THE PHYSICS BOOK

DK

CONTENTS

ELECTRICITY AND MAGNETISM • TWO FORCES UNITE

COPYRIGHT

How to use this eBook

Preferred application settings

For the best reading experience, the following application settings are recommended:

- Color theme: ***White background***
- Font size: ***At the smallest point size***
- Orientation: ***Landscape*** *(for screen sizes over 9”/23cm)*, ***Portrait*** *(for screen sizes below 9”/23cm)*
- Scrolling view: ***[OFF]***
- Text alignment: ***Auto-justification [OFF]*** *(if the eBook reader has this feature)*
- Auto-hyphenation: ***[OFF]*** *(if the eBook reader has this feature)*
- Font style: ***Publisher default setting [ON]*** *(if the eBook reader has this feature)*
- Images: ***Double tap*** *on the images to see them in full screen and be able to zoom in on them*

FOREWORD

I fell in love with physics as a boy when I discovered that this was the subject that best provided answers to many of the questions I had about the world around me – questions like how magnets worked, whether space went on forever, why rainbows form, and how we know what the inside of an atom or the inside of a star looks like. I also realized that by studying physics I could get a better grip on some of the more profound questions swirling around in my head, such as: What is the nature of time? What is it like to fall into a black hole? How did the Universe begin and how might it end?

Now, decades later, I have answers to some of my questions, but I continue to search for answers to new ones. Physics, you see, is a living subject. Although there are many things we now know with confidence about the laws of nature, and we have used this knowledge to develop technologies that have transformed our world, there is still much more we do not yet know. That is what makes physics, for me, the most exciting area of knowledge of all. In fact, I sometimes wonder why everyone isn't as in love with physics as I am.

But to bring the subject alive – to convey that sense of wonder – requires much more than collecting together a mountain of dry facts. Explaining how our world works is about telling stories; it is about acknowledging how we have come to know what we know about the Universe, and it is about sharing in the joy of discovery made by the many great scientists who first unlocked nature's secrets. How we have come to our current understanding of physics can be as important and as joyful as the knowledge itself.

This is why I have always had a fascination with the history of physics. I often think it a shame that we are not taught at school about how concepts and ideas in science first developed. We are expected to simply accept them unquestioningly. But physics, and indeed the whole of science, isn't like that. We ask questions about how the world works and we develop theories and hypotheses. At the same time, we make observations and conduct experiments, revising and improving on what we know.

Often, we take wrong turns or discover after many years that a particular description or theory is wrong, or only an approximation of reality. Sometimes, new discoveries are made that shock us and force us to revise our view entirely.

One beautiful example of this that has happened in my lifetime was the discovery, in 1998, that the Universe is expanding at an accelerating pace, leading to the idea of so-called dark energy. Until recently, this was regarded as a complete mystery. What was this invisible field that acted to stretch space against the pull of gravity? Gradually, we are learning that this is most likely something called the vacuum energy. You might wonder how changing the name of something (from “dark energy” to “vacuum energy”) can constitute an advance in our understanding. But the concept of vacuum energy is not new. Einstein had suggested it a hundred years ago, then changed his mind when he thought he’d made a mistake, calling it his “biggest blunder”. It is stories like this that, for me, make physics so joyous.

This is also why *The Physics Book* is so enjoyable. Each topic is made more accessible and readable with the introduction of key figures, fascinating anecdotes, and the timeline of the development of the ideas. Not only is this a more honest account of the way science progresses, it is also a more effective way of bringing the subject alive.

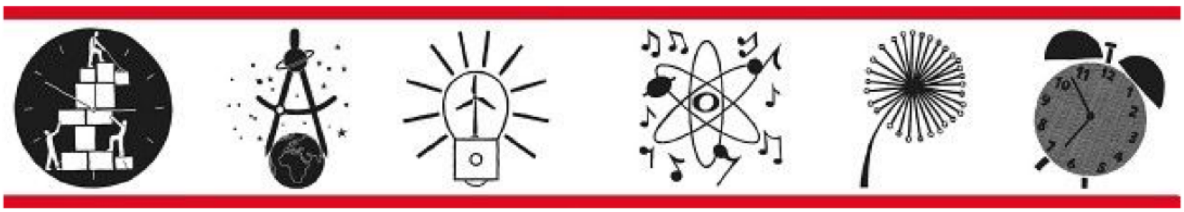
I hope you enjoy the book as much as I do.

Jim Al-Khalili

INTRODUCTION

We humans have a heightened sense of our surroundings. We evolved this way to outmanoeuvre stronger and faster predators. To achieve this, we have had to predict the behaviour of both the living and the inanimate world. Knowledge gained from our experiences was passed down through generations via an ever-evolving system of language, and our cognitive prowess and ability to use tools took our species to the top of the food chain.

We spread out of Africa from around 60,000 years ago, extending our abilities to survive in inhospitable locations through sheer ingenuity. Our ancestors developed techniques to allow them to grow plentiful food for their families, and settled into communities.



Experimental methods

Early societies drew meaning from unrelated events, saw patterns that did not exist, and spun mythologies. They also developed new tools and methods of working, which required advanced knowledge of the inner workings of the world – be it the seasons or the annual flooding of the Nile – in order to expand resources. In some regions, there were periods of relative peace and abundance. In these civilized societies, some people were free to wonder about our place in the Universe. First the Greeks, then the Romans tried to make sense of the world through patterns they observed in nature. Thales of Miletus, Socrates, Plato, Aristotle, and others began to reject supernatural explanations and produce rational answers in the quest to create absolute knowledge – they began to experiment.

At the fall of the Roman Empire, so many of these ideas were lost to the Western world, which fell into a dark age of religious wars, but they continued to flourish in the Arab world and Asia. Scholars there continued to ask questions and conduct experiments. The language of mathematics was invented to document this new-found knowledge. Ibn al-Haytham and Ibn Sahl were just two of the Arab scholars who kept the flame of scientific knowledge alive in the 10th and 11th centuries, yet their discoveries, particularly in the fields of optics and astronomy, were ignored for centuries outside the Islamic world.

A new age of ideas

With global trade and exploration came the exchange of ideas. Merchants and mariners carried books, stories, and technological marvels from east to west. Ideas from this wealth of culture drew Europe out of the dark ages and into a new age of enlightenment known as the Renaissance. A revolution of our world view began as ideas from ancient civilizations became updated or outmoded, replaced by new ideas of our place in the Universe. A new generation of experimenters poked and prodded nature to extract her secrets. In Poland and Italy, Copernicus and Galileo challenged ideas that had been considered sacrosanct for two millennia – and they suffered harsh persecution as a result.

Then, in England in the 17th century, Isaac Newton's laws of motion established the basis of classical physics, which was to reign supreme for more than two centuries. Understanding motion allowed us to build new tools – machines – able to harness energy in many forms to do work. Steam engines and watermills were two of the most important of these – they ushered in the Industrial Revolution (1760–1840).

"Whosoever studies works of science must… examine tests and explanations with the greatest precision."

Ibn al-Haytham

The evolution of physics

In the 19th century, the results of experiments were tried and tested numerous times by a new international network of scientists. They shared their findings through papers, explaining the patterns they observed in the language of mathematics. Others built models from which they attempted to explain these empirical equations of correlation. Models simplified the complexities of nature into digestible chunks, easily described by simple geometries and relationships. These models made predictions about new behaviours in nature, which were tested by a new wave of pioneering experimentalists – if the predictions were proven true, the models were deemed laws which all of nature seemed to obey. The relationship of heat and energy was explored by French physicist Sadi Carnot and others, founding the new science of thermodynamics. British physicist James Clerk Maxwell produced equations to describe the close relationship of electricity and magnetism – electromagnetism.

By 1900, it seemed that there were laws to cover all the great phenomena of the physical world. Then, in the first decade of the 20th century, a series of discoveries sent shock waves through the scientific community, challenging former "truths" and giving birth to modern physics. A German, Max Planck, uncovered the world of quantum physics. Then fellow countryman Albert Einstein revealed his theory of relativity. Others discovered the structure of the atom and uncovered the role of even smaller, subatomic particles. In so doing, they launched the study of particle physics. New discoveries weren't confined to the microscopic – more advanced telescopes opened up the study of the Universe.

Within a few generations, humanity went from living at the centre of the Universe to residing on a speck of dust on the edge of one galaxy among billions. Not only had we seen inside the heart of matter and released the energy within, we had charted the seas of space with light that had been travelling since soon after the Big Bang.

Physics has evolved over the years as a science, branching out and breaching new horizons as discoveries are made. Arguably, its main areas of concern now lie at the fringes of our physical world, at scales both larger than life and smaller than atoms. Modern physics has found applications in many other fields, including new technology, chemistry, biology, and astronomy. This book presents the biggest ideas in physics, beginning with the everyday and ancient, then moving through classical physics into the tiny atomic world, and ending with the vast expanse of space.

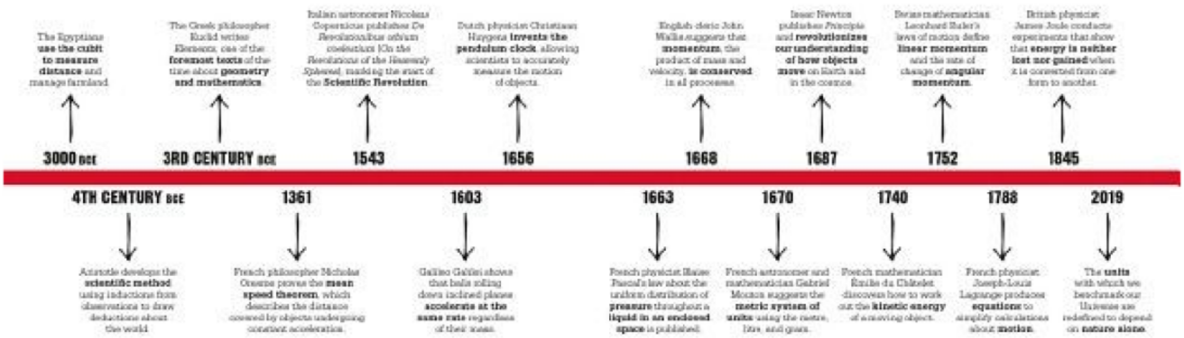
"One cannot help but be in awe when he contemplates the mysteries of eternity, of life, of the marvellous structure of reality."

Albert Einstein

INTRODUCTION

Our survival instincts have made us creatures of comparison. Our ancient struggle to survive by ensuring that we found enough food for our family or reproduced with the correct mate has been supplanted. These primal instincts have evolved with our society into modern equivalents such as wealth and power. We cannot help but measure ourselves, others, and the world around us by metrics. Some of these measures are interpretive, focusing upon personality traits that we benchmark against our own feelings. Others, such as height, weight, or age, are absolutes.

For many people in the ancient and modern world alike, a measure of success was wealth. To amass fortune, adventurers traded goods across the globe. Merchants would purchase plentiful goods cheaply in one location before transporting and selling them for a higher price in another location where that commodity was scarce. As trade in goods grew to become global, local leaders began taxing trade and imposing standard prices. To enforce this, they needed standard measures of physical things to allow them to make comparisons.



Language of measurement

Realizing that each person's experience is relative, the ancient Egyptians devised systems that could be communicated without bias from one person to another. They developed the first system of metrics, a standard method for measuring the world around them. The Egyptian cubit allowed engineers to plan buildings that were unrivalled for millennia and to devise farming systems to feed the burgeoning population. As trade with ancient Egypt became global, the idea of a common language of measurement spread around the world.

