

The Renaissance and the Scientific Revolution

The Scientific Revolution is usually said to have occurred in the seventeenth century, but all treatments of this period of great scientific discovery inevitably begin with Nicolaus Copernicus, a Polish canon and astronomer working from a Catholic cathedral in the first half of the fifteenth century – a thoroughly Renaissance man in both time and spirit.

The Renaissance

The Renaissance began in Italy sometime around the mid-fourteenth century and heralded a number of cultural shifts in Europe. Primarily, the Renaissance, or “rebirth,” was a rebirth of Classical Greco-Roman culture. The Italian commercial and aristocratic elite saw this Classical culture as a source not just for scientific knowledge and rules of logical discourse – as it had been for the Scholastic thinkers of the Late Middle Ages – but also for the deepening and enrichment of the human spirit. Humanist scholars and artists flourished in this new cultural climate, and during the Renaissance there was a reaction against Aristotle and a revival of Platonism, in part due to Plato’s superior literary style.

Forsaking the ideal of monastic poverty, the Renaissance embraced the enrichment of human life as it could be afforded by personal wealth. “There was ... an emphatic emergence of a new consciousness -- expansive, rebellious, energetic and creative, individualistic, ambitious and often unscrupulous, curious, self-confident, committed to this life and this world,” writes Richard Tarnas in his book *The Passion of the Western Mind*. All in all, the Renaissance thinkers had a much more positive view of humanity and its capacities than the view embraced by the predominant thinkers of the Middle Ages.

Although many of these cultural changes, particularly the shift toward a curious, self-confident style of individualism, would eventually lead to renewed interest in the universe, this was not the case initially. Humanist thinkers favored human-centered subjects such as politics and history over the study of natural philosophy or applied mathematics. Later, however, scholarly interest did swing toward the restoration of the ancient knowledge of the universe. Some historians refer to this period as the Scientific Renaissance, which in turn led to the Scientific Revolution of the seventeenth century. The emphasis of the Scientific Renaissance was on the recovery of scientific knowledge, whereas the focus of the Scientific Revolution was on scientific discovery.

Nicolaus Copernicus

Copernicus was a scholar as opposed to a scientist in the modern sense of the word. As did many scholars of the time, he immersed himself in the newly translated Classical literature – not with the intention of making new discoveries, but in order to recover old discoveries. Copernicus is sometimes credited with discovering the heliocentric model of the solar system; but in fact, he read about it in a book. Ancient Greek thinkers – principle among them the pre-Socratic philosopher Aristarchus – had proposed such a system centuries before the Common Era.

Copernicus read about this model and realized that it explained, in a simple manner, many aspects of the motion of the planets – aspects that were explained by complex, implausible explanations when using Ptolemy's geocentric model. Copernicus felt that a satisfactory representation of the solar system should be coherent and physically plausible and not require a different construction for each phenomenon (as Ptolemy's system did). To Copernicus, Ptolemy's system was ugly and therefore could not represent the work of a divine Creator. (Upon hearing, in the late thirteenth century, of Ptolemy's model of the universe and of the extremely complicated mathematics it required, Pope Alfonso X is said to have replied, "If the Lord Almighty had consulted me before embarking on creation, I should have recommended something simpler.")

As early as 1514, Copernicus circulated among his friends a short manuscript describing his heliocentric views. He was reluctant to publish it. Most contemporary scholars believe that this reluctance was not due to fear concerning the reaction of the Church; the Church did not take a hard line on the issue at the time, and was generally supportive of Copernicus. It was only later, during the period of the Counter-Reformation, that thinkers such as Giordano Bruno and Galileo Galilei suffered retribution for their views on the nature of the universe.

In 1533, Johann Widmannstetter, the personal secretary to Pope Clement VII, delivered a series of lectures in the Vatican gardens outlining Copernicus' theory. Clement and several cardinals heard the lectures and were interested in the theory. Clement's successor, Paul III, probably heard of Copernicus' ideas from Cardinal Nikolaus von Schonberg, a confidante of popes Leo X, Clement VII, and Paul III. At Pope Paul III's urging, Schonberg wrote Copernicus on November 1, 1536, saying in part, "Therefore, learned man, without wishing to be inopportune, I beg you most emphatically to communicate your discovery to the learned world."

In spite of this support, Copernicus waited six years to publish his views after receiving Schonberg's encouraging letter. Finally, his friend and student, Georg Rheticus, convinced him that it was time to do so. Copernicus died in 1543. He is said to have received a copy of his printed book, titled *On the Revolutions of the Celestial Spheres* and consisting of about 200 pages written in Latin, for the first time on his deathbed.

The likely explanation for his reluctance to publish was that Copernicus was concerned about how his ideas would be received by both the devout masses and by his fellow scholars, who all were deeply committed to the Aristotelian worldview. To put this seemingly outrageous idea forward with no evidence – other than its greater simplicity – would invite heavy criticism. In his dedication of the book to Pope Paul III, Copernicus mentioned his concern that after people heard of his views, he would be "hissed off the stage."

Nicolaus Copernicus

(1473-1543 * Poland)



Reintroduced the heliocentric model

- Simplified explanation of: retrograde motion, variable brightness of planets, Mercury and Venus always appearing near Sun

Opposed because:

- It contradicted the Bible
- Geocentric universe had been incorporated into the very theology of Christianity (heaven, hell, the centrality of humanity)
- The evidence available at the time strongly suggested that the earth did not move

A portrait of Nicolaus Copernicus by an unknown artist. Terms of use: The portrait image in the above fact sheet is in the public domain.

In fact, the initial religious reaction against Copernicus' theory came not from Catholics but from Protestants. The Copernican hypothesis contradicted several passages in Scripture concerning the fixity of the earth, and biblical literalism was Protestantism's absolute authority. Even before the publication of the book, Martin Luther heard of Copernicus' theory and is reported to have said, "The fool wants to turn the whole art of astronomy upside-down. However, as Holy Scripture tells us, Joshua bid the sun to stand still and not the earth." But 73 years after its publication, the Catholic Church also put the book on a list of titles Catholics were forbidden to read.

Tycho Brahe

Copernicus got it right about the earth revolving around the sun, but he got it wrong about the way in which the earth and other planets orbit the sun. Copernicus continued to use the circles-within-circles planetary orbits of Ptolemy's model, and Copernicus' model consisted of a moving earth in a cosmos otherwise ruled by Aristotelian and Ptolemaic assumptions. Astronomical observations soon showed that Copernicus' model was somewhat better at predicting the exact locations of the planets in the sky at a given future date, but these predictions still were not completely accurate, and thus both the Ptolemaic and Copernican models were wrong.

The sixteenth-century Danish astronomer Tycho Brahe set himself the task of coming up with the correct model. Brahe realized that progress in astronomy required systematic, rigorous observation – night after night – using the most accurate

instruments available. Such a program became his life's work. Brahe improved and enlarged existing astronomical instruments and built entirely new ones. The telescope had not yet been invented, so all of Brahe's instruments relied on the use of the naked eye. Brahe began making observations and recording data in 1572 and continued to do so until his death in 1601.

Brahe's model of the solar system was a hybrid of previous geocentric and heliocentric models. Accepting simpler explanations for the locations of Mercury and Venus in the sky and for the retrograde motion of Mars and the outer planets, Brahe asserted that the planets must orbit the sun, as in Copernicus' model. However, Brahe was convinced that the earth did not orbit the sun, in part because he never was able to measure parallax – a phenomenon in which fixed stars appear to shift their positions with respect to one another and an unavoidable prediction for a moving earth. As accurate as Brahe's measurements were, more than 200 years of technological advances would be required before parallax was observed. In Brahe's model, the other planets orbited the sun, and the sun, in turn, orbited the earth – making Brahe's model geocentric.

Tycho Brahe (1546-1601 * Denmark)



- Accumulated decades of very accurate data on the locations of celestial objects
- Developed geocentric model based on observational evidence that the earth did not move
- Hired Kepler in 1600 to mathematically analyze his data with the aim of proving his model correct

An undated portrait of Tycho Brahe by Eduard Ender. Terms of use: The portrait image in the above fact sheet is in the public domain.

Brahe planned to use his extensive data on the locations of the planets to demonstrate the correctness of his model. His idea was to use the model to calculate the position in the sky of a planet at some point in the past. He would then go back to his data to show that the calculation produced the actual observed location. If Brahe's model could consistently do this, as Ptolemy's and Copernicus' could not, then his

model would be shown to be correct. However, these calculations were extremely difficult. Brahe ultimately could not perform them himself, so in 1600 he hired the German mathematician Johannes Kepler to do them for him.

Johannes Kepler

Although he was hired to make the calculations necessary to demonstrate the correctness of Brahe's geocentric model, Johannes Kepler had for some time been a convinced Copernican. Not that he believed that Copernicus' model was correct in all its details; he knew that its slight inaccuracies meant that ultimately it was incorrect. But the aesthetic superiority of Copernicus' heliocentric view was compelling to Kepler.

Brahe died shortly after Kepler was hired. Kepler succeeded Brahe as the mathematician and astrologer to the Holy Roman Emperor, with the responsibility of completing Brahe's unfinished work. Kepler now had access to Brahe's decades of unprecedentedly accurate astronomical observations. He had entered Brahe's employment with a specific heliocentric model of his own, and Kepler now had the opportunity to check his model against the data.

Kepler soon found that his model was wrong – but he did not give up. Over a period of four years he repeatedly devised new models, checked them against the data, and found that they were wrong. In these attempts he focused on the planet Mars. He reasoned that a divine Creator would not have created a different orbit for each planet; that would be unaesthetic, something incompatible with Kepler's view of God. If Kepler could figure out the orbit of Mars, he was sure it would be the orbit of all the other planets as well.

After years of unsuccessful attempts using various combinations of circles, Kepler gave up on this approach. Finally, in 1605, he hit upon the correct combination of path and speed that would match his calculations to Brahe's observations. Mars moves in an elliptical path, with varying speeds depending on the distance between it and the sun. Mars speeds up as it approaches the sun and slows as it recedes. It does this in such a way that an imaginary line drawn between Mars and the sun sweeps out equal areas in equal time intervals. As Kepler had suspected, this orbit worked for the other planets as well. Although Kepler's manuscript presenting this discovery was completed in 1605, it was not published until 1609 due to legal disputes over Kepler's use of Brahe's observations, which were the property of his heirs.

Kepler's correct orbit model was arrived at strictly by trial and error. Kepler had no model in mind that allowed him to predict it and no clear explanation for why the planets moved in this way. Such an explanation would not be found for another 50 years, when Isaac Newton presented the answer. However, the accuracy with which Kepler's model was able to predict the past locations of the planets in the sky, as verified by Brahe's observations, left little doubt that Kepler's model of orbit was correct.

Johannes Kepler (1571-1630 * Germany)



- Believed for aesthetic reasons in heliocentric model
- Determined laws of planetary motion by trial and error, checking calculations against Brahe's data
- Like Copernicus, believed in the physical reality of the model

A portrait of Johannes Kepler by an unknown artist. Terms of use: The portrait image in the above fact sheet is in the public domain.

Galileo Galilei

Galileo Galilei was a contemporary of Kepler's, and, like Kepler, he was a convinced Copernican long before there was anything other than aesthetic reasoning for supporting the heliocentric model. Other than this agreement, the two men had little in common. Kepler was very mild-mannered, somewhat sickly, and modest. Galileo was the opposite. Kepler was a Protestant and Galileo a Catholic, and both were strong in their faith. Galileo dismissed much of Kepler's work as useless fiction and refused to accept elliptical orbits for the planets, continuing to believe that planetary orbits had to be circular in some way.

Galileo is significant in science for two distinct reasons. First of all, he was the first, in 1609, to use a telescope to study the heavens and in this way he made several important discoveries that undermined the Ptolemaic model accepted by most scholars and both the Catholic and Protestant churches. However, these discoveries did not prove that the earth itself orbited the sun, as Galileo liked to claim. Secondly, he is generally credited with inventing the scientific method as we understand it today – or at the very least, being the first to apply it systematically.

Although Galileo did not invent the telescope, he was the first to use it to gain knowledge of the heavens. Among his discoveries were the mountains and craters on the moon. Because the moon was part of the celestial realm, Aristotle and Christian teachings required it to be perfect. It was clearly "blemished," perhaps signifying that as the closest celestial object to the earth, it was a transitional object between the

imperfect earth and the absolutely perfect heavens beyond. In any case, scholars and churches of the time taught that the moon was a perfectly smooth and spherical object. Looking at the moon with the naked eye, it would have been easy to believe this to be true.

But through Galileo's relatively low-power telescope, it clearly was not true. Galileo had trouble convincing others of this. His colleagues either refused to look through the telescope or claimed that the irregularities were an artifact of the telescope itself rather than a true image of the moon. The resemblance of the moon's features to those on the earth misled Galileo somewhat. He thought that the dark, relatively smooth surfaces on the moon were oceans and named them seas. Today we call them *maria*, the Latin word for seas.

Galileo also discovered that the planet Venus went through phases just as the moon does. This discovery was important because it proved that Venus orbited the sun rather than the earth, thus proving the Ptolemaic model wrong. Galileo also was able to demonstrate what some others had suspected: The Milky Way, the band of diffuse light that arcs across the night sky from horizon to horizon, is actually composed of hundreds of thousands of stars. In addition, Galileo observed sunspots and used them to calculate the speed of rotation of the sun to be about one revolution every 25 days.

But perhaps Galileo's most important discovery was finding the four (now called Galilean) moons of Jupiter. One of the strongest arguments in favor of the geocentric model was the fact that our moon orbits the earth. No one disputed this. But the accepted argument of the day went further to say that the earth could not possibly move because if it did, it would leave the moon behind. In the days before the discovery of gravity, this was a very powerful argument. However, whether one believed in a geocentric or a heliocentric universe, it was clear that Jupiter moved; it had to orbit something, whether that object was the earth or the sun. The fact that Jupiter was somehow able to move without leaving its moons behind destroyed the prevailing argument of the time.

As many astronomy students may know, Galileo got into serious trouble with the Catholic Church later in his life, culminating in his being called before the Inquisition in 1633. The root of his problem with the Church began in 1616. At that time, when with the Counter-Reformation was well underway, the Catholic Church had joined Protestant churches in opposing the Copernican model. Galileo went to Rome to try to persuade the Church authorities not to ban Copernicus' ideas. Although the church did not officially ban the Copernican model, Cardinal Robert Bellarmine ordered Galileo not to "hold or defend" the idea that the earth moves and the sun stands still at the center. This decree, however, did not prevent Galileo from discussing the heliocentric hypothesis as a hypothesis rather than a fact. In 1623 Cardinal Maffeo Barberini, a friend and admirer of Galileo, was elected Pope Urban VIII. Galileo felt it was now safe to take a stronger position with respect to the heliocentric model. His book, *Dialogue Concerning the Two Chief World Systems*, was published in 1632.

Before publishing, Galileo discussed the book with Urban. The pope asked that Galileo give arguments both for and against the heliocentric and geocentric models and offered some of his own in favor of the geocentric over the heliocentric model. But in the *Dialogue* as it was published, the arguments for the geocentric model and against the heliocentric model are made by Simplicio, a word which in Italian has the

connotation of “simpleton.” In Galileo’s book, Simplicio frequently came across as a fool, and the work clearly is not a balanced discussion of the two models but rather a polemic for the heliocentric model – a model that Galileo, in 1616, had been forbidden to support. To make matters worse, Galileo is said to have put the exact words of the pope into the mouth of his character Simplicio. The Pope was not amused, and Galileo was called to Rome to face the Inquisition.

Galileo was threatened with torture if he did not publicly recant, which ultimately he did, avoiding torture but being found “vehemently suspect of heresy” and sentenced to house arrest, under which he lived for the remainder of his life. In spite of his troubles with the Roman Catholic Church, Galileo remained a devout Catholic throughout his life. His justification for proposing theories of the universe contrary to the model of the Bible is summarized in his statement, “The Bible tells you how to go to heaven, not how the heavens go.”

His trial before the Inquisition ended Galileo’s work as an astronomer. Fortunately for science, it did not end his work as a physicist. During his near-decade of house arrest, Galileo made original contributions to the science of motion through an innovative combination of experimentation and applied mathematics. Galileo was perhaps the first to clearly state that the laws of nature are mathematical. His studies of motion laid the groundwork for Isaac Newton’s formulation of his three laws of motion. The first of these laws, logically just a special case of the second law, is simply a restatement of work done by Galileo, and was included specifically to recognize Galileo’s contribution. Galileo’s empirical approach to his studies of motion is what we now know as the scientific method.

Galileo Galilei

(1564-1642 * Italy)



First to use telescope to study heavens

- Mountains and craters on the moon
- Rotation of the sun
- Phases of Venus
- Moons of Jupiter
- Stars in the Milky Way

Revealed heavens in their gross materiality

1633 - condemned by Inquisition

Developed the Scientific Method

A portrait of Galileo Galilei by Giusto Sustermans. Terms of use: The portrait image in the above fact sheet is in the public domain.

Our study of the Scientific Revolution is not yet complete. Kepler showed the heliocentric model to be correct by determining the orbits of the planets around the sun, but he found no explanation for why they move in these particular orbits. Galileo has made important discoveries in mechanics, completely discrediting Aristotle's theory of motion, but was not able to replace the Aristotelian model with a similarly comprehensive theory. The unfinished work of Kepler and Galileo would have to wait another 25 years to be completed by the genius of Isaac Newton.

Isaac Newton

It is no exaggeration to say that Isaac Newton is the single most important contributor to the development of modern science. The Latin inscription on Newton's tomb, despite its bombastic language, is thus justified in proclaiming, "Mortals! Rejoice at so great an ornament to the human race!" It is perhaps a slight exaggeration to say, as Alexander Pope did in an epitaph for Newton: "Nature and Nature's laws lay hid in night; God said, Let Newton be! and all was light."

Newton entered Cambridge University's Trinity College in 1661. The Cambridge curriculum at that time was still strongly Classical in viewpoint, but Newton preferred to read the more advanced ideas of modern philosophers such as Descartes and astronomers such as Copernicus, Galileo, and Kepler. Notebooks he kept at the time show that in his private studies, Newton already had begun to master the field of

mathematics. Apparently, no one at Cambridge recognized Newton's genius. Newton obtained his degree from Cambridge in 1665 without honors or distinction.

The university temporarily closed for the next two years as a precaution against the Great Plague of the time, and Newton returned to his mother's farm. During these two years, when he was ages 23 and 24, Newton filled notebook after notebook with his ideas and experimental observations. These notebooks may arguably reflect the two most productive years in the entire history of science.

In that relatively short period of time, Newton made brilliant and important discoveries regarding light and color. He continued his studies of mathematics and invented calculus, which he then used to describe the motion of objects. Finally, and perhaps most significant of all, Newton developed a mathematical equation describing gravity. Thus Newton not only knew how the planets moved; he also knew why they moved that way. What Kepler had laboriously determined through trial and error, Newton, using his laws of motion and gravity, could calculate on the back of an envelope.

Newton returned to Cambridge in 1667, and was elected a minor fellow at Trinity, where his talents were beginning to be recognized. The next year he became a senior fellow upon taking his master of arts degree, and in 1669, before he had reached his twenty-seventh birthday, Newton became the Lucasian Professor of Mathematics. The duties of this appointment offered Newton the opportunity to organize the results of his earlier optical researches, and in 1672 he published his work on light and color. This work established his reputation as a scientist of the first magnitude.

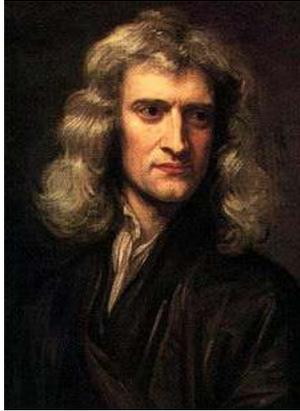
Newton was, however, a highly secretive and suspicious person who found it extremely difficult to submit his ideas to the scrutiny of others. Many of the great discoveries made during the two years on the farm remained unpublished for decades. It was not until 1684 that Edmond Halley finally persuaded Newton to make his work on motion and gravity known.

Halley was intensely interested in the orbits of planets and also those of comets. He and fellow scientist Robert Hooke suspected that an inverse-square relationship produced the orbits, but they were not able to deduce from this hypothesis a theoretical orbit that would match the observed planetary motions. Halley traveled to Cambridge to seek the advice of Newton. What would be the orbit of a body subjected to such a force? Newton told Halley he had already solved the problem – the orbit would be an ellipse – but that he had mislaid his calculations to prove it.

Shortly afterwards Newton sent Halley a copy of his demonstration. Realizing the significance of what Newton had done, Halley, utilizing great skill and tact, persuaded the reluctant Newton to develop and publish his ideas on celestial mechanics. Newton's *Mathematical Principles of Natural Philosophy* (commonly known as the *Principia* from its Latin title), containing Newton's three laws of motion and his law of gravity, was published in 1687. Halley read the manuscript, corrected the proofs, and paid the publication costs out of his own pocket.

