The LANGUAGE of the UNIVERSE

COLIN STUART
XIMO ABADÍA

A VISUAL EXPLORATION OF MATHEMATICS

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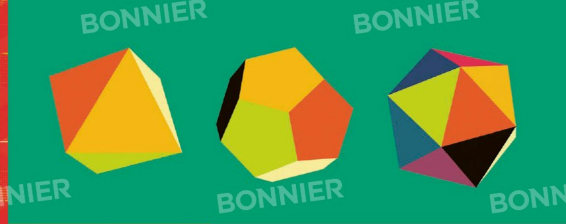


For Isobel – there's beauty in numbers – C.S.

For Baby, Babas and Manuel – X.A.

BIG PICTURE PRESS

First published in the UK in 2019 by Big Picture Press,
an imprint of Bonnier Books UK,
The Plaza, 535 King's Road, London, SW10 0SZ
www.templarco.co.uk/big-picture-press
www.bonnierbooks.co.uk

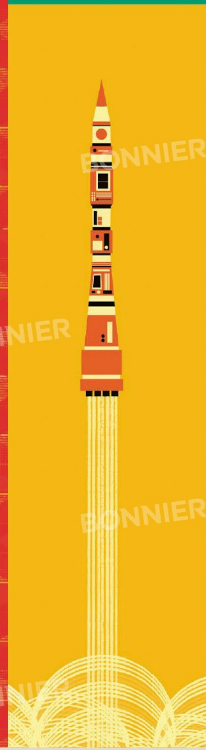
1 3 5 7 9 10 8 6 4 2

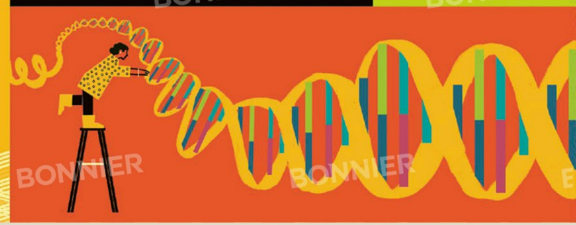
ISBN 978-1-78741-407-5

This book was typeset in Ulissa and BSKombat.
The illustrations were created with graphite,
wax and ink, and coloured digitally.

Edited by Carly Blake and Joanna McInerney
Designed by Adam Allori and Kieran Hood
Production Controller Emma Kidd

Printed in Malaysia



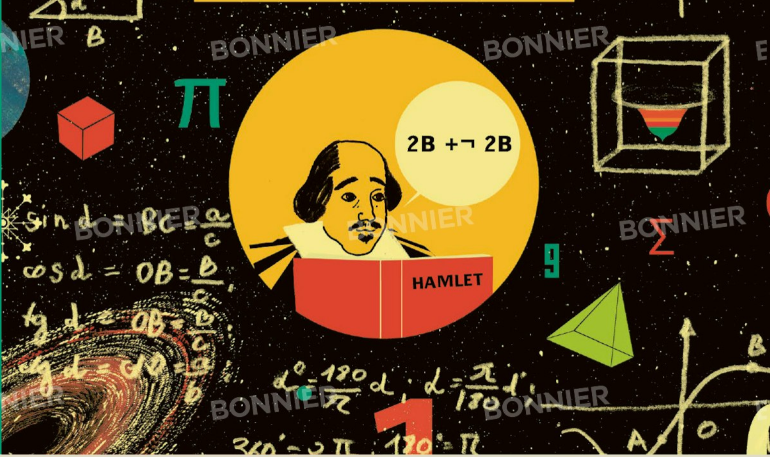


MATHS IN THE NATURAL WORLD

PHYSICS, CHEMISTRY AND ENGINEERING

The Language of the Universe

Maths can be bamboozling. With all its symbols and letters, it looks like it's written in another language – and it is. **MATHEMATICS is the Language of the Universe**. Numbers are like words, plusses and minuses are like full stops and commas, and equations are like sentences. The greatest poets, authors and playwrights light up the world with their beautiful arrangements of words. Yet, when it comes to maths, the Universe is a better writer than all of them combined. Even Shakespeare had nothing on Nature.



Our History with Numbers

Humans have been using numbers for tens of thousands of years, since around the same time that we learnt how to speak. In the 1970s, archaeologists discovered an ancient baboon leg bone in South Africa and someone had clearly carved 29 marks into it, perhaps to count the days of the phases of the Moon. The bone and its marks are over 40,000 years old – it shows just how long humans have been adding up.

Fast forward to the twenty-first century and we've mastered maths like never before. Numbers are the beating heart of the Internet, computer games and the latest technological wonders. Recent medical treatments, movie special effects and the latest pop songs would all be impossible without maths.

Finding Fibonacci

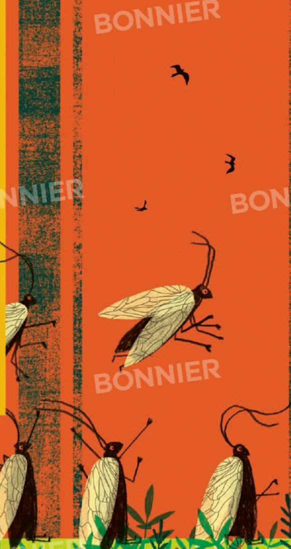
The natural world is awash with maths. From armadillos to pine cones, animals and plants secretly use numbers in their fight for survival every single day.

