

## The Scientific Revolution

In the Late Middle Ages, an élite group of intellectuals had gained insight into natural phenomena by the tentative approach to objective methods of observing and understanding nature. The empiricism of some progressive artists, anatomists, travellers, navigators, alchemists and other progress-oriented people had spurred curiosity and the desire to gain  
5 insight into what our world was like and to understand it in a wider context.

The 16th century saw an explosion of scientific curiosity which resulted in a vast number of scientific discoveries. In the 17th century, then, the clear definition of scientific methodology was completed and the traditional Aristotelian worldview was abandoned to be replaced by a new, science-based, view of the world. This era of invention and discovery was  
10 later dubbed the “Scientific Revolution”. At the end of this period the view of the world had revolutionized and would later provide the basis for a new age, the “Modern” Age.

### ***Causes of the Scientific Revolution***

Various factors were responsible for the breakthrough of the Scientific Revolution.

In the Late Middle Ages, the growing number of universities supplied a platform for intellectual discourse across national boundaries. The generally acknowledged canon of the  
15 seven “Liberal Arts,” which included mathematics, geometry and astronomy, provided every academic with knowledge of the essentials of scientific studies. Moreover, scholastic scholars taught that “doubt” was a basic approach to finding out what was “true”. This was the starting point for the conception of new methods to understand the natural order of the world. The invention of book printing made it possible for scholars to propagate their ideas quickly and  
20 relatively cheaply into all corners of the Western world.

During the Renaissance new impetus was provided for the development of a scientific worldview. When in the first half of the 15th century the Byzantine Empire was finally overthrown by the Turks, a large number of Greek scholars and intellectuals fled to the West. They brought with them the texts of those ancient Greek philosophers who contradicted  
25 Aristotle. As a consequence, the absolute authority of Aristotle as a natural philosopher was challenged.

The voyages of discovery (q. v.) provided stimuli in manifold ways. Newly discovered countries contained hitherto unknown plants, animals, and landscapes. The desire to explore, study, and survey the fauna and flora of the Americas, of the Far East, and of the Pacific  
30 islands was due mainly to economic considerations, as many of the plants and animals provided useful food, or drugs, or spice. The Europeans, moreover, were confronted with people from distant countries hitherto unknown, and their cultures, which considerably broadened their horizon and shook their confidence and their conviction that European civilization was unrivalled in the world. Voyages into unknown areas of the world across open

seas required improved methods and instruments for accurate positioning at sea. New findings in astronomy, geometry, and mathematics provided the basis for these. Improved mathematical and astronomical calculations also made it possible to revise and perfect the inaccurate Roman calendar.

### ***The Development of Scientific Methodology***

5 The foundations for a specifically scientific methodology were laid down by some scholastic thinkers from the 13th century onwards (see the chapter on Science and Technology in the Middle Ages). Roger Bacon, for example, only accepted knowledge which had been inquired at the original source. To him, *Scientia experimentalis*, i. e. science based upon empirical methods was the only “true” science, and he expressed strong disapproval of theoretical  
10 speculation or assumption, as he thought they would lead away from truth. Characteristic of his methodology was the cycle of *observation*, *hypothesis*, *experimentation*, and the possibility of objective *verification*. Bacon also promoted mathematics, which he regarded as the ABC of philosophy. His ideas were, however, denounced as heretical by his Church authorities, however, and thus became almost forgotten. The undisputed authority of the  
15 Aristotelian world view was not shaken, yet. Only a few members of the intellectual elite dared follow in Bacon’s footsteps, knowingly or unknowingly. 250 years after Bacon, Leonardo da Vinci also promoted research based upon careful and systematic observations from which he drew his conclusions.

In the context of the humanist movement, Aristotle lost his aura as the one and only  
20 authority in scientific matters (see above). The voyages of discovery had changed people’s outlook on the world, and many of them were convinced that the authorities were not always reliable; they started to doubt the correctness of traditional opinions and began to observe, to describe the natural world, and to experiment in order to arrive at reliable conclusions about nature. The new set of methods which was beginning to emerge was built upon the systematic  
25 questioning of all traditional doctrines on natural matters, upon systematic observation, systematic experimentation, and the application of mathematical laws.

The first true scientist to launch an open attack on the undisputed authorities on scientific issues, the Bible and Aristotle, was Galileo Galilei (1564–1642). In his Letter to the Grand  
Duchess Christina (1615) and his Dialogue Concerning the Two Chief World Systems  
30 (*Dialogo sopra i due massimi sistemi del mondo*, 1632) he made it quite clear to the world that, to his mind, scientific truths could only be obtained through observation and experiment.

The champion of modern science at an early stage was the English statesman and philosopher Francis Bacon (1561–1626). Bacon was not a scientist himself, but he understood and propagated the essence of scientific thinking and the importance of science for future  
35 generations. In his important and influential book *Novum Organum Scientiarum*, (1620, Engl. *New Instrument of Science*) he challenges the “idols” of philosophical thought. Aristotle and

other authorities are refuted, as they establish axioms “by argumentation” and thus hamper the understanding of natural matters. Instead of such misleading ways of finding truth, Bacon invited his contemporaries to establish axioms “derived from the senses and particulars” as thus they would “easily discover the way to new particulars” so that at last they would arrive “at the most general axioms.” This inductive methodology for the study of science had experimental research as its cornerstone – it was practical and empirical.

Bacon’s contemporary René Descartes, a mathematician, natural philosopher and scientist, followed a completely different path to finding truth; his approach was theoretical and rational. In his book *Discours de la méthode pour bien conduire sa raison et*

*chercher la vérité dans les sciences* (1637, Engl. *Discourse on Method*), Descartes advocated a deductive methodical approach to acquiring

reliable knowledge. Very early in his thinking, he understood that everything that was accepted as undisputedly true was possibly false. He, therefore, searched for a way to arrive at undoubtedly “true” conclusions. Descartes decided that his own reason was the only instrument by which he could achieve this goal. He reasoned that obviously the mind was able to understand a large number of ideas and concepts that had existed even before human experience had helped to discover them, like, for example, mathematical principles, or concepts of cause and effect. This ability of the mind would enable him to radically re-think the world. Starting out with himself, he stated that his own mind gave certainty to his own existence (“Cogito, ergo sum,” English: “I think, therefore I am”). If enquiring systematically and stringently, it would also be possible for human thinkers to make objective and true statements about everything existing. In this way, Descartes established a method of enquiry which would enable mankind to understand nature.



Image 1: Frontispiece to Johannes Kepler, *Tabulae Rudolphinae*. 1627. The pillars bear the names of important astronomers. The newly built columns in the foreground bear the names of Copernicus and Tycho Brahe, while the rather dated ones on the right and left hand sides of the “House of astronomy” have the names of eminent ancient scientists, like Ptolemy, Hipparchus and Aristotle on them. Dangling from the pillars are astronomical instruments. (Source:Wikimedia Commons)

## **Landmarks of the Scientific Revolution**

### **Mathematics, physics, astronomy**

It was the mathematical and astronomical problems discussed in the Late Middle Ages that were found to be most challenging for inquiring minds. In the Late Middle Ages, the Church authorities had encouraged mathematicians to study the movements of celestial bodies and apply their mathematical knowledge and skills, so that the long-desired and ambitious project of the reform of the Calendar could be completed. This took until 1582, when the new calendar was introduced by Pope Gregory XIII.

For this reason, it is not surprising to find astronomers and mathematicians driven by the motivation to understand God's creation and its perfection in the universe. One of them was the Polish clergyman Nicolaus Copernicus (1473–1543) whose main interest was astronomy and mathematics. As early as 1507–1515, he wrote a book in which he declared Ptolemy's earth-centred astronomy as faulty and suggested that the heliocentric universe was probable. This book was not published in his lifetime. His major work *On the Revolutions of the Celestial Spheres* was completed in 1530. Copernicus had worked on it for more than 20 years. Even as a student in Bologna, he had lived at the home of a professor of mathematics who blamed the geocentric system of Ptolemy for containing too many contradictions. It was then that Copernicus started to doubt the veracity of the Ptolemaic universe. Copernicus was a devout clergyman; throughout his lifetime he had strong inclinations towards the spiritual and mystical aspects of his religion, and it was for this reason that he was convinced that the Ptolemaic system was too complicated and did not really reflect God's creation. Copernicus thought that God's universe must be based upon simpler, more harmonious, mathematical principles, and it was his objective to find these principles. By way of mathematical calculation, he eventually understood that Ptolemy had been all wrong, and that the Sun, instead of the Earth, was at the centre of the universe, with the planets revolving around it in perfect circles. He also understood that the Earth revolved around its own axis in 24 hours, and that the Earth's revolution around the Sun was completed in exactly one year. Even though Copernicus himself was convinced that this heliocentric theory was indubitably true, he also saw what dangers might arise from the publication of his revolutionary theses. He saw that everything he had written was against the Bible, and that most of his theses would be regarded as illogical or absurd by his contemporaries, so he hesitated to publish his theory until the year of his death. Even though his major work *De Revolutionibus Orbium Coelestium (On the Revolutions of the Celestial Spheres)* was completed by 1530, it was not published (in Nuremberg) until shortly before Copernicus' death on May 24, 1543.