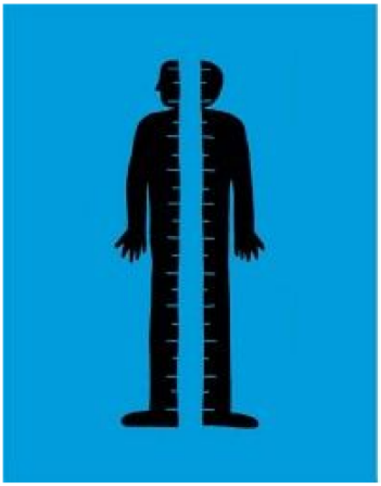
The Scientific Revolution (1543–1700) brought about a new need for these metrics. For the scientist, metrics were to be used not for trading goods but as a tool with which nature could be understood. Distrusting their instincts, scientists developed controlled environments in which they tested connections between different behaviours – they experimented. Early experiments focused on the movement of everyday objects, which had a direct effect upon daily life. Scientists discovered patterns in linear, circular, and repetitive oscillating motion. These patterns became immortalized in the language of mathematics, a gift from ancient civilizations that had then been developed in the Islamic world for centuries. Mathematics offered an unambiguous way of sharing the outcomes of experiments and allowed scientists to make predictions and test these predictions with new experiments. With a common language and metrics, science marched forward. These pioneers discovered links between distance, time, and speed and set out their own repeatable and tested explanation of nature.

Measuring motion

Scientific theories progressed rapidly and with them the language of mathematics changed. Building on his laws of motion, English physicist Isaac Newton invented calculus, which brought a new ability to describe the change in systems over time, not just calculate single snapshots. To explain the acceleration of falling objects, and eventually the nature of heat, ideas of an unseen entity called energy began to emerge. Our world could no longer be defined by distance, time, and mass alone, and new metrics were needed to benchmark the measurement of energy.

Scientists use metrics to convey the results of experiments. Metrics provide an unambiguous language that enables scientists to interpret the results of an experiment and repeat the experiment to check that their conclusions are correct. Today, scientists use the Système international (SI) collection of metrics to convey their results. The value of each of these SI metrics and their link to the world around us are defined and decided upon by an international group of scientists known as metrologists.

This first chapter charts these early years of the science we today call physics, the way in which the science operates through experimentation, and how results from these tests are shared across the world. From the falling objects that Italian polymath Galileo Galilei used to study acceleration to the oscillating pendulums that paved the way to accurate timekeeping, this is the story of how scientists began to measure distance, time, energy, and motion, revolutionizing our understanding of what makes the world work.



MAN IS THE MEASURE OF ALL THINGS

MEASURING DISTANCE

IN CONTEXT

KEY CIVILIZATION

Ancient Egypt

BEFORE

***c.* 4000** BCE Administrators use a system of measuring field sizes in ancient Mesopotamia.

***c.* 3100** BCE Officials in ancient Egypt use knotted cords – pre-stretched ropes tied at regular intervals – to measure land and survey building foundations.

AFTER

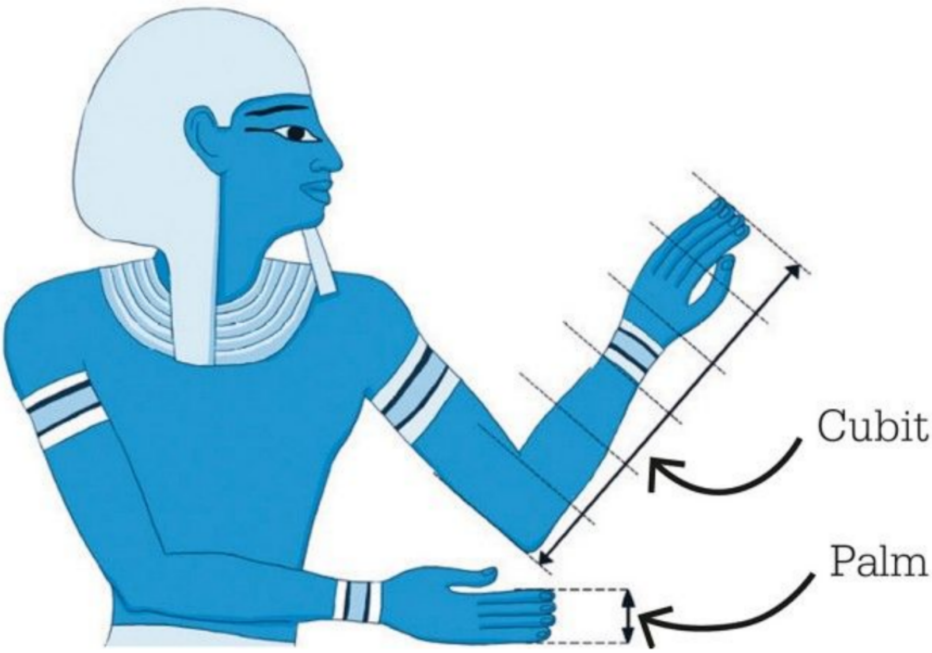
1585 In the Netherlands, Simon Stevin proposes a decimal system of numbers.

1799 The French government adopts the metre.

1875 Signed by 17 nations, the Metre Convention agrees a consistent length for the unit.

1960 The eleventh General Conference on Weights and Measures sets the metric system as the International System of Units ("SI", from the French *Système international*).

When people began to build structures on an organized scale, they needed a way to measure height and length. The earliest measuring devices are likely to have been primitive wooden sticks scored with notches, with no accepted consistency in unit length. The first widespread unit was the "cubit", which emerged in the 4th and 3rd millennia BCE among the peoples of Egypt, Mesopotamia, and the Indus Valley. The term cubit derives from the Latin for elbow, *cubitum*, and was the distance from the elbow to the tip of the outstretched middle finger. Of course, not everyone has the same length of forearm and middle finger, so this "standard" was only approximate.



The Egyptian royal cubit was based on the length of the forearm, measured from the elbow to the middle fingertip. Cubits were subdivided into 28 digits (each a finger's breadth in length) and a series of intermediary units, such as palms and hands.

Imperial measure

As prodigious architects and builders of monuments on a grand scale, the ancient Egyptians needed a standard unit of distance. Fittingly, the royal cubit of the Old

Kingdom of ancient Egypt is the first known standardized cubit measure in the world. In use since at least 2700 BCE, it was 523–529 mm (20.6–20.8 in) long and was divided into 28 equal digits, each based on a finger's breadth.

Archaeological excavations of pyramids have revealed cubit rods of wood, slate, basalt, and bronze, which would have been used as measures by craftsmen and architects. The Great Pyramid at Giza, where a cubit rod was found in the King's Chamber, was built to be 280 cubits in height, with a base of 440 cubits squared. The Egyptians further subdivided cubits into palms (4 digits), hands (5 digits), small spans (12 digits), large spans (14 digits, or half a cubit), and *t'sers* (16 digits or 4 palms). The *khet* (100 cubits) was used to measure field boundaries and the *ater* (20,000 cubits) to define larger distances.

Cubits of various length were used across the Middle East. The Assyrians used cubits in *c.* 700 BCE, while the Hebrew Bible contains plentiful references to cubits – particularly in the Book of Exodus's account of the construction of the Tabernacle, the sacred tent that housed the Ten Commandments. The ancient Greeks developed their own 24-unit cubit, as well as the *stade* (plural *stadia*), a new unit representing 300 cubits. In the 3rd century BCE, the Greek scholar Eratosthenes (*c.* 276 BCE–*c.* 194 BCE) estimated the circumference of Earth at 250,000 stadia, a figure he later refined to 252,000 stadia. The Romans also adopted the cubit, along with the inch – an adult male's thumb – foot, and mile. The Roman mile was 1,000 paces, or *mille passus*, each of which was five Roman feet. ROMAN colonial expansion from the 3rd century BCE to the 3rd century CE introduced these units to much of western Asia and Europe, including England, where the mile was redefined as 5,280 feet in 1593 by Queen Elizabeth I.

"You are to make upright frames of acacia wood for the Tabernacle. Each frame is to be ten cubits long and a cubit and a half wide."

Exodus 26:15–16

The Bible

Cubit rods – such as this example from the 18th dynasty in ancient Egypt, *c.* 14th century BCE – were used widely in the ancient world to achieve consistent measurements.

Going metric

In his 1585 pamphlet *De Thiende* (*The Art of Tenths*), Flemish physicist Simon Stevin proposed a decimal system of measurement, forecasting that, in time, it would be widely accepted. More than two centuries later, work on the metric system was begun by a committee of the French Academy of Sciences, with the metre being defined as one ten-millionth of the distance from Earth's equator to the North Pole. France became the first nation to adopt the measurement, in 1799.

International recognition was not achieved until 1960, when the *Système international* (SI) set the metre as the base unit for distance. It was agreed that 1 metre (m) is equal to 1,000 millimetres (mm) or 100 centimetres (cm), and 1,000 m make up 1 kilometre (km).

"A mile shall contain eight furlongs, every furlong forty poles, and every pole shall contain sixteen foot and a half."

Queen Elizabeth I

Changing definitions

In 1668, English clergyman John Wilkins followed Stevin's proposal of a decimal-based unit of length with a novel definition: he suggested that 1 metre should be set as the distance of a pendulum swing with a two-second period. Dutch physicist Christiaan Huygens (1629–95) calculated this to be 39.26 in (997 mm).

In 1889, an alloy bar of platinum (90%) and iridium (10%) was cast to represent the definitive 1-metre length, but because it expanded and contracted very slightly at different temperatures, it was accurate only at the melting point of ice. This bar is still kept at the International Bureau of Weights and Measures in Paris, France. When SI definitions were adopted in 1960, the metre was redefined in terms of the wavelength of electromagnetic emissions from a krypton atom. In 1983, yet another definition was adopted: the distance that light travels in a vacuum in 1/299,792,458 of a second.

See also: Free falling • Measuring time • SI units and physical constants • Heat and transfers

A PRUDENT QUESTION IS ONE HALF OF WISDOM

THE SCIENTIFIC METHOD

IN CONTEXT

KEY FIGURE

Aristotle (*c.* 384–322 BCE)

BEFORE

585 BCE Thales of Miletus, a Greek mathematician and philosopher, analyses movements of the Sun and Moon to forecast a solar eclipse.