Take a closer look at the beautiful sunflower. The seeds in the centre are **arranged in spiral patterns**. Count the number of spirals in a clockwise direction, then the number in an anticlockwise direction…

You should get the answers 21 and 34. These numbers are incredibly special because they are part of one of the most famous sequences in maths: the **FIBONACCI SEQUENCE**. It is named after an Italian mathematician who lived around 1200. To recreate this number pattern all you have to do is **add up the previous two numbers**. It starts with 1,1. So the next number is 2 (1 + 1), then 3 (1 + 2), followed by 5 (2 + 3). If you keep going you'll end up with:
1, 1, 2, 3, 5, 8, 13, 21, 34, 55 and so on.

Protecting Yourself with Primes

The forests of the Eastern United States are the stage for a most remarkable event. For 13 long years winged insects called **CICADAS** patiently live underground, even though they are fully grown after just eight. Then, suddenly, they all burst out of the ground together to feast on the surrounding trees, find mates, and lay their eggs. Within weeks the baby cicadas burrow back underground, where they spend the next 13 years growing and waiting their turn.



Why are these bugs so patient? It's all to do with **PRIME NUMBERS**. A prime number is one that can **only be divided by two numbers: 1 and itself**. The sequence of prime numbers goes: **2, 3, 5, 7, 11, 13, 17** and so on. Different cicada groups are known to emerge every 7, 13 or 17 years – all prime numbers.

In Search of the Symmetrical

Mathematicians love to explore **SYMMETRY**. If an object has **the property of symmetry, it can be rotated or flipped and still look exactly the same**. There are some fascinating examples in the natural world.

Both a starfish and snowflake have what mathematicians call **ROTATIONAL SYMMETRY** – **if you turn them by a certain amount they don't look any different**. How many different ways can you turn a starfish without changing its appearance?

The answer is **five**, so a mathematician would say it has **FIVE-FOLD SYMMETRY**. There are 360 degrees in a circle, so you have to turn the starfish **72 degrees** each time to reach the next matching position. What about a stunning snowflake? How would you describe its symmetry and how many degrees do you have to turn it each time?

Answer: Six-fold symmetry, 60 degrees

Fun with Fractals

Maths doesn't get much prettier than a FRACTAL. These **beautiful never-ending patterns have copies of themselves hidden within them** – zoom in or out and you'll see the same shape repeated over and over again.

Take a look at this fern. One of the side branches is just a miniature version of the whole plant. Look even more closely and you'll see that a side branch of that side branch is also the same!

Teamwork with Tessellation

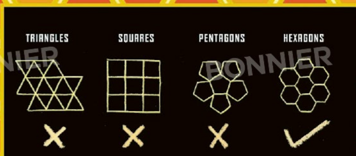
Some of the most famous animals on the planet avoid getting eaten by using a clever trick based on the mathematical idea of TESSELLATION. A tessellation is **a repeating pattern of shapes arranged close together without overlapping or leaving gaps**. Fill an empty area with a smaller tessellating shape, such as a square, triangle or diamond, and it's harder to see the individual tiles.

Zebras use a similar technique to confuse predators. Their distinctive BLACK AND WHITE STRIPES mean that it is **harder for a hungry lion to pick out an individual from a herd**. Other creatures try to **remain hidden by blending in with with their surroundings** such as trees or snowy ground. Scientists call this CAMOUFLAGE. The **green baron caterpillar** is a master of this art, seemingly disappearing as soon as it settles on a leaf.

Packing the Perimeter

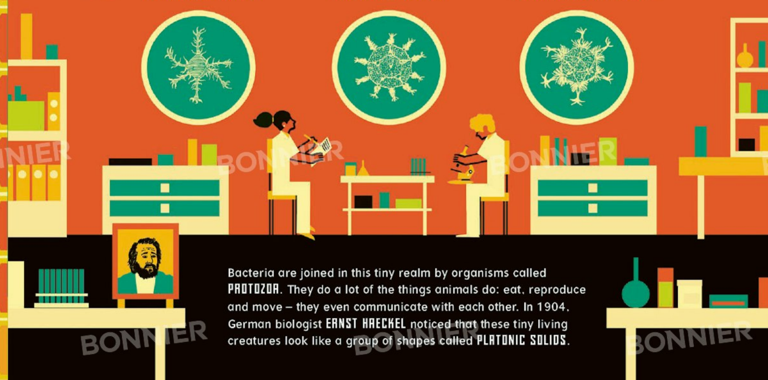
Have you ever packed a suitcase with clothes before going on a trip? If you have, you'll know some ways waste more room than others. You'd do well to take a lesson in space-saving from the honeybee – Nature's expert packer.

Bees skillfully construct their homes from honeycomb, which is made out of a wax produced by their bodies. Their building block of choice is the **HEXAGON**. Why this **six-sided shape** and not a triangle or a circle? It's **the best way to fill an area with the same shape without any gaps**. This means the bees can build their homes in the quickest time using the least amount of wax and get the most amount of storage space. People have marvelled at the work of the bee for centuries, but it took until 1998 for mathematician **THOMAS HALES** to officially prove there was no better way of packing space.



The Platonic Protozoa

The natural world is teeming with living things on a scale too small for your eyes to see. In your own body there are more **tiny microorganisms** called **BACTERIA** than your own cells! They're so small that more than 100 sitting side-by-side would fit across the full stop at the end of this sentence. This microscopic universe has a beautiful link to maths.



