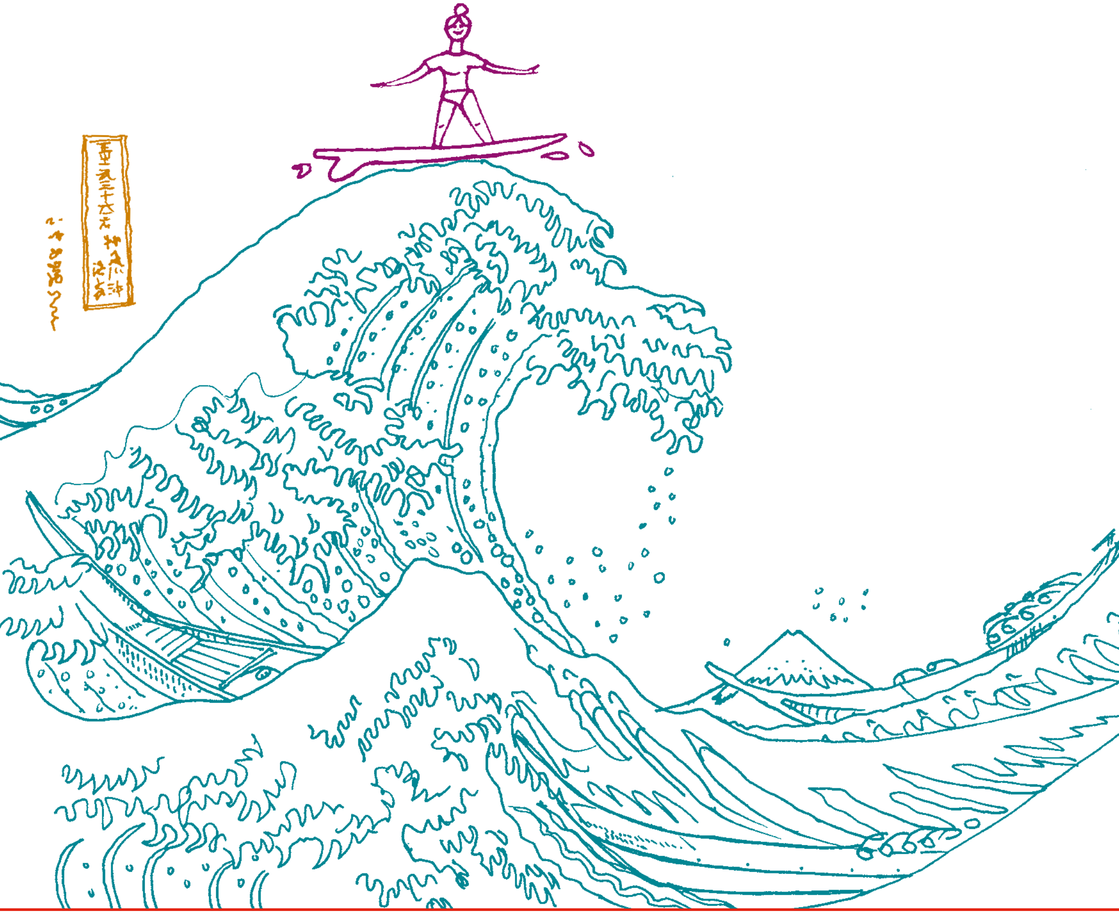
IOP Education | Stories from physics booklet 4

Waves: light, sound and other oscillations

By Richard Brock



IOP Institute of Physics

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Introduction

The story of physics is intertwined with the stories of people. Richard has collected some amazing, amusing and enlightening stories and I am very pleased that the IOP is able to help him to share them. I'm sure that you will be inspired by the stories and their engaging retelling here. They will be of interest to any teacher and are ready to use with students to bring the discipline alive and illustrate its reliance on human ingenuity and frailty.

In this booklet, we reach the creative climax of the Enlightenment, coinciding with the establishment of the London Physical Society (which grew into the IOP) in 1874. This period was immensely productive with the emergence of big ideas and explanations in classical physics as the great thinkers investigated new and interlinked phenomena. Happily, they were imaginative, well-resourced and eccentric; and adventurous enough to have a go at anything that might reveal the underlying nature of waves.

Charles Tracy

IOP Head of Education

Message from the author

Waves are a fascinating phenomenon to teach because they occur across a diversity of contexts and over a vast range of scales. However, the abstracted descriptions of waves found in curricula can present challenges for students. This booklet provides an assortment of stories that can help to contextualise waves and spark your students' interest.

There are stories drawn from the history of physics, including why the distinguished physicist, Blondlot, came to believe in non-existent N-rays and how Tesla accidentally pre-empted Röntgen's discovery of X-rays. You can read about how Newton fudged his data, why John Scott Russell chased a wave for several miles down a canal and the polarisation navigation system the Vikings probably didn't use.

You will also find out about contemporary research related to waves. Discover why mussels don't like radio waves and read about the mysterious signals from space that researchers found were being emitted from their own kitchen. Find out which animal caused a glitch in the Laser Interferometer Gravitational-Wave Observatory (LIGO) because it wanted some ice.

Finally, the booklet contains some stories that are just great stories. There is Frederick Collins who built a radio receiver using a cat and another using a human brain. You will learn about forbidden colours and maybe experience your own sensitivity to polarised light. Be inspired by the story of the one-handed Estonian lens maker who worked in a bowling alley and whose lens continues to help the Kepler telescope discover exoplanets.

I am grateful to the Institute of Physics for making this collection of the stories a reality. In particular, I want to thank Caroline Davis for managing the project and editing the booklets, and to Stuart Redfern for his wonderful illustrations.

Richard Brock

Radio waves

Hertz's useless discovery

Perhaps the physicist most closely associated with electromagnetic waves is Heinrich Hertz, who first provided empirical evidence for the waves predicted by James Clerk Maxwell. Despite the impact of his work, at the time, Hertz was less than enthusiastic about the value of his research.

Following his discovery of radio waves, Hertz commented:

> "I do not think that the wireless waves I have discovered will have any practical application."

When prompted by his students to consider the usefulness of his experiment, Hertz responded:

> "It's of no use whatsoever. This is just an experiment that proves Maestro Maxwell was right —we just have these mysterious electromagnetic waves that we cannot see with the naked eye, but they are there."

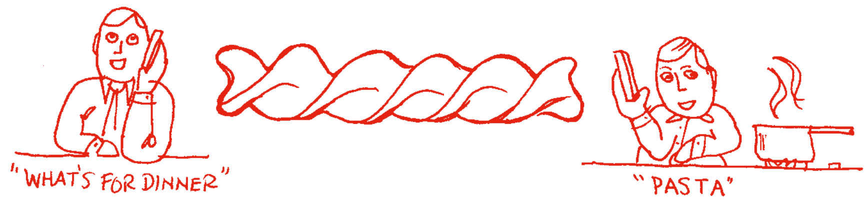
Unimpressed, when a determined student pressed Hertz on the implications of his discovery he shrugged and replied, "Nothing I guess."

Hertz suffered badly from toothaches and, in 1889, had all his teeth removed in an attempt to reduce his suffering. However, the pain returned, this time in his nose and throat, causing him to stop his research and become depressed. Hertz attempted to carry on teaching but had to undergo several operations and died, before his 37th birthday, from an incurable form of vasculitis. Poignantly, in his final letter to his parents before his death, Hertz wrote:

> "If anything should really befall me, you are not to mourn; rather you must be proud a little and consider that I am among the especially elect destined to live for only a short while and yet to live enough. I did not desire or choose this fate, but since it has overtaken me, I must be content; and if the choice had been left to me, perhaps I should have chosen it myself."

Radio pasta

A team of Italian and Swedish researchers have found a way to develop fusilli-shaped radio beams, with a view to reducing radio wave congestion. The popularity of mobile phones means that the number of radio frequency bands available is decreasing. By twisting radio waves clockwise or anti-clockwise about their axis, the researchers found that multiple signals could be transmitted on the same frequency channel without interference.



Sferics, tweeks and whistlers

In addition to the radio waves produced by human beings' transmitters, low frequency radio waves from a number of natural sources can be detected in the Earth's atmosphere. Lightning strikes generate bursts of radio waves known as *radio atmospherics*, or *sferics,* which last only a few milliseconds but can travel for thousands of kilometres in the wave guide formed by the Earth and ionosphere.

Sferics typically have frequencies in the Very Low Frequency (VLF) range of 0.1-10 kHz. When sferics propagate over long distances, the different frequencies penetrate the ionosphere to different depths, disperse and arrive at different times, creating a sound similar to bird song. Hence waves in the 1-7 kHz range are called *tweeks*.

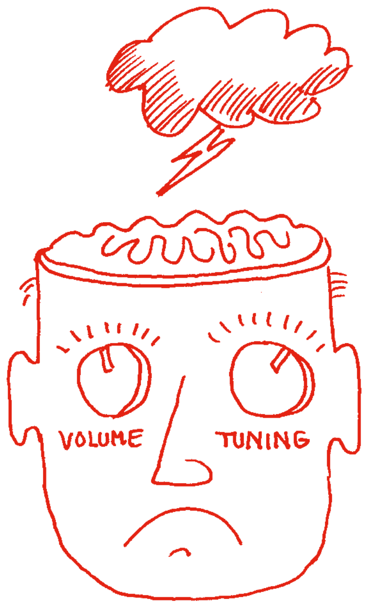
Radio waves from lightning strikes may escape the ionosphere and pass into the magnetosphere. Here, they interact with free electrons travelling along magnetic field lines to create VLF radio signals of decreasing frequency which are called *whistlers*. Samples of these different radio bursts can be heard at the NASA Space Weather website: **spaceweather.com/glossary/inspire.html**

Radio killed the zebra mussel

Zebra mussels are an invasive species that have caused significant damage in the Great Lakes in the United States. Researchers have developed a new method for killing the pest that does not use poisons that can harm other species. They have found that exposing the mussels to radio waves forces the molluscs to emit minerals, such as calcium, which are essential for the maintenance of their shells, killing the creature. The radio waves were found to have lesser effects on other species of mussels, crabs and crayfish.

Transmitting radio into the brain

During the early days of radio technology, in 1903, Frederick Collins published a paper in which he set out to determine the effects of 'electric waves' on the brain. He developed a receiver with an aerial consisting of two needles encased in glass.



Collins obtained an animal brain (the species was not specified) from a butcher, inserted the two needles into the organ and reported there was no change to the reception. He repeated the experiment with the brain of a dead cat and then, because he was interested in extending the study to living subjects, reported the somewhat unlikely claim, that "another cat under the influence of an anaesthetic, willingly lent itself to the subject for the investigations to be made on brain matter in the living state". Collins observed that the device caused the cat to twitch spasmodically.

Not satisfied with his result, Collins reported, somewhat cryptically, that "on a certain afternoon a magnificent specimen of a human brain came into my possession immediately after its removal from the cranium, and within hours of the death of the physical body". Whilst he was measuring the resistance of the brain, a thunderstorm occurred. Collins observed that the readings measured from needles inserted into hemispheres of the brain fluctuated wildly between the positive and negative ends of the scale.

Collins concluded with a claim worthy of Dr Frankenstein:

> "In these tests I was favoured with circumstances which, with me, might never occur again, for the reason that a fresh human brain was necessary, and that an electrical storm should be in progress when all was in readiness was quite remarkable."

Collins became a highly respected electrical engineer and formed a company to manufacture wireless telephones. He toured the country claiming that wireless telephones could soon be installed in cars and aircraft, demonstrating his equipment and selling stock in the company. However, the funds were invested in further demonstrations, rather than technology and, in 1911, Collins was convicted and imprisoned for a year for mail fraud. After his release, Collins went on to publish over a hundred books, many related to radio communication.

The Quiet Zone

In 1958, the United States Government declared a 180 km by 190 km area as the National Radio Quiet Zone. On the border between Virginia, West Virginia and Maryland, the area surrounds the National Radio Astronomy Observatory in Greenbank, West Virginia. At its centre is the Robert C. Byrd Green Bank Telescope, the largest land-based moveable object on the planet.

The telescope is said to be sensitive to 'a billionth of a billionth of a millionth of a Watt... the energy of a snowflake hitting the ground'. The Quiet Zone restrictions ban mobile phones, baby monitors, microwave ovens and wireless doorbells. Even petrol driven cars are not allowed within a mile of the telescope due to the electromagnetic emissions from their spark plugs. Enforcement officers patrol the local area looking for sources of radio frequency emissions.

Lamarr's radio-controlled torpedo

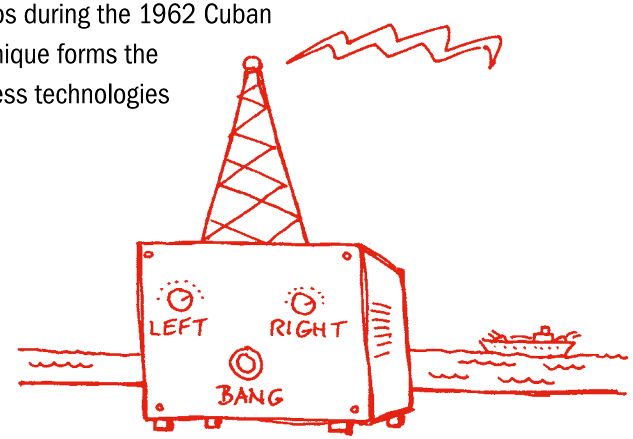
Hedy Lamarr was an Austrian-American film actress in Hollywood in the 1930s and 1940s. She was described as 'the most beautiful woman in the world', starred in a film that was banned due to its scandalous scenes and was married and divorced six times.

For a while, Lamarr dated the reclusive millionaire Howard Hughes, a film producer and aviation tycoon. She suggested alterations to the designs of his aircraft and Hughes encouraged her interest in technology, placing his scientists and engineers at her disposal.

During her unhappy marriage to Austrian weapons manufacturer Freidrich Mandl, Lamarr's husband brought her to business meetings. She listened in to discussions and developed the idea of a radio-controlled torpedo. She proposed the concept of frequency-hopping, a process in which a signal is transmitted over a range of different frequencies, to prevent the jamming of radio-guided weapons. With the avant-garde composer George Antheil, Lamarr patented the idea but, when she approached the U.S. Navy, they dismissed her invention.

Following the publication of a scandalous autobiography, Lamarr spent the last years of her life as a recluse, communicating largely by telephone. She died in 2000.

The military belatedly realised the potential of frequency-hopping and the technology was used on ships during the 1962 Cuban missile crisis. Lamarr's technique forms the basis of contemporary wireless technologies such as WiFi and Bluetooth.



Philo Farnsworth: from farm to fusor

Philo Farnsworth was an early pioneer of television technology and a prolific inventor. Among other things, he developed a device to sterilise milk using radio waves.

Farnsworth's family had moved to a log cabin built by Farnsworth's father in Beaver, Utah, when Farnsworth was 12 years old. In the attic of the cabin, Farnsworth discovered a set of scientific books and magazines. The curious boy devoured the contents of the texts and, inspired, installed a motor to power the family washing machine. Whilst still in high school, Farnsworth began working on television technology.

Previous attempts at developing television systems had used mechanical spinning discs, but he proposed a fully electronic system using a scanning electron beam. He claimed he had the idea for the scanning beam whilst ploughing lines on the family farm. Farnsworth received backing from two philanthropists and, fittingly, the first image he showed his backers on the new technology was an image of a dollar sign.

The Radio Corporation of America (RCA) offered to buy Farnsworth's patents, but the inventor refused as he felt the financial tie would limit his freedom. The company sued Farnworth and, in court, RCA's lawyers mocked the idea that a schoolboy could have developed the technology. Farnworth's defence team called his former chemistry teacher as a witness because the schoolboy had shown his teacher early schematics for his invention and RCA eventually lost the case.

In addition to these inventions, Farnsworth patented the notion of the circular sweep radar display which is still used in radar systems today. Farnworth is co-credited with the invention of the Farnsworth-Hirsch fusor, a device that causes nuclear fusion by accelerating ions in an electric field.

Microwaves

From a melting bar to an exploding egg

The idea for a device that uses microwaves to heat food came to Percy Spencer in 1945. At the time, he was working for Raytheon, the American defence and industrial corporation which had the first contract to mass produce magnetrons, devices that emit microwaves. These had been used as a component of radar systems during the Second World War.

After walking past a working magnetron, Spencer discovered that the confectionery bar in his pocket had melted, even though he had felt no sensation of heat. Whilst many books report that the bar Spencer carried was made of chocolate, Spencer's grandson, Rob, has claimed that it is more likely that the bar was a peanut cluster as his grandfather often carried one to feed squirrels and chipmunks.

After noticing the melted bar, Spencer is reported to have sent a messenger boy to get some corn kernels and produced the first batch of microwave popcorn. The following day, he used the magnetron to cook an egg and watched as it began to tremor and quake. A curious colleague who moved in for a closer look was splattered with hot yolk as the egg exploded in his face.

Hearing microwaves

During the Second World War, radio operators reported being able to perceive microwaves as auditory stimuli. The effect has been recreated under laboratory conditions and a number of people reported buzzing or knocking sounds when exposed to microwaves. It is thought that the sound is produced because microwaves can cause a small heating effect in tissue in the head leading to thermal expansion that generates an audible pressure wave.

The timetable polariser

Some of the earliest work on the use of microwaves to transmit signals was carried out by the Indian physicist J. C. Bose. At Calcutta Town Hall, he demonstrated that the waves could propagate both through walls and the body of the governor, and used microwaves to activate relays that triggered a bell and fired a cannon ball. In 1897, Bose demonstrated the waves before the Royal Society in London. Amongst the

apparatus he developed was a polariser that was constructed from a thick volume of Bradshaw's Railway Timetable with sheets of tinfoil placed between the pages.

Microwave miscellany

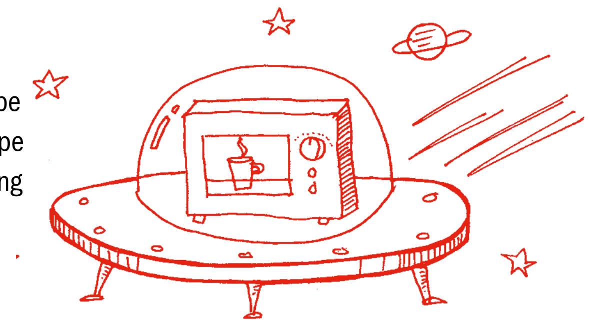
- Salty foods may warm up slightly more quickly than food without seasoning in a microwave oven. Although the main mechanism by which food is heated is through the absorption of microwaves by water molecules, in solution, Na^+ and Cl^- ions experience a force due to the changing electric and magnetic. Hence salty water will heat faster than pure water in a microwave.

- Melting ice in a microwave oven is a slow process because ice has different dielectric properties from liquid water and is almost transparent to microwaves.

- The reversing direction of microwave turntables is not a feature designed to encourage uniform heating, as is sometimes believed. In a response to a question in the *New York Times*, Robert J. Thomas, a professor of electrical engineering, pointed out that the change in direction of rotation occurs because the motors used in microwaves are typically cheap and require a torque to start moving when starting from stationary. The turntable is usually pressed against the load from the last rotation so starts to turn in the opposite direction.

Mysterious microwaves from space

Over a period of four years, scientists using the Parkes Radio Telescope in New South Wales, Australia had been detecting mysterious, fleeting bursts of radio signals. The researchers wrote a report on the preprint server ArXiv describing the strange broadcasts, which they labelled 'perytons'. It was subsequently discovered that the signals could be replicated by directing the telescope in a particular direction and opening the door of the microwave in the facility's break room.



Visible light

Wheatstone's stage fright

One of the first public remarks on the electromagnetic nature of light occurred partly by accident. In 1846, Charles Wheatstone (who invented the concertina, stereoscope and, of course, the Wheatstone Bridge) had been due to deliver a lecture at the Royal Society but allegedly panicked and fled before the talk. Faraday stepped in to take his place and improvised a lecture but, lacking enough material to fill the time, he introduced some speculations to the audience. He hypothesised that all of space was permeated by electric and magnetic field lines which, when disturbed, vibrated and that light was a manifestation of such vibrations. Maxwell reported that Faraday's conjectures, to some extent, prefigured his own electromagnetic theory.

Forbidden colours

A model of colour perception, proposed in 1872 by Ewald Hering, argued colour vision involves two opponent pairs of colours: red-green and yellow-blue. It has long been believed that the opponency of colours is an inherent feature of vision and that it was impossible to see reddish-green or blueish-yellow. This effect arises because colour perception appears to use a red-green channel and a blue-yellow channel.

However, Californian visual scientists H D Crane and T P Piantanida showed that under special conditions people can experience these 'forbidden' colours. In 1983, they drew figures in which two touching vertical bands of colour run parallel to each other: a red and green line and, in a separate figure, a blue and yellow line. Using an eye tracker, the researchers moved the images in response to the participants' eye movements in order to keep them in the same place in the viewers' visual field. The participants reported that, as they stared at the bands of colour, the colours appeared to flood together allowing them to see colours which they had never seen before, including, for example, a colour that was both red and green at the same time.

The types of yellow

Yellow light can be perceived as the result of two mechanisms: 'physical yellow' which results from the incidence of 600 nm light on the eye and 'psychological yellow' which occurs when the eye detects equal amounts of red and green light. Humans cannot distinguish between these two different causes of the perception of yellow.

The Purkinje effect and Purkinje images

Jan Evangelista Purkyně, a 19th century Czech anatomist, gave his name to several well-known effects.

Depending on the intensity of lighting, we see colours differently. The wavelengths of light the human eye is sensitive to vary with the intensity of light, an effect known as the *Purkinje effect*. In lower intensity lights, peripheral rod cells are stimulated and the eye's peak sensitivity to light shifts towards green in comparison to a peak sensitivity to yellow for vision in daylight. For example, in twilight, a red flower may appear black and objects in moonlight may appear greyish-green.

A separate phenomenon is the series of reflections that occur from the structures of the eye, known as *Purkinje images*. The first Purkinje image occurs due to reflection from the anterior surface of the cornea, the second from the posterior surface of the cornea, the third from the anterior surface of the lens, and the fourth from the posterior surface of the lens and is inverted. The reflections can be used by eye tracking technology to determine the movement of the eye.

Purkyně enjoyed great fame due to his research. It is claimed correspondents needed only to address a letter to 'Purkyně, Europe' for the message to reach him.

Tetrachromia and colour blindness

- Whilst data on prevalence is still somewhat uncertain, between 15-47% of women and around 8% of men, are potential *tetrachromats*. That is, they have four cones and a greater ability to perceive differences in colours – some tetrachromats may be able to distinguish two million shades of colours.

- In contrast to the prevalence of tetrachromacy, men are 16 times as likely as women to be colour blind. Complete colour blindness, *achromatopsia*, is rare, affecting only 3 in 100,000 people. However, on the island of Pingelap in Micronesia, the prevalence is somewhere between 4-10% as the islanders are descended from survivors of a typhoon in the 1700s, one of whom carried the gene for the condition.

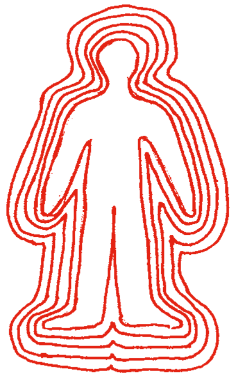
- The human retina has a smaller number of blue than red or green cones, and, in the fovea, there are no blue cones at all. Therefore, a sufficiently small blue dot, directly

Tetrachromia and colour blindness *continued*

in the centre of the visual field cannot be recognised as blue. Viewed at a distance, white and yellow, blue and black, and red and magenta, will look identical. This effect has been known for many years, and naval signalling flags and the colours in heraldry were designed such that the colours could not be confused when viewed at a distance.

- Unlike the three cones humans possess, some species, for example mantis shrimps and butterflies, possess up to 12 spectral sensitivities. It is surprising, then, that mantis shrimp have a poorer ability to distinguish colours than humans. The shrimp can only distinguish colours differing in wavelength by 25 nm, whilst humans can detect differences of between 1-4 nm. Instead, it is hypothesised that the 12-receptor system gives an advantage by increasing the speed of colour processing.

You look radiant!



The human body literally glitters. A Japanese research team has discovered that the human body emits light photons at an intensity so low human eyes would need to be a thousand times more sensitive to detect them. The photon emission is highest in the morning and lowest in the evening, correlating negatively with levels of cortisol in the body. The radiation occurs most intensely from the face and in particular the cheeks. The mechanism for the emission of photons is thought to be connected to the generation of free radicals by metabolic processes.

Cosmic latte

Researchers have attempted to determine a 'cosmic colour' by averaging the frequency of light emitted by 200,000 galaxies within 2 billion light years of the Earth. Though the researchers initially reported the mean colour was somewhere between turquoise and aquamarine, a bug in their software caused a miscalculation and they subsequently reported the new average is beige – a colour sometimes referred to as 'cosmic latte'. You can experience 'cosmic latte' on the NASA website **apod.nasa.gov/apod/ap091101.html**

Infrared and ultraviolet

Seeing red (and beyond)

- Human vision can be sensitive to infrared radiation. A study has shown that some observers perceive infrared laser radiation of wavelength 1060 nm as a pale greenish colour. The effect occurs due to the simultaneous absorption of two infrared photons by the photopigments in the eye.

- There is some evidence that aphakic patients (those whose lenses have been removed) have an increased sensitivity to ultraviolet radiation. Following lens removal surgery, some patients have reported being able to perceive ultraviolet radiation. A letter in the journal *Nature* described the case of one such patient who perceived the world as brighter following the surgery, in particular, blues stood out more intensely.

- The artist Claude Monet underwent surgery on his right eye to remove a cataract that resulted in the removal of the lens. Following the surgery, Monet produced paintings by covering one eye. An analysis of the canvasses he produced when he was using his left eye suggests warm colours predominated, whereas in work produced using his right eye, cooler colours are dominant.

- Two groups of snakes (including boa constrictors, rattlesnakes and pythons) have the ability to sense infrared radiation. The snakes have free nerve endings which can respond to temperature differences as small as 0.001°C.

- Though it had been proposed that polar bear fur fibres act like fibre optics, this claim has turned out to be unsupported by evidence. Polar bear fur is, however, an excellent insulator and opaque to infrared, hence the creatures are almost invisible on infrared cameras.

- We perceive visible light when a photon hits the retina, triggering a chemical reaction which is reversible. This reaction involves breaking chemical bonds. The energy required to do this ranges from 0.01 eV (Van der Waals bonds) to 5 eV (covalent bonds). We can see visible light as the energy of visible photons runs from 1.6 eV (red) to 3.4 eV (violet) within the energy range required to break these bonds. This means it is difficult for the human eye to detect radiations of

Seeing red (and beyond) *continued*

significantly higher frequencies than visible light via this mechanism. Ultraviolet photons can damage human tissues and, though most people have a mechanism to correct such damage, sufferers from the rare genetic condition *xeroderma pigmentosum* lack the process and must avoid exposure to ultraviolet radiation. The damage caused by ultraviolet radiation occurs through the release of 'pinball protons' from the base pairs in DNA that can cause a chain of lesions as they pass through the genetic material.

Hiding in the infrared

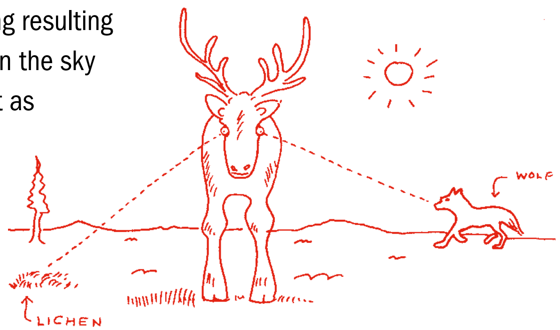
During the Battle of the Atlantic in the Second World War, the breaking of the enigma code allowed Allied Forces to increase the rate at which they sank German U-boats. Seeking an explanation for the additional losses, Karl Dönitz, a German admiral, came to believe that U-boats were being detected by their infrared emissions – a false belief amplified by rumours spread by British agents. The Germans accepted the story and responded by painting their U-boats with an infrared emission reducing paint. Rather than hiding the U-boats, the new coating increased the vessels' radar signature, making them more vulnerable to attack.

Infrared identification

The black and olive American flags that appear on some US military uniforms are covert infrared reflectors that enable friendly soldiers to be identified with night vision goggles.

Polar UV

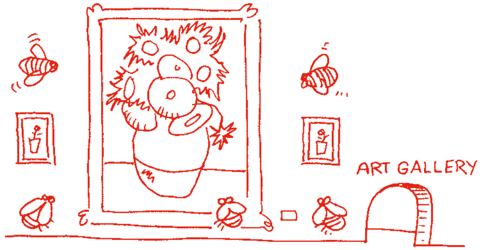
Levels of ultraviolet (UV) radiation can be high close to the North and South Poles. The effect occurs due to scattering resulting from the low position of the Sun in the sky and because snow and ice reflect as much as 80% of UV radiation. In snowy areas, high levels of UV radiation can lead to a kind of sunburn of the retina known as snow blindness. Most mammal



eye lenses have therefore evolved to block UV radiation. However, it appears that reindeer may have developed some ability to detect UV radiation in the wavelength range of 300-320 nm for two important reasons: firstly, because a lichen they eat strongly absorbs UV and secondly, the fur of a key predator, the wolf, is highly reflective of UV radiation. Additionally, they may benefit from the variable reflection of UV from different kinds of snow.

Apian art appreciation

A study which examined whether bees were attracted to paintings of flowers investigated the reactions of the insects to paintings by Van Gogh, Caulfield and Gauguin. The Van Gogh painting attracted the most bees and the researchers conducting the study hypothesised that bees prefer bee-blue and UV blue to other colours, as flowers of these colours are typically high in nectar.



Hippo sun cream

Hippopotamuses secrete a clear fluid that helps to control their body temperature. The fluid turns red-brown within a few minutes of release and gave rise to the myth that the creatures sweat blood. Researchers have found that the fluid blocks both UV and visible light of wavelengths 200-600 nm and so protects the animals from sunburn. The fluid contains red and orange pigments which researchers have labelled *hipposudoric* and *norhipposudoric* acid.

X-rays

Blondlot's N-rays

French physicist Prosper-René Blondlot demonstrated that X-rays travelled at the speed of light. But he is perhaps now best remembered for his work on N-rays. Blondlot investigated the effect of X-rays on electrical sparks and, in 1903, concluded that an additional form of radiation was causing changes to the brightness of the spark. He labelled the radiation N-rays and carried out a series of experiments to deduce further properties of the rays, noting that they were emitted by the Sun and materials under strain and that they influenced organic matter.

Other scientists followed up his work and published research on N-rays, with one researcher reporting that his desk plant emitted the radiation. Though supportive studies appeared for a number of years after Blondlot's 'discovery', the American physicist, Robert H Wood, visited Blondlot's laboratory in 1904 and debunked the N-ray phenomenon by observing that Blondlot's observations were caused by psycho-physiological effects.

Aptly, Wood's career in physics had been spurred by a personal experience of 'invisible rays'. As a boy, Wood had been intent on becoming a priest but after seeing an aurora chose to study physics instead to understand the 'invisible rays' that caused the phenomenon.

The incident is often cited as a demonstration of the dangers of experimenter bias.

Röntgen's rays

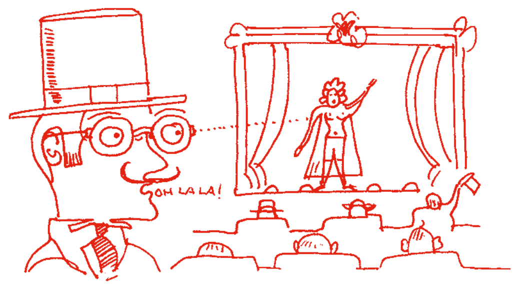
The story of the discovery of X-rays in 1895 highlights Wilhelm Röntgen's sensitivity to detail. The first piece of evidence that a new kind of radiation existed was a small glimmer of light on a florescent screen placed in front of a cathode ray tube in a darkened laboratory. In order to find the source of the light, Röntgen switched the cathode ray tube on and off and noted the glimmer disappeared. He then placed a piece of black cardboard, a book of 100 pages and a wooden shelf between the screen and the tube and observed that the bright spot remained unchanged. When he held a small lead disc in front of the screen, he saw the shadows of his own bones.

Following his experiments, Röntgen arrived unusually late for dinner with his family in their living quarters above his laboratory and "did not speak, ate little and then left abruptly to return to the experiments that had so disturbed him that afternoon". After the discovery, he confessed: "I have not the slightest idea of the rays' nature."

Röntgen's academic career had an inauspicious start. After a classmate drew a caricature of a teacher on a firescreen, Röntgen was asked to name the perpetrator by the irate teacher. He refused to reveal who had drawn the picture and was subsequently expelled.

During a housing crisis in inter-war Germany, Röntgen used a ploy to convince the authorities that he could not take in lodgers. He moved furniture, removed a connecting door and demonstrated experiments to inspectors to make his study and guest room look like laboratories.

X-rays seized the public imagination and soon a number of wild claims appeared in the press: X-rays could be used to project anatomical diagrams directly into the brains of medical students, X-rays could turn cheap metal into gold and a Parisian doctor claimed he had photographed thoughts with the new radiation.



The discovery led to a moral panic, with one commentator speculating that "the century of the box" would see decent-minded individuals dress themselves in shielding to protect their privacy. In 1896, a London company offered X-ray proof underwear for sale. A petitioner in New Jersey campaigned for legislation outlawing the use of X-ray opera glasses in the theatre whilst an enterprising, if somewhat confused correspondent wrote to Edison: "Dear Sir: Will you please send me one pound of X-Rays and bill as soon as possible."

Röntgen has been described as a reticent man: except for one lecture at his own university, a month after receiving the Nobel Prize, he declined all invitations to speak.

Unexpected sources of X-rays

- Though the emission of X-rays from lightning had been predicted several decades ago, it is only in recent years that the high-energy radiation has been detected. However, the mechanism by which lightning produces X-rays is currently poorly understood.
- Peeling Sellotape generates X-rays and a team at the University of California have produced enough X-rays to take an image of one scientist's fingers by uncoiling tape in a vacuum. The phenomenon is a form of *triboluminescence*, the release of energy from the breaking of chemical bonds when mechanical energy is applied to a material.
- Triboluminescence was first reported in 1605 when Francis Bacon observed that lumps of sugar released light when scraped. Many common sweets will display the effect and a paper reports the spectra of radiation given off by an American Wint-O-Green Lifesaver™. Diamonds are both triboluminescent and *thermoluminescent*: a thirteenth century bishop, Albertus Magnus, noted that the precious stones emitted light when placed in warm water and Robert Boyle observed that a diamond fluoresced when struck with a bodkin.

The risks of X-ray research

Thomas Edison nearly lost his eyesight using fluoroscopes (devices that produce real time X-ray images) from exposure to X-rays through the viewfinder. When asked about his work with X-rays, he replied: "Don't talk to me about X-rays, I'm afraid of them."

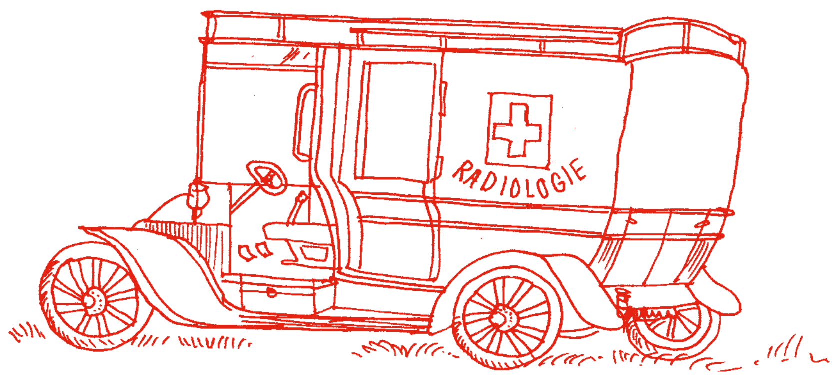
Edison's assistant, Clarence Madison Dally, who was subjected to the fluoroscopy, suffered greatly from his exposure: he had both of his arms amputated following severe ulceration to his hands and died soon after of cancer.

X-ray of an author

Mark Twain may have inadvertently been the subject of the first X-ray. A few months before Röntgen's discovery, Nikola Tesla had used a Geissler tube (an early form of discharge tube) to take a picture of Twain. The tube had emitted X-rays, which had spoiled the plate before the cap of the camera had been removed, producing a photographic plate with an image of an adjusting screw. Following the news of Röntgen's discovery, Tesla is reported to have smashed the plate on the floor exclaiming: "Damned fool! I never saw it!"

Curie's X-ray ambulances

Marie Curie responded rapidly to the outbreak of the First World War: within 10 days of the mobilisation of French troops, she had received a document from the Minister of War authorising her to organise radiological workers into mobile units. She raised funds for a team of medics in cars equipped with X-ray equipment, working with a surgeon to control the apparatus to image bones and detect foreign bodies in tissues. The X-ray vehicles became known as 'les petites Curies'



Moseley's obituary

The British physicist, Henry Moseley, showed that every element had a unique X-ray emission spectrum. Moseley was known for his doggedness as an experimentalist and his dedication to his work meant that one colleague reported that Moseley had an unrivalled knowledge of where to get a meal at three o'clock in the morning in Manchester.

Moseley was killed at Gallipoli in 1915 aged 27. His supervisor, Ernest Rutherford, wrote an obituary in the journal *Nature*. He expressed his horror at the loss:

> "It is a national tragedy that our military organisation at the start was so inelastic as to be unable, with few exceptions, to utilise the offers of services of our scientific men except as combatants in the firing line. Our regret for the untimely end of Moseley is all the more poignant that we cannot but recognise that his services would have been far more useful to his country in one of the numerous fields of scientific inquiry rendered necessary by the war than by exposure to the chances of a Turkish bullet."

Had he lived, commentators have suggested that Moseley would have won the Nobel prize in 1917.

Gamma rays

Villard's deviable rays

The discoverer of gamma rays, Paul Villard, received little credit for his work during his lifetime and his contribution was only fully recognised a century after his original research. Villard had used a Crookes tube to study cathode rays that were referred to as 'deviable' rays because they could be deflected by magnetic fields. He obtained a sample of radium from the Curies and discovered that the element also emitted deviable rays. However, he noted that his source also emitted a type of radiation that was not deflected by magnetic fields and reported the discovery in 1900. Perhaps because Villard did not label the rays and went on to research X-rays and cathode rays, his contribution has only recently been acknowledged. Rutherford later named the rays Villard had observed 'gamma rays', to join the alpha and beta radiations he had already identified.

Dark lightning

In 1925, C. R. T. Wilson proposed that the electric fields in clouds might accelerate electrons to relativistic speeds causing the release of gamma rays. The Fermi Gamma-Ray Telescope has recently correlated observations of gamma ray bursts with the locations of thunderstorms. The processes in storms that generate gamma rays release very little light so have been called 'dark lightning'. Near the tops of storms, the dose of radiation emitted could be equivalent to 100 chest X-rays, or a full CT scan.

Gamma gems

The colour of gemstones is sometimes altered by exposing them to gamma rays. Colourless quartz will become smoky and pale whilst colourless diamonds can be turned blue, green, red and yellow through irradiation. Only a year after Antoine-Henri Becquerel's discovery of radioactivity in 1896, William Crookes buried a diamond in radium bromide powder for several months and discovered it turned a bluish-green colour. The effect occurs due to carbon atoms being knocked out of the crystal lattice by the passage of gamma rays.

Gamma ray bursts

In the 1960s, the United States launched the Vela satellites to monitor nuclear weapons tests. On 2 July 1967, two of the satellites detected a burst of radiation unlike that of any known nuclear weapon. Unconcerned, the scientists monitoring the satellites filed the unusual data away for later analysis. The launch of further satellites allowed researchers to confirm that the radiation was not of a terrestrial origin and was labelled a 'gamma ray burst'.

Each gamma ray burst has a unique intensity spectrum, leading to the astronomers' joke: "If you've seen one gamma ray burst, you've seen one gamma ray burst."

The bursts are thought to be the most powerful explosions in the universe and come in two types:

- 'short-hard' bursts which are hypothesised to arise from the merger of a binary system of compact objects such as two neutron stars, or a neutron star and a black hole
- 'long-soft' bursts which are related to the deaths of short-lived massive stars.

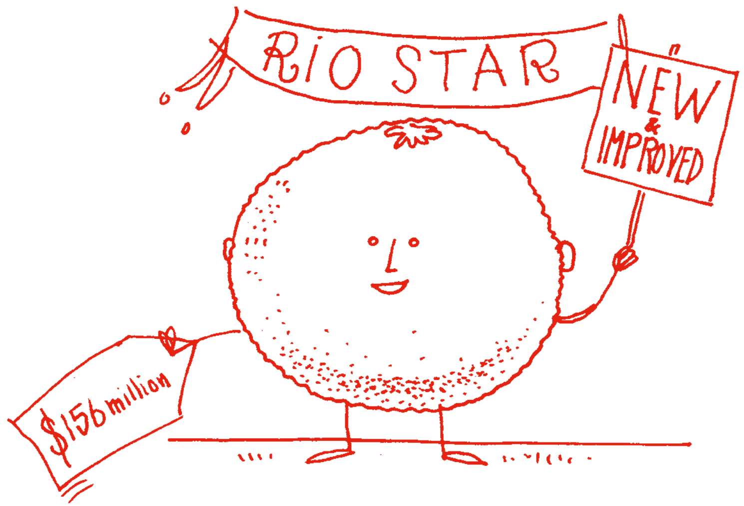
A large, local gamma ray burst could cause a number of devastating impacts on the Earth. The radiation will disassociate N_2 and O_2 molecules in the atmosphere leading to the depletion of the ozone layer and increased irradiation of the planet's surface in ultraviolet radiation. In addition, the disassociation would lead to increased production of NO_2, increasing atmospheric opacity causing global cooling. The increased NO_2 levels would also increase the acidity of rain, harming aquatic organisms.

Given these devastating effects, gamma ray bursts have been hypothesised to have caused past mass extinctions. It is estimated that a gamma ray burst originating from within 9,800 light years (3 kpc) of the Earth would constitute a serious threat to life and such events are estimated to occur every 170 million years.

Gamma ray bursts are emitted as beams of radiation so an event would have to be directed at Earth to be a risk. A candidate object for a dangerous burst event exists. The star WR-104's rotational axis is aligned within 16° of the Earth and is around 8,150 light years (2.5 kpc) away. However, no reliable estimates exist of whether a gamma ray burst from WR-104 is likely. It is assumed that a number of gamma ray burst have occurred in the past – one such incident is believed to have occurred in the year 774 or 775, explaining the unusually high levels of carbon-14 detected in Japanese tree rings from this time.

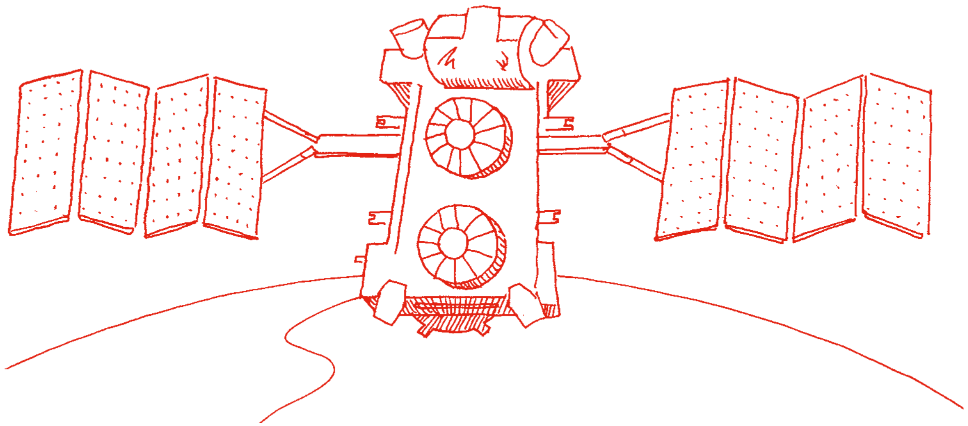
Gamma grapefruits

Gamma radiation has been used to induce mutations in the selective breeding of fruit. Seeds of a cultivar of oranges and grapefruits were exposed to gamma radiation and 1,270 seeds were planted, from which 16 mutant, seedless varieties were produced. Thermal neutron irradiation was used to 'improve' the red colour in Rio Star grapefruits which is estimated to have led to increased sales of $156 million in 1997.



Bomb detecting with space telescope spare parts

NASA's Compton Gamma Ray Observatory was launched in 1991 and produced much useful data on astronomical high-energy radiation. In 1999, the telescope suffered a gyroscope failure and was successfully 'deorbited' in 2000. However, researchers realised that the spacecraft's sensors make good bomb detectors as they can provide information on the direction of a gamma ray source which conventional detectors do not. They recycled spare parts built for the spacecraft's gamma ray detectors as detectors for dirty bombs that contain a mixture of conventional explosives and radioactive substances.



Gamma lenses

For centuries, glass has been used to make lenses that refract visible light. As the frequency of radiation increases, waves are refracted less when travelling between media so it had been assumed that gamma ray lenses were not a realistic possibility. However, in the 1990s, it was found that X-rays could be diffracted by beryllium, and carbon lenses and gamma ray lenses have been constructed from silicon and gold. It is believed that short-lived electron-positron pairs generated by the electric fields of the nuclei in the lens interact with gamma radiation to change its path. It is hoped that the gamma ray lenses will have applications in medical diagnosis, for example, in tracking the absorption of the anti-depressant medication, lithium.

The Goiânia incident

In 1985, a private radiotherapy clinic in Goiânia, Brazil was being moved to new premises. During the course of the transfer, a caesium-137 teletherapy unit was stolen by two people who believed it might have scrap value. The individuals took the source assembly home and attempted to dismantle it, rupturing a capsule which contained caesium chloride, a source of gamma radiation. The men sold the remnants of the source assembly to a junkyard. The owner of the yard noticed that the material glowed blue in the dark.

Over the following days, friends and relatives of the owner came to observe the striking phenomenon and some of the visitors took small fragments of the material away with them. A six year-old girl handled pieces of the source bare-handed whilst eating a meal. After five days, some of those exposed to the radiation began to complain of gastrointestinal symptoms but their conditions were not initially linked to radiation exposure.

A concerned relative took some of the material to the health authorities. She travelled by bus, carrying the caesium in a bag, and placed it on the desk of a doctor, reporting that the material was: "killing her family". The doctor happened to know a medical physicist who, by chance, was visiting the organisation. In order to determine the nature of the material, the physicist borrowed a scintillometer from a government nuclear agency. Even when he was some distance from the bag containing the fragments, the meter went to full-scale deflection. This unlikely reading led the physicist to assume that the meter was defective, so he returned to the nuclear agency to collect a different scintillometer.

Whilst the physicist was away, the health authority doctor became concerned and called the fire brigade. The physicist only just returned in time to stop the firemen from throwing the source into the river. He argued for the immediate evacuation of the health authority building and the junkyard premises and 22 people were identified as having had a high level of exposure to the source. In total, 249 people had detectable exposure to radiation as a result of the incident, four people died from irradiation and several others required hospital treatment.

In 1988, The International Atomic Energy Agency described the incident as: "one of the most serious radiological accidents to have occurred to date".

Sound

Boombox lung

High amplitude sounds can cause *pneumothorax*, a build-up of air in the pleural space that leads to the detachment of a lung from the chest wall, commonly called a 'collapsed lung'. Low frequency, high intensity sound can be damaging to the lungs, particularly if the sound matches the resonant frequency of the functional tissue, 128 Hz.

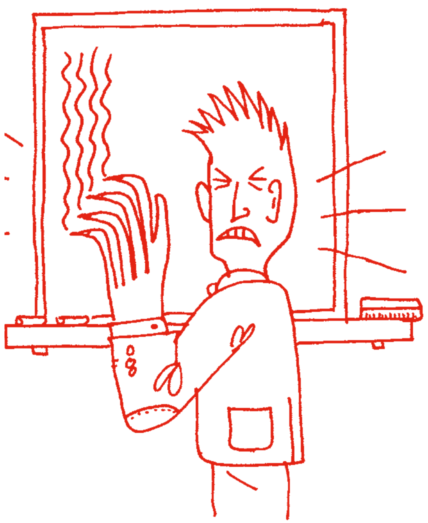
A report describes four case studies of pneumothorax induced by loud sounds, including a 19 year-old male smoker who had installed a 1000 W bass speaker in his car. Whilst listening to music, the young man experienced a sudden pain in the right side of his chest and became breathless due to the reoccurrence of pneumothorax.

The loudest LEAF

In order to test its satellites' resilience to the noise of launch, the European Space Agency has built the Large European Acoustic Facility (LEAF). The facility has walls made of steel-reinforced concrete, 0.5 m thick, and contains noise generators which can produce sound of up to 154 decibels. The ESA reports that no human could survive hearing the system at maximum output.

The physics of fingernail scrapping ...

Researchers from Northwestern University, Illinois, have written a paper attempting to determine the cause of the 'obnoxious' sound of fingernails on a blackboard. They report that, contrary to expectations, it is not the high frequencies that cause the unpleasant sensation, but elements of the signal at frequencies in the middle of the human auditory range. The authors note that the sound resembles the warning cries of macaque monkeys.



... and screaming

Another team has proposed the theory that the quality that makes screams unpleasant is roughness, the frequency with which loudness varies. Roughness occurs in screams at rates of between 30-150 Hz, much higher than for normal communication (4-5 Hz).

Newton's experimental fudges

In the 1600s, estimates for the speed of sound in air ranged from 180 ms^{-1} to 450 ms^{-1}. Newton set out to determine the speed of sound himself and made a measurement in the cloister (covered walk) of Trinity College, Cambridge, adjusting a pendulum until it swung in time with a returning echo. In the 63 m cloister, he found that the echo was slower than the swing of a 14 cm pendulum but quicker than a 20 cm pendulum. This placed the speed of sound between 280 and 331 ms^{-1}. However, based on a comparison of densities, Newton had also estimated the speed of sound in air to be 295 ms^{-1}. He subsequently amended his experimental data arguing the echo was slower than a 13 cm pendulum but faster than one of 18 cm. The historian of science, Richard Westfall, has noted that this is one of a number of occasions on which Newton fudged the data to fit his preconceptions.

Sounds in popular culture

In order to substantiate the claim made in the Meghan Trainor song that it's 'All About That Bass,' a paper reports the result of a calculation of the velocity that humans would have to travel at for their de Broglie wavelengths to be in the range of bass sound frequencies. They assume base frequencies to be in the range 20-200 Hz and calculated that, for average masses, men would need to travel at 2.9×10^{-42} ms^{-1} and women at 3.5×10^{-43} ms^{-1} meaning that, contrary to the song's claim, lighter people are more about the bass than their heavier counterparts.

The same author, in a separate paper, presents an analysis of the "feasibility of using screams to meet the energy requirements of Great Britain" based on the energy generation method used in the film *Monsters, Inc*. The researcher measured the intensity of a scream as 8 Wm^{-2} and concluded that screams are not a viable means of meeting the country's energy needs.

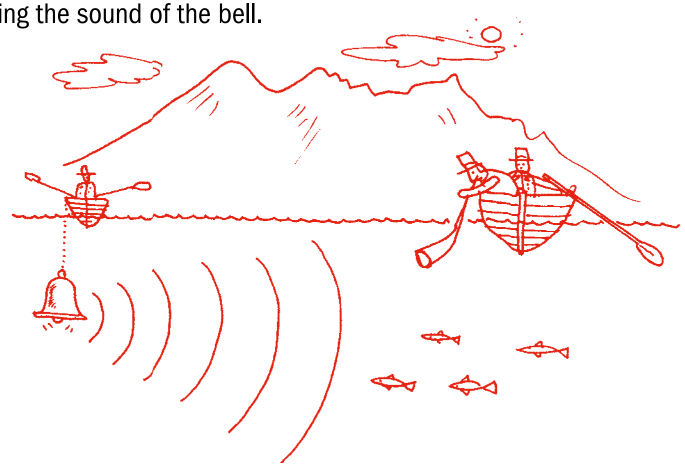
The undersea sound pipe

The speed of sound waves travelling in seas and oceans varies with depth due to changes in temperature and density under the water's surface. The speed of sound initially falls with depth as temperature drops beneath warm surface waters, but then rises again as pressure increases at greater depth. This speed distribution creates a sound duct, known as the *sound fixing and ranging (SOFAR) channel* or *deep sound channel.*

The SOFAR channel is found at a depth that rises from 1000 m at mid-latitudes, to close to the ocean's surface in polar regions. Much like a fibre optic cable guides light rays, so the varying refractive index of sea water refracts sound waves along the channel's axis. The channel enables blue whales to communicate over long distances. Researchers have found that the sound of small, underwater explosions can travel thousands of kilometres in the SOFAR channel.

Colladon's bell

The Swiss scientist, Jean-Daniel Colladon, a pioneer of research into fibre optics, conducted a curious experiment to measure the speed of sound in water. In 1841, Colladon and his father took two boats onto Lake Geneva. Colladon's father lowered a bell into the lake. A striking mechanism triggered by a small explosive charge in his boat was attached to the bell. Colladon, in another boat some distance away, listened for the sound of the bell using an underwater listening tube. He calculated the speed of sound in water from the time difference between seeing the flash of the explosion and hearing the sound of the bell.



The variety of watery waves

Rogue waves

For centuries, sailors have spoken of *rogue waves*, which are freakishly large waves that appear without warning. Rogue ocean waves are defined as waves twice the *significant wave height*, the mean height of the largest third of recorded waves. Between 1969 and 1994 more than 22 supercarriers have been lost to rogue waves. Waves as high as 26 m have been reported and rogue waves are expected to occur every 10,000 waves. A number of effects have been proposed to explain rogue waves including spatial focusing of waves by changing seabed topography and the co-occurrence of meteorological phenomena.

The first rogue wave to be recorded by an instrument was named the Draupner wave, after the gas platform where it was observed. On 1 January 1995, whilst the significant wave height was 12 m, a 25.6 m wave was recorded at the gas platform in the North Sea. The wave caused only minor damage to the platform.

Researchers from the universities of Oxford and Edinburgh have recently been successful in recreating rogue waves in the laboratory. They found that the phenomenon occurred when wave groups crossed at an angle of 120°.

Internal waves

Waves are not restricted to the surface of fluids but can occur, under the right conditions, within them as well. Internal waves can occur at the boundary between layers of fluid with different densities. The amplitude of internal waves can be an order of magnitude greater than that of surface waves. This is because the generation of internal waves requires less energy than for surface waves as the difference in densities between layers is typically less than for the water-air boundary. Some of the largest ocean waves are internal waves – in the Luzon Strait, in the South China Sea, subsurface internal waves with a height of 170 m have been recorded.

Solitary waves

In 1834, John Scott Russell, a Scottish engineer and scientist, noticed an unusual type of wave whilst conducting experiments to increase the efficiency of steamboats:

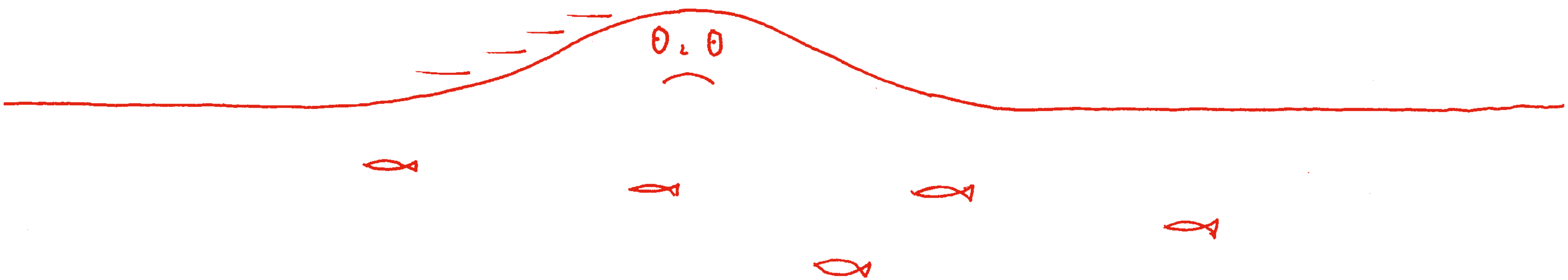
> "I was observing the motion of a boat which was rapidly drawn along a narrow channel by a pair of horses, when the boat suddenly stopped – not so the mass of water in the channel which it had put in motion; it accumulated round the prow of the vessel in a state of violent agitation, then suddenly leaving it behind, rolled forward with great velocity, assuming the form of a large solitary elevation, a rounded, smooth and well-defined heap of water, which continued its course along the channel apparently without change of form or diminution of speed. I followed it on horseback, and overtook it still rolling on at a rate of some eight or nine miles an hour, preserving its original figure some thirty feet long and a foot to a foot and a half in height. Its height gradually diminished, and after a chase of one or two miles. I lost it in the windings of the channel. Such, in the month of August 1834, was my first chance interview with that singular and beautiful phenomenon which I have called the Wave of Translation."

Other researchers investigated Scott Russell's waves of translation in tanks and found that the waves had a curious property – unlike other waves, a wave of translation retained its bell-shape and velocity as it travelled and the waves would not merge if a small wave was overtaken by a larger wave.

Waves of translation are now called *solitary waves.* They were not well understood in the 19th century, but turned out to have interesting applications in other fields. Sixty years later, Enrico Fermi, John Pasta and Stanislaw Ulam, working at Los Alamos, were trying to understand the surprising result that the predicted thermal conductivity of atomic lattices was infinite when the lattices were modelled as a series of one-dimensional springs.

The apparent paradox was solved by Norman Zabusky and Joseph Kruskal in a paper published after Fermi's death. They proposed localised excitations called *solitons*, which turned out to be related to the curious wave Scott Russell had observed.

The calculations for Fermi, Pasta and Ulan's work were carried out on MANIAC, one of the earliest computers built in 1952 for the Manhattan Project's work on the hydrogen bomb. The programming for the paper was done by the mathematician Mary Tsingou who is credited, along with Pasta, with creating one of the first computer graphics displays – a visualisation of an explosion problem on an oscilloscope.



Ocean waves

Ocean waves have been classified into seven types reflecting the different processes by which they are generated and based on their time periods:

Classification	Cause	Period
Capillary waves	The wind (with surface tension providing the restoring force)	Less than 0.1 seconds
Ultra-gravity waves	Pressure differences due to action of the wind	0.1 - 1 second
Ordinary gravity waves		1 - 30 seconds
Infra-gravity waves		30 seconds to 5 minutes
Long-period waves	Storms and earthquakes	5 minutes to 12 hours
Ordinary tidal waves	Gravitational attraction	12 hours to 24 hours
Trans-tidal waves	Gravitational attraction and storms	24 hours and up

Rossby or planetary waves

Gigantic meandering waves occur naturally in the atmospheres and oceans of planets. *Rossby waves*, also known as *planetary waves*, are long wavelength atmospheric and oceanic oscillations that usually propagate parallel to lines of longitude. The waves are driven by the Coriolis force (an apparent force that causes changes to the motion of objects within rotating systems) and pressure gradients, causing fluids travelling northwards from the equator to be deflected to the east and vice versa. The amplitude of Rossby waves is primarily in the horizontal direction because the restoring force for the oscillations is the Coriolis force.

- The waves have very long wavelengths: Rossby ocean waves have wavelengths of hundreds of kilometres and atmospheric waves thousands of kilometres. In contrast to such large wavelengths, oceanic Rossby waves typically have surface amplitudes of only around 10 cm and so are hard to detect by eye but can be observed by satellites. These small surface amplitudes can be deceptive – although there is only a 10 cm variation on the ocean surface, the same waves may cause oscillations as large as 90 m in the subsurface temperature gradient.

- The horizontal wave speed of Rossby waves depends on their latitude. Whilst waves close to the equator cross the Pacific Ocean in a few months, at mid-latitudes they can take 10-20 years to complete the crossing.

- Astronomers have recently observed that Rossby waves exist in the Sun. Researchers tracked bright points in the Sun's corona to monitor the passage of the waves. Animations of Rossby waves on the Earth and on the Sun can be seen on the NASA website: **nasa.gov/feature/goddard/2017/ waves-on-sun-give-nasa-new-insight-into-space-weather-forecasting**

Traffic waves

Researchers have modelled flowing traffic as analogous to a fluid and have applied wave equations to predict the behaviour of cars in heavy traffic. The wave-equation models suggest that jams can occur spontaneously in homogeneous traffic flow, if the density of vehicles exceeds a particular value. Traffic can be modelled as existing in a number of states, for example free flowing and traffic jams, with phase transitions occurring between the states.

Reflection

Performing twice at the Royal Albert Hall

When the Royal Albert Hall was opened by the Prince of Wales in 1871, his address was difficult to hear due to an echo which “repeated the words with a mocking emphasis which at another time would have been amusing”. A number of methods for reducing the poor acoustics were attempted without success. The echo was so pronounced that musicians joked that the Royal Albert Hall was the only venue where a performer was guaranteed that their work would be heard twice.

The phenomenon was substantially rectified in 1968 when the BBC’s Ken Shearer developed the idea of ‘mushrooms’, large discs that hang from the base of the dome, to prevent reflection from the curved ceiling.

Reflective retinas

The red-eye effect that can appear in photographs is caused by the reflection of the camera flash from blood vessels at the back of the eye. Red-eye reduction systems typically work by firing a number of rapid flashes of light, which cause the subject’s pupils to contract, reducing reflection from the retina.

Liquid mirrors

It has long been known that spinning a shallow dish of a reflective liquid, such as mercury, can create a parabolic mirror, like those used in reflecting telescopes. A number of attempts to construct liquid mirror telescopes were made in the 18th and 19th centuries. Liquid mirrors cost less to construct than conventional solid glass mirrors which are expensive to cast, grind and polish into a precisely parabolic shape. However, as Robert Wood of John Hopkins University observed in 1908, slight changes in angular velocity and inaccuracies in levelling the container supporting the fluid caused surface ripples that distorted the image.

Recently, a Belgian and Canadian project has developed a liquid mirror telescope that is being installed in Devasthal, India. The primary mirror has a diameter of 4 m and consists of a base fluid covered in a 1 mm layer of mercury.

The true mirror

In 1995, an American inventor, John Walter, developed a device that he calls a 'true mirror', which does not reverse images in the way normal mirrors do. It consists of two perpendicular mirrors in a box, the second mirror acting to undo the reversal of the first. Walter reports that whilst some people don't notice any difference in their reflection, others either loved or hated their un-reversed reflection.

Hubble's troublesome mirror

During the construction of the Hubble Space Telescope's mirror, a device called a null corrector was used to shine a beam of light onto the surface of the mirror and analyse the reflection to find imperfections in the mirror's surface. To test the surface of the mirror, engineers used both a reflective null corrector, which used mirrors, and a refractive null corrector, which used lenses and was supposedly less accurate than the reflective corrector. The null correctors were so sensitive that they could only be used in the middle of the night when there were no vibrations due to passing traffic.

When the reflective null corrector showed an error that had not been detected by the cruder refractive device, it was assumed that the refractive device was poorly calibrated and the mirror was ground to remove the 'defects' spotted by the reflective device. When a final check was done with the refractive corrector, it showed a spherical aberration of a quarter of a wavelength but it was assumed that this was to be expected with a crude measuring device. The quarter wavelength error turned out to be a real error. The project's chief scientist, C. Robert O'Dell, spoke for the team who worked on the project saying: "All of us feel horrible."

It is thought that the error in the null corrector arose because the lens of the device wouldn't descend far enough, and, because the operating engineers were close to a deadline, three household washers were inserted into the million-dollar measuring device.

In 1993, the company responsible for producing the mirror was ordered to pay NASA $25 million. Entirely replacing the defective mirror was not practical, so a shuttle mission fitted corrective optics (consisting of five pairs of mirrors), much like a pair of glasses to remedy the effects of the defect.

Serious damage to the mirror was prevented on another occasion when an optician, Wilhelm R. Geissler, accidentally typed '1.0' instead of '0.1' into the computer controlling an automated polishing tool. Fortunately, a technician with the mind-numbing job of spending hours monitoring the tool for just such an error, managed to hit the kill switch in time to prevent serious damage.

The first fibres

As early as 1888, doctors were using bent glass rods to illuminate the insides of their patients' bodies. By the beginning of the 20th century, dentists had begun to use curved quartz as dental illuminators. A significant innovation on the path to the development of fibre optics was made by Charles Vernon Boys, a British physics teacher. Boys used a tiny crossbow to fire a needle threaded with a piece of straw which had been dipped in molten glass to create glass fibres 27 m long but only 2.5 μm in diameter. One of Boys' students was the writer H. G. Wells who reported that his teacher was more interested in his research than his students; he "messed about with the blackboard, galloped through an hour of talk, and bolted back to the apparatus in his room".

The patent on using a bundle of rods or fibres to transmit images was originally acquired by John Logie Baird, the inventor of television, in the 1920s as a potential means of transmitting images.

The mirror maestro

A significant figure in the development of the telescope was the optician Bernhard Schmidt, born in Estonia in 1879. He began experimenting at a very early age and his first attempts to make lenses involved grinding together the ends of bottles he had found on the beach with sand. Aged 15, Schmidt lost his right hand in an accident with a homemade pipe-bomb but, undeterred, continued to hone his skills in grinding lenses and making mirrors.

The mirror maestro *continued*

Schmidt set up a workshop in an abandoned bowling alley and would spend days working, neglecting to eat, smoking cigars and drinking corn liquor. In the early years of the 20th century, Schmidt's business grew and famous astronomers, including Karl Schwarzschild, sought out his products. He tested his mirrors by creating artificial stars, silvered glass balls which he hung in trees in a park and illuminated with a searchlight.

When his mirror business collapsed in the difficult economic climate after the First World War, Schmidt went on an expedition to the Philippines to photograph an eclipse. On the sea journey, he had the idea for a revolutionary new telescope, now known as the Schmidt camera, that uses a corrector plate to remedy the aberration of spherical mirrors. When Schmidt tested his prototype by observing a distant graveyard, he found that he was able to read the names on the tombstones. Schmidt cameras have wide fields of views and the Kepler Space Telescope, launched in 2009, contains a Schmidt camera which is used to hunt for exoplanets.

Accounts of Schmidt's death vary. Official records report that he died of pneumonia, but the director of the Hamburg Observatory where Schmidt was working provided a more detailed description of the events leading to the lens maker's death. After several days of drinking, Schmidt arrived at the observatory and began to insult colleagues resulting in a fight in which his clothes were torn. He was detained in an asylum, forced to take cold baths (a common treatment for mental health issues at the time), wear a straitjacket and died with little recognition of his contribution to astronomy.

Refraction

Snell's window

Anglers can hide themselves from their prey by exploiting a phenomenon arising from total internal reflection. When the surface of a pool of water is flat, a fish beneath the surface will observe the entire hemisphere above the water in a cone of angle 97°, a region known as *Snell's window* or the *optical man-hole*. So if anglers position themselves at a low viewing angle relative to the surface of the water, their image is squashed and out of focus to the fish and they will remain undetected.

Gassy refraction

A cloud of gas in the Milky Way was observed refracting the radio wave emissions of a distant quasar, to form multiple images of the object. This rare scattering event in 2008-2009 lasted for around 50 days as the gas cloud moved through the line of sight of the quasar.

Mirages

Refraction due to the temperature gradients in the atmosphere can cause a number of mirage effects.

- *Inferior mirages* occur over hot ground surfaces such as roads. They are caused when rays of light bend upwards leading to an inverted image, producing the illusion of water, because the lower part of the inverted image is often of the sky.
- *Superior mirages* result from a temperature inversion when a layer of colder air lies on a layer of warmer air, causing rays to bend downwards so an image appears above the true object.

Mirages *continued*

- *Looming* is a refraction phenomenon in which the visible horizon is lifted or lowered and distant objects appear displaced or distorted; the effect can occur when warm air lies on cold water. Looming is also associated with warm winds, such as the *Alpine föhn*, which can cause vertical temperature differences of 15° over 100 m. The temperature differences lead to changes in the refractive index of air causing the looming effect.

A *fata morgana* arises from more complicated temperature variations than the layered effect found in looming and leads to mirages in which an image may appear a number of times. The name arises from the crystal castle in the sea inhabited by Morgan Le Fay, King Arthur's half-sister. The effect can lead to greatly elongated images and are common in the Strait of Messina, between Sicily and mainland Italy.

Visibility is normally limited by the curvature of the Earth but refraction in the atmosphere can extend the visible area.

- In the *hillingar effect*, a vertical temperature gradient of over 0.11 Km^{-1} can make distant land visible.
- In the *Novaya Zemlya effect*, refraction can give the impression that the Sun is rising earlier than expected.
- The *Min Min light* phenomenon, whereby lights appear to follow travellers and which has been reported in western Queensland, has also been explained by over-the-horizon refraction.

Alexander's band

In around AD 200, Alexander of Aphrodisius observed that, during rain, the area between primary and secondary rainbows appears considerably darker than the surrounding sky. This area has been labelled *Alexander's band*. The phenomenon occurs because the refractive index of light means that light from raindrops in the region of the sky between the two rainbows cannot reach the observer.

Diffraction

Early diffraction experiments

One of the earliest reports of diffraction used a feather as a grating. In a 1673 letter, James Gregory wrote to John Collins who acted as 'post office' to disseminate information in the scientific community:

> "If ye think fit, ye may signify to Mr Newton a small experiment, which (if he know it not already) may be worthy of his consideration. Let in the Sun's light by a small hole to a darkened house, and at the hole place a feather, (the more delicate and white the better for this purpose) and it shall direct to a white wall or paper opposite to it a number of small circles and ovals, (if I mistake them not) whereof one is somewhat white, (to wit, the middle, which is opposite to the Sun) and all the rest severally coloured. I would gladly hear his thoughts of it."

Glories and sun dogs

The Sun's *corona*, brilliantly coloured rings that appear around the star, are a diffraction effect caused by the scattering of light by water droplets smaller than 60 μm in diameter in clouds (raindrops are too large to cause the effect). The phenomenon is formed when a series of diffraction patterns undergo differential scattering. A more common phenomenon is iridescent clouds which show similar colour patterns to corona but without a circular structure.

One particularly striking refraction phenomenon is the *glory*, a coloured halo seen around a person's head. Glories, or *anticorona*, share some properties with corona, but occur at the anti-solar point (the point on the celestial sphere directly opposite the sun from a particular point of view).

Under some conditions, a series of bright lights can be seen close to the Sun giving the impression of multiple suns, referred to as *sun dogs*, *mock suns* or *parhelia*. The effect tends to occur when there is a layer of high cirrus clouds in which hexagonal ice crystals act as prisms, refracting light at an angle of 22°. Sometimes, a full halo at an angle of 22° is visible round the Sun, caused by the reflection and refraction of light by ice crystals in thin high cirrus clouds; a similar effect is also sometimes observable around the Moon.

Interference, standing waves and dispersion

Young's sonic wager

Despite his many scientific successes, British polymath Thomas Young was not successful in all his endeavours. The *Parlour Book* of Emmanuel College, Cambridge contains a record of a wager set in 1799:

> "Young will produce a pamphlet or paper on sound more satisfactory than anything that has already appeared, before he takes his Bachelor's degree."

Whilst Young indeed published a paper on sound and light in 1800, he was judged to have lost the bet. However, Young's biographer argues it is "doubtful whether a competent tribunal would now uphold the decision on appeal".

Interfering physicists

A legend at Emmanuel College suggests that Young developed his model of interference after observing the ripples generated by a pair of swans on the college pond. Perhaps inspired by the pond, Young later used a thought experiment involving a body of water when responding to a criticism of his theory:

> "Suppose a number of equal waves of water to move upon the surface of a stagnant lake, with a certain constant velocity, and to enter a narrow channel leading out of the lake; suppose, then, another similar cause to have excited another equal series of waves, which arrive at the same channel with the same velocity, and at the same time with the first. Neither series of waves will destroy the other, but their effects will be combined; if they enter the channel in such a manner that the elevations of the one series coincide with those of the other, they must together produce a series of greater joint elevations; but if the elevations of one series are so situated as to correspond to the depressions of the other, they must exactly fill up those depressions, and the surface of the water must remain smooth; at least, I can discover no alternative, either from theory or from experiment. Now, I maintain that similar effects take place whenever two portions of light are thus mixed; and this I call the general law of interference of light."

Before Young's work on interference, Newton used the notion of superposition to explain a curious tidal effect near Hanoi. An English traveller, Francis Davenport, had

published a letter describing the difficulty of accessing the city of Tongkin, now Hanoi, due to the unusual pattern of tides. Edmund Halley had commented on the phenomenon and Newton developed an explanation of the effect in the *Principia.* He argued that two components of tides, one from "the sea of China", the other from "the Indian sea" arrived at Tongkin with different time delays, leading to a superposition effect. However, despite this apparent understanding of superposition, he did not transfer the model to other aspects of his work, for example, his explanation of the colours formed on soap bubbles.

Green flash

The *green flash* is a rare optical phenomenon visible at sunrise and sunset. Under the right conditions, just as the Sun is about to disappear beneath the horizon, the last visible piece of its rim may shine with a green light.

The phenomenon can be understood by imagining the Sun to consist of a series of overlapping discs of different wavelengths. When it is overhead, the discs align exactly and the Sun appears yellow. When the Sun is lower in the sky, atmospheric refraction displaces the discs by different amounts, and as the Sun sinks below the horizon, the last discs to be visible are the green and blue/purple discs. However, as much of the blue light is scattered by the atmosphere, the final disc to be seen is the green one, registering as a green flash.

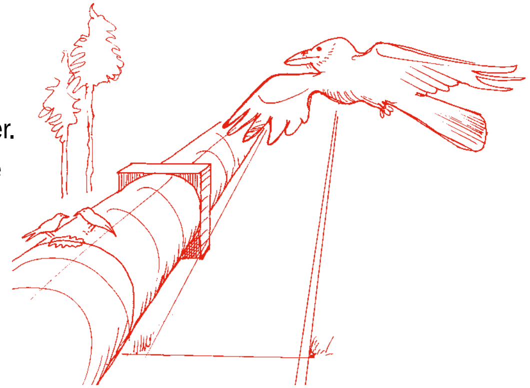
Venusian standing waves

The Japanese Akatsuki Probe has detected a gigantic standing wave in the atmosphere of Venus. The pressure wave extends over 10,000 km between the poles of the planet and is believed to be produced by surface winds colliding with the 4,500 m high Aphrodite Terra Mountain range near the planet's equator.

Gravity waves or ravens?

In 2017, researchers at LIGO (the Laser Interferometer Gravitational-Wave Observatory) in the United States noticed glitches in their data which, on investigation, turned out to have an unexpected source – ravens. The birds had been seen close to pipes that vented nitrogen gas and peck marks were discovered on the ice that accumulated on the gas lines.

Gravity waves or ravens? *continued*



As the pipes were connected to an internal vacuum chamber, vibrations caused by the pecking altered the path light travelled along in the interferometer. The problem was solved by covering the lines with an insulating material.

The team captured photos of ravens in the act of pecking at the ice and a member of the LIGO team commented: "I guess we can't blame them for desiring shave ice on a hot desert afternoon."

Not Newton's rings

Newton's rings are a well-known interference phenomenon that occurs when an observer looks vertically down through a plano-convex lens of large focal length, placed curved side down, on a glass plate. Dark rings appear because rays of monochromatic light reflected from the glass plate interfere with rays reflected from the surface of the lens. If white light shines onto the lens, coloured interference patterns can be seen. Though the rings now bear Newton's name, he only developed a partial explanation for their occurrence. In fact, they were first observed by Hooke and Boyle.

Cliffs and clapotis

Waves reflected from vertical cliff faces can form a standing wave when they interfere with incoming waves in a process called *clapotis*. Clapotis rarely results in completely destructive interference as energy will be absorbed by shallow sea beds or transferred to waves scattered by an imperfectly perpendicular cliff face. When large waves strike sea walls, clapotis can produce impressive plumes where the incident and reflected waves superimpose – these may also cause substantial erosion to the structure. When waves strike a barrier at an angle, the crests formed by interference may make a diamond-shaped pattern, known as *clapotis gaufré*.

Polarisation

Malus' malady

French physicist and mathematician Étienne-Louis Malus was originally to have studied at an engineering school but, following the French Revolution, the school was suppressed and he temporarily became a manual labourer. The engineer overseeing his work noted that Malus had developed an approach to the project that minimised the fatigue of the other labourers. Realising his potential, the manager arranged for him to attend the École Polytechnique.

After his studies, Malus joined the French Army and was stationed in Giessen in Germany where he fell in love with the daughter of the chancellor of the university. But, before they were able to marry, Malus received orders to move to Toulon to join an expeditionary force. During fighting in the Middle East in Jaffa, the French forces were overrun and many officers were killed. However Malus escaped death because he had fallen asleep in a trench.

As the war went on, Malus caught the plague and wrote his first book on optics whilst convalescing in a hut with a palm-leaf roof. The physicist Arago (also himself no stranger to adventure) commented:

> "No army in the world ever before counted in its ranks an officer who occupied himself in the spare hours of advanced posts with researches so complete and so profound."

Malus discovered that light could be polarised by reflection through a chance observation. From his home in the Rue d'Enfer, Paris, he used a crystal of Iceland spar (a transparent calcite) to observe light reflected from the windows of the Luxembourg Palace and noted that the two images produced changed in intensity as he rotated the crystal.

In contrast to his eponymous law (which describes the relationship between the transmitted intensity of a beam of plane-polarised light and the orientation of a polariser it passes through) some of Malus' other ideas on light were less well-founded. He suggested that light was composed of a combination of *caloric* (the

Malus' malady *continued*

hypothetical fluid that was proposed to explain heat flow) and oxygen. He also argued that colours depended on the ratio of these two components and that red light had a greater heating effect because it contained more caloric.

Polarisation pollution

Many organisms use polarised light for orientation. Ecologists have expressed concerns about the impact of artificial sources of polarised light on such creatures:

- Newly emerged caddisfly larvae are naturally attracted to polarised light reflected from the surface of bodies of water but become drawn to the vertical glass surfaces of buildings close to rivers due to their polarised reflections.
- Turtles ingest plastic bags because they reflect polarised light in a similar manner to their prey.
- Open-air oil reservoirs have strongly polarising surfaces, which can attract insects, and consequently bird life, which can become trapped in the oil.

Ecologists have recommended that rough building materials should replace shiny surfaces, particularly in the vicinity of rivers and bodies of water, to minimise polarised light pollution.

Seeing polarised light

Unlike the animals described above, humans are largely polarisation-blind. However, some individuals may be able to perceive a polarisation effect known as *Haidinger's brush*.

This appears as a tiny, yellowish figure-of-eight-shaped image about 3° in longitudinal diameter that may be seen in highly polarised light. It is suggested that the effect is most easily seen at the zenith of a clear sky, near sunset and sunrise. After a couple of minutes of observing, the sky may take on a marbled appearance and the brush should appear as a subtle mark against the sky.

Some people find the effect easier to observe than others. It can also be seen by observing a computer screen through a polarising filter for a couple of seconds and then quickly rotating the polaroid. The effect arises because pigments in the macula

of the retina have a radial arrangement and linearly polarised light is absorbed more strongly in some parts of the pigments than others, causing a visible effect when the direction of polarisation of light is suddenly changed.

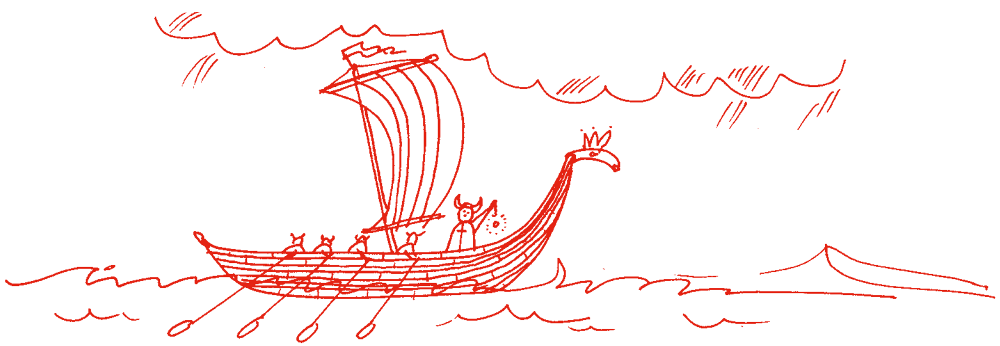
Polarisation points

Scattering of light by molecules in the atmosphere alters the polarisation of light emitted from the sun. The average degree of polarisation of the sky is around 40% and is maximum at the zenith of the sky. The highest degree of polarisation occurs when the sun is just below the horizon. There are three points of zero polarisation in the sky, known as *neutral points*, named after the scientists who discovered them:

- Arago's point (25° above the anti-solar direction)
- Babinet's point (10-20° above the sun on a vertical circle passing through it)
- Brewster's point (10-20° below the sun on the vertical circle passing through it).

Viking sat nav

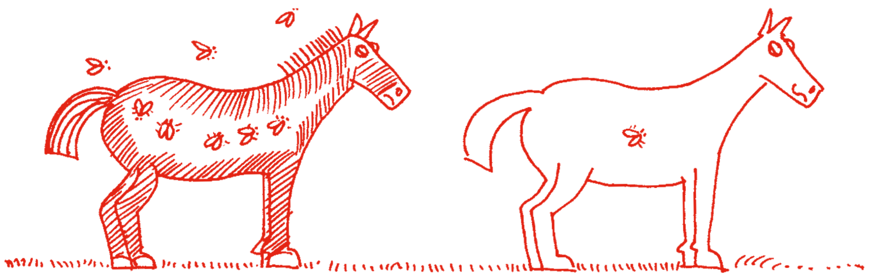
Historians have speculated about how Viking seafarers were able to navigate in cloudy conditions that obscured the Sun and stars. One theory put forward is that, like some insects, they determined the direction of the Sun using the polarisation of the sky. Viking sagas refer to a 'sunstone', which is conjectured to have been cordierite or tourmaline. When crystals of these stones are held up to the sky and rotated, the sky appears to brighten and darken, except at polarisation neutral points (see above) which can be used to determine the direction of the Sun. However, a study has concluded that the degree of polarisation of overcast skies is so low that it is unlikely that Viking sailors would have been able to use the effect.



Like flies to polarised light

White horses may seem to be at an evolutionary disadvantage: they are easily spotted by predators and suffer from higher incidences of skin cancers and eye problems due to their greater sensitivity to UV light than darker coloured breeds. However, scientists have recently discovered an unexpected advantage due to their optical properties.

The coats of white horses reflect light with lower degrees of polarisation than that of brown or black horses. This observation is significant as *tabanid flies*, blood-sucking insects which can transmit diseases, are strongly attracted to horizontally polarised light. Researchers tested this hypothesis with a number of experiments, including one in which they built models of horses of different colours that they coated with a sticky substance. The brown and black models collected 15 and 25 times more tabanids respectively in comparison to the sticky white horse model.



Resonance

Spooky eye rolling

Research by the American Air Force has found the resonant frequency of the human eyeball to be around 19 Hz. To determine that figure, 15 human volunteers were exposed to vertical vibrations in the range of 5-50 Hz and their eye movements were observed by monitoring reflection from the cornea.

This resonance may lead to the perception of unusual visual effects. Researchers have made the controversial claim that 19 Hz infrasound may be responsible for the perception of paranormal phenomena. Ultrasound waves were found to be present in areas of a 14th century cellar in Coventry where people had reported paranormal experiences.

Twain's 'unspeakable and pressing necessity'

Nikola Tesla encouraged Mark Twain to stand on an electrotherapy device he had invented consisting of a platform supported by elastic cushions that was vibrated with compressed air. Tesla proposed that the device would encourage regular bowel movements and reported that, during a trial: "Suddenly, Twain felt an unspeakable and pressing necessity which had to be promptly satisfied."

Tesla's earth-shaking brush with the law

Whilst testing an electromechanical oscillator, Tesla attached the device to a metal pillar in his building. He observed that the oscillator caused different objects in the room to vibrate. However, the oscillations travelled down the pillar causing nearby buildings to shake, windows to shatter and two police officers to be dispatched to investigate the cause of the disturbance. Having noticed a worrying vibration in the floor and walls of his room, Tesla had just smashed the device with a sledgehammer when the two policemen arrived. He is reported to have politely dismissed the officers by stating:

> "Gentlemen, I am sorry. You are just a trifle too late to witness my experiment. I found it necessary to stop it suddenly and unexpectedly and in an unusual way… However, if you will come around this evening I will have another oscillator attached to this platform and each of you can stand on it. You will, I am sure, find it a most interesting and pleasurable experience. Now you must leave, for I have many things to do. Good day, gentlemen."

Tesla's earth-shaking brush with the law *continued*

He later related to a reporter that, after hiding a similar oscillator in his coat pocket, he placed the device on the steel frame of a building under construction and observed:

> "Gradually the trembling increased in intensity and extended throughout the whole great mass of steel. Finally, the structure began to creak and weave, and the steelworkers came to the ground panic-stricken, believing that there had been an earthquake. Rumours spread that the building was about to fall, and the police reserves were called out. Before anything serious happened, I took off the vibrator, put it in my pocket, and went away. But if I had kept it on ten minutes more, I could have laid that building flat in the street. And, with the same vibrator, I could drop Brooklyn Bridge in less than an hour."

Aerobic resonance

In 2011, the *Korea Times* reported that an exercise class caused large vertical vibrations in a 39-storey shopping mall in Seoul. A *Tae Bo* exercise class (a mix of taekwondo and boxing) taking place on the 12th floor caused oscillations that could be felt on a number of other storeys. Inspectors recreated the conditions of the phenomenon by asking 23 people to carry out Tae Bo exercises whilst they used laser Doppler vibrometers to monitor the transfer of oscillations. They noted vibrations on the 38th floor were ten times the expected amplitude and concluded that the frequency of the Tae Bo exercises matched the resonant frequency of the building.

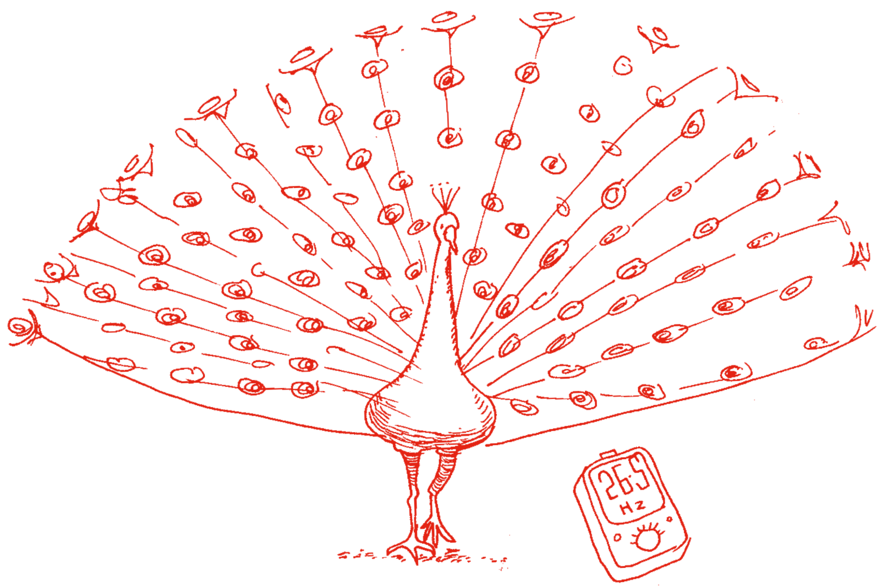
Poor taste in music? Blame your skull's resonance!

An intriguing paper given at a meeting of the *Acoustical Society of America* has suggested that your musical preferences may be determined by the resonant frequencies of your skull. The human cochlea is embedded in the skull's temporal bone, which creates a resonant structure that selectively amplifies some frequencies. This structure explains the commonly reported observation that people report that their voice sounds different when they listen to recordings of themselves compared to their own perception of their speech.

The authors of the paper asked participants to tap their heads whilst a microphone was attached to their temporal bone to determine the resonant frequencies of each individual's skull. The resonant frequencies were found to be in the range of 35 to 65 Hz, with women having, on average, higher fundamental frequencies than men due to their smaller mean skull size. The fundamental resonant frequency of the participants' skulls was found to predict which musical keys the listener preferred.

Peacocks' mating resonance

A study of the biomechanics of male peacocks' tail feathers during their mating displays suggests that the oscillations are controlled in such a way that the iridescent eyespots remain nearly stationary in order to captivate female birds. Researchers used high-speed video to determine that male peacocks generated a pulsating sound by rubbing their feathers together at a mean frequency of 26.5 Hz. The peacocks were capable of vibrating their feathers at, or near to, their resonant frequencies in a manner that stimulated maximum amplitude vibrations for minimum energy expenditure and the oscillations typically had a node near the eyespot of the feather.



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