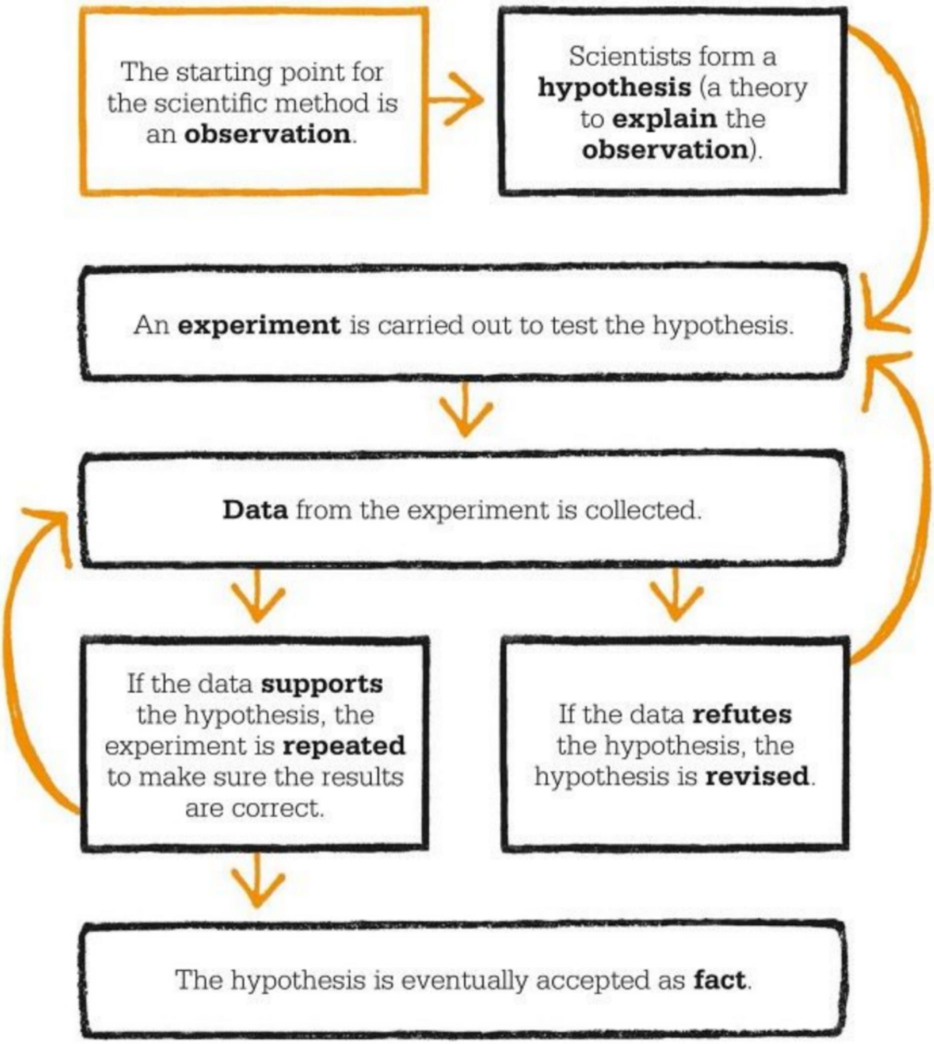
AFTER

1543 Nicolaus Copernicus's *De Revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*) and Andreas Vesalius's *De humani corporis fabrica* (*On the Workings of the Human Body*) rely on detailed observation, marking the beginning of the Scientific Revolution.

1620 Francis Bacon proposes the inductivist method, which involves making generalizations based on accurate observations.

Careful observation and a questioning attitude to findings are central to the scientific method of investigation, which underpins physics and all the sciences. Since it is easy for prior knowledge and assumptions to distort the interpretation of data, the scientific method follows a set procedure. A hypothesis is drawn up on the basis of findings, and then tested experimentally. If this hypothesis fails, it can be revised and re-examined, but if it is robust, it is shared for peer review – independent evaluation by experts.

People have always sought to understand the world around them, and the need to find food and understand changing weather were matters of life and death long before ideas were written down. In many societies, mythologies developed to explain natural phenomena; elsewhere, it was believed that everything was a gift from the gods and events were pre-ordained.



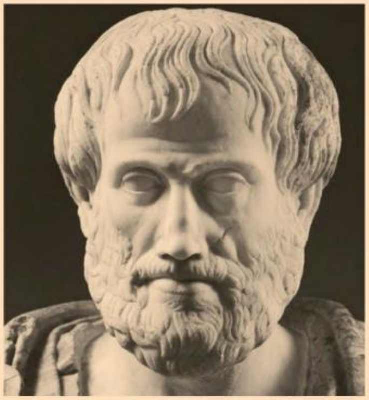
Early investigations

The world's first civilizations – ancient Mesopotamia, Egypt, Greece, and China – were sufficiently advanced to support "natural philosophers", thinkers who sought to interpret the world and record their findings. One of the first to reject supernatural explanations of natural phenomena was the Greek thinker Thales of Miletus. Later, the philosophers Socrates and Plato introduced debate and argument as a method of advancing understanding, but it was Aristotle – a prolific investigator of physics, biology, and zoology – who began to develop a scientific method of enquiry, applying logical reasoning to observed phenomena. He was an empiricist, someone who believes that all knowledge is based on experience derived from the senses, and that reason alone is not enough to solve scientific problems – evidence is required.

Travelling widely, Aristotle was the first to make detailed zoological observations, seeking evidence to group living things by behaviour and anatomy. He went to sea with fishermen in order to collect and dissect fish and other marine organisms. After discovering that dolphins have lungs, he judged they should be classed with whales, not fish, and separated four-legged animals that give birth to live young (mammals) from those that lay eggs (reptiles and amphibians).

However, in other fields Aristotle was still influenced by traditional ideas that lacked a grounding in good science. He did not challenge the prevailing geocentric idea that the Sun and stars rotate around Earth. In the 3rd century BCE, another Greek thinker, Aristarchus of Samos, argued that Earth and the known planets orbit the Sun, that stars are very distant equivalents of "our" Sun, and that Earth spins on its axis. Though correct, these ideas were dismissed because Aristotle and his student Ptolemy carried greater authority. In fact, the geocentric view of the Universe was held to be true – due in part to its enforcement by the Catholic Church, which discouraged ideas that challenged its interpretation of the Bible – until it was superseded in the 17th century by the ideas of Copernicus, Galileo, and Newton.

ARISTOTLE



The son of the court physician of the Macedonian royal family, Aristotle was raised by a guardian after his parents died when he was young. At around the age of 17, he joined Plato's Academy in Athens, the foremost centre of learning in Greece. Over the next two decades, he studied and wrote about philosophy, astronomy, biology, chemistry, geology, and physics, as well as politics, poetry, and music. He also travelled to Lesvos, where he made ground-breaking observations of the island's botany and zoology.

In *c.* 343 BCE, Aristotle was invited by Philip II of Macedon to tutor his son, the future Alexander the Great. He established a school at the Lyceum in Athens in 335 BCE, where he wrote many of his most celebrated scientific treatises. Aristotle left Athens in 322 BCE and settled on the island of Euboea, where he died at the age of about 62.

Key works

Metaphysics

On the Heavens

Physics

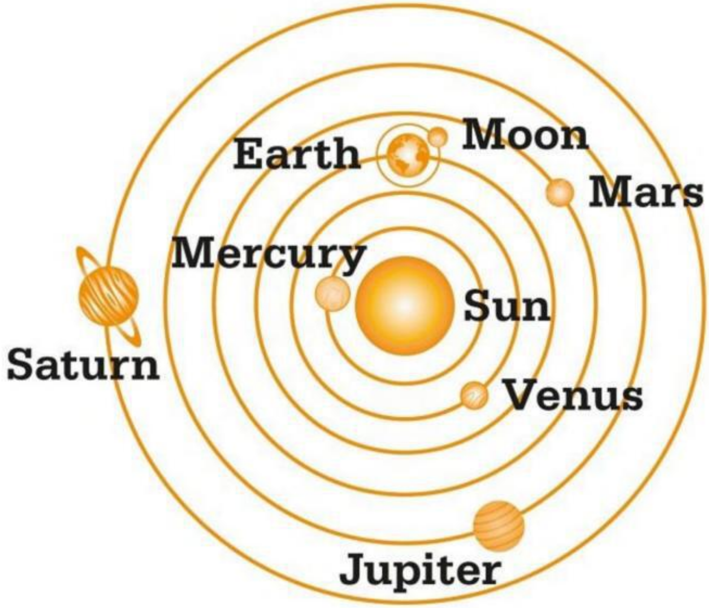
"All truths are easy to understand once they are discovered; the point is to discover them."

Galileo Galilei

Testing and observation

Arab scholar Ibn al-Haytham (widely known as "Alhazen") was an early proponent of the scientific method. Working in the 10th and 11th centuries CE, he developed his own method of experimentation to prove or disprove hypotheses. His most important work was in the field of optics, but he also made important contributions to astronomy and mathematics. Al-Haytham experimented with sunlight, light reflected from artificial light sources, and refracted light. For example, he tested – and proved – the hypothesis that every point of a luminous object radiates light along every straight line and in every direction.

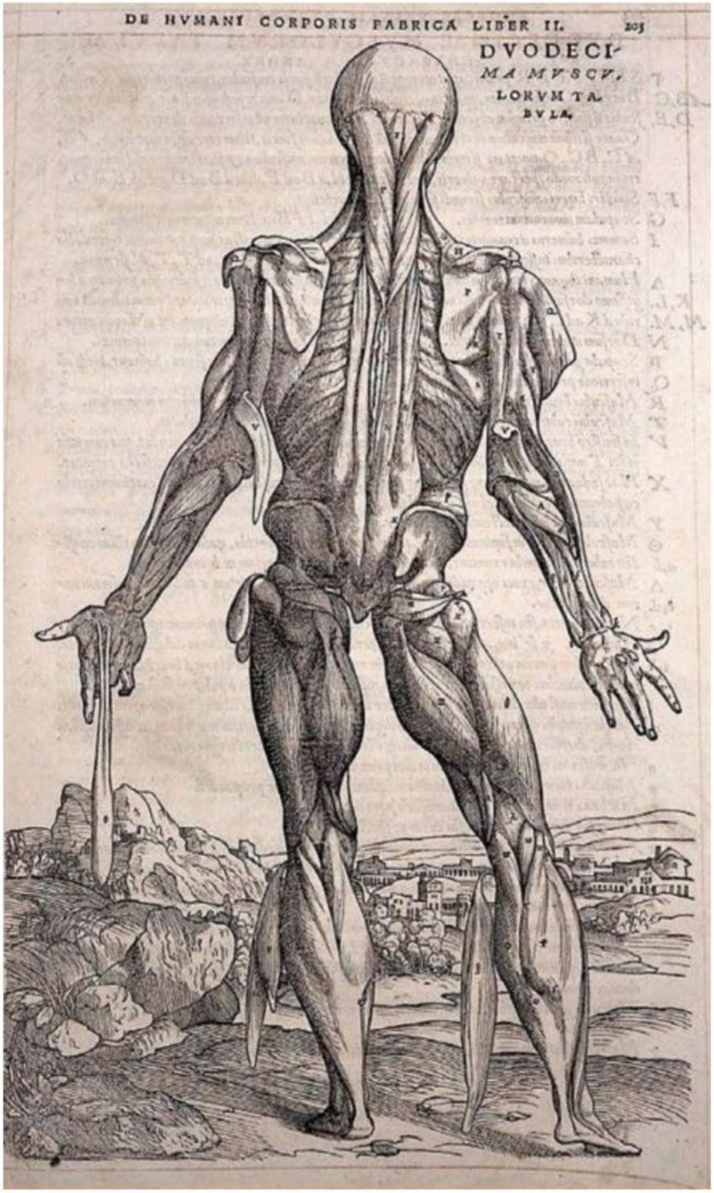
Unfortunately, al-Haytham's methods were not adopted beyond the Islamic world, and it would be 500 years before a similar approach emerged independently in Europe, during the Scientific Revolution. But the idea that accepted theories may be challenged, and overthrown if proof of an alternative can be produced, was not the prevailing view in 16th-century Europe. Church authorities rejected many scientific ideas, such as the work of Polish astronomer Nicolaus Copernicus. He made painstaking observations of the night sky with the naked eye, explaining the temporary retrograde ("backward") motion of the planets, which geocentrism had never accounted for. Copernicus realized the phenomenon was due to Earth and the other planets moving around the Sun on different orbits. Although Copernicus lacked the tools to prove heliocentrism, his use of rational argument to challenge accepted thinking marked him out as a true scientist. Around the same time, Flemish anatomist Andreas Vesalius transformed medical thinking with his multi-volume work on the human body in 1543. Just as Copernicus based his theories on detailed observation, Vesalius analysed what he found when dissecting human body-parts.



