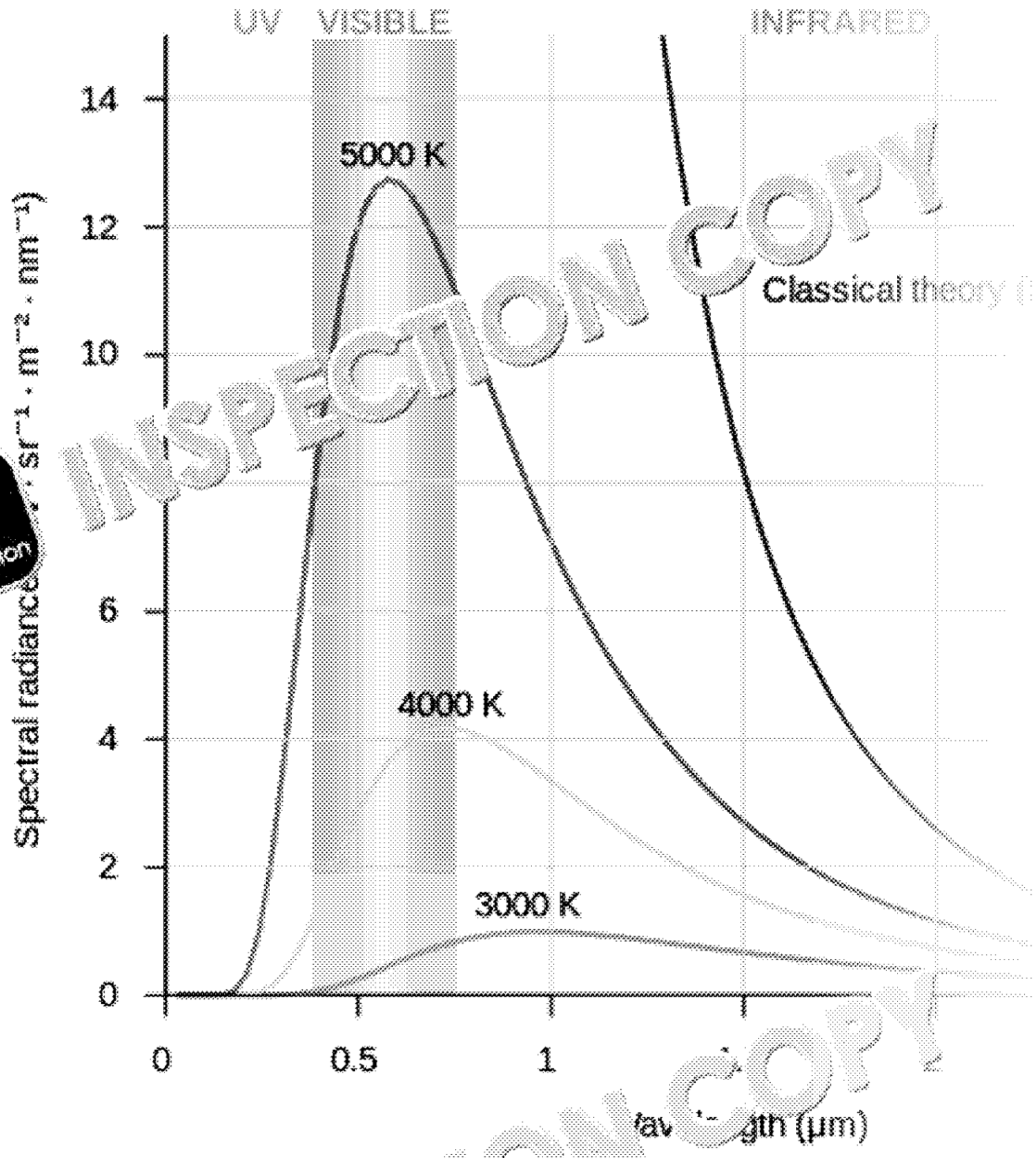
$$\lambda_x = \frac{2L}{n_x}$$

where n_x is an integer. A simple periodic function is the sine function, so the modes that describe the EM radiation in this cube are of the form:

$$\sin\left(\frac{\pi n_x}{L}x\right)$$

Following the derivation through leads to Planck's law of radiation:

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_B T}}-1}$$



The graph above sh[illegible] for different temperatures, as well as the Rayle[illegible] theory plotted for 5000 K. The peak for temperatures of around 5000 K is in t[illegible] visible spectrum of light.

[illegible]ting thing about the derivation of Planck's law was the modes that are s[illegible] represent the energies of electromagnetic radiation possible and only a discrete (a[illegible] of these modes are allowed. This contradicts the assumption of classical physics tha[illegible] quantity.

Planck initially thought the quantisation of electromagnetic radiation to formulate h[illegible] workaround and didn't mean anything physically significant. A couple of years later[illegible] a model for the photoelectric effect. The physics at the time expected the energy o[illegible] photoelectric effect to increase with the intensity of the incident light. However, exp[illegible] frequency of light that determined the energy of the electrons. Einstein suggested t[illegible] packets called photons, and one photon collides with one electron only, suggesting[illegible] particle.

The energy of a single photon can be extracted from Planck's law:

$$E = \frac{hc}{\lambda} = hf$$

The quantisation of matter (1913)

Niels Bohr also suggested that the energy of atoms is quantised. Specifically, that electrons can only exist around the atom in discrete orbits, depending on their energy.

Think of the circumference of each electron orbit. Similar to the standing waves in Planck's derivation, each electron orbit is a standing wave that 'holds' the energy of the orbital. Only certain standing waves are allowed, so the energy of the orbital is quantised.

The similarity between the quantisation of light and matter is further realised through wave-particle duality. Hypothesised by Louis de Broglie, waves, such as light, can act like particles (so reflect, refract and diffract) and particles, such as electrons, can act like waves (so diffract, refract and reflect). This is backed up with evidence from experiments, despite being unintuitive.

The Schrödinger equation (1925)

The shape of an electron orbital is modelled by a **wave function** – this gives the probability of finding an electron in a specific place. Erwin Schrödinger developed an equation that modelled how a wave function changes with time.

The Schrödinger equation is fundamental to quantum physics. It is best to describe and solve for a particle trapped in an infinite potential well.

Did you know?

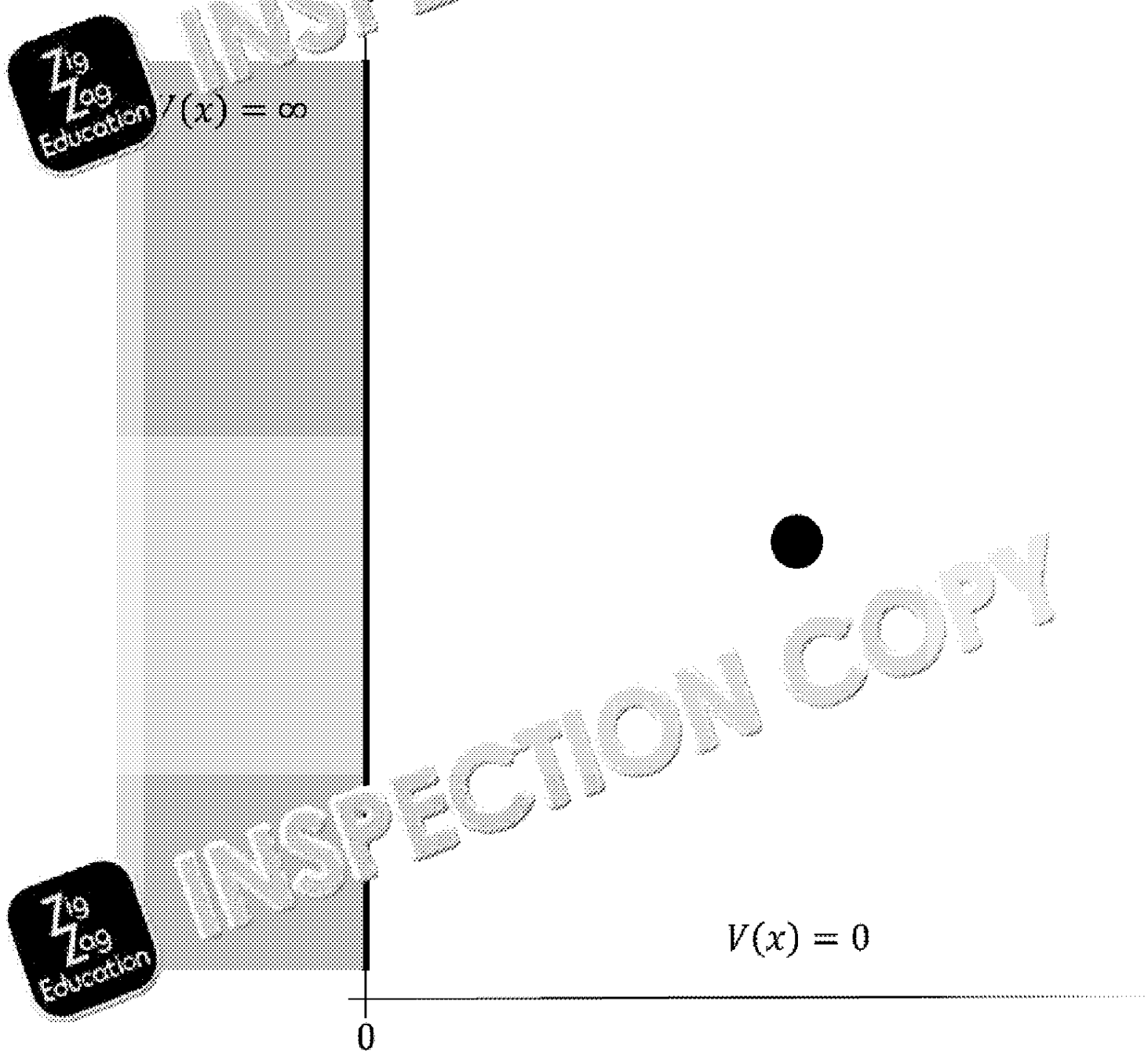
Max Planck was awarded the Nobel Prize in **1918** for his derivation that led to the discovery of photons, **Albert Einstein** was awarded the Nobel Prize in **1921** for his work on the photoelectric effect, **Niels Bohr** was awarded the Nobel Prize in **1922** for his work on quantised orbitals in atoms, and **Louis de Broglie** was awarded the Nobel prize in **1929** for his work on the wave nature of electrons. A successful 11 years for quantum theory!

Particle trapped in an infinite potential well

For simplicity, we will ignore the progression of time and only consider motion in or

A particle is trapped in an infinite well, that is, it's trapped betwee[illegible] of infin escape. Outside the well, there is a barrier of potential en[illegible] V([illegible]∞, and insid of V(x) = 0.

The position of the particle can b[illegible] by the time-independent Schrödinger



$$-\frac{\hbar}{2m}\frac{\partial^2}{\partial x^2}\psi(x) = E\psi(x)$$

To describe the particle in this well, this equation needs to be solved for $\psi(x)$, calle function of a particle is a description of the particle in space and time, giving the pr in a particular location at a particular point in time.

Solving the Schrödinger equation for our particle in an infinite well gives the solutio

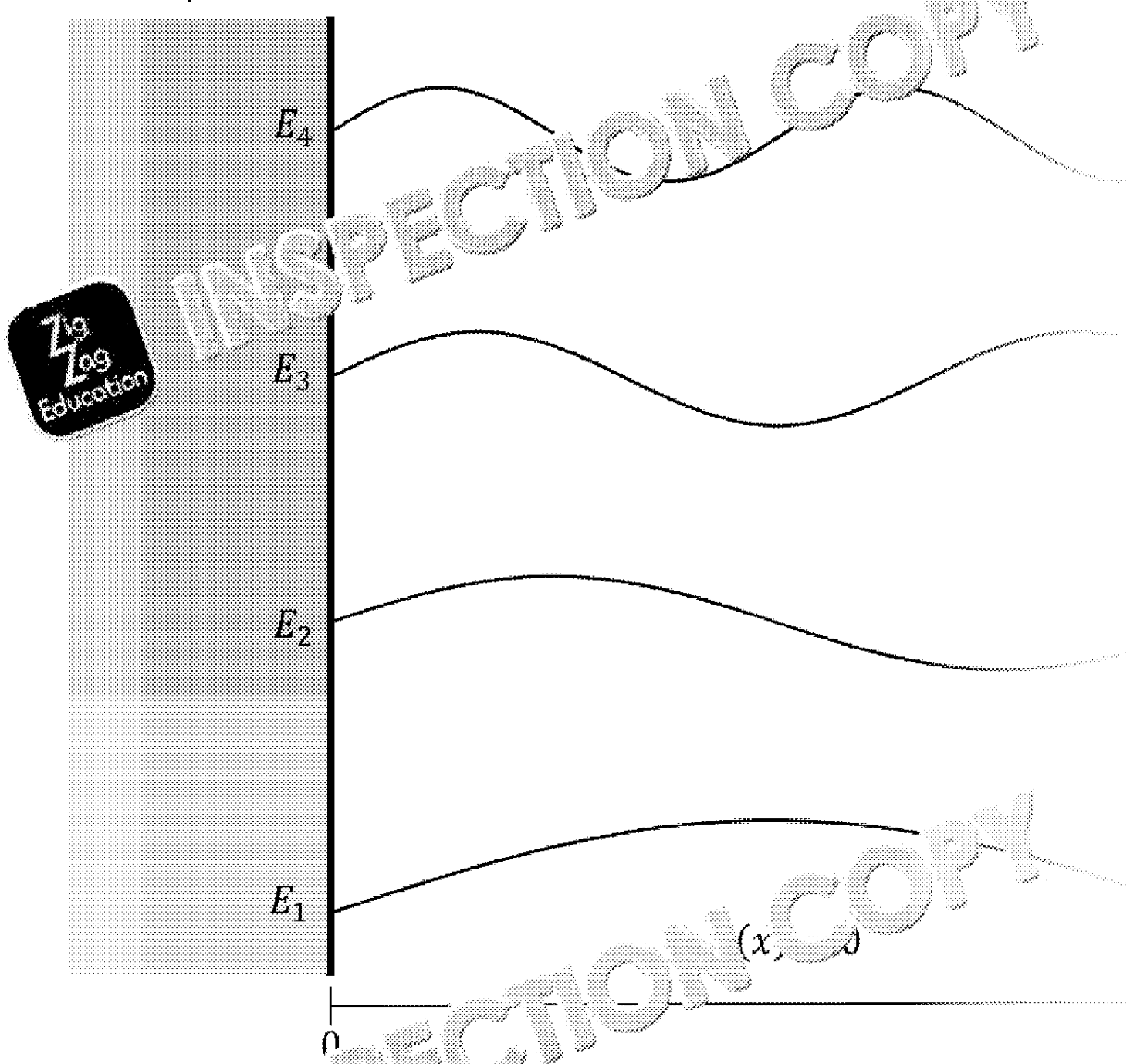
$$\psi_n(x) = \sqrt{\frac{2}{L}}\sin\left(\frac{n\pi}{L}x\right)$$

where n is an integer (representi[illegible] discrete possible solutions). You n solution of the electroma[illegible]diatic modes in the derivation of Planck's law. T states crop up oft[illegible]mechanics. It's also possible to derive the energy f fu[illegible]

$$E_n = \frac{n^2\pi^2\hbar^2}{2mL^2}$$

As the mode of the wave function increases, so does the energy of the particle.

Each wave function corresponds to a possible state the particle can be in. Each stat
the particle, given by the energy equation above. The particle cannot exist within t
have one of the quantised energies from this equation. Below is a plot of the first f
in an infinite potential well.



For e[illegible] sta[illegible] lity of finding the particle at a point x is given by the squ

Example

For an electron in its ground state (the lowest possible state, $n = 1$), in a poten
what is the probability of finding the electron in the centre 2 pm of the well?

$$p(4 < x < 6) = \int_4^6 p(x)\,dx = \frac{2}{10}\int_4^6 \sin^2\left(\frac{\pi x}{10}\right) dx$$

$$p(4 < x < 6) = \frac{2}{10}\left(1 + \frac{5}{2\pi}\left(\sin\left(\frac{4\pi}{5}\right) - \sin\left(\frac{6\pi}{5}\right)\right)\right)$$

$$p(4 < x < 6) = [illegible]$$

So there is a 39 % chance of finding the partic[illegible] tw[illegible]n [illegible] and $x = 6$, [illegible]
how this probability doesn't depend o[illegible] [illegible] the electron, only its energy
dimensions. The energy of th[illegible] [illegible] ground state is:

$$E_1 = \frac{\pi^2 \hbar^2}{2(9.11 \times 10^{-31})(1 \times 10^{-11})^2}$$

$$E_1 = 6.02 \times 10^{-16}\ \text{J}$$

$$E_1 = 3.8\ \text{keV}$$

The orbital of an electron in an atom is a type of potential well. This potential well functions, and, therefore, energy levels that can exist. This is why Niels Bohr suggested have discrete energies, which led to his Nobel Prize.

The predictions from the Schrödinger equation and other quantum mechanical theories experiments. Today, quantum mechanics and its related theories are considered some theories ever developed.

But what do these equations mean? That is, what is the physical significance of the wave fu Bohr, Heisenberg and others set to answer these questions. Their description is the interpretation.

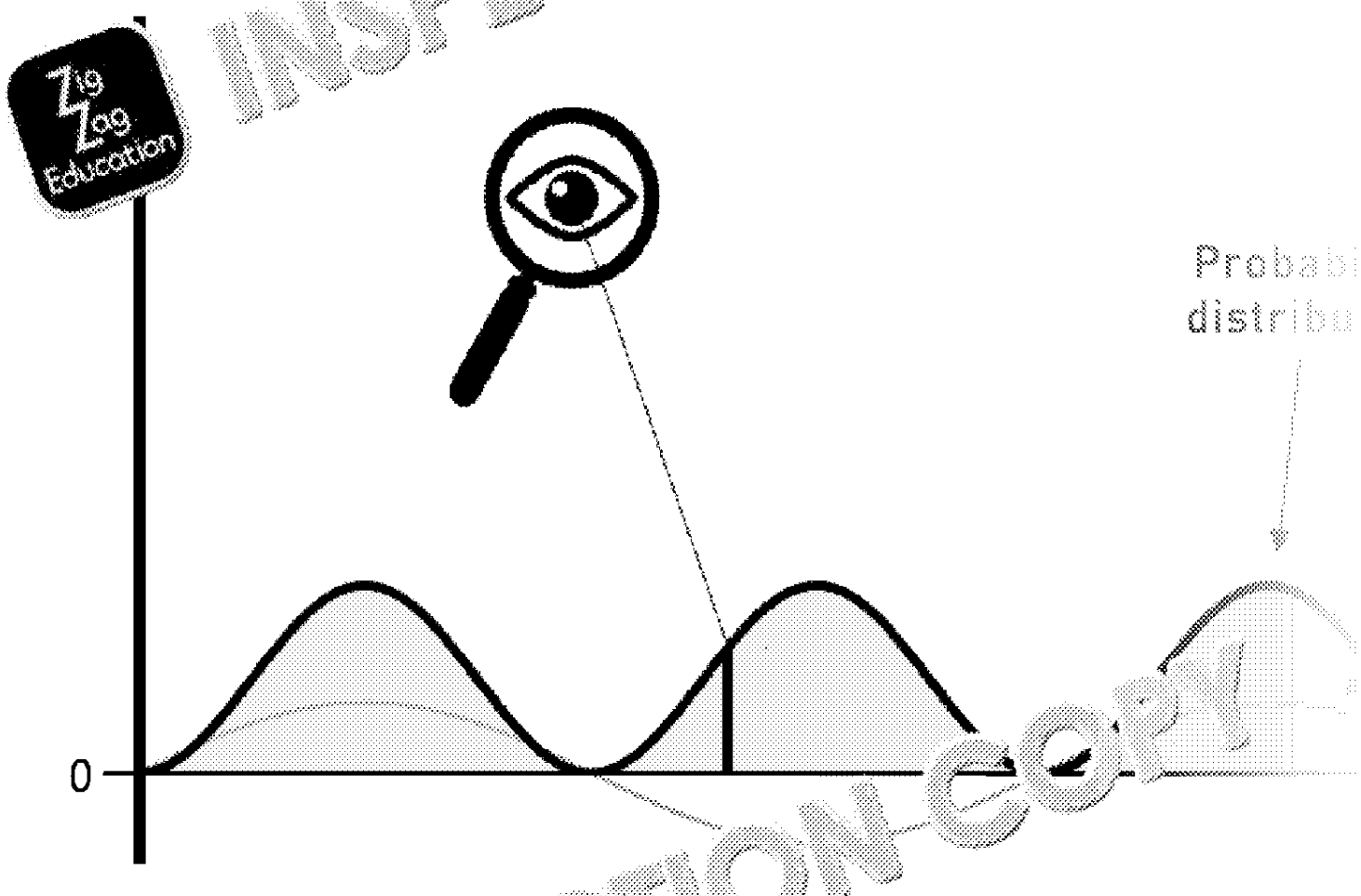
Copenhagen interpretation

Developed between 1925 and 1927, the Copenhagen interpretation came from a meeting of world-leading physicists to try and determine the physical meaning of the theories and results emerging from quantum mechanics.

Normally probabilities are one number, like the probability of getting a head on a coin flip. A probability distribution is a graph that represents all the values a system can take and the probability of each value (in the case of our particle in an infinite well, the values are positions along the x-axis).

The interpretation states that a system is in all possible states at once. So our particle in the infinite well is at all positions along the x-axis at the same time! Just let that sink in for a second. The particle only 'decides' to be in a particular position when forced to by being observed, or interacting with its environment.

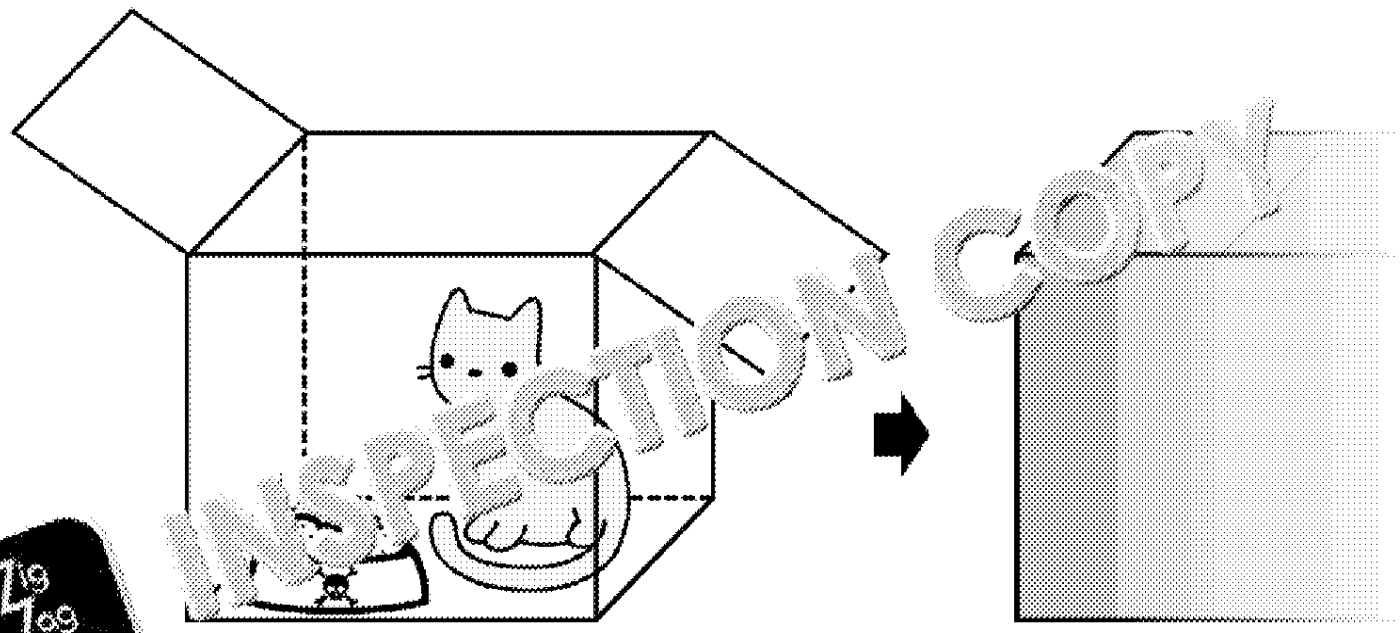
Each state has an associated probability calculated from its wave function. Below is the function, $\psi_3(x)$ and its associated probability distribution for our particle in an infinite has this wave function when its energy is measured. When the system is influenced by an measurement, the system collapses into one state, depending on the associated pro



So the wave function for our particle collapses into one position, i.e. we measure the the centre. Repeating the measurement would find the particle in another position. If are repeated many times, the probability distribution will start to appear. Measuring finding the particle mostly in the grey areas and barely in between them.

