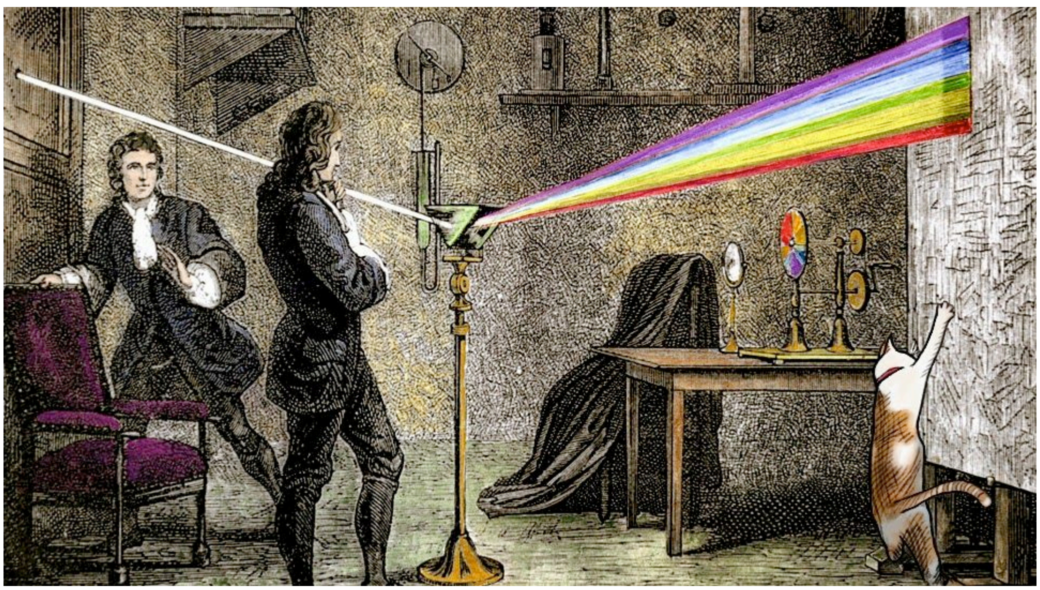
Isaac Newton



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1 Isaac Newton

Isaac Newton (1643 – 1727) was the leading mathematician of his generation. He laid the foundation for differential and integral calculus. His work on optics, laws of motion, and gravitation made him one of the world's top scientists.

Newton is best known for his three laws of motion and his law of universal gravitation described in his book "The Mathematical Principles of Natural Philosophy". For nearly 300 years this publication was the foundation of classical mechanics. Newton used his law of universal gravitation to prove Kepler's laws of planetary motion, to account for ocean tides, the trajectories of comets, and the precession of the equinoxes.

Newton studied light extensively. He introduced the term color spectrum to describe the colors produced when shinning white light through a glass prism.

Newton shares credit with Gottfried Wilhelm Leibniz for development of differential and integral calculus. He also contributed to the study of power series, the binomial theory, and approximating the roots of functions. In addition, he formulated an empirical law of cooling and made the first theoretical calculation for the speed of sound

Newton's life can be divided into three distinct periods. The first was his boyhood days from 1643 up to 1669. Second, his highly productive period as Lucasian professor of mathematics at Cambridge University from 1669 to 1687. The third period of his life was nearly as long as the other two combined. During this period Newton served as a highly paid government official in London with little interest in mathematical research.

2 Newton's Early Life

Isaac Newton was born near Grantham, England on 4 January 1643. His father, also named Isaac Newton, was a wealthy famer who owned land and live stock. However, he was completely uneducated without the ability to even sign his own name.

Isaac did not have a happy childhood. His father died three months before he was born. When he was two years old his mother remarried and placed Isaac in the care of his grandparents James and Margery Ayscough. Isaac was essentially considered an orphan who was poorly treated by his grandfather. It is clear from his writings that Isaac harbored a deep hatred for both his grandfather and step father (Barnabas Smith). For a long time he and his mother were not on good terms either.

Isaac lived in an extended family consisting of his mother, his grandmother, one half-brother, and two half-sisters after his stepfather died in 1653. His grandfather died some time earlier.

Isaac attended grammar school in Grantham but, according to his school records, was an idle inattentive student. This situation seems to have change later. During the final years of grammar school Isaac lived with the school's headmaster, a man named Stokes, who apparently had a very positive influence on Isaac.

Isaac entered Trinity College Cambridge, on June 5, 1661 with the intent of obtaining a law degree. How he acquired an interest in mathematics is unclear. It appears his interest in mathematics began in the autumn of 1663 when he was exposed to books written by some of the most prominent mathematician of the time. Isaac received his bachelor's degree in April 1665. That summer he returned home to Lincolnshire when plague caused the University to be closed.

His scientific genius suddenly emerged while at home. In a period of less than two years, while still under the age of 25, he achieved major advances in mathematics, optics, physics, and astronomy. His mathematical work included defining the basis for differential and integral calculus, several years before independently being discovered by Leibniz.

Newton returned to Cambridge University in 1667 when the school reopened following the plague. He was elected as a fellow in July 1668 after being awarded his Master's Degree. Dr. Isaac Barrow, the Lucasian Chair of Mathematics at Cambridge, sent a number of Newton's papers to several leading mathematicians in the hope that Newton's mathematical work would be recognized. [The Lucasian Chair Of Mathematics at Cambridge University was founded in 1663 by Henry Lucas, the University's Member of Parliament, and was officially established by King Charles II on 18 January 1664. The position is considered one of the most prestigious academic post in the world]. Barrow resigned as The Lucasian Chair Of Mathematics in 1669 to devote himself to other interests. He recommended that Newton (still only 27 years old) be appointed his replacement, a recommendation that the University accepted.

3 Color and Purity of Light

Newton began his work as Lucasian Chair of Mathematics with the study of optics. In fact, optics was the subject of his first lecture course in January 1670.

While working at home during the plague, Newton had reached the conclusion that white light was not a simple entity. Every scientist since Aristotle had believed that white light was pure. However, chromatic aberration produced by the lens of refracting telescopes suggested to Newton that perhaps white light was not pure at all but instead made of several different colors. When he passed a thin beam of sunlight (Figure 1) through a glass prism he discovered that the white light was separated into a spectrum of seven distinct colors: red, orange, yellow, green, blue, indigo, and violet, as illustrated in Figure 2. Others claimed that the spectrum obtained was the result of the "pure white light" being corrupted as it traveled through the prism glass. The more glass that the light passed through, the more corrupt the light would become.

To disprove this, Newton passed light through two prisms as illustrated in Figure 3.

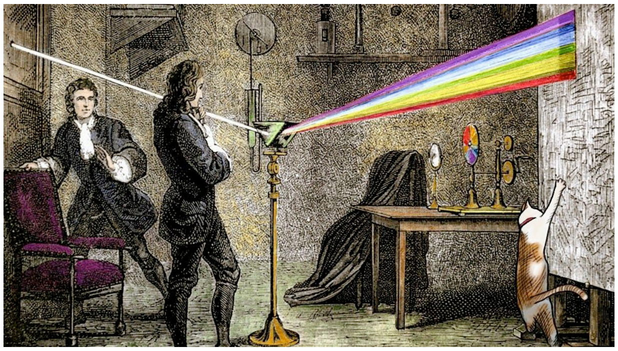

Figure 1 Passing a beam of light through a prisim (source: pinterest)

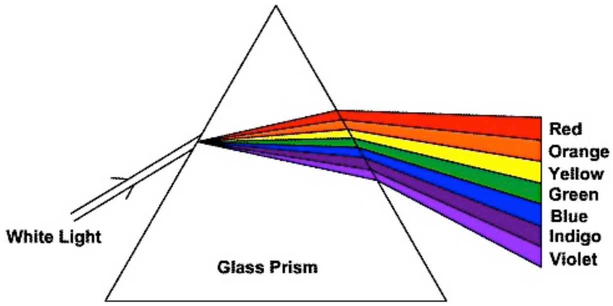

Figure 2 Spectrum of White Light (source: sc4science.weebly.com)

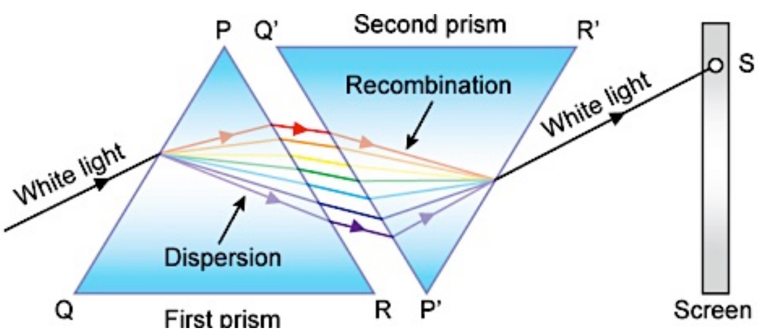

Figure 3 Recombining of light spectrum (source: Eduladder)

The white light was separated into the color spectrum after passing through the first prism. The spectrum was then passed through a second prism rotated 180 degrees with respect to the first prism. Instead of further corrupting the light, the second prism instead recombined the spectrum back into white light. This experiment proved that white light was not "pure", as commonly believed, but instead made up of a spectrum of colors.

Using his understanding of color, Newton designed a reflecting telescope that minimized much of the chromatic aberration present in refracting telescopes. Instead of using lenses Newton utilized mirrors. He placed a concaved mirror at the base of the telescope tube and a flat mirror at an angle of 45^o at the top end of the tube. The concaved mirror focused the light coming into the telescope while the flat mirror directed it into the eye piece.

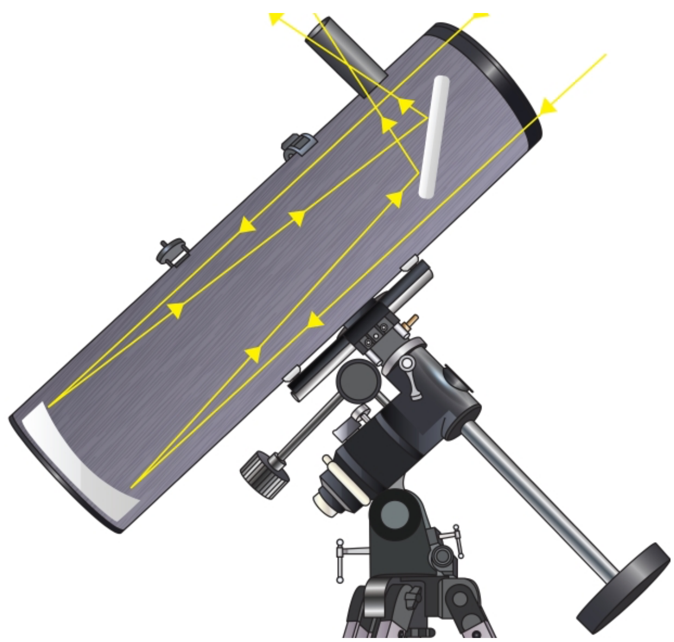

Figure 4 Newtonian Telescope (Source: Space Answers, by Jonathan O'Callaghan)

4 Debate Over the Physical Nature of Light

In 1672 Newton was elected a fellow of the British Royal Society. That same year he published his first scientific paper on light and color in the "Philosophical Transactions of the Royal Society". In his publication Newton claimed that light was composed of tiny colored particles. Robert Hooke, also a member of the Royal Society, had published his wave theory of light and color a few years earlier. Hooke responded to Newton’s publication by claiming that what was original in Newton’s paper (Newton’s particle theory of light) was wrong and what was correct in the paper had been stolen from him (Hooke). Newton fired back with his explosive temper trying his best to humiliate Hook in public. The angry argument between Newton and Hooke lasted for years.

Dutch physicist, mathematician and astronomer Christiaan Huygens agreed with Hooke believing that light was composed of waves. Huygens published his wave theory of light in 1690, complete with the supporting mathematics. Huygens claimed that reflection, refraction, and diffraction could all be explained by his theory. According to Huygens light waves had to travel through some medium, just like water waves traveling through water and sound waves traveling through air. So he proposed that light waves traveled through an aether that exists throughout the universe.

It appears that Newton suffered a nervous breakdown in 1678. The following year his mother died. For a number of years following these events, Newton withdrew into his shell, mixing as little as possible with people.

While Newton wanted fame and recognition of his work, he despised being criticized. The easiest way to avoid being criticized was to publish nothing. Consequently, Newton did not publish “Opticks” , the full account of his optical research, until 1704, the year after the 1703 death of Hooke.

Newton, Hooke, and Huygens all agreed that the speed of light was finite. In his 1687 treatise “The Mathematical Principles of Natural Philosophy” Newton states “For it is now certain from the phenomena of Jupiter’s satellites, confirmed by the observations of different astronomers, that light is propagated in succession and requires about seven or eight minutes to travel from the Sun to the Earth” a remarkably close estimate for the speed of light. Perhaps because of Newton's already high reputation, his particle theory of light reigned until wave theory was revived in the 19th century.

5 Newton’s Laws of Motion

Newton's greatest achievement was his work in physics and celestial mechanics. This work lead to his three laws of motion and his law of universal gravitation. Newton had deduced early versions of his three laws by 1666. The final version of these laws, along with his law of universal gravitation, were published in his 1687 book “The Mathematical Principles of Natural Philosophy”. For nearly 300 years this publication was the foundation of classical mechanics. Newton used his law of universal gravitation to prove Kepler’s laws of planetary motion, to account for ocean tides, the trajectories of comets, and the precession of the equinoxes.

5.1 Newton's First Law:

"Every body remains at rest or in uniform motion in a straight line until acted upon by a force."

This law defines the concept of momentum. Specifically:

$$\vec{M} = m\vec{v}$$

where

$\vec{M}$ = momentum
m = the body's mass
$\vec{v}$ = the body's velocity

5.2 Newton's Second Law:

"The acceleration caused by the net force acting on a body is in the same direction and proportional in magnitude to the force and inversely proportional to the body's mass."

In equation form:

$$\vec{a} = \frac{\vec{F}}{m}$$

where

$\vec{a}$ = the acceleration of the body
$\vec{F}$ = the net force (vector sum of all the forces acting on the body)
m = the mass of the body.

This equation can be rewritten in the familiar form

$$\vec{F} = m\vec{a}$$

The net force acting on a body is also equal to the body's time rate of change in momentum, that is

$$\vec{F} = \frac{d(m\vec{v})}{dt}$$

This form of the force equation is particularly important in launching satellites into orbit since the mass of the booster rocket, as well as its velocity, changes as the rocket burns fuel.

5.3 Newton's Third Law:

"For every action there is always an equal and opposite reaction."

Whenever one body exerts a force on a second body, the second body always exerts a force on the first. Furthermore, these forces are equal in magnitude but opposite in direction. That is, a single isolated force is impossible.

6 Centripetal and Centrifugal Forces

Newton discovered that forces are acting on an object when it is moving in uniformly circular motion.

According to his second law of motion the force acting on an object is equal to

$$\vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt}$$

where

m = the mass of the object,

$\vec{a}$ = its acceleration,

$\vec{v}$ = its velocity, and

t = time

In uniform circular motion, the magnitude of the object's velocity $|v|$ is constant. If v is constant then

$$\vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt} = m[0] = 0$$

and no net force is acting on the object. However, while the magnitude of the velocity is constant, its direction is continuously changing as the object moves around the center of its circular orbit. In this case

$$\vec{a} = \frac{d\vec{v}}{dt} \neq 0$$

It turns out that the acceleration of an object moving in uniform circular motion is

$$\vec{a} = \frac{d\vec{v}}{dt} = \frac{v^2}{r}$$

where r = the distance of the object from the center of its circular orbit.

The direction of acceleration is toward the center of the circle as illustrated in Figure 5 where the dark blue circle represents the object.

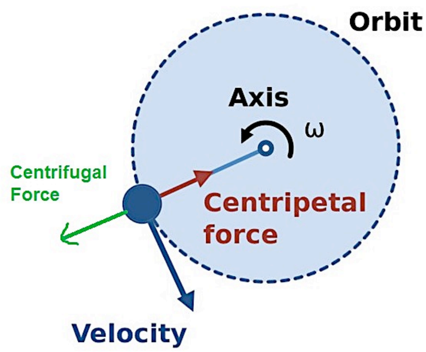

Figure 5 Centripetal Force (source: MLP Forums)

Consequently, the force acting on the object is

$$F = ma = m\left[\frac{v^2}{r}\right]$$

This force acts inward (the red arrow in Figure 37) toward the center of the curved path and is responsible for the object's circular motion. This force is called **centripetal force**.

The velocity of the object in its orbit can be determined if the radius r of its orbit and its orbital period T are known. In that case

$$v = \frac{2\pi r}{T}$$

According to Newton's third law, "for every action there is always an equal and opposite reaction". The action, or centripetal force, acting on the object in Figure 37 is the force exerted on the object by a "string" tying the object to a rotating pin at the center of the circle, or the Sun's gravity acting on the Earth (the object). The reaction is the force of the object pulling against the string, or the Earth pulling against the Sun's gravity. This reaction is called **centrifugal force**.

7 Newton's Law of Universal Gravitation

While at home during the 1665 - 1666 plague, Newton observed an apple fall from a tree, so the story goes. Newton wondered if the gravity which attracted the apple to the Earth might also attract the moon to the Earth. This was a radical idea at the time since it was believed that the laws governing celestial motion were very different from those governing the motion of objects on the Earth. Newton was suggesting that they were the same.

Newton knew the centripetal force on an object in uniform circular motion, like the moon, was equal to

$$F = m\left[\frac{v^2}{r}\right]$$

He also knew that the velocity v was equal to

$$v = \frac{2\pi r}{T}$$

Combining these two equations resulted in

$$F = m\left[\frac{(2\pi)^2 r^2}{rT^2}\right] = (2\pi)^2 m\left[\frac{r}{T^2}\right]$$

From Kepler's third law of planetary motion it was known that

$$T^2 \propto r^3$$

Substituting r^3 into the force equation for T^2 produced an inverse square law for an object in uniform circular motion. That is

$$F = (2\pi)^2 m\left[\frac{r}{T^2}\right] \propto (2\pi)^2 m\left[\frac{r}{r^3}\right] \propto (2\pi)^2 m\left[\frac{1}{r^2}\right]$$

that is

$$F = H \cdot \frac{m}{r^2}$$

where H is a constant of proportionality.

Newton concluded from his laws of motion that while the Earth exerted a gravitational force on the moon, the moon must also exert an equal and opposite force on the Earth. He reasoned that the magnitude of the force depended on both the mass of the Earth and that of the moon and was inversely proportional to the square of the distance between them. That is

$$F \propto \frac{m_{Earth} m_{moon}}{r^2}$$

Generalizing this equation lead Newton to his universal law of gravitation. Specifically,

"all matter attracts all other matter with a force proportional to the product of their masses and inversely proportional to the square of the distance between them".

In equation form

$$F = G\frac{m_1 m_2}{r^2}$$

where G is the constant of proportionality, better known as the universal gravitational constant.

We know today that the universal gravitational constant $G = 6.673 \cdot 10^{-11} \;\; nt\, m^2/kg^2$.

It is believed that Newton made these calculations in 1666. However, his results were not published until 1687 when they appeared in his book "The Mathematical Principles of Natural Philosophy".

Newton applied his law of universal gravitation to orbiting bodies, projectiles, pendulums, and free-fall near the Earth. He demonstrated that the planets were attracted toward the Sun by a force varying according to the inverse square law and concluded further that all heavenly bodies mutually attract one another. He proved Kepler's laws of planetary motion, accounted for ocean tides, the trajectories of comets, and the precession of the equinoxes. As a result of this work Newton became an internationally known leader in scientific research.

8 The Second Half of Newton's Life

James II converted to Catholicism in 1669. In 1685 he became king of Great Britain. Following his inauguration he gradually developed a distrust of Protestants and began appointing Roman Catholics as officers in the army, as judges and officers of state. He also appointed Catholics to key leadership positions at Cambridge University. Newton was a staunch Protestant and strongly opposed to what he saw as an attempt by the King to take control of the University. Newton responded by preparing critical documents used by the University to defend itself against the King's policies. Elsewhere, political uprisings were occurring. Opponents of the King asked William of Orange to form an army capable of deposing King James. William did so and defeated the army of King James. James fled in exile to France on 23 December 1688.

The University of Cambridge elected Newton as one of its two members to Parliament. In February 1689 Parliament declared that James had abdicated the thrown and offered the crown to William and his wife Mary as joint monarchs.

Newton was at the height of his standing. He was seen as a leader of the university and one of the most eminent mathematicians in the world. However, his election to Parliament became a turning point in his life.

Newton retired from research after suffering a second nervous breakdown in 1693. He left Cambridge and took a government position in London as Warden of the Royal Mint in 1696, being promoted to Master of the mint in 1699. However, he did not resign his positions at Cambridge until 1701.

Newton made significant contributions at the Mint. He led the Mint through a difficult period of recoinage and actively pursued measures to prevent coinage counterfeiting. As Master of the Mint, coupled with the income from his mother's estate, Newton became a very rich man

In 1703 Newton was elected president of the Royal Society, a position that he held until his death. Two years later (1705) Newton was knighted by Queen Anne. He was the first scientist to be so honored.

Toward the end of his life, Newton, a life long bachelor, lived in Cranbury Park southwest of London with his niece and her husband. He lived there until his death in 1727. His half-niece, Catherine Barton Conduitt, served as his hostess for social events held at Newton's house in London. According to letters which he wrote to her when she was recovering from smallpox, he was a "very loving Uncle"

9 Robert Hooke

In addition to his work on light, Robert Hooke (1635 – 1703) discovered the law of elasticity (the mechanics of springs) which bears his name (Hooke's Law). Hooke's work on elasticity resulted in his development of the balance spring which enabled him to build a portable time piece, the first watch. A bitter dispute between Hooke and Huygens arose over who had first invented the spring operated watch. This dispute lasted for many years after the death of the two men. However, a note dated 23 June 1670 describing a demonstration of a balance-controlled watch before the Royal Society seems to indicate that Hooke was indeed the first to invent the watch.

Hooke was the first to suggest that matter expands when heated and suggested that air was made of small widely spaced particles. He also proposed that heat was caused by the rapid movement of particles within matter.

In a communications to the Royal Society in 1666 Hooke explained that: 1) Heavenly bodies are attracted to each other. 2) That all bodies having a simple motion will continue to move in a straight line unless continually deflected by some extraneous force, causing them to describe a circle, an ellipse, or some other curve. 3) That the attraction between bodies increases the closer they get. In the process of developing these ideas, Hooke came close to proving that gravity followed an inverse square law. These same concepts were, of course, being studied by Newton. The fierce dispute between Hooke and Newton over who actually discovered the inverse square law first, coupled with the dispute over the wave verses particle nature of light, sent Newton into such a rage that he removed from is own work nearly all references to Hooke.

In addition to physics, Hooke did work in biology including building a microscope used in his work, studied astronomy, and was an architect working as a surveyor for the City of London. He also built a reflecting telescope which he used to study Mars, the rotation of Jupiter, and the Orion constellation.

10 Christiaan Huygens

Christiaan Huygens (1629 – 1695) was the second son of a well to do distinguished Dutch family which gave him access to the highest intellectual and social circles. Huygens became a founding member of the French Academy of Sciences.

Huygens invented the first working pendulum clock in 1656 which he patented the following year. The pendulum clock was a breakthrough in timekeeping and became the most accurate type of clock for nearly 300 years. While Hooke is credited with inventing the watch, Huygens was probably the first to build a watch using a spiral balance spring, which he did in 1675.

Huygens was the first to derive the formula for centripetal force and the correct laws of elastic collision. In addition, he was a pioneer in the mathematics of probability.

Huygens built his own 50 power refracting telescope which he used to discover the rings of Saturn and the Saturn moon Titan, the largest of Saturn’s moons.

However, Huygens is best know for his wave theory of light which he proposed in 1678 and published in his book “Treatise on Light” in 1690. His treatise is considered the first mathematical theory of light. Unfortunately, Newtons particle theory of light persisted for the next 100 years, despite Huygens’s compelling arguments for his wave theory backed by extensive mathematics.

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