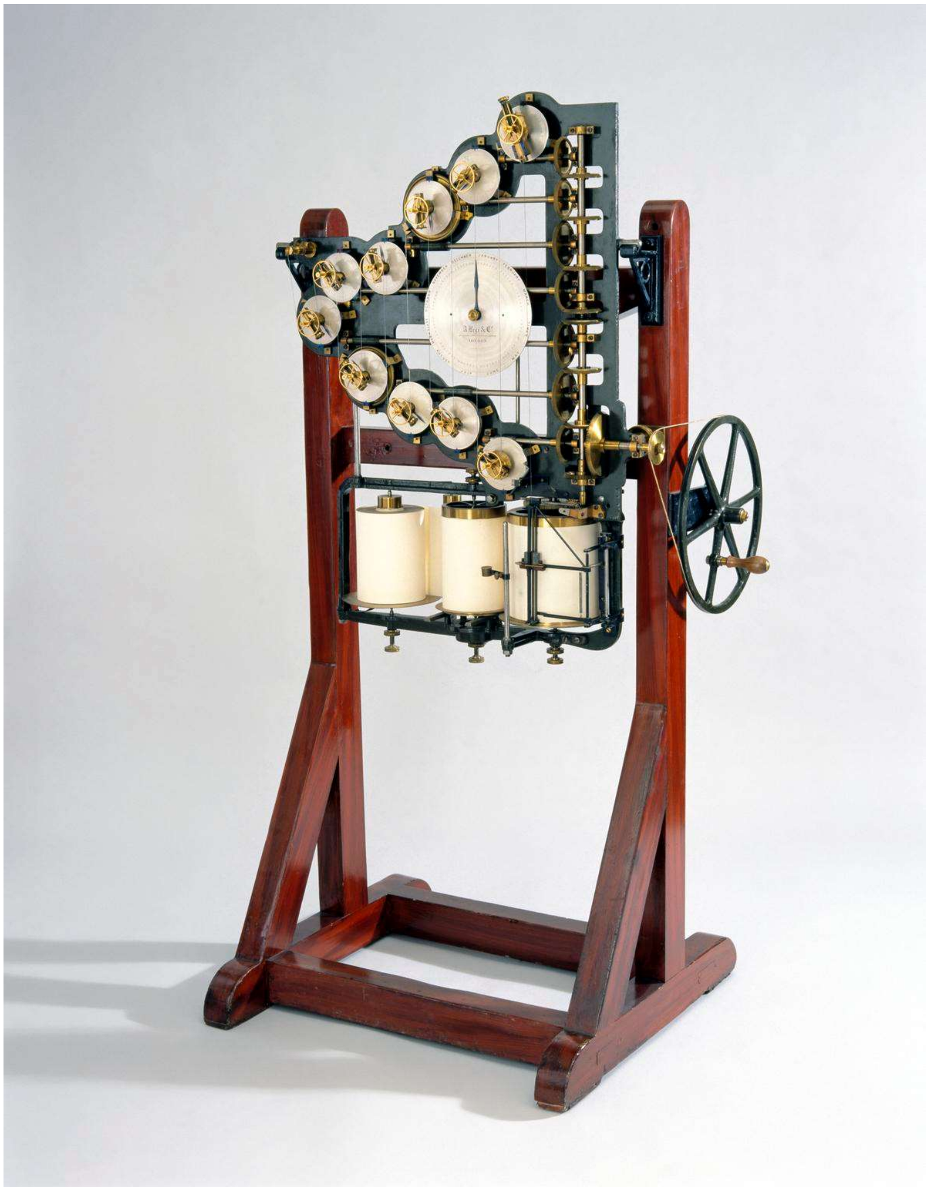
COMPUTER OF THE TIDES



Lord Kelvin's Machine to Disprove Evolution

Charles Petzold

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Introduction

On display in the Science Museum in South Kensington, London, is a magnificent assemblage of brass and wood that stands as tall as a person, as gorgeous as it is mysterious.[1] Protected from inquisitive fingers by plexiglass, the machine features a large enticing hand crank on one side. Perhaps a little maintenance might be required first, but if you were to turn that crank, you would see ten smaller wheels bob up and down in graceful patterns, and watch a pen plot out a graph on the paper roll.