The interesting thing about this interpretation is that a quantum mechanical system states at the same time. It's only when an observation of the system is made that the collapses, resulting in the system being in one state; the one that matches the measu

Schrödinger described this principle with a famous analogy called Schrödinger's cat.



A cat is placed into a box with a vial of poison connected to a radioactive nucleus. T sealed. At any point, the nucleus could decay, breaking the vial, releasing the poison be known whether the nucleus has decayed or not until it is observed. Thus, it is in a two possibilities.

While the box is closed, and the nucleus is both decayed and undecayed (quantum simultaneously considered to be alive and dead, with the probability of the cat's fat wave function. It is only when the box is opened that the state of the cat is determi function collapses into a single possibility.

Schrodinger suggested this analogy to point out the flaw in the Copenhagen interpr

Why couldn't the cat be considered an observer? If humans are observers, so could Does an observer have to be alive? Or could a single atom that interacts with a syst

And then, once we open our box and (hopefully) living cat, what has happened the possibility of a dead cat been erased? Or is there a parallel universe where the more gruesome sight? Or, does every collapsing wave function of every atom, ele universe with a different result?

Comprehension questions

1. Describe how the possible modes of electromagnetic radiation in a confined sp quantisation of energy.
2. What does the Copenhagen interpretation say about the quantum states of a s
3. Describe how the famous analogy known as Schrödinger's cat applies to quant

Discussion

How does the Copenhagen interpretation affect larger, classical systems? Is there a systems quantum mechanics applies to? Does the fact that we don't observe quant suggest that quantum mechanics is wrong, or that there's some more complic

Extension

Quantum tunnelling is a weird phenomenon where a particle can 'tunnel' through a because its wave function extends into the barrier. Research this phenomenon and h fusion. Write up your findings as an A4 poster to be used in a science fair.

Meta-magic

3.3 Waves

Keywords	
Material	The type of matter which a[illegible] objects [illegible]de from
Black body	An object that ab[illegible]rbs a[illegible] [illegible]t radiation on it.
Refractive index	The meas[illegible]e of [illegible]o[illegible] light slows down when it propa[illegible]

What's [illegible] about metamaterials?

[illegible]netic radiation, i.e. light, is made up of an electric field and a [illegible]field, each oscillating with the other. Natural materials generally only affect the electric part of light, causing common optical effects such as refraction. However, it is possible to develop materials that also interact with the magnetic part, leading to new effects unseen in nature. These materials are called metamaterials because they go beyond what is observed in nature (meta – Greek preposition meaning 'beyond').

Every time a news article reports on new findings in metamaterial science, a reference to Harry Potter's invisibility cloak tends to be made. This is because some metamaterials have the ability to bend light around an object witho[illegible] object, effectively making the object invisible. Although current metama[illegible]ls can [illegible] certain wavelengths of light in the infrared or radio wave parts [illegible]ect[illegible]m, and Realistically, it will be many decades before commercial a[illegible]plica[illegible]on [illegible]t can bend [illegible] That doesn't mean metamaterials should be ignored until [illegible]esearch gets to this [illegible] are many revolutionary applications of [illegible]t ma[illegible]ls.

Radiative s[illegible]

[illegible]em [illegible]e that the Earth and its atmosphere act approximately like a blac[illegible] [illegible]sorbs radiation from space, mainly from the Sun, and emits radiation ba[illegible] i[illegible] due to its temperature. For a body at constant temperature, the emissio[illegible] and absorption of radiation is equal. However, the Earth receives a large amount of radiation from the Sun during the day, and then very little during the night. This ca[illegible] the temperature of the atmosphere to vary accordingly, normally lagging behind th[illegible] intensity of radiation by a few hours. This is nothing new, everyone knows it gets h[illegible] during the day and cold at night.

During the night there is very little radiation being absorbed by the atmosphere fro[illegible] space, but there is a lot of infrared radiation being emitted into space. The temper[illegible] absolute zero at 2.7 K. The temperature of the Earth's atmosphere and surface is ab[illegible] not radiating on the Earth, there is a large temperature gradient from th[illegible]ound o[illegible] 300 K mostly emit radiation with wavelengths in the range 8–1[illegible]th happens which Earth's atmosphere barely interacts with. Therefor[illegible]any [illegible]di[illegible]a emitted up temperature will just escape into space. The coo[illegible]s of [illegible]can, therefore, be u[illegible] Earth's surface!

This principle was used [illegible]sia[illegible] make ice in the desert. They would fill sh[illegible] the end of the da[illegible]mp[illegible]tures in the desert drop rapidly at night, but not be[illegible] [illegible]ld [illegible] (via infrared radiation) that would escape up into the sky o[illegible] [illegible]hall[illegible]w, the surface area that could radiate heat was larger, improving the[illegible] [illegible]ature of the water to drop below 0 °C causing it to freeze. The Persians [illegible] be[illegible]e sunrise and store the ice in cool ice houses to use later on.

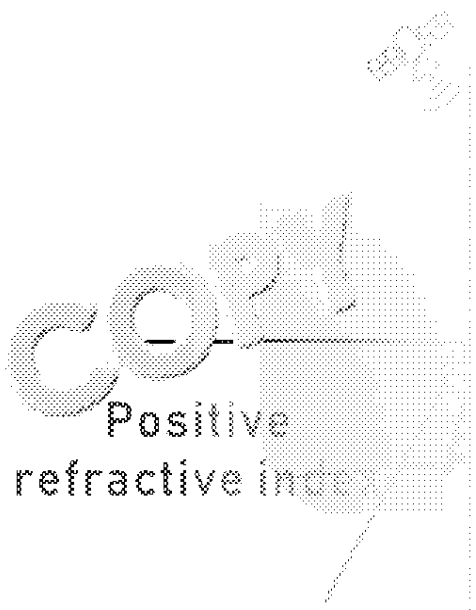
The issue with this cooling technique is it can only be used at night. During the day overwhelms the emitted radiation from objects, causing their temperature to increase come in. Aaswath Raman and Shanhui Fan run a company called Raman Lab. They reflects most light but allows a small window (8–13 μm) of wavelengths to pass this this material, any incident radiation from the Sun will be reflected, but the infra object due to its temperature can pass through the material and escape into space.

This is very unintuitive because an object coated in the material will cool down when (with no direct line of sight to space, and not into the Sun. Theoretically, this m the temperature of an object 40 °C below its surrounding temperature, although 5 °C below ambient temperatures have been reached.

One application of Raman Lab's metamaterial is a filter on cooling panels. These an air-conditioning system. Water flows from the air-conditioning unit and positioned on the roof of the building. The water then cools in these panels and flo system. Field trials have shown this increases the efficiency of the cooling system by

Adaptable antennas

A typical antenna will emit a signal in all directions at once. If there is only once receiver, say a satellite in space, then the majority of the energy used to emit the signal misses the satellite and is wasted. A satellite dish is better as it can be directed at the satellite to emit a beam containing the signal; however, this involves the mechanical movement of the dish.



A new type of antenna is a flat panel antenna. They have no mechanical parts instead using a mix of electronics and software to control the direction of the signal. One such flat antenna developed by scientists uses metamaterials to further improve the function of the flat antenna. It consists of individual elements, each able to refract light in a certain direction. These have a negative refractive index (see right). The individual elements can be turned on and off by electronics in such a way as to track the satellite as it moves across the sky, even though it is not actually moving. These antennas are much more efficient than standard antennas but are small compared to satellite dishes, making them useful for mobile applications such as phones.

Comprehension questions

1. What is the definition of a metamaterial?
2. What wavelength range do objects at 300 K mostly emit electromagnetic radiation?
3. How did the Persians create ice in the middle of the dessert?
4. What is meant by a negative refractive index?

Discussion

In groups of three or four, try to come up with as many applications of Raman Lab's metamaterial as you can. Your list could include transportation, civil engineering,

Extension

Research how metamaterials that bend light around an object, i.e. make it invisible to certain wavelengths, work and if the Harry Potter cloak of invisibility is a possibility in the near future. Present your findings to your class as a two-minute presentation.

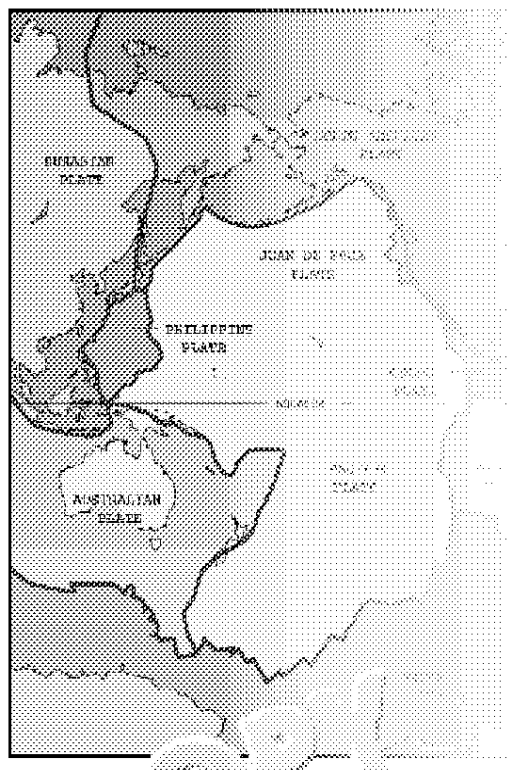
Earthquakes: Shaking Thin

3.3 Waves

Keywords

Seismic waves	Waves that travel through [illegible]
Attenuation	The reduction in [illegible] wave as it travels through a [illegible]
Plasma	The fourth [illegible] where atoms are partially or fully [illegible]

Earth is still mostly a ball of molten rock from when it formed [illegible] billion years ago. The outer surface has cooled due to its exposure to the cold space.



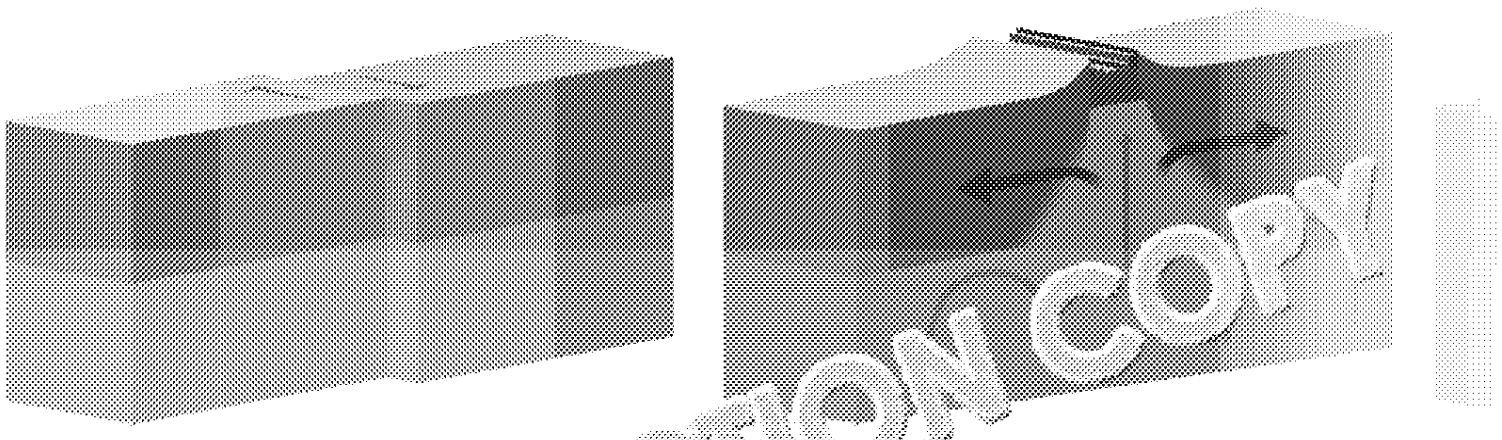
This outer layer is split into plates (like puzzle pieces) that move around due to convection currents in the mantle – a thick layer of magma around the Earth's core. These plates are budged up tightly to one another, with high friction coefficients. When the stress becomes too high for the plate boundary (the limit known as the local strength) the plates slip causing a shockwave of vibrations to propagate through the plates and molten rock. This is called an earthquake.

Earth's crust is split into eight major plates with a few smaller ones. The way plates [illegible] be categorised into three ways:

A **transform boundary** is [illegible] by two plates moving in different directions relative [illegible] are moving horizontally, this boundary is known as a transform fault. A common example [illegible] San Andreas fault on the west coast of America. These faults can result in very [illegible]

[illegible] boundaries can produce earthquakes, although they tend to be small as [illegible] reach the surface and cool, creating volcanoes and islands if positioned [illegible] was formed around 16 million years ago).

Convergent boundaries result in a less dense plate sliding on top of the more dense [illegible] dense plate down into the mantle. This can lead to the construction of mountain ranges [illegible] also to strong earthquakes.



1. Transform boundary 2. Divergent boundary

Seismic waves

Earthquakes release a lot of energy. The size of an earthquake is commonly measured using the Richter scale, although this doesn't distinguish large earthquakes from one another.

A modern replacement of the Richter scale is the moment magnitude scale (MMS), used for earthquakes of more than 5 on the Richter scale. An earthquake in 1994 in Northridge, California measured 6.4 on the Richter scale and 6.7 on the moment magnitude scale. A lower bound for the energy released can be calculated from the MMS, M_W, as:

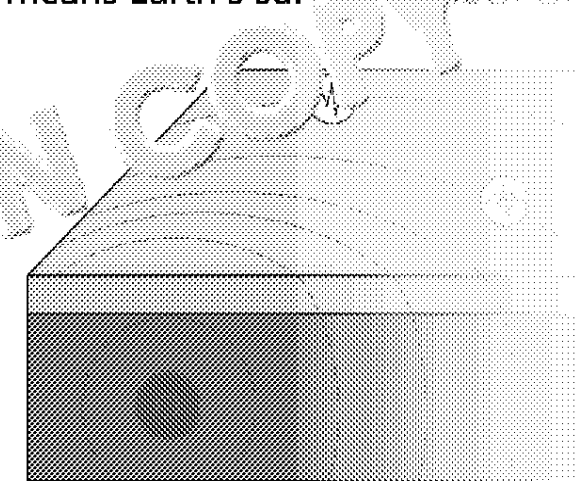
$$E > 10^{\frac{3M_W}{2} + 11.25}$$

which for the Northridge earthquake is an energy of:

$$E > 2.0 \times 10^{21} \text{ J}$$

The largest bomb ever denoted by humans was the Tsar Bomba in 1961. It released earthquake in California released more than 9500 times the energy of the Tsar Bomb Richter scale, a medium-level earthquake.

Most of this energy is used to deform rocks or cause heating near the epicentre (so some is radiated away from the epicentre as seismic waves. In our 3D world this en directions. However, the position of the epicentre means Earth's surface is such that another. This part of the surface will, therefore, receive more energy and much more quickly after the earthquake has occurred.



Energy is radiated away in the form of three-dimensional waves. These seismic waves can be split into three parts, each arriving at a detection point at different times due to their nature. They are:

1. [illegible]
2. [illegible]
3. Surface waves (also known as L-waves)

The P-waves (stands for primary waves) are longitudinal, like sound waves, and trav around 10 km/s.

S-waves (stands for secondary waves), on the other hand, are transverse and travel

Finally, surface waves carry the majority of the energy (so cause the most destructio surface (as the name suggests), so have further to travel to a detection point.

The different arrival times of the parts of a seismic wave can be used to determine h is from the epicentre. Using many detections sites, the position [illegible] of the ep

Seismographs

Detection points dotted around the globe use **seismographs** to determine any motion in the ground. The basic principle of a seismograph is to use a pin point that moves across paper due to some motion.

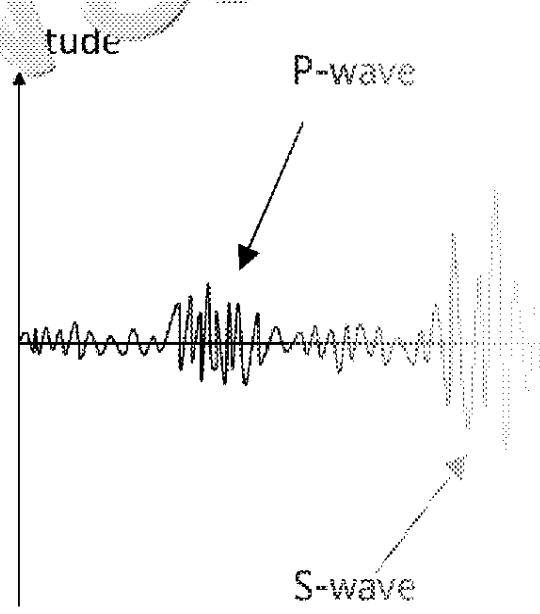
The simple seismograph shown on the right will oscillate due to movement in the vertical direction, moving the heavy weight up and down relative to the paper, drawing these oscillations on the moving paper. By having three of these oriented for each (x, y and z), the 3D motion of the ground at a detection point can be determined. Modern seismographs use digital sensors to detect motion, providing much more accurate data.

A simple seismograph recorded during an earthquake is shown below. The first pulse is the arrival of the P-waves, then come the S-waves, and finally the majority of the energy of the earthquake hits the detection point as the surface waves.

Waves are attenuated (lose energy) when they travel through a medium. Seismic waves are no different. The further a detection point is from the epicentre, the smaller the amplitude of the measured waves. By comparing this distance to other seismographs, the positon of the epicentre can be determined.

Replacing the seismograph

Nowadays, seismographs are digital and much more sensitive than the mechanical amplitude apparatus described above. However, they are not the only method to detect earthquakes. The movement of tectonic plates constantly emits extremely low frequency (ELF) electromagnetic radiation. The plates are also hot, so emit infrared (IR) radiation, just like any black body.



Therefore, the future of predicting earthquakes will see an array of satellites constantly orbiting and monitoring tectonic plates in the ELF and IR parts of the electromagnetic spectrum. Signatures in these parts of the spectrum that lead to earthquakes can be used to predict future earthquakes weeks in advance, as opposed to millions of lives. To do this, though, the equipment must be extremely sensitive and

Sun surfing

Helioseismology is the study of waves that propagate through the Sun. These wave
to tectonic plates, but by the complex temperature and pressure oscillat[illegible]in the
a plasma, unlike the rocky Earth, so the waves propagate differ[illegible]th researc
applications in the containment of plasmas in fusion reac[illegible]rs a[illegible]d p[illegible]dicting solar fl
communications here on Earth.

Waves travelling through the Su[illegible]lassified into three types:

- **P-waves**
  Similar to the[illegible]s th[illegible]travel through Earth, these are fast longitudinal wa
  Sun.

- **[illegible]ves**
  [illegible]caused by the gravity due to the mass of the Sun, these slower waves are foun
  They are analogous to the S-waves that travel through the Earth. As they occu
  observation of G-waves has been made, but their existence is implied by other

- **F-waves**
  Also known as surface gravity waves, these are transverse waves that propaga
  like water waves over the sea.

Comprehension questions

1. Name one example of a transform fault line.
2. What is the minimum energy released by an ea[illegible]hqu[illegible]ke w[illegible]s measured to
   moment scale?
3. What fact, other than the arri[illegible]f di[illegible]ent types of seismic waves, is us
   the epicentre of an ear[illegible]ke an[illegible]y?
4. Describe the fu[illegible]e[illegible]th[illegible]quake prediction.

Discussion

Discuss whether it is more important to invest money into researching geoseismolo
through the Earth) or helioseismology (study of waves through the Sun).

Extension

The Solar and Heliospheric Observatory (SOHO) satellite has been monitoring the S
years. Research this satellite and its findings and present your research as a fact she

.

Interferometers: Getting into Su

3.3.2 Refraction, diffraction and interference

Keywords

Superposition	The interference of two waves wh[illegible] either add or subtract from [illegible] resultant wave
Relativity	The idea that [illegible] system can depend on the relative [illegible] and [illegible]
Space-time	[illegible] four-dimensional continuum that comprises of three spatial [illegible] dimension.

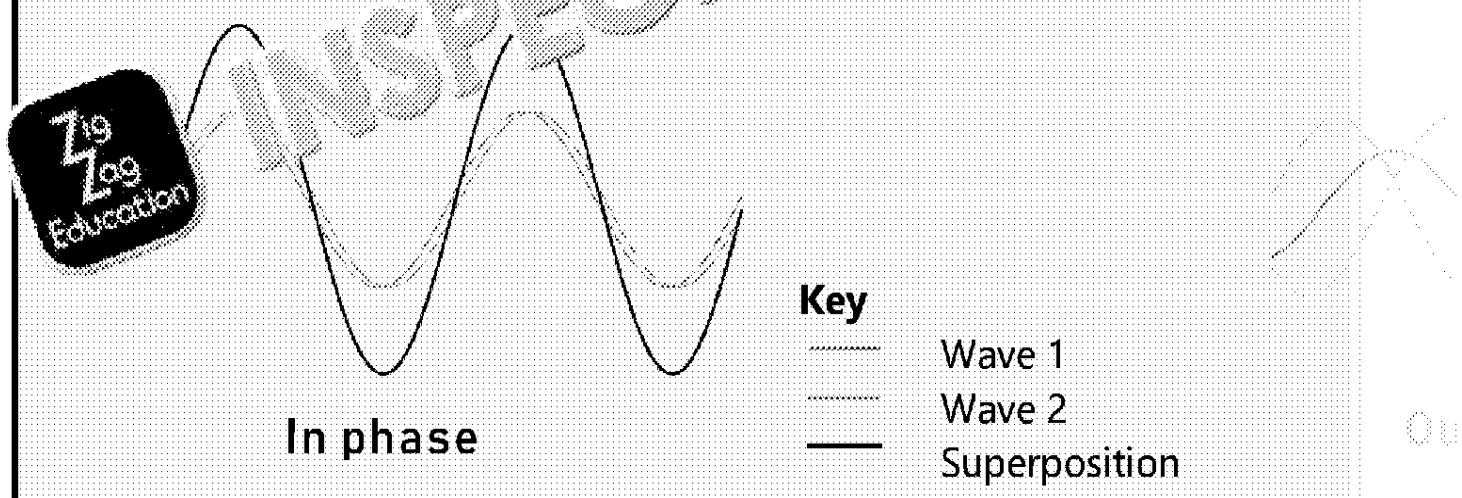
A [illegible]ometer is a tool that measures the intereference between two waves. Th[illegible] extremely small changes in distances, useful in many scientific experiments.

Basic principles

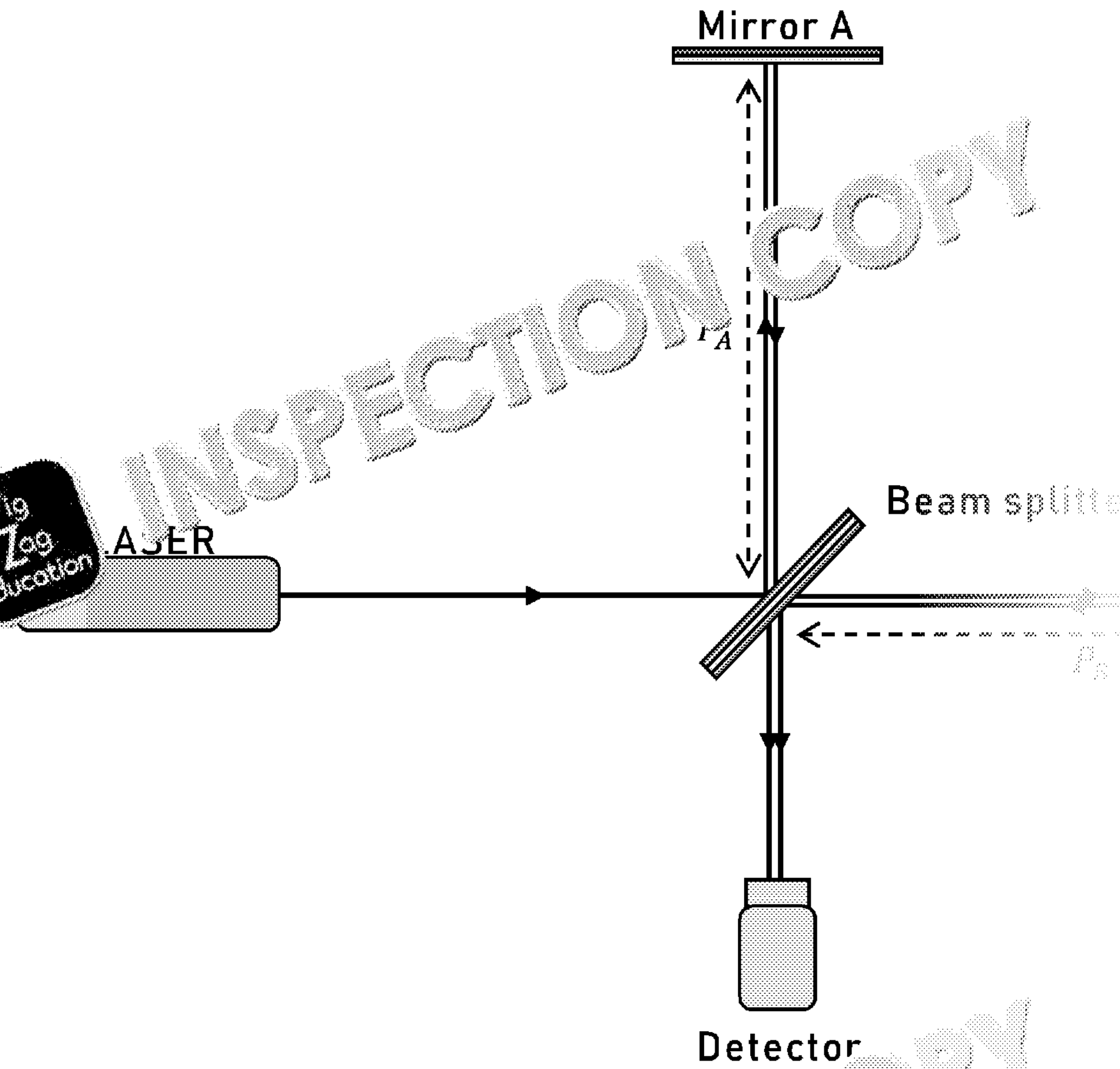
The linear interferometer is the simplest form of interferometer. Devised by Albert [illegible] device shines light at a beam splitter, creating two beams, A and B, that propagate [illegible] These beams reflect off mirrors and return to the beam splitter.

The waves of these two beams interefere and propagate towards a detector. The b[illegible] the same source of light, so are initially coherent (in phase); however, if the path le[illegible] different they return to the beam splitter and interefere out of phase. The measure[illegible] therefore, be smaller due to waves destructively interferi[illegible].

The superposition of two waves that [illegible] arly in phase produces a wave with [illegible] superposition of two waves that are [illegible]y out of phase.



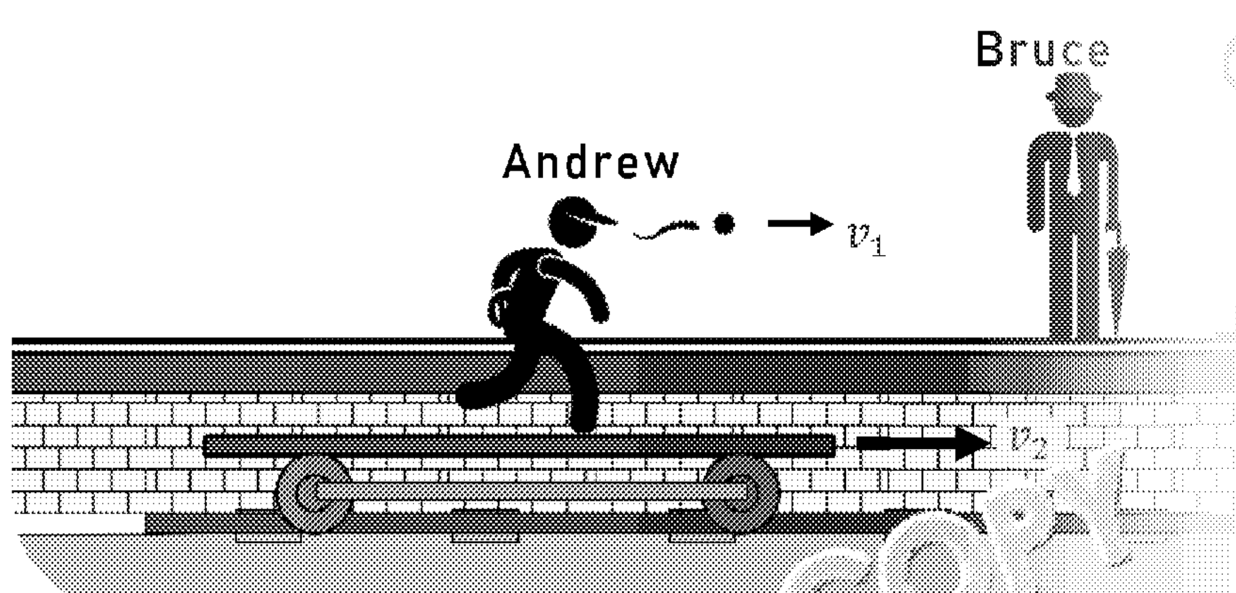
The phase difference between the waves is related to the difference in path length [illegible] using extremely coherent light, such as LASER light, with small wavelengths, small [illegible] can be measured.



The first and most famous application of the inte... me... s performed by Alb
in 1887. At the time it was thought th... law... physics obeyed Galilean relativi
to how velocities of objects ar... perceived by different observers.

Galilean Relativity

...sid... baseball pitcher, Andrew, travelling on a train at a speed of v_2 m s
...d of v_1 m s^{-1} in the direction of travel of the train. An observer on the pl
...ravel at a speed of $v_1 + v_2$. This simple addition of velocities for different ob



During the nineteenth century, ph... s ... ug... that just like the way sound wave
must propagate through a ... m called the 'aether'. Also during the mid ninete
calculated that light ... at a constant speed.

...elat... tells us that if Andrew shone light in the direction of motion of the
...ght as its intial speed plus the speed of the train. Therefore, the speed o
B... different. It was thought that this constant speed calculated by Maxwell wa
its aether, a constant in the background. Up until this point, however, the aether ha
observed. No other matter interacts with this aether, it's only suggested to explain

This is where the Michelson–Morley experiment comes in. Their hypothesis was that this aether, the two arms of the interferometer will be travelling at different speeds results in a difference in path length which will result in some change in interference experiment found no change in the path length between the two arms.

Light propagated along each arm at the same speed; therefore it was not constant just constant to any observer. This contradicts Galilean relativity and eventually led relativity, making this one of the most influential experiments in science.

Detecting gravitational waves

Einstein revolutionised how we thought about time and space with his theory his theory of general relativity. While the special theory of relativity applies at constant speeds, general relativity applies to accelerating objects.

One aspect of general relativity is its application to gravitational fields. Imagine you weighing scale. Standing on the weighing scale when the elevator is stationary gives elevator starts accelerating upwards at $g = 9.81\ m\ s^{-1}$, the weight would instead read space and accelerating upwards at 9.81 m s^{-1}, the weighing scales would still read W inertial effects (acceleration) and gravitational effects are indistinguishable, and can

General relativity explains gravity as a curvature in space and time, which light follows. This means that gravitational effects can only travel at the speed of light and no faster.

This weird consequence means that if the Sun were to suddenly disappear, the Earth would continue to orbit about the point where the Sun was for another 8 minutes (the time it takes light from the Sun to reach Earth). The theory implies that the speed of light is not unique to light, but is the speed limit for how fast information can travel through the universe.

Special relativity and general relativity describe space and time to be one four-. Objects with mass distort this space-time, causing it to 'bend' towards as gravitational forces between objects with mass.

If an object with a large enough mass distorts space-time with a large enough pow like water waves rippling across the surface. The energy needed to create these ripp is enormous, even on the cosmological scale. Therefore, only events like the merg holes will result in gravitational waves, and even these waves are small.

Detecting these waves requires extremely precise equipment, such as an interferom emitted from somewhere in outer space will pass through the Earth, causing the spa to oscillate. The length of the arms of an interferometer will, therefore, vary and the

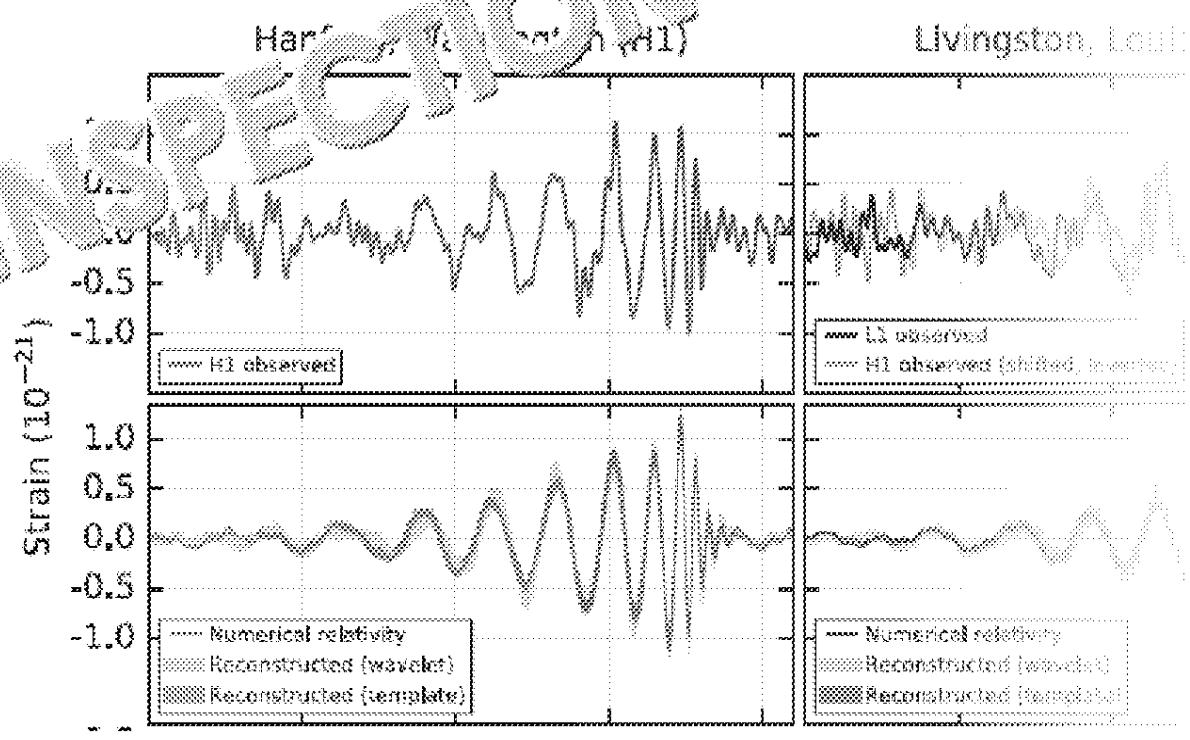
The Laser Interferometer Gravitational Wave Observatory (LIGO) is designed to do e consists of two interferometers situated 3000 km apart in the USA. By using two inte source of the gravitational waves can be deduced.

Each interferometer has arms that are 4 km long, 50 times longer than the interferometer used by Michelson and Morley. At the end of each arm are 40 kg mirrors suspended as part of a four-segment pendulum (a pendulum hanging fr a pendulum that is hanging from a pendulum that is hanging from a pendulum). This any vibrations from the ground, reducing noise in meaurements. There ar tricks to reduce noise, such as passive and active seismic isolation m ms.

To further increase the sensitivity of the interferometers, mirrors are added near the travels up and down its arm many times before interfering at the beam splitter. This

the LIGO interferometers 1120 km long, 144,000 times longer than the interferomet
Morley! All of this means the LIGO interferometers can detect a change in arm leng

After only a few days of operation, on 14th September 2015, both LIGO d[illegible]tion sit
gravitational wave. It was created by the merging of two 30 M[illegible]s the mass
1.3 billion light years away (this means this event happen[illegible]illi[illegible]ears ago, a
after turning the interferometers on!). Below is t[illegible]s[illegible]na[illegible]ected by each LIGO de



Since then, four other black hole mergers have been detected and the first neutron
17th August 2017. LIGO is currently on pause but will continue operation[illegible]ate 20

The European Space Agency hopes to build its own gravit[illegible]d[illegible]tor – an spac
Antenna (LISA) will work on the same principles as LIGO [illegible]t wi[illegible]e arms 2.5 mill
contend with interference caused by vibrati[illegible]ther sources, making LISA a b
smaller and lower-frequency grav[illegible]a[illegible]ve

Comprehension questions

1. [illegible]n how the interference between two beams allows an interferometer to
[illegible]es in distance.
2. What was the aim of the Michelson–Morley experiment?
3. What was proposed by Einstein to solve the issue of the results of the Michels
4. How large were the black holes that merged to create the first detected gravita

Discussion

Previously, astronomy has collected all of its data by looking into the sky and detec
electromagnetic radiation emitted by the stars and galaxies. Now with the advent of
there is a new way to study the universe. Discuss as a group the implications of this
universe.

Extension

The Laser Interferometer Space Antenna (LISA) [illegible]ort, is a proposed set of satel
position themselves to form a hu[illegible]er. It will differ from a standard line
three spacecraft, arrang[illegible]ith sides that are 2.5 million km long. Descr
be used in a scien[illegible]ng [illegible]vention.

Holograms: Seeing Things That a

3.3.2 Refraction, diffraction and interference

Keywords	
Laser	A device that emits coherent l[illegible]at a [illegible]re [illegible]equency
Lens	A transparent object [illegible]ht in a way to converge or d
Interference	The superpos[illegible]es when they propagate through t

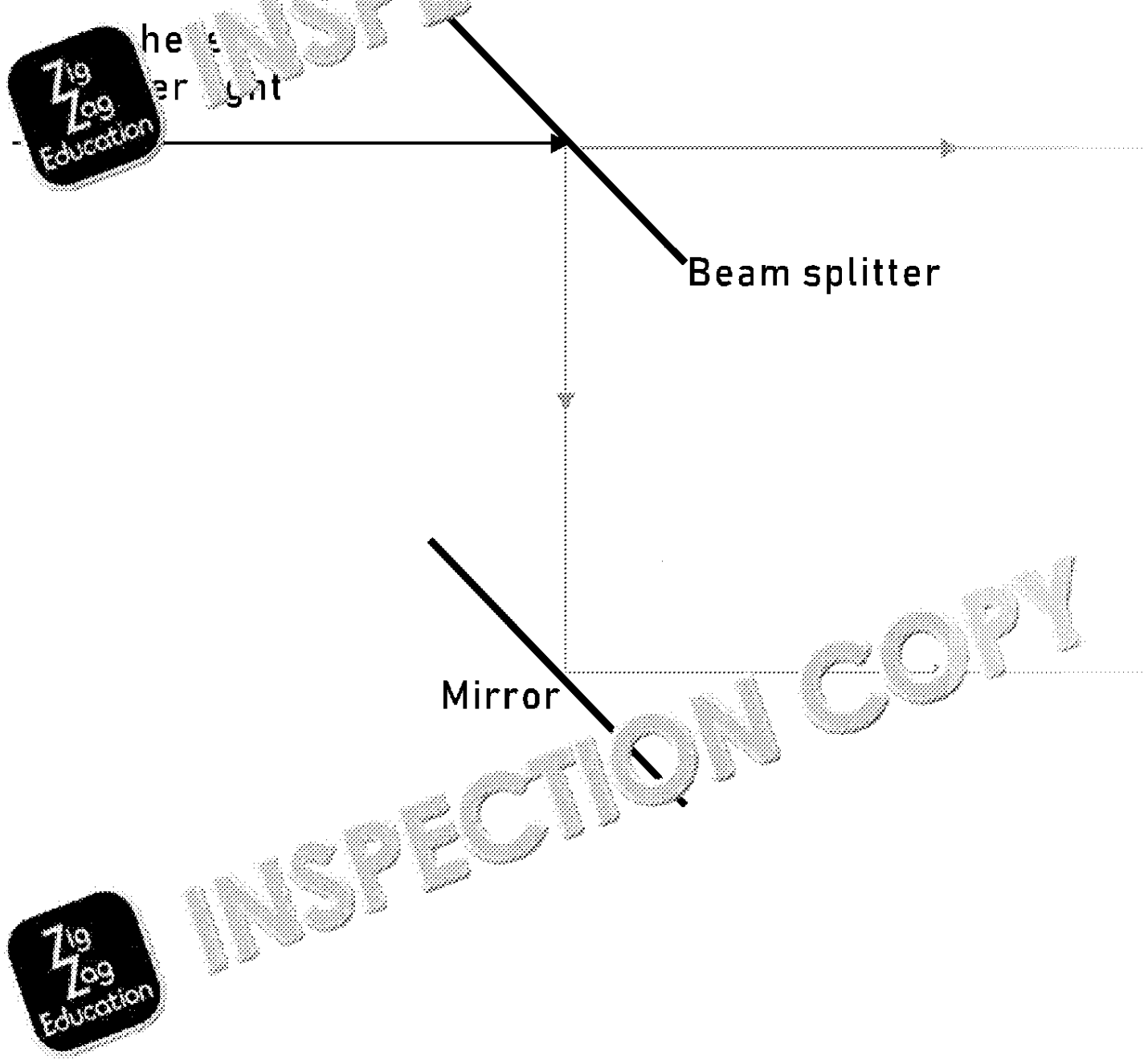
In Greek, holo[illegible]ple and -gram means 'message', so a hologram is a whol[illegible]d i[illegible]ologram' has been used to mean a message or image created[illegible]ppears to float in space as if a real object was there. This illusion can be [illegible]the most common uses coherent laser light with holographic plates.

Laser holography

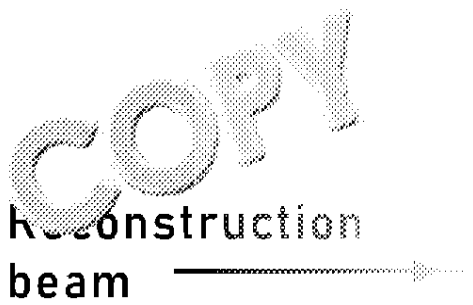
A laser beam is split into two using a beam splitter. One of these beams is directed[illegible]reflected off the object towards a holographic plate. The second beam skips the ob[illegible]the holographic plate using a mirror. This second beam is known as the reference b[illegible]

The two beams meet and interfere at the holographic plate. Their interference patt[illegible]holographic plate, just like the way a camera takes a picture by exposing a photogr[illegible]

The pattern recorded on the holographic plate doesn't look like the [illegible]ct b the re[illegible]information to display a 3D image of the object is encode[illegible]is p[illegible]rn. To displ[illegible]holographic plate must be illuminated with laser l[illegible]ide[illegible]tical to that used to recon[illegible]reconstruction beam either transmits th[illegible]u[illegible]ro[illegible]s off of the holographic plat[illegible]an observer.



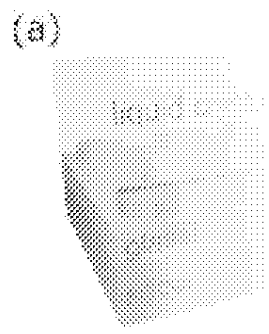
The emerging wave front from the holographic plate is exactly the same as if the object was actually there. Therefore, optical manipulation such as placing a lens in the path of the wave front will magnify the image of the object, just as if the observer was looking at the real object through the lens.



A common example of reflecting holograms can be found on credit cards or bank cards. These holograms are hard to reproduce, making fraudulent [illegible] more difficult, strengthening the security [illegible].

Dynamic holograms

The classic laser holography process is equivalent to taking photos and printing them out. But what is the holographic equivalent of videos and are they even possible?



Well, the technology is young but with the use of metamaterials, generating holograms that can change with time are possible. A metamaterial is a material that 'goes beyond' what is naturally possible. Basically, these are materials that are designed and engineered to manipulate light in a specific way.

In early 2017, a team of scientists published a paper on a metamaterial they had developed. Their [illegible] would turn nano-sized silicon discs on and off [illegible] the direction of polarised light passing through the discs so the later interference produces a holographic image. The sites are controlled electrically so can switch on and off in quick enough succession to produce a dynamic hologram.

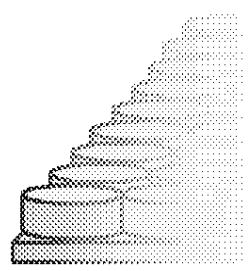
Star Wars-esque dynamic holograms won't be replacing our video calling any time soon as the primary method of communciation.

Acoustic holography

Holograms aren't specific to light. Any wave can be used to create a hologram, including sound. The process works slightly differently to laser holography. The basic principle is to produce two waves that interfere to create a pattern of pressure variations in the medium in which they travel.

One method uses a 3D printed sheet placed on top of a speaker. This sheet is designed in such a way as to transmit the sound to create the desired pressure waves. Another method uses an array of speakers that emit waves that interfere with one another, creating pockets of high and low pressure.

This second method has the application of levitating small objects. The object gets stuck in the pressure well, with high pressure air surrounding it. The force due to these high pressure areas is strong enough to counteract the weight of the object, and any small perturbations by the object, keeping the object in place. This application could be useful in manufacturing or in medicine where there is a need to transport an object without making direct contact with the object.



The holographic principle

The three-dimensional image produced by a holographic plate looks exactly like the in theory, whereas in reality things like resolution and dirty mirrors/lenses interfere of the information that generates this three-dimensional virtual image is stored on plate. This storing of information of an n-dimensional object on an $(n-1)$-dimensi **holographic principle**.

The holographic principle comes from **string theory**. In string theory, all particles dimensional strings or loops. Although these strings are one-dimensional, they multidimensional fields we see in the world around us. In fact, in string theory, the dimensional (9 spatial dimensions + time) representation of an 11-dimensio

aphic principle also applies to black holes, and can explain the black hol

A black hole is the remnant of a very massive star. It's so dense that not even ligh surface around a black hole called the event horizon, where anything that crosses it no chance of escaping. As the object falls into the black hole it takes its information molecules and how they are arranged to make up the object.

A problem arises when merging this extreme case of gravity with quantum mechan mechanics state that information cannot be created or destroyed, just moved arou into a black hole isn't destroyed, where does it go? According to the holographic p information contained by the matter is displayed as deformations in the 2D surface horizon.

Some scientists have taken this principle one step further and suggested the inform stored on a two-dimensional surface, just as on the surface of a black hole. This im hologram, projected from this hypothetical two-dimensional surface. If this is true, noise due to this hologram should be detectable by gravitational wave detectors, s but as yet there is no experimental evidence for the theory.

Comprehension questions

1. What is meant by the reference beam?
2. Describe the construction of a metamaterial that can produce dynamic holograp
3. Describe one application of acoustic holography.
4. How does the holographic principle propose a solution to a problem found wh quantum mechanics?

Discussion

Discuss the possible implications of the holographic principle if it applies to our enti does this theory affect your view of the universe?

Extension

Holograms are commonly used on credit cards and bank notes as a form of security other common application of holograms. Present your findings as a short report

3.3.2 Refraction, diffraction and interference

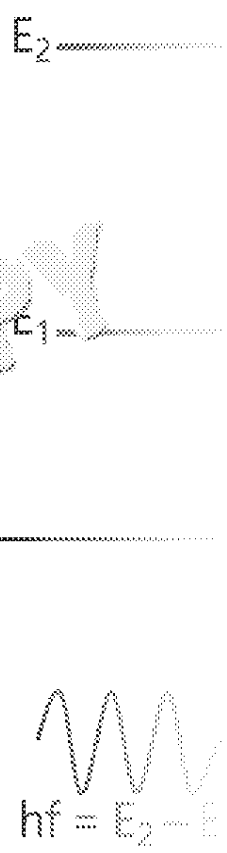
Keywords	
Ground state	The lowest possible en[illegible] state of a particle. Note that th[illegible]
Energy transition	The gain or los[illegible] energy by a particle, causing it to trans[illegible]
Optical resonator	The pa[illegible] where light resonates and amplifies, [illegible]

Fundamental principles

[illegible]on in an atom has an associated energy level. These energy levels are di[illegible] [illegible]n electron is only allowed to have energies that correpsond to these ener[illegible] change energy level if it gains or loses energy. It can do this via three ways.

Spontaneous emission

An electron in an excited state (a higher energy level than normal) will eventually transition into its ground state. The average time it takes to do this is called the **damping time constant** and is typically a few nanoseconds. When the electron does decay to its lower energy level, it emits a photon with an energy equal to the difference in energy levels. The higher the excited energy level, the shorter the wavelength of the emitted photon. This emission of a photon is called **spontaneous emission**.

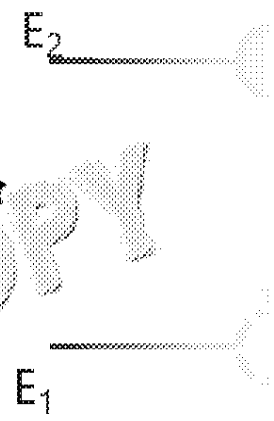


Absorption

As the name sugg[illegible]a[illegible]rption[illegible] where an electron in a low ener[illegible] state [illegible]s [illegible]coming photon to transition to a higher [illegible]te (th[illegible] opposite of spontaneous emission). The incident [illegible]st have the exact same energy as the energy difference b[illegible] the low and high energy levels, otherwise the photon will just miss the electron without interacting with it.

Stimulated emission

Consider an electron in a high energy state, as for spontaneous emission. If an incident photon with an energy equal to the energy transition ($E_2 - E_1$) comes along, the photon will interact with the electron, causing the electron to transition to the lower energy level. The change in energy causes a new photon to be emitted with an energy equal to the energy transition ($E_2 - E_1$). There are now two photons, each with an energy equal to the energy transition ($E_2 - E_1$) that are in phase with each other. This first photon stimulated the emission of a second photon, hence the name **stimulated emission**.

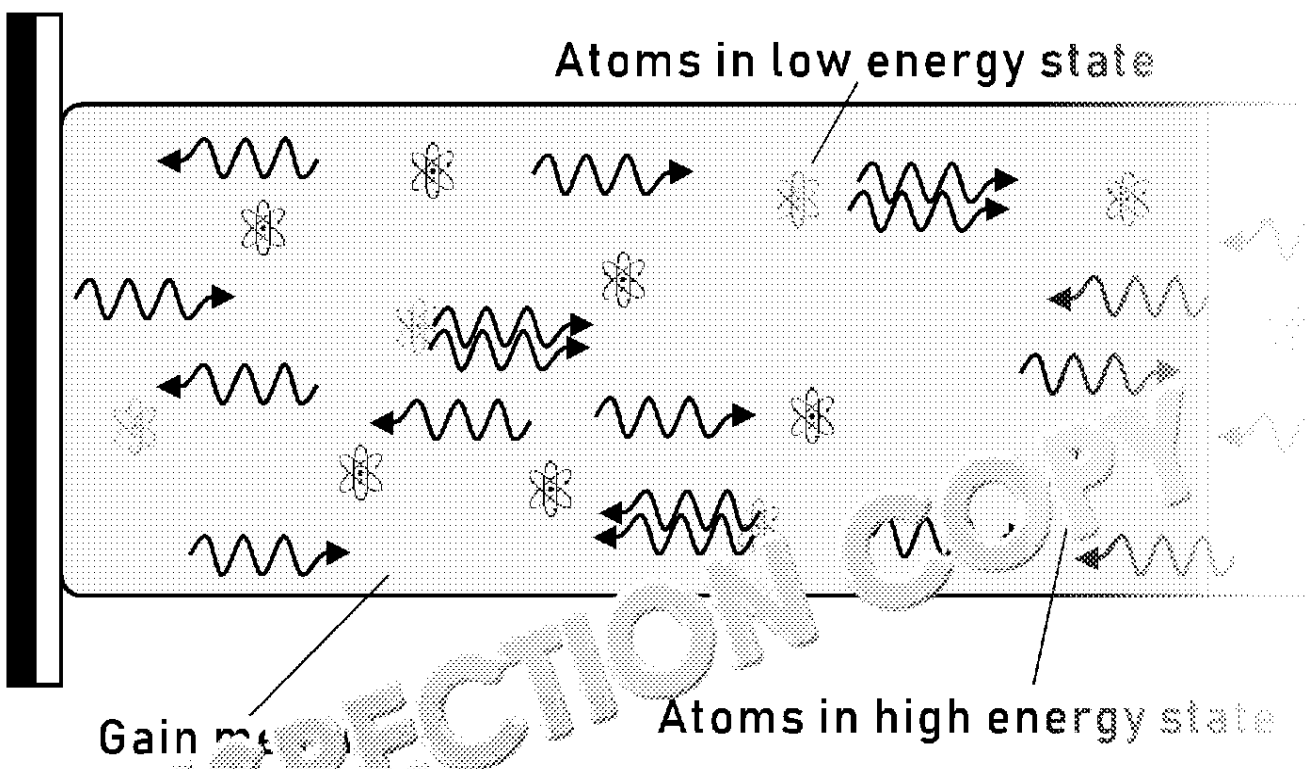


How a laser works

A laser uses the principle of stimulated emission to create many coherent photons o
frequency. The photons are generated using a **gain medium**. This a m l in an
plasma) that is excited by either external light sources (**optical**) or an ele
pumping).

The emission of one photon (via spontaneous emission) from one of the excited ato
start a chain reaction of photon production via stimulated emission. If the number o
larger than the number in the lower energy state, the rate of stimulated em
absorption, resulting in a net gain of photons travelling through the gain medium.

The power of generated photons can be further increased by placing the gain med
(this is called an optical cavity). This is basically adding two mirrors either end
causing it to pass backwards and forwards through the gain medium, stimulating the emissio



This process produces light inside the gain medium. Releasing this light through
a beam of coherent light, useful in many applications. This device is called a L
Light **A**mplification by **E**mission of **R**adiation, or LASER for short.

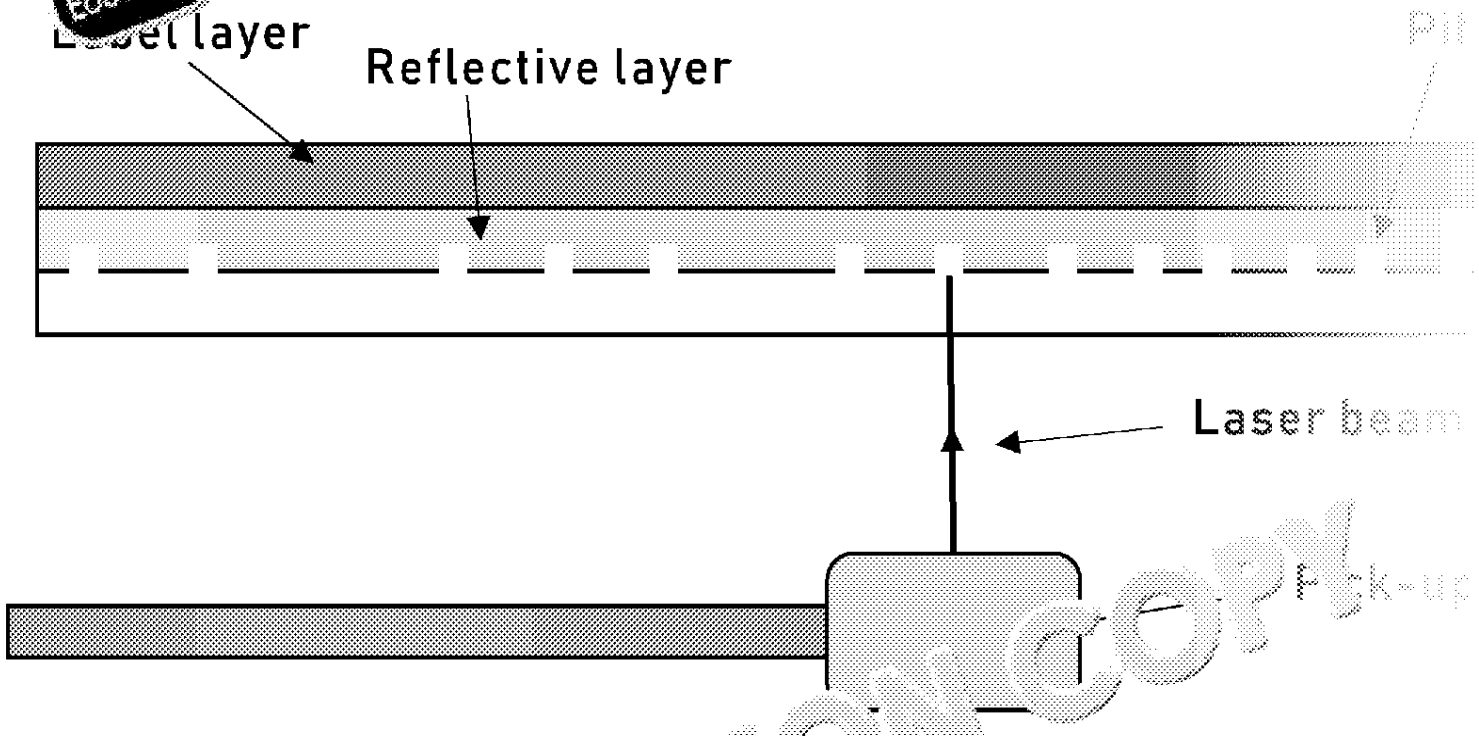
Applications of lasers

Lasers have a huge number of applications, from barcode scanners and optical disc
and cutting-edge research.

Optical disc drives

An optical disc drive is a common method of storing data. Information is stored on
The discs used are split into three types: compact discs (CDs), digital ver[illegible] discs
types are ordered in increasing storage capacity but are also or[illegible]nc[illegible]asing

The basic optical drive is made of a **pick-up hea[illegible]H)** that can move along the r
servomechanism. Information is stored on the [illegible] a series of 'pits' in one line
The PUH usually contains a semi[illegible] a lens for focusing the laser light a
detect the reflected ligh[illegible] di[illegible]. The lens also has a servomechanism to adj
laser light is focus[illegible]ma[illegible]ot on the disc.



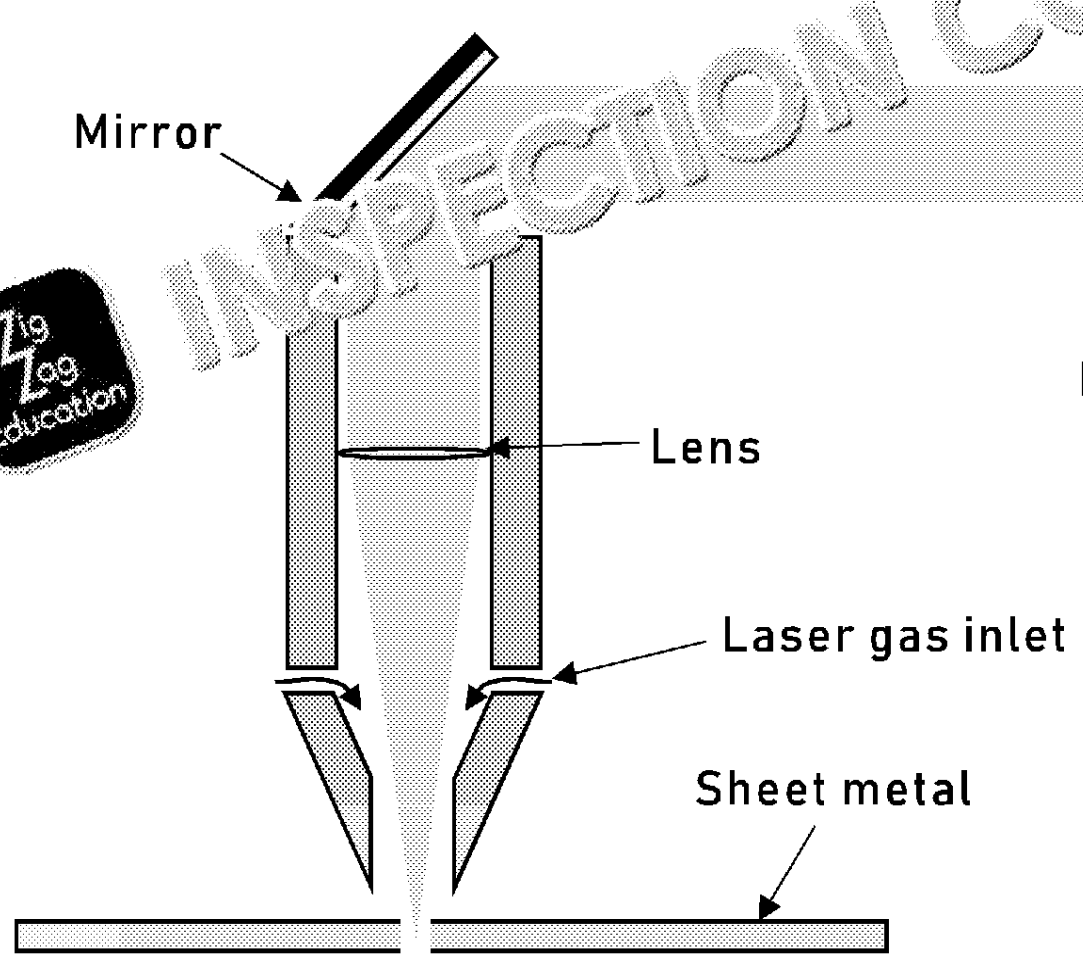
Discs can come in variat[illegible]d-only, recordable (write once) and rewritable
the read-only disc[illegible]M, whi[illegible]comes with pre-written data, such as a music CD.

[illegible]s st[illegible]d as a series of 'pits' and 'raises' in a reflective layer, similar to
[illegible]of each pit is around 1/5 the wavelength of the laser light used. This me
d[illegible]ctively interferes with the incoming laser light. The reduction in amplitude of
the photodiodes, recording the hard-coded information electronically.

To increase the data storage capacity of a disc, the distance between adjacent pits
the pits are read correctly and the laser dot doesn't spread over multiple pits, the
be decreased. This is why the older CDs use infrared light (λ = 780 nm) whereas
light (λ = 405 nm), hence the name Blu-ray.

Laser cutters

Powerful lasers can be used to cut through materials such as stainless steel or alum
head can be moved using servomotors, allowing intricate designs to be cut into the
cleanly and smoothly cuts the metal in comparison to conventi[illegible]ng methods.



The most common laser type used in laser cutting is the C[illegible]er, which uses CO
emits infrared light with a wavelength of about 1[illegible]m. The emitted beam has a diam
reflected off mirrors towards the sheet metal, passing through a lens. The lens focu
point, increasing the intensity of the beam. This also allows a small amount of m
the process efficient compared to conventional cutting techniques.

During cutting, the part being cut, a gas is injected around the point of cutting t
used for mild steel, which is cut using an oxygen-fuelled burning process.
like stainless steel and aluminium, which have lower melting points, so the

Comprehension questions

1. Describe how light is amplified in a gain medium.
2. What is the approximate ratio between the wavelength of light used by a PUH
   created in a disc?
3. Why is a gas used in a laser cutter?

Discussion

With the rise of solid state drives (SSDs) which use microchips (which are faster to re
discs to store information, discuss the future of optical drives and hard discs.

Extension

Lasers come in a variety of [illegible]ratings. Powerful lasers can be dangerous, especia
someone's eye. Each laser is categorised into a class; the higher the
[illegible]at is. Research the laser safety standards and present your findings as

3.3.2 Refraction, diffraction and interference

Keywords	
Photon	An elementary particle that is a quantum excitation of the electr
Focal length	The distance between a lens or parabolic mirror and its point of
Wave function	The property of a particle that describes its position wi

Light is made up of oscillations in the electromagnetic field called photons. These p
macroscopic effects such as absorption, transmission and reflection.

When light is reflected off an object and enters our eye, our brain then determines t
object. The object will absorb and reflect certain wavelengths by different amounts
as the colour of the object.

However, light doesn't interact with everything. This could be because the energy h
energy of incident photons, or the object is much smaller than the wavelength of th
interactions are very rare. So how do we image things which don't interact with ligh

Schlieren photography

Air doesn't interact with light very much. To see any sort of effect, the light must
pass through huge amounts of air, like the scattering of blue light as it propagates
through kilometres of our atmosphere (and hence the sky looks blue). But air has
some density and light propagates through materials of different densities at
different speeds. Materials of higher density, such as water, slow down light
compared to materials of lower density such as air.

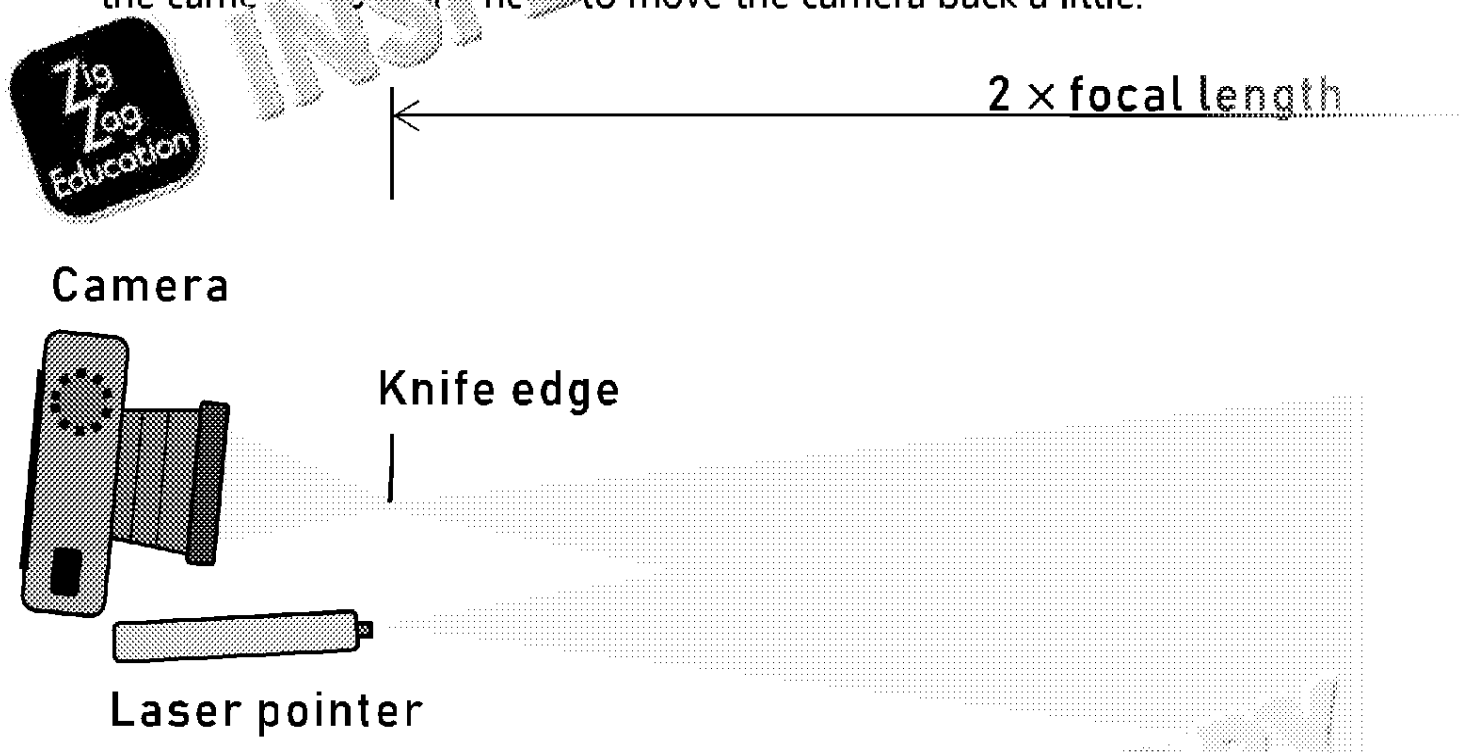
The density of air is not constant. It can vary due to turbulences such as the wind, o
due to pressure changes, like sound. In 1864, August Toepler, a German physicist, was
supersonic motion (faster than the speed of sound). The resulting motion
dense pressure waves in the air.

To see these pressure waves, August Toepler developed an imaging technique calle
('Schlieren' means streak in German. This technique amplifies the refraction of light
of varying density, resulting in images like the image of a flammable liquid set alight
hot, less dense air is seen to rise above the cool, denser air to the sides, similar to th

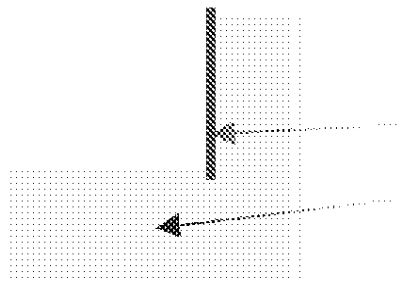
How does it work?

There are a number of ways to set up a schlieren imaging system, the most common below. You will need a high-definition camera, a point source of light such as a laser and a parabolic mirror.

- Set up the camera and light source close together, both pointing in the same direction.
- Then position the parabolic mirror at twice the focal length away from the camera on the diagram below.
- Next, turn the light source on and place the filter or knife edge to cut the reflected light from the camera. Then move the camera back a little.



- The point source of light is reflected by the parabolic mirror and is focused back to the source.
- Angle the mirror slightly so this focused light instead just misses the source and the camera.
- The light should then pass a knife edge or the edge of a colour filter. This edge will block some light going in one direction, but allowing light in a slightly different direction to pass on (see the diagram on the right).



Remember that any variation in density in the air near the mirror will cause reflected light to be blocked. Therefore, some densities of air, say low density, will be blocked by the knife / by the filter and will not pass through. This gives our final image some contrast so we see the different densities.

A small point source of light is used, so any change in direction of the light, due to slight variations in air density, will cause the focused light to miss the normal focal point and create an image in the camera showing the slight variations in air density as light and dark contrast by the knife edge.

Schlieren photography is used a lot in aerospace and aeronautical engineering. Combining the behaviour observed in wind tunnels, and designing models, build a picture of how aerodynamic photography is not unique to variations in air density, however; it can be used to investigate as the temperature diffuses through a tank of water (remember the hotter a fluid is, the less dense it is).

Probing the nanoscale

How do you image something that is too small to interact with the light, such as an something smaller than an atom, like an electron, or use the interaction of the atom two methods that are used in scanning tunnelling microscopy (STM) and atomic for

Scanning tunnelling microscopy (STM)

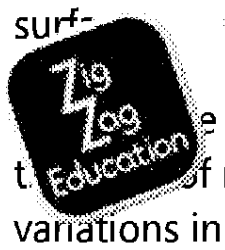
Scanning tunnelling microscope (STM) take advantage of quantum tunnelling. Th a particle to tunnel through a potential energy barrier because its wave function 'sp

The wave function of a particle is a quantum description of the particle and is relate a particular position. The probability of finding a particle far away from t bility of a particle tunnelling through a potential barrier is small, but it isn't

An STM uses a tungsten tip that is close, but not 'touching' the surface of a material that is to be imaged. The word touching doesn't mean much here, because we are talking about the interactions of atoms which never actually touch, just interact via potential fields.

A potential difference is set up between the tip and the material. This decreases the energy barrier between the tip and surface, increasing the tunnelling current that occurs. The tip and surface are connected to a series of actuators (precision motors) and a computer. These work together to keep the tunnelling current, the number of electrons that tunnel from the to the surface (or vice versa), constant.

The tunnelling current is directly proportional to the distance between the tip and surface, so if the surface has a bump in it the tip will raise and lower over the bump. This movement of the tip is recorded by the computer and eventually enough data is collected to generate an image of the topology of the material surface.



The image is the image of a molecular structure shown on the right. To give you a sense of the scale of measurements an STM makes, if the STM were the size of the Eiffel tower the variations in height due to the 'bumps' of each atom would be around 2 cm!

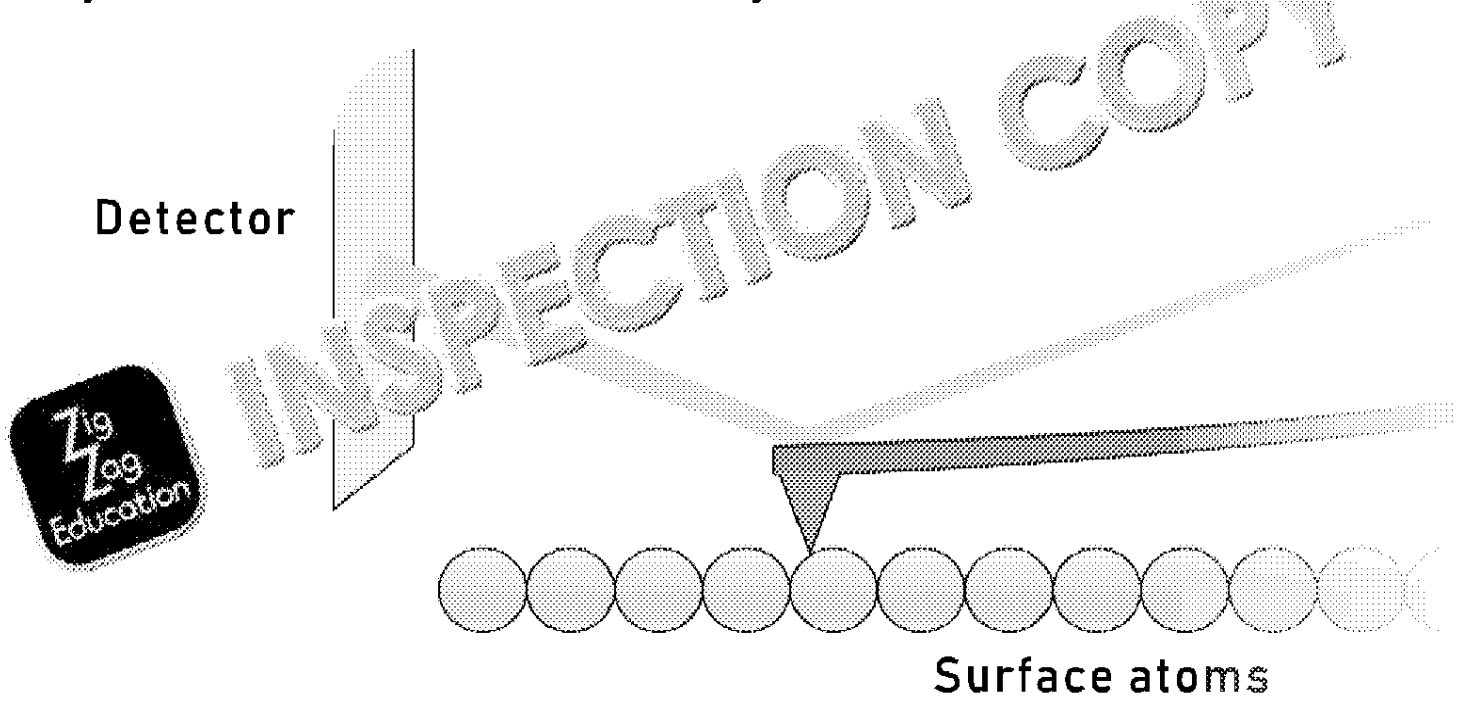
STMs can also be used to manipulate atoms. By allowing the tunnelling current to increase to a particular atom, the tunnelling current increases. This results in an attractive force between the tip which allows the tip to drag and position the atom anywhere on the surface. IBM did this technique called 'A Boy and His Atom' (**https://www.youtube.com/watch?v=oSCX78-8-q0**).

Atomic force microscopy (AFM)

The disadvantage of STMs is that the surface must be able to conduct electricity, or the circuit is incomplete and no potential difference between the surface and tip is set up. Atomic force microscopes, however, can also image the surface of insulating materials.

An AFM uses a technique that is very sensitive to variations in the movement of a tip over a surface. The tip in this case moves up and down purely due to the electrostatic repulsion between the microscopic valleys that we perceive as touch. To measure such tiny variations

The tip used is a cantilever, a spring-like object that will experience a restoring force equilibrium position, such as being pushed up or down by the atoms of the surface of this cantilever, and a detector is positioned in the path of this reflected laser beam away from the surface and cantilever so any small variation in the cantilever's ampli



The difficulty with AFM is the number of sources of forces that can act on the cantil cantilever could be due to:

- **Van der Waals forces**. These are the forces caused by the electrostatic attract is an object that is positively charged on one side, and negatively charged on t (due to the electric field) and attract one another.
- **Electrostatic forces**. These are caused purely by the attraction or repulsion du tip and surface.
- **Chemical forces**. These are caused by the covalent or ionic bonds between at These forces tend to be short range co[illegible] the others.
- **Capillary forces.** A liquid layer on the surface (or condensation in the air) will surface, creating a sort of attraction between the two. The meniscus (the bounda result in strong forces that dominate all other forces. To get around this, the A in water so that no meniscus can form, or is used in a vacuum.

Comprehension questions

1. Name the pieces of apparatus needed to set up a schlieren photography stati
2. Describe how schlieren photography is useful to aerospace engineers.
3. What is meant by quantum tunnelling?
4. Describe capillary forces acting on an AFM and how they can be reduced/remo

Discussion

Discuss the possible applications of STMs and AFMs. Recall that an STM can move surface.

Extension

Research another way to image things with electromagnetic radiation and similar style to this article, on this imaging technique. Possible topics to research are

- electron microscopy
- medical imaging such as ultrasound

Optical Fibres

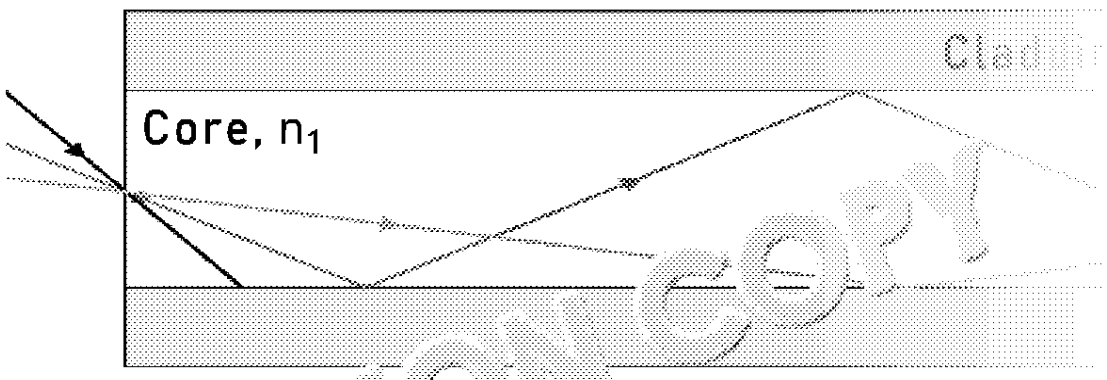
3.3.2.3 Refraction at a plane surface

Keywords	
Cladding	The outer material of a fibre-optic cable with the lower refractive
Core	The inner material of a fibre-optic cable, with the higher refractive
Dispersion	The spreading out of different parts of a signal as it propagates

Optical fibres are a type of waveguide that transmit light in a controlled manner over long distances, modulating light signals resulting in fast (at light speed) data connections between

How they work

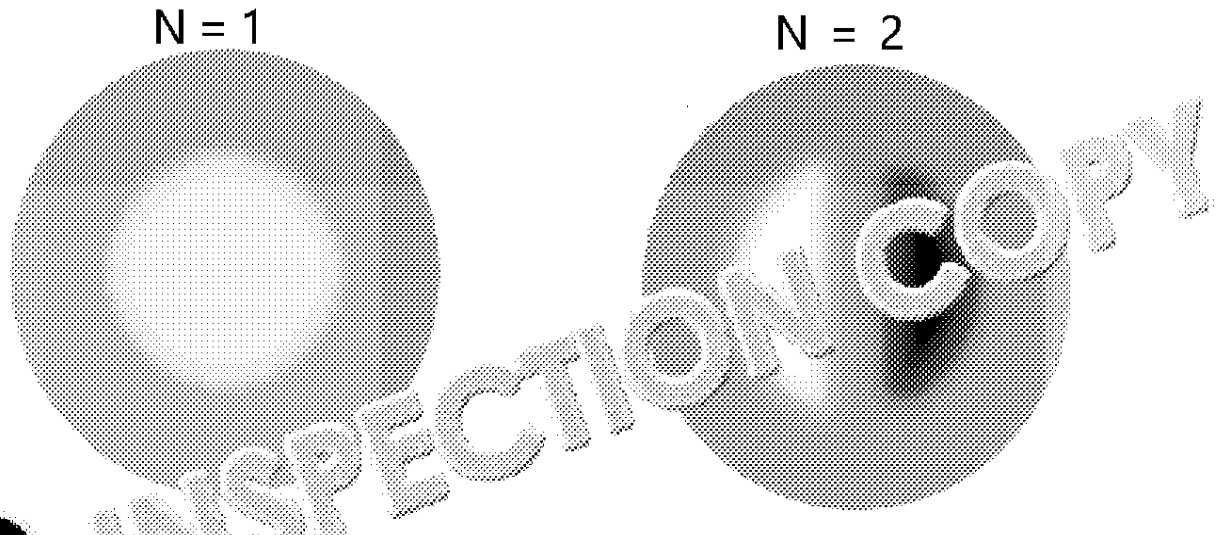
The basic fibre is constructed with a core encased in a cladding. The core has a higher refractive index than the cladding ($n_1 > n_2$), so a light ray that is incident at the boundary between the two materials at greater than the critical angle will be totally reflected. This principle is called total internal reflection and is the basis of how waveguides such as fibre-optic cables.



A waveguide will have a number of modes depending on its dimensions and refractive index. A mode is an electromagnetic field that propagates through the waveguide without changing shape. A waveguide can be constructed with different amounts of the waveguide's modes supported. The principle comes from maths where you can expand trigonometric functions such as

$$\sin(x) = x - \frac{1}{6}x^3 + \frac{1}{120}x^5 - \frac{1}{5040}x^7 + \ldots$$

In this analogy, the powers of x are the different modes and the coefficients in front of each term is how much each mode has to the overall function ($\sin x$). The first three modes ($N = 1,2,3$) for a circular waveguide are shown below:



The white and black represent positive and negative amplitudes of the waveguide. The number of modes a waveguide can hold is finite, typically only a few. A waveguide can also be designed so that only the fundamental mode ($N = 1$) can propagate through it with all others being absorbed. This removes the effect of dispersion but is also expensive to manufacture.

Dispersion

A pulse of light can be made up of many different components that each travel at a travels at the same speed through a vacuum, different wavelengths travel at different even for a single wavelength in a medium, depending on the angle it passes have a shorter path length, meaning it will travel a different distance and take more at the same speed.

If the length of the fibre-optic cable is long enough, these different components ca times, which could interfere with the reading of the signal. There are three types of

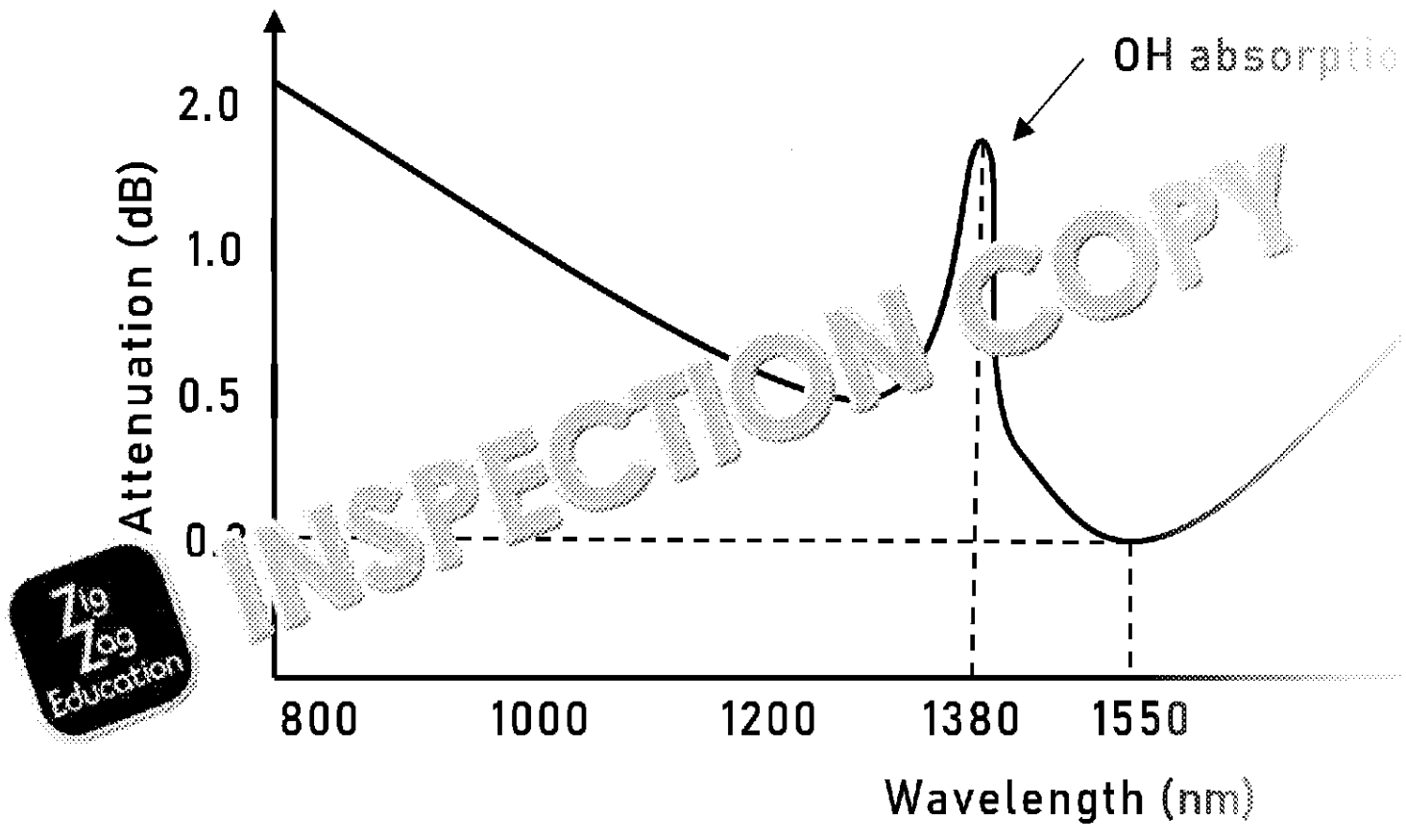
1. **Intermodal dispersion**: Different modes in a multi-mode fibre have different p fibre were invented to remove this type of dispersion. Single-mode fibr ver, so the cheaper multi-mode fibres are used for short-distance transm
2. **Chromatic dispersion**: Different frequencies of light (i.e. different colours, also radiation outside the visible part of the spectrum) travel at different speeds. Th subdivided into two other types of dispersion:
   - Material dispersion: The refractive index of a material may vary depending travelling through it.
   - Waveguide dispersion: The way the materials have been used to make the frequency dependence on the refractive index, even though the materials dependence.

   A pulse of light will have a range of frequencies when generated, meaning the propagation. For a high density of information, as in today's signal transmissio which becomes a problem. A regenerator is positioned at 50–100 km intervals a signal and remove this chromatic dispersive effect. Also, using laser light (coher frequency) reduces the effect of this dispersion.
3. **Polarisation mode dispersion**: Different polarisations of modes can also trave the light before it enters the fibre will remove this effect.

Attenuation

Material is completely transparent to all wavelengths of light. The atoms of the wavelengths, exciting their electrons to higher energy levels. Combine this with the will be exempt from impurities, which results in the absorption of some light propag

The longer the signal travels down a fibre, the more light is absorbed. The measure light is called its attenuation and is measured in decibels, dB. Below is the absorptio common material in fibre optics.



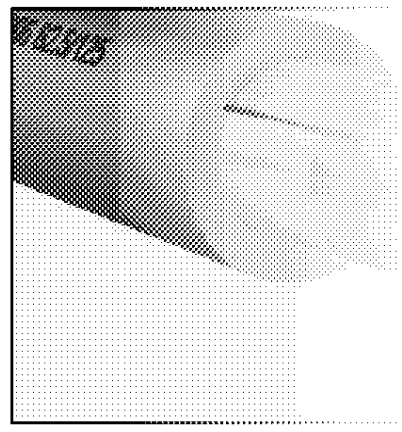
From the attenuation spectrum of silica it can be seen that the wavelengths of 155[illegible] the spectrum) experience the lowest attenuation, which is why this wavelength is us[illegible] communications. The peak at 1380 nm is caused by O–H bonds (oxygen and hydro[illegible] This impurity is mainly water, which is why fibre-optic cables must be m[illegible]actured also why food, which contains water, heats up in a microwave.

Silica glass is typically used as both the core and cladding in optical fibres, with the[illegible] small amount of material to slightly decrease its refractive index. Optical fibres wor[illegible] the core and cladding are very similar, with a typical difference of less than 1 %.

Real-world fibre optics

[illegible]ntic cables

[illegible]res are used to transmit data between continents. For example, a transatlantic telecommunications cable (TAT) connects Europe to North America via a shielded optical fibre (see right). A network of these cables ensures large amounts of data can continuously be sent between the continents. Without them, we wouldn't be able to use websites based in America, or make phone calls to people across the pond.



These cables run along the sea bed, placed by a large boat that unreels them over t[illegible] one coast to the other. A robot then moves across the sea floor (as it's t[illegible]eep for[illegible] using water jets to dig a trench and lay the cable in. The cable [illegible]ab[illegible] to with[illegible] its environment.

The most common fault in TATs is a break, usually due to an anchor from a boat dragging and cutting the cable. To reduce the risk of this happening, cables are buried and have layers and layers of shielding, as seen in the cross section of a TAT above.

[illegible]pes

[illegible] fibre can also transmit an image. This makes them very useful in [illegible]icine and industry because optical fibres are thin and can bend around corners without distorting the image (there is a limit to how much a fibre bends before the signal is distorted, however).

An endoscope is used in medicine to get a better look at something within the body. It's made of two fibre-optic cables that both join to the capturing lens. The first fibre-optic cable is used to supply a light source. Light travels down this cable into the body, reflects off the part of the body that is to be looked at, and then is reflected into the second fibre-optic cable. This image is sent through the second cable up to the doctor's eye.

Optical fibres are also used in cutting-edge research into stimulating synapses. A synapse is the tiny gap between two neurone cells in the nervous system (including the brain) that transmit signal as electrical impulses. By manually stimulating synapses with fibres for diseases like motor neurone disease can be researched and treated. Optical fibres that use infrared radiation for stimulation have the advantage of sending a precise impulse at the synapse with physical contact (no inflammation from injury, etc.); however, it can [illegible]ting in the tissue.

Comprehension questions

1. Draw an image that represents the second mode of an optical fibre.
2. What type of fibre-optic cable is used for short distance transmission and why
3. Describe one type of dispersion.
4. What wavelength of light is typically used in fibre-optic cables made of silica, a

Discussion

Communication satellites are becoming ever more popular and it is predicted that t
telecommunication cables we currently use today. The connection speeds will be ab
currently performed by TATs. Discuss the advantages and disadvantages of
ation satellites.

Extension

A photonic crystal fibre is created using only one material. An array of 'holes' acts a
whereas the centre is purely the material used and acts like the core. Research phot
report on the research currently being done on them.

Big Engineering: The International S

3.4 Mechanics and materials

Keywords	
Monolithic	An object built with one piece
Orbit	The curved trajectory of … caused by the gravitational at… orbits
Module	A self-… unit that combines with other modules to mak…

The …nati… Station (ISS) is the largest structure ever built by humans in … the necessary materials into space and constructing the structure in a mic… …dertaking, but is worth the data and experience we gain about living and

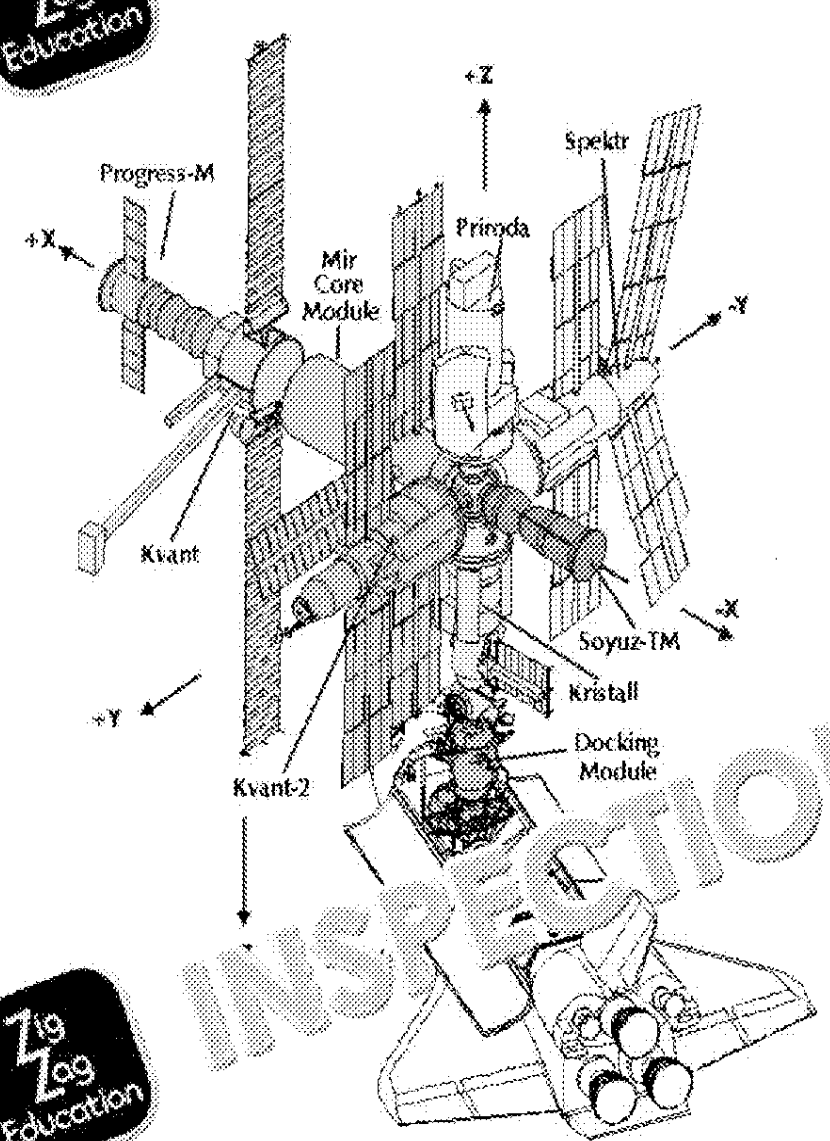
Before the ISS

The first ever space station was the Salyut 1; a monolithic (launched in one piece) space station launched on 19th April 1971 by the Soviet Union. It stayed in orbit for 175 days before re-entering on 11th October.

The following six Salyut missions throughout the seventies were all successful, apart from one which failed during its launch. All monolithic space stations were sent into space unmanned, so th… failed missions only resulted in financial loss.

A Soyuz … Salyut 1

The last Salyut mission, Salyut 7, stayed in o… …nger than its predecessors, a total of 3216 days … 198… and 1991. However, it was only occupied by … 16… days, up until June 1986. Salyut 7 provided the leg… …ansition between monolithic space st… and … stations, the type used today.



The space shuttle Atlantis docking with Mir

Using everything they had learn… the Soviets launched their first … into low Earth orbit in 1986. Mi… habitable modules and several … in space. These modules were … in orbit using six launches of the … launch of the American space sh… module in 1995.

This was the first long-term spa… human presence – the space sta… years, twelve and … of which had a conti… …bitation of … longe… suc… …ord until it was …

M… was a centre for groundbrea… collaborations between scientist… UK, France, Germany, Hungary, … studies took advantage of micro… positioning, including experime… space on humans, plants and an… biotechnologies which were pre… comparably high gravity; testing… future missions; astrophysics ex… molecules taken from space; an…

allowed monitoring of climate change, changing land use, weather systems and nat
than simply a scientific laboratory – with tensions high surrounding the Soviet Unio
scientific collaboration which broke language and cultural barriers was an importan

After the Soviet Union (USSR) collapsed in 1991, the operation of the Mir space stat
Russian Federal Space agency (now known as Roscosmos) was decided to deorbit
1999 due to a lack of funding. Mir broke up in the Earth's atmosphere in the early h
21st March 2001. How a satellite behaves during its deorbit is very unpredictable be
speed trajectory through the increasing density of Earth's atmosphere introduces s
making any prediction of the numerous fragments may end up difficult.

NASA had two space stations in orbit before the ISS was built. The first was Sky
launched the Saturn V rocket (the rocket that took man to the moon). Three
1973 and 1979 before its re-entry above Perth, Australia on 11th July 1979.
international media event creating excitement and panic, so much so the president
on national television to calm the nation. NASA said the chance of debris hitting a

Building the ISS

The first module of the ISS was the Russian Zarya module, launched on 20th November 1998. Two weeks later, space shuttle Endeavour brought the Unity module to be connected to Zarya, laying the foundations of the American and Russian partnership to build the ISS that would later follow. The ISS wasn't manned until after 26th July 2000, when the third module, the Russian Zvezda was added. Since then, another 29 launches have taken up modules and sections built by NASA, Roscosmos, the Japan Aerospace Exploration Agency (JAXA), the Canadian Space Agency (CSA) and the European Space Agency (ESA) to the space station to be fitted, making the ISS an international collaboration.

On 14th April 2001 the shuttle Endeavour took the Canadarm2 to the ISS, a robotic arm built by the CSA that helps with docking and maintenance of the ISS. On 8th April 2016, A Falcon 9 rocket launched by SpaceX took the Bigelow Expandable activity module to the space station. This module is flat packed until it reaches its destination, then is inflated up to its operational size. The hope is for future space infrastructure to use a similar principle in launch vehicles. The launch by the Falcon 9 was the first time a private company to be fitted, and was the first module to be fitted in nearly five years.

The ISS is split into two parts, The US orbital section (USOS) and the Russian orbital section (ROS). Astronauts and cosmonauts can easily travel between the two, but generally stick to their own sections.

The ISS provides a microgravity and space environment for many experiments to be carried out in. Since January 2018, 230 people from 18 countries have visited the ISS. It only has a capacity of six people at one time, so astronauts and cosmonauts tend to stay at the space station for six months at a time. There have been exceptions, as in 2015/2016 when astronaut Scott Kelly and cosmonaut Mikhail Kornienko both stayed on the ISS for a year. Kelly has a twin, Mark, who stayed on Earth during the mission. When Scott came back, the two were medically examined to determine the differences and changes the space environment causes to the human body.

A picture taken of the Earth from board the space shuttle

The results provided more evidence the human body does indeed change in space:

- Our bones become less dense and muscles waste away – because of this, it's i astronauts to keep up a strict exercise regime, to remain healthy on their retur
- Humans grow a few inches taller – without the constant pressure of gravity, as fact, in January 2018, the three inches Japanese astronaut [illegible] K[illegible]ai had over the 6 foot height limit for astronauts, and he feared he might be too tall t (Thankfully, this height limit has a little wiggle room and he made it home safel
- Although the space station has shielding, cosmic radiation is still much higher stint in space can raise an astronaut's risk of cancer. Astronauts can even see t report seeing intense flashes of light in their vision while in space, which i passing through their eyes and producing reactions.
- [illegible] are also some unexpected effects; red blood cell production decreases, deform and produce eyesight problems, and changes to DNA have even

However, when an astronaut returns to Earth, most of these changes revert back to interesting change is the lengthening of telomeres, the end parts of chromosomes this mean that living in space makes you younger?

Another interesting finding from studying astronauts is the difference between men more research needs to be done, but preliminary findings suggest that women's ey impairment than men, whereas men are less likely to faint when standing after retur lose less blood in space.

Breaking the ISS

All good things must come to an end and the ISS is no exception. NASA have com 2025, whereas Roscosmos have endorsed the RC[illegible]il 2024. Currently, the Soyuz supplies and astronauts to the ISS; however this will change in 2019 and 2020 when and CTS-100 (Boeing) will come into operation. Talks are also underway to extend as well as a new joint partnership between NASA and Roscosmos to develop the re

Revision questions

1. In total, how may Salyut missions were successful?
2. What was significant about the re-entry of Skylab?
3. What are the names of the two sections of the ISS?
4. Name two changes to the human body when in space for extended periods of

Discussion

The research from the ISS helps us understand how humans can travel and live in sp is important to carry out this research.

Extension

The replacement for the ISS will likely be designed over the next 10 years to be ope In 20 years' time there will likely be an occupied location on the Moon and possibly more th Come up with properties the replacement for the ISS (in a similar orbit around Earth space exploration in 20 years' time.

Fluid Dynamics: Going with t

3.4 Mechanics and materials

Keywords	
Fluid	A substance that easily flows and is susceptible to external force
Viscosity	The measure of resistance to internal forces by a fluid due to int
Fluid packet	A piece of a fluid with constant mass but changing volume and s

A fluid is a substance that has no fixed shape but instead can flow and take the shap
pl[illegible] all fluids. Fluid dynamics is the study of fluids as they chang
variables involved in such a system makes it a very complex branch of ph
l[illegible]e of applications; from aerospace and marine engineering to rocket scien
dynamics found in fusion reactors or stars.

A three-dimensional viscous fluid can be described with just five equations:

1. **A continuity equation**. This ensures that for a given volume in the fluid, the total mass in the volume + any new mass that enters the volume – any mas is continuous with time, i.e. we don't randomly gain/lose mass in our fluid.
2. **Three Navier–Stokes equations**. These equations describe how fluid packets fluids) interact with each other. There are three equations, [illegible] spatial
3. **An energy equation**. Called the Bernoulli equation, this equates that energy i

The Navier–Stokes equations

These equations are the heart and soul of fluid dynamics. They are derived from ste
Ne[illegible]s th[illegible] still has not been proven if solutions for the equations ex
[illegible]s or[illegible] the big problems in mathematics, with a $1,000,000 prize for who

T[illegible]utions from this equation, researchers instead use computers to basically
they find the ones that work. This brute force approach will only give an approxima
depends on the computing time and power. The longer the program runs the calcu
computing power, the more precise the calculated solution is.

The Navier–Stokes equation describes fluids with Newtonian viscosity; any force will
the rate of change of velocity at the point, i.e. Newton's 2nd law. Most fluids have N
of a non-Newtonian fluid is custard. It's possible to move a spoon through custard
change in velocity will result in the custard in being very viscous and rigid.

The model used to describe fluids is similar to the particle model used to describe gases, but instead particles are replaced with fluid pa[illegible] (also called fluid parcels). These are very small 'pieces' of fluid with constant mass but which can have a changing volume and shape. The Navier–Stokes equation describes how all these fluid packets interact with one another.

Based
custard
m/wat

For simplicity we will only consider the Navier–Stokes equation in one dimension. It
ex[illegible] in the x-direction:

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{dx} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{4}{3}\frac{\eta}{\rho}\frac{\partial^2 v}{\partial x^2}$$

Note: The x direction is chosen to be in the horizontal plane, so gravity does not pl
Navier–Stokes equation will have an extra gravitational term on the right-hand side

$\frac{\partial v}{\partial t}$	Partial derivative of the velocity with respect to tim This is called the **temporal derivative te** ra makes the equation dynamic (changing wi time
$\frac{\partial v}{dx}$	Partial derivative of ve. y with respect to position, x.
$\frac{\partial p}{\partial x}$	al derivative of the pressure with respect to on, x.
$\frac{\partial^2 v}{\partial x^2}$	The second partial derivative of the velocity with respect to position, x.
ρ	Density of fluid
p	Pressure of fluid
η	Viscosity of fluid

The three-dimensional Navier–Stokes equation is a lot more complicated, because t
dimension are all dependent on each other.

The nondimensionalised Navier–Stokes equatio

Computers can't understand equations of physics, they can only calculate solutions
the computational physicists to understand the results. To make an equation of phy
first be nondimensionalised. This process basically removes all the units from each
nondimensionalised 1D Navier–Stokes equations:

$$\left(\frac{l_0}{t_0 v_0}\right)\frac{\partial v}{\partial t} + v\frac{\partial v}{dx} = -\left(\frac{p_0}{\rho v_0^2}\right)\frac{\partial p}{\partial x} + \left(\frac{\eta}{\rho v_0 l_0}\right)\frac{\partial^2 v}{\partial x^2}$$

sionless Navier–Stokes equation has three constants that determine how
larger the constant, the more effect that term has). If a constant is really small, we c

$\frac{l_0}{t_0 v_0}$ This term determines the acceleration of fluid packets in a fluid
fast (small t_0) compared to the size parameter of the system, l_0
be large.

$\frac{p_0}{\rho v_0^2}$ This term is the ratio of the pressure and kinetic energy of the s
kinetic energy, there is no dynamic system to describe and so

$\frac{\eta}{\rho v_0 l_0}$ This term is equal to the inverse of the **Reynolds number**, $\frac{1}{Re}$
inertial force ($\rho v_0 \propto$ momentum) and the viscou

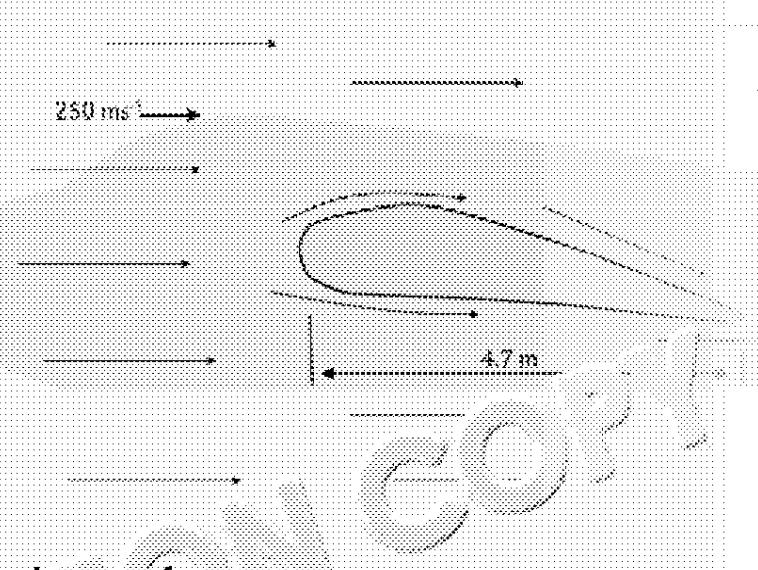
> Inertia is the property of an obje to k
> moving if it has velo al
> therefore, th an exerts on other
> obj its p due to its motion (think of
> pushing through snow).

The Reynolds number

This number is an important quantity in fluid dynamics. For low Reynolds numbers dominated by laminar flow (comparable to sheets of paper sliding past each other), numbers the flow of the fluid becomes more turbulent (compar[illegible] useful because it doesn't matter what the exact values of [illegible] just what the based on this principle that engineers will scale t[illegible] object, say an aircraft, keeping the Reynolds number constant [illegible] engineers can test the aerodynam tunnel using a much smaller [illegible]. As long as the shape is the same, the Reynolds model in the wind tu[illegible] aircraft during flight and the fluid dynamic

Example

[illegible] flies at 250 m s^{-1} at an altitude of 15 km. The density and viscosity of air $\rho = 0.20$ kg m^{-3} and $\eta = 1.4 \times 10^{-5}$ N s m^{-2}. The width of the cross section of the $l_0 = 4.7$ m.



The Reynolds number in this case is therefo[illegible]

$$Re = \frac{\rho v_0 l_0}{\eta} = \frac{0.2 \times 250 \times 4.7}{1.4 \times 10^{-5}} = 1.7 \times 10^{7}$$

[illegible] is really large, meaning the fluid flow will be turbulent around the [illegible] of the Reynolds number, $\frac{1}{Re}$, determines how much the inertial term con[illegible] equation. For this plane wing the term is negligible (viscosity forces dominate [illegible]

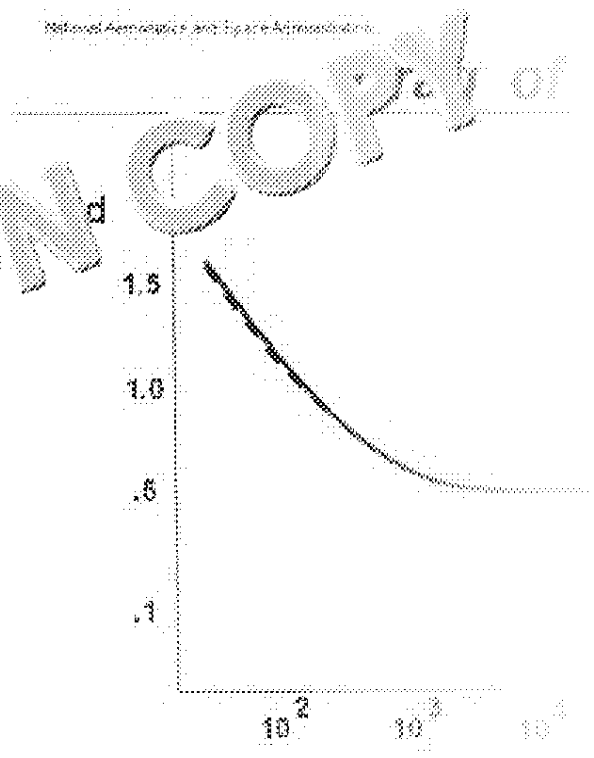
Dragging on

Any object that moves through a fluid will experience a drag force caused by the friction between the fluid packets and the object. The magnitude of the force can be calculated using the drag equation:

$$F_D = \frac{1}{2}\rho v^2 A C_D$$

The drag coefficient depends on the shape object and the Reynolds number.

For low Reynolds numbers (high viscosity, low speed), the drag coefficient, C_D, is inversely proportional to the Reynolds number, Re. The result is that the drag force is proportional to the velocity of the object, $F_D \propto v$.



For high Reynolds numbers, the drag coefficient tends to stay constant, resulting in proportional to the square of the speed, $F_D \propto v^2$. Above is a graph showing the drag Reynolds number for a sphere.

F_D – Force exerted by fluid on object (N)
ρ – Density of fluid (kg m^{-3})
v – Velocity of fluid relative to object (m s^{-1})
A – Cross-sectional area of object (m^2)
C_D – Drag coefficient (dimensionless)

But what's the point?

The above mentioned theory has a strong basis in many fields of research and develo of which are described below.

Weather prediction

Weather is the state of the atmosphere in a certain place at a certain time. The atm changes and interacts with itself in a highly complex manner. The sheer size of the the weather at a certain place very difficult. The weather also depends on the dyna from the Sun during the day, the rotation of the Earth, etc., which all further compli

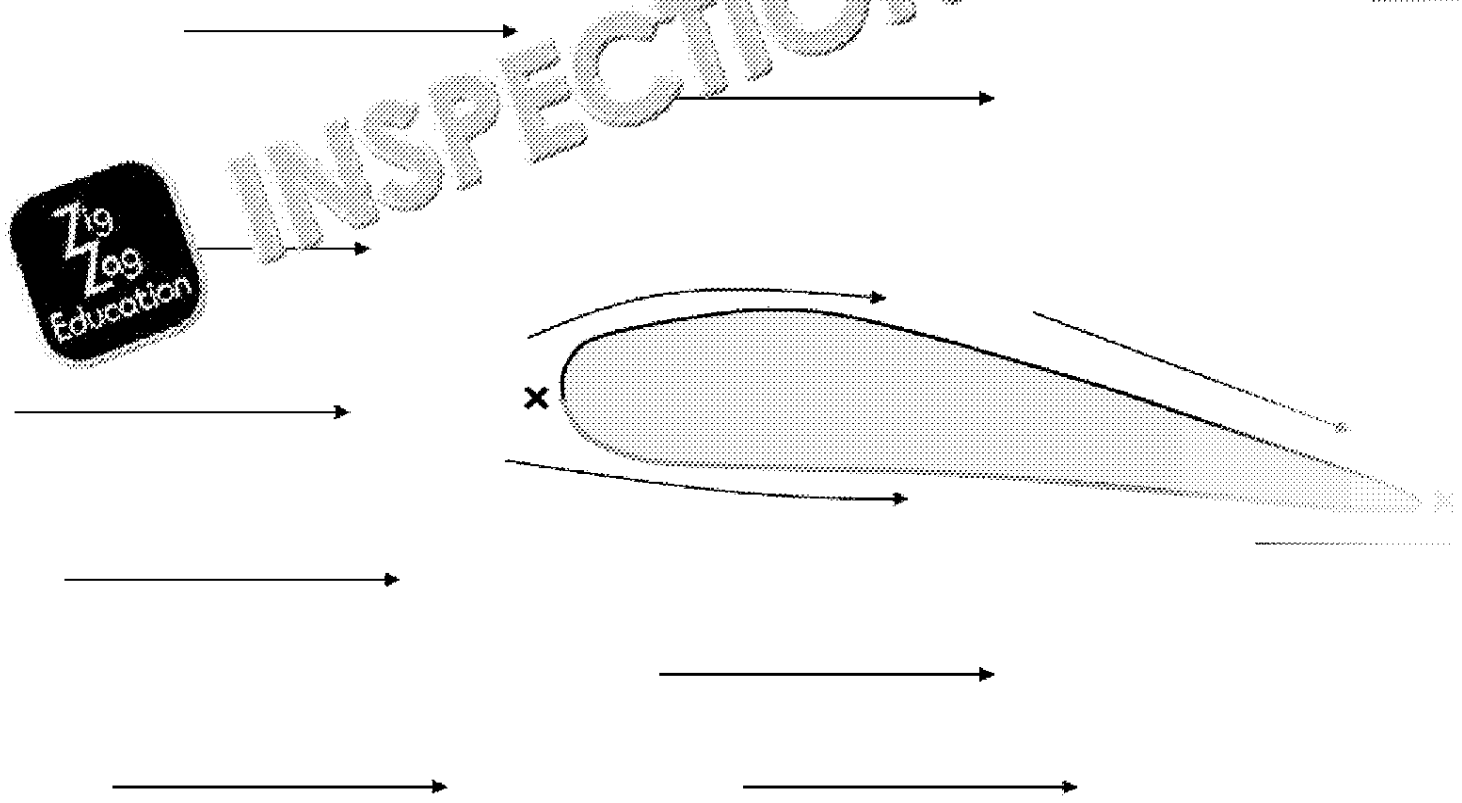
Fluid dynamics, mainly the Navier–Stokes equation, can be used in conjunction with the possible future states of the weather for a certain place. The most likely outcom people in that place.

The primary goal of predicting the weather isn't just so we can decide what clothes any changes that could lead to natural disasters (e.g. storms, tornados, typhoons to increased risk of forest fires), flooding, etc. Getting a warning out to the right pe correct precautions being taken ultimately saving lives. Weather prediction also al precautions before weather changes, increasing their yield and improving the ef also allows weather forecasters to plan their route so as not to be caught in storms, reduci flights.

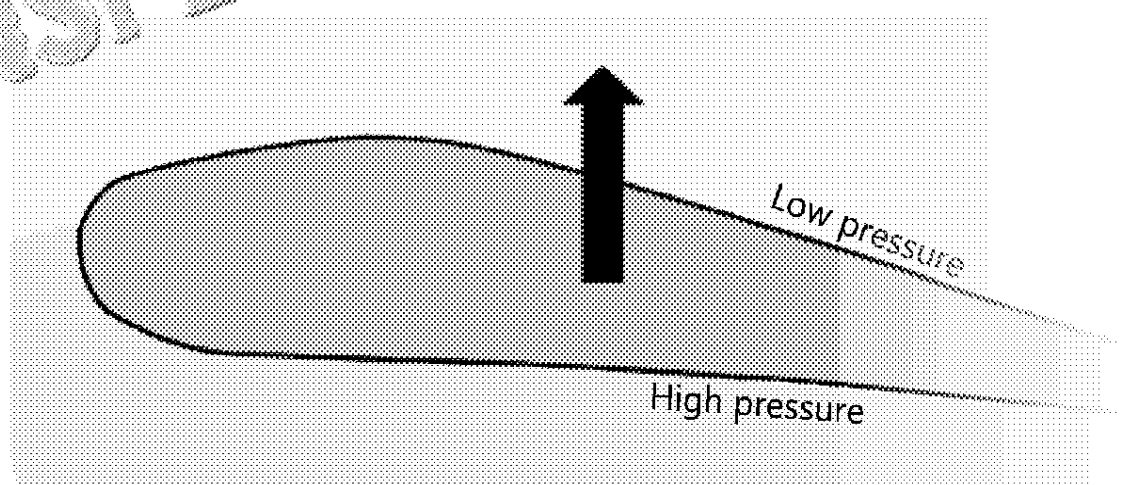
Aerofoils and hydrofoils

Anyone that has lived on Earth knows that air and water are in great abundance. Bo
behave in accordance with the theory of fluid dynamics. As humans hav advanced
of fluids has been exploited to provide us with quicker means of t rt, including

Fluids can be manipulated with an object called a foi A diagram of a foil is shown



The foil splits the fluid into two parts at the first point marked with a ✕. The path
bottom of the foil (in grey) is shorter than the path along the top of the foil (in
both parts of the fluid to meet at the second ✕ at the same time. Therefore, the flu
flow faster. Bernoulli's principle states that an increase in velocity of a fluid results in
difference in speeds of the two parts of the fluid therefore, creates a pressure differ
force called upthrust.



If the foil operates in air, it's called an aerofoil, more commonly known as a wing.
If it operates in water, it's called a hydrofoil.

Boats using hydrofoils are uncommon but do exist. Their main purpose is to
create upthrust from the flowing water, pushing the boat up and out of the
water, reducing friction between the hull and water, allowing the boat to reach
much higher speeds.

Comprehension questions

1. Name the five equations that can describe the dynamical evolution of a fluid.
2. Write down an equation that can be used to calculate the Reynolds number of
3. A rocket is part way through its launch at an altitude of 28 [illegible] density of a 2.46×10^{-2} kg m^{-3} and the rocket is travelling at 1.8 [illegible] m s^{-1}. If the rocket has a [illegible] and a drag coefficient of 0.15, what is the drag force acting on the rocket at this
4. Describe how a foil produces upthrust when it is subjected to a flowing fluid.

Discussion

[illegible]e importance of funding research into chaotic systems, such as fluids, if the [illegible] getting an exact solution to their behaviour.

Extension

Foils aren't just used as wings for planes or as a source of upthrust for hydrofoil boa[illegible] other use of foils and present your findings as a factsheet about the application.

3.4.1 Force, energy and momentum

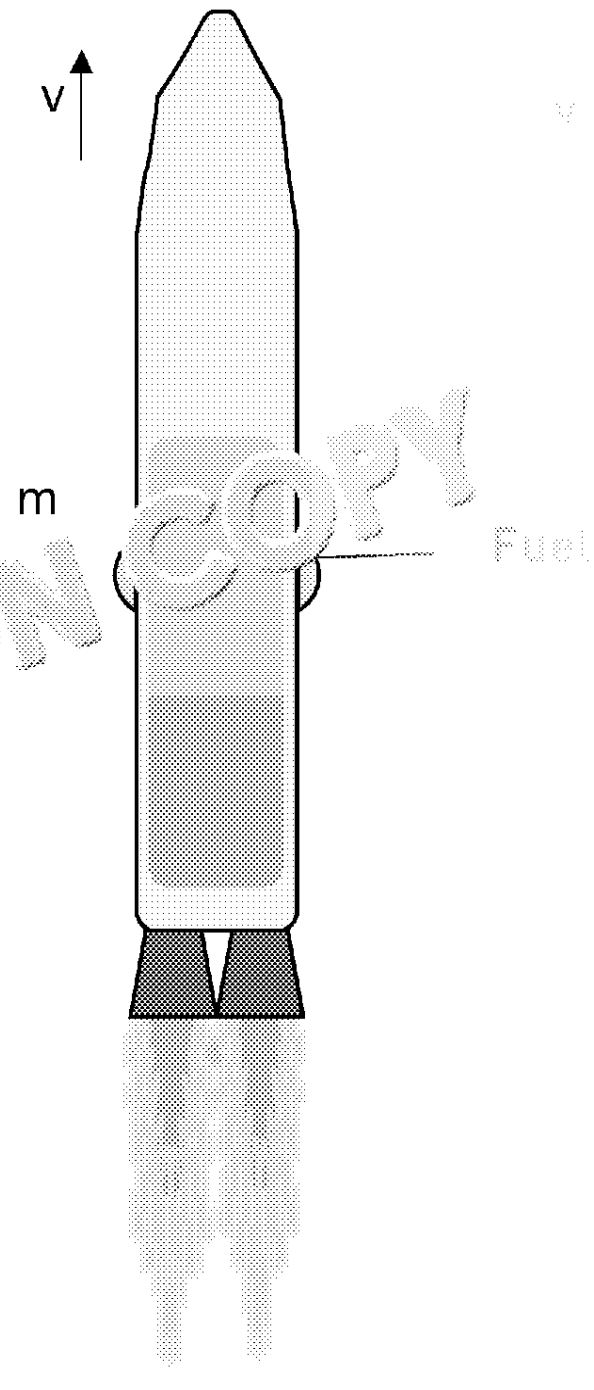
Keywords	
Exhaust gases	The burnt propellant that exit th eng ne of a rocket at high ve
Orbit	The path of an obje t s t is v tionally bound to another ob
Eccentricity	The measure of how ell ellipse is stretched compared to a

Rockets have t e u space, allowed us to build an array of satellites for comm ons, allowed us to send probes deep into the solar system and interstellar on. But realistically, how hard is the science behind them?

Rocket physics

Disclaimer: All of the following maths you will come across if you study A Level Maths.

You will be familiar with the motion of projectiles and how they behave in gravity. A rocket is a type of projectile, so the equations you have come across apply. The issue with rockets is the majority of their mass is their fuel. They use this fuel as they launch, meaning their mass changes throughout the flight.



To start let's consider a rocket at two different times during its launch, t_1 and t_2.

To derive the equation, we equate the momentum due to the exhaust gases released between t_1 and t_2 to equal the change in momentum of the rocket. Let's build an equation that describes this in terms of the impulses experienced by the rocket and exhaust gases between t_1 and t_2 (ignoring gravity and air resistance):

Initial momentum of rocket and fuel.

$t = t_1$

$$mv = -\delta m v_e + (m - \delta m)(v + \delta v)$$

Final momentum of exhaust gases. It's negati bec a ar do n ar s.

Final momentum of rocket a r sed f el

Ke
– Initial mass of rocke
δm – Change in mass o
v – Initial velocity of roc
δv – Change in velocity
δm_e – Change in mass o
v_e – Velocity of exhaust

Expanding this gives:

$$mv = -v_e\delta m + mv + m\delta v - v\delta m - \delta m\delta v$$

We can ignore the last term $\delta m\delta v$ because we assume the change in mass and velocity is small, making this term negligble. Cancelling other terms gives:

$$0 = -v_e\delta m - v\delta m + m\delta v$$

This equation describes the motion between t_1 and t_2. Dividing by the change in time to get a more ... equation with infinitesimal changes, i.e. a ... equation:

$$0 = m\frac{dv}{dt} - (v+v_e)\frac{dm}{dt}$$

$$m\frac{dv}{dt} = (v + v_e)\frac{dm}{dt}$$

You may recongise the left-hand side as Newton's second law, the right-hand side is a slight variation of this with a changing mass. So the force, also called the thrust, acting on the rocket is given by:

$$T = (v + v_e)\frac{dm}{dt}$$

Key
T – Thrust

The term $v + v_e$ is the velocity of the exhaust gases relative to the rocket ... the exhaust gases leave the rocket ... is to be a constant ... ut the ... Therefore, our equation says ... the change in mass, i.e. the more exhaust gases the rocket spits out the back, the larger the thrust on the rocket – makes sense.

