

FIGURE 308 A simple way to measure bullet speeds.

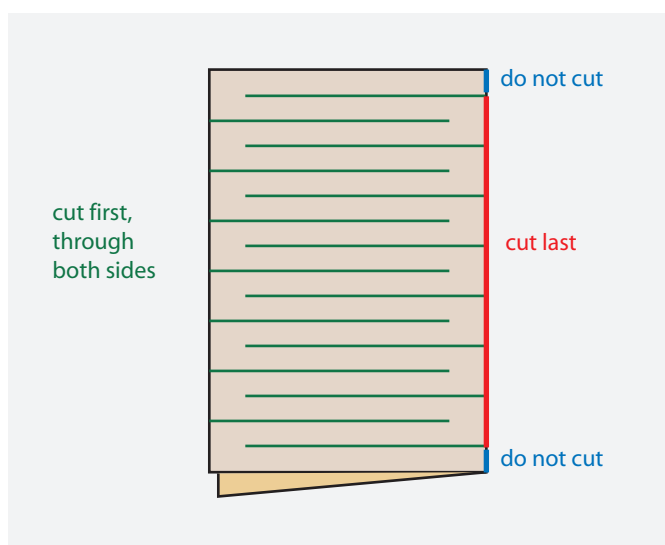


FIGURE 309 How to make a hole in a postcard that allows stepping through it.

**Challenge 73**, page 62: See Figure 309 for a way to realize the feat.

**Challenge 74**, page 62: Within 1 per cent, one *fifth* of the height must be empty, and four fifths must be filled; the exact value follows from  $\sqrt[3]{2} = 1.25992\dots$

**Challenge 75**, page 62: One pencil draws a line of between 20 and 80 km, if no lead is lost when sharpening. Numbers for the newly invented plastic, flexible pencils are not available.

**Challenge 79**, page 63: The bear is white, because the obvious spot of the house is at the North pole. But there are infinitely many additional spots (without bears) near the South pole: can you find them?

**Challenge 80**, page 63: We call  $L$  the initial length of the rubber band,  $v$  the speed of the snail relative to the band and  $V$  the speed of the horse relative to the floor. The speed of the snail relative to the floor is given as

$$\frac{ds}{dt} = v + V \frac{s}{L + Vt} . \quad (129)$$

This is a so-called *differential equation* for the unknown snail position  $s(t)$ . You can check – by simple insertion – that its solution is given by

$$s(t) = \frac{v}{V} (L + Vt) \ln(1 + Vt/L) . \quad (130)$$

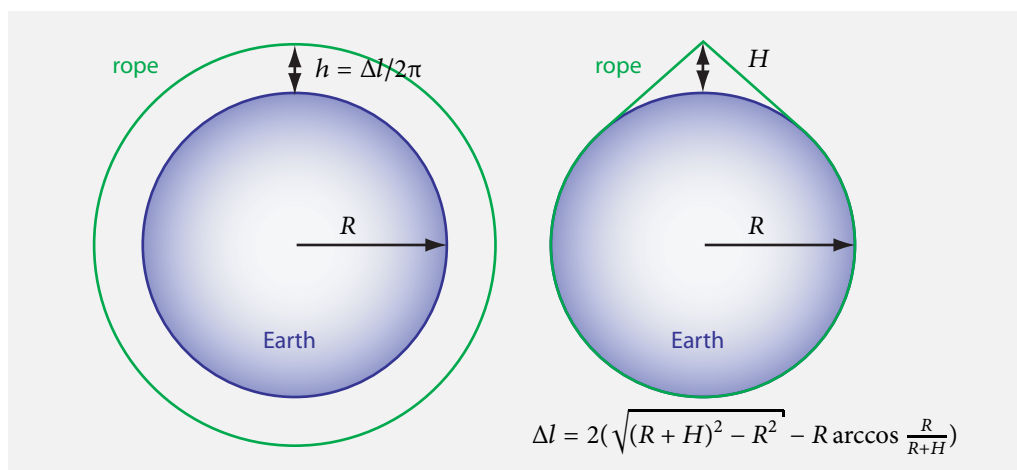


FIGURE 310 Two ways to lengthen a rope around the Earth.

Therefore, the snail reaches the horse at a time

$$t_{\text{reaching}} = \frac{L}{V} (e^{V/v} - 1) \quad (131)$$

which is finite for all values of  $L$ ,  $V$  and  $v$ . You can check, however, that the time is very large indeed, if realistic speed values are used.

**Challenge 81**, page 63: Colour is a property that applies only to objects, not to boundaries. In the mentioned case, only spots and backgrounds have colours. The question shows that it is easy to ask questions that make no sense also in physics.

**Challenge 82**, page 63: You can do this easily yourself. You can even find websites on the topic.

**Challenge 84**, page 64: Clocks with two hands: 22 times. Clocks with three hands: 2 times.

**Challenge 85**, page 64: 44 times.

**Challenge 86**, page 64: For two hands, the answer is 143 times.

**Challenge 87**, page 64: The Earth rotates with a speed of 15 minutes per minute.

**Challenge 88**, page 64: You might be astonished, but no reliable data exist on this question. The highest speed of a throw measured so far seems to be a 45 m/s cricket bowl. By the way, much more data are available for speeds achieved with the help of rackets. The  $c. 70$  m/s of fast badminton smashes seem to be a good candidate for record racket speed; similar speeds are achieved by golf balls.

**Challenge 89**, page 64: A *spread out* lengthening by 1 m allows even many cats to slip through, as shown on the left side of Figure 310. But the right side of the figure shows a better way to use the extra rope length, as Dimitri Yatsenko points out: a *localized* lengthening by 1 mm then already yields a height of 1.25 m, allowing a child to walk through. In fact, a lengthening by 1 m performed in this way yields a peak height of 121 m!

**Challenge 90**, page 64: 1.8 km/h or 0.5 m/s.

**Challenge 92**, page 64: The question makes sense, especially if we put our situation in relation to the outside world, such as our own family history or the history of the universe. The different usage reflects the idea that we are able to determine our position by ourselves, but not the time in which we are. The section on determinism will show how wrong this distinction is.

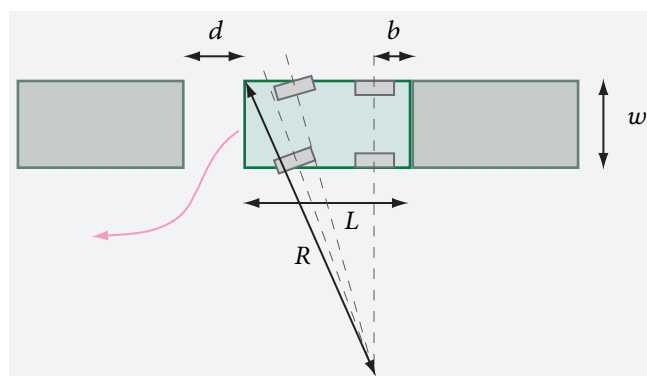


FIGURE 311 Leaving a parking space – the outer turning radius.

**Challenge 93**, page 64: Yes, there is. However, this is not obvious, as it implies that space and time are not continuous, in contrast to what we learn in primary school. The answer will be found in the final part of this text.

**Challenge 94**, page 64: For a curve, use, at each point, the curvature radius of the circle approximating the curve in that point; for a surface, define two directions in each point and use two such circles along these directions.

**Challenge 95**, page 65: It moves about 1 cm in 50 ms.

**Challenge 96**, page 65: The surface area of the lung is between 100 and 200 m<sup>2</sup>, depending on the literature source, and that of the intestines is between 200 and 400 m<sup>2</sup>.

**Challenge 97**, page 65: A limit does not exist in classical physics; however, there is one in nature which appears as soon as quantum effects are taken into account.

**Challenge 98**, page 65: The final shape is a full cube without any hole.

**Challenge 99**, page 65: The required gap  $d$  is

$$d = \sqrt{(L - b)^2 - w^2 + 2w\sqrt{R^2 - (L - b)^2}} - L + b, \quad (132)$$

as deduced from Figure 311. See also R. HOYLE, *Requirements for a perfect s-shaped parallel parking manoeuvre in a simple mathematical model*, 2003. In fact, the mathematics of parallel parking is beautiful and interesting. See, for example, the web page [rigtriv.wordpress.com/2007/10/01/parallel-parking/](http://rigtriv.wordpress.com/2007/10/01/parallel-parking/) or the explanation in EDWARD NELSON, *Tensor Analysis*, Princeton University Press, 1967, pp. 33–36. Nelson explains how to define vector fields that change the four-dimensional configuration of a car, and how to use their algebra to show that a car can leave parking spaces with arbitrarily short distances to the cars in front and in the back.

**Challenge 100**, page 66: A smallest gap does not exist: any value will do! Can you show this?

**Challenge 101**, page 66: The following solution was proposed by Daniel Hawkins.

Assume you are sitting in car A, parked behind car B, as shown in Figure 312. There are two basic methods for exiting a parking space that requires the reverse gear: rotating the car to move the centre of rotation away from (to the right of) car B, and shifting the car downward to move the centre of rotation away from (farther below) car B. The first method requires car A to be partially diagonal, which means that the method will not work for  $d$  less than a certain value, essentially the value given above, when no reverse gear is needed. We will concern ourselves with the second method (pictured), which will work for an infinitesimal  $d$ .

In the case where the distance  $d$  is less than the minimum required distance to turn out of the parking space without using the reverse gear for a given geometry  $L, w, b, R$ , an attempt to turn

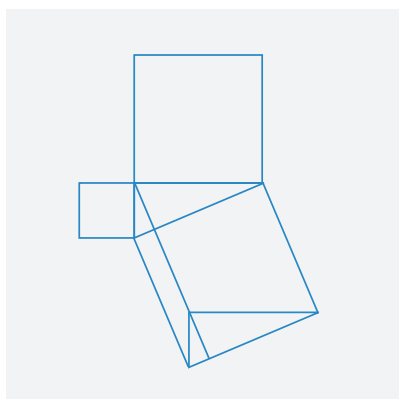


- The back wheels stay in alignment, but the front wheels (which we control), must turn different amounts to rotate about the same centre.
- The centres of rotation for left and right turns are on opposite sides of the car
- For equal magnitudes of left and right turns, the centres of rotation are equidistant from the nearest edge of the car. [Figure 312](#) makes this much clearer.
- All possible centres of rotation are on the same line, which also always passes through the back wheels.
- When the back wheels are ‘straight’ (straight will always mean in the same orientation as the initial position), they will be vertically aligned with the centres of rotation.
- When the car is turning about one centre, say the one associated with the maximum left turn, then the potential centre associated with the maximum right turn will rotate along with the car. Similarly, when the cars turns about the right centre, the left centre rotates.

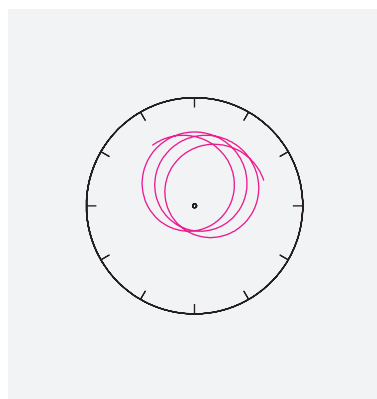
Now that we know the properties of Ackermann steering, we can say that in order to maximize the shift downward while preserving the orientation, we must turn left about the 1st centre such that the 2nd centre rotates a *horizontal* distance  $d$ , as shown in [Figure 312](#). When this is achieved, we brake, and turn the steering wheel the complete opposite direction so that we are now turning right about the 2nd centre. Because we shifted leftward  $d$ , we will straighten out at the exact moment car A comes in contact with car B. This results in our goal, a downward shift  $m$  and leftward shift  $d$  while preserving the orientation of car A. A similar process can be performed in reverse to achieve another downward shift  $m$  and a *rightward* shift  $d$ , effectively moving car A from its initial position (before any movement) downward  $2m$  while preserving its orientation. This can be done indefinitely, which is why it is possible to get out of a parking space with an infinitesimal  $d$  between car A and car B. To determine how many times this procedure (both sets of turning and straightening) must be performed, we must only divide  $T$  (remember  $T$  is the amount by which car A must be shifted downward in order to turn out of the parking spot normally) by  $2m$ , the total downward shift for one iteration of the procedure. Symbolically,

$$n = \frac{T}{2m} . \quad (133)$$

In order to get an expression for  $n$  in terms of the geometry of the car, we must solve for  $T$  and



**FIGURE 313** A simple drawing – one of the many possible one – that allows proving Pythagoras' theorem.



**FIGURE 314** The trajectory of the middle point between the two ends of the hands of a clock.

2m. To simplify the derivations we define a new length  $x$ , also shown in [Figure 312](#).

$$x = \sqrt{R^2 - (L - b)^2}$$

$$\begin{aligned} T &= \sqrt{R^2 - (L - b + d)^2} - x + w \\ &= \sqrt{R^2 - (L - b + d)^2} - \sqrt{R^2 - (L - b)^2} + w \end{aligned}$$

$$\begin{aligned} m &= 2x - w - \sqrt{(2x - w)^2 - d^2} \\ &= 2\sqrt{R^2 - (L - b)^2} - w - \sqrt{(2\sqrt{R^2 - (L - b)^2} - w)^2 - d^2} \\ &= 2\sqrt{R^2 - (L - b)^2} - w - \sqrt{4(R^2 - (L - b)^2) - 4w\sqrt{R^2 - (L - b)^2} + w^2 - d^2} \\ &= 2\sqrt{R^2 - (L - b)^2} - w - \sqrt{4R^2 - 4(L - b)^2 - 4w\sqrt{R^2 - (L - b)^2} + w^2 - d^2} \end{aligned}$$

We then get

$$n = \frac{T}{2m} = \frac{\sqrt{R^2 - (L - b + d)^2} - \sqrt{R^2 - (L - b)^2} + w}{4\sqrt{R^2 - (L - b)^2} - 2w - 2\sqrt{4R^2 - 4(L - b)^2 - 4w\sqrt{R^2 - (L - b)^2} + w^2 - d^2}}.$$

The value of  $n$  must always be rounded *up* to the next integer to determine how many times one must go backward and forward to leave the parking spot.

**Challenge 102**, page 66: Nothing, neither a proof nor a disproof.

**Challenge 103**, page 67: See volume II, on [page 20](#). On extreme shutters, see also the discussion in Volume VI, on [page 120](#).

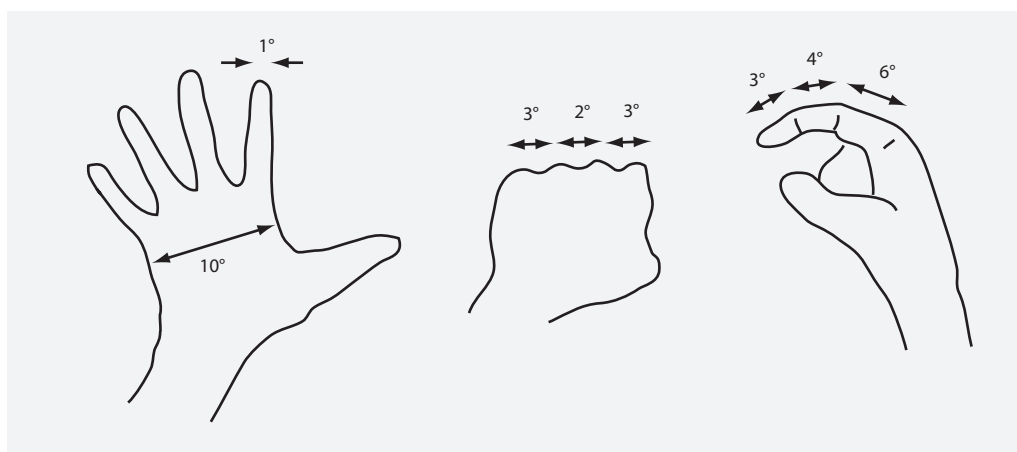


FIGURE 315 The angles defined by the hands against the sky, when the arms are extended.

**Challenge 104**, page 67: A hint for the solution is given in [Figure 313](#).

**Challenge 105**, page 67: Because they are or were liquid.

**Challenge 106**, page 67: The shape is shown in [Figure 314](#); it has eleven lobes.

**Challenge 107**, page 67: The cone angle  $\varphi$ , the angle between the cone axis and the cone border (or equivalently, *half* the apex angle of the cone) is related to the solid angle  $\Omega$  through the relation  $\Omega = 2\pi(1 - \cos \varphi)$ . Use the surface area of a spherical cap to confirm this result.

**Challenge 109**, page 68: See [Figure 315](#).

**Challenge 113**, page 69: Hint: draw all objects involved.

**Challenge 114**, page 69: The curve is obviously called a *catenary*, from Latin ‘catena’ for chain. The formula for a catenary is  $y = a \cosh(x/a)$ . If you approximate the chain by short straight segments, you can make wooden blocks that can form an arch without any need for glue. The St. Louis arch is in shape of a catenary. A suspension bridge has the shape of a catenary before it is loaded, i.e., before the track is attached to it. When the bridge is finished, the shape is in between a catenary and a parabola.

**Challenge 115**, page 70: The inverse radii, or curvatures, obey  $a^2 + b^2 + c^2 + d^2 = (1/2)(a + b + c + d)^2$ . This formula was discovered by René Descartes. If one continues putting circles in the remaining spaces, one gets so-called circle packings, a pretty domain of recreational mathematics. They have many strange properties, such as intriguing relations between the coordinates of the circle centres and their curvatures.