The graph drawn by this machine shows the projected rise and fall of the ocean tides for a particular seaport. This is a *tide-predicting machine* from the 1870s, and today it is regarded as an early example of a special-purpose analog computer.

Analog computers aren't spoken of much these days. They have nearly disappeared from the world in deference to the digital computers that now pervade our lives. Digital computing has been so successful and has achieved such dominance that the word "computer" now intrinsically means "digital computer." This is progress, of course, but analog computers have also largely been purged from our collective sense of the history of computing. The very idea of analog computing seems too quaint and even embarrassing for these modern digital times. This is not right. Analog computers are too interesting, too clever, and too pretty to be historically neglected.

Digital refers to discrete countable objects. The word comes from the Latin for *finger*. Digital computers represent everything — text, pictures, sound, video, and computer programs themselves —by numbers encoded in bits and bytes. The computer processes these numbers and performs mathematical calculations by combining bits and bytes in simple logical operations.[2]

The word *analog* is derived from the Greek and Latin for *proportionate*, and refers to continuous quantities. We still use analog devices for some kinds of measurements: A ruler is an analog device. Numbers are printed on the ruler, but you generally use those merely as reference points to estimate the actual distance. A clock with hands is an analog device. (But a clock with hands on a computer or phone screen is a digital clock masquerading as an analog clock.) If your bathroom scale has a spinning dial, that's an analog device. Tire-pressure gauges are often analog. A thermometer with a column of liquid is an analog device.

There were once both analog calculators (most famously, the slide rule) and analog computers. Analog computers don't store numbers as bits and bytes. Early analog computers, such as the tide-predicting machine, carried out mathematical computations using gears and wheels and pulleys. Later analog computers employed electrical circuits and sometimes even hydraulic apparatuses, but they are all characterized by representing values as continuous quantities rather than discrete digits.

The tide-predicting machine that is the subject of this book was the brainchild of the Scottish physicist William Thomson (1824–1907), who during the nineteenth century was the most renowned scientist of the British Empire. Thomson's major achievement was in thermodynamics, the science that relates energy, work, and heat. He was the first person to use the word "energy" in its modern sense, and he coined the term "kinetic energy." In the early 1850's, Thomson formulated what we today call the first two laws of thermodynamics: Energy is conserved. Entropy increases. Thomson also seems to be the first person to grasp the cosmological ramifications of entropy — how the universe will eventually run down when all its energy becomes useless uniform heat.

Thomson was not just a theoretician. He was also an inventor. He was deeply involved in the science and technology of laying the first transatlantic telegraph cables between the British Isles and North America, an achievement for which he was knighted in 1866 and became Sir William Thomson.

Thomson's achievements were so great that in 1892 he became the first British scientist to be ennobled, meaning that he was made a baron, a peer of the realm, and could sit in the House of Lords and have a say in the future course of the empire. There was already a Lord Thomson so William Thomson got to pick his new name. He chose the name of the river that wound past the University of Glasgow where he taught for over 50 years, and he became Lord Kelvin. The Kelvin temperature scale is named after him as well as other discoveries and concepts.

William Thomson's work with the tides combined the theoretical and the practical, the brain of the academic and the hands of the engineer.

For centuries, philosophers and scientists had wrestled with the complex interaction of celestial and terrestrial influences that results in the periodic (though by no means simple) rise and fall of the ocean waters. By Thomson's era, the physical cause of the tides was well known, but tide prediction had not yet been established on scientific principles.

Tide gauges that record the rise and fall of the waters had been in use by the time Thomson began his research, but he pioneered a way to reduce the data acquired from these gauges into a collection of simple components, and then recombine these components to predict the tides in the future. Thomson coined the term *harmonic analysis* to describe this process.