Most people of his time could not, or would not, accept that Copernicus' theory was true. Criticism by the Catholic Church was mild, at first; Lutheran and Calvinist authorities

rejected it categorically. No more than two handfuls of scholars, in the decades to come, were really convinced of its truth. One of them, the Danish astronomer Tycho Brahe (1546–1601) adopted a compromising view. He, who had made astronomical measurements of utmost precision of the solar system and of hundreds of stars, who – before the telescope was  
5 invented – had detected a new star (1572) and even a comet (1577), did not fully accept Copernicus’ theory. He still saw the Earth as the centre of God’s universe; the known planets, however, in his view, revolved around the Sun, and he thought the Sun travelled around the Earth each year.

Even though Brahe’s understanding of the machinery of the universe was faulty, the data  
10 he had collected about the stars and the solar system provided the basis for the improved theory of heliocentrism by Brahe’s assistant Johann Kepler (1571–1630). Kepler was a convinced follower of Copernicus. In his capacity as imperial mathematician and court astronomer to Emperor Rudolf II, he performed a vast number of calculations and made observations in a variety of scientific fields, which he published in a number of books. The  
15 most important of his scientific discoveries was the three laws on the motions of planets, by which he improved on Copernicus’ theory: for example, he found out that planets do not follow a perfectly circular path round the sun, as Copernicus had thought they did, but that their orbits are elliptical, with the sun in one of the focuses of the ellipses. Moreover, he understood that the distance of a planet from the sun determines its velocity. The calculations  
20 he had performed were summed up in his books *Epitome Astronomiae Copernicanae* (1618–1621) and *Tabulae Rudolphinae* (1625). Both these books provided a collection of reliable data for further research on the subject: Galileo Galilei and Isaak Newton, among others, made use of them for their own pioneering discoveries.

Galileo Galilei (1564–1642) was an Italian mathematician, physicist, and astronomer who  
25 excelled in many fields of science. It was one of his main achievements that he was able to shatter the commonly held convictions of the truth of Aristotelian physics. He did this by performing controlled experiments on falling and moving objects; the laws governing falling bodies, which he discovered and expressed in the language of mathematics, proved that Aristotle and his followers were all wrong with respect to this topic. The same was even truer  
30 for Galileo’s ideas on the motion of objects which diametrically contradicted the model formulated by Aristotelian physicists.

Immediately after Galileo had heard of the invention of the telescope (1608 by the Dutch  
spectacle and lens maker Hans Lippershey), he had his own improved instruments built in Venice in 1609. With these he discovered hitherto unknown celestial bodies and phenomena:  
35 four moons circling Jupiter, the stars of the Milky Way, the phases of Venus, sunspots, and the craters, mountains, valleys, and plains on the surface of the Moon.

Galileo had been an adherent of the Copernican theory from the beginning of his career on; his observations through the telescope now strengthened his conviction that Copernicus’

ideas were beyond doubt. When, in 1613, he published some of these discoveries together with the assertion of the Copernican theory, traditionalist rivals of his in Pisa and Florence denounced his views as heretical and informed the Inquisition in Rome. Compromise was offered to him by Church authorities in 1616 by allowing Copernicanism as scientific hypothesis and as a device for calculations. Galileo seems to have accepted. Again, in 1633, he was summoned to Rome. This time he was made to abjure and he was convicted to house arrest until the end of his life.

Galileo's discoveries and ideas could, however, not be suppressed, neither in Catholic universities, nor in those of the Protestant territories. His last and greatest book, the *Discourses ... Concerning Two New Sciences*, was published in Leiden in 1638 and summed up most of what Galileo had published previously. This book was discussed in the scientific community in all countries of Europe and paved the way for broader and more systematic studies, which eventually culminated in the achievements of one of the greatest physicists of all times, Isaac Newton (1642–1727)

Newton is generally considered the culminating genius of physics. His mathematical achievements (e. g. the development of calculus) together with his systematic and innovative experiment-based research made him the founding father of modern physics. It was his achievements in the fields of optics and, more so, mechanics and gravitation, which provided the basis of the physical sciences and which could, in later decades, be extended to a system of scientific knowledge that was universally accepted until late into the 19th century.