Copernicus's heliocentric model, so-called because it made the Sun (*helios* in Greek) the focus of planetary orbits, was endorsed by some scientists but outlawed by the Church.

"If a man will begin with certainties, he shall end in doubts, but if he will be content to begin with doubts, he shall end in certainties."

Francis Bacon



Anatomical drawings from 1543 reflect Vesalius's mastery of dissection, and set a new standard for study of the human body, unchanged since the Greek physician Galen (129–216 CE).

Experimental approach

For Italian polymath Galileo Galilei, experimentation was central to the scientific approach. He carefully recorded observations on matters as varied as the movement of the planets, the swing of pendulums, and the speed of falling bodies. He produced theories to explain them, then made more observations to test the theories. He used the new technology of telescopes to study four of the moons orbiting Jupiter, proving Copernicus's heliocentric model – under geocentrism, all objects orbited Earth. In 1633 Galileo was tried by the Church's Roman Inquisition, found guilty of heresy, and placed under house-arrest for the last decade of his life. He continued to publish by smuggling papers to Holland, away from the censorship of the Church.

Later in the 17th century, English philosopher Francis Bacon reinforced the importance of a methodical, sceptical approach to scientific enquiry. Bacon argued that the only means of building true knowledge was to base axioms and laws on observed facts, not relying (even if only partially) on unproven deductions and conjecture. The Baconian method involves making systematic observations to establish verifiable facts; generalizing from a series of facts to create axioms (a process known as "inductivism"), while being careful to avoid generalizing beyond what the facts tell us; then gathering further facts to produce an increasingly complex base of knowledge.

Unproven science

When scientific claims cannot be verified, they are not necessarily wrong. In 1997, scientists at the Gran Sasso laboratory in Italy claimed to have detected evidence of dark matter, which is believed to make up about 27 per cent of the Universe. The most likely source, they said, were weakly interacting massive particles (WIMPs). These should be detected as tiny flashes of light (scintillations) when a particle strikes the nucleus of a "target" atom. However, despite the best efforts of other research teams to replicate the experiment, no other evidence of dark matter has been found. It is possible that there is an unidentified explanation – or the scintillations could have been produced by helium atoms, which are present in the experiment's photomultiplier tubes.

The scientific method in practice

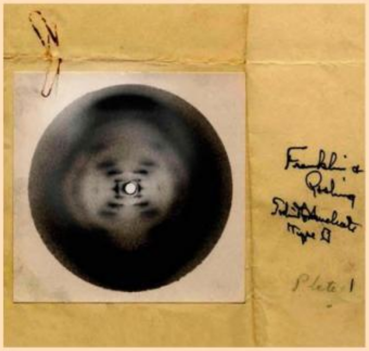
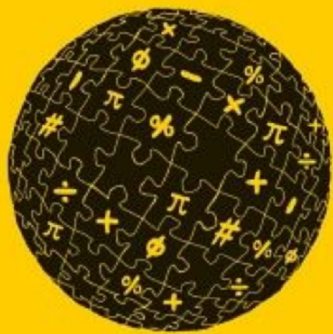


Photo 51, taken by Franklin, is a 1952 X-ray diffraction image of human DNA. The X-shape is due to DNA's double-helix structure.

Deoxyribonucleic acid (DNA) was identified as the carrier of genetic information in the human body in 1944, and its chemical composition was shown to be four different molecules called nucleotides. However, it was unclear how genetic information was stored in DNA. Three scientists – Linus Pauling, Francis Crick, and James Watson – put forward the hypothesis that DNA possessed a helical structure, and realized from work done by other scientists that if that was the case, its X-ray diffraction pattern would be X-shaped. British scientist Rosalind Franklin tested this theory by performing X-ray diffraction on crystallized pure DNA, beginning in 1950. After refining the technique over a period of two years, her analysis revealed an X-shaped pattern (best seen in "Photo 51"), proving that DNA had a helical structure. The Pauling, Crick, Watson hypothesis was proven, forming the starting point for further studies on DNA.

See also: Free falling • SI units and physical constants • Focusing light • Models of the Universe • Dark matter



ALL IS NUMBER

THE LANGUAGE OF PHYSICS

IN CONTEXT

KEY FIGURE

Euclid of Alexandria (*c.* 325–*c.* 270 BCE)

BEFORE

3000–300 BCE Ancient Mesopotamian and Egyptian civilizations develop number systems and techniques to solve mathematical problems.

600–300 BCE Greek scholars, including Pythagoras and Thales, formalize mathematics using logic and proofs.

AFTER

***c.* 630** CE Indian mathematician Brahmagupta uses zero and negative numbers in arithmetic.

***c.* 820** CE Persian scholar al-Khwarizmi sets down the principles of algebra.

***c.* 1670** Gottfried Leibniz and Isaac Newton each develop calculus, the mathematical study of continuous change.

Physics seeks to understand the Universe through observation, experiment, and building models and theories. All of these are intimately entwined with mathematics. Mathematics is the language of physics – whether used in measurement and data analysis in experimental science, or to provide rigorous expression for theories, or to describe the fundamental "frame of reference" in which all matter exists and events take place. The investigation of space, time, matter, and energy is only made possible through a prior understanding of dimension, shape, symmetry, and change.

Driven by practical needs

The history of mathematics is one of increasing abstraction. Early ideas about number and shape developed over time into the most general and precise language. In prehistoric times, before the advent of writing, herding animals and trading goods undoubtedly prompted the earliest attempts at tallying and counting.

As complex cultures emerged in the Middle East and Mesoamerica, demands for greater precision and prediction increased. Power was tied to knowledge of astronomical cycles and seasonal patterns, such as flooding. Agriculture and architecture required accurate calendars and land surveys. The earliest place value number systems (where a digit's position in a number indicates its value) and methods for solving equations date back more than 3,500 years to civilizations in Mesopotamia, Egypt, and (later) Mesoamerica.

"Number is the ruler of forms and ideas, and the cause of gods and daemons."

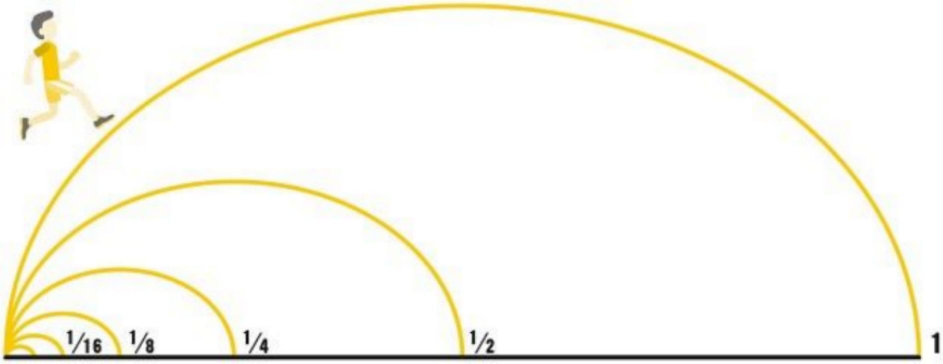
Pythagoras

Adding logic and analysis

The rise of ancient Greece brought about a fundamental change in focus. Number systems and measurement were no longer simply practical tools; Greek scholars also studied them for their own sake, together with shape and change. Although they inherited much specific mathematical knowledge from earlier cultures, such as elements of Pythagoras's theorem, the Greeks introduced the rigour of logical argument and an approach rooted in philosophy; the ancient Greek word *philosophia* means "love of wisdom".

The ideas of a theorem (a general statement that is true everywhere and for all time) and proof (a formal argument using the laws of logic) are first seen in the geometry of the Greek philosopher Thales of Miletus in the early 6th century BCE. Around the same time, Pythagoras and his followers elevated numbers to be the building blocks of the Universe.

For the Pythagoreans, numbers had to be "commensurable" – measurable in terms of ratios or fractions – to preserve the link with nature. This world view was shattered with the discovery of irrational numbers (such as √2, which cannot be exactly expressed as one whole number divided by another) by the Pythagorean philosopher Hippasus; according to legend, he was murdered by scandalized colleagues.



The dichotomy paradox is one of Zeno's paradoxes that show motion to be logically impossible. Before walking a certain distance a person must walk half that distance, before walking half the distance he must walk a quarter of the distance, and so on. Walking any distance will therefore entail an infinite number of stages that take an infinite amount of time to complete.

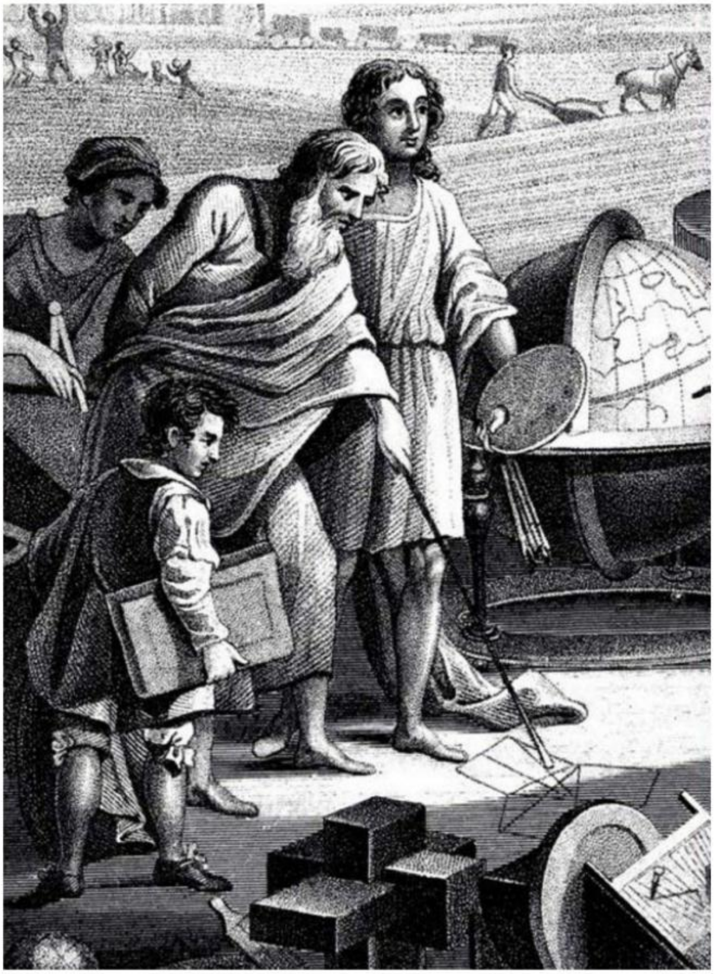
Titans of mathematics

In the 5th century BCE, the Greek philosopher Zeno of Elea devised paradoxes about motion, such as Achilles and the tortoise. This was the idea that, in any race where the pursued has a head start, the pursuer is always catching up – eventually by an infinitesimal amount. Such puzzles, which were logical – if simple to disprove in practice – would worry generations of mathematicians. They were resolved, at least partially, in the 17th century by the development of calculus, a branch of mathematics that deals with continuously changed quantities.

Central to calculus is the idea of calculating infinitesimals (infinitely small quantities), which was anticipated by Archimedes of Syracuse, who lived in the 3rd century BCE. To calculate the approximate volume of a sphere, for instance, he halved it, enclosed the hemisphere in a cylinder, then imagined slicing it horizontally, from the top of the hemisphere, where the radius is infinitesimally small, downwards. He knew that the thinner he made his slices, the more accurate the volume would be. Reputed to have shouted "Eureka!" on discovering that the upward buoyant force of an object immersed in water is equal to the weight of the fluid it displaces, Archimedes is notable for applying maths to mechanics and other branches of physics in order to solve problems involving levers, screws, pulleys, and pumps.

Archimedes studied in Alexandria, at a school established by Euclid, often known as the "Father of Geometry". It was by analysing geometry itself that Euclid established the template for mathematical argument for the next 2,000 years. His 13-book treatise, *Elements*, introduced the "axiomatic method" for geometry. He defined terms, such as "point", and outlined five axioms (also known as postulates, or self-evident truths), such as "a line segment can be drawn between any two points". From these axioms, he used the laws of logic to deduce theorems.

By today's standards, Euclid's axioms are lacking; there are numerous assumptions that a mathematician would now expect to be stated formally. *Elements* remains, however, a prodigious work, covering not only plane geometry and three-dimensional geometry, but also ratio and proportion, number theory, and the "incommensurables" that Pythagoreans had rejected.



Greek philosophers drew in the sand when teaching geometry, as shown here. Archimedes is said to have been drawing circles in the sand when he was killed by a Roman soldier.

Language and symbols

In ancient Greece and earlier, scholars described and solved algebraic problems (determining unknown quantities given certain known quantities and relationships) in everyday language and by using geometry. The highly-abbreviated, precise, symbolic language of modern mathematics – which is significantly more effective for analysing problems and universally understood – is relatively recent. Around 250 CE, however, the Greek mathematician Diophantus of Alexandria introduced the partial use of symbols to solve algebraic problems in his principal work *Arithmetica,* which influenced the development of Arabic algebra after the fall of the Roman Empire.

The study of algebra flourished in the East during the Golden Age of Islam (from the 8th century to the 14th century). Baghdad became the principal seat of learning. Here, at an academic centre called the House of Wisdom, mathematicians could study translations of Greek texts on geometry and number theory or Indian works discussing the decimal place-value system. In the early 9th century, Muhammad ibn Musa al-Khwarizmi (from whose name comes the word "algorithm") compiled methods for balancing and solving equations in his book *al Jabr* (the root of the word "algebra"). He popularized the use of Hindu numerals, which evolved into Arabic numerals, but still described his algebraic problems in words.

French mathematician François Viète finally pioneered the use of symbols in equations in his 1591 book, *Introduction to the Analytic Arts*. The language was not yet standard, but mathematicians could now write complicated expressions in a compact form, without resorting to diagrams. In 1637, French philosopher and mathematician René Descartes reunited algebra and geometry by devising the coordinate system.

Islamic scholars gather in one of Baghdad's great libraries in this 1237 image by the painter Yahya al-Wasiti. Scholars came to the city from all points of the Islamic Empire, including Persia, Egypt, Arabia, and even Iberia (Spain).

“Imaginary numbers are a fine and wonderful refuge of the divine spirit... almost an amphibian between being and non-being.”

Gottfried Leibniz

More abstract numbers

Over millennia, in attempts to solve different problems, mathematicians have extended the number system, expanding the counting numbers 1, 2, 3... to include fractions and irrational numbers. The addition of zero and negative numbers indicated increasing abstraction. In ancient number systems, zero had been used as a placeholder – a way to tell 10 from 100, for instance. By around the 7th century CE, negative numbers were used for representing debts. In 628 CE, the Indian mathematician Brahmagupta was the first to treat negative integers (whole numbers) just like the positive integers for arithmetic. Yet, even 1,000 years later, many European scholars still considered negative numbers unacceptable as formal solutions to equations.

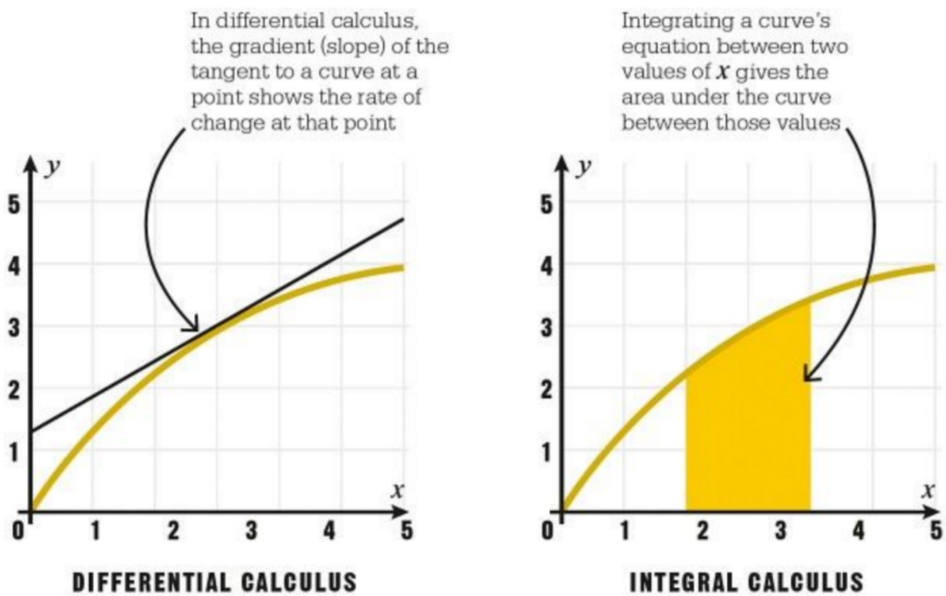
The 16th-century Italian polymath Gerolamo Cardano not only used negative numbers, but, in *Ars Magna*, introduced the idea of complex numbers (combining a real and imaginary number) to solve cubic equations (those with at least one variable to the power of three, such as x^3, but no higher). Complex numbers take the form $a + bi$, where a and b are real numbers and i is the imaginary unit, usually expressed as $i = \sqrt{-1}$. The unit is termed “imaginary” because when squared it is negative, and squaring any real number, whether it is positive or negative, produces a positive number. Although Cardano’s contemporary Rafael Bombelli set down the first rules for using complex and imaginary numbers, it took a further 200 years before Swiss mathematician Leonhard Euler introduced the symbol i to denote the imaginary unit.

Like negative numbers, complex numbers were met with resistance, right up until the 18th century. Yet they represented a significant advance in mathematics. Not only do they enable the solution of cubic equations but, unlike real numbers, they can be used to solve all higher-order polynomial equations (those involving two or more terms added together and higher powers of a variable x, such as x^4 or x^5). Complex numbers emerge naturally in many branches of physics, such as quantum mechanics and electromagnetism.

"A new, a vast, and a powerful language is developed for the future use of analysis, in which to wield its truths so that these may become of more speedy and accurate practical application for the purposes of mankind."

Ada Lovelace

British computer scientist

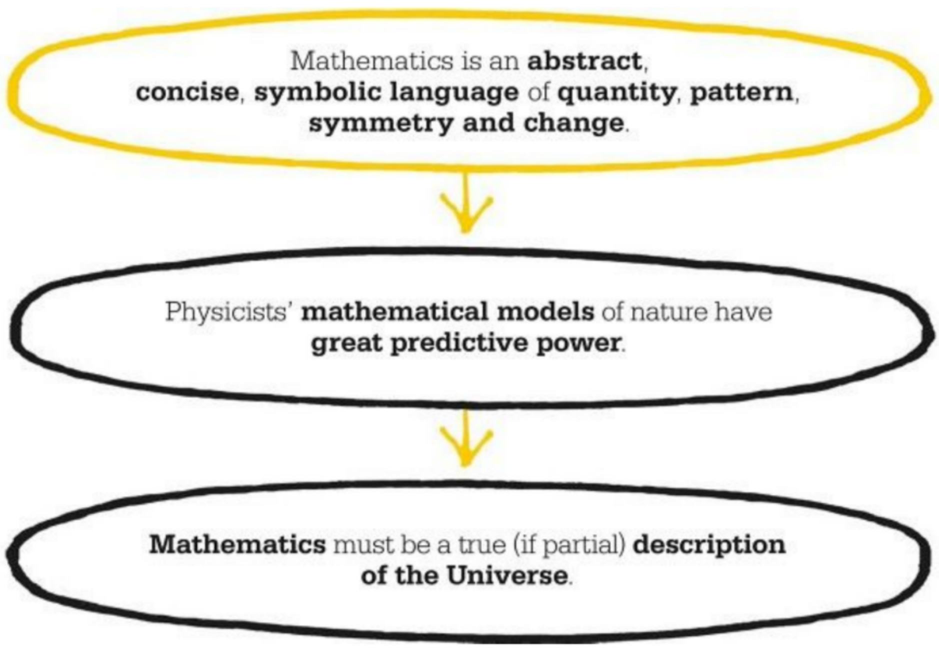


Differential calculus examines the rate of change over time, shown geometrically here as the rate of change of a curve. Integral calculus examines the areas, volumes, or displacement bounded by curves.

Infinitesimal calculus

From the 14th century to the 17th century, together with the increasing use of symbols, many new methods and techniques emerged. One of the most significant for physics, was the development of "infinitesimal" methods in order to study curves and change. The ancient Greek method of exhaustion – finding the area of a shape by filling it with smaller polygons – was refined in order to compute areas bounded by curves. It objects, called groups, to encode different kinds of symmetries. For example, all squares exhibit the same reflectional and rotational symmetries, and so are associated with a particular group. From his research, Galois determined that, unlike for quadratic equations (with a variable to the power of two, such as $\boldsymbol{x}^2$, but no higher), there is no general formula to solve polynomial equations of degree five (with terms such as $\boldsymbol{x}^5$) or higher. This was a dramatic result; he had proved that there could be no such formula, no matter what future developments occurred in mathematics.

Subsequently, algebra grew into the abstract study of groups and similar objects, and the symmetries they encoded. In the 20th century, groups and symmetry proved vital for describing natural phenomena at the deepest level. In 1915, German algebraist Emmy Noether connected symmetry in equations with conservation laws, such as the conservation of energy, in physics. In the 1950s and 1960s, physicists used group theory to develop the Standard Model of particle physics.



Modelling reality

Mathematics is the abstract study of numbers, quantities, and shapes, which physics employs to model reality, express theories, and predict future outcomes – often with astonishing accuracy. For example, the electron g-factor – a measure of its behaviour in an electromagnetic field – is computed to be 2.002 319 304 361 6, while the experimentally determined value is 2.002 319 304 362 5 (differing by just one part in a trillion).

Certain mathematical models have endured for centuries, requiring only minor adjustments. For example, German astronomer Johannes Kepler's 1619 model of the Solar System, with some refinements by Newton and Einstein, remains valid today. Physicists have applied ideas that mathematicians developed, sometimes much earlier, simply to investigate a pattern; for instance, the application of 19th-century group theory to modern quantum physics. There are also many examples of mathematical structures driving insight into nature. When British physicist Paul Dirac found twice as many expressions as expected in his equations describing the behaviour of electrons, consistent with relativity and quantum mechanics, he postulated the existence of an anti-electron; it was duly discovered, years later.

While physicists investigate what "is" in the Universe, mathematicians are divided as to whether their study is about nature, or the human mind, or the abstract manipulation of symbols. In a strange historical twist, physicists researching string theory are now suggesting revolutionary advances in pure mathematics to geometers (mathematicians who study geometry). Just exactly how this illuminates the relationship between mathematics, physics, and "reality" is yet to be seen.

Emmy Noether was a highly creative algebraist. She taught at the University of Göttingen in Germany, but as a Jew was forced to leave in 1933. She died in the US in 1935, aged 53.

EUCLID

Although his *Elements* were immensely influential, few details of Euclid's life are known. He was born around 325 BCE, in the reign of Egyptian pharaoh Ptolemy I and probably died around 270 BCE. He lived mostly in Alexandria, then an important centre of learning, but he may also have studied at Plato's academy in Athens.

In *Commentary on Euclid*, written in the 5th century CE, the Greek philosopher Proclus notes that Euclid arranged the theorems of Eudoxus, an earlier Greek mathematician, and brought "irrefutable demonstration" to the loose ideas of other scholars. Thus, the theorems of the 13 books of Euclid's *Elements* are not original, but for two millennia they set the standard for mathematical exposition. The earliest surviving editions of the *Elements* date from the 15th century.

Key works

Elements

Data

Catoptrics

Optics

See also: Measuring distance • Measuring time • Laws of motion • SI units and physical constants • Antimatter • The particle zoo and quarks • Curving spacetime

BODIES SUFFER NO RESISTANCE BUT FROM THE AIR

FREE FALLING

IN CONTEXT

KEY FIGURE

Galileo Galilei (1564–1642)

BEFORE

***c.* 350 BCE** In *Physics*, Aristotle explains gravity as a force that moves bodies towards their "natural place", down towards the centre of Earth.

1576 Giuseppe Moletti writes that objects of different weights free fall at the same rate.

AFTER

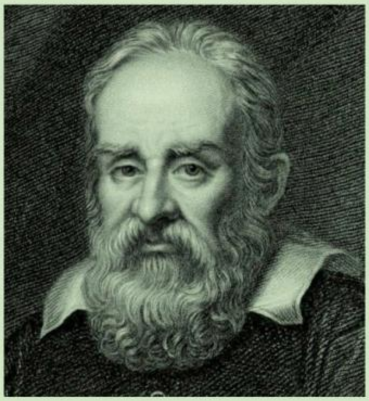
1651 Giovanni Riccioli and Francesco Grimaldi measure the time of descent of falling bodies, enabling calculation of their rate of acceleration.

1687 In *Principia*, Isaac Newton expounds gravitational theory in detail.

1971 David Scott shows that a hammer and a feather fall at the same speed on the Moon.

When gravity is the only force acting on a moving object, it is said to be in "free fall". A skydiver falling from a plane is not quite in free fall – since air resistance is acting upon him – whereas planets orbiting the Sun or another star are. The ancient Greek

GALILEO GALILEI



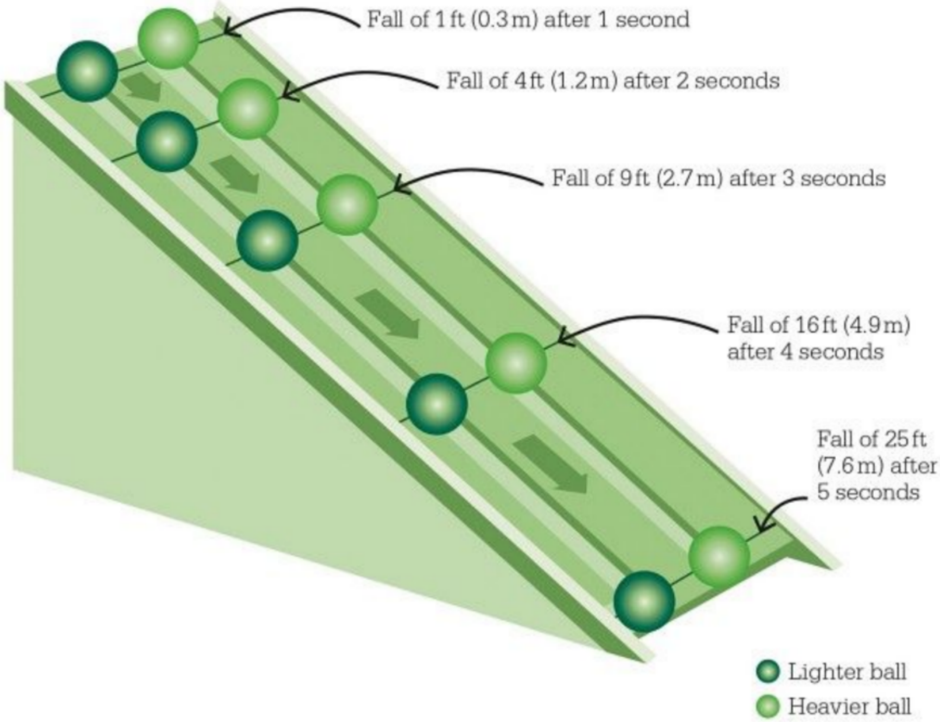
The oldest of six siblings, Galileo was born in Pisa, Italy, in 1564. He enrolled to study medicine at the University of Pisa at the age of 16, but his interests quickly broadened and he was appointed Chair of Mathematics at the University of Padua in 1592. Galileo's contributions to physics, mathematics, astronomy, and engineering mark him out as one of the key figures of the Scientific Revolution in 16th- and 17th- century Europe. He created the first thermoscope (an early thermometer), defended the Copernican idea of a heliocentric Solar System, and made important discoveries about gravity. Because some of his ideas challenged Church dogma, he was called before the Roman Inquisition in 1633, declared to be a heretic, and sentenced to house arrest until his death in 1642.

Key works

1623 *The Assayer*

1632 *Dialogue Concerning the Two Chief World Systems*

1638 *Discourses and Mathematical Demonstrations Relating to Two New Sciences*



Galileo showed that objects of different mass accelerate at a constant rate. By timing how long a ball took to travel a particular distance down a slope, he could work out its acceleration. The distance fallen was always proportional to the square of the time taken to fall.

Balls on ramps

From 1603, Galileo set out to investigate the acceleration of free-falling objects. Unconvinced that they fell at a constant speed, he believed that they accelerated as they fell – but the problem was how to prove it. The technology to accurately record such speeds simply did not exist. Galileo's ingenious solution was to slow down the motion to a measurable speed, by replacing a falling object with a ball rolling down a sloping ramp. He timed the experiment using both a water clock – a device that weighed the water spurting into an urn as the ball travelled – and his own pulse. If he doubled the period of time the ball rolled, he found the distance it travelled was four times as far.

Leaving nothing to chance, Galileo repeated the experiment "a full hundred times" until he had achieved "an accuracy such that the deviation between two observations never exceeded one-tenth of a pulse beat". He also changed the incline of the ramp: as it became steeper, the acceleration increased uniformly. Since Galileo's experiments were not carried out in a vacuum, they were imperfect – the moving balls were subject to air resistance and friction from the ramp. Nevertheless, Galileo concluded that in a vacuum, all objects – regardless of weight or shape – would accelerate at a uniform rate: the square of the elapsed time of the fall is proportional to the distance fallen.

In this fresco by Giuseppe Bezzuoli, Galileo is shown demonstrating his rolling-ball experiment in the presence of the powerful Medici family in Florence.

Quantifying gravitational acceleration

In spite of Galileo's work, the question of the acceleration of free-falling objects was still contentious in the mid-17th century. From 1640 to 1650, Jesuit priests Giovanni Riccioli and Francesco Grimaldi conducted various investigations in Bologna. Key to their eventual success were Riccioli's time-keeping pendulums – which were as accurate as any available at the time – and a very tall tower. The two priests and their assistants dropped heavy objects from various levels of the 98-m (321-ft) Asinelli

Tower, timing their descents. The priests, who described their methodology in detail, repeated the experiments several times.

Riccioli believed that free-falling objects accelerated exponentially, but the results showed him that he was wrong. A series of falling objects were timed by pendulums at the top and bottom of the tower. They fell 15 Roman feet (1 Roman foot = 29.57 cm) in 1 second, 60 feet in 2 seconds, 135 feet in 3 seconds, and 240 feet in 4 seconds. The data, published in 1651, proved that the distance of descent was proportional to the square of the length of time the object was falling – confirming Galileo's ramp experiments. And for the first time, due to relatively accurate time-keeping, it was possible to work out the value of acceleration due to gravity: 9.36 (±0.22) m/s^2. This figure is only about 5 per cent less than the range of figures accepted today: around 9.81 m/s^2.

The value of $\boldsymbol{g}$ (gravity) varies according to a number of factors: it is greater at Earth's poles than at the equator, lower at high altitudes than at sea level, and it varies very slightly according to local geology, for example if there are particularly dense rocks near Earth's surface. If the constant acceleration of an object in free fall near Earth's surface is represented by $\boldsymbol{g}$, the height at which it is released is $\boldsymbol{z}_0$ and time is $\boldsymbol{t}$, then at any stage in its descent, the height of the body above the surface $\boldsymbol{z} = \boldsymbol{z}_0 - {}^1/_2\, \boldsymbol{gt}^2$, where $\boldsymbol{gt}$ is the speed of the body and $\boldsymbol{g}$ its acceleration. A body of mass $\boldsymbol{m}$ at a height $\boldsymbol{z}_0$ above Earth's surface possesses gravitational potential energy $\boldsymbol{U}$, which can be calculated by the equation $\boldsymbol{U} = \boldsymbol{mgz}_0$ (mass × acceleration × height above Earth's surface).

"When Galileo caused balls... to roll down an inclined plane, a light broke upon all students of nature."

Immanuel Kant

German philosopher

The hammer and the feather

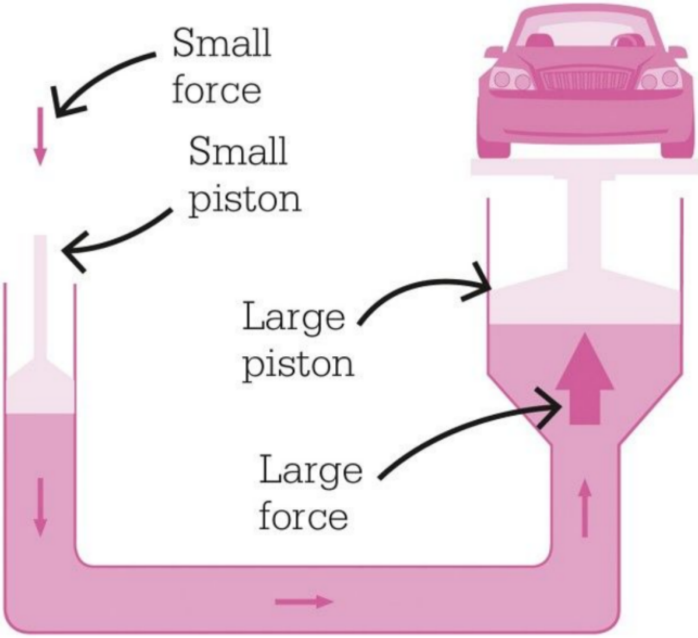
In 1971, American astronaut David Scott – commander of the Apollo 15 Moon mission – performed a famous free-fall experiment. The fourth NASA expedition to land on the Moon, Apollo 15 was capable of a longer stay on the Moon than previous expeditions, and its crew was the first to use a Lunar Roving Vehicle.