Both aspects of this job — analyzing the raw data and then using the derived components to project future tidal levels — required a lot of computational grunt work that swamped even the resources that Thomson had available (his students at the University of Glasgow). In designing machines to do part of this job, Thomson's stated goal was "to substitute brass for brain in the great mechanical labour of calculating,"[3] as concise a statement as ever of the rationale for automated computing.

The importance of Thomson's tidal research went far beyond the science. Obviously having a good understanding of the tides is crucial for oceanic commerce, and for the navy of an island nation, and even more so for an empire. It might not be surprising that one of the first tide-predicting machines was built for a port in India.

But there was another reason why Thomson began his research into the tides.

William Thomson was one of many people who did not feel comfortable with the process that Charles Darwin described in his 1859 book *On the Origin of Species by Means of Natural Selection*. While some of Thomson's objections were undoubtedly quite personal and based on religious beliefs, Thomson was also distressed that the proponents of evolution tended to assume that the Earth was extremely old — or possibly even *infinitely* old — a notion that blatantly disregarded the fundamentals of thermodynamics and the implications of entropy. In exploring various scientific methods to determine the age of the Earth, Thomson believed that the tides might play an important distinct role.

This means that the tide-predicting machine is not only an artifact from the early history of mechanized computing. It was also an armament — decidedly a peculiar and unique armament — in the 19th century Darwin Wars.

In telling the story of the tide-predicting machine I have found it necessary to expand the timeframe beyond the decade or so during which William Thomson developed his tidal theory and designed his machines. I have taken an historical approach to delve into the science of the tides, and to describe the accumulated physical and mathematical knowledge that Thomson drew upon.

We sometimes imagine scientists working in ivory towers far above the petty squabbles of politics, religion, and society. But this is not so. I do not believe that the history of science can be divorced from political, social, and cultural history, so I have tried to put everything into its proper context.

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As of year-end 2016, only a draft preview of the first of an anticipated ten chapters of *Computer of the Tides* has been completed. I anticipate that the remainder of the book will not be finished until the early 2020's. The book does not yet have a publisher.

An earlier draft of Chapter 1 was workshopped in February 2016 under the direction of Kaylie Jones, and has benefited from her feedback as well as that of Stacy Kaplan, J. Patrick Redmond, Terri Taylor, Theasa Tuohy, Janine Veto, and my wife Deirdre Sinnott, who has also read and commented on this chapter in its several manifestations.

I also thank Jon Forrest, John Welch, and Michael Griffiths for catching typos in previous drafts of this chapter. The latest draft can be downloaded from:

http://www.charlespetzold.com/cott/ComputerOfTheTides-Chapter01.pdf

Send comments, corrections, and critiques to cp@charlespetzold.com.

Charles Petzold
New York City and Roscoe, New York

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[1] As of December 8, 2016, object number 1876-1129 is part of the new Mathematics: The Winton Gallery. The image on the cover page is from http://collection.sciencemuseum.org.uk/objects/co53901/thomsons-lord-kelvin-first-tide-predicting-machine-1876-tide-predictor.

[2] For an overview of digital computing see Charles Petzold, *Code: The Hidden Language of Computer Hardware and Software* (Microsoft Press, 1999).

[3] William Thomson, “The Tide Gauge, Tidal Harmonic Analyser, and Tide Predicter,” *Minutes of the Proceedings of the Institute of Civil Engineers*, Vol. LXV, 1881 (https://books.google.com/books?id=Xl5DAQAAMAAJ), pg. 10, reprinted in Lord Kelvin, *Mathematical and Physical Papers*, Volume VI, page 280 (where it is misdated as 1882).

