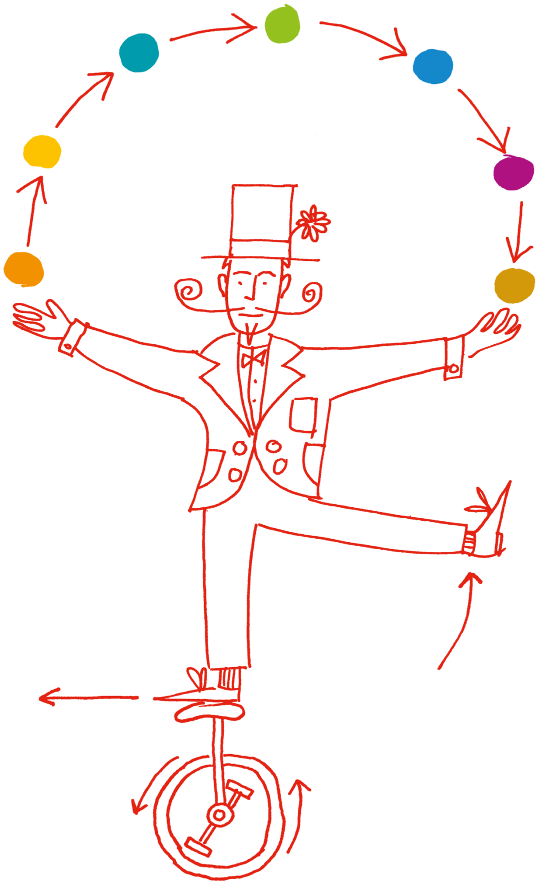
IOP Education | Stories from physics booklet 2

Forces and motion

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.

This booklet is the second in the series and, appropriately, takes us into some of the stories behind quintessential school physics: the Galilean and Newtonian view of the world. These anecdotes bring to life the people behind the well-known names who, over the last 500 years, have contributed to the explanations with which we are now so familiar - their eccentricities, frailties, mischievousness and humanity.

Charles Tracy

IOP Head of Education

Message from the author

The domain of forces and motion is rich in stories that can enhance physics teaching. The stories in this booklet are drawn from both the history of science and cutting-edge research. For example, you can read the story of how Clarence Birdseye (of frozen food fame) came to finance a stock market trader's anti-gravity institute. Or, you can find out how the Tom and Jerry satellites precisely measure the Earth's gravitational field.

The stories about forces and motion cover a wide range of scales: from the smallest force ever measured to the bite strength of an extinct mega-piranha. You will read about the forces exerted on shoelaces, penguin poo and on henchmen in James Bond films. The booklet will tell you how physics can help you to avoid speeding tickets and how a manhole cover became one of the fastest man-made objects ever recorded.

I have compiled these booklets to provide short stories that you can add to your lessons alongside the conceptual content. When planning a lesson related to forces and motion, dip into the booklet to find stories related to the topic you are teaching that enrich your lessons and spark interest in physics. I am grateful to the Institute of Physics for their support and encouragement with the Stories from Physics project.

I would like to thank Caroline Davis for championing this project and her careful and thoughtful editing. I am also grateful to Stuart Redfern for his witty illustrations that have brought the stories to life

So, let me tell you some stories about physics...

Richard Brock

Time

The time-travelling astronaut

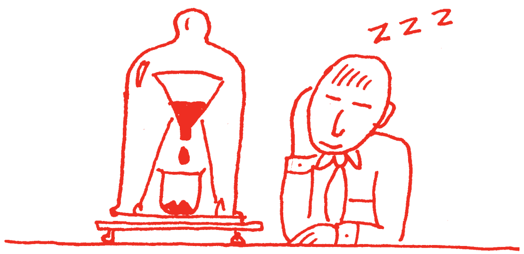
Russian cosmonaut Sergei Krikalev holds the record for time spent in orbit around the Earth: 803 days. It is calculated that the time dilation caused by his orbital motion means that Krikalev is 0.02 seconds younger than other people born at the same time as him on Earth.

It has(n't) been a long day

The length of the day has not been constant throughout the Earth's history. For the last 2,700 years, the length of a day has increased by about 1.8 ms per century. Because of this variation, in the past, the Earth completed more rotations on its axis per orbit of the sun. Fossil evidence from corals suggests that the length of the year 370 million years ago was between 385 and 410 days. A number of factors are causing the change in rotational speed of the Earth including: an acceleration in the rotation of the Moon, frictional forces due to the motion of the tides, and change to the Earth's shape caused by the melting of glaciers making the Earth less oblate. As the mean solar day, defined as 86,400 seconds, does not precisely match the period of the Earth's rotation, approximately once a year, a leap second is introduced to Coordinated Universal Time.

The longest running experiments

What is possibly the world's longest running science experiment was set up at the University of Queensland, Australia in 1927. The experimental apparatus consists of a quantity of pitch in a glass funnel which scientists monitor to study the flow of the viscous material and the process of drop formation. It takes between 7 and 13 years for a drop to form, but only a tenth of a second for the fluid to fall. The ninth drop fell in 2014 and it is possible to join the watch for the tenth via a webcam at: thetenthwatch.com



- In 1840, the Reverend Robert Walker set up a bell connected to a dry pile (a type of battery) in the entrance to the Clarendon Laboratory at the University of Oxford – the bell has been ringing continuously ever since. The bell's clapper oscillates at a frequency of about 2 Hz and draws 1 nA from the cell.
- A clock that rivals the Clarendon bell for its longevity can be found in the foyer of the physics department at the University of Otago in Dunedin, New Zealand. The Beverly clock has, in principle, not needed winding since its manufacture in 1864 because it is driven by ambient fluctuations in air temperature which cause an airtight metal box to expand and contract.
- The Science Museum in London houses 'The Clock of the Long Now', a timepiece designed to display the correct time for 10,000 years.
- A light bulb at a fire station in Livermore, California has been in nearly continuous operation for a hundred years. The bulb's luminosity has decreased over its life: it was initially rated at 60 W but now has an output of only 4 W.

The London-Bath time difference

In the 1850s, the expansion of the rail network emphasised differences in local times across the UK. For example, it was noted that London time (used at all stations) was 11 minutes ahead of Bath and Bristol and 14 minutes ahead of Exeter. A curious solution to this problem was developed in Exeter: the dial of the clock at St John's Church was fitted with a silver minute hand to display railway time, and a gilt minute hand to show local time.

The flight of 'Mr Clocks'

One of the best-known tests of the time dilation prediction of Einstein's theory of relativity was the Hafele-Keating experiment. Hafele and Keating flew twice round the world on commercial flights (once eastward and once westward) with four-caesium beam atomic clocks and compared the time on the flown clocks with others that had remained stationary. The project was relatively cheap for cutting edge research, requiring the purchase of eight round-the-world tickets for $7,600. The atomic clocks travelled under the assumed name of 'Mr Clocks' and required two adjacent seats due to their size. When the airborne clocks were compared with the stationary ones, the differences in the time readings were consistent with the predictions of Einstein's theory of relativity.

Distance

The Isochronic map

In 1883, Francis Galton, Charles Darwin's cousin, developed an '*Isochronic Passage Chart for Travellers*' which indicated, by coloured shading, the time it would take a traveller starting in London to travel to different parts of the world. To reach the farthest areas of the map, including parts of Australia and New Zealand, would have taken 40 days of travel. Recently, a travel company produced an updated version of the map for journeys in 2016. The maximum travel time on the modern map is just a little over one and a half days.

The bun gauge

Many measuring devices have been developed in the history of science but one of the most unusual is the bun gauge in the collection of the National Museum of American History. The device was used to ensure burger buns were of uniform dimensions.

Getting leverage

Archimedes is supposed to have said: 'Give me a lever and a place to stand and I'll move the Earth'. An estimate in a paper suggests that the lever required to perform this feat would be longer than the size of the observable universe.

Cat and mouse satellites

The GRACE (Gravity Recovery and Climate Experiment) mission, launched by NASA in 2002, makes use of two satellites, Tom and Jerry, in order to map the Earth's gravitational field. The satellites can measure differences in the Earth's gravitational field of the order of 1 milligal or about a millionth of the gravitational field strength at the Earth's surface. The mission uses a distance measuring technique to determine the gravitational field strength. The satellites orbit at a distance of approximately 220 km from each other and small differences in the Earth's mass distribution slightly perturb their orbits. A microwave ranging system measures the distance between Tom and Jerry with an accuracy of a few microns. Changes in the spacing between the satellites can be used to calculate gravitational anomalies. The data collected by the mission are being used to measure changes to the masses of ice-sheets and to estimate ocean pressures which can help to determine fluctuations in sea levels.