Apollo 15 also featured a greater focus on science than earlier Moon landings. At the end of the mission's final lunar walk, Scott dropped a 1.32-kg geological hammer and a 0.03-kg falcon's feather from a height of 1.6 m. In the virtual vacuum conditions of the Moon's surface, with no air resistance, the ultralight feather fell to the ground at the same speed as the heavy hammer. The experiment was filmed, so this confirmation of Galileo's theory that all objects accelerate at a uniform rate regardless of mass was witnessed by a television audience of millions.

"In questions of science, the authority of a thousand is not worth the humble reasoning of a single individual."

Galileo Galilei

See also: Measuring distance • Measuring time • Laws of motion • Laws of gravity • Kinetic energy and potential energy



Liquids cannot be compressed and are used to transmit forces in hydraulics systems such as car jacks. A small force applied over a long distance is turned into a larger force over a small distance, which can raise a heavy load.

See also: Laws of motion • Stretching and squeezing • Fluids • The gas laws

THE MOST WONDERFUL PRODUCTIONS OF THE MECHANICAL ARTS

MEASURING TIME

IN CONTEXT

KEY FIGURE

Christiaan Huygens (1629–95)

BEFORE

***c.* 1275** The first all-mechanical clock is built.

1505 German clockmaker Peter Henlein uses the force from an uncoiling spring to make the first pocket watch.

1637 Galileo Galilei has the idea for a pendulum clock.

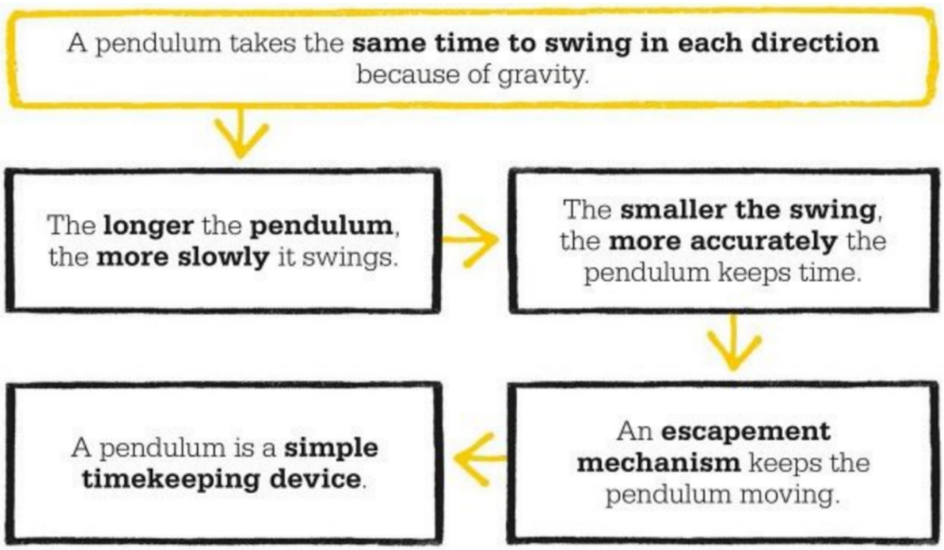
AFTER

***c.* 1670** The anchor escapement mechanism makes the pendulum clock more accurate.

1761 John Harrison's fourth marine chronometer, H4, passes its sea trials.

1927 The first electronic clock, using quartz crystal, is built.

1955 British physicists Louis Essen and Jack Parry make the first atomic clock.

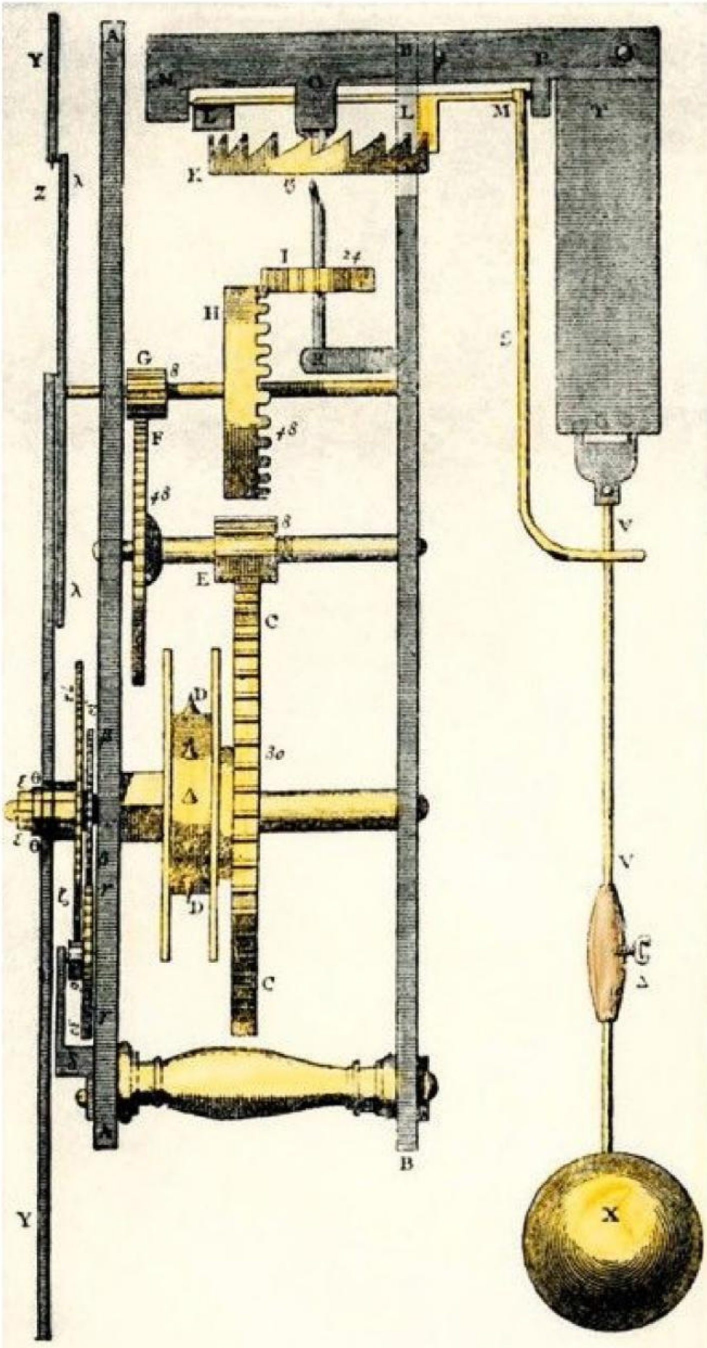


Two inventions in the mid-1650s heralded the start of the era of precision timekeeping. In 1656, Dutch mathematician, physicist, and inventor Christiaan Huygens built the first pendulum clock. Soon after, the anchor escapement was invented, probably by English scientist Robert Hooke. By the 1670s, the accuracy of timekeeping devices had been revolutionized.

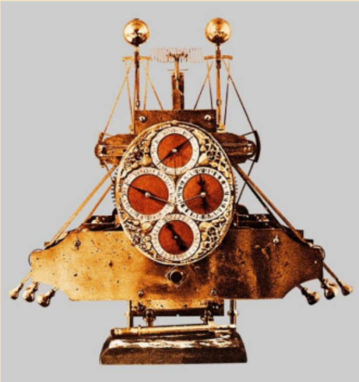
The first entirely mechanical clocks had appeared in Europe in the 13th century, replacing clocks reliant on the movement of the Sun, the flow of water, or the burning of a candle. These mechanical clocks relied on a "verge escapement mechanism", which transmitted force from a suspended weight through the timepiece's gear train, a series of toothed wheels. Over the next three centuries, there were incremental advances in the accuracy of these clocks, but they had to be wound regularly and still weren't very accurate.

In 1637, Galileo Galilei had realized the potential for pendulums to provide more accurate clocks. He found that a swinging pendulum was almost isochronous, meaning the time it took for the bob at its end to return to its starting point (its period) was roughly the same whatever the length of its swing. A pendulum's swing could produce a more accurate way of keeping time than the existing mechanical clocks. However, he hadn't managed to build one before his death in 1642.

Huygens' first pendulum clock had a swing of 80–100 degrees, which was too great for complete accuracy. The introduction of Hooke's anchor escapement, which maintained the swing of the pendulum by giving it a small push each swing, enabled the use of a longer pendulum with a smaller swing of just 4–6 degrees, which gave much better accuracy. Before this, even the most advanced non-pendulum clocks lost 15 minutes a day; now that margin of error could be reduced to as little as 15 seconds.


Y
A
B
P
T
N
O
L
L
M
K
I
24
H
G
8
F
48
48
8
E
C
D
30
D
C
V
V
X
B
Y
Z
A

Harrison's marine chronometer

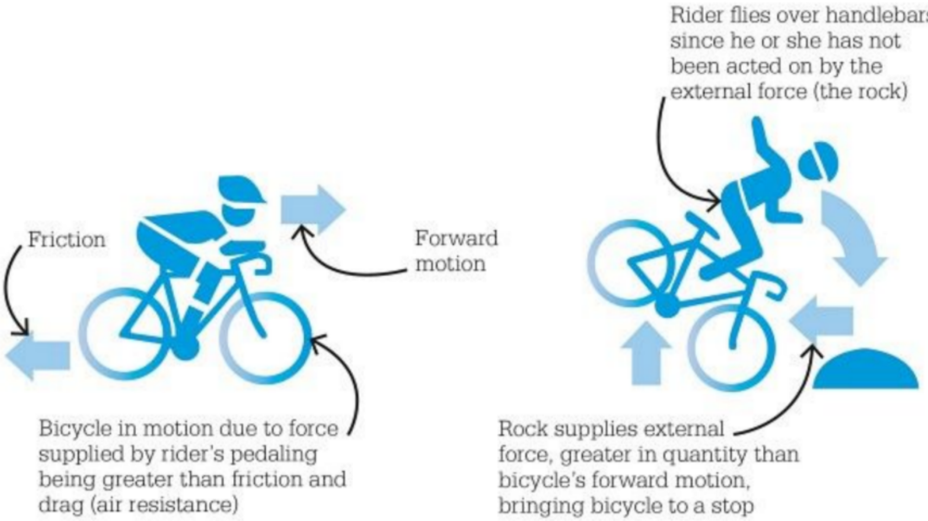


John Harrison's prototype chronometer, H1, underwent sea trials from Britain to Portugal in 1736, losing just a few seconds on the entire voyage.

In the early 18th century, even the most accurate pendulum clocks didn't work at sea – a major problem for nautical navigation. With no visible landmarks, calculating a ship's position depended on accurate latitude and longitude readings. While it was easy to gauge latitude (by viewing the position of the Sun), longitude could be determined only by knowing the time relative to a fixed point, such as the Greenwich Meridian. Without clocks that worked at sea, this was impossible. Ships were lost and many men died, so, in 1714, the British government offered a prize to encourage the invention of a marine clock.