Go, wond’rous creature! mount where Science guides,
Go, measure Earth, weigh air, and state the tides;
Instruct the planets in what orbs to run,
Correct old Time, and regulate the Sun;

— Alexander Pope, *An Essay on Man*, Part II, Lines 19–22

Chapter 1. Isaac Newton, MP

In January of 1689, the most powerful and influential men of England journeyed to London. From the farthest reaches of their country they came. From Ogle Castle in Northumberland, from Trelevan in Cornwall, from Brome House in Kent, from Kirby Cane in Norfolk, from Oakley Park in Shropshire — over 700 aristocrats, baronets, knights, army officers, governors, mayors, sheriffs, judges, and the just plain wealthy left their homes to travel to England's capital city.[1] London was blustery and bitterly cold that month.[2] The Thames was nearly frozen over, but there was serious work to be done.

These men were members of Parliament, and in January 1689, they took their seats in the Palace of Westminster for a decidedly unusual task. Most Parliaments of that era considered proposals made by the monarch. This particular Parliament instead needed to determine who exactly this monarch should be. The next man or woman to reign over England could well be decided by their votes.

With a population of over half a million, the London of 1689 was the biggest city in Europe and one of the most modern. Particularly after the Great Fire of 1666, London had enjoyed extensive renovation and new construction. Stone and brick replaced wood. Many streets were paved to accommodate both pedestrians and horse-drawn vehicles such as hackney coaches. Gas lamps began appearing on some streets and outside public buildings.[3]

The London of 1689 was an exciting if not particularly exotic place. About one-sixth of England's population spent time in London at some point during their lives.[4] A big allure was shopping. England was shifting from an agrarian society to a capitalist manufacturing economy. Numerous shops on the London streets and the many boats on the Thames revealed a bustling commerce.[5]

The urban European phenomenon of coffeehouses had also reached London. A mix of social classes sipped coffee while discussing news and information about trade and politics. In January 1689, one of the big topics of conversation involved the profound disruptive changes happening to England, and how this Parliament had to confront the challenging job of sorting it all out.

Yet, this was not, strictly speaking, a Parliament. A Parliament must be summoned by the king, and it wasn't certain if there still were a king. There was a king just a few weeks earlier and he was still alive, but King James II had fled England and was camped out in France.

Because this was not technically a Parliament, it was called a Convention Parliament, and it operated on the fringes of legality.[6] Its first job was to determine if James II has effectively abdicated or vacated the throne. If so, who should replace him? Was it even Parliament's role to choose who that should be? And if it were, what concessions could Parliament extract from this new ruler in return for the precious crown?

The dispute of course involved religion. The Protestant Reformation was originally intended to merely reform the Roman Catholic Church. Instead, it led to upheavals in religious belief, governments, and society in general as Christians began making political and religious judgments for themselves rather than blindly relying on papal authority.

In England, the Protestant Reformation occurred during the reign of Henry VIII, who had famous extra-theological reasons for opposing Rome. After Henry's death in 1547, England was whipped back and forth over the spectrum of Christian belief, from the intense Calvinism of Henry's son Edward to the violent Catholicism of his daughter Mary. The long reign of Elizabeth from 1558 to 1603 established England as solidly Protestant, and England continued to be Protestant as the Tudors gave way to the more autocratic Scottish Stuarts descended from the older sister of Henry VIII. English Protestants read their Bible in a translation created by a committee during the reign of Elizabeth's successor, James I, and they pronounced the words "papist" and "popery" with scorn.

Religious belief in England still varied widely, however. There were Roman Catholics in England as well as many non-conformist Protestants who believed that the Church of England hadn't gone nearly far enough in shucking off its Catholic heritage. During the 17th century, these conflicts became particularly turbulent. England managed to avoid much of the Thirty Years' War that engulfed Europe in the early 17th century, but she had her own battles over religion. In the middle of the 17th century, the country witnessed "a world turn'd upside down" (in the words of a popular ballad of the period) — a long and bloody Civil War, the beheading of King Charles I, Parliamentary rule over England, and the emergence of various Protestant sects.

The Restoration of the crown in 1660 with the morally relaxed reign of Charles II was a welcome relief from the turmoil of the Civil War. But danger loomed ahead: By the late 1670s, Charles II still had no legitimate children, and it appeared that he would be succeeded by his younger brother James, a strongly committed Catholic.