δv is given by:

$$\delta v = \left(v + v_e\right)\frac{\delta m}{m}$$

Key
v_i – Initial velocity of rocket
v_f – Final velocity of rocket
m_i – Initial mass of rocket
m_f – Final mass of rocket

Integrating this gives:

$$v_f = \left(v + v_e\right)\ln\left(\frac{m_i}{m_f}\right) ...$$

$$\int_{v_i}^{v_f} \delta v = (v+v_e)\int_{m_f}^{m_i} \frac{1}{m}\delta m$$

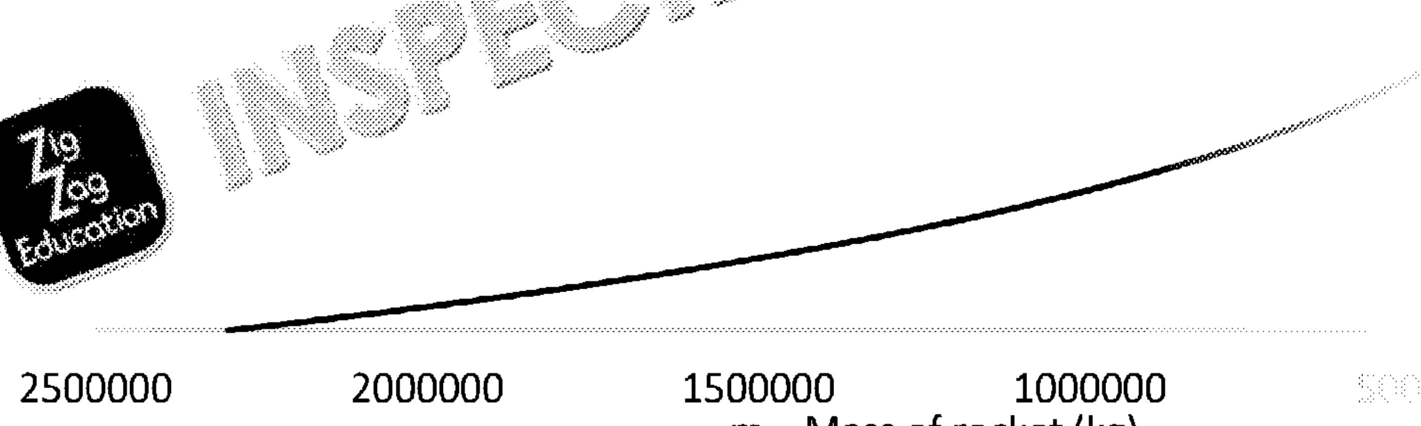
$$v_f - v_i = \left(v + v_e\right)\ln\left(...\right)$$

Which gives us the ve... time after some initial ... that $v + v_e$ is a consta...

Below is a plot of this ... Notice how as the roc... burning fuel, its accel... without including air ... altitude (less air at hig... effects of air resistan... resultant force acting ...

Key
F_r – Resultant force
C – Drag coefficien...
ρ – Density of air
A – Cross-sectiona... direction of motio...
g – Gravitational fi...

Note how the mass o... the rocket, v, the den... field strength, g, and ... mass, $\frac{dm}{dt}$, are all variab... on the rocket, and th... vertically upwards th... reality rockets will an... the Earth. This is one ... science is so complica...



Orbital mechanics

Getting into space is the hard part. The vast majority of the mass of a rocket is the fuel in the launch stage.

During launch the rocket will angle itself so it ends up on a trajectory to its desired orbit. This is basically a projectile's trajectory with enough horizontal velocity that it constantly misses falling back down.

The rocket tends to have multiple stages (different engine designs work efficiently at different speeds). Once the last stage has deployed the cargo into space, say a new space telescope, the rocket stage is no longer necessary (although new commercial rockets land themselves, reducing the cost of space travel). The telescope is now in free flight, only acted upon by the Earth's gravity.

An object can orbit the Earth (or any object with a gravitational pull) in four ways:

- circular
- elliptical
- parabolic
- hyperbolic

Circular orbits are realistically impossible and parabolic and hyperbolic orbits only describe fly-bys rather than a repetition of motion. Therefore, we will focus on elliptical orbits.

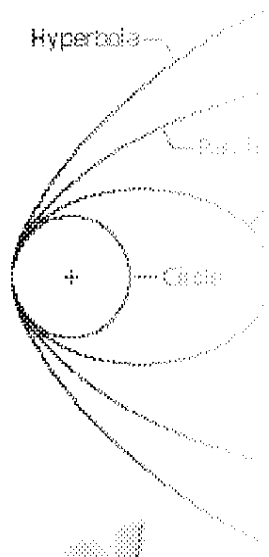
An ellipse is a stretched circle. Instead of one centre it has two, called focal points. The sum of the distance from one focal point, A, to a point on the ellipse, C, and the distance from the other focal point, B, to the point on the ellipse, C, is a constant.

$$AC + BC = \text{constant}$$

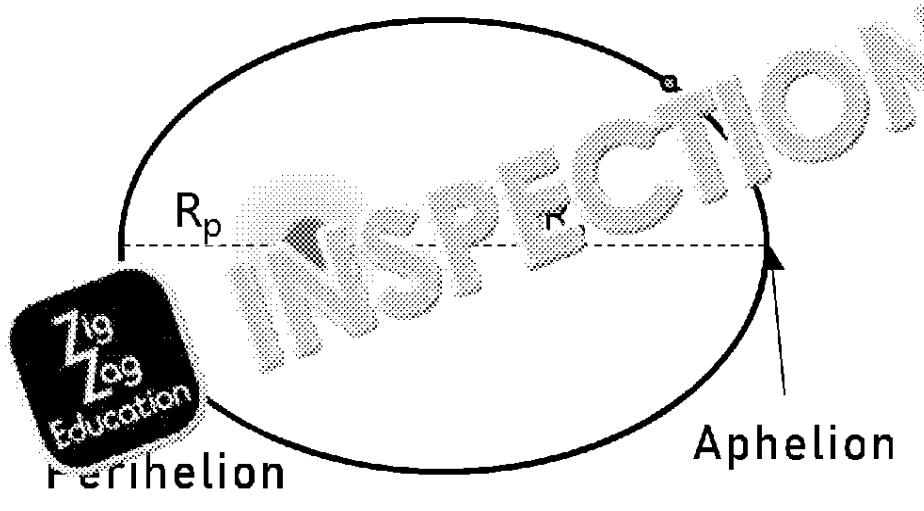
The distance between a focal point and the centre of the ellipse is:

$$e \times a$$

Where e is the eccentricity of the ellipse ($0 < e < 1$) and a is the semimajor axis (this distance is the same for both foci).



For the following explanation we will use the exmaple of a comet orbiting around the Sun. An elliptical orbit will arise when the comet enters the gravitational field of the Sun with a velocity not perpendicular to the gravitational force (all of the planets in our solar system have elliptical orbits around the Sun). The point in the orbit closest to the Sun is called the perihelion (periapsis for an object that isn't the Sun) and the point furthest from the Sun is called the aphelion (apoapsis for other objects).



One of Kepler's laws states

$$R_a = a(1 + e)$$

Combining these two gives

$$R_p$$

Remember a = semimajor

Orbital motion

Now we know the basics of ellipses, let's look at the motion of an object following an elliptical trajectory, i.e. an orbit. The potential energy of an object in a gravitational field is given by:

$$E_p = -\frac{GMm}{r}$$

And the kinetic ener[illegible] motion is given by:

$$E_k = \frac{1}{2}mv^2$$

Energy is transferred between one and the other during an orbit, but the total energy is always constant. Therefore, picking two points in the orbit:

$$\frac{1}{2}mv_1^2 - \frac{GMm}{r_1} = \frac{1}{2}mv_2^2 - \frac{GMm}{r_2}$$

Rearranging gives:

$$v_1^2 - v_2^2 = 2GM\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

A useful feature of elliptical orbits is:

$$R_a v_a = R_p v_p$$

Rearranging and substi[illegible]int, our energy equation gives:

$$v_a = \sqrt{\frac{2GR_p}{(R_p + R_a)}} \quad \text{and} \quad v_p = \sqrt{\frac{2GMR_a}{R_p(R_p + R_a)}}$$

Rearranging these gives:

$$R_a = \frac{R_p}{\frac{2GM}{R_p v_p^2} - 1} \quad \text{and} \quad R_p = \frac{R_a}{\frac{2GM}{R_a v_a^2} - 1}$$

These are known as [illegible] one dep[illegible]n the [illegible] ellip[illegible]bit is given

These equations des[illegible] of an object can chan[illegible] rocket engines on. T[illegible] axis and, therefore, t[illegible] orbiting object is giv[illegible]

Where r is the distan[illegible] ellipse and the orbiti[illegible] the velocity of an orbi[illegible] shape:

[illegible] is the radius of the o[illegible] approaching the peri[illegible] This is why planets cl[illegible] those planets further

For a rocket that's pe[illegible] the gravity of an obje[illegible] rocket will travel at its[illegible] perihelion. It is at thi[illegible] on will be most effect[illegible] potential is at its lowe[illegible] by the engine will not[illegible] gravitational potentia[illegible] transferred into kinet[illegible]

Oberth effect

Comprehension questions

1. At the beginning of its launch, a rocket turns its engines on to full power. The r
of exhaust gases is 7500 kg s^{-1} and it leaves the rocket at 1200 m [illegible] What is t
2. State one mathematical property of ellipses.
3. What are the names given to the closest and furthest point [illegible] orbit aroun
4. The orbit of Mars has an eccentricity of [illegible] its s[illegible] major axis is 2.28 × 1
when it travels through its perih[illegible]06 [illegible] m away from the Sun? The m

Discussion

[illegible]10 y[illegible] the aerospace industry have seen more private companies laun
[illegible]p new technologies, such as SpaceX and Blue Origin with their vertical-la
p[illegible]mpanies leading the way in space exploration is a good or bad thing, and
company were the first to send man to Mars.

Extension

The typical rocket is comprised of a main stage with either a second or a second an
rocket launches with the main stage and drops it behind when it runs out of fuel. It
and third stages at different points in the launch. This means unnecessary weight is
but also allows engines attached to each stage to be specially designed to operate
(recall atmospheric pressure decreases with altitude). An alternative is to use an aer
shape throughout the launch to adapt to the changing atmospheric pres[illegible]. Resea
and write a report on your findings.

3.4.1.3 Motion along a straight line

Keywords

Reference frame	A coordinate system specific to the reference in train which is known reference frame compar
Electromagnetic radiation	(as well as light, this is an excitation in the el fundamental field in nature)
Paradox	A statement that, despite sounding true, leads to consequences

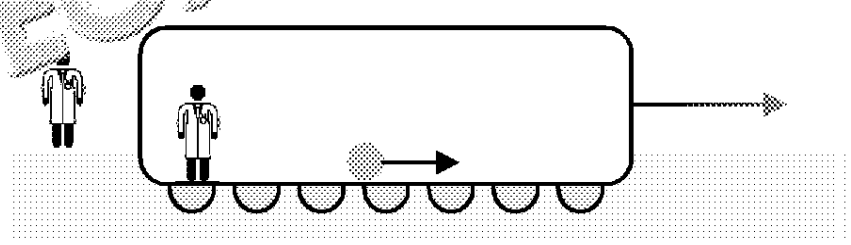
In 1905 Albert Einstein wrote and published one of the most influential scientific pa The paper brought together ideas about space, time, mass and energy, and solved widely discussed problems in physics at the time. This paper, *Zur Elektrodynamik be Electrodynamics of Moving Bodies*, set out Einstein's theory of special relativity, whic the most important bases of modern physics.

It's all relative

One of the most important aspects of physics is the idea of **relativity**, the idea that equivalent. This is actually a quite simple idea:

Consider a passenger on a train with a ball. The train is entirely sealed and its and can perfectly see everything happening inside. The train travels past the platform at

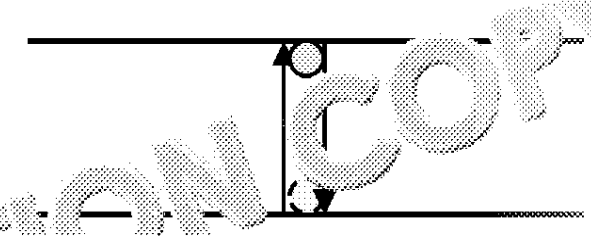
The passenger takes their ball and bowls it down the train aisle in the same direction scientist on the train kindly measures the ball's speed and confirms that it is travelli



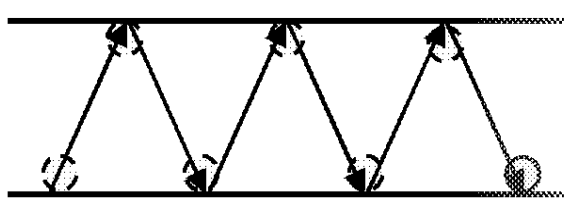
However, another scientist standing on the platform also measures the speed of the because they've measured the speed of the ball added to the speed of the train.

Neither scientist is wrong – the scientist on the train is correct in saying that the ball **reference frame of the train**, and the scientist on the platform is correct in saying t 15 m s^{-1} in the **reference frame of the platform**.

Now instead of rolling the ball forwards, imagine the ball being rolled side to side of the train. The scientist on the train sees the ball simply travelling back and forth



According to the scientist on the platform, however, the ball is travelling back and f the motion of the train.



Again, both scientists are correct in their observations, but because of their differen
different effects. Neither scientist is more right than the other, they're just measurin
different points.

In fact, all physics works exactly as you'd expect, no matter the r[illegible] in one, as l
isn't accelerating. In any reference frame, momentum a[illegible]nergy is conserved, c
fields act exactly the same. If the train were perfe[illegible]ly opa[illegible]ue with no windows, a p
know the train was moving at all, no ma[illegible]er whi[illegible]ce experiments they perfor
sped up, slowed down, or turned around though they might notice the engine

This idea is known a[illegible]a[illegible]ea[illegible]lativity, and is a simple but crucial aspect of physi

[illegible]lling light

Be[illegible]een 1855 and 1873, a Scottish scientist called James Clark Maxwell published a
turned the idea of Galilean relativity on its head. In his papers, Maxwell set out the l
describe how electromagnetic fields propagate. One crucial aspect of the Maxwell
electromagnetic waves travel at the speed of light, c, which is given by

$$c = \sqrt{\frac{1}{\mu_0 \varepsilon_0}}$$

where ε_0 is the permittivity of free space, and μ_0 is the permeability of free space. B
electric and magnetic waves in a vacuum, and most importantly are cons[illegible]s. This
constant, with all light travelling at a fixed speed. This raised a [illegible]ue in whic
travel at this fixed speed?

Think back to our train, but instead of r[illegible]a[illegible]gine the passenger is shining
According to Maxwell, the light s[illegible]d[illegible]ra[illegible]e, but we have no indication which
light as travelling at c a[illegible]h[illegible]d measure c plus 10 m s^{-1}. Maxwell's equatio
special referen[illegible]a[illegible]i wh[illegible]light travelled at its 'correct' speed, in complete vio
[illegible] fra[illegible]quivalent in terms of physics.

for this, the idea of an **aether** was put forwards. This aether was propos
w[illegible]ght travelled at its true speed. Two scientists, Albert Michelson and Edward
experiments in an attempt to measure the effect of the aether. The experiments inv
light in different directions and at different times of the day – depending on the mo
of light should have varied slightly as the light travelled different paths through the

Instead what was found was that the speed of light is constant, regardless of which
it from. The Michelson–Morley experiment would go on to be considered the most
time.

On the right track

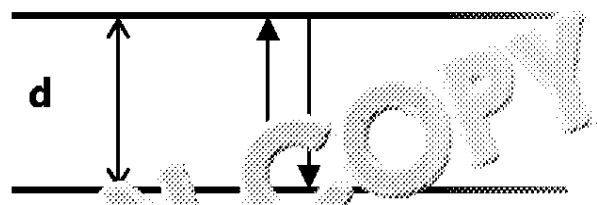
Einstein's solution to this problem couldn't have been sim[illegible]he[illegible]ptevt, and

Galilean relativity and the invariance of the s[illegible]ht [illegible]m the two postulates o
relativity:

1. In an inertial (non-acce[illegible]ig) re[illegible]ce frame, the laws of physics are invari
2. The speed of li[illegible]v[illegible]n[illegible]all reference frames, independent of the motio

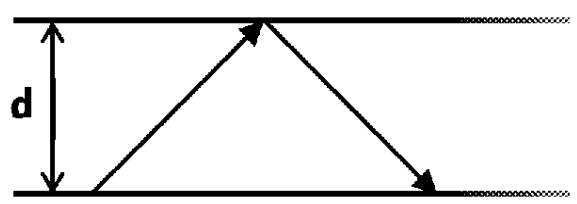
as [illegible]g point, Einstein made a startling claim: to account for these t
[illegible]d bend, stretch and squash to accommodate the measurements of diffe

On our train, the passenger once again shines their laser; this time so that a single p
mirrors on either side of the aisle.



The time it takes for the photon to travel from one mirror to the other, and back to
$t = \frac{2d}{c}$.

The scientist on the platform sees something quite different, though. Instead of rel
also moving forward at the same speed as the train, much like the ball fro



This time the distance between the mirrors is d, but in the time taken for the photon
train and photon have moved forward by a distance vt.

This actually means that the photon has travelled further according to the scientist o
to the scientist on the train. If the speed of light is invariant, this can only mean that
longer to bounce from one mirror to the other and back according to the scientist o

We can even work out by how much the two scientists diffe

We first need to define the variables in the two reference frames.

On the train, the scientist measures a distance x and a time t for the photon's path.
measures a distance x' and time t'. Both scientists agree that the reference frames
each other.

x scientist in the train:

and

$$t = \frac{2d}{c}$$

For the scientist on the platform:

$$x' = \sqrt{v^2t'^2 + 4d^2}$$

and

$$t' = \frac{\sqrt{v^2t'^2 + 4d^2}}{c}$$

The equation for x' jus
comes from Pythagor
theorem – can you wo
through yourself?

Now we can isolate t' in this equation:

$$t'^2\left(c^2 - v^2\right) = 4d^2$$

$$t'^2 = \frac{4d^2}{c^2 - v^2}$$

$$t'^2 = \frac{\frac{4d^2}{c^2}}{\frac{v^2}{c^2}}$$

$$t' = \sqrt{\frac{\frac{4d^2}{c^2}}{1 - \frac{v^2}{c^2}}}$$

We know that $t = \frac{2d}{c}$, so

$$= \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

For a train travelling at 10 m s^{-1}, this distance is hardly noti[illegible] – [illegible] s measured the platform would measure the time taken as 1.000 000 000[illegible] s (that's 15 zero

If the train were to speed up though, the difference becomes a lot more noticeable. 1 s on the train is measured as 1.05 s, but at 87 % of the speed of light, the time m on the train becomes [illegible] measured from the platform. For this reason, speeds faste be relativistic.

the distance

The above proof shows how time can distort to maintain the speed of light, but spa

Consider a rod lying along the aisle in the train.

The two scientists decide to measure the length of the rod by timing [illegible] one end to the other. The scientist on the train measures the length of the rod to b

We know already that the two scientists measure different times, so they must also scientist on the platform would measure the rod to be of length L′:

$$L' = L\sqrt{1 - \frac{v^2}{c^2}}$$

[illegible]d travelling at 95 % of the speed of light would be measured by a statio

As a matter of fact

Time dilation and length contraction aren't just matters of theory, they're real exper
don't see these effects in everyday life because they only become appar
has ever travelled, but in the world of particle physics, travelling
day occurrence.

When cosmic rays hit the upper atmosph
muon neutrino, and an electron

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu_e}$$

cay
ng the ground, even if it was travelling at the speed of light. What is mo
muons make it to the surface.

While this doesn't make sense for classical physics, special relativity makes it simple
decay in the reference frame of someone standing on the Earth because they're tra
lifetime increases.

Travelling at 0.996 c, the average lifetime extends from 2.2 μs to 25 μs – over ten ti

But what about the muons' reference frame? There still shouldn't be enough time
before decaying! This can be explained by special relativity as well – the muons are
distance from the upper atmosphere to the ground contracts, reducing the
that the muons can cover a greater distance in the same amount

Twin peaks

There's a famous paradox in spe
people try to use to poke holes in

Imagine two twin
very way, with only a few minutes difference in their
sp
av
at speeds approaching the speed of light. After a short
th
ronaut twin inside. Due to time dilation, what was only a short tr
onger for Earth, just like the photon on the train. The astronaut twin re
m
lder than herself.

But wait! Since all reference frames are equivalent, this can be thought of from the
the spaceship. In this point of view, it's the Earth that is speeding away at close to t
earthbound twin that stays young.

Which one is it? Does the effect not happen at all? Or is one of the reference fram
why?

The answer is that reference frames are only equivalent when they're **not** accelerat
spaceship has to accelerate up to a fraction of the speed of light away fr
returning. This accelerating reference frame takes the problem
realm of
realm of **general relativity**. When making this correction
much younger.

General relativity is another of Ei
As its name implies, it is a gener
allowing similar ideas to
d t
celerating reference frames. General relati
important and
of physics, and governs all gravitational interactions
s a
way to integrate general relativity and quantum mechanics
way
a theory which describes all of physics.

Comprehension questions

1. What are the two scientific principles that were at odds with each other in class how did they lead to special relativity?
2. An electron travels through a particle accelerator at 2.38 × c. A scientist travelling around the particle accelerator in 880 ns. How long does this take for electron?
3. How can the extended lifetime of a muon in a cosmic ray be explained from the observer on Earth and the reference frame of the muon?

Discussion

Relativity only applies to very high speeds, but that doesn't mean it can't have t... Try and come up with as many possible applications and technologies th... relativity.

Extension

The ladder paradox is a special relativity paradox like the twin paradox discussed ab...

In it, someone runs near the speed of light holding a ladder in the direction of their... the ladder decreases. The person runs through a barn in which the ladder usually ca... the length contraction, the ladder should suddenly fit according to an observer at r... closed. However, according to the runner, it is the barn that appears shorter so the... greater extent.

Do some research and think about the problem yourself, and try and come up with...

Energy Storage

3.5.1 Current electricity

Keywords	
Generator	A device that turns kinetic ener… the r…ation of a turbine, in… energy
Inertia	The willingnes… a… o… remain in motion if in motion or …
Charge	The m… …perty of an object caused by an imbalance of …

…g e…y …a technological challenge with well-established solutions, but … …e right time is another challenge in itself. Storage solutions for energy … …basis behind **capacitors** that are vital to digital circuits, as in computers, … such as **batteries**. This article will talk through the various ways energy is stored.

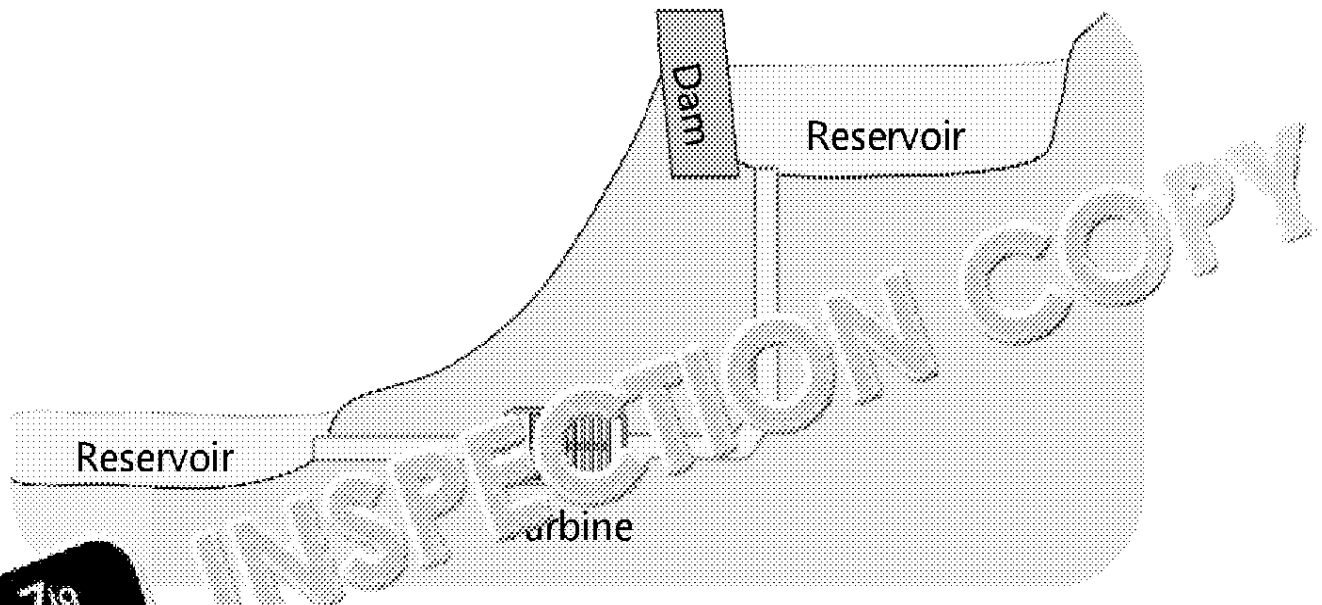
As society moves towards renewable sources which aren't as damaging to the envi… resources, the problem may not be generating energy, but storing it. Solar panels … during the day, but what happens at night? What happens to wind farms when it's … windy for the wind turbines to function safely)? And with climate change and huma… rivers, not even hydroelectric power might be reliable.