Bacteria are joined in this tiny realm by organisms called **PROTOZOA**. They do a lot of the things animals do: eat, reproduce and move – they even communicate with each other. In 1904, German biologist **ERNST HAECKEL** noticed that these tiny living creatures look like a group of shapes called **PLATONIC SOLIDS**.

More recently, biologists have discovered that **many viruses also have an icosahedral structure**.

Getting to Grips with Geometry

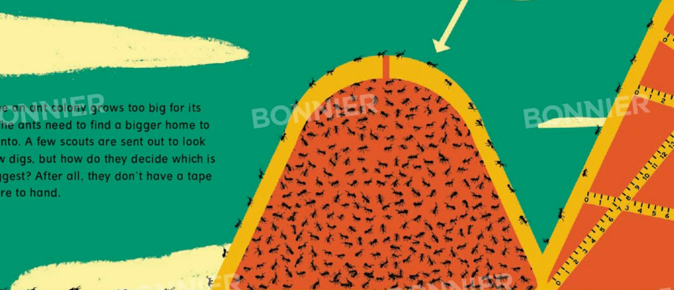
When it comes to love, maths can be the difference between finding a mate or not – at least if you're a member of the animal kingdom. The name of the game is **GEOMETRY – the study of points, lines and the shapes they make**. Mathematician and astronomer Johannes Kepler once said "Where there is matter, there is geometry".

One of the most famous users of geometry is the male peacock, with its bright, shimmering tail that features a pattern of colourful eyespots. Growing such an impressive fan of feathers takes many steps and things can go wrong at any stage. If the geometry of the male's pattern isn't perfect it can be a sign to a potential mate that they are not healthy and are best avoided.

The Awesome Ant

Watching a colony of ants can be hypnotic. They are the ultimate team players, all working together for the survival of the group. They're also excellent mathematicians and use their number-crunching skills when looking for a new place to live.

Imagine an ant colony grows too big for its nest. The ants need to find a bigger home to move into. A few scouts are sent out to look for new digs, but how do they decide which is the biggest? After all, they don't have a tape measure to hand.



This discovery was first calculated by French mathematician **GEORGES LOUIS LECLERC** in the 1700s. He worked out the probability of random lines crossing by throwing bread baguettes on to a floor made of planks and recording when they landed over a crack. Ants have been shown to 'count' the **INTERSECTIONS** of their trails and use that to pick the biggest homes for their colony. Clever stuff! Particularly for a creature with a brain a million times small than a human's.

Animal Addition

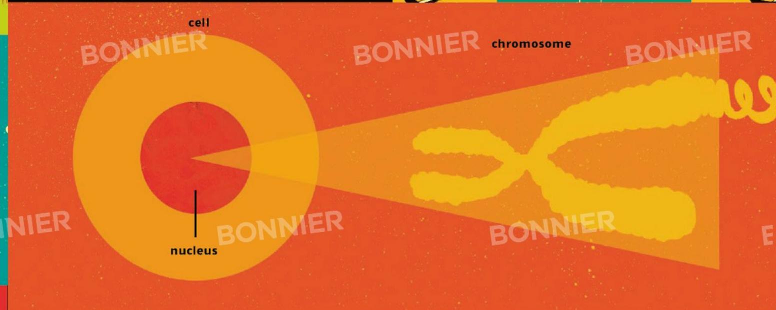
If you think that humans are the only animals that can add up, think again. Scientists have observed a wide range of species doing sums with numbers.

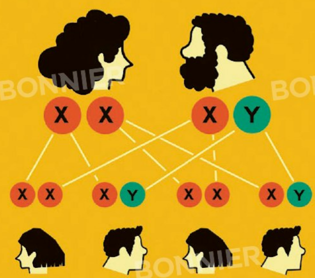
In one experiment, scientists tested the mathematical skills of three-day-old chickens. Scientists set up two screens and the chicks watched as they put 1 ball behind the first screen and 4 balls behind the second. Almost all chicks moved to the screen with the most balls.

That was only half the game. The scientists then removed 2 of the 4 balls and put them behind the first screen. So the first screen now had 3 balls and the second had 2. The young chicks had to work out the sums 4 - 2 and 2 + 1. Amazingly, 80 per cent of chicks correctly moved to the screen with 3 balls.

Created from Chromosomes

Many living things – including humans – are the children of two parents. **A set of instructions for how to make the child** are passed on in the form of **GENES**. Each person has two copies of every gene, one from each parent.





Among many other things, genes helped determine whether you were born a boy or a girl. Genes are collected together into **structures** called **CHROMOSOMES**. The chromosomes that are linked to whether you're born a boy or a girl are given the letters **X** and **Y**. Though there are some variations, genetically you can either be **female (XX)** or **male (XY)**. Everyone has an X chromosome from their mother. If you were born a boy, your father gave you a **Y CHROMOSOME**. If you were born a girl, your father gave you an **X CHROMOSOME**.