Broadening your horizons

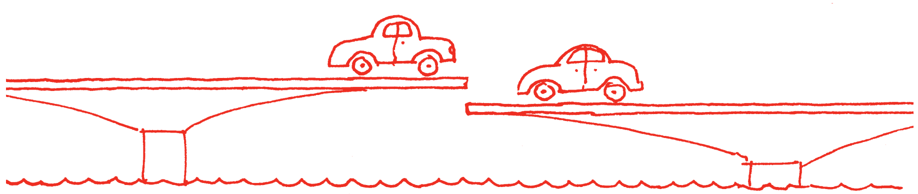
A straightforward geometrical calculation can determine an approximation for the distance to the horizon given an observer's height above the surface of the Earth: $d=\sqrt{13H}$ km, where d is the distance to the horizon in km and H is the vertical height in metres of the observer above the ground. A person with their eyes 2 m above the ground will see the horizon at a distance of approximately 5 km. A further correction can be made to account for the deviation of the path of light due to refraction.

Not a level-playing field?

Countries base their measurements of elevation above sea level on different reference locations, as shown in the table below:

Country	Reference Location
Austria	Trieste
France	Marseille
Germany	Amsterdam
Great Britain	Newlyn
Italy	Genoa
Switzerland	Marseille

The use of different sea level reference locations caused a problem during the construction of the Hochrheinbrücke bridge between Switzerland and Germany in 2003 and 2004. The German engineers based their measurements on sea level in the North Sea, while the Swiss used a standard set to the level of the Mediterranean, a difference of 27 cm. While the engineers were aware of the difference in standards, at some point an error led to the correction being applied twice, leading to a height difference of 54 cm. It is reported that the engineering company's insurance covered the additional costs incurred because of the error.



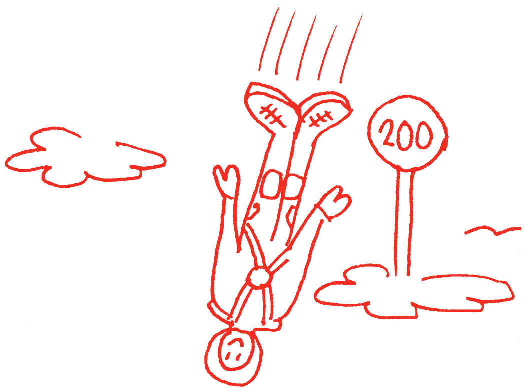
Speed

The speedy steel plate

One of the fastest moving man-made objects ever detected was a manhole cover. As a result of the Pascal-B nuclear test in Nevada in 1957, a 900 kg steel plate cap was blown off the top of a test shaft at a speed of more than 66 km/s. The plate was never found, and the experiment's designer, Dr Brownlee, believes that although the plate may have exceeded Earth's escape velocity, it is likely to have been vaporised by compression heating in the atmosphere. The calculated velocity is an estimate as the high-speed camera footage of the incident captured the cap in just one frame.

Terminal velocity: skydivers and raindrops

- The terminal velocity of a skydiver in the spread-eagled position is around 220 km/hr and, in the head-down position, 320 km/hr. The terminal velocity of a skydiver is sensitive to the density of air, which varies with altitude: at 10,000 m a terminal velocity of 77 m/s is predicted, at 1,000 m only 45 m/s.



- Terminal velocities can be surprisingly slow – a skydiver with a round canopy, of area 75 m^2 and drag coefficient around 0.8, and a total mass, including equipment of 95.3 kg, has been calculated to have a terminal velocity as low as 5 m/s. The aerodynamics of modern parachutes are more complex than for simple round canopies, as the canopy typically develops some lift. Skydivers typically reach 99% of their terminal velocity within 70 m of falling.
- Meteorologists report that they may have been miscalculating the speed of rainfall after they discovered raindrops with 'super-terminal' velocities. A team in Mexico measured the shadows of raindrops passing through an infrared laser and found that over half of drops exceeded their predicted terminal velocity. The researchers concluded that the effect may be caused by the breakup of drops into differently sized fragments which, temporarily, travel with the speed of the parent drop.

Using physics to avoid speeding tickets

Two students at the University of Leicester published a paper considering whether a car could travel fast enough to be red-shifted out of a speed camera's field of vision. They concluded that a car would have to travel at the unlikely velocity of 0.178 times the speed of light, a velocity that would cause a Ferrari 458 to contract by just over 7 cm.

Dimitri Krioukov deployed a more successful use of physics to avoid punishment after he was pulled over for driving through a stop sign. He posted a paper on ArXiv to explain that the police officer had been taken in by a perceptual illusion. Krioukov claimed that his rapid linear deceleration to a stop followed by acceleration, was mistakenly perceived as movement at approximately constant speed because the police office perceived the angular rather than the linear speed of the car. It is reported that Krioukov did not have to pay the $400 fine.

The fast and the slow

- Cracks in glass plates can travel at speeds from 1 m/s to 1,500 m/s depending on the length of the crack and the stresses in the glass. One particular form of glass, known as Prince Rupert's Drops, displays some particularly unusual properties. The teardrop-shaped beads have a fine tail and are produced by dripping molten glass into cold water. The head of the drop can withstand being crushed in a vice (it is reported drops can withstand compressions of 15,000 N), yet breaking the tail results in the whole drop shattering. The accepted explanation, developed in 1665 by Robert Hooke, argues that the differential cooling of the drop leads to compressive stresses in the surface of the drop which contrast with the high tensile stress in the interior. Cracks in the drops have been recorded with high-speed cameras to travel at speeds in the range 1,450-1,900 m/s.

- In 1999, researchers used an ultra-cold atomic gas to reduce the speed of light to 17 m/s.
- Ultra-fast video technology has revolutionised the way in which the passage of light can be visualised. A team has developed a technique that captures images at a rate of 100 billion frames per second, which enables the propagation of light to be recorded.

- Scientists have calculated estimates for the potential fastest speeds with which a ballpoint pen could write. The answers are dependent on the viscosity of the ink so change with ambient temperature: 181 m/s in the Sahara Desert and 192 m/s in Siberia.
- The immense forces at galactic centres result in stars being accelerated to great velocities. One such 'hypervelocity star' was detected in the Milky Way halo travelling at around 850 km/s.
- In 1919, a large tank in Boston burst releasing a wave of molasses that travelled at 56 km/hr, killing 21 and injuring 150 people.
- The fastest speed a human has ever travelled is 11 km/s, reached by the three men crew of Apollo 10 during re-entry to the Earth's atmosphere.
- Two researchers at the University of Minnesota debated whether swimmers would travel faster or slower in higher viscosity liquids than water: most experts in fluid mechanics they consulted felt the swimmer would travel slower in the more viscous liquid. Eager to find an empirical answer to the problem, the scientists mixed 310 kg of gum with water and added the fluid to a 650 m^3 swimming pool, leading to a liquid with a viscosity double that of water. Their results indicated that the change in viscosity did not alter swimming speed. They propose this outcome might be explained as most of the swimmer's drag is due to their form and viscous drag is responsible for only 10% of form drag.

The wetness and efficiency of walking

A long-standing debate has focused on whether you will get wetter if you run or walk in the rain. Proponents of the 'running will keep you drier' hypothesis argue that it minimises your exposure to the rain, but those who favour walking as the drier option counter that runners will incur extra wetness on their front surface. Two published analyses suggest that running is the better option. It is reported that people who run will remain 30-50% drier than those who walk, especially in heavy or windy rain conditions. Another analysis suggested that the most effective solution was for the pedestrian to run at their maximum velocity, regardless of the speed of the rain or their dimensions. However, a paper in the *European Journal of Physics* argued that the effect was dependent on the shape of the walker.

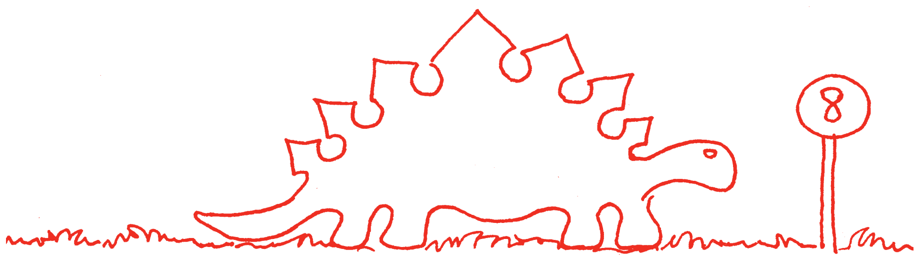
In terms of energy expenditure, a study concluded that the peak efficiency of walking (between 35-40%) occurred at intermediate speeds, whereas the efficiency of running increases with speed (from 45% to 80%). Humans will typically switch their gait from walking to running at speeds somewhere in the range of 6.8 - 7.9 km/hr. Walking and running are both much less efficient approaches to locomotion than the motion of birds and fish.