British inventor John Harrison solved the problem in 1761. His marine chronometer used a fast-beating balance wheel and a temperature-compensated spiral spring to achieve remarkably accurate timekeeping on transatlantic journeys. The device saved lives and revolutionized exploration and trade.

See also: Free falling • Harmonic motion • SI units and physical constants • Subatomic particles



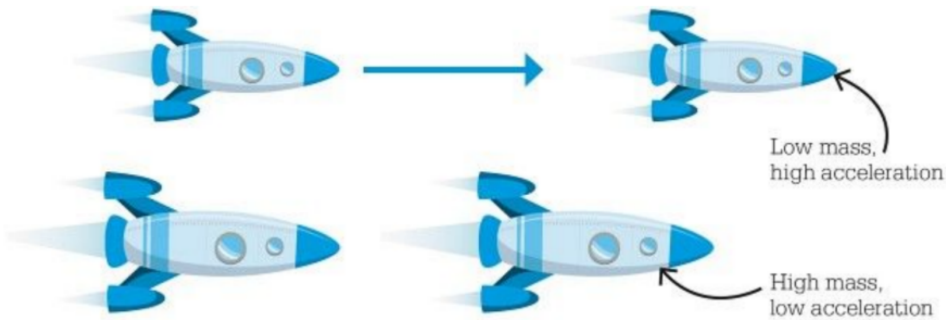
The bicycle is in motion due to the force supplied by the pedalling of the rider, until the external force of the rock acts upon it, causing it to stop.

Law of inertia

Newton's first law of motion, which is sometimes called the law of inertia, explains that an object at rest stays at rest, and an object in motion remains in motion with the same velocity unless acted upon by an external force. For instance, if the front wheel of a bicycle being ridden at speed hits a large rock, the bike is acted upon by an external force, causing it to stop. Unfortunately for the cyclist, he or she will not have been acted upon by the same force and will continue in motion – over the handlebars.

For the first time, Newton's law enabled accurate predictions of motion to be made. Force is defined as a push or pull exerted on one object by another and is measured in Newtons (denoted N, where 1 N is the force required to give a 1 kg mass an acceleration of 1 m/s^2). If the strength of all the forces on an object are known, it is possible to calculate the net external force – the combined total of the external forces – expressed as $\Sigma \boldsymbol{F}$ (Σ stands for "sum of"). For example, if a ball has a force of 23 N pushing it left, and a force of 12 N pushing it right, $\Sigma \boldsymbol{F}$ = 11 N in a leftward direction. It is not quite as simple as this, since the downward force of gravity will also be acting on the ball, so horizontal and vertical net forces also need to be taken into account.

There are other factors at play. Newton's first law states that a moving object that is not acted upon by outside forces should continue to move in a straight line at a constant velocity. But when a ball is rolled across the floor, for example, why does it eventually stop? In fact, as the ball rolls it experiences an outside force: friction, which causes it to decelerate. According to Newton's second law, an object will accelerate in the direction of the net force. Since the force of friction is opposite to the direction of travel, this acceleration causes the object to slow and eventually stop. In interstellar space, a spacecraft will continue to move at the same velocity because of an absence of friction and air resistance – unless it is accelerated by the gravitational field of a planet or star, for example.



Two rockets with different masses but identical engines will accelerate at different rates. The smaller rocket will accelerate more quickly due to its lower mass.

Change is proportional

Newton's second law is one of the most important in physics, and describes how much an object accelerates when a given net force is applied to it. It states that the rate of change of a body's momentum – the product of its mass and velocity – is proportional to the force applied, and takes place in the direction of the applied force.

This can be expressed as $\Sigma \boldsymbol{F} = \boldsymbol{ma}$, where $\boldsymbol{F}$ is the net force, $\boldsymbol{a}$ is the acceleration of the object in the direction of the net force, and $\boldsymbol{m}$ is its mass. If the force increases, so does acceleration. Also, the rate of change of momentum is inversely proportional to the mass of the object, so if the object's mass increases, its acceleration decreases. This can be expressed as $\boldsymbol{a} = \Sigma \boldsymbol{F}/\boldsymbol{m}$. For example, as a rocket's fuel propellant is burned during flight, its mass decreases and – assuming the thrust of its engines remains the same – it will accelerate at an ever-faster rate.

"The laws of motion... are the free decrees of God."

Gottfried Leibniz

Equal action and reaction

Newton's third law states that for every action there is an equal and opposite reaction. Sitting down, a person exerts a downward force on the chair, and the chair exerts an equal upward force on the person's body. One force is called the action, the other the reaction. A rifle recoils after it is fired due to the opposing forces of such an action–reaction. When the rifle's trigger is pulled, a gunpowder explosion creates hot gases that expand outwards, allowing the rifle to push forward on the bullet. But the bullet also pushes backwards on the rifle. The force acting on the rifle is the same as the force that acts on the bullet, but because acceleration depends on force and mass (in accordance with Newton's second law), the bullet accelerates much faster than the rifle due to its far smaller mass.

Notions of time, distance, and acceleration are fundamental to an understanding of motion. Newton argued that space and time are entities in their own right, existing independently of matter. In 1715–16, Leibniz argued in favour of a relationist alternative: in other words, that space and time are systems of relations between objects. While Newton believed that absolute time exists independently of any observer and progresses at a constant pace throughout the Universe, Leibniz reasoned that time makes no sense except when understood as the relative movement of bodies. Newton argued that absolute space "remains always similar and immovable", but his German critic argued that it only makes sense as the relative location of objects.

From Leibniz to Einstein

image
not
available

image
not
available

image
not
available

image
not
available

image
not
available

image
not
available

Getty Images: Bettmann (bl). **97 Getty Images:** Stocktrek Images / Richard Roscoe (br). **98 ESO:** (bl). **99 Getty Images:** Alicia Llop (br). **103 Alamy Stock Photo:** History and Art Collection (tr). **Dreamstime.com:** Franco Nadalin (bl). **107 iStockphoto.com:** Danielle Kuck (br). **109 Getty Images:** Imagno / Hulton Archive (bl). **110 SuperStock:** Fototeca Gilardi / Marka (tr). **111 Dreamstime.com:** Victor Zastol`skiy / Vicnt (bl). **115 Getty Images:** Science & Society Picture Library (bl). **NASA:** Far-infrared: ESA / Herschel / PACS / SPIRE / Hill, Motte, HOBYS Key Programme Consortium; X-ray: ESA / XMM-Newton / EPIC / XMM-Newton-SOC / Boulanger (tl). **117 Getty Images:** Mark Garlick / Science Photo Library (tr). **123 Wellcome Collection http://creativecommons.org/licenses/by/4.0/:** (tr). **125 Dreamstime.com:** Danielkmalloy (tr). **127 Alamy Stock Photo:** Interfoto / Personalities (bl). **129 Alamy Stock Photo:** Prisma Archivo (bc). **Dreamstime.com:** Ovydyborets (bc/background). **Wellcome Collection http://creativecommons.org/licenses/by/4.0/:** (tr). **132 Getty Images:** Science & Society Picture Library (bl). **133 iStockphoto.com:** choness (bc). **135 Alamy Stock Photo:** Granger Historical Picture Archive (tr); World History Archive (tl). **137 Wellcome Collection http://creativecommons.org/licenses/by/4.0/:** (bl). **139 Alamy Stock Photo:** Science History Images (tr). **145 Getty Images:** Corbis Historical / Stefano Bianchetti (bl). **147 Alamy Stock Photo:** World History Archive (tr). **149 Alamy Stock Photo:** Everett Collection Historical (cla). **151 iStockphoto.com:** querbeet (bc). **Wellcome Collection http://creativecommons.org/licenses/by/4.0/:** (tr). **153 Alamy Stock Photo:** Pictorial Press Ltd (cb). **155 Science Photo Library:** Emilio Segre Visual Archives / American Institute Of Physics (tl). **156 Getty Images:** Ken Kiefer 2 (bc). **158 Getty Images:** Roger Ressmeyer / Corbis / VCG (br). **166 Dreamstime.com:** James Steidl (br). **167 Alamy Stock Photo:** FLHC 80 (tl). **Wellcome Collection http://creativecommons.org/licenses/by/4.0/:** (tr). **169 Alamy Stock Photo:** The Granger Collection (bl). **Unsplash:** Michael Heuser / @gum_meee (cra). **174 Science Photo Library:** (tl). **175 Getty Images:** Science & Society Picture Library (bc). **Wellcome Collection http://creativecommons.org/licenses/by/4.0/:** (tr). **177 Getty Images:** Science Photo Library / David Parker (tl). **179 Alamy Stock Photo:** Science History Images / Photo Researchers (tl). **181 Alamy Stock Photo:** Durk Gardenier (cra). **182 Getty Images:** De Agostini Picture Library (tl). **183 Unsplash:** Lanju Fotografie / @lanju_fotografie (tl). **185 iStockphoto.com:** Darunechka (br). **186 Wellcome Collection http://creativecommons.org/licenses/by/4.0/:** (bl). **189 Getty Images:** Imagno / Hulton Archive (tr). **191 NASA:** ESA, R. Ellis (Caltech), and the HUDF 2012 Team (br). **193 Alamy Stock Photo:** Cola Images (cla). **195 Alamy Stock Photo:** World History Archive (tr). **197 Science Photo Library:** Mark A. Schneider (cla). **199 Alamy Stock Photo:** Archive Pics (tr). **201 Alamy Stock Photo:** Lordprice Collection (tr). **Pixabay:** KatinkavomWolfenmond / 57 images (bc). **203 Alamy Stock Photo:** Geraint Lewis (bl). **Science Photo Library:** Max-Planck-Institut Fur Radioastronomie (tr). **210 NASA:** (tl). **211 Alamy Stock Photo:** Science History Images (tr). **214 Alamy Stock Photo:** Science History Images (bl). **215 Getty Images:** ullstein picture Dtl. (bl). **216 Getty Images:** Encyclopaedia Britannica / Universal Images Group (br). **217 Science Photo Library:** Emilio Segre Visual Archives / American Institute Of Physics (tr). **219 Getty Images:** Bettmann (br). **221 Alamy Stock Photo:** Pictorial Press Ltd (cla). **223 Getty Images:** Mark Garlick / Science Photo Library (bc). **Science Photo Library:** Peter Menzel (tr). **225 Getty Images:** Bettmann (bl). **228 Science Photo Library:** Patrick Gaillardin / Look At Sciences (tc). **229**

Picture Research Manager Taiyaba Khatoon

Pre-Production Manager Balwant Singh

Production Manager Pankaj Sharma

Managing Art Editor Sudakshina Basu

Senior Managing Editor Rohan Sinha

Digital Production

Digital Programme Manager Miguel Cunha
Senior Manager Lakshmi Rao

Producer Suruchi Kakkar

Software Engineer Rachana Kishore

Production Manager Nain Rawat

Production Coordinator Manish Bhatt

original styling by

STUDIO 8

First published in Great Britain in 2020 by Dorling Kindersley Limited, 80 Strand, London, WC2R 0RL

A Penguin Random House Company

A CIP catalogue record for this book is available from the British Library.

ISBN: 9780241412725

This digital edition published 2020
ISBN: 9780241450048

A WORLD OF IDEAS:
SEE ALL THERE IS TO KNOW

www.dk.com