**Challenge 116**, page 70: One option: use the three-dimensional analogue of Pythagoras’s theorem. The answer is 9.

**Challenge 117**, page 70: There are two solutions. (Why?) They are the two positive solutions of  $l^2 = (b + x)^2 + (b + b^2/x)^2$ ; the height is then given as  $h = b + x$ . The two solutions are 4.84 m and 1.26 m. There are closed formulas for the solutions; can you find them?

**Challenge 118**, page 71: The best way is to calculate first the height  $B$  at which the blue ladder touches the wall. It is given as a solution of  $B^4 - 2hB^3 - (r^2 - b^2)B^2 + 2h(r^2 - b^2)B - h^2(r^2 - b^2) = 0$ . Integer-valued solutions are discussed in MARTIN GARDNER, *Mathematical Circus*, Spectrum, 1996.

**Challenge 119**, page 71: Draw a logarithmic scale, i.e., put every number at a distance corresponding to its natural logarithm. Such a device, called a *slide rule*, is shown in [Figure 316](#). Slide

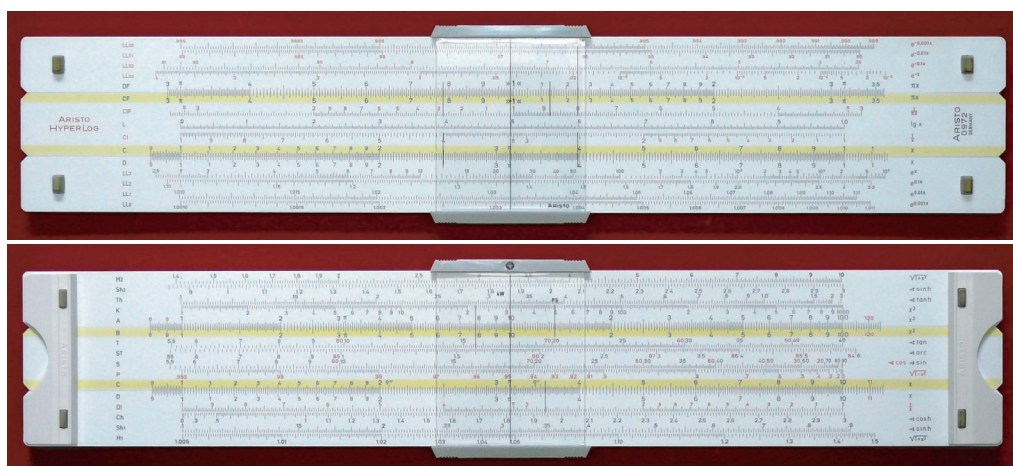


FIGURE 316 A high-end slide rule, around 1970 (© Jörn Lütjens).

rules were the precursors of electronic calculators; they were used all over the world in prehistoric times, i.e., until around 1970. See also the web page [www.oughtred.org](http://www.oughtred.org).

**Challenge 120**, page 71: Two more days. Build yourself a model of the Sun and the Earth to verify this. In fact, there is a small correction to the value 2, for the same reason that the makes the solar day shorter than 24 hours.

**Challenge 121**, page 71: The Sun is exactly behind the back of the observer; it is setting, and the rays are coming from behind and reach deep into the sky in the direction opposite to that of the Sun.

**Challenge 123**, page 71: The volume is given by  $V = \int Adx = \int_{-1}^1 4(1 - x^2)dx = 16/3$ .

**Challenge 124**, page 71: Yes. Try it with a paper model.

**Challenge 125**, page 72: Problems appear when quantum effects are added. A two-dimensional universe would have no matter, since matter is made of spin 1/2 particles. But spin 1/2 particles do not exist in two dimensions. Can you find additional reasons?

**Challenge 126**, page 72: Two dimensions of time do not allow ordering of events and observations. To say ‘before’ and ‘afterwards’ becomes impossible. In everyday life and all domains accessible to measurement, time is definitely one-dimensional.

**Challenge 127**, page 72: No experiment has ever found any hint. Can this be nevertheless? Probably not, as argued in the last volume of this book series.

**Challenge 130**, page 73: The best solution seems to be 23 extra lines. Can you deduce it? To avoid spoiling the fun of searching, no solution is given here. You can find solutions on [blog.vixra.org/2010/12/26/a-christmas-puzzle](http://blog.vixra.org/2010/12/26/a-christmas-puzzle).

**Challenge 131**, page 74: If you solve this so-called ropelength problem, you will become a famous mathematician. The length is known only with about 6 decimals of precision. No exact formula is known, and the exact shape of such ideal knots is unknown for all non-trivial knots. The problem is also unsolved for all non-trivial ideal *closed* knots, for which the two ends are glued together.

**Challenge 132**, page 76: From  $x = gt^2/2$  you get the following rule: square the number of seconds, multiply by five and you get the depth in metres.

**Challenge 133**, page 76: Just experiment.

**Challenge 134**, page 77: The Academicians suspended one cannon ball with a thin wire just in front of the mouth of the cannon. When the shot was released, the second, flying cannon ball flew through the wire, thus ensuring that both balls started at the same time. An observer from far away then tried to determine whether both balls touched the Earth at the same time. The experiment is not easy, as small errors in the angle and air resistance confuse the results.

**Challenge 135**, page 77: A parabola has a so-called focus or focal point. All light emitted from that point and reflected exits in the same direction: all light rays are emitted in parallel. The name ‘focus’ – Latin for fireplace – expresses that it is the hottest spot when a parabolic mirror is illuminated. Where is the focus of the parabola  $y = x^2$ ? (Ellipses have two foci, with a slightly different definition. Can you find it?)

**Challenge 136**, page 78: The long jump record could surely be increased by getting rid of the sand stripe and by measuring the true jumping distance with a photographic camera; this would allow jumpers to run more closely to their top speed. The record could also be increased by a small inclined step or by a spring-suspended board at the take-off location, to increase the take-off angle.

**Challenge 137**, page 78: It may be held by Roald Bradstock, who threw a golf ball over 155 m. Records for throwing mobile phones, javelins, people and washing machines are shorter.

**Challenge 138**, page 79: Walk or run in the rain, measure your own speed  $v$  and the angle from the vertical  $\alpha$  with which the rain appears to fall. Then the speed of the rain is  $v_{\text{rain}} = v / \tan \alpha$ .

**Challenge 139**, page 79: In ice skating, quadruple jumps are now state of the art. In dance, no such drive for records exists.

**Challenge 140**, page 79: Neglecting air resistance and approximating the angle by  $45^\circ$ , we get  $v = \sqrt{dg}$ , or about 3.8 m/s. This speed is created by a steady pressure build-up, using blood pressure, which is suddenly released with a mechanical system at the end of the digestive canal. The cited reference tells more about the details.

**Challenge 141**, page 79: On horizontal ground, for a speed  $v$  and an angle from the horizontal  $\alpha$ , neglecting air resistance and the height of the thrower, the distance  $d$  is  $d = v^2 \sin 2\alpha / g$ .

**Challenge 142**, page 79: Astonishingly, the answer is not clear. In 2012, the human record is eleven balls. For robots, the present record is three balls, as performed by the Sarcoman robot. The internet is full of material and videos on the topic. It is a challenge for people and robots to reach the maximum possible number of balls.

**Challenge 143**, page 79: It is said so, as raindrops would then be ice spheres and fall with high speed.

**Challenge 144**, page 80: Yes! People have gone to hospital and even died because a falling bullet went straight through their head. See S. MIRSKY, *It is high, it is far*, Scientific American p. 86, February 2004, or C. TUIJN, *Vallende kogels*, Nederlands tijdschrift voor natuurkunde 71, pp. 224–225, 2005. Firing a weapon into the air is a crime.

**Challenge 145**, page 80: This is a true story. The answer can only be given if it is known whether the person had the chance to jump while running or not. In the case described by R. CROSS, *Forensic physics 101: falls from a height*, American Journal of Physics 76, pp. 833–837, 2008, there was no way to run, so that the answer was: murder.

**Challenge 146**, page 80: For jumps of an animal of mass  $m$  the necessary energy  $E$  is given as  $E = mgh$ , and the work available to a muscle is roughly speaking proportional to its mass  $W \sim m$ . Thus one gets that the height  $h$  is independent of the mass of the animal. In other words, the specific mechanical energy of animals is around  $1.5 \pm 0.7$  J/kg.

**Challenge 147**, page 80: Stones *never* follow parabolas: when studied in detail, i.e., when the change of  $g$  with height is taken into account, their precise path turns out to be an ellipse. This

shape appears most clearly for long throws, such as throws around a sizeable part of the Earth, or for orbiting objects. In short, stones follow parabolas only if the Earth is assumed to be flat. If its curvature is taken into account, they follow ellipses.

**Challenge 148**, page 81: The set of all rotations around a point in a plane is indeed a vector space. What about the set of all rotations around *all* points in a plane? And what about the three-dimensional cases?

**Challenge 151**, page 81: The scalar product between two vectors  $\mathbf{a}$  and  $\mathbf{b}$  is given by

$$\mathbf{a}\mathbf{b} = ab \cos \angle(\mathbf{a}, \mathbf{b}) . \quad (134)$$

How does this differ from the vector product?

**Challenge 154**, page 84: One candidate for the lowest practical acceleration of a physical system are the accelerations measured by gravitational wave detectors. They are below  $10^{-13} \text{ m/s}^2$ . But these low values are beaten by the acceleration of the continental drift after the continents ‘snap’ apart: they accelerate from 7 mm/a to 40 mm/a in a ‘mere’ 3 million years. This corresponds to a value of  $10^{-23} \text{ m/s}^2$ . Is there a theoretical lowest limit to acceleration?

**Challenge 155**, page 85: In free fall (when no air is present) or inside a space station orbiting the Earth, you are accelerated but do not feel anything. However, the issue is not so simple. On the one hand, constant and homogeneous accelerations are indeed not felt if there is no non-accelerated reference. This indistinguishability or equivalence between acceleration and ‘feeling nothing’ was an essential step for Albert Einstein in his development of general relativity. On the other hand, if our senses were sensitive enough, we would feel something: both in the free fall and in the space station, the acceleration is neither constant nor homogeneous. So we can indeed say that accelerations found in nature can always be felt.

**Challenge 156**, page 85: Professor to student: What is the derivative of velocity? Acceleration! What is the derivative of acceleration? I don’t know. *Jerk!* The fourth, fifth and sixth derivatives of position are sometimes called *snap*, *crackle* and *pop*.

**Challenge 158**, page 87: One can argue that any source of light must have finite size.

**Challenge 160**, page 89: What the unaided human eye perceives as a tiny black point is usually about  $50 \mu\text{m}$  in diameter.

**Challenge 161**, page 89: See volume III, page 170.

**Challenge 162**, page 89: One has to check carefully whether the conceptual steps that lead us to extract the concept of point from observations are correct. It will be shown in the final part of the adventure that this is not the case.

**Challenge 163**, page 89: One can rotate the hand in a way that the arm makes the motion described. See also volume IV, page 132.

**Challenge 164**, page 89: The number of cables has no limit. A visualization of tethered rotation with 96 connections is found in volume VI, on page 182.

**Challenge 165**, page 90: The blood and nerve supply is not possible if the wheel has an axle. The method shown to avoid tangling up connections only works when the rotating part has *no* axle: the ‘wheel’ must float or be kept in place by other means. It thus becomes impossible to make a wheel *axle* using a single piece of skin. And if a wheel without an axle could be built (which might be possible), then the wheel would periodically run over the connection. Could such a axle-free connection realize a propeller?

By the way, it is still thinkable that animals have wheels on axles, if the wheel is a ‘dead’ object. Even if blood supply technologies like continuous flow reactors were used, animals could not make such a detached wheel grow in a way tuned to the rest of the body and they would have

difficulties repairing a damaged wheel. Detached wheels cannot be grown on animals; they must be dead.

**Challenge 166**, page 92: The brain in the skull, the blood factories inside bones or the growth of the eye are examples.

**Challenge 167**, page 92: In 2007, the largest big wheels for passengers are around 150 m in diameter. The largest wind turbines are around 125 m in diameter. Cement kilns are the longest wheels: they can be over 300 m along their axis.

**Challenge 168**, page 92: Air resistance reduces the maximum distance achievable with the soccer ball – which is realized for an angle of about  $\pi/4 = 45^\circ$  – from around  $v^2/g = 91.7$  m down to around 50 m.

**Challenge 173**, page 98: One can also add the Sun, the sky and the landscape to the list.

**Challenge 174**, page 99: There is no third option. Ghosts, hallucinations, Elvis sightings, or extraterrestrials must all be objects or images. Also shadows are only special types of images.

**Challenge 175**, page 99: The issue was hotly discussed in the seventeenth century; even Galileo argued for them being images. However, they are objects, as they can collide with other objects, as the spectacular collision between Jupiter and the comet Shoemaker-Levy 9 in 1994 showed. In the meantime, satellites have been made to collide with comets and even to shoot at them (and hitting).

**Challenge 176**, page 100: The minimum speed is roughly the one at which it is possible to ride without hands. If you do so, and then *gently* push on the steering wheel, you can make the experience described above. Watch out: too strong a push will make you fall badly.

The *bicycle* is one of the most complex mechanical systems of everyday life, and it is still a subject of research. And obviously, the world experts are Dutch. An overview of the behaviour of a bicycle is given in [Figure 317](#). The main result is that the bicycle is stable in the upright position at a range of medium speeds. Only at low and at large speeds must the rider actively steer to ensure upright position of the bicycle.

For more details, see the paper J. P. MEIJAARD, J. M. PAPADOPOULOS, A. RUINA & A. L. SCHWAB, *Linearized dynamics equations for the balance and steer of a bicycle: a benchmark and review*, Proceedings of the Royal Society A 463, pp. 1955–1982, 2007, and J. D. G. KOIJMAN, A. L. SCHWAB & J. P. MEIJAARD, *Experimental validation of a model of an uncontrolled bicycle*, Multibody System Dynamics 19, pp. 115–132, 2008. See also the [audiophile.tam.cornell.edu/~als93/Bicycle/index.htm](http://audiophile.tam.cornell.edu/~als93/Bicycle/index.htm) website.

**Challenge 177**, page 102: The total weight decreased slowly, due to the evaporated water lost by sweating and, to a minor degree, due to the exhaled carbon bound in carbon dioxide.

**Challenge 178**, page 102: This is a challenge where the internet can help a lot. For a general introduction, see the book by LEE SIEGEL, *Net of Magic – Wonders and Deception in India*, University of Chicago Press, 1991.

**Challenge 179**, page 103: If the moving ball is not rotating, after the collision the two balls will depart with a *right* angle between them.

**Challenge 180**, page 103: As the block is heavy, the speed that it acquires from the hammer is small and easily stopped by the human body. This effect works also with an anvil instead of a concrete block. In another common variation the person does not lie on nails, but on air: he just keeps himself horizontal, with head and shoulders on one chair, and the feet on a second one.

**Challenge 181**, page 104: Yes, the definition of mass works also for magnetism, because the precise condition is not that the interaction is central, but that the interaction realizes a more general condition that includes accelerations such as those produced by magnetism. Can you deduce the condition from the definition of mass as that quantity that keeps momentum conserved?

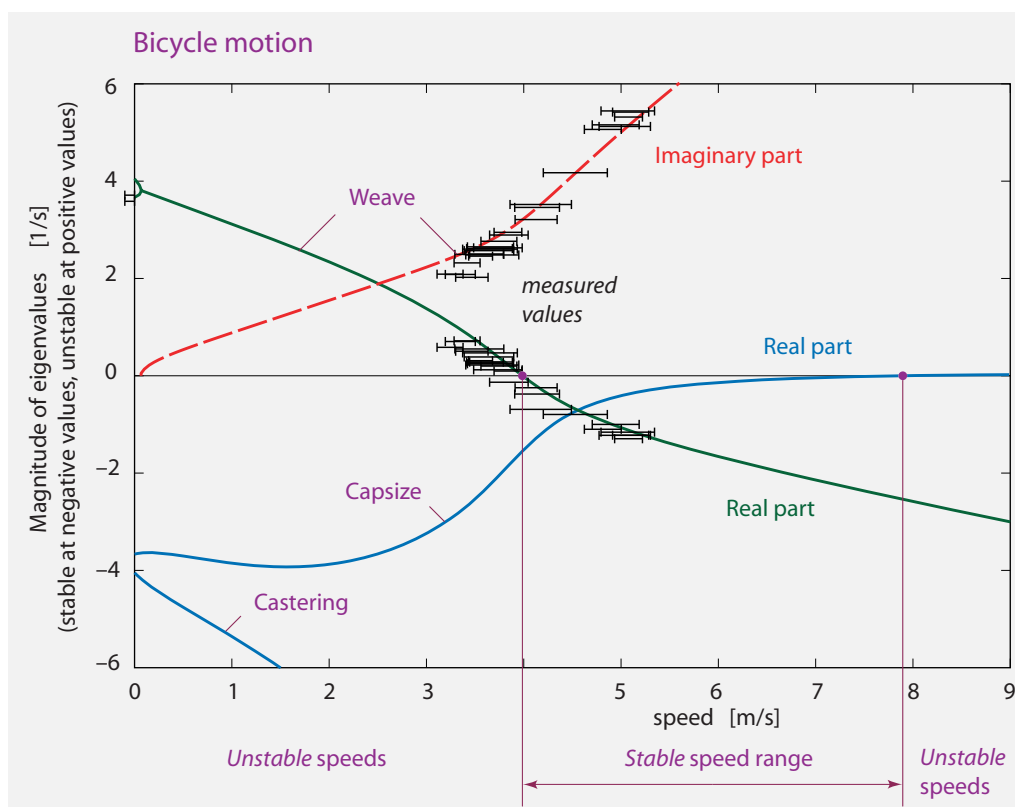


FIGURE 317 The measured (black bars) and calculated behaviour (coloured lines) – more precisely, the dynamical eigenvalues – of a bicycle as a function of its speed (© Arend Schwab).