Prehistorical speeds

Analysis of human footprints dating back 20,000 years suggests that one individual, known as T8, was running at 20 km/hr and still accelerating. This is not quite as fast as the current human speed record but nonetheless impressive for an individual running barefoot and in mud. Analysis of archaeological relics has led to the estimation of the velocity of various different weapon systems:

Weapon	Velocity km/hr
Reed Shaft	217
Apache Arrow	155
Sioux Arrow	108
Javelin	92
7ft Dart	76

Based on estimates that extrapolate from mammals, it has been calculated that smaller bipedal dinosaurs could travel at 35-40 km/hr while larger bipedal dinosaurs were limited to the range 15-20 km/hr. It is assumed that quadrupedal dinosaurs were restricted to walking pace, with Stegosaurus travelling at a maximum speed of 6-8 km/hr. Well preserved tracks from a 'dinosaur stampede' found in Queensland, Australia, gave evidence for coelurosaurs and ornithopods travelling at 13 km/hr and 15.5 km/hr respectively.



Acceleration

Jerks and jounces

In addition to the familiar first and second derivatives of displacement, velocity and acceleration, engineers occasionally use the jerk (the rate of change of acceleration) and the jounce (the rate of change of jerk).

Rocket man and the perils of acceleration

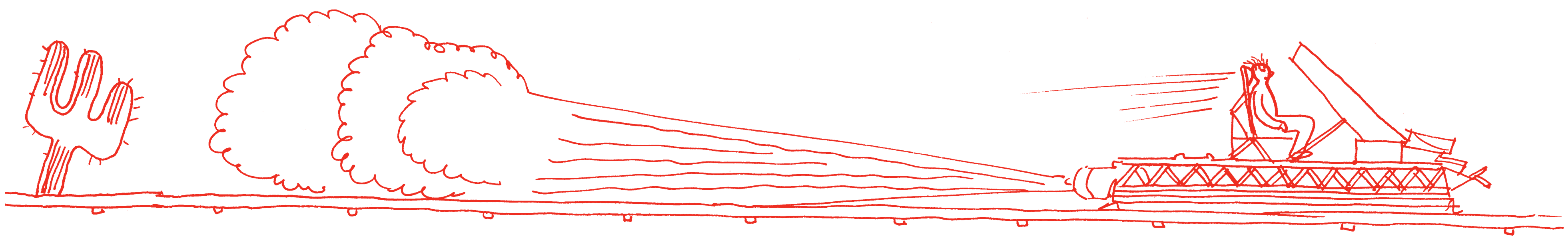
The highest empirically recorded acceleration survived by a human was experienced by the test pilot John Stapp while strapped to a rocket sled that could produce just under 180 kN of thrust. He experienced a peak acceleration of 42.6 g and one second of acceleration at 25 g. In five seconds, he reached 1020 km/hr and was then decelerated in just 1.4 seconds. He suffered temporary blindness from burst blood vessels in his eyes, cracked ribs, broken wrists and damage to his circulatory and respiratory systems.

A paper analysing survival rates from falls reports the case of a woman who fell six storeys, and though it is estimated she experienced a deceleration of 140g, she suffered no significant injuries. The sudden jolt caused by opening a parachute can lead to decelerations between 9 - 12 g and can cause neck pain in skydivers.

British standards for vibration exposure in vehicles suggest that accelerations over 0.32 m/s^2 may be mildly uncomfortable and acceleration greater than 2 m/s^2 extremely uncomfortable. A roller coaster fans' website lists the highest accelerations experienced on roller coasters around the world:

Acceleration	**Roller coaster**
6.3 g	Tower of Terror, Gold Reef City, Johannesburg, South Africa
5.9 g	Shockwave, Six Flags over Texas, Arlington, Texas
5.5 g	Detonator, Thorpe Park, Surrey, UK

Though humans struggle to tolerate high accelerations, researchers in Japan have discovered bacteria can be successfully cultivated in an ultracentrifuge at accelerations over 400,000 g. Carnivorous aquatic bladderworts use a suction trap mechanism to capture prey; the fluid accelerated by the mechanism can reach a peak acceleration of 600 g. However, this acceleration is dwarfed by the abilities of fungi that live on herbivore dung. Ascomycota and zygomycota use fluid-filled stalks, like squirt guns, to accelerate spores up to 180,000 g. In the animal world, mantis shrimp appendages have been recorded as reaching accelerations of up to 104,000 m/s^2.



The development of Newton's first law

Galileo's comments may have influenced Newton's development of the first law of motion. In the English translation of *The Dialogue*, Galileo wrote in the margin:

> *The motion impressed by the projicient is onely in a right line. The project[ile] moveth by the Tangent of the circle of the motion precedent in the point of separation. A grave project[ile], as soon as it is separated from the projicient, beginneth to decline.*

Galileo's comment can be interpreted to mean that a body released from circular motion will follow a tangent to the circle and a heavy body will begin dropping immediately. A diagram suggests that Galileo assumed that the released body would travel at constant speed.

While Galileo can be considered to have noted the three essential components of Newton's first law, (constant speed motion in a straight line and the effect of an external force), he did not state a universal form of a law of inertia.

Newton was also influenced by Descartes. He is said to have taken the form of his law from Descartes' first law of nature:

> *...each particular part of matter continues always to be in the same state unless collision with others constrains it to change that state. This is to say, if the part has some size, it will never become smaller unless others divide it; if it is round or square, it will never change that figure without others constraining it to do so; if it is stopped in some place, it will never depart from that place unless others chase it away; and if it has once begun to move, it will always continue with an equal force until others stop or retard it.*

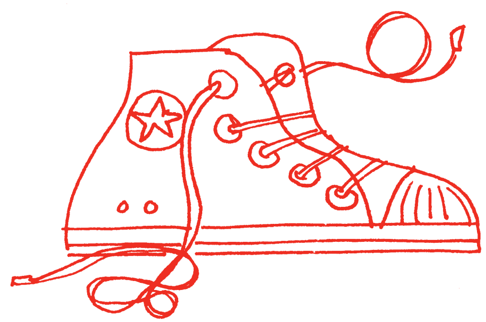
Newton was both inspired and irritated by Descartes' writing and, it is argued, his inclusion of the word *Principia* in the title of his texts was a jibe at Descartes' use of the term. Newton did not include an explicit numerical measure or symbol for acceleration in his work; the expression of his second law as $F=ma$ first emerged more than half a century after the *Principia* was published, in a paper by Euler. Similarly, Cavendish, in his paper *Weighing the Earth*, makes no mention of the concept of acceleration due to gravity and only refers to the quantities of length and time.

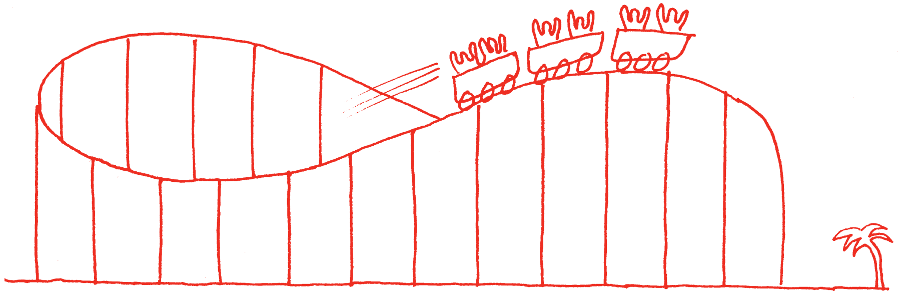
Animal acceleration

Researchers have recently attempted to answer the questions of why the largest animals are not the fastest. They suggest that the relationship between speed and body mass follows a hump-shaped distribution. An animal's maximum speed is limited by the time available for acceleration which is dependent on the amount of fast-twitch fibre an animal possesses and their ability to store energy.
For example, small animals such as mice may possess the ability to accelerate rapidly but cannot sustain that acceleration for long, so their maximum speed is relatively low. Elephants, by contrast, cannot accelerate as quickly as mice but can maintain their acceleration for longer periods. Animals of medium size, such as cheetahs and marlins, therefore, are found to have the highest maximum speed.
In applying their models to dinosaurs, the researchers predict that the maximum speed of a velociraptor would have been 55 km/hr, tyrannosaurus 27 km/hr and triceratops 24 km/hr.

Shoelace acceleration

Researchers have investigated the causes of shoelaces coming untied during walking. A team from the University of California at Berkeley used slow-motion video footage to examine how shoelaces come undone. They report that the striking of the shoe against the ground initially serves to loosen the knot and the whipping motion of the ends of the laces causes the knot to slip. The peak acceleration of the knot was found to be 7 *g* – similar to that experienced by the Apollo spacecraft during re-entry. The data showed that knot failure happened suddenly, with little warning, within a few impact cycles.





Rollercoaster!

An engineer, Alfred Clark, published a series of articles about the dynamics of rollercoasters in *Rollercoaster!* the official publication of American Coaster Enthusiasts. Clark examines roller coaster riders' perceptions that they float out of their seats on the first hill of a roller coaster. He calculates that, even for the extreme 72-degree hill on the Intamin Shuttle roller coaster, the normal force exerted on riders, which they perceive as their weight, will be only be reduced to about 30% of its original value. Clark suggests the effects of friction and the sensation of wind may affect the riders' perceptions.

In the third paper in the sequence, Clark analyses the differences between travelling in the first and last cars of a roller coaster. He argues that the train of cars decelerates while climbing a hill until the central car reaches the top. It then accelerates once the centre of mass of the roller coaster starts to fall. This means that riders in the first car experience a less thrilling ride than other passengers because their car reaches peak height while slowing down. Riders in the last car accelerate over the hill and experience a whipping motion. At the top of the hill, riders in the first car experience a tangential force that makes them slide forwards whereas those in the final car will be pushed backwards into their seats. The effect is reversed at the bottom of a hill and riders in the middle car will experience the greatest acceleration.

Forces

Forceful creatures

Scientists have investigated the forces animals can exert. For example, paleobiologist Gregory Erickson and his team measured the bite force of all 23 species of crocodiles using force transducers. They noted that the maximum bite force exerted by all species exceeded the sheer force of bones. The highest force measured, 16,414 N, was exerted by a salt-water crocodile, much higher than the largest bite force recorded in a mammal, 4,500 N by a spotted hyena. Researchers studying black piranhas have measured the maximum bite strength of the fish to be 320 N for a 1.1 kg individual. The scientists report that a piranha's bite force is around thirty times larger than its bodyweight, a ratio unparalleled amongst vertebrates. Extinct creatures had even stronger bites: a mega-piranha with a body mass of 73 kg is estimated to have had a biting force as high as 9,500 N. Bone analysis has allowed researchers to estimate the bite force of Tyrannosaurus rex as between 183,000 and 235,000 N for a bilateral bite. At the opposite end of the scale, a study has revealed that a Venus flytrap exerts a force of 450 mN and a maximum pressure of 9 kPa. Lemurs have been shown to have impressive arm strength – on average mouse lemurs were found to be able to pull over ten times their own bodyweight.

The smallest force detected

A team of researchers from the Lawrence Berkeley National Laboratory at the University of California have measured what is thought to be the lowest force ever recorded. A cloud of atoms was trapped in an optical cavity and caused to oscillate, and its frequency was measured using a laser beam. A force of 42 yN (42×10^{-24} N) was recorded.

Newton's quirks

Newton's eccentric character is often commented upon. He kept a record of the sins he felt he had committed including:

- Making a Mousetrap on Thy day
- Peevishness with my mother
- Punching my sister
- Denying a crossbow to my mother and grandmother though I knew of it
- Robbing my mother's box of plums and sugar and
- using a fellow student's towel to spare my own.

Newton predicted that the Day of Judgement could not come before 2060 and would perhaps occur even later. While investigating the formation of colours, Newton reports he took a bodkin and pushed it 'as neare to the backside of my eye as I could' causing circles to appear in his vision. After staring at the Sun for an extended period he reported that white paper appeared red when he looked at it with his damaged eye, and green when viewed through a pinhole. During the time Newton served as a member of parliament, the only record of his contribution is a request for a window to be closed. Newton argued that the vapour of comets' tails might be attracted to the Earth and '... so for the conservation of the seas, and fluids of the planets, comets seem to be required'.

Interpreters have observed that Newton's writing contains a number of alternative conceptions that are similar to those students hold. For example, at some points in his work, Newton implied that forces are transferred between objects during collisions and assumed that the motion of the planets required a centrifugal force.

... and those he inspired

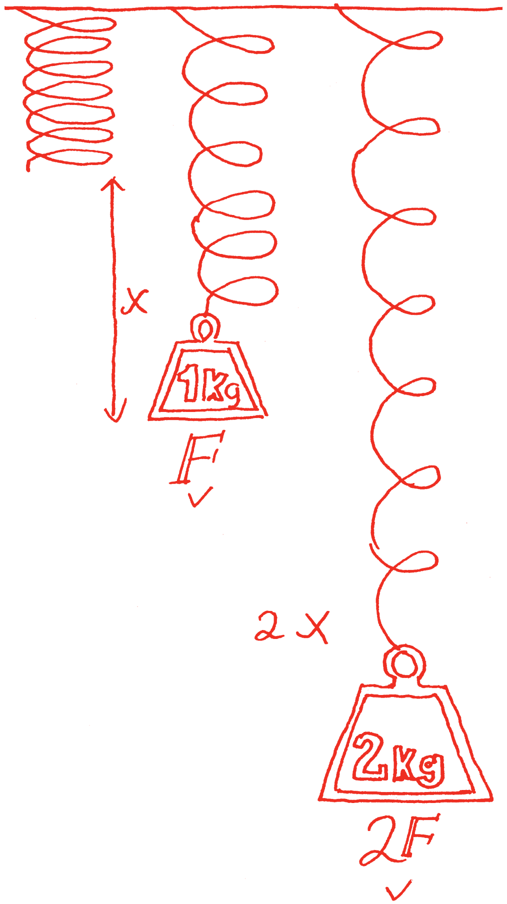
A curious addendum to Newton's story is the fate of his manuscripts, many of which were eventually acquired by Roger Babson. Babson was an MIT-educated engineer, who credited the successful investments during the 1929 crash that made him a rich man, to his application of Newton's third law to the stock market. He believed that Newton had saved him from financial ruin and so set about purchasing Newton's original manuscripts. In 1948 Babson set up the Gravity Research Foundation to find ways to develop 'antigravity'. He published an essay '*Gravity – our number one enemy*' in which he described his sister's death by drowning and his own battle with tuberculosis in childhood, and concluded: '"Old man Gravity" is not only directly responsible for millions of deaths each year, but also for millions of accidents'. His foundation held its inaugural meeting in 1951 and attendees were provided with special gravity chairs to aid circulation and Babson promoted an 'anti-gravity' pill. One of the financial backers of Babson's Foundation was the inventor and industrialist Clarence Birdseye. Babson donated money to several universities to fund research into anti-gravity devices and his donations are commemorated at Tufts University by a monument inscribed with the words:

This monument has been erected by the Gravity Research Foundation
Roger W. Babson Founder
It is to remind students of the blessings forthcoming when
a semi-insulator is discovered in order to harness gravity
as a free power and reduce airplane accidents
1961

A Tufts tradition has developed around the memorial: when a student earns their PhD in the department of cosmology (established with Babson's money) they kneel in front of the stone and their dissertation advisor drops an apple on their head.

The puzzle of Hooke's law

When Hooke first announced his spring law, in 1676, he published it in the form of an anagram, giving the letters: *cediinnoopsssttuu*. Two years later, he gave the answer to the puzzle – the letters can be rearranged to spell: *Ut Pondus sic Tensio*, or as the extension, so the weight. The use of anagrams was seen as a technique for protecting ideas: a coded theorem could be sent out to colleagues to establish a dated record of the discovery, without giving away the idea before publication in full.



As his income was modest, Hooke worked as Robert Boyle's assistant while he was studying at Oxford and was employed to tutor Boyle in mathematics. Perhaps as a result of his work with Boyle, Hooke appears to have conflated the phenomena of compression of gases and of springs. At one point in his writing he argued that air could be used to demonstrate his 'Rule or Law of Nature' and he presented 'A Table of the elaftic [sic] power of the Air'. In other places in his work he appears to have been aware of the mathematical differences between the two contexts.

The controversial thruster

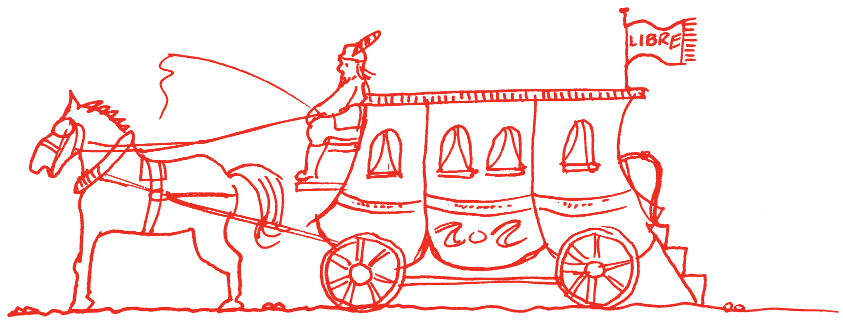
For many years there has been speculation that the propagation of an electromagnetic field inside a microwave cavity might be used to generate thrust. Rumours surrounding the development of a device based on this principle increased in 2016 when a team at NASA's Johnson Space Centre published a paper claiming some successful results from experiments with an electromagnetic propulsion device. They report measuring a thrust to power ratio of 1.2×10^{-6} N/W. However, their result is controversial as it may imply a violation of Newton's third law and a number of early critiques of the research have appeared online.

Pascal's genius

In Gilberte Pascal's biography of her famous brother, she claims that, when Blaise was five years old, his father refused to teach him any mathematics save for the statement that the subject was 'a way of making precise figures and finding the proportions among them'. Gilberte reported that based only on this statement, during his playtime, Blaise drew mathematical figures and developed axioms.

Pascal was frequently unwell, and on one occasion was paralysed from the waist down, and required crutches to walk. He was treated with brandy-soaked stockings.

Pascal made two notable mechanical contributions. He invented an early mechanical calculator which went into production with 50 prototypes produced in 1645. Pascal also launched the first municipal horse-bus system in Paris in 1662. The horse-drawn omnibuses followed a fixed route at regular intervals independent of the number of passengers. The initial fleet consisted of seven coaches that could carry 6-8 passengers and the service was, at first, free to use.



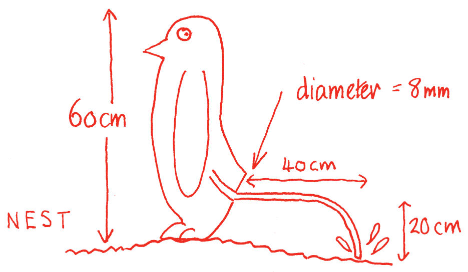
Some curious scientific papers related to force

A number of unusual papers related to force have been published including:

- An analysis of the force required to drag sheep over various surfaces
- The forces that act in a ponytail and the statistical physics of hair fibre bundles
- The frictional coefficient of banana skins (the reported coefficient is 0.07).

Projectile penguin poo

The forces involved in penguin defecation are reported in a 2003 paper: *Pressures produced when penguins pooh – calculations on avian defaecation*. Chinstrap and Adélie penguins can generate pressures of 60 kPa to project faeces of a viscosity resembling olive oil over distances of over 40 cm. The authors claim: 'From a few "spot-on" photographs, we estimated the aperture, from which the semi-liquid excretory material is released'. The authors conclude with a call for further research to settle the question: 'Whether the bird deliberately chooses the direction into which it decides to expel its faeces or whether this depends on the direction from which the wind blows at the time of evacuation are questions that need to be addressed on another expedition to Antarctica'.



Pulling apart phone directories

A recent paper has analysed the causes of the high frictional force that results from the interleaving of two phone books. It is reported that attempts to separate two interleaved phone books using trucks and military tanks have failed. The difficulty of pulling the books apart arises because the force exerted to separate the pages amplifies the small frictional force arising from the interaction of the pages.
The relationship between the size of the frictional force and the number of pages is non-linear. A roughly tenfold increase in the number of pages (from N=12 to N=100) resulted in an increase in the traction force required by four orders of magnitude.
The authors of the study conclude that the high magnitude of frictional force arises because the pages of the books do not lie exactly parallel to each other, resulting in loads perpendicular to the paper-paper interfaces.

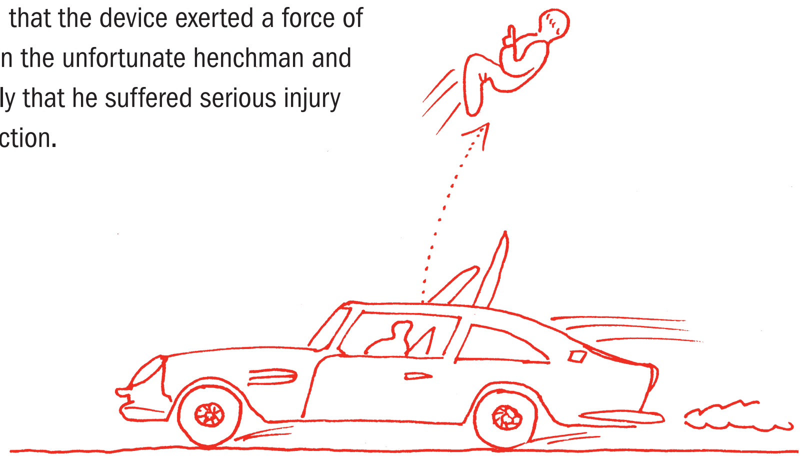
Losing weight the Canadian way

The GRACE satellites, (see also page 6), use microwave beams to measure tiny changes to distributions of mass in the Earth. The satellites have been used to investigate a gravitational anomaly, the relatively low gravitational field around the Hudson Bay in northeast Canada. The effect is hypothesised to arise from two possible causes: the rebounding of the Earth's crust in the area following the melting of glaciers, or the motion of the crust due to convection currents in the mantle. Unfortunately, the effect of the anomaly on your weight will be small – the phenomenon leads to a reduction in the gravitational field strength of around 0.005%.

Forces in films and popular culture

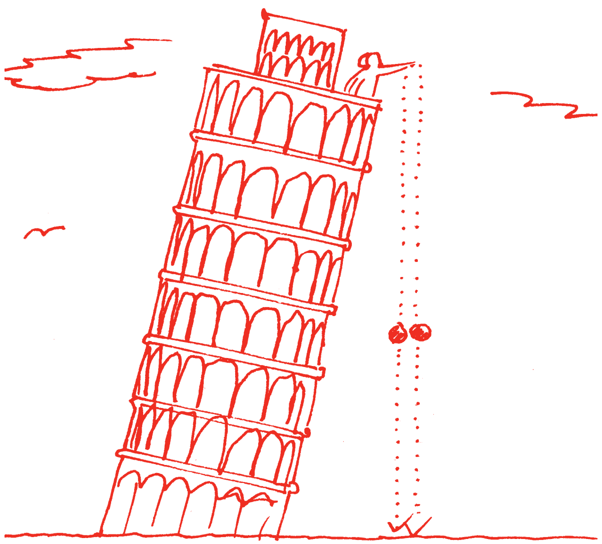
A paper in the *Journal of Interdisciplinary Science Topics* considers:
'The Viability of Coming in Like a Wrecking Ball'. The author estimates that the deceleration experienced by a wrecking ball will be around 288 *g* and concludes that: 'it is clear that a human being cannot possess the characteristics of a wrecking ball without sustaining significant injury, and other objects should be sought as an analogy'.

Another paper, in the same journal, examines whether a character in the James Bond film *Skyfall* could shoot through a train coupling. The analysis suggests that, assuming no plastic deformation, the force of the bullet would be less than a third that required to break the steel coupling. Another Bond related paper analysed the motion of the ejector seat in the film *Goldfinger* and concluded that the device exerted a force of 1,930 N on the unfortunate henchman and it is unlikely that he suffered serious injury due to ejection.



The history of the force concept

The modern concept of force has progressed through a number of iterations. Aristotle argued that 'everything moved must be moved by something' and distinguished between forces inherent in objects and forces that emanate from substances. Writers in the 14th-16th centuries promoted the Aristotelian concept of motive force and, despite Galileo's critique of the idea in the *Dialogues Concerning Two New Sciences*, the concept was still being used by members of the Royal Society as late as the 1690s. One of the proponents of the Aristotelian model, John Buridan, argued that a permanent force was impressed on a projectile unless resistive forces acted and that the force was proportional to the quantity of matter and speed of the object. The assertion that 'whenever A acts upon B, B reacts upon A' was mentioned as early as 1564 by Valles and was widely held by physicists from the 1630s onwards. Like Aristotle, Newton in the *Principia*, refers to two kinds of forces: *Vis insita*, inertial forces which are seen as inherent to bodies and *vis impressa*, forces exerted on a body, such as pressure and impact forces. Newton argued that *vis insita* was proportional to the mass of the body. Newton tended to work through the use of proportions rather than the use of equations: the familiar formula giving the magnitude of gravitational attraction between two masses is not found in the *Principia*. Leibnitz proposed an alternative classification of forces, arguing that moving force (*vis mortix*) came in two forms: living force (*vis viva*) and dead force (*vis mortix*). Dead force was conceptualised as having a drive to motion without an accompanying motion, for example, the force in a stretched spring.



Emotional pressure

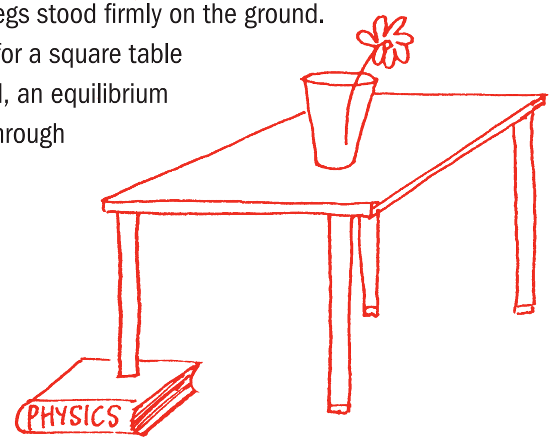
The concept of pressure was preceded by some emotive terminology: the Flemish mathematician and engineer, Stevin referred to the 'violence' water can inflict and Pascal described the 'suffering' of walls of a container. Stevin is credited with proposing the concept of the parallelogram of forces (the concept of the resolution of velocities is found in the work of Aristotle). Stevin is notable also for proposing that objects of different mass accelerate at the same rate, two years before Galileo, and for carrying out an experiment in which a one-pound and a ten-pound lead ball were dropped thirty feet and the time of their impact judged by the sound of their collision with the floor. Stevin is credited with the design of a land yacht, which contemporary accounts report carried up to 28 people and covered 97 km in less than two hours, faster than any other vehicle of the time.

The devil's suitcase

George Gamow relates a prank carried out by the French physicist, Jean Perrin. Perrin is reported to have packed a running aviation gyroscope into a suitcase, which he checked in at a Paris railway station. When a porter carrying the case tried to turn a corner, the suitcase refused to turn, twisting his wrist. The porter reportedly exclaimed: 'The devil himself must be inside' and ran off.

The wobbly table problem

A physicist working in the CERN café became frustrated with its wobbly tables and began to study their stability. André Martin found that it was always possible to rotate the table so that all four legs stood firmly on the ground. He later published a proof that, for a square table with four legs on irregular ground, an equilibrium state can be found by rotation through an angle of less than 90°.

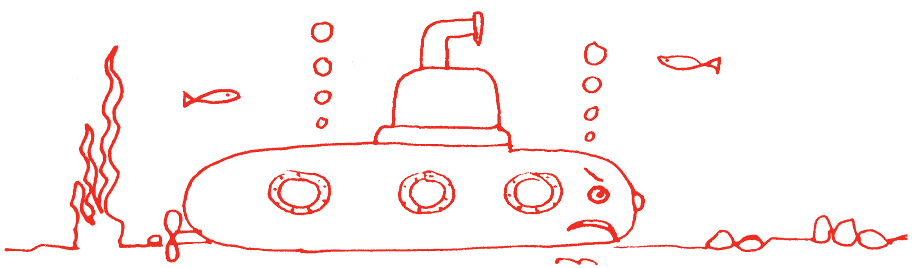


The invention of the air bag

The inventor of the air bag, John W Hetrick, attributes his invention to an accident that occurred when he was out a Sunday drive with his wife and young daughter in 1952. Hetrick swung his car into a ditch in order to avoid a deer, and he and his wife flung their hands up to protect their daughter. While driving home after the crash, he had the idea of an object coming out of the dashboard to soften a collision and began to develop sketches of his idea. His invention was further inspired by an accident he witnessed during the Second World War. While repairing a torpedo, the compressed air inside the weapon was accidentally released, firing the torpedo's canvas cover to the ceiling. Hetrick's original patent for the air bag used a spring-loaded mass as the trigger, probably would not have worked in practice, and he never earned any money from his invention. Most contemporary systems use nitrogen generated from the reaction between sodium azide, potassium nitrate and silicon dioxide in order to fill the airbag rapidly. The first recorded head-on collision in which both cars deployed airbags occurred in 1990 in Culpeper, Virginia – both drivers suffered only minor injuries.

Getting to the bottom of Archimedes' principle

A special case of Archimedes' principle occurs when an object rests at the bottom of a tank of liquid. For example, when a submarine rests on the floor of the ocean, it cannot rise simply by blowing water out of its buoyancy tanks as it has no water underneath it to provide an upward force, only water pressing down from above. Hence, definitions of Archimedes' principle that emphasise the effect of a net force due to a difference in pressure are seen as seen as exemplary, rather than definitions that simply link buoyancy to the weight of water displaced.



Speed of light subs

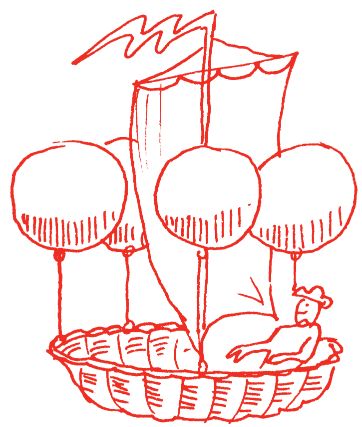
A thought experiment, sometimes called Supplee's paradox, asks what would happen to a submarine that travelled at close to the speed of light parallel to the surface of the water. Observers stationary with respect to the water might assume that the relativistic contraction of the vessel would cause it to displace less water and hence sink, while observers at rest relative to the submarine might assume the reverse effect. A detailed analysis suggests that the submarine would sink.

Buoyant birds

Diving birds tend to have plumage that traps less air in comparison to non-diving birds as the trapped gas exerts an additional buoyancy force. Hence, diving birds may have thicker feathers than other species to compensate for the poorer insulating properties of their plumage. As birds dive deeper, the trapped air becomes compressed, reducing its volume and also the upward force on the bird, increasing the power available at increased depths.

The vacuum airship

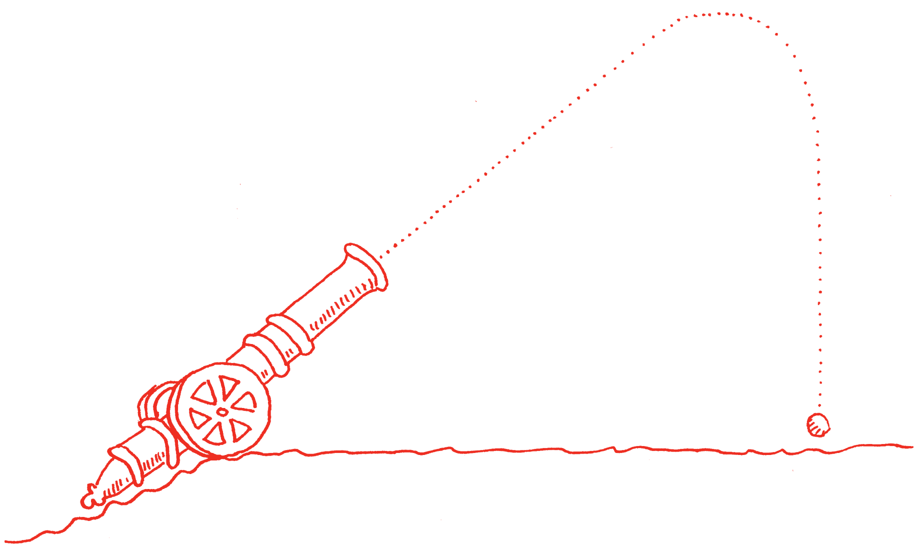
In the 1670s, following an idea proposed by Roger Bacon, Francesco Lana de Trezi designed an airship that generated lift from evacuated copper spheres. Lana de Trezi's aircraft consisted of a boat hull with a mast, sail and four copper spheres that would have their air pumped out. Unfortunately for Lana de Trezi, it is estimated that spheres made of copper light enough to float (requiring a thickness of 0.1 mm) would collapse when evacuated. The O-Boot project in Italy is attempting to use modern materials to make Lana de Trezi's dream a reality.



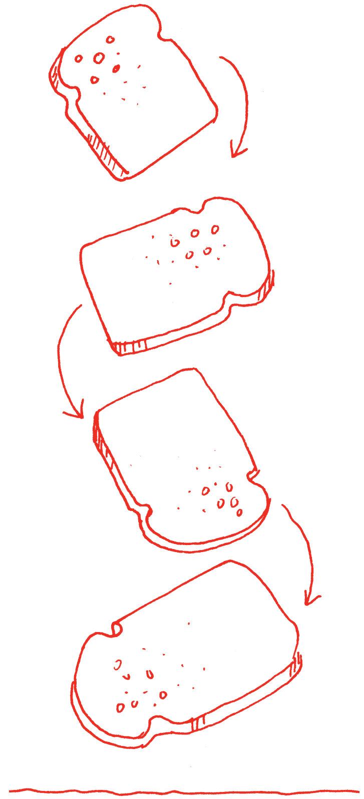
Projectile Motion

Early perceptions of projectile motion

In 1537, Nicolò Tartaglia, an Italian mathematician, published *Nova Scientia*, a work that has subsequently been recognised as the foundational text in ballistics. Tartaglia, through calculation and observation, reported that the maximum range of a cannon occurred at an angle of 45°. However, his understanding differs from modern models of projectile motion – Tartaglia assumed that the trajectory of a cannon ball could be approximated using straight lines and circular arcs. He may have been inspired by representations of projectile motion from the Middle Ages that represented trajectories with an initial linear section, followed by a circular arc and then a final vertical descent. Though these descriptions of motion seem clearly mistaken to modern eyes, they approximate well to the motion of projectiles when drag forces act. The description of the path of a projectile as parabolic emerged from experiments that are reported to have been carried out jointly by Galileo and his patron, Guidobaldo del Monte, by rolling a ball dipped in ink across an inclined plane to establish the geometrical form of projectile motion.



Murphy's Law



An analysis has been carried out on the dynamics of pieces of toast in order to test the prediction of Murphy's Law that toast is more likely to land butter side down than up. In experimental work to test the hypothesis, the coefficient of static friction for bread (0.29) was found to be slightly higher than for toast (0.25). Matthews reports that toast is indeed more likely to land butter side down but argues that one factor that accounts for this result is human height, which determines the height of tables. A table 3 m high is recommended to prevent butter-side-down collisions. However, the maximum safe height of a humanoid creature that limits the danger of fatal falls is calculated to also be around 3 m and hence Matthews concludes despairingly: 'all human-like organisms are destined to experience the 'tumbling toast' manifestation of Murphy's Law because of the values of the fundamental constants in our universe'. The author dismisses two solutions to the toast problem: the building of tables which are 3 m high is 'impractical' and he argues that the reduction of toast to 2.5 cm squares is 'unsatisfactory'. Matthews suggests that toast that is beginning to fall should be given 'a smart swipe forward with the hand' to limit the period over which the toast is exposed to a gravitational torque.

There is another intriguing connection between acceleration and Murphy's Law. There is a hypothesis that the phrase originates from a development engineer, Edward Murphy, who worked on the rocket sled tests in which John Stapp participated, described on page 12. During one test, an assistant wired the strain gauges that would measure deceleration back-to-front, resulting in a loss of data. Murphy's expression of exasperation with his assistant might be the original use of the phrase.

Falling cats

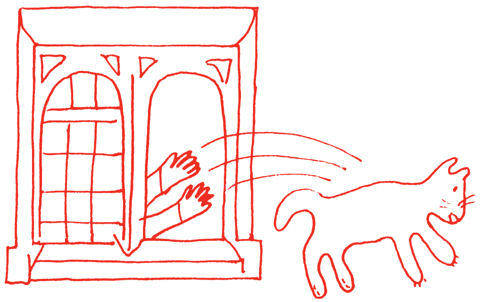
A number of scientific investigations have studied the motion of falling cats. Galileo had one of the characters in his dialogue deliver this quip to attack an Aristotelian:

> *'his author must believe that if a dead cat falls out of a window, a live one cannot possibly fall too, since it is not a proper thing for a corpse to share in qualities that are suitable for the living.*

Maxwell wrote in a letter during his time at Cambridge:

> *There is a tradition in Trinity that when I was here I discovered a method of throwing a cat so as not to light on its feet, and that I used to throw cats out of windows. I had to explain that the proper object of research was to find how quick the cat would turn round, and that the proper method was to let the cat drop on a table or bed from about two inches, and that even then the cat lights on her feet.*

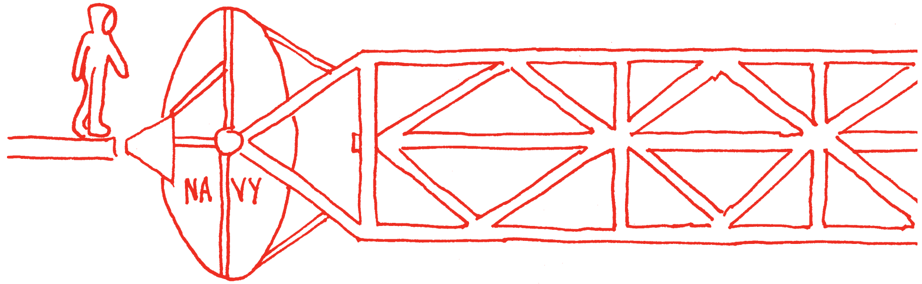
Some Stanford University physicists presented an analysis of the motion of falling felines based on a model of the cat as two joined cylinders. A more recent paper presents evidence from dropping a toy cat fitted with an accelerometer. The researchers argue that changes in acceleration cause a fear response in a cat and hence define a variable, the 'coefficient of the cat's fear' as the derivative of acceleration during free fall. The authors present an explanation for the urban legend that cats often die when falling from a height of seven storeys but may survive falls from both greater and lesser heights. They argue that a seven-storey fall takes about two seconds, which corresponds with the upper limit of the coefficient of fear and so cats falling from relatively small heights may be unprepared to land.



A falling cat may appear to violate the principle of conservation of angular momentum, as it is seemingly able to rotate without the application of an external torque. However, it has been argued that a falling cat moves its body in such a way that the front and back halves rotate in opposite directions, resulting in a zero net change in angular momentum.

Circular Motion

You spin me right round



Ultracentrifuges are devices used to separate materials and can achieve accelerations of up to 1,000,000 times the acceleration due to gravity and speeds of 150,000 rpm. The first human centrifuge was designed by Erasmus Darwin, Charles Darwin's grandfather, who was interested in the origin of vertigo. He labelled his device a 'rotative couch'. Darwin's friend, James Watt, drew up detailed blueprints for the apparatus but the device was never built. NASA researchers found that fish tolerate the effects of high acceleration surprisingly well and hypothesised that immersion in water might have a similar protective effect on humans. Hence the researchers built an aluminium capsule, named the *iron maiden*, large enough to contain a human, that could be filled with water and attached to a centrifuge. The iron maiden was tested on R. Flanagan Gray, a physician at the Jonsville Laboratory. Flanagan Gray stayed alert for 25 seconds while spinning, reaching a peak acceleration of 32 g and setting a new endurance record. He reported suffering only mild sinus pain during the trial.

As humans can tolerate small accelerations reasonably well, engineers have suggested that spacecraft might reduce travel time by moving with a constant low value of acceleration rather than an initial high acceleration followed by a long period of constant velocity. To test this claim, centrifuge-training officer Carl Clark volunteered to spend 24 hours in a centrifuge experiencing 2 g acceleration. The gondola of the centrifuge was fitted with a reclining chair and a small electric stove so Clark could cook and eat while being accelerated. Clark managed to work, eat and sleep during the experiment and reported the only side effect of the experience was mild fatigue.

Gravity lends a hand

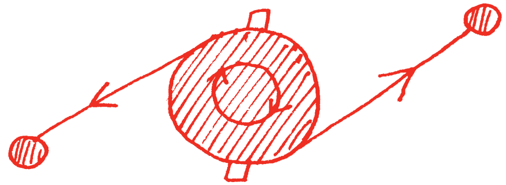
Gravity assists are used to alter the path and speed of spacecraft. Perhaps the most extended gravity assist ever achieved was proposed by the Italian mathematician Gaetano Crocco and applied in the Voyager mission. In a 'rare moment of great elation', Crocco noted that a spacecraft launched in 1977 would encounter an alignment of the planets highly favourable to providing multiple gravity assists that hadn't occurred since 1801 and wouldn't reoccur for 176 years. The spacecraft would first encounter Jupiter, two years after launch, where it would be accelerated by 11 km/s and deflected though 97° towards Saturn, which it would reach the following year, then encounter Neptune and Pluto. He labelled this route the 'grand tour'.

The rogue asteroid

An asteroid passing close to Earth may have its orbit deflected in such a way as to cause a collision in the future; regions which cause this kind of alteration to trajectories are known as *gravitational keyholes*. For example, in 2029, the asteroid Apophis will pass close to Earth and, should it pass through a 610 m wide keyhole, it will experience a gravitational force that will put it on a trajectory to collide with the Earth in 2036. Calculations suggest the probability of such a collision are vanishingly small.

Yo-yo satellites

Some satellites are deliberately spun about an axis perpendicular to their orbital plane in order to prevent their position drifting. As in a gyroscope, this provides some inertia against perturbations and angular velocities of between 30 and 100 rpm are typical. In an alternative application, a technique known as *yo-yo de-spin* has been used to slow the rotation of a satellite. Two masses attached to lengths of cord released from opposite sides of the craft, like the extended arms of a pirouetting skater, are used to cause the rotational velocity of the satellite to decrease. Yo-yo de-spin was used on early, unmanned space flights in the 1950s and on recent missions, including the 1999 Mars Polar Lander and the 2003 Mars Exploration Rover.



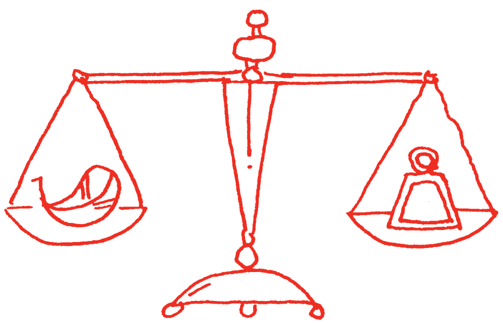
Newton's misconception

Just as is the case for some students, Newton is reported to have struggled to change his conception of motion from one involving centrifugal forces to a notion of centripetal force. Newton first tried to conceptualise circular motion by imagining that a half rotation was equivalent to a perfectly elastic rebound. When this method produced results with mismatching dimensions, he tried to resolve the components of circular motion along the sides of a square inscribed within the path of the body. Though he was able to correctly derive the equation for centripetal force from this method, he continued to conceptualise a centre-fleeing rather than a centre-seeking force.

Mass and Weight

A pound of lead or a pound of feathers?

The old riddle that asks whether a pound of feathers is heavier than a pound of lead is not as simple as it seems. Some approaches to weight measurement will measure forces in addition to the gravitational force on an object, complicating the riddle. In the case of the feathers, their relatively large volume means that they displace more air than the lead, so for the same mass, the feathers will experience a greater buoyancy force. Therefore, if not weighed in a vacuum, the feathers will experience a lower net downward force. A different approach to mass measurement to avoid this problem might be to measure inertial mass. For example, tethered, horizontal springs might be attached to either side of the objects to be weighed. By displacing the samples, the time periods of the system could be used to determine their mass. However, in this method, the moving bodies will 'entrain' (ie force to move with it) a non-negligible mass of air. In a simulation of the experiment, researchers calculated that a 5 cm by 10 cm bronze sheet (standing in for lead) would entrain 0.01 g of air, while a block of polystyrene (representing the feathers) of the same mass would entrain 0.5 g of air, giving different results for the mass of the objects. Psychologists report that blindfolded volunteers given boxes of equal size containing secured equal masses of lead and feathers, felt the box containing the lead was heavier on 74% of trials. The researchers argued that perception of heaviness is related to an object's dynamical symmetry: objects with symmetric mass distributions feel lighter than ones with asymmetric distributions.



A brief history of the concepts of mass and weight

The term 'mass' is derived from the Latin *massa* meaning a lump of dough or paste. In many ancient cultures, despite standardisation of units such as length and volume, different units of weights were used for different goods and measures varied from place to place. Therefore, it has been argued that weight was not conceived of as a unified concept but rather as a property of individual objects, like colour or smell. This view may have been the cause of Aristotle's perception that heavy objects fall faster than light ones. Ancient Greek philosophers thought weight derived from centrifugal forces whereas Romans thinkers believed weight resulted from a natural tendency of objects to fall. Aristotle argued that the heavy elements, earth and water, have gravity, a tendency to move to the centre of the universe, whereas light elements, air and fire, have levity, a tendency to move away from the centre of the universe. Galileo, philosophers of science have argued, understood the concept of inertial mass without ever offering an explicit definition of the term.

Newton used the term *pondus* which translates to 'weight' to refer to a measure of matter but was aware of a distinction between quantity of matter and gravitational force. He reported that, because of 'the want of a suitable word' he would 'represent and designate quantity of matter by weight' though he clarifies that by weight 'I mean the quantity or amount of matter being moved, apart from considerations of gravity, so long as there is no question of gravitating bodies'. Newton defined mass in the following way: 'The quantity of matter is the measure of the same, arising from its density and bulk conjointly'. Ernst Mach suggested that Newton's definition was circular and proposed an argument that mass is a concept constructed simply to make sense of the motion of objects.

While contemporary textbooks typically define mass either as the quantity of matter or as an object's ability to resist changes in motion, Hecht argues that it is impossible to create a completely operational definition of mass as valid measurement is not practically possible.

The Gimli glider

On 23rd July 1983, a Boeing 737 jet flying from Montreal to Edmonton completely ran out of fuel and had to glide for 30 minutes to an abandoned Royal Canadian Air Force base at Gimli. The first officer had used a conversion factor to convert the volume of fuel required into a mass. However, he erroneously used a conversion from litres into pounds, rather than kilograms. Flight controllers directed the plane to a landing strip which they believed was abandoned but, on the day of the flight, was being used as a car racetrack. This problem was compounded by the silent nature of the glide landing. Fortunately, the pilots managed to land the plane without serious injury to any of the passengers or people on the ground.

Negative mass

The equations of Newtonian and relativistic gravitation do not exclude the possibility of negative mass. Counterintuitively, in one model, given a pair of bodies with equal magnitude but opposite signs of mass, a positive mass would attract a negative mass, while a negative mass would repel a positive mass (so-called 'runaway motion', which the model's proposer described as 'preposterous'). A negative gravitational mass would fall vertically downwards on the Earth, while on a negative mass planet both positive and negative mass objects would fall upwards. Researchers at Washington State University have observed a 'negative mass' phenomenon in a Bose-Einstein condensate. The team cooled rubidium atoms to close to absolute zero and noticed that, unlike normal materials, which accelerate in the direction of the applied force, the atoms of the condensate accelerated in the opposite direction. One of the researchers, Michael Forbes, commented that: 'It looks like the rubidium hits an invisible wall'.

Galileo's prank letters

During his time in Venice, Galileo and a friend sent letters to a Jesuit priest pretending to be a rich widow with religious doubts. Galileo also wrote to a former colleague, a mathematics professor at the University of Padua, pretending to be an amateur mathematician who needed help.

Is it possible to jump into orbit?

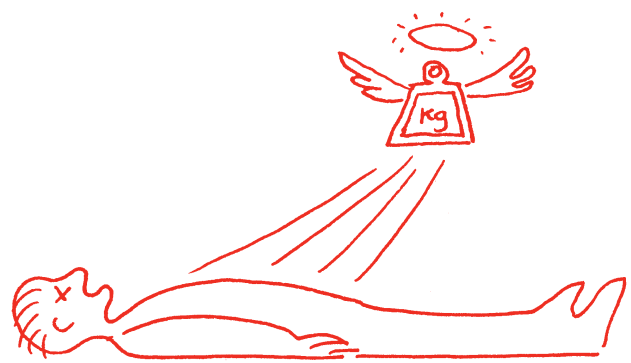
A paper has considered whether it is possible to jump into orbit on a body of small mass, such as Mars's moon Deimos. The authors conclude that it is impossible to jump from the surface of Mars's moon into a trajectory that would lead to a stable orbit though comment that it may be possible to enter orbit by jumping vertically from a high point on the surface or by building a platform which is then collapsed. Deimos's escape velocity is only 5.8 m/s and it is calculated that a stone dropped from waist height would take around 30 s to reach the ground.

Pay-per-gram

Samoan Air has begun charging customers by their mass. The rates vary depending on the route but range from $1 to $4.16 per kilogram. The head of the airline argues that the pricing strategy was the fairest way for the airline to charge their passengers.

Weighing the soul

The Boston physician, Dr Duncan MacDougall, carried out one of the strangest mass measurements ever performed, reported in a paper published in 1907. MacDougall measured the mass of six patients before and immediately after their deaths and recorded mass difference of between 8 and 35 g. In a similar experiment with dogs, no difference in mass was detected, which was explained by the assumption that dogs have no soul. Later work, by a Swedish psychiatrist, established a figure of around 21 g for the mass of the soul.



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