Energy storage in the national grid

Modern life has become dependent on a constant power supply. Without this, our technological infrastructure would power down, reverting us back to the pre-industrial era. Power stations are constantly running to meet demand. However, the demand for power varies throughout the day, depending on many factors. In the UK, it is the job of the National Grid to make sure there is enough power in the country all of the time. Any excess power should be sent to other countries, although this is difficult. Ideally, the national grid will store the excess energy to be used at a later point when demand is high. The demand of the national grid tends to follow a predictable pattern each day, with exceptions such as TV pickup.

> When a large n… same progra… Cup final, Prime… crucial episode… end for everyo… people will go t… resulting in a … called TV pick… demand by up…

Gas power stations are the quickest type to react, yet still take up to an hour to fully turn on. Therefore, storage solutions are needed that have a large capacity, but can also be quick to respond.



C…d is **pumped storage**: a reservoir of water is held up high, and when power is needed, this water is released through a turbine and into a lower reservoir. The reservoir has a large gravitational store which

Total p… during …

decreases as electricity is generated. The driven turbine generates electricity that c
Any excess power from the grid can be used to pump the water from the lower reso
reservoir, storing the energy for future use.

The Ffestiniog power station in north-west Wales is a pumped st[illegible] hydroelectric
fastest-responding power stations in the world, being abl[illegible] ne[illegible]t 360 MW of
demand.

Pumped storage power stations d[illegible]t [illegible]rs[illegible]onse times and capacity requirem
national grid; however, th[illegible]t[illegible]fficient. The Ffestiniog power station uses
water back up to [illegible]q[illegible]r[illegible]voir than it generates when the water falls.

oth[illegible]ays to store energy. One such method is thermal energy storage w
mal energy in media such as water or molten salts. These can hold energy
a[illegible]ally used in conjunction with solar power generation to spread out the powe

Flywheels

A flywheel is essentially a large disc with the majority of its mass concentrated on its outermost section. The disc is rotated by a driving shaft, say from a turbine, storing the energy as rotational kinetic energy. Due to the conservation of angular momentum, the flywheel will continue to rotate, only losing a little energy due to frictional forces. The energy can be withdrawn through the rotating shaft when needed, reducing the angular speed of the flywheel. The kinetic energy store
a flywheel is given by:

$$E = \frac{1}{2} I\omega^2$$

E – Energy
I – M[illegible]
[illegible] speed
m – [illegible]ass in outermost section of flywheel

I –

Flywheels are commonly used in mechanical applications such as steam or petrol engines. The energy generated by such engines comes in bursts with periods of no power. The flywheel stores and releases the generated energy, spreading the power out during each cycle. This makes the overall power output of the engine smoother and easier to apply.

For more rotational mechanics, look at the content of topic 3.11, engineering ph

Batteries

A battery is a device that stores energy. So technically, the flywheel and pumped st types of batteries; they store mechanical and gravitational energy. The t batter electrical type.

An electrical battery is a chemical store of energy. Batteries come in two types:

1. **Primary** – the battery is produced fully charged so it can immediately output discarded once it's complet
2. **Secondary** – the b ds to be charged before its first use. These batter their elect reactions are reversible.

ba es are the most common as they are much more efficient. the energy density of a battery, the better it is. This is why **li -ion batteries** are the most common type of electrochemical batteries currently available.

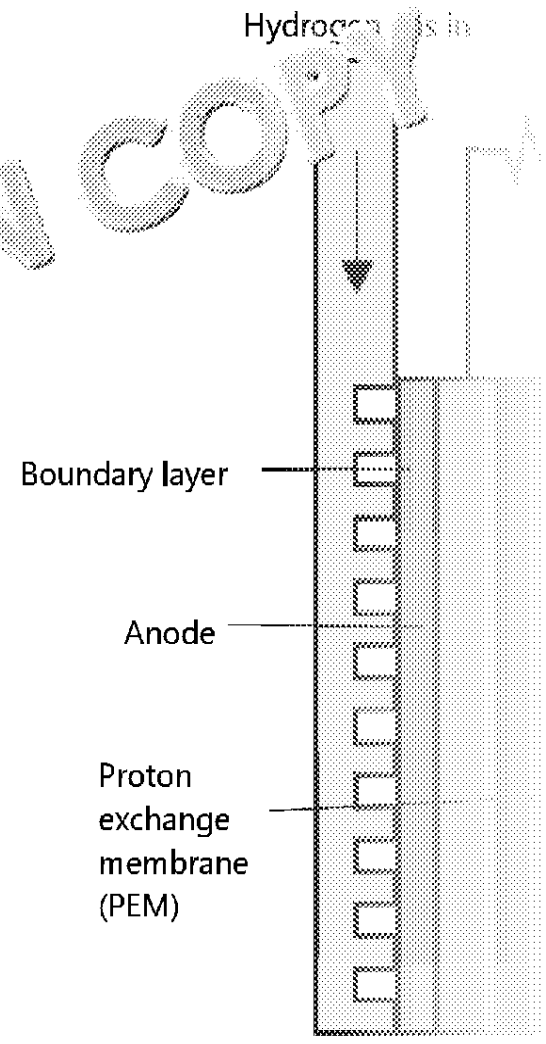
A lithium-ion cell is constructed of an anode (positive terminal) and cathode (negative terminal) suspended in salt solution containing lithium ions (called the electrolyte). When the anode and cathode are connected via a circuit, the lithium ions will be attracted to the cathode, causing the cathode to become positively charged. Electrons then flow through the external circuit to this positive cathode until the battery is completely discharged. Applying a current in the reverse direction to the cell (electrons flow into anode) causes the lithium ions to flow back to the anode, charging the cell once more.

Battery technology has drastically improved in recent years resulting in applications portable batteries and power grid st co ing ever more popular. In the UK developing battery storage in a structure under the enhanced frequency response contract was to build a y tat that can store energy for short periods of time supply the n t g . The first completed project was E.ON's Blackburn Meadow atte ation can supply the national grid with power in less than a second umped storage solutions. Many of these projects have caused the natio crease, rising from 2.5 GW in early 2017 to 8 GW at the end of 2017.

The future of batteries will see the incorporation of metamaterials such as graphen at Harvard University have developed an electrochemical system that can store larg between 2D layers of graphene. The graphene provides a low-resistance pathway f the anode to cathode, increasing the ion capacity of the battery; therefore, increasi charge capacity of the battery (**https://phys.org/news/2018-06-physics-batteries**). other ions, such as magnesium ions, could also be the future of batteries. Magnesi of research because they have a theoretical energy density by volume that's 50 % g

Hydrogen fuel cells

Standard combustion engines use fossil fuels and release harmful gases into the environment. An alternative to fossil fuels is **hydrogen fuel cells**. The fuel is simply hydrogen gas, H_2 that mixes with oxygen from the air. The result is generated electricity, some dissipated heat, and water vapour; nothing harmful there.



A **catalyst** in the boundary layer next to the anode causes hydrogen molecules to split into hydrogen ions (two protons) and two electrons. The **proton exchange membrane (PEM)** only allows protons (i.e. hydrogen ions) to pass through, and not electrons. The ions pass through the PEM to the cathode (to react with the oxygen atoms), making the cathode positively charged (similar to a lithium cell). Electrons are attracted to flow around the external circuit, doing work as they do, and then neutralise the hydrogen ions, which react with oxygen atoms to form water vapour.

Hydrogen fuel cells are much more efficient than standard combustion engines and the production of hydrogen gas is less harmful compared to extracting fossil fuels. However, the current mass systems to favour charging and s power electrical vehicles, rather than hydrogen fuels cells.

Capacitors

A capacitor is a quick way to store electrical energy. Two electrodes are separated by an electric field for a short time. The capacitor is charged when a potential difference until the capacitor reaches a critical point, where it then discharges. The capacitance (the charge it can hold) is measured in farads, F, and a typical capacitor has a capacitance to charge for several seconds.

Supercapacitors have a much higher capacitance (10 F to 100 F) compared to typical capacitors and can hold charge for much longer, too, bridging the temporal gap between capacitors and batteries in quick charge/discharge applications, such as regenerative braking or static random access memory.

Computers use **random access memory (RAM)** to temporarily store information while running programs or calculations, similar to short-term memory in humans. Most RAM in computers will be **dynamic (DRAM)** which uses normal capacitors. Due to the short discharge time of these capacitors the information stored would very quickly be lost. Therefore, DRAM uses a separate refresh circuit to keep the information stored. **Static random access** (SRAM) instead uses supercapacitors which can hold information for much longer. A separate refresh circuit is, therefore, not needed, which makes the RAM much faster to respond.

The principle of regenerative braking is to convert the kinetic energy of a decelerating car into energy that can be used to power the car. Instead of dissipating this kinetic energy as heat, it can be used to power the car. This increases the overall efficiency of the car. For example, the electric motors on the wheels can be used for absorbing the kinetic energy of the car and generating power that is stored in the system. **Kinetic energy recovery systems** (KERS) are also installed in cars such as those in Formula One in 2009. The energy is stored in a flywheel or battery and can be discharged in later acceleration.

Comprehension questions

1. Other than pumped storage, name one way energy is stored and later used by
2. A flywheel has a radius of 25 cm and a mass in the outermost region of 13.5 kg. Calculate the kinetic energy stored in the flywheel if it's spun to an angular speed of 283 rad s^{-1}.
3. Describe how flywheels aid petrol and steam engines.
4. Describe the difference between DRAM and SRAM.

Discussion

A private company wishes to generate its own electricity on-site to completely disconnect from the national grid. It will generate its power using an array of solar panels and a wind turbine. The power output from these sources varies a lot and doesn't match their demand. Research what options are available to the company and decide which solution is the best.

Extension

Prepare a two-minute presentation to explain what a hydrogen fuel cell is and how it works. Present to your classmates. To aid with the explanation, draw a diagram of a hydrogen fuel cell and

Mark Scheme

Article	Question	
When Particles Collide	**1**	First calculate the force acting on the proton: $F = \frac{qV}{d}$ $F = \frac{(1.60 \times 10^{-19})}{(3.5 \times 10^{-2}}$ $F = 2.057 \times 10^{-16}$ Then use Newton's second law to find the acceleration: $a = \frac{F}{m}$ $a = \frac{2.057 \times 10^{-16}}{1.67 \times 10^{-27}}$ $a = 1.23 \times 10^{11}$ m
	2	They are cheap and easy to build and maintain compared to particle accelerators.
	3	A charged particle moving in the presence of a magnetic field experiences a force. This force (due to Fleming's left-hand rule) acts perpendicular to the motion of the charged particle, acting like a centripetal force, changing the direction of motion of the particle and causing it to move in a circle.
	4	Protons are injected through Linac2 and into the PS where they are then accelerated to 1.4 GeV until being injected into the Super Proton Synchrotron. They are further accelerated to 25 GeV before being injected into the super proton synchrotron (SPS). The SPS accelerates the protons to 450 GeV before, finally, injecting them into the LHC. In the LHC the protons have an energy of 6.5 TeV before collision.
	Discussion	Points that could be discussed: Advantages: • large amount of funding • wide range of expertise • central place of work allows quick communication Disadvantages: • Scientists and engineers need to relocate. • Political influences between involved nations. • There may be difficulty in deciding where to build with many involved nations. • Individual projects can only use the equipment for a short time.
What's the Antimatter with You?	**1**	Einstein's relation between energy and mass is: $E^2 = m^2c^4 + p^2c^2$ Which if we square root gives: $E = \pm\sqrt{m^2c^4 + p^2c^2}$ A square root can have positive and negative solutions at the front of the square root sign. The energy can be negative, hinting at the symmetrical nature of matter.
	2	Annihilation is the combination of a particle and its antiparticle resulting in the annihilation of the particles and the release of energy in the form of gamma photons propagating in opposite directions (to conserve momentum). The energy of the gamma photons is equal to the rest mass energy of the particles (by $E = mc^2$).
	3	Containing the antimatter before it annihilates with normal matter is normally done by slowing the antimatter down and containing it using strong magnetic fields.

Article	Question	Answer
What's the Antimatter with You?	**4**	The results are accurate to 1 part in 1 billion. Th measurements taken, one of the measurements measurements. Therefore, the 99 99 mea theory give us high confid nce in the theory. b measurements that match the theory, so certainty i
	Discussion	Points that could be discussed: • the importance of research into antimatter • its use as a fuel for power generation / rocket • compare to other energy resources • potential use as a weapon, and consequen hands • enforcing laws on the use and production
s Neutrino, Pussycat?	**1**	Reacts with a proton in water, which is then abs cadmium), which releases a gamma ray which through a medium than light does, and creates like a 'sonic boom'.
	2	The Sun only produces electron neutrinos via f neutrinos oscillate between muon and tau neut neutrinos are detected, so only around a third
	3	Neutrinos would be their own antiparticles. Lep conserved in all interactions, which could explai than antimatter in the universe.
	Discussion	Points that could be discussed: • Neutrinos aren't affected by matter-betwee • They can pass through regions of space tha • They can travel long distances without bein • They are produced in large quantities by fi supernovae). • They can give information about gravitation information.
to the World	**1**	Electromagnetic radiation is a wave, so can inte constructive or destructive interference. When t modes that don't set up standing waves (wavel integer wavelengths equal to dimension of spa cancelling each other out. The waves that do se survive and be the only wavelengths of electron leads to certain energies allowed, hence the qu the confined space.
	2	It states that the system is simultaneously in all observation, such as a measurement, is made o
	3	The analogy describes the state of a cat that is simultaneously alive and dead. It is only when t state of the cat is determined. The analogy also interpretation of quantum mechanics, which say mechanical system can be in all possible states system is observed does it fall into one state. S to show how flawed the Copenhagen interp simultaneously alive and dead, it's either one o we can see it or not.

Article	Question	Answer
Gateway to the Quantum World	**Discussion**	Points that could be discussed: • For larger systems, all aspects of the syste with each other. • This is essentially an 'observation' – atom collapses th wa e for into a larger state • Qu n cts cancel out at larger scale nt m effects only apply to very small s e ects can be seen (certain experiments ha quantum effects) • Quantum mechanics is very well studied, so with larger-scale observations for the above
gic	**1**	A metamaterial is a material that goes beyond normal materials. This typically means it manip electromagnetic radiation, resulting in effects it
	2	8–13 μm
	3	The Persians would fill a shallow bath with wate The ambient temperatures in the dessert at nig lack of clouds), which would cause the water to shallow water would radiate heat into the atmo infrared radiation emitted is barely absorbed by water past its freezing point.
	4	A negative refractive index means the compone parallel to the boundary is refle sing th back in one direction ass through a bo
	Discussion	Points that could be discussed: • ngs / transport vehicles in the ates use as a heat shield for Sun-facing satellite • keeping fresh produce from farms cool • extra layer on thermos flasks to keep drink
ke. Things	**1**	e.g. the San Andreas fault line
	2	$E > 10^{\frac{3}{2} \times 2.5 + \cdots}$ $E > 5.6 \times 10^{22}$ J
	3	The amplitude of the seismic waves as they are (lose their energy) as they propagate through a the amplitude of a seismic wave, the further it site.
	4	The use of satellites that are sensitive to the El spectrum will result in the detection of earthqu This will allow the affected area to properly pre millions of lives.
	Discussion	Points that could be discussed: • Research into geoseismology can decrease earthquakes occur, po ily saving a lot • Ge y c elp develop better co as th way buildings are designed and • Researching helioseismology could help d systems against solar flares. These solar fla satellites, including the satellites that prod • Studying helioseismology could help us un reactors here on earth, solving our energy

Article	Question	Answer
Interferometers: Getting into Superposition	**1**	Initially the beams are in phase because they o coherent light source. The beams then travel vi superimposing to create a resultant wave. The wave depends on how in phase or out of phase out of phase the beams, the smaller the amplit length of one beam will result in a phase diffe allows the change in path length to be meas
	2	The aim was to measure the difference in spee arms of an interferometer. The interferometer through the aether, so one arm was travelling a the aether compared to the other arm. If light relative to this aether, a difference in the speed measured by the interferometer.
	3	Einstein proposed that the speed of light was c observer is. It is space and time that vary betwe speed of light constant.
	4	They were each approximately 30 solar masses
	Discussion	Points that could be discussed: • Better research into black holes could be p escape black holes, making them invisible t • There could be better research into neutro behaviour. • Dark matter is only known to interact with gravitational waves will give insight into • It could be a new method to back up and electromagnetic telescopes.
Holograms: Seeing Things That aren't There	**1**	A reference beam is used as a source of light reflected beam from the object. The holographi interference will then display an image of the o identical reference beam.
	2	An array of nano-sized silicon discs that can tu computer
	3	To transport parts of a device in the manufactu physically touched To deliver medicine or other medical treatment the human body
	4	The holographic principle states that informatio is stored as deformation on the surface of the b information isn't lost/destroyed, which satisfies mechanics.
	Discussion	Points that could be discussed: • Where is this 2D surface where all informat • Why would the universe be a hologram? • What is the physical meaning of a hologra • A hologram is an image projected from a 2 information in our universe is stored on a 2 space which our holographic universe is pr Could there be new unfound physics based • How is the information stored on the 2D s hologram, what is the equivalent of the re

Article	Question	Answer
Laser Focus	**1**	A gain medium has more excited atoms than a photon with the right energy will cause an elec to its ground state, emitting another photon, th emission. These photons will cause more photo stimulated emission, resulting in a chain reactio gain medium, more generated photons pass th Result is the amplification of light in the ga
	2	Either oxygen is used to help burn the material cutter, or nitrogen is used to push the excess m be disposed of.
	Discussion	Points that could be discussed: • SSDs will replace optical discs for informati replaced tape. • Use of CDs, DVDs and Blu-ray will diminish wirelessly downloaded. • Storage of information at the site it is used cloud services become ever more popular. • An advantage of using SSDs and cloud ser the reduced risk of loss of data due to mec • A disadvantage of using cloud services ove having so much information stored in one p
Imaging the Invisible	**1**	For a simple set-up to photograph different in apparatus will be needed: • a camera • a laser or point source of light • a knife edge or colour filter • a parabolic mirror
	2	It allows the engineers to see minute differenc help the engineers design aerofoils or other ae to perform as they require.
	3	Quantum tunnelling is the effect of a quantum moving through a potential energy barrier. This has an associated wave function that is related the particle at a particular position. The wave fu further away from the particle's expected positi the wave function of the particle spills over the chance of finding the particle on the other side side, the particle has tunnelled through the bar
	4	Capillary forces are created by a meniscus, a bo gas (such as water and air), that creates an attr objects it is connected to. These forces can be s the experiment entirely in a fluid which is water therefore, the water is not
	Discussion	Points that could be discussed: • Irregularities in surface roughness and defects cou • STMs can image the conductive properties design nanostructures. • STMs can manipulate single atoms, so can • STMs can be used to design, build and test semiconductors. • AFMs can analyse non-conducting objects crystals of amino acids • Imaging the nano-sized biological objects understanding and even cures for diseases.

Article	Question	Answer
Optical fibres	**1**	
	2	A m[illegible] mode [illegible], because multi-mode fibres [illegible] the effects from modal dispersion an
		Any one of the following: 1. **Intermodal dispersion**: Different modes different speeds, which is why single-mod remove this type of dispersion. Single-mo however, so the cheaper multi-mode fibre transmission. 2. **Chromatic dispersion**: Different frequenc colours, although this also applies to EM r part of the spectrum) travel at different sp can be sub-divided into two other types of • Material dispersion: The refractive ind depending on the frequency of light t • Waveguide dispersion: The way the n make the waveguide [illegible] a freq refractive index [illegible] even though the mat frequency dependence. A [illegible] of light will have a range of f meaning the pulse spreads out with p of information, as in today's signal tra to overlap, which becomes a problem at 60–70 km intervals along a fibre to remove this chromatic dispersive effe (coherent light with the same frequen dispersion. 3. **Polarisation mode dispersion**: Different po travel at different speeds. Polarising the ligh remove this effect.
	4	1550 nm, because this wavelength experiences silica, meaning a signal can travel further down
	Discussion	Points that could be discussed: Advantages: • no risk of damage or breakage [illegible] to and • can constantly change [illegible] of connect Disadvantages: • diff[illegible] costly to install and maintain • [illegible] damage from radiation and objec
Big Engineering: The International Space Station		6 [illegible] 2 failed during its launch.
	2	It was an international media event because the debris falling on populated areas.
	3	The US orbital section, USOS, and the Russian o

Article	Question	Answer
	4	Any two from: • Bones become less dense. • Humans grow a few inches t[illegible] • Muscles start to wast[illegible]we • Red blood cell p[illegible]duc[illegible]decreases. • Imm[illegible]ms [illegible]aken.
	Discussion	[illegible]at [illegible]d be discussed: • H[illegible]man travel in space allows us to inhabit • The longer we can get humans to survive i[illegible] send humans. • It gives us access to planets/asteroids with such as metals that are rare here on Earth. • By sending humans into space we reduce t[illegible] extinct (due to global disasters, etc.). • Research could help understand and devel[illegible] potentially saving lives here on Earth. • The increase in funding for the research ca[illegible] expands the space industry.
Fluid Dynamics: Going with the Flow	1	The continuity equation, three Navier–Stokes e[illegible] equation.
	2	$Re = \frac{\rho v_0 l_0}{\eta}$
	3	$\frac{1}{2}\rho^2 A_0$ $F_D = \frac{1}{2} \times (1.3 \times 10^{-2}) \times 1000$ $F_D = 5.7 \times 10^{1}$ N
	4	[illegible] the incoming air into two parts: o[illegible]e foil, the other travels underneath. These pa[illegible] of the foil at the same time. The top of the foil i[illegible] so the air travelling over the top must travel fa[illegible] at the same time as the air travelling under the that the faster a fluid travels, the lower the pres[illegible] pressure on the top of the foil and high pressur[illegible] upward force called upthrust.
	Discussion	Points that could be discussed: • An exact solution isn't needed to gain insi[illegible] system. • Techniques developed for one chaotic syst[illegible] chaotic systems. • An exact solution may be possible, it just h[illegible] • The information learnt from studying chao[illegible] areas/industries. • The computational pow[illegible]ed to resea[illegible] purpose/application f[illegible]powerful computer supercomputers and future technologies.
It's Not Exactly Rocket Science	1	$T = (v + v_e)\left(\frac{dm}{dt}\right)$ $T = (0 + 1200)(75$ $T = 9 \times 10^{5}$ N
	2	Any one from: • $AC + BC = constant$ where A and B are the ellipse • The distance between the centre of the ell[illegible] to $e \times a$, where e is the eccentricity of the e[illegible]
	3	Periapsis and apoapsis respectively

Article	Question	Answer
	4	$v = \sqrt{GM\left(\frac{2}{r} - \frac{1}{a}\right)}$ $v = \sqrt{G(\quad \cdot 10^{3}\quad)\left(\frac{2}{(2.06 \times 10^{11}}\right.}$ $v = 2.66 \times 10^{4}$ m s^{-1}
	Discussion	Points that could be discussed: • More efficient rockets (drive by basic busin… space cheaper. • A quicker turnaround of rockets makes mo… becomes much more regular, leading to m… • Competition in the space industry drives i… developed. • Advertisements in space or on a mission to… or importance that space or the mission to… • Expanding the space industry to many priv… universal standards being lost, although thi…
Special Effects	1	Galilean relativity (all non-accelerating referenc… Maxwell's equations (giving a fixed value for c)… time slows down and speeds up depending on… always travels at c through a vacuum.
	2	$t' = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}}$ $t = 2.30 \times 10^{-9} \times \sqrt{1 - \frac{(\quad)^2}{(\quad)^2}}$ $t = 536$ ns
		Fo… observer, the time it takes for the muon… because of time dilation, and for the muon only… For the muon, the Earth is travelling at relativi… covers through the atmosphere is contracted… whole atmosphere in its lifetime.
	Discussion	Points that could be discussed: • particle accelerators • medical imaging • mass spectrometry • GPS • high-precision equipment where even a sm… timing can have a big effect
Energy Storage	1	Thermal energy storage in media such as wate…
	2	$I = mr^2$ $I = 13.5 \times 0.25^2$ $I = 0.8$ kg m^2 $E = \frac{1}{2}I\omega^2$ $E = \frac{1}{2} \times 0.844 \times 2$ $E = 3.4 \times 10^{4}$ J
		…e flywheel stores and releases the generated… spreading the power out during each cycle. Thi… output of the engine smoother and easier to u…
	4	DRAM uses a refresher circuit to keep the stor… whereas SRAM uses supercapacitors which can… longer, removing the need for a refresher circ…

Article	Question	Answer
Energy Storage	**Discussion**	Points that could be discussed: • The company could use a miniature pump • They could use large flywhee • They could use batteri as t t used • They could use h drog n f e cells. • Industri d b ies make most sens s o s ge can be sufficiently argued