Newton's work was generally accepted and acclaimed, not only in Britain, but also across Europe. Unlike Copernicus, who had to fear ridicule, or Galileo, who met hostile criticism and even persecution, Newton's career was a series of rewards by the state, society, and the scientific community: he was Member of Parliament for Cambridge, held an important office as Master of the Royal Mint, was long-standing chairman of the renowned Royal Society of London, and was eventually knighted (1705) by Queen Anne. The acclaim of Newton's scientific achievements was universal. With him, the victory of the Scientific Revolution had been completed.

## Other Scientific Disciplines

The refutation of Ptolemaic geocentrism and of Aristotelian physics in the course of the 17<sup>th</sup> century was revolutionary indeed; the Scientific Revolution, however, was not just restricted to mathematics, physics or astronomy. The new attitudes towards nature and the definition of a new scientific methodology were effective also in other disciplines, like medicine, chemistry, or engineering.

In 1543 Andreas Vesalius, a Flemish physician, published *De corporis humani fabrica* (*On the Structure of the Human Body*), a book which was groundbreaking in the study of human anatomy. Every detail shown and explained there was based upon experiment – he



himself had dissected human corpses and recorded only what he had seen. This procedure was declared scandalous and against the Christian religion, yet, it once and for all times showed doctors how to acquire reliable knowledge about the human body. The real scandal for his contemporaries, however, was that in his book he proved that the undisputed champion of  
5 traditional medicine, the Roman physician Aelius Galenus (2nd century A. D.) had made more than 200 errors. He thus shattered the reliability of the whole system of the traditional medical sciences that rested firmly on the doctrines of Galen and his disciples.

The science of anatomy advanced further when, in 1628, the English physician William Harvey (1578–1657) published a book in which, among other things, he described the system  
10 of blood circulation and of the organs involved in humans and animals. He became the founding father of functional anatomy.

Many of the pioneering discoveries would not have been possible without some of the inventions made in the 16th and 17th centuries by instrument makers and lens makers. It was the telescope, invented in 1608 by the Dutch lens maker Hans Lippershey, which had enabled  
15 Galileo Galilei to look into the universe and to make use of his discoveries for the formulation of general physical laws (q. v. above). The invention of the microscope by Zacharias Janssen (1590) enabled the Italian physician Marcello Malpighi (1628–1694) to discover the smallest blood vessels, the capillaries, and to extend anatomical research into the realm of plants. Equally important was that the Dutchman Antoni van Leeuwenhoek (1632–1723) could build  
20 much improved microscopes, with the help of which, among other things, he discovered red blood cells, spermatozoa, bacteria and other single-celled organisms. Another Dutchman, the physicist Christiaan Huygens (1629–1695), who had made groundbreaking discoveries in the field of optics and who constructed improved optical instruments, invented the pendulum clock (1659). From then on, even the smallest intervals of time could be measured with  
25 greatest precision.

### ***The Impact of the Scientific Revolution***

The 16th and 17th centuries saw revolutionary scientific discoveries and the definition of scientific methods. However, the number of followers of the new scientific worldview was very small, indeed. The Catholic Church, and, even more so, the Protestants, were extremely sceptical of the new school of science. They openly rejected the new discoveries as unbiblical.  
30 Towards the end of the 17th century, the resistance of Protestant theologians gradually gave way to sceptical appreciation, while the position of the Catholic Church became more rigid in the course of the Counter-Reformation. Only in England was there open support, mainly by some Puritan religious groups. Most of the scientists knew of the reservations of most clerics about their discoveries. Copernicus, for example, did not dare publish his heliocentric view of  
35 the universe until shortly before his death, and Galileo, in his later years, got into conflict with the Inquisition. He was treated with great leniency, however. Many of the scientists even had

religious motives for their inquiry – they wanted to understand and describe how perfectly God had created and ordered the universe.

Some national governments encouraged scientific research. They hoped that even the states would someday profit from scientific discoveries. They expected more power and more material gain for themselves. In 1662, Charles II of England founded and funded the Royal Society of London for Improving Natural Knowledge. This institution promoted scientific enquiry by providing buildings, research facilities, and money. Moreover, they enabled the exchange of ideas by publishing scientific books and by bringing eminent members together in regular sessions. The French government, four years later, followed the English example; the Académie des Sciences of Paris was founded in 1666 by the French chief minister Colbert.

Almost all of the ordinary people continued to believe in magic, witchcraft, and astrology. The educated elite became only gradually acquainted with the revolutionary ideas of scientists. Most of them refused to accept them as true. Only a small minority did. It was only in the course of the 18th century that the relevance of science and scientific inquiry was acknowledged by the mainstream of intellectual life.

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