Page 185

**Challenge 182**, page 106: Rather than using the inertial effects of the Earth, it is easier to deduce its mass from its gravitational effects.

**Challenge 187**, page 107: At first sight, relativity implies that tachyons have imaginary mass; however, the imaginary factor can be extracted from the mass–energy and mass–momentum relation, so that one can define a real mass value for tachyons. As a result, faster tachyons have smaller energy and smaller momentum than slower ones. In fact, both tachyon momentum and tachyon energy can be a negative number of any size.

**Challenge 188**, page 109: The leftmost situation has a tiny effect, the second situation makes the car roll forward and backwards, the right two pictures show ways to open wine bottles without an bottle opener.

**Challenge 189**, page 109: Legs are never perfectly vertical; they would immediately glide away. Once the cat or the person is on the floor, it is almost impossible to stand up again.

**Challenge 190**, page 109: Momentum (or centre of mass) conservation would imply that the environment would be accelerated into the opposite direction. Energy conservation would imply that a huge amount of energy would be transferred between the two locations, melting everything in between. Teleportation would thus contradict energy and momentum conservation.

**Challenge 191**, page 110: The part of the tides due to the Sun, the solar wind, and the interactions between both magnetic fields are examples of friction mechanisms between the Earth and the Sun.

**Challenge 192**, page 110: With the factor  $1/2$ , increase of (physical) kinetic energy is equal to the (physical) work performed on a system: total energy is thus conserved only if the factor  $1/2$  is added.

**Challenge 194**, page 112: It is a smart application of momentum conservation.

**Challenge 195**, page 112: Neither. With brakes on, the damage is higher, but still equal for both cars.

**Challenge 196**, page 113: Heating systems, transport engines, engines in factories, steel plants, electricity generators covering the losses in the power grid, etc. By the way, the richest countries in the world, such as Sweden or Switzerland, consume only half the energy per inhabitant as the USA. This waste is one of the reasons for the lower average standard of living in the USA.

**Challenge 202**, page 117: Just throw the brick into the air and compare the dexterity needed to make it turn around various axes.

**Challenge 203**, page 118: Use the definition of the moment of inertia and Pythagoras' theorem for every mass element of the body.

**Challenge 204**, page 119: Hang up the body, attaching the rope at two different points of the body. The crossing point of the prolonged rope lines is the centre of mass.

**Challenge 205**, page 119: See Tables 19 and 20.

**Challenge 206**, page 119: Spheres have an orientation, because we can always add a tiny spot on their surface. This possibility is not given for microscopic objects, and we shall study this situation in the part on quantum theory.

**Challenge 209**, page 120: Yes, the ape can reach the banana. The ape just has to turn around its own axis. For every turn, the plate will rotate a bit towards the banana. Of course, other methods, like blowing at a right angle to the axis, peeing, etc., are also possible.

**Challenge 210**, page 121: Self-propelled linear motion contradicts the conservation of momentum; self-propelled change of orientation (as long as the motion stops again) does not contradict any conservation law. But the deep, underlying reason for the difference will be unveiled in the final part of our adventure.

**Challenge 212**, page 121: The points that move exactly along the radial direction of the wheel form a circle below the axis and above the rim. They are the points that are sharp in [Figure 79](#) of [page 121](#).

**Challenge 213**, page 122: Use the conservation of angular momentum around the point of contact. If all the wheel's mass is assumed in the rim, the final rotation speed is half the initial one; it is independent of the friction coefficient.

**Challenge 215**, page 123: Probably the 'rest of the universe' was meant by the writer. Indeed, a moving part never shifts the centre of gravity of a closed system. But is the universe closed? Or a system? The last part of our adventure addresses these issues.

**Challenge 219**, page 124: Hint: energy and momentum conservation yield two equations; but in the case of three balls there are three variables. What else is needed? See F. HERRMANN & M. SEITZ, *How does the ball-chain work?*, American Journal of Physics 50, pp. 977–981, 1982. The bigger challenge is to build a high precision ball-chain, in which the balls behave as expected, minimizing spurious motion. Nobody seems to have built one yet, as the internet shows. Can you?

**Challenge 220**, page 124: The method allowed Phileas Fogg to win the central bet in the well-known adventure novel by JULES VERNE, *Around the World in Eighty Days*, translated from *Le tour du monde en quatre-vingts jours*, first published in 1872.

**Challenge 221**, page 125: The human body is more energy-efficient at low and medium power output. The topic is still subject of research, as detailed in the cited reference. The critical slope is estimated to be around  $16^\circ$  for uphill walkers, but should differ for downhill walkers.

**Challenge 223**, page 125: Hint: an energy per distance is a force.

**Challenge 224**, page 126: The conservation of angular momentum saves the glass. Try it.

**Challenge 225**, page 126: First of all, MacDougall's experimental data is flawed. In the six cases MacDougall examined, he did not know the exact timing of death. His claim of a mass decrease cannot be deduced from his own data. Modern measurements on dying sheep, about the same mass as humans, have shown no mass change, but clear weight pulses of a few dozen grams when the heart stopped. This temporary weight decrease could be due to the expelling of air or moisture, to the relaxing of muscles, or to the halting of blood circulation. The question is not settled.

**Challenge 227**, page 126: Assuming a square mountain, the height  $h$  above the surrounding crust and the depth  $d$  below are related by

$$\frac{h}{d} = \frac{\rho_m - \rho_c}{\rho_c} \quad (135)$$

where  $\rho_c$  is the density of the crust and  $\rho_m$  is the density of the mantle. For the density values given, the ratio is 6.7, leading to an additional depth of 6.7 km below the mountain.

**Challenge 229**, page 127: The can filled with liquid. Videos on the internet show the experiment. Why is this the case?

**Challenge 232**, page 127: The matter in the universe could rotate – but not the universe itself. Measurements show that within measurement errors there is no mass rotation.

**Challenge 233**, page 128: The behaviour of the spheres can only be explained by noting that elastic waves propagate through the chain of balls. Only the propagation of these elastic waves, in particular their reflection at the end of the chain, explains that the same number of balls that hit on one side are lifted up on the other. For long times, friction makes all spheres oscillate in phase. Can you confirm this?

**Challenge 234**, page 128: When the short cylinder hits the long one, two compression waves start to run from the point of contact through the two cylinders. When each compression wave arrives at the end, it is reflected as an expansion wave. If the geometry is well chosen, the expansion wave coming back from the short cylinder can continue into the long one (which is still in his compression phase). For sufficiently long contact times, waves from the short cylinder can thus depose much of their energy into the long cylinder. Momentum is conserved, as is energy; the long cylinder is oscillating in length when it detaches, so that not all its energy is translational energy. This oscillation is then used to drive nails or drills into stone walls. In commercial hammer drills, length ratios of 1:10 are typically used.

**Challenge 235**, page 128: The momentum transfer to the wall is double when the ball rebounds perfectly.

**Challenge 236**, page 129: If the cork is in its intended position: take the plastic cover off the cork, put the cloth around the bottle or the bottle in the shoe (this is for protection reasons only) and repeatedly hit the bottle on the floor or a fall in an inclined way, as shown in [Figure 72](#) on [page 109](#). With each hit, the cork will come out a bit.

If the cork has fallen inside the bottle: put half the cloth inside the bottle; shake until the cork falls unto the cloth. Pull the cloth out: first slowly, until the cloth almost surrounds the cork, and then strongly.

**Challenge 237**, page 129: Indeed, the lower end of the ladder always touches the floor. Why?

**Challenge 238**, page 129: The atomic force microscope.

**Challenge 240**, page 129: Running man:  $E \approx 0.5 \cdot 80 \text{ kg} \cdot (5 \text{ m/s})^2 = 1 \text{ kJ}$ ; rifle bullet:  $E \approx 0.5 \cdot 0.04 \text{ kg} \cdot (500 \text{ m/s})^2 = 5 \text{ kJ}$ .

**Challenge 241**, page 130: It almost doubles in size.

**Challenge 242**, page 130: At the highest point, the acceleration is  $g \sin \alpha$ , where  $\alpha$  is the angle of the pendulum at the highest point. At the lowest point, the acceleration is  $v^2/l$ , where  $l$  is the length of the pendulum. Conservation of energy implies that  $v^2 = 2gl(1 - \cos \alpha)$ . Thus the problem requires that  $\sin \alpha = 2(1 - \cos \alpha)$ . This results in  $\cos \alpha = 3/5$ .

**Challenge 243**, page 130: One needs the mass change equation  $dm/dt = \pi \rho_{\text{vapour}} r^2 |v|$  due to the mist and the drop speed evolution  $m dv/dt = mg - v dm/dt$ . These two equations yield

$$\frac{dv^2}{dr} = \frac{2g}{C} - 6 \frac{v^2}{r} \quad (136)$$

where  $C = \rho_{\text{vapour}}/4\rho_{\text{water}}$ . The trick is to show that this can be rewritten as

$$r \frac{d}{dr} \frac{v^2}{r} = \frac{2g}{C} - 7 \frac{v^2}{r}. \quad (137)$$

For large times, all physically sensible solutions approach  $v^2/r = 2g/7C$ ; this implies that for large times,

$$\frac{dv}{dt} \frac{v^2}{r} = \frac{g}{7} \quad \text{and} \quad r = \frac{gC}{14} t^2. \quad (138)$$

About this famous problem, see for example, B. F. EDWARDS, J. W. WILDER & E. E. SCIME, *Dynamics of falling raindrops*, European Journal of Physics 22, pp. 113–118, 2001, or A. D. SOKAL, *The falling raindrop, revisited*, preprint at [arxiv.org/abs/0908.0090](https://arxiv.org/abs/0908.0090).

**Challenge 244**, page 130: One is faster, because the moments of inertia differ. Which one?

**Challenge 245**, page 130: There is no simple answer, as aerodynamic drag plays an important role. There are almost no studies on the topic. By the way, competitive rope jumping is challenging; for example, a few people in the world are able to rotate the rope 5 times under their feet during a single jump. Can you do better?

**Challenge 246**, page 130: Weigh the bullet and shoot it against a mass hanging from the ceiling. From the mass and the angle it is deflected to, the momentum of the bullet can be determined.

**Challenge 248**, page 130: The curve described by the midpoint of a ladder sliding down a wall is a circle.

**Challenge 249**, page 131: The switches use the power that is received when the switch is pushed and feeds it to a small transmitter that acts a high frequency remote control to switch on the light.

**Challenge 250**, page 131: A clever arrangement of bimetals is used. They move every time the temperature changes from day to night – and vice versa – and wind up a clock spring. The clock itself is a mechanical clock with low energy consumption.

**Challenge 251**, page 131: The weight of the lift does not change at all when a ship enters it. A twin lift, i.e., a system in which both lifts are mechanically or hydraulically connected, needs no engine at all: it is sufficient to fill the upper lift with a bit of additional water every time a ship enters it. Such ship lifts without engines at all used to exist in the past.

**Challenge 254**, page 133: This is not easy; a combination of friction and torques play a role. See for example the article J. SAUER, E. SCHÖRNER & C. LENNERZ, *Real-time rigid body simulation of some classical mechanical toys*, 10th European Simulation and Symposium and Exhibition (ESS '98) 1998, pp. 93–98, or [www.lennerz.de/paper\\_ess98.pdf](http://www.lennerz.de/paper_ess98.pdf).

Page 166 **Challenge 257**, page 135: See [Figure 123](#) for an example. The pole is not at the zenith.

**Challenge 258**, page 135: Robert Peary had forgotten that on the date he claimed to be at the North Pole, 6th of April 1909, the Sun is very low on the horizon, casting very long shadows, about ten times the height of objects. But on his photograph the shadows are much shorter. (In fact, the picture is taken in such a way to hide all shadows as carefully as possible.) Interestingly, he had even convinced the US congress to officially declare him the first man on the North Pole in 1911. (A rival crook had claimed to have reached it before Peary, but his photograph has the same mistake.) Peary also cheated on the travelled distances of the last few days; he also failed to mention that the last days he was pulled by his partner, Matthew Henson, because he was not able to walk any more. In fact Matthew Henson deserves more credit for that adventure than Peary. Henson, however, did not know that Peary cheated on the position they had reached.

**Challenge 260**, page 136: Laplace and Gauss showed that the eastward deflection  $d$  of a falling object is given by

$$d = 2/3\Omega \cos \varphi \sqrt{2h^3/g} . \quad (139)$$

Here  $\Omega = 72.92 \mu\text{rad/s}$  is the angular velocity of the Earth,  $\varphi$  is the latitude,  $g$  the gravitational acceleration and  $h$  is the height of the fall.

**Challenge 261**, page 139: The Coriolis effect can be seen as the sum two different effects of equal magnitude. The first effect is the following: on a rotating background, velocity changes over time. What an inertial (non-rotating) observer sees as a *constant* velocity will be seen a velocity that *changes* over time by the rotating observer. The acceleration seen by the rotating observer is negative, and is proportional to the angular velocity and to the velocity.

The second effect is change of velocity in space. In a rotating frame of reference, different points have different velocities. The effect is negative, and proportional to the angular velocity and to the velocity.

In total, the Coriolis acceleration (or Coriolis effect) is thus  $\mathbf{a}_C = -2\boldsymbol{\omega} \times \mathbf{v}$ .

**Challenge 262**, page 140: A *short* pendulum of length  $L$  that swings in two dimensions (with amplitude  $\rho$  and orientation  $\varphi$ ) shows two additional terms in the Lagrangian  $\mathcal{L}$ :

$$\mathcal{L} = T - V = \frac{1}{2}m\rho^2 \left( 1 + \frac{\rho^2}{L^2} \right) + \frac{l_z^2}{2m\rho^2} - \frac{1}{2}m\omega_0^2\rho^2 \left( 1 + \frac{\rho^2}{4L^2} \right) \quad (140)$$

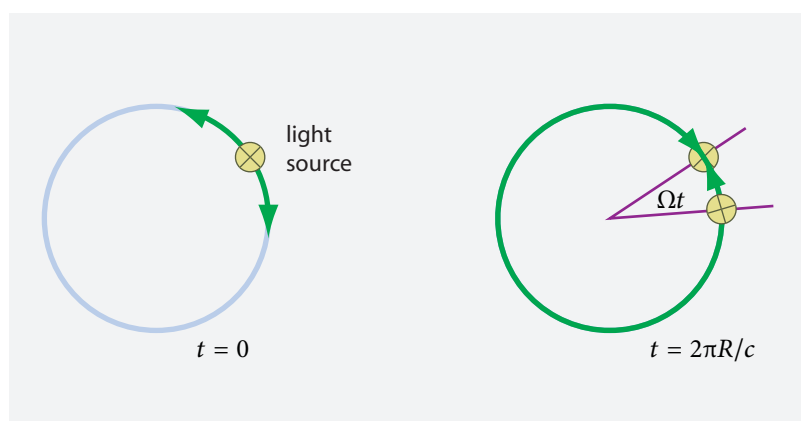
where as usual the basic frequency is  $\omega_0^2 = g/L$  and the angular momentum is  $l_z = m\rho^2\dot{\varphi}$ . The two additional terms disappear when  $L \rightarrow \infty$ ; in that case, if the system oscillates in an ellipse with semiaxes  $a$  and  $b$ , the ellipse is fixed in space, and the frequency is  $\omega_0$ . For *finite* pendulum length  $L$ , the frequency changes to

$$\omega = \omega_0 \left( 1 - \frac{a^2 + b^2}{16L^2} \right) . \quad (141)$$

The ellipse turns with a frequency

$$\Omega = \omega \frac{3}{8} \frac{ab}{L^2} . \quad (142)$$

These formulae can be derived using the least action principle, as shown by C. G. GRAY, G. KARL & V. A. NOVIKOV, *Progress in classical and quantum variational principles*, [arxiv.org/abs/physics/0312071](https://arxiv.org/abs/physics/0312071). In other words, a short pendulum in elliptical motion shows a precession even *without* the Coriolis effect. Since this precession frequency diminishes with  $1/L^2$ , the effect is small for long pendulums, where only the Coriolis effect is left over. To see the Coriolis effect in a short pendulum, one thus has to avoid that it starts swinging in an elliptical orbit by adding a mechanism that suppresses elliptical motion.



**FIGURE 318**  
Deducing the expression for the Sagnac effect.

**Challenge 263**, page 141: The Coriolis acceleration is the reason for the deviation from the straight line. The Coriolis acceleration is due to the change of speed with distance from the rotation axis. Now think about a pendulum, located in Paris, swinging in the North-South direction with amplitude  $A$ . At the Southern end of the swing, the pendulum is further from the axis by  $A \sin \varphi$ , where  $\varphi$  is the latitude. At that end of the swing, the central support point overtakes the pendulum bob with a relative horizontal speed given by  $v = 2\pi A \sin \varphi / 23 \text{ h}56 \text{ min}$ . The period of precession is given by  $T_F = v / 2\pi A$ , where  $2\pi A$  is the circumference  $2\pi A$  of the envelope of the pendulum's path (relative to the Earth). This yields  $T_F = 23 \text{ h}56 \text{ min} / \sin \varphi$ . Why is the value that appears in the formula not 24 h, but 23 h56 min?

**Challenge 264**, page 141: Experiments show that the axis of the gyroscope stays fixed with respect to distant stars. No experiment shows that it stays fixed with respect to absolute space, because this kind of "absolute space" cannot be defined or observed at all. It is a useless concept.

**Challenge 265**, page 141: Rotation leads to a small frequency and thus colour changes of the circulating light.

**Challenge 266**, page 141: The weight changes when going east or when moving west due to the Coriolis acceleration. If the rotation speed is tuned to the oscillation frequency of the balance, the effect is increased by resonance. This trick was also used by Eötvös.

**Challenge 267**, page 141: The Coriolis acceleration makes the bar turn, as every moving body is deflected to the side, and the two deflections add up in this case. The direction of the deflection depends on whether the experiment is performed on the northern or the southern hemisphere.

**Challenge 268**, page 141: When rotated by  $\pi$  around an east-west axis, the Coriolis force produces a drift velocity of the liquid around the tube. It has the value

$$v = 2\omega r \sin \theta, \quad (143)$$

as long as friction is negligible. Here  $\omega$  is the angular velocity of the Earth,  $\theta$  the latitude and  $r$  the (larger) radius of the torus. For a tube with 1 m diameter in continental Europe, this gives a speed of about  $6.3 \cdot 10^{-5} \text{ m/s}$ .

The measurement can be made easier if the tube is restricted in diameter at one spot, so that the velocity is increased there. A restriction by an area factor of 100 increases the speed by the same factor. When the experiment is performed, one has to carefully avoid any other effects that lead to moving water, such as temperature gradients across the system.

**Challenge 269**, page 142: Imagine a circular light path (for example, inside a circular glass fibre) and two beams moving in opposite directions along it, as shown in Figure 318. If the fibre path

rotates with rotation frequency  $\Omega$ , we can deduce that, after one turn, the difference  $\Delta L$  in path length is

$$\Delta L = 2R\Omega t = \frac{4\pi R^2 \Omega}{c}. \quad (144)$$

The phase difference is thus

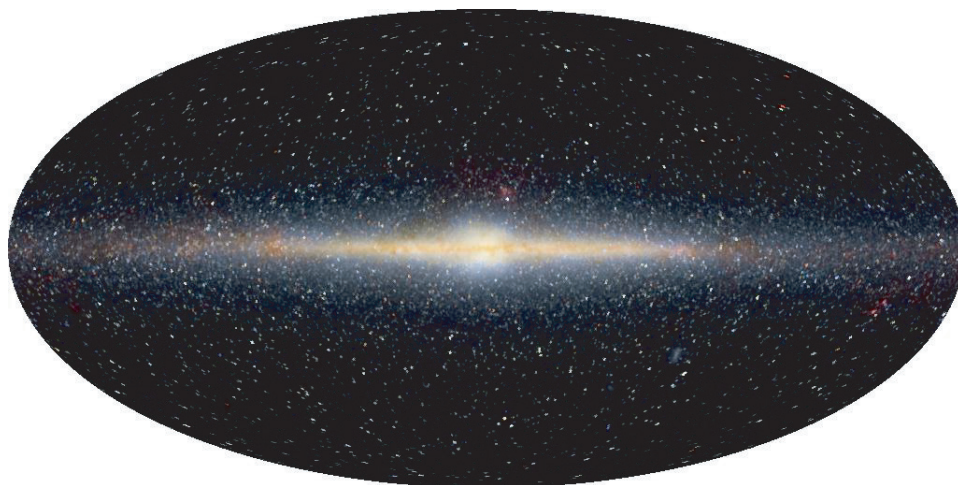
$$\Delta\varphi = \frac{8\pi^2 R^2}{c\lambda} \Omega \quad (145)$$

if the refractive index is 1. This is the required formula for the main case of the Sagnac effect.

It is regularly suggested that the Sagnac effect can only be understood with help of general relativity; this is wrong. As just done, the effect is easily deduced from the invariance of the speed of light  $c$ . The effect is a consequence of special relativity.

**Challenge 270**, page 145: The metal rod is slightly longer on one side of the axis. When the wire keeping it up is burned with a candle, its moment of inertia decreases by a factor of  $10^4$ ; thus it starts to rotate with (ideally)  $10^4$  times the rotation rate of the Earth, a rate which is easily visible by shining a light beam on the mirror and observing how its reflection moves on the wall.

**Challenge 272**, page 152: The original result by Bessel was  $0.3136''$ , or 657.7 thousand orbital radii, which he thought to be 10.3 light years or 97.5 Pm.



**FIGURE 319** How the night sky, and our galaxy in particular, looks in the near-infrared (NASA false colour image).

**Challenge 274**, page 155: The galaxy forms a stripe in the sky. The galaxy is thus a flattened structure. This is even clearer in the infrared, as shown more clearly in **Figure 319**. From the flattening (and its circular symmetry) we can deduce that the galaxy must be rotating. Thus other matter must exist in the universe.

**Challenge 276**, page 158: See [page 189](#).

**Challenge 278**, page 158: The scale reacts to your heartbeat. The weight is almost constant over time, except when the heart beats: for a short duration of time, the weight is somewhat lowered at each beat. Apparently it is due to the blood hitting the aortic arch when the heart pumps it upwards. The speed of the blood is about 0.3 m/s at the maximum contraction of the left ventricle. The distance to the aortic arch is a few centimetres. The time between the contraction and the reversal of direction is about 15 ms. And the measured weight is not even constant for a dead person, as air currents disturb the measurement.

**Challenge 279**, page 158: Use Figure 97 on page 138 for the second half of the trajectory, and think carefully about the first half. The body falls down slightly to the west of the starting point.

**Challenge 280**, page 158: Hint: starting rockets at the Equator saves a lot of energy, thus of fuel and of weight.

**Challenge 283**, page 161: The flame leans towards the inside.

**Challenge 284**, page 161: Yes. There is no absolute position and no absolute direction. Equivalently, there is no preferred position, and no preferred direction. For time, only the big bang seems to provide an exception, at first; but when quantum effects are included, the lack of a preferred time scale is confirmed.

**Challenge 285**, page 161: For your exam it is better to say that centrifugal force does not exist. But since in each stationary system there is a force balance, the discussion is somewhat a red herring.

**Challenge 288**, page 162: Place the tea in cups on a board and attach the board to four long ropes that you keep in your hand.

**Challenge 289**, page 162: The ball leans in the direction it is accelerated to. As a result, one could imagine that the ball in a glass at rest pulls upwards because the floor is accelerated upwards. We will come back to this issue in the section of general relativity.

**Challenge 290**, page 162: The friction of the tides on Earth are the main cause.

**Challenge 291**, page 163: An earthquake with Richter magnitude of 12 is 1000 times the energy of the 1960 Chile quake with magnitude 10; the latter was due to a crack throughout the full 40 km of the Earth's crust along a length of 1000 km in which both sides slipped by 10 m with respect to each other. Only the impact of a large asteroid could lead to larger values than 12.

**Challenge 293**, page 163: Yes; it happens twice a year. To minimize the damage, dishes should be dark in colour.

**Challenge 294**, page 163: A rocket fired from the back would be a perfect defence against planes attacking from behind. However, when released, the rocket is effectively flying backwards with respect to the air, thus turns around and then becomes a danger to the plane that launched it. Engineers who did not think about this effect almost killed a pilot during the first such tests.

**Challenge 295**, page 163: Whatever the ape does, whether it climbs up or down or even lets himself fall, it remains at the same height as the mass. Now, what happens if there is friction at the wheel?

**Challenge 296**, page 163: Yes, if he moves at a large enough angle to the direction of the boat's motion.

**Challenge 297**, page 163: See the article by C. UCKE & H. -J. SCHLICHTING, *Faszinierendes Dynabee*, Physik in unserer Zeit 33, pp. 230–231, 2002.

**Challenge 298**, page 164: See the article by C. UCKE & H. -J. SCHLICHTING, *Die kreisende Büroklammer*, Physik in unserer Zeit 36, pp. 33–35, 2005.

**Challenge 299**, page 164: If a wedding ring rotates on an axis that is not a principal one, angular momentum and velocity are not parallel.

**Challenge 300**, page 164: The moment of inertia for a homogeneous sphere is  $\Theta = \frac{2}{5}mr^2$ .

**Challenge 301**, page 164: The three moments of inertia for the cube are equal, as in the case of the sphere, but the values are  $\Theta = \frac{1}{6}ml^2$ . The efforts required to put a sphere and a cube into rotation are thus different.

**Challenge 304**, page 165: Yes, the moon differs in this way. Can you imagine what happens for an observer on the Equator?

**Challenge 305**, page 167: A straight line at the zenith, and circles getting smaller at both sides. See an example on the website [apod.nasa.gov/apod/ap021115.html](http://apod.nasa.gov/apod/ap021115.html).

**Challenge 307**, page 167: The plane is described in the websites cited; for a standing human the plane is the vertical plane containing the two eyes.

**Challenge 308**, page 168: If you managed, please send the author the video!

**Challenge 309**, page 169: As said before, legs are simpler than wheels to grow, to maintain and to repair; in addition, legs do not require flat surfaces (so-called ‘streets’) to work.

**Challenge 310**, page 170: The staircase formula is an empirical result found by experiment, used by engineers world-wide. Its origin and explanation seems to be lost in history.

**Challenge 311**, page 170: Classical or everyday nature is right-left symmetric and thus requires an even number of legs. Walking on two-dimensional surfaces naturally leads to a minimum of four legs. Starfish, snails, slugs, clams, eels and snakes are among the most important exceptions for which the arguments are not valid.

**Challenge 313**, page 173: The length of the day changes with latitude. So does the length of a shadow or the elevation of stars at night, facts that are easily checked by telephoning a friend. Ships appear at the horizon by showing their masts first. These arguments, together with the round shadow of the earth during a lunar eclipse and the observation that everything falls downwards everywhere, were all given already by Aristotle, in his text *On the Heavens*. It is now known that everybody in the last 2500 years knew that the Earth is a sphere. The myth that many people used to believe in a flat Earth was put into the world – as rhetorical polemic – by Copernicus. The story then continued to be exaggerated more and more during the following centuries, because a new device for spreading lies had just been invented: book printing. Fact is that for 2500 years the vast majority of people knew that the Earth is a sphere.

**Challenge 314**, page 177: The vector  $SF$  can be calculated by using  $SC = -(GmM/E) SP/SP$  and then translating the construction given in the figure into formulae. This exercise yields

$$SF = \frac{K}{mE} \quad (146)$$

where

$$K = \mathbf{p} \times \mathbf{L} - GMm^2 \mathbf{x}/x \quad (147)$$

is the so-called *Runge–Lenz vector*. The Runge–Lenz vector is directed along the line that connects the second focus to the first focus of the ellipse (the Sun). We have used  $\mathbf{x} = SP$  for the position of the orbiting body,  $\mathbf{p}$  for its momentum and  $\mathbf{L}$  for its angular momentum. The Runge–Lenz vector  $K$  is *constant* along the orbit of a body, thus has the *same* value for any position  $\mathbf{x}$  on the orbit. (Prove it by starting from  $\mathbf{x}K = xK \cos \theta$ .) The Runge–Lenz vector is thus a *conserved* quantity in universal gravity. As a result, the vector  $SF$  is also constant in time.

The Runge–Lenz vector is also often used in quantum mechanics, when calculating the energy levels of a hydrogen atom, as it appears in all problems with a  $1/r$  potential. (In fact, the incorrect name ‘Runge–Lenz vector’ is due to Wolfgang Pauli; the discoverer of the vector was, in 1710, Jakob Hermann.)

**Challenge 316**, page 178: On orbits, see [page 192](#).

**Challenge 317**, page 178: The low gravitational acceleration of the Moon,  $1.6 \text{ m/s}^2$ , implies that gas molecules at usual temperatures can escape its attraction.

**Challenge 318**, page 179: The tip of the velocity arrow, when drawn over time, produces a circle around the centre of motion.

**Challenge 319**, page 179: Draw a figure of the situation.

**Challenge 320**, page 179: Again, draw a figure of the situation.

**Challenge 321**, page 180: The value of the product  $GM$  for the Earth is  $4.0 \cdot 10^{14} \text{ m}^3/\text{s}^2$ .

**Challenge 322**, page 180: All points can be reached for general inclinations; but when shooting horizontally in one given direction, only points on the first half of the circumference can be reached.

**Challenge 323**, page 182: On the moon, the gravitational acceleration is  $1.6 \text{ m/s}^2$ , about one sixth of the value on Earth. The surface values for the gravitational acceleration for the planets can be found on many internet sites.

**Challenge 324**, page 182: The Atwood machine is the answer: two almost equal masses  $m_1$  and  $m_2$  connected by a string hanging from a well-oiled wheel of negligible mass. The heavier one falls very slowly. Can show that the acceleration  $a$  of this ‘unfree’ fall is given by  $a = g(m_1 - m_2)/(m_1 + m_2)$ ? In other words, the smaller the mass difference is, the slower the fall is.

**Challenge 325**, page 183: You should absolutely try to understand the origin of this expression. It allows understanding many important concepts of mechanics. The idea is that for small amplitudes, the acceleration of a pendulum of length  $l$  is due to gravity. Drawing a force diagram for a pendulum at a general angle  $\alpha$  shows that

$$\begin{aligned} ma &= -mg \sin \alpha \\ ml \frac{d^2\alpha}{dt^2} &= -mg \sin \alpha \\ l \frac{d^2\alpha}{dt^2} &= -g \sin \alpha . \end{aligned} \quad (148)$$

For the mentioned small amplitudes (below  $15^\circ$ ) we can approximate this to

$$l \frac{d^2\alpha}{dt^2} = -g\alpha . \quad (149)$$

This is the equation for a harmonic oscillation (i.e., a sinusoidal oscillation). The resulting motion is:

$$\alpha(t) = A \sin(\omega t + \varphi) . \quad (150)$$

The amplitude  $A$  and the phase  $\varphi$  depend on the initial conditions; however, the oscillation frequency is given by the length of the pendulum and the acceleration of gravity (check it!):

$$\omega = \sqrt{\frac{l}{g}} . \quad (151)$$

(For arbitrary amplitudes, the formula is much more complex; see the internet or special mechanics books for more details.)

**Challenge 326**, page 183: Walking speed is proportional to  $l/T$ , which makes it proportional to  $l^{1/2}$ . The relation is also true for animals in general. Indeed, measurements show that the maximum walking speed (thus not the running speed) across all animals is given by

$$v_{\text{maxwalking}} = (2.2 \pm 0.2) \text{ m}^{1/2}/\text{s} \sqrt{l} . \quad (152)$$

**Challenge 330**, page 186: There is no obvious candidate formula. Can you find one?

**Challenge 331**, page 186: The acceleration due to gravity is  $a = Gm/r^2 \approx 5 \text{ nm/s}^2$  for a mass of 75 kg. For a fly with mass  $m_{\text{fly}} = 0.1 \text{ g}$  landing on a person with a speed of  $v_{\text{fly}} = 1 \text{ cm/s}$

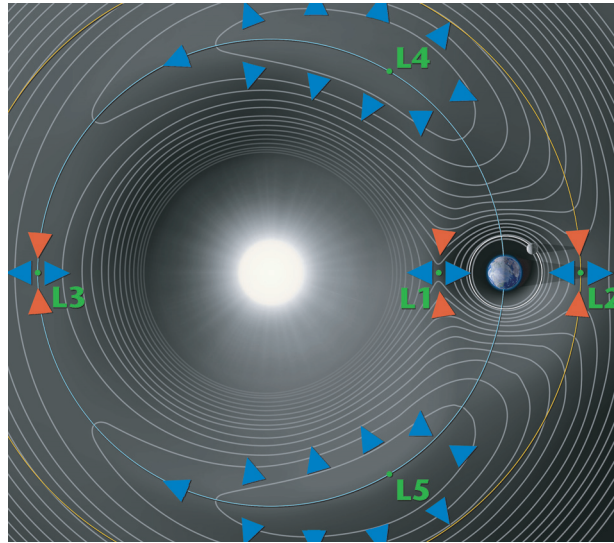


FIGURE 320 The Lagrangian points and the effective potential that produces them (NASA).

and deforming the skin (without energy loss) by  $d = 0.3$  mm, a person would be accelerated by  $a = (v^2/d)(m_{\text{ny}}/m) = 0.4 \mu\text{m/s}^2$ . The energy loss of the inelastic collision reduces this value at least by a factor of ten.

**Challenge 332**, page 187: The calculation shows that a surprisingly high energy value is stored in thermal motion.

**Challenge 333**, page 188: Yes, the effect has been measured for skyscrapers. Can you estimate the values?

**Challenge 336**, page 188: The easiest way to see this is to picture gravity as a flux emanating from a sphere. This gives a  $1/r^{d-1}$  dependence for the force and thus a  $1/r^{d-2}$  dependence of the potential.

**Challenge 338**, page 190: Since the paths of free fall are ellipses, which are curves lying in a plane, this is obvious.

**Challenge 340**, page 191: A flash of light is sent to the Moon, where several Cat's-eyes have been deposited by the Lunokhod and Apollo missions. The measurement precision of the time a flash take to go and come back is sufficient to measure the Moon's distance change. For more details, see challenge 8.

**Challenge 342**, page 193: A body having zero momentum at spatial infinity is on a parabolic path. A body with a lower momentum is on an elliptic path and one with a higher momentum is on a hyperbolic path.

**Challenge 345**, page 194: The Lagrangian points L4 and L5 are on the orbit,  $60^\circ$  before and behind the orbiting body. They are stable if the mass ratio of the central and the orbiting body is sufficiently large (above 24.9).

**Challenge 346**, page 194: The Lagrangian point L3 is located on the orbit, but precisely on the other side of the central body. The Lagrangian point L1 is located on the line connecting the planet with the central body, whereas L2 lies outside the orbit, on the same line. If  $R$  is the radius of the orbit, the distance between the orbiting body and the L1 and L2 point is  $\sqrt[3]{m/3M} R$ , giving around 4 times the distance of the Moon for the Sun-Earth system. L1, L2 and L3 are saddle points, but effectively stable orbits exist around them. Many satellites make use of these properties, including



**FIGURE 321** The famous ‘vomit comet’, a KC-135, performing a parabolic flight (NASA).

the famous WMAP satellite that measured the ripples of the big bang, which is located at the ‘quiet’ point L2, where the Sun, the Earth and the Moon are easily shielded and satellite temperature remains constant.

**Challenge 347**, page 197: This is a resonance effect, in the same way that a small vibration of a string can lead to large oscillation of the air and sound box in a guitar.

**Challenge 349**, page 199: The expression for the strength of tides, namely  $2GM/d^3$ , can be rewritten as  $(8/3)\pi G\rho(R/d)^3$ . Now,  $R/d$  is roughly the same for Sun and Moon, as every eclipse shows. So the density  $\rho$  must be much larger for the Moon. In fact, the ratio of the strengths (height) of the tides of Moon and Sun is roughly 7 : 3. This is also the ratio between the mass densities of the two bodies.

**Challenge 350**, page 200: The total angular momentum of the Earth and the Moon must remain constant.

**Challenge 352**, page 201: Wait for a solar eclipse.

**Challenge 354**, page 203: Unfortunately, the myth of ‘passive gravitational mass’ is spread by many books. Careful investigation shows that it is measured in exactly the same way as inertial mass.

Both masses are measured with the same machines and set-ups. And all these experiments mix and require both inertial and passive gravitational mass effects. For example, a balance or bathroom scale has to dampen out any oscillation, which requires inertial mass. Generally speaking, it seems impossible to distinguish inertial mass from the passive gravitational mass due to all the masses in the rest of the universe. In short, the two concepts are in fact identical.

**Challenge 356**, page 203: These problems occur because gravitational mass determines potential energy and inertial mass determines kinetic energy.

**Challenge 358**, page 205: Either they fell on inclined snowy mountain sides, or they fell into high trees, or other soft structures. The record was over 7 km of survived free fall. A recent case made the news in 2007 and is told in [www.bbc.co.uk/jersey/content/articles/2006/12/20/michael\\_holmes\\_fall\\_feature.shtml](http://www.bbc.co.uk/jersey/content/articles/2006/12/20/michael_holmes_fall_feature.shtml).

**Challenge 360**, page 207: For a few thousand Euros, you can experience zero-gravity in a parabolic flight, such as the one shown in [Figure 321](#). (Many ‘photographs’ of parabolic flights found on the internet are in fact computer graphics. What about this one?)

How does zero-gravity *feel*? It feels similar to floating underwater, but without the resistance of the water. It also feels like the time in the air when one is diving into the water. However, for cosmonauts, there is an additional feeling; when they rotate their head rapidly, the sensors for orientation in our ear are not reset by gravity. Therefore, for the first day or two, most cosmonauts have feelings of vertigo and of nausea, the so-called *space sickness*. After that time, the body adapts and the cosmonaut can enjoy the situation thoroughly.

**Challenge 361**, page 207: The centre of mass of a broom falls with the usual acceleration; the end thus falls faster.

**Challenge 362**, page 207: Just use energy conservation for the two masses of the jumper and the string. For more details, including the comparison of experimental measurements and theory, see N. DUBELAAR & R. BRANTJES, *De valversnelling bij bungee-jumping*, Nederlands tijdschrift voor natuurkunde 69, pp. 316–318, October 2003.

**Challenge 363**, page 207: About 1 ton.

**Challenge 364**, page 207: About 5 g.

**Challenge 365**, page 208: Your weight is roughly constant; thus the Earth must be round. On a flat Earth, the weight would change from place to place, depending on your distance from the border.

**Challenge 366**, page 208: Nobody ever claimed that the centre of mass is the same as the centre of gravity! The attraction of the Moon is negligible on the surface of the Earth.

**Challenge 368**, page 209: That is the mass of the Earth. Just turn the table on its head.

**Challenge 370**, page 209: The Moon will be about 1.25 times as far as it is now. The Sun then will slow down the Earth–Moon system rotation, this time due to the much smaller tidal friction from the Sun’s deformation. As a result, the Moon will return to smaller and smaller distances to Earth. However, the Sun will have become a red giant by then, after having swallowed both the Earth and the Moon.

**Challenge 372**, page 210: As Galileo determined, for a swing (half a period) the ratio is  $\sqrt{2}/\pi$ . (See challenge 325). But not more than two, maybe three decimals of  $\pi$  can be determined in this way.

**Challenge 373**, page 210: Momentum conservation is not a hindrance, as any tennis racket has the same effect on the tennis ball.

**Challenge 374**, page 210: In fact, in velocity space, elliptic, parabolic and hyperbolic motions are all described by circles. In all cases, the hodograph is a circle.

Ref. 163

**Challenge 375**, page 211: This question is old (it was already asked in Newton’s times) and deep. One reason is that stars are kept apart by rotation around the galaxy. The other is that galaxies are kept apart by the momentum they got in the big bang. Without the big bang, all stars would have collapsed together. In this sense, the big bang can be deduced from the attraction of gravitation and the immobile sky at night. We shall find out later that the darkness of the night sky gives a second argument for the big bang.

**Challenge 376**, page 211: The choice is clear once you notice that there is no section of the orbit which is concave towards the Sun. Can you show this?

**Challenge 378**, page 212: The escape velocity, from Earth, to leave the Solar System – without help of the other planets – is 42 km/s. However, if help by the other planets is allowed, it can be less than half that value (why?).

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If the escape velocity from a body were the speed of light, the body would be a black hole; not even light could escape. Black holes are discussed in detail in the volume on relativity.

**Challenge 379**, page 212: Using a maximal jumping height of  $h = 0.5$  m on Earth and an estimated asteroid density of  $\rho = 3 \text{ Mg/m}^3$ , we get a maximum radius of  $R^2 = 3gh/4\pi G\rho$ , or  $R \approx 2.4$  km.



**FIGURE 322** The analemma photographed, at local noon, from January to December 2002, at the Parthenon on Athens' Acropolis, and a precision sundial (© Anthony Ayiomamitis, Stefan Pietrzik).

**Challenge 380**, page 212: A handle of two bodies.

**Challenge 382**, page 212: In what does this argument differ from the more common argument that in the expression  $ma = gMm/R^2$ , the left  $m$  is inertial and the right  $m$  is gravitational?

**Challenge 384**, page 212: What counts is *local* verticality; with respect to it, the river always flows downhill.

**Challenge 385**, page 213: The shape of an analemma at local noon is shown in [Figure 322](#). The shape is known since over 2000 years! The shape of the analemma also illustrates why the earliest sunrise is not at the longest day of the year.

The vertical extension of the analemma in the figure is due to the obliquity, i.e., the tilt of the Earth's axis (it is twice  $23.45^\circ$ ). The horizontal extension is due to the combination of the obliquity and of the ellipticity of the orbit around the Sun. Both effects lead to roughly equal changes of the position of the Sun at local noon during the course of the year. The asymmetrical position of the central crossing point is purely due to the ellipticity of the orbit. The shape of the analemma, sometimes shown on globes, is built into the shadow pole or the reading curve of precision sundials. Examples are the one shown above and the one shown on [page 45](#). For more details, see B. M. OLIVER, *The shape of the analemma*, *Sky & Telescope* 44, pp. 20–22, 1972, and the correction of the figures at 44, p. 303, 1972,

**Challenge 386**, page 215: Capture of a fluid body is possible if it is split by tidal forces.

**Challenge 387**, page 216: The tunnel would be an elongated ellipse in the plane of the Equator, reaching from one point of the Equator to the point at the antipodes. The time of revolution would not change, compared to a non-rotating Earth. See A. J. SIMONSON, *Falling down a hole through the Earth*, *Mathematics Magazine* 77, pp. 171–188, June 2004.

**Challenge 389**, page 216: The centre of mass of the Solar System can be as far as twice the radius from the centre of the Sun; it thus can be outside the Sun.

**Challenge 390**, page 216: First, during northern summer time the Earth moves faster around the Sun than during northern winter time. Second, shallow Sun's orbits on the sky give longer days because of light from when the Sun is below the horizon.

**Challenge 391**, page 216: Apart from the visibility of the Moon, no effect of the Moon on humans has ever been detected. Gravitational effects – including tidal effects – electrical effects, magnetic effects and changes in cosmic rays are all swamped by other effects. Indeed the gravity of passing trucks, factory electromagnetic fields, the weather and solar activity changes have larger influences on humans than the Moon. The locking of the menstrual cycle to the moon phase is a visual effect.

**Challenge 392**, page 216: Distances were difficult to measure. It is easy to observe a planet that is before the Sun, but it is hard to check whether a planet is behind the Sun. Phases of Venus are also predicted by the geocentric system; but the phases it predicts do not match the ones that are observed. Only the phases deduced from the heliocentric system match the observed ones. Venus orbits the Sun.

**Challenge 393**, page 216: See the mentioned reference.

**Challenge 394**, page 217: True.

**Challenge 395**, page 217: For each pair of opposite shell elements (drawn in yellow), the two attractions compensate.

**Challenge 396**, page 218: There is no practical way; if the masses on the shell could move, along the surface (in the same way that charges can move in a metal) this might be possible, provided that enough mass is available.

**Challenge 400**, page 219: Yes, one could, and this has been thought of many times, including by Jules Verne. The necessary speed depends on the direction of the shot with respect of the rotation of the Earth.

**Challenge 401**, page 219: Never. The Moon points always towards the Earth. The Earth changes position a bit, due to the ellipticity of the Moon's orbit. Obviously, the Earth shows phases.

**Challenge 403**, page 219: There are no such bodies, as the chapter of general relativity will show.

**Challenge 405**, page 221: The oscillation is a purely sinusoidal, or harmonic oscillation, as the restoring force increases linearly with distance from the centre of the Earth. The period  $T$  for a homogeneous Earth is  $T = 2\pi\sqrt{R^3/GM} = 84$  min.

**Challenge 406**, page 223: The period is the same for all such tunnels and thus in particular it is the same as the 84 min period that is valid also for the pole to pole tunnel. See for example, R. H. ROMER, *The answer is forty-two – many mechanics problems, only one answer*, Physics Teacher 41, pp. 286–290, May 2003.

**Challenge 407**, page 223: If the Earth were *not* rotating, the most general path of a falling stone would be an ellipse whose centre is the centre of the Earth. For a rotating Earth, the ellipse precesses. Simoson speculates that the spirographics swirls in the Spirograph Nebula, found at [antwrp.gsfc.nasa.gov/apod/ap021214.html](http://antwrp.gsfc.nasa.gov/apod/ap021214.html), might be due to such an effect. A special case is a path starting vertically at the equator; in this case, the path is similar to the path of the Foucault pendulum, a pointed star with about 16 points at which the stone resurfaces around the Equator.

Ref. 178

**Challenge 408**, page 223: There is no simple answer: the speed depends on the latitude and on other parameters. The internet also provides videos of solar eclipses seen from space, showing how the shadow moves over the surface of the Earth.

**Challenge 409**, page 224: The centrifugal force must be equal to the gravitational force. Call the constant linear mass density  $d$  and the unknown length  $l$ . Then we have  $GMd \int_R^{R+l} dr/r^2 = \omega^2 d \int_R^{R+l} r dr$ . This gives  $GMd l / (R^2 + Rl) = (2Rl + l^2)\omega^2 d / 2$ , yielding  $l = 0.14$  Gm. For more on space elevators or lifts, see challenge 574.

**Challenge 411**, page 224: The inner rings must rotate faster than the outer rings. If the rings were solid, they would be torn apart. But this reasoning is true only if the rings are inside a certain limit, the so-called *Roche limit*. The Roche limit is that radius at which gravitational force  $F_g$  and tidal force  $F_t$  cancel on the surface of the satellite. For a satellite with mass  $m$  and radius  $r$ , orbiting a central mass  $M$  at distance  $d$ , we look at the forces on a small mass  $\mu$  on its surface. We get the condition  $Gm\mu/r^2 = 2GM\mu r/d^3$ . A bit of algebra yields the approximate Roche limit value

$$d_{\text{Roche}} = R \left( 2 \frac{\rho_M}{\rho_m} \right)^{1/3}. \quad (153)$$

Below that distance from a central mass  $M$ , fluid satellites cannot exist. The calculation shown here is only an approximation; the actual Roche limit is about two times that value.

**Challenge 414**, page 228: The load is 5 times the load while standing. This explains why race horses regularly break their legs.

**Challenge 415**, page 228: At school, you are expected to answer that the weight is the same. This is a good approximation. But in fact the scale shows a slightly larger weight for the steadily running hourglass compared to the situation where the all the sand is at rest. Looking at the momentum flow explains the result in a simple way: the only issue that counts is the momentum of the sand in the upper chamber, all other effects being unimportant. That momentum slowly decreases during running. This requires a momentum flow from the scale: the effective weight increases. See also the experimental confirmation and its explanation by F. TUINSTRAS & B. F. TUINSTRAS, *The weight of an hourglass*, Europhysics News 41, pp. 25–28, March 2010, also available online.

Ref. 87

If we imagine a photon bouncing up and down in a box made of perfect mirrors, the ideas from the hourglass puzzle imply that the scale shows an increased weight compared to the situation without a photon. The weight increase is  $Eg/c^2$ , where  $E$  is the energy of the photon,  $g = 9.81 \text{ m/s}^2$  and  $c$  is the speed of light. This story is told by E. HUGGINS, *Weighing photons using bathroom scales: a thought experiment*, The Physics Teacher 48, pp. 287–288, May 2010,

**Challenge 416**, page 229: The electricity consumption of a rising escalator indeed increases when the person on it walks upwards. By how much?

**Challenge 417**, page 229: Knowledge is power. Time is money. Now, power is defined as work per time. Inserting the previous equations and transforming them yields

$$\text{money} = \frac{\text{work}}{\text{knowledge}}, \quad (154)$$

which shows that the less you know, the more money you make. That is why scientists have low salaries.

**Challenge 418**, page 229: In reality muscles keep an object above ground by continuously lifting and dropping it; that requires energy and work.

**Challenge 421**, page 234: Yes, because side wind increases the effective speed  $v$  in air due to vector addition, and because air resistance is (roughly) proportional to  $v^2$ .

**Challenge 422**, page 234: The lack of static friction would avoid that the fluid stays attached to the body; the so-called boundary layer would not exist. One then would have no wing effect.

**Challenge 424**, page 235: True?

**Challenge 426**, page 236: From  $dv/dt = g - v^2(1/2c_w A \rho/m)$  and using the abbreviation  $c = 1/2c_w A \rho$ , we can solve for  $v(t)$  by putting all terms containing the variable  $v$  on one side, all terms with  $t$  on the other, and integrating on both sides. We get  $v(t) = \sqrt{gm/c} \tanh \sqrt{cg/m} t$ .

**Challenge 427**, page 237: For extended deformable bodies, the intrinsic properties are given by the mass density – thus a function of space and time – and the state is described by the density of kinetic energy, local linear and angular momentum, as well as by its stress and strain distributions.

**Challenge 428**, page 237: Electric charge.

**Challenge 429**, page 238: The phase space has  $3N$  position coordinates and  $3N$  momentum coordinates.

**Challenge 430**, page 238: We recall that when a stone is thrown, the initial conditions summarize the effects of the thrower, his history, the way he got there etc.; in other words, initial conditions summarize the past of a system, i.e., the effects that the environment had during the

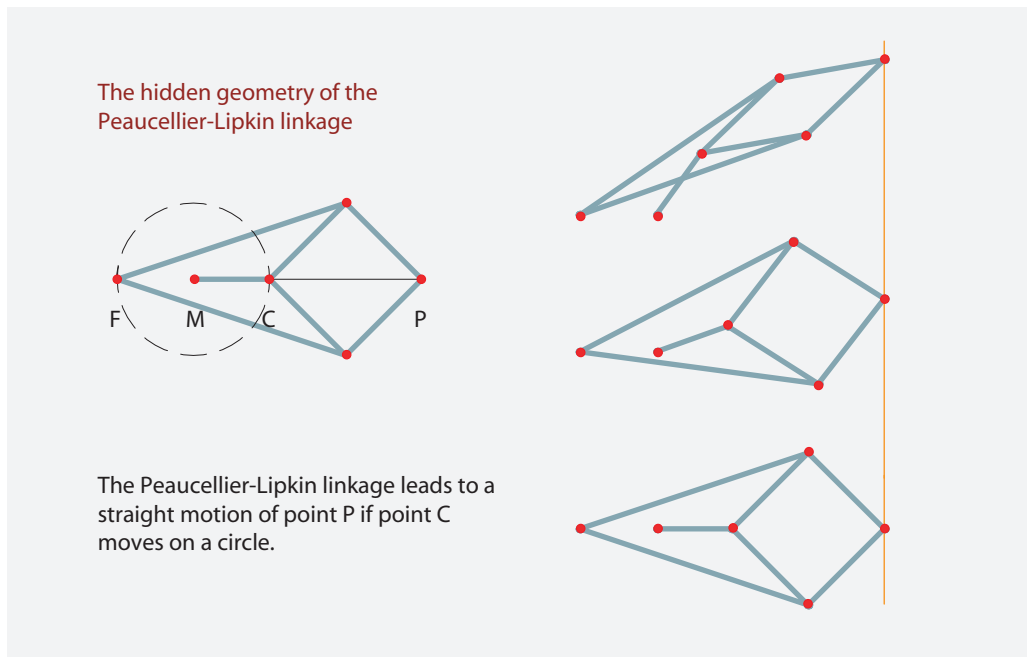


FIGURE 323 How to draw a straight line with a compass (drawn by Zach Joseph Espiritu).

history of a system. Therefore, the universe has no initial conditions and no phase space. If you have found reasons to answer yes, you overlooked something. Just go into more detail and check whether the concepts you used apply to the universe. Also define carefully what you mean by 'universe'.

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**Challenge 431**, page 238: The light mill is an example.

**Challenge 433**, page 240: A system showing energy or matter motion faster than light would imply that for such systems there are observers for which the order between cause and effect are reversed. A space-time diagram (and a bit of exercise from the section on special relativity) shows this.

**Challenge 434**, page 240: If reproducibility would not exist, we would have difficulties in checking observations; also reading the clock is an observation. The connection between reproducibility and time shall become important in the final part of our adventure.

**Challenge 435**, page 241: Even if surprises were only rare, each surprise would make it impossible to define time just before and just after it.

**Challenge 438**, page 242: Of course; moral laws are summaries of what others think or will do about personal actions.

**Challenge 439**, page 243: The fastest glide path between two points, the *brachistochrone*, turns out to be the *cycloid*, the curve generated by a point on a wheel that is rolling along a horizontal plane.

The proof can be found in many ways. The simplest is by Johann Bernoulli and is given on [en.wikipedia.org/wiki/Brachistochrone\\_problem](https://en.wikipedia.org/wiki/Brachistochrone_problem).

**Challenge 441**, page 244: When F, C and P are aligned, this circle has a radius given by  $R = \sqrt{FC \cdot FP}$ ; F is its centre. In other words, the Peaucellier-Lipkin linkage realizes an inversion at a circle.

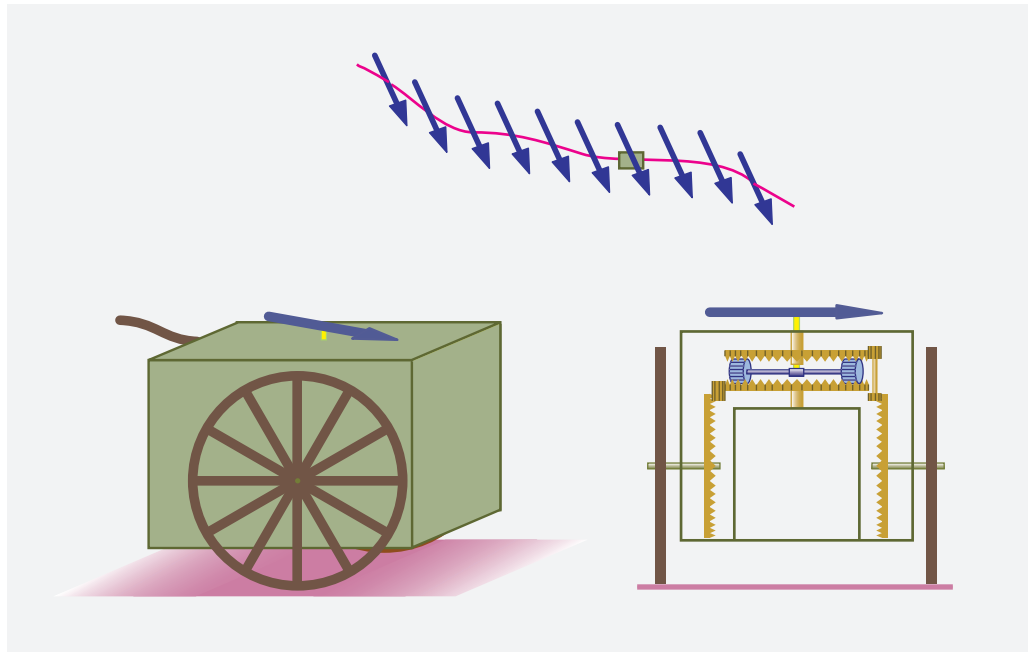


FIGURE 324 The mechanism inside the south-pointing carriage.



FIGURE 325 Falling brick chimneys – thus with limited stiffness – fall with a V shape (© John Glaser, Frank Siebner).

**Challenge 442**, page 244: When F, C and P are aligned, the circle to be followed has a radius given by half the distance FC; its centre lies midway between F and C. Figure 323 illustrates the situation.

**Challenge 443**, page 244: Figure 324 shows the most credible reconstruction of a south-pointing carriage.

**Challenge 445**, page 245: The water is drawn up along the sides of the spinning egg. The fastest way to empty a bottle of water is to spin the water while emptying it.

**Challenge 446**, page 246: The right way is the one where the chimney falls like a V, not like an inverted V. See challenge 361 on falling brooms for inspiration on how to deduce the answer.

Two examples are shown in [Figure 325](#). It turns out that the chimney breaks (if it is not fastened to the base) at a height between half or two thirds of the total, depending at the angle at which this happens. For a complete solution of the problem, see the excellent paper G. VARESCHI & K. KAMIYA, *Toy models for the falling chimney*, American Journal of Physics 71, pp. 1025–1031, 2003.

**Challenge 448**, page 252: The definition of the integral given in the text is a simplified version of the so-called *Riemann integral*. It is sufficient for all uses in nature. Have a look at its exact definition in a mathematics text if you want more details.

**Challenge 454**, page 255: In one dimension, the expression  $F = ma$  can be written as  $-dV/dx = md^2x/dt^2$ . This can be rewritten as  $d(-V)/dx - d/dt[d/dx(\frac{1}{2}m\dot{x}^2)] = 0$ . This can be expanded to  $\partial/\partial x(\frac{1}{2}m\dot{x}^2 - V(x)) - d/dt[\partial/\partial \dot{x}(\frac{1}{2}m\dot{x}^2 - V(x))] = 0$ , which is Lagrange's equation for this case.

**Challenge 456**, page 256: Do not despair. Up to now, nobody has been able to imagine a universe (that is not necessarily the same as a 'world') different from the one we know. So far, such attempts have always led to logical inconsistencies.

**Challenge 458**, page 256: The two are equivalent since the equations of motion follow from the principle of minimum action and at the same time the principle of minimum action follows from the equations of motion.

**Challenge 460**, page 258: For gravity, all three systems exist: rotation in galaxies, pressure in planets and the Pauli pressure in stars that is due to Pauli's exclusion principle. Against the strong interaction, the exclusion principle acts in nuclei and neutron stars; in neutron stars maybe also rotation and pressure complement the Pauli pressure. But for the electromagnetic interaction there are no composites other than our everyday matter, which is organized by the Pauli's exclusion principle alone, acting among electrons.

**Challenge 461**, page 259: Aggregates often form by matter converging to a centre. If there is only a small asymmetry in this convergence – due to some external influence – the result is a final aggregate that rotates.

**Challenge 462**, page 262: Angular momentum is the change with respect to angle, whereas rotational energy is again the change with respect to time, as all energy is.

**Challenge 463**, page 262: Not in this way. A small change can have a large effect, as every switch shows. But a small change in the brain must be communicated outside, and that will happen roughly with a  $1/r^2$  dependence. That makes the effects so small, that even with the most sensitive switches – which for thoughts do not exist anyway – no effects can be realized.

**Challenge 465**, page 262: This is a wrong question.  $T - U$  is not minimal, only its average is.

**Challenge 466**, page 263: No. A system tends to a minimum potential only if it is dissipative. One could, however, deduce that conservative systems oscillate around potential minima.

**Challenge 467**, page 263: The relation is

$$\frac{c_1}{c_2} = \frac{\sin \alpha_1}{\sin \alpha_2}. \quad (155)$$

The particular speed ratio between air (or vacuum, which is almost the same) and a material gives the *index of refraction*  $n$ :

$$n = \frac{c_1}{c_0} = \frac{\sin \alpha_1}{\sin \alpha_0} \quad (156)$$

**Challenge 468**, page 263: The principle for the growth of trees is simply the minimum of potential energy, since the kinetic energy is negligible. The growth of vessels inside animal bodies is minimized for transport energy; that is again a minimum principle. The refraction of light is the

path of shortest time; thus it minimizes change as well, if we imagine light as moving entities moving without any potential energy involved.

**Challenge 469**, page 264: Special relativity requires that an invariant measure of the action exist. It is presented later in the walk.

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**Challenge 470**, page 264: The universe is not a physical system. This issue will be discussed in detail later on.

**Challenge 471**, page 264: Use either the substitution  $u = \tan t/2$  or use the historical trick

$$\sec \varphi = \frac{1}{2} \left( \frac{\cos \varphi}{1 + \sin \varphi} + \frac{\cos \varphi}{1 - \sin \varphi} \right). \quad (157)$$

**Challenge 472**, page 264: A skateboarder in a cycloid has the same oscillation time independently of the oscillation amplitude. But a half-pipe needs to have vertical ends, in order to avoid jumping outside it. A cycloid never has a vertical end.

**Challenge 475**, page 267: We talk to a person because we know that somebody understands us. Thus we assume that she somehow sees the same things we do. That means that observation is partly viewpoint-independent. Thus nature is symmetric.

**Challenge 476**, page 270: Memory works because we recognize situations. This is possible because situations over time are similar. Memory would not have evolved without this reproducibility.

**Challenge 477**, page 271: Taste differences are not fundamental, but due to different viewpoints and – mainly – to different experiences of the observers. The same holds for feelings and judgements, as every psychologist will confirm.

**Challenge 478**, page 273: The integers under addition form a group. Does a painter's set of oil colours with the operation of mixing form a group?

**Challenge 480**, page 273: There is only one symmetry operation: a rotation about  $\pi$  around the central point. That is the reason that later on the group  $D_4$  is only called the approximate symmetry group of Figure 202.

**Challenge 486**, page 278: Scalar is the magnitude of any vector; thus the speed, defined as  $v = |\boldsymbol{v}|$ , is a scalar, whereas the velocity  $\boldsymbol{v}$  is not. Thus the length of any vector (or pseudo-vector), such as force, acceleration, magnetic field, or electric field, is a scalar, whereas the vector itself is not a scalar.

**Challenge 489**, page 278: The charge distribution of an extended body can be seen as a sum of a point charge, a charge dipole, a charge quadrupole, a charge octupole, etc. The quadrupole is described by a tensor.

Compare: The inertia against motion of an extended body can be seen as sum of a point mass, a mass dipole, a mass quadrupole, a mass octupole, etc. The mass quadrupole is described by the moment of inertia.

**Challenge 493**, page 281: The conserved charge for rotation invariance is angular momentum.

**Challenge 497**, page 285: The graph is a *logarithmic spiral* (can you show this?); it is illustrated in Figure 326. The travelled distance has a simple answer.

**Challenge 498**, page 285: An oscillation has a period in time, i.e., a discrete time translation symmetry. A wave has both discrete time and discrete space translation symmetry.

**Challenge 499**, page 285: Motion reversal is a symmetry for any closed system; despite the observations of daily life, the statements of thermodynamics and the opinion of several famous physicists (who form a minority though) all ideally closed systems are reversible.

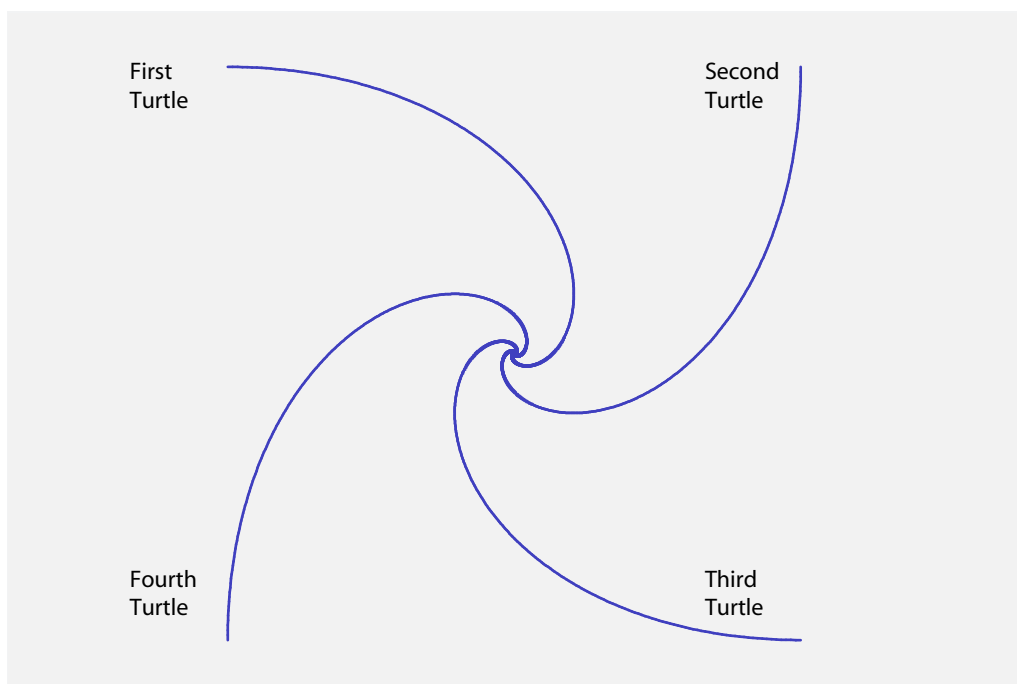


FIGURE 326 The motion of four turtles chasing each other (drawn by Zach Joseph Espiritu).

**Challenge 500**, page 285: The symmetry group is a Lie group and called  $U(1)$ , for 'unitary group in 1 dimension'.

**Challenge 501**, page 285: See challenge 301

**Challenge 502**, page 285: There is no such thing as a 'perfect' symmetry.

**Challenge 504**, page 286: The rotating telephone dial had the digits 1 to 0 on the corners of a regular 14-gon. The even and the odd numbers were on the angles of regular heptagons.

**Challenge 508**, page 289: Just insert  $x(t)$  into the Lagrangian  $L = 0$ , the minimum possible value for a system that transforms all kinetic energy into potential energy and vice versa.

**Challenge 517**, page 300: The potential energy is due to the 'bending' of the medium; a simple displacement produces no bending and thus contains no energy. Only the gradient captures the bending idea.

**Challenge 519**, page 300: The phase changes by  $\pi$ .

**Challenge 520**, page 301: A wave that carries angular momentum has to be transversal and has to propagate in three dimensions.

**Challenge 521**, page 301: Waves can be damped to extremely low intensities. If this is not possible, the observation is not a wave.

**Challenge 522**, page 301: The way to observe diffraction and interference with your naked fingers is told on page 101 in volume III.

**Challenge 533**, page 315: Interference can make radio signals unintelligible. Due to diffraction, radio signals are weakened behind a wall; this is valid especially for short wavelengths, such as those used in mobile phones. Refraction makes radio communication with submarines impossible for usual radio frequencies. Dispersion in glass fibres makes it necessary to add repeaters in sea cables roughly every 100 km. Damping makes it impossible to hear somebody speaking

at larger distances. Radio signals can lose their polarisation and thus become hard to detect by usual Yagi antennas that have a fixed polarisation.

**Challenge 535**, page 320: Skiers scrape snow from the lower side of each bump towards the upper side of the next bump. This leads to an upward motion of ski bumps.

**Challenge 536**, page 320: If the distances to the loudspeaker is a few metres, and the distance to the orchestra is 20 m, as for people with enough money, the listener at home hears it first.

**Challenge 537**, page 320: As long as the amplitude is small compared to the length  $l$ , the period  $T$  is given by

$$T = 2\pi\sqrt{\frac{l}{g}}. \quad (158)$$

The formula does not contain the mass  $m$  at all. Independently of the mass  $m$  at its end, the pendulum has always the same period. In particular, for a length of 1 m, the period is about 2 s. Half a period, or one swing thus takes about 1 s. (This is the original reason for choosing the unit of metre.)

For an extremely long pendulum, the answer is a finite value though, and corresponds to the situation of challenge 26.

**Challenge 538**, page 320: In general, the body moves along an ellipse (as for planets around the Sun) but with the fixed point as centre. In contrast to planets, where the Sun is in a *focus* of the ellipse and there is a perihelion and an apohelion, such a body moves *symmetrically* around the *centre* of the ellipse. In special cases, the body moves back and forward along a straight segment.

**Challenge 540**, page 320: This follows from the formula that the frequency of a string is given by  $f = \sqrt{T/\mu}/(2l)$ , where  $T$  is the tension,  $\mu$  is the linear mass density, and  $l$  is the length of a string. This is discussed in the beautiful paper by G. BARNES, *Physics and size in biological systems*, The Physics Teacher 27, pp. 234–253, 1989.

**Challenge 542**, page 321: The sound of thunder or of car traffic gets lower and lower in frequency with increasing distance.

**Challenge 545**, page 321: Neither; both possibilities are against the properties of water: in surface waves, the water molecules move in circles.

**Challenge 546**, page 322: Swimmers are able to cover 100 m in 48 s, or slightly better than 2 m/s. (Swimmer with fins achieve just over 3 m/s.) With a body length of about 1.9 m, the critical speed is 1.7 m/s. That is why short-distance swimming depends mainly on training; for longer distances the technique plays a larger role, as the critical speed has not been attained yet. The formula also predicts that on the 1500 m distance, a 2 m tall swimmer has a potential advantage of over 45 s on one with a body height of 1.8 m. In addition, longer swimmers have an additional advantage: they swim shorter distances in pools (why?). It is thus predicted that successful long-distance swimmers will get taller and taller over time. This is a pity for a sport that so far could claim to have had champions of all sizes and body shapes, in contrast to many other sports.

**Challenge 549**, page 324: To reduce noise reflection and thus hall effects. They effectively diffuse the arriving wavefronts.

**Challenge 551**, page 324: Waves in a river are never elliptical; they remain circular.

**Challenge 552**, page 324: The lens is a cushion of material that is ‘transparent’ to sound. The speed of sound is faster in the cushion than in the air, in contrast to a glass lens, where the speed of light is slower in the glass. The shape is thus different: the cushion must look like a large biconcave optical lens.

**Challenge 553**, page 324: Experiments show that the sound does not depend on air flows (find out how), but does depend on external sound being present. The sound is due to the selective amplification by the resonances resulting from the geometry of the shell shape.

**Challenge 554**, page 324: The Sun is always at a different position than the one we observe it to be. What is the difference, measured in angular diameters of the Sun? Despite this position difference, the timing of the sunrise is determined by the position of the horizon, not by the position of the Sun. (Imagine the it would not: in that case a room would not get dark when the window is closed, but eight minutes later ...) In short, there is no measurable effect of the speed of light on the sunrise.

**Challenge 557**, page 326: An overview of systems being tested at present can be found in K. - U. GRAW, *Energiereservoir Ozean*, Physik in unserer Zeit 33, pp. 82–88, Februar 2002. See also *Oceans of electricity – new technologies convert the motion of waves into watts*, Science News 159, pp. 234–236, April 2001.

**Challenge 558**, page 326: In everyday life, the assumption is usually justified, since each spot can be approximately represented by an atom, and atoms can be followed. The assumption is questionable in situations such as turbulence, where not all spots can be assigned to atoms, and most of all, in the case of motion of the vacuum itself. In other words, for gravity waves, and in particular for the quantum theory of gravity waves, the assumption is not justified.

**Challenge 564**, page 333: There are many. One would be that the transmission and thus reflection coefficient for waves would almost be independent of wavelength.

**Challenge 565**, page 334: A drop with a diameter of 3 mm would cover a surface of  $7.1 \text{ m}^2$  with a 2 nm film.

**Challenge 566**, page 338: The wind will break tall trees that are too thin. For small and thus thin trees, the wind does not damage.

**Challenge 567**, page 338: The critical height for a column of material is given by  $h_{\text{crit}}^4 = \frac{\beta}{4\pi g} m \frac{E}{\rho^2}$ , where  $\beta \approx 1.9$  is the constant determined by the calculation when a column buckles under its own weight.

**Challenge 569**, page 339: One possibility is to describe particles as clouds; another is given in the last part of the text.

Ref. 258 **Challenge 570**, page 341: The results gives a range between 1 and  $8 \cdot 10^{23}$ .

**Challenge 572**, page 345: Check your answers with the delightful text by P. GOLDRICH, S. MAHAJAN & S. PHINNEY, *Order-of-Magnitude Physics: Understanding the World with Dimensional Analysis, Educated Guesswork, and White Lies*, available on the internet.

**Challenge 573**, page 345: Glass shatters, glass is elastic, glass shows transverse sound waves, glass does not flow (in contrast to what many books state), not even on scale of centuries, glass molecules are fixed in space, glass is crystalline at small distances, a glass pane supported at the ends does not hang through.

**Challenge 574**, page 345: No metal wire allows building such a long wire or rope. Only the idea of carbon nanotubes has raised hope again; some dream of wire material based on them, stronger than any material known so far. However, no such material is known yet. The system faces many dangers, such as fabrication defects, lightning, storms, meteoroids and space debris. All would lead to the breaking of the wires – if such wires will ever exist. But the biggest of all dangers is the lack of cash to build it. Nevertheless, numerous people are working towards the goal.

**Challenge 575**, page 346: The  $3 \times 3 \times 3$  cube has a rigid system of three perpendicular axes, on which a square can rotate at each of the 6 ends. The other squares are attached to pieces moving around these axes. The  $4 \times 4 \times 4$  cube is different though; just find out. From  $7 \times 7 \times 7$  onwards, the parts do not all have the same size or shape. The present limit on the segment number in commercially available ‘cubes’ is  $17 \times 17 \times 17$ ! It can be found at [www.shapeways.com/shops/oskarpuzzles](http://www.shapeways.com/shops/oskarpuzzles). The website [www.oinkleburger.com/Cube/applet](http://www.oinkleburger.com/Cube/applet) allows playing with virtual cubes up to  $100 \times 100 \times 100$ , and more.

**Challenge 578**, page 347: A medium-large earthquake would be generated.

**Challenge 579**, page 347: A stalactite contains a thin channel along its axis through which the water flows, whereas a stalagmite is massive throughout.

**Challenge 580**, page 347: About 1 part in a thousand.

**Challenge 582**, page 348: Even though the iron core of the Earth formed by collecting the iron from colliding asteroids which then sunk into the centre of the Earth, the scheme will not work today: in its youth, the Earth was much more liquid than today. The iron will most probably not sink. In addition, there is no known way to build a measurement probe that can send strong enough sound waves for this scheme. The temperature resistance is also an issue, but this may be solvable.

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**Challenge 584**, page 351: Atoms are not infinitely hard, as quantum theory shows. Atoms are more similar to deformable clouds.

**Challenge 588**, page 360: If there is no friction, all three methods work equally fast – including the rightmost one.

**Challenge 591**, page 362: The constant  $k$  follows from the conservation of energy and that of mass:

$$k = \sqrt{\frac{2}{\rho(A_1^2/A_2^2 - 1)}}. \quad (159)$$

The cross sections are denoted by  $A$  and the subscript 1 refers to any point far from the constriction, and the subscript 2 to the constriction.

**Challenge 594**, page 368: The pressure destroys the lung. Snorkeling is only possible at the water surface, not below the water! This experiment is even dangerous when tried in your own bathtub! Breathing with a long tube is only possible if a pump at the surface pumps air down the tube at the correct pressure.

**Challenge 596**, page 370: Some people notice that in some cases friction is too high, and start sucking at one end of the tube to get the flow started; while doing so, they can inhale or swallow gasoline, which is poisonous.

**Challenge 601**, page 372: Calculation yields  $N = J/j = (0.0001 \text{ m}^3/\text{s})/(7 \mu\text{m}^2 \cdot 0.0005 \text{ m/s})$ , or about  $6 \cdot 10^9$ ; in reality, the number is much larger, as most capillaries are closed at a given instant. The reddening of the face shows what happens when all small blood vessels are opened at the same time.

**Challenge 602**, page 373: Throwing the stone makes the level fall, throwing the water or the piece of wood leaves it unchanged.

**Challenge 603**, page 373: The ship rises higher into the sky. (Why?)

**Challenge 605**, page 373: The motion of a helium-filled balloon is opposite to that of an air-filled balloon or of people: the helium balloon moves towards the front when the car accelerates and to the back when the car decelerates. It also behaves differently in bends. Several films on the internet show the details.

**Challenge 608**, page 373: The pumps worked in suction; but air pressure only allows 10 m of height difference for such systems.

**Challenge 609**, page 373: This argument is comprehensible only when we remember that ‘twice the amount’ means ‘twice as many molecules’.

**Challenge 610**, page 373: The alcohol is frozen and the chocolate is put around it.

**Challenge 611**, page 374: The author suggested in an old edition of this text that a machine should be based on the same machines that throw the clay pigeons used in the sports of trap

TABLE 62 Gaseous composition of dry air, at present time<sup>a</sup> (sources: NASA, IPCC).

G A S	S Y M B O L	V O L U M E P A R T <sup>b</sup>
Nitrogen	N <sub>2</sub>	78.084 %
Oxygen (pollution dependent)	O <sub>2</sub>	20.946 %
Argon	Ar	0.934 %
Carbon dioxide (in large part due to human pollution)	CO <sub>2</sub>	403 ppm
Neon	Ne	18.18 ppm
Helium	He	5.24 ppm
Methane (mostly due to human pollution)	CH <sub>4</sub>	1.79 ppm
Krypton	Kr	1.14 ppm
Hydrogen	H <sub>2</sub>	0.55 ppm
Nitrous oxide (mostly due to human pollution)	N <sub>2</sub> O	0.3 ppm
Carbon monoxide (partly due to human pollution)	CO	0.1 ppm
Xenon	Xe	0.087 ppm
Ozone (strongly influenced by human pollution)	O <sub>3</sub>	0 to 0.07 ppm
Nitrogen dioxide (mostly due to human pollution)	NO <sub>2</sub>	0.02 ppm
Iodine	I <sub>2</sub>	0.01 ppm
Ammonia (mostly due to human pollution)	NH <sub>3</sub>	traces
Radon	Ra	traces
Halocarbons and other fluorine compounds (all being humans pollutants)	20 types	0.0012 ppm
Mercury, other metals, sulfur compounds, other organic compounds (all being human pollutants)	numerous	concentration varies

a. Wet air can contain up to 4 % water vapour, depending on the weather. Apart from gases, air can contain water droplets, ice, sand, dust, pollen, spores, volcanic ash, forest fire ash, fuel ash, smoke particles, pollutants of all kinds, meteoroids and cosmic ray particles. During the history of the Earth, the gaseous composition varied strongly. In particular, oxygen is part of the atmosphere only in the second half of the Earth's lifetime.

b. The abbreviation *ppm* means 'parts per million'.

shooting and skeet. In the meantime, Lydéric Bocquet and Christophe Clanet have built such a stone-skipping machine, but using a different design; a picture can be found on the website [ilm-perso.univ-lyon1.fr/~lbocquet](http://ilm-perso.univ-lyon1.fr/~lbocquet).

**Challenge 612**, page 374: The third component of *air* is the noble gas argon, making up about 1 %. A longer list of components is given in Table 62.

**Challenge 613**, page 374: The *pleural cavity* between the lungs and the thorax is permanently below atmospheric pressure, usually 5 mbar, but even 10 mbar at inspiration. A hole in it, formed for example by a bullet, a sword or an accident, leads to the collapse of the lung – the so-called *pneumothorax* – and often to death. Open chest operations on people have become possible only after the surgeon Ferdinand Sauerbruch learned in 1904 how to cope with the problem. Nowadays however, surgeons keep the lung under *higher* than atmospheric pressure until everything is sealed again.

**Challenge 614**, page 374: The fountain shown in the figure is started by pouring water into the



**FIGURE 327** A way to ride head-on against the wind using wind power (© Tobias Klaus).

uppermost container. The fountain then uses the air pressure created by the water flowing downwards.

**Challenge 615**, page 375: Yes. The bulb will not resist two such cars though.

**Challenge 616**, page 375: Radon is about 8 times as heavy as air; it is the densest gas known. In comparison, Ni(CO) is 6 times, SiCl<sub>4</sub> 4 times heavier than air. Mercury vapour (obviously also a gas) is 7 times heavier than air. In comparison, bromine vapour is 5.5 times heavier than air.

**Challenge 618**, page 375: Yes, as the *ventomobil* shown in [Figure 327](#) proves. It achieves the feat already for low wind speeds.

**Challenge 619**, page 375: None.

**Challenge 621**, page 375: He brought the ropes into the cabin by passing them through liquid mercury.

**Challenge 623**, page 376: There are no official solutions for these questions; just check your assumptions and calculations carefully. The internet is full of such calculations.

**Challenge 624**, page 377: The soap flows down the bulb, making it thicker at the bottom and thinner at the top, until it reaches the thickness of two molecular layers. Later, it bursts.

**Challenge 625**, page 377: The temperature leads to evaporation of the involved liquid, and the vapour prevents direct contact between the two non-gaseous bodies.

**Challenge 626**, page 378: For this to happen, friction would have to exist on the microscopic scale and energy would have to disappear.

**Challenge 627**, page 378: The longer funnel is empty before the short one. (If you do not believe it, try it out.) In the case that the amount of water in the funnel outlet can be neglected, one can use energy conservation for the fluid motion. This yields the famous Bernoulli equation  $p/\rho + gh + v^2/2 = \text{const}$ , where  $p$  is pressure,  $\rho$  the density of water, and  $g$  is  $9.81 \text{ m/s}^2$ . Therefore, the speed  $v$  is higher for greater lengths  $h$  of the thin, straight part of the funnel: the longer funnel empties first.

But this is strange: the formula gives a simple free fall relation, as the *air* pressure is the same above and below and disappears from the calculation. The expression for the speed is thus independent of whether a tube is present or not. The real reason for the faster emptying of the tube is thus that a tube forces more water to flow out than the lack of a tube. Without tube, the diameter of the water flow *diminishes* during fall. With tube, it stays *constant*. This difference leads to the faster emptying for longer tubes.

Alternatively, you can look at the *water* pressure value *inside* the funnel. You will discover that the water pressure is lowest at the start of the exit tube. This internal water pressure is lower for longer tubes and sucks out the water faster in those cases.

**Challenge 628**, page 378: The eyes of fish are positioned in such a way that the pressure reduction by the flow is compensated by the pressure increase of the stall. By the way, their heart is positioned in such a way that it is helped by the underpressure.

**Challenge 630**, page 378: This feat has been achieved for lower mountains, such as the Monte Bianco in the Alps. At present however, there is no way to safely hover at the high altitudes of the Himalayas.

**Challenge 632**, page 378: Press the handkerchief into the glass, and lower the glass into the water with the opening first, while keeping the opening horizontal. This method is also used to lower people below the sea. The paper ball in the bottle will fly towards you. Blowing into a funnel will keep the ping-pong ball tightly into place, and the more so the stronger you blow. Blowing through a funnel towards a candle will make it lean towards you.

**Challenge 639**, page 388: In 5000 million years, the present method will stop, and the Sun will become a red giant. But it will burn for many more years after that.

**Challenge 640**, page 390: Bernoulli argued that the temperature describes the average kinetic energy of the constituents of the gas. From the kinetic energy he deduced the average momentum of the constituents. An average momentum leads to a pressure. Adding the details leads to the ideal gas relation.

**Challenge 641**, page 390: The answer depends on the size of the balloons, as the pressure is not a monotonous function of the size. If the smaller balloon is not too small, the smaller balloon wins.

**Challenge 644**, page 391: Measure the area of contact between tires and street (all four) and then multiply by 200 kPa, the usual tire pressure. You get the weight of the car.

**Challenge 648**, page 394: If the average square displacement is proportional to time, the liquid is made of smallest particles. This was confirmed by the experiments of Jean Perrin. The next

step is to deduce the number of these particles from the proportionality constant. This constant, defined by  $\langle d^2 \rangle = 4Dt$ , is called the diffusion constant (the factor 4 is valid for random motion in two dimensions). The diffusion constant can be determined by watching the motion of a particle under the microscope.

We study a Brownian particle of radius  $a$ . In two dimensions, its square displacement is given by

$$\langle d^2 \rangle = \frac{4kT}{\mu} t, \quad (160)$$

where  $k$  is the Boltzmann constant and  $T$  the temperature. The relation is deduced by studying the motion of a particle with drag force  $-\mu v$  that is subject to random hits. The linear drag coefficient  $\mu$  of a sphere of radius  $a$  is given by

$$\mu = 6\pi\eta a, \quad (161)$$

where  $\eta$  is the kinematic viscosity. In other words, one has

$$k = \frac{6\pi\eta a}{4T} \frac{\langle d^2 \rangle}{t}. \quad (162)$$

All quantities on the right can be measured, thus allowing us to determine the Boltzmann constant  $k$ . Since the ideal gas relation shows that the ideal gas constant  $R$  is related to the Boltzmann constant by  $R = N_A k$ , the Avogadro constant  $N_A$  that gives the number of molecules in a mole is also found in this way.

**Challenge 653**, page 402: The possibility of motion inversion for all observed phenomena is indeed a fundamental property of nature. It has been confirmed for all interactions and all experiments every performed. Independent of this is the fact that realizing the inversion might be extremely hard, because inverting the motion of many atoms is usually not feasible.

**Challenge 654**, page 403: This is a trick question. To a good approximation, any tight box is an example. However, if we ask for complete precision, all systems radiate some energy, lose some atoms or particles and bend space; *ideal* closed systems do *not* exist.

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**Challenge 659**, page 405: We will find out later that the universe is not a physical system; thus the concept of entropy does not apply to it. Thus the universe is neither isolated nor closed.

**Challenge 661**, page 406: Egg white starts to harden at lower temperature than yolk, but for complete hardening, the opposite is true. White hardens *completely* at 80°C, egg yolk hardens considerably at 66 to 68°C. Cook an egg at the latter temperature, and the feat is possible; the white remains runny, but does not remain transparent, though. Note again that the cooking time plays no role, only the precise temperature value.

**Challenge 663**, page 407: Yes, the effect is easily noticeable.

**Challenge 666**, page 407: Hot air is less dense and thus wants to rise.

**Challenge 667**, page 407: Keep the paper wet.

**Challenge 668**, page 407: Melting ice at 0°C to water at 0°C takes 334 kJ/kg. Cooling water by 1°C or 1 K yields 4.186 kJ/kgK. So the hot water needs to cool down to 20.2°C to melt the ice, so that the final mixing temperature will be 10.1°C.

**Challenge 669**, page 408: The air had to be dry.

**Challenge 670**, page 408: In general, it is impossible to draw a line through three points. Since absolute zero and the triple point of water are fixed in magnitude, it was practically a sure bet that the boiling point would not be at precisely 100°C.

**Challenge 671**, page 408: No, as a water molecule is heavier than that. However, if the water is allowed to be dirty, it is possible. What happens if the quantum of action is taken into account?

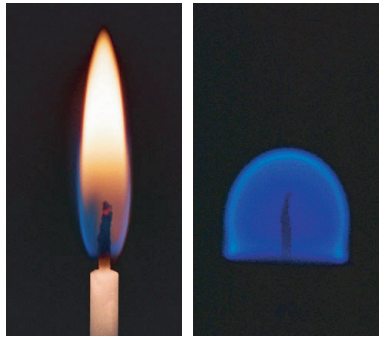


FIGURE 328 A candle on Earth and in microgravity (NASA).

**Challenge 672**, page 408: The danger is not due to the amount of energy, but due to the time in which it is available.

**Challenge 673**, page 409: The internet is full of solutions.

**Challenge 674**, page 409: There are  $2^n$  possible sequences of  $n$  coin throws. Of those,  $n!/(n/2)!$  contain  $n/2$  heads and  $n/2$  tails. For a fair coin, the probability  $p$  of getting  $n/2$  heads in  $n$  throws is thus

$$p = \frac{n!}{2^n \left(\frac{n!}{2}\right)!} \quad (163)$$

We approximate this result with the help of Gosper's formula  $n! \approx \sqrt{(2n + \frac{1}{3})\pi} \left(\frac{n}{e}\right)^n$  and get

$$p \approx \frac{\sqrt{(2n + \frac{1}{3})\pi} \left(\frac{n}{e}\right)^n}{2^n \left(\sqrt{(n + \frac{1}{3})\pi} \left(\frac{n}{2e}\right)^{\frac{n}{2}}\right)^2} = \frac{\sqrt{2n + \frac{1}{3}}}{\left(n + \frac{1}{3}\right)\sqrt{\pi}} \quad (164)$$

For  $n = 1\,000\,000$ , we get a probability  $p \approx 0.0007979$ , thus a rather small value between  $\frac{1}{1254}$  and  $\frac{1}{1253}$ .

**Challenge 675**, page 409: The entropy can be defined for the universe as a whole only if the universe is a closed system. But is the universe closed? Is it a system? This issue is discussed in the final part of our adventure.

**Challenge 678**, page 410: For such small animals the body temperature would fall too low. They could not eat fast enough to get the energy needed to keep themselves warm.

**Challenge 681**, page 410: The answer depends on the volume, of course. But several families have died overnight because they had modified their mobile homes to be airtight.

**Challenge 682**, page 410: The metal salts in the ash act as catalysts, and the sugar burns instead of just melting. Watch the video of the experiment at [www.youtube.com/watch?v=BfBgAaeaVgk](http://www.youtube.com/watch?v=BfBgAaeaVgk).

**Challenge 687**, page 411: It is about  $10^{-9}$  that of the Earth.

**Challenge 689**, page 411: The thickness of the folds in the brain, the bubbles in the lung, the density of blood vessels and the size of biological cells.

**Challenge 690**, page 411: The mercury vapour above the liquid gets saturated.

**Challenge 691**, page 411: A dedicated NASA project studied this question. Figure 328 gives an example comparison. You can find more details on their website.

**Challenge 692**, page 411: The risks due to storms and the financial risks are too high.

**Challenge 693**, page 412: The vortex inside the tube is cold near its axis and hot in the regions away from the axis. Through the membrane in the middle of the tube (shown in [Figure 285](#) on [page 412](#)) the air from the axis region is sent to one end and the air from the outside region to the other end. The heating of the outside region is due to the work that the air rotating inside has to do on the air outside to get a rotation that consumes angular momentum. For a detailed explanation, see the beautiful text by MARK P. SILVERMAN, *And Yet it Moves: Strange Systems and Subtle Questions in Physics*, Cambridge University Press, 1993, p. 221.

**Challenge 694**, page 412: No.

**Challenge 695**, page 412: At the highest possible mass concentration, entropy is naturally the highest possible.

**Challenge 696**, page 412: The units do not match.

**Challenge 697**, page 412: In the case of water, a few turns mixes the ink, and turning backwards increases the mixing. In the case of glycerine, a few turns *seems* to mix the ink, and turning backwards undoes the mixing.

**Challenge 698**, page 413: Put them in clothes.

**Challenge 702**, page 413: Negative temperatures are a conceptual crutch definable only for systems with a few discrete states; they are not real temperatures, because they do not describe equilibrium states, and indeed never apply to systems with a continuum of states.

**Challenge 703**, page 415: This is also true for the shape of human bodies, the brain control of human motion, the growth of flowers, the waves of the sea, the formation of clouds, the processes leading to volcano eruptions, etc.

Page 319 **Challenge 706**, page 422: See the puzzle about the motion of ski moguls.

**Challenge 711**, page 425: First, there are many more butterflies than tornadoes. Second, tornadoes do not rely on small initial disturbances for their appearance. Third, the belief in the butterfly 'effect' completely neglects an aspect of nature that is essential for self-organization: friction and dissipation. The butterfly 'effect', assuming that it existed, would require that dissipation in the air should have completely unrealistic properties. This is not the case in the atmosphere. But most important of all, there is no experimental basis for the 'effect': it has never been observed. Thus it does not exist.

**Challenge 721**, page 437: No. Nature does not allow more than about 20 digits of precision, as we will discover later in our walk. That is not sufficient for a standard book. The question whether such a number can be part of its own book thus disappears.

**Challenge 722**, page 437: All three statements are hogwash. A drag coefficient implies that the cross area of the car is known to the same precision. This is actually extremely difficult to measure and to keep constant. In fact, the value 0.375 for the Ford Escort was a cheat, as many other measurements showed. The fuel consumption is even more ridiculous, as it implies that fuel volumes and distances can be measured to that same precision. Opinion polls are taken by phoning at most 2000 people; due to the difficulties in selecting the right representative sample, that gives a precision of at most 3 % for typical countries.

**Challenge 724**, page 438: Space-time is defined using matter; matter is defined using space-time.

**Challenge 725**, page 438: Fact is that physics has been based on a circular definition for hundreds of years. Thus it is possible to build even an exact science on sand. Nevertheless, the elimination of the circularity is an important aim.

**Challenge 726**, page 439: Every measurement is a comparison with a standard; every comparison requires light or some other electromagnetic field. This is also the case for time measurements.

**Challenge 727**, page 439: Every mass measurement is a comparison with a standard; every comparison requires light or some other electromagnetic field.

**Challenge 728**, page 439: Angle measurements have the same properties as length or time measurements.

**Challenge 730**, page 455: Mass is a measure of the amount of energy. The ‘square of mass’ makes no sense.

**Challenge 733**, page 457: About 10  $\mu\text{g}$ .

**Challenge 734**, page 458: Probably the quantity with the biggest variation is mass, where a prefix for  $1 \text{ eV}/c^2$  would be useful, as would be one for the total mass in the universe, which is about  $10^{90}$  times larger.

**Challenge 735**, page 459: The formula with  $n - 1$  is a better fit. Why?

**Challenge 738**, page 460: No! They are much too precise to make sense. They are only given as an illustration of the behaviour of the Gaussian distribution. Real measurement distributions are not Gaussian to the precision implied in these numbers.

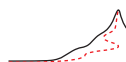
**Challenge 739**, page 460: About 0.3 m/s. It is *not* 0.33 m/s, it is *not* 0.333 m/s and it is *not* any longer strings of threes!

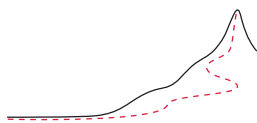
**Challenge 741**, page 466: The slowdown goes *quadratically* with time, because every new slowdown adds to the old one!

**Challenge 742**, page 466: No, only properties of parts of the universe are listed. The universe itself has no properties, as shown in the last volume.

**Challenge 743**, page 527: For example, speed inside materials is slowed, but between atoms, light still travels with vacuum speed.

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“ Aiunt enim multum legendum esse, non multa. ”  
Plinius, *Epistulae*.\*

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\* 'Read much, but not anything.' Ep. 7, 9, 15. Gaius Plinius Secundus (b. 23/4 Novum Comum, d. 79 Vesuvius eruption), Roman writer, especially famous for his large, mainly scientific work *Historia naturalis*, which has been translated and read for almost 2000 years.

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also called the limbic system, contains the amygdala, the hypothalamus and the hippocampus; the human (and primate) (rational) brain, called the neocortex, consists of the famous grey matter. For images of the brain, see the atlas by JOHN NOLTE, *The Human Brain: An Introduction to its Functional Anatomy*, Mosby, fourth edition, 1999. Cited on page 25.

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```
« Graphics'Animation'
Nxpixels=72; Nypixels=54; Nframes=Nxpixels 4/3;
Nxwind=Round[Nxpixels/4]; Nywind=Round[Nypixels/3];
front=Table[Round[Random[]],{y,1,Nypixels},{x,1,Nxpixels}];
back =Table[Round[Random[]],{y,1,Nypixels},{x,1,Nxpixels}];
frame=Table[front,{nf,1,Nframes}];
Do[ If[ x>n-Nxwind && x<n && y>Nywind && y<2Nywind,
      frame[[n,y,x]]=back[[y,x-n]] ],
    {x,1,Nxpixels}, {y,1,Nypixels}, {n,1,Nframes}];
film=Table[ListDensityPlot[frame[[nf]], Mesh-> False,
      Frame-> False, AspectRatio-> N[Nypixels/Nxpixels],
      DisplayFunction-> Identity], {nf,1,Nframes}]
ShowAnimation[film]
```

But our motion detection system is much more powerful than the example shown in the lower left corners. The following, different film makes the point.

```
« Graphics'Animation'
Nxpixels=72; Nypixels=54; Nframes=Nxpixels 4/3;
Nxwind=Round[Nxpixels/4]; Nywind=Round[Nypixels/3];
front=Table[Round[Random[]],{y,1,Nypixels},{x,1,Nxpixels}];
back =Table[Round[Random[]],{y,1,Nypixels},{x,1,Nxpixels}];
frame=Table[front,{nf,1,Nframes}];
Do[ If[ x>n-Nxwind && x<n && y>Nywind && y<2Nywind,
      frame[[n,y,x]]=back[[y,x]] ],
    {x,1,Nxpixels}, {y,1,Nypixels}, {n,1,Nframes}];
film=Table[ListDensityPlot[frame[[nf]], Mesh-> False,
      Frame-> False, AspectRatio-> N[Nypixels/Nxpixels],
      DisplayFunction-> Identity], {nf,1,Nframes}]
ShowAnimation[film]
```

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- 63 Long jump data and literature can be found in three articles all entitled *Is a good long jumper a good high jumper?*, in the *American Journal of Physics* 69, pp. 104–105, 2001. In particular, world-class long jumpers run at  $9.35 \pm 0.15$  m/s, with vertical take-off speeds of  $3.35 \pm 0.15$  m/s, giving take-off angles of about (only) 20°. A new technique for achieving higher take-off angles would allow the world long jump record to increase dramatically. Cited on page 78.
- 64 The study of shooting faeces (i.e., shit) and its mechanisms is a part of modern biology. The reason that caterpillars do this was determined by M. WEISS, *Good housekeeping: why do shelter-dwelling caterpillars fling their frass?*, *Ecology Letters* 6, pp. 361–370, 2003, who also gives the present record of 1.5 m for the 24 mg pellets of *Epargyreus clarus*. The picture of the flying frass is from S. CAVENEY, H. MCLEAN & D. SURRY, *Faecal firing in a skipper caterpillar is pressure-driven*, *The Journal of Experimental Biology* 201, pp. 121–133, 1998. Cited on page 79.
- 65 H. C. BENNET-CLARK, *Scale effects in jumping animals*, pp. 185–201, in T. J. PEDLEY, editor, *Scale Effects in Animal Locomotion*, Academic Press, 1977. Cited on page 80.
- 66 The arguments of Zeno can be found in ARISTOTLE, *Physics*, VI, 9. It can be found translated in almost any language. The [classics.mit.edu/Aristotle/physics.6.vi.html](https://classics.mit.edu/Aristotle/physics.6.vi.html) website provides an online version in English. Cited on pages 83 and 524.
- 67 See, for example, K. V. KUMAR & W. T. NORFLEET, *Issues of human acceleration tolerance after long-duration space flights*, NASA Technical Memorandum 104753, pp. 1–55, 1992, available at [ntrs.nasa.gov](https://ntrs.nasa.gov). Cited on page 85.
- 68 Etymology can be a fascinating topic, e.g. when research discovers the origin of the German word ‘Weib’ (‘woman’, related to English ‘wife’). It was discovered, via a few texts in Tocharian – an extinct Indo-European language from a region inside modern China – to mean originally ‘shame’. It was used for the female genital region in an expression meaning ‘place of shame’. With time, this expression became to mean ‘woman’ in general, while being shortened to the second term only. This connection was discovered by the linguist Klaus T. Schmidt; it explains in particular why the word is not feminine but neutral, i.e., why it uses the article ‘das’ instead of ‘die’. Julia Simon, private communication.  
Etymology can also be simple and plain fun, for example when one discovers in the *Oxford English Dictionary* that ‘testimony’ and ‘testicle’ have the same origin; indeed in Latin the same word ‘testis’ was used for both concepts. Cited on pages 86 and 101.
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- 70 A good biology textbook on growth is ARTHUR F. HOPPER & NATHAN H. HART, *Foundations of Animal Development*, Oxford University Press, 2006. Cited on page 89.
- 71 This is discussed for example in C. L. STONG, *The amateur scientist – how to supply electric power to something which is turning*, *Scientific American* pp. 120–125, December 1975. It also

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- 75 The locomotion of the spiders of the species *Cebrennus villosus* has been described by Ingo Rechenberg from Berlin. See the video at [www.youtube.com/watch?v=Aayb\\_h3IRyQ](http://www.youtube.com/watch?v=Aayb_h3IRyQ). Cited on page 90.
- 76 The first experiments to prove the rotation of the flagella were by M. SILVERMAN & M. I. SIMON, *Flagellar rotation and the mechanism of bacterial motility*, *Nature* 249, pp. 73–74, 1974. For some pretty pictures of the molecules involved, see K. NAMBA, *A biological molecular machine: bacterial flagellar motor and filament*, *Wear* 168, pp. 189–193, 1993, or the website [www.nanonet.go.jp/english/mailmag/2004/011a.html](http://www.nanonet.go.jp/english/mailmag/2004/011a.html). The present record speed of rotation, 1700 rotations per second, is reported by Y. MAGARIYAMA, S. SUGIYAMA, K. MURAMOTO, Y. MAEKAWA, I. KAWAGISHI, Y. IMAE & S. KUDO, *Very fast flagellar rotation*, *Nature* 371, p. 752, 1994.
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- 108 The influence of the Coriolis effect on icebergs was studied most thoroughly by the physicist turned oceanographer Walfrid Ekman (b. 1874 Stockholm, d. 1954 Gostad); the topic was suggested by the great explorer Fridtjof Nansen, who also made the first observations. In his honour, one speaks of the Ekman layer, Ekman transport and Ekman spirals. Any text on oceanography or physical geography will give more details about them. Cited on page 139.

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$$\pi + 3 = \sum_{n=1}^{\infty} \frac{n 2^n}{\binom{2n}{n}} \quad (165)$$

or the beautiful formula discovered in 1996 by Bailey, Borwein and Plouffe

$$\pi = \sum_{n=0}^{\infty} \frac{1}{16^n} \left( \frac{4}{8n+1} - \frac{2}{8n+4} - \frac{1}{8n+5} - \frac{1}{8n+6} \right). \quad (166)$$

The mentioned site also explains the newly discovered methods for calculating specific binary digits of  $\pi$  without having to calculate all the preceding ones. The known digits of  $\pi$  pass all tests of randomness, as the [mathworld.wolfram.com/PiDigits.html](http://mathworld.wolfram.com/PiDigits.html) website explains. However, this property, called *normality*, has never been proven; it is the biggest open question about  $\pi$ . It is possible that the theory of chaotic dynamics will lead to a solution of this puzzle in the coming years.

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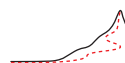
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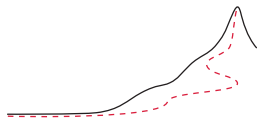
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- is the literature on precision *electric current* measurements; there is a race going on for the best way to do this: counting charges or measuring magnetic forces. The issue is still open. On *mass* and atomic mass measurements, see the volume on relativity. On high-precision *temperature* measurements, see [Ref. 288](#). Cited on page [454](#).
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# CREDITS

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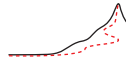
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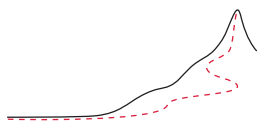
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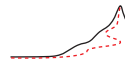
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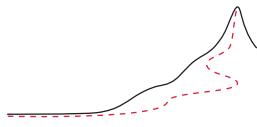
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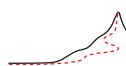
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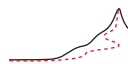
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