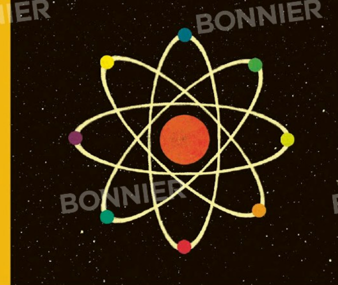
Natural Selection Basics

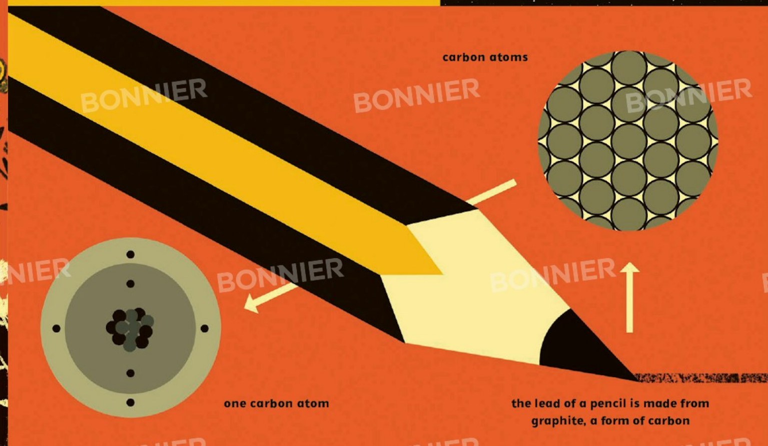
The natural world is an amazing place full of awe and wonder. If you're not careful, though, you might get the wrong idea about how it works. You might congratulate the bee for being so clever as to work out the right shape to make its honeycomb, celebrate the sunflower for the smart way it sorts its seeds or commend the cicada for avoiding being eaten.

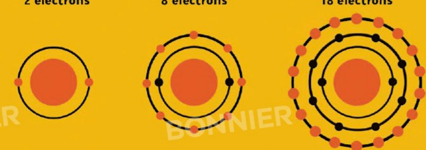
In truth it wasn't a decision made by the bee, flower or bug – it was a mistake. **CHARLES DARWIN** famously published a very important book called ***On the Origin of Species*** in 1859, in which he wrote about a process called **NATURAL SELECTION**. Whenever a living thing passes on its genes, the information is never copied perfectly, and the child is slightly different from its parents. These small mistakes are called **MUTATIONS**.

The Amazing Atom

Everything in the Universe, from planets to people to paper, is made up of **tiny building blocks** called **ATOMS**. Each atom has a centre known as the **NUCLEUS**, with particles called **ELECTRONS** orbiting it like planets circling around the Sun.



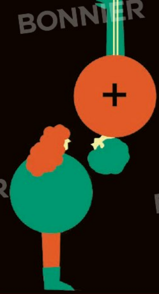




Electrons are huddled together around the nucleus in groups called **SHELLS**. Each shell can only hold a certain number of electrons. In the first shell it's just 2, the second 8 and the third 18. Can you work out the pattern in this sequence? Do you think you can work out the maximum number of electrons that can fit in the fourth shell?

Atom Patterns and the Periodic Table

In the heart of an atom is the nucleus, which is made up of particles called **PROTONS** and **NEUTRONS**. Usually an atom has the same number of protons as it does electrons (page 36). The **number of protons** is known as the atom's **ATOMIC NUMBER**.

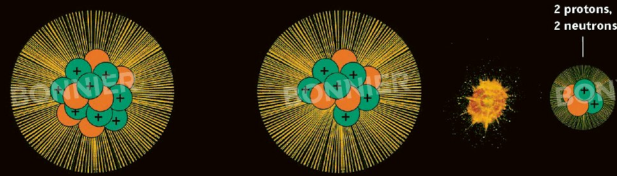


In 1864, English chemist **JOHN NEWLANDS** spotted a pattern hidden within the elements. He noticed that **the properties of a substance are similar in every eighth element**. So **LITHIUM** (3) is similar to **SODIUM** (11) and **POTASSIUM** (19). This pattern is known as the **LAW OF OCTAVES**.

1 H Hydrogen						
3 Li Lithium	4 Be Beryllium					
11 Na Sodium	12 Mg Magnesium					
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium
55 Cs Caesium	56 Ba Barium	57–71	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium
87 Fr Francium	88 Ra Radium	89–103	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium
	Lanthanides	57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium
	Actinides	89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium

Getting the Hang of Half-Lifes

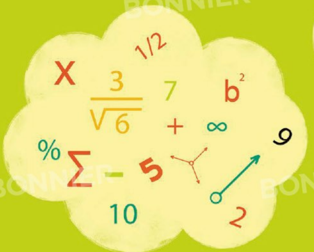
Some atoms are like werewolves or vampires – they are able to change into something else. Although, unlike these creatures, it is very hard for them to change back again. They are called **RADIOACTIVE ATOMS**.



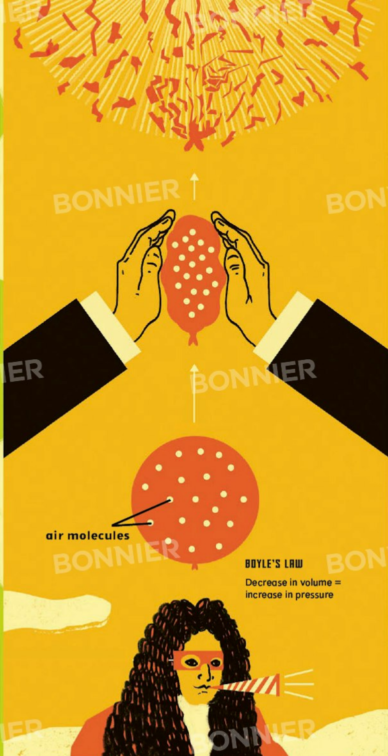
Remember, **the number of protons in an atom's nucleus tells you what element it is**. If a nucleus loses or gains protons then it is no longer the same element. Sometimes the nucleus of a radioactive atom becomes unstable and spits out two protons and two neutrons [**ALPHA DECAY**]. Other times, a neutron suddenly changes into a proton and an electron [**BETA DECAY**]. This gives the nucleus an extra proton, meaning it shape-shifts into the next element in the periodic table. The atom 'burps out' the spare electron (along with an anti-neutrino).

Learning the Laws of Gases

Even the air has maths hidden inside it. Every breath involves numbers.



A gas such as air can be described in several ways. You can talk about its **VOLUME – how much space it takes up**, or its **TEMPERATURE – how hot or cold it is**. But a gas also has **PRESSURE – how much force it creates on a particular area**. All these things are related by mathematical laws of nature discovered by different scientists as far back as the 1600s.



In the 1660s, chemist **ROBERT BOYLE** found that when you **multiply the pressure of a particular gas by its volume you always get the same number** (as long as you keep the temperature the same). This means that if you decrease one, the other increases by exactly the same amount. So if you halve the volume of a gas you double its pressure. This is known as **BOYLE'S LAW**.

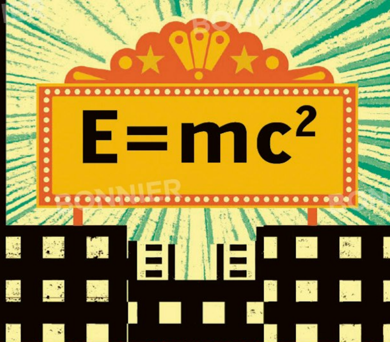
Thinking About Time

Have you ever stopped to think about **TIME**? Time is strange and not like space. In **SPACE** you have choices about the direction you can travel in. You can walk one way and, if you change your mind, turn around and go back the way you came. Time is very different.

With time you're always racing into the future. You can't travel back to your past again (unless you have a time machine hidden away somewhere!). Scientists say that **time has an arrow – it always points in the same direction, from past to future**.

Einstein's Energetic Equation

There is no mathematical equation more famous than Einstein's $E=mc^2$. Here, the **E stands for energy**, the **m for mass** and **c^2 for the speed of light multiplied by itself**.



What Einstein is really saying here is that **energy and mass are the same thing** – two sides of a coin. You can turn energy into mass and mass into energy. That's exactly how the **SUN** is powered – deep in its core mass is turned into light energy.

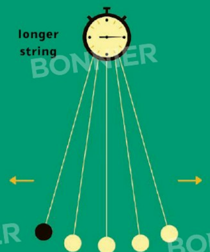
The Secrets of Circuits

Picture a world without electricity. No light bulbs to illuminate the darkness, no television to entertain us, no smartphones or cinemas. Every time you flick a switch or plug something in there is maths working hard to keep the power on.

Like cars zooming around a race track, it is **electrons flowing around wires in electric circuits** that provide us with **ELECTRICITY**. Their **speed** is measured by something called the **ELECTRIC CURRENT**. Like a current of water in a river, a stronger electric current means the electricity is flowing faster. Current is measured in **AMPERES**. One ampere of electrical current means **6 million trillion electrons are flowing through the wire every second**!

Playing with Pendulums and Springs

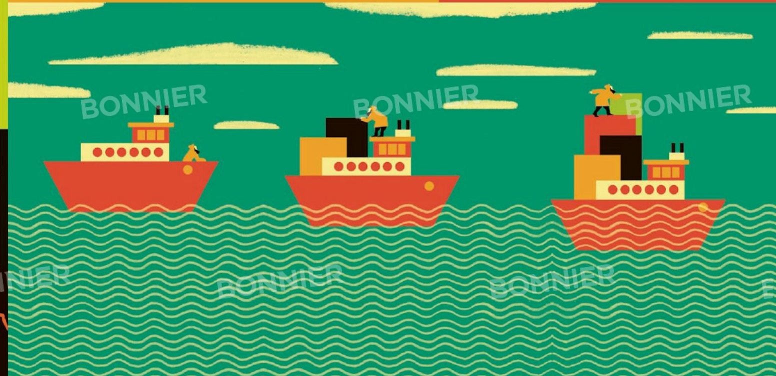
In the late 1500s, Italian mathematician and astronomer **GALILEO GALILEI** found himself mesmerised by the chandelier in Pisa Cathedral. It was swinging back and forth, but he had no clock to time how long it took. So he used the only thing he could: his heartbeat.



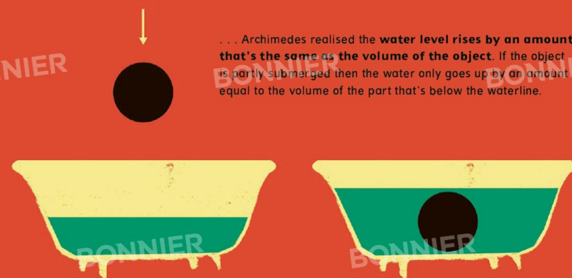
He went on to experiment more with **PENDULUMS** – **weights (or bobs) swinging on a string**. He was able to show that it isn't the weight of the bob that affects how long it takes a pendulum to swing (the **period**), but the length of the string. Galileo discovered that **the period of a pendulum is linked to the square root of the string length**. The square root of a number is the value that can be multiplied by itself to give the original number. For example, the square root of 4 is 2, because 2 x 2 = 4. So if you make a pendulum four times longer it will take twice as long to swing.

The Physics of Floating

Imagine getting so excited by something you discovered in your bathtub that you run out of the house and down the street, shouting at the top of your voice having completely forgotten to put your clothes back on.



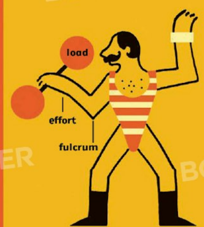
. . . Archimedes realised the **water level rises by an amount that's the same as the volume of the object**. If the object is partly submerged then the water only goes up by an amount equal to the volume of the part that's below the waterline.

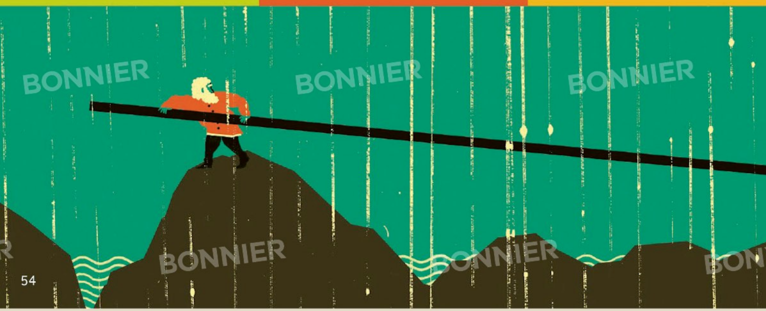


How to Lift with Levers

When was the last time you went to the playground to whizz around on a roundabout, soar on a swing or slip down the slide? If you played on the see-saw you might have noticed something interesting that can be explained by maths.

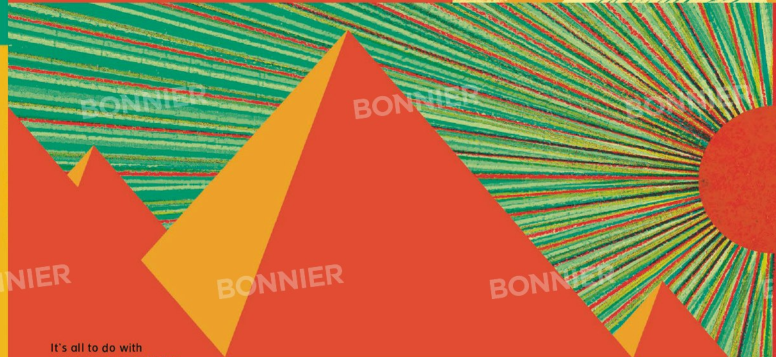
If you spotted that someone a different weight to you has to move closer or further away from the middle to keep it balanced, then you already know how levers work without even realising it! Archimedes is not only known for supposedly running down the street naked (page 52), he is also quoted as saying "Give me a lever long enough, and a fulcrum on which to place it, and I shall move the world". A FULCRUM is **the point about which a lever turns**, just like the middle of a see-saw (sometimes it's also called the **pivot**). There are three types, or classes, of lever.





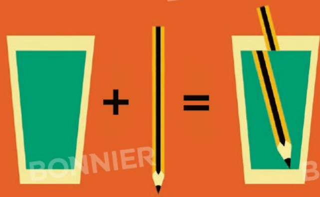
Putting Pythagoras into Practice

Sweating under the intense heat of the Sun, huge teams of people worked to build one of the wonders of the ancient world. But have you ever wondered how the Egyptians managed to get the corners of their pyramids so perfectly square?



It's all to do with **PYTHAGORAS'S THEOREM** and **RIGHT-ANGLED TRIANGLES**. Imagine taking some rope and tying knots in it to create 12 equal sections then using the knotted rope to make a triangle with a 90-degree (right) angle and knots at each corner. You'd see that the two straight sides of the triangle have three and four sections along them and the **diagonal side** (called the **HYPOTENUSE**) has five.

Reflecting on Refraction



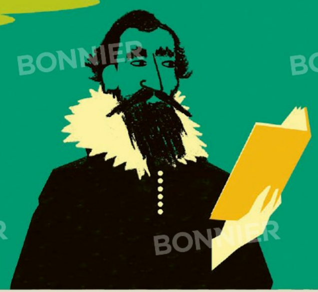
Have you ever been in the bath with your hands in the water and noticed that your fingers look like they have shrunk? Perhaps you've seen a pencil appearing bent or broken when it's half in and half out of a glass of water? These illusions are light playing a trick on us.

Pull your hand or the pencil out of the water and nothing has really happened to them. The distortion you could see is due to light travelling through two different substances – air and water – at different speeds. The light slows down when it hits the water, causing it to travel at a different angle than before.

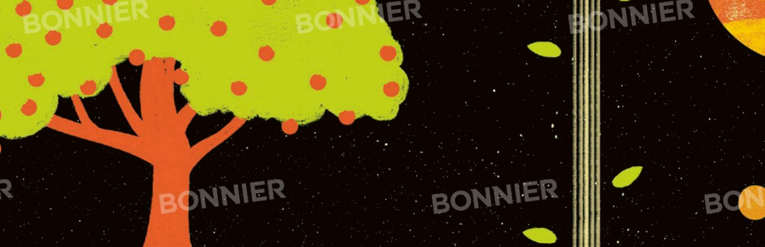
When light is bent like this it is called **REFRACTION**. Every substance has a number known as its **REFRACTIVE INDEX** (normally given the letter **n**). The higher a substance's number, the more it bends light. For air, n = 1.0003 and for water, n = 1.33, so you can see why light slows down and bends as it moves from the air to the water.

Kepler's Clockwork Planets

There once was a man who lived in a castle on a tiny island between Sweden and Denmark. His name was **TYCHO BRAHE** and he was so passionate about maths that he lost the tip of his nose in a sword fight with his third cousin over a mathematical formula. For the rest of his life he wore a metal nose!



From his castle, Brahe looked up into the night sky and kept careful records of the positions of the stars and the planets. After his death, his assistant **JOHANNES KEPLER** searched through all the numbers looking for mathematical patterns in the planets. He soon discovered there are **three rules about the way planets orbit the Sun**. They are now known as **KEPLER'S LAWS**.

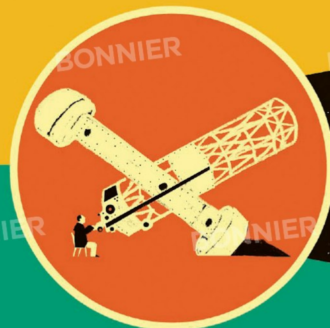


Nailing Gravity with Newton

Kepler wasn't able to explain *why* his laws were true, only that they were. It would take mathematician and physicist **ISAAC NEWTON** to explain what was really going on. Newton was in his mother's garden when he saw an apple fall from a tree and hit the ground. In an instant he realised one of the Universe's most important mathematical secrets: **everything is attracted to everything else by a force called GRAVITY**.

Hurtling Through Space with Hubble

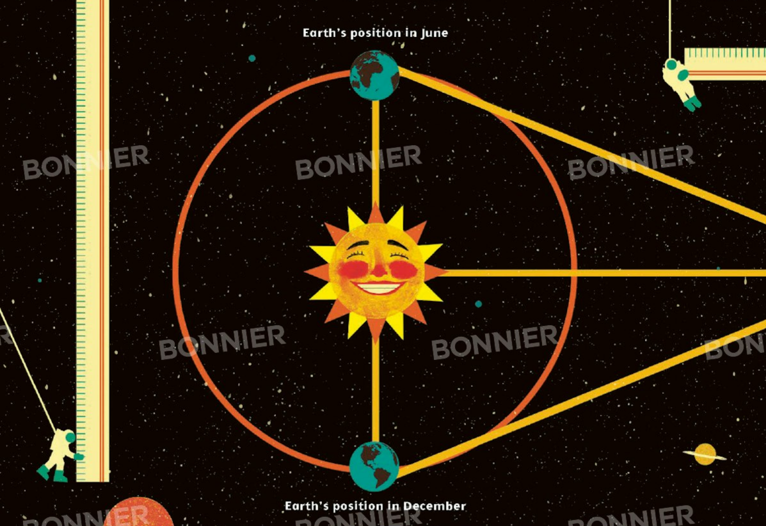
Where did the Universe come from? It is one of the biggest questions you can ask about the world around you. The man who gave us part of the answer to this was American astronomer **EDWIN HUBBLE**.



In the 1920s, Hubble was studying **big groups of stars in space** called **GALAXIES**. He wanted to know two things about each galaxy: how far away it is and how fast it is moving. After carefully making those measurements he found something extraordinary. **Almost every galaxy in the Universe is moving away from us.** What's more, the furthest galaxies appear to be flying away the fastest.

Dealing with Distances in Space

How exactly do you measure distances in space? It's not like you can reach out into the Solar System and beyond with a big ruler. The answer – of course – is maths.



One way of measuring cosmic distances is called **PARALLAX** and it works like this. Close one eye and hold up your finger at arm's length. Line you finger up with the line that separates these two pages. Then change the eye that's open. What happened? You should see your finger jump across on to one of the pages. Remember where your finger landed.

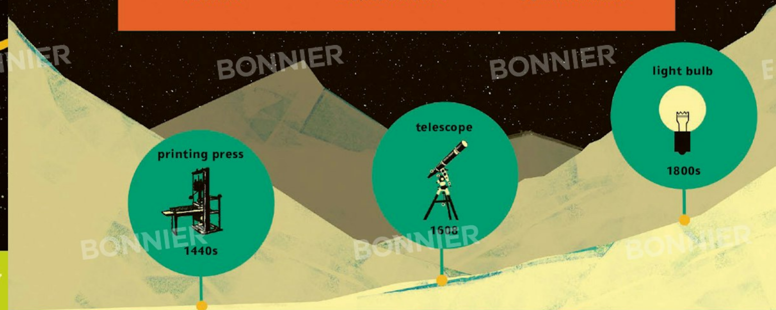
Let's Talk Technological Change

The world has undergone huge change thanks to the explosion of computer technology. Computers work by doing calculations on small computer chips packed full of devices called transistors. In the 1960s engineer **GORDON MOORE** predicted that the number of transistors we could cram on to a computer chip would double every two years. Mathematicians call this **EXPONENTIAL GROWTH**. In 1985, two Nintendo games consoles were as powerful as the computer that guided the Apollo 11 astronauts all the way to the Moon just 16 years earlier in 1969.

1958
1 transistor

1980s
275,000 transistors

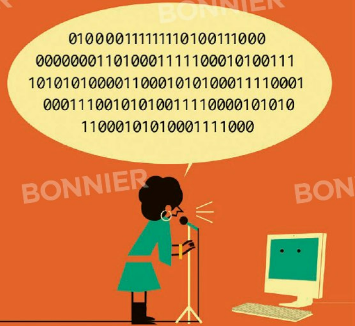
2010s
8 billion transistors



To understand the power of exponential growth, imagine that for every lie Pinocchio tells, his nose grows by an amount that's double the amount before. The first time he fibs it grows 5 centimetres, but the second lie sees it grow by another 10 centimetres. He'd only have to tell a total of 33 lies for his nose to stretch all the way to the Moon!

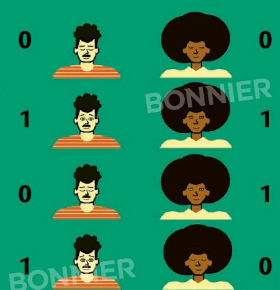
Calculating with Computers

What if you could only speak two words? You might think your language would be extremely limited, yet computers get by using only two numbers: **0 and 1**. They are known as **b**inary dig**its** or **BITS**.



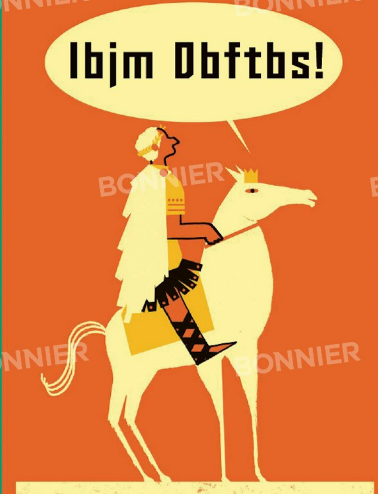
You have more in common with a bit than you might think. Throughout your life you are either asleep or awake. Similarly, **a bit can be thought of as either off (0) or on (1)**. The more bits you put together, the more information you can store.

Picture two people called Bowie and Isobel. Between them there are four different possibilities of being awake or asleep: they are both asleep (00), they are both awake (11), Bowie sleeps while Isobel is awake (01), and Bowie is awake while Isobel sleeps (10). Each one is a unique combination of information. The more people you introduce, the higher the number of possible combinations you can describe.

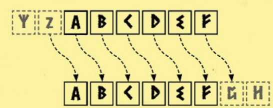


Getting Crafty with Cryptography

Imagine if you could see the information flying all around you right now. Every room is flooded with **DATA – strings of zeroes and ones** – pinging between connected devices such as computers, smartphones and tablets. But with all this data everywhere, how do you keep your information safe from people who might want to steal it?



The answer is **ENCRYPTION – turning important information into a code that only certain people can crack**. The science of codes is called **CRYPTOGRAPHY** and people have been writing in code for thousands of years. Roman emperor **JULIUS CAESAR** invented a cipher, or code, to keep his messages hidden. He would substitute every letter for the next one along in the alphabet.

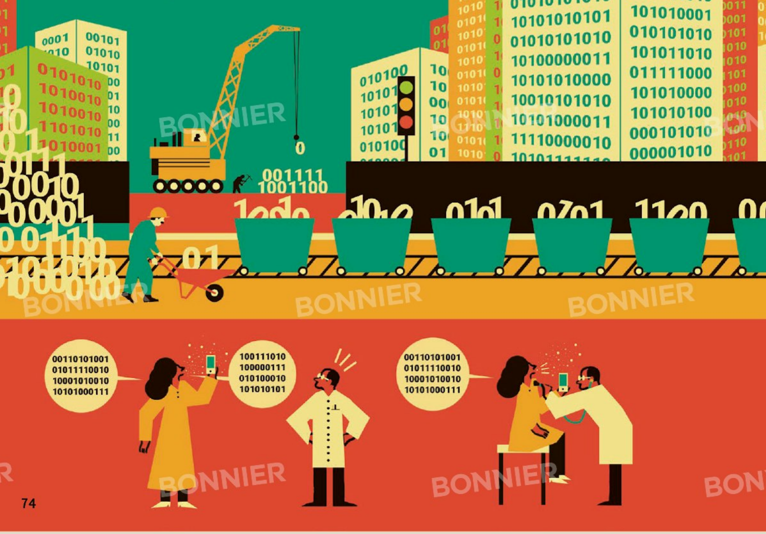


'Hail Caesar!' would become 'Ibjm Dbftbs!'. Only someone who knew the code could easily read his messages.

Building the Future with Big Data

In 2017, we created 2.5 quintillion bytes of data every single day. That's more in one year than in the last 5,000 years of human history combined! How long does it take for us to create the same amount of data as every book ever written? Less than a second.

We've never had as much information about the way we live our lives and the world around us as we do now. We are living in the age of **'big data'** and mathematicians are inventing new ways to look through all of it to spot patterns and trends. Scientists create **computer programs** called **ALGORITHMS** to 'mine' the data for important information.



The World Needs You

We have come a long way since our ancestors ventured down from the trees and started walking on two legs. The marvels of the modern technological world would look like magic to people who lived just a few centuries ago. But it's not magic – it's maths. Our success is built on the realisation that we live in a universe of numbers. **Mathematics is at the heart of everything we do**.