Isaac Newton

(1642 - 1727 * England)



- Copernican system destroyed Aristotle's explanation of motion and offered nothing to take its place.
- 1687 - Principia. Laws of motion and the law of gravity.
- Established physical basis for Kepler's laws as well as the trajectory motion of cannonballs.
- Basis for later mechanistic-deterministic world view.

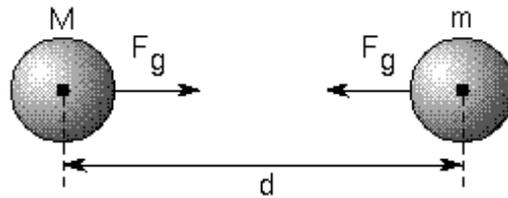
A portrait of Isaac Newton by Godfrey Kneller. Terms of use: The portrait image in the above fact sheet is in the public domain.

With the publication of the *Principia*, it seemed as if the science of mechanics was complete. The relationship between applied force and subsequent motion was now firmly established. The single cosmological force, gravity, had been completely described. Objects moved in accordance with strict natural laws that could be understood mathematically. Some continental scientists and philosophers were at first skeptical of Newton's work. They felt that Newton's concept of gravity as a force acting through a distance was insufficiently mechanical to be correct. Newton was also bothered by this consideration. In a letter to a fellow scientist, he wrote:

That gravity should be innate, inherent, and essential to matter, so that one body may act on another body at a distance through a vacuum, ... is to me so great an absurdity that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it.

However, the spectacular success of Newton's mathematical description of the motion of both earthly and heavenly objects soon overcame the philosophical objections, and Newton was celebrated as the greatest scientist who had ever lived. We will return to the problem of action-at-a-distance in a later reading.

Newton's universal law of gravitation



$$F_g = \frac{GMm}{d^2}$$

- Objects with mass exert a force on one another that is proportional to the product of their masses and inversely proportional to the square of the distance between their centers.
- Predicted the existence of Neptune.

As with many geniuses, Newton was a complex, and in many ways, highly neurotic individual. He was paranoid regarding his discoveries and often delayed publication for fear that someone would steal his ideas. He was constantly embroiled in extensive and bitter disputes with other scientists. One of the most infamous of these arguments was with the philosopher and scientist Gottfried Leibniz over who should receive credit for the invention of calculus. Although many of the great scientists have appreciated, and in some cases even contributed to, the arts, Newton was not one of them. He was not the least interested in music; he characterized great works of sculpture as “stone dolls”; and he described poetry as “a kind of ingenious nonsense.”

Newton was an unorthodox Christian, a monotheist who rejected the divinity of Jesus. For this reason, he constantly delayed his ordination as an Anglican minister as was required by the various academic and official positions he held over his lifetime. Though heretical in his views, Newton was nonetheless highly religious. He wrote a number of tracts dealing with a literal interpretation of the Bible and was a strong believer in prophetic interpretations of the Bible. He also was an astrologer and an alchemist at a time when most scientists had long ago abandoned these vocations. During his lifetime, Newton actually wrote more about the Bible and occult studies than he did about science and mathematics.

After his death, Newton's body was discovered to contain massive amounts of mercury, probably resulting from his alchemical pursuits. The affects of mercury poisoning may explain some of Newton's eccentricities. He was buried in Westminster Abby with the greatest of honors.

Newton viewed the material universe as consisting of atoms whose motion is determined by precise mathematical laws. Newton and virtually all of his contemporaries took the existence of a divine Creator as an accepted fact. However,

this mechanical universe brought into question the role of such a divine Creator with respect to the universe. Did the Creator interfere with the mechanical cause and effect from time to time? Or, did the Creator create the universe and the laws governing it and then allow the universe to evolve in accordance with those laws?

Newton believed the former. He felt that divine intervention was necessary for the creation of the solar system and also necessary to keep it operating smoothly. Most of the scientists and philosophers that succeeded Newton rejected his theistic arguments. Newton's rival Leibniz, for example, thought that God created the universal machine, set it in motion, and then had no need to intervene further in its operation. The universe unfolded according to mathematical laws with all the precision and inevitability of a well-made clock. This religious perspective is known as *Deism*.

Later, the French physicist and mathematician Pierre Simon Laplace developed this idea further, saying:

We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes.

Laplace's perspective today is known as the mechanistic-deterministic worldview.