Could a country remain Protestant while ruled by a Catholic king? Some people didn't want to risk it, and they sought to exclude James from the royal succession. If the succession skipped James, it would continue with James' daughter Mary, and then by his second daughter Anne, both of whom were raised apart from the influence of their father's religion. Mary, moreover, had the advantage that her husband was also her cousin: William of Orange, the Stadtholder of the Dutch Republic, was a son of a daughter of Charles I, and hence also in line for the English succession.

The national debate over the exclusion of James became so intense that political parties developed: The Tories believed the royal succession to be sacred and immune from tampering, while the Whigs favored a Parliament that had a say in who sits on the throne. But Charles II never kept a Parliament in session long enough for it to do anything, and in 1685 he died without an heir.

When younger brother James became King James II in 1685, he acted fast. He began implementing programs of tolerance for both Catholics and various Protestant sects, but nevertheless prompted a wide suspicion that tolerance for Catholics would soon be followed by intolerance for Anglicans and the other Protestants. James II also had an uncomfortably close relationship with his cousin King Louis XIV of France. Like French kings in general, the Sun King exercised a much more authoritarian type of rule than the English were traditionally accustomed. An alliance with Catholic France seemed detrimental to a country with a blossoming economy based on manufacturing, commerce, and free trade.

James II had two adult daughters from an earlier marriage, but no male heirs either from that marriage or his more recent Catholic wife. A couple years into James' reign, there was still hope that England could just wait it out and then his daughter Mary would become queen. But in June 1688 James II had a son, meaning that his Catholic and autocratic reign would likely continue beyond his death. This prospect was so intolerable that rumors took hold that the Queen's entire pregnancy had been faked, or that her baby was stillborn and an imposter baby had been sneaked into the birthing room in a warming pan.

Within three weeks of the birth of this male heir to James II, seven prominent Englishmen wrote a letter to William of Orange in Holland suggesting that if he were to invade England to overthrow James II and take the throne with his wife Mary, such an act would be unopposed and even welcomed by the people of England.

That this plan succeeded as well as it did was a testament to the unpopularity of James II and a warm spot in English hearts for his daughter Mary. The Dutch forces that invaded in November 1688 found little resistance, and James fled England, dumping the Great Seal of the Realm (used for certifying royal documents) in the River Thames on his way out. He settled in exile with his wife and young son in France under the protection of cousin Louis.

In an earlier age, William's invasion and James' retreat might have been enough for a successful regime change. Indeed, some 200 years earlier, in 1485, a man with only a slim claim to the throne defeated Richard III in the Battle of Bosworth Field to end the long and bloody War of the Roses. That victor was Henry Tudor, who was crowned Henry VII, married the dead king's niece, and became the ancestor of every English sovereign ever since. That was the last time the English crown was won on a battlefield.

In the modern age of 1688, however, a military victory (even one without much actual fighting) was insufficient. Parliament would have to approve. The biggest fear was another civil war. If the transition could be settled by civilized Parliamentarians, so much the better, and in December 1688 William summoned the Convention Parliament to legitimize his conquest.

Most of the members of the House of Lords and the House of Commons who navigated this legislative revolution over the course of 1689 have long ago faded into the fog of history. One of the few familiar names is that of the 56-year-old Christopher Wren, whose explorations into astronomy, weather, and medicine were all overshadowed by his architecture. Among the many London churches that Wren designed following the Great Fire was St. Paul's Cathedral, and he was still alive in 1710 to see it finished.

But among these bewigged and serious men sat someone whose reputation today by far exceeds anyone else in this parliament or any other parliament, in this year of 1689 or in any other year, in England or anywhere else in the world, and that was Isaac Newton.

Isaac Newton was one of two members of the House of Commons representing Cambridge, where he lived and sometimes lectured, where he performed experiments in optics as well as alchemy, where he researched astronomy as well as Biblical chronology, straddling the modern and ancient ages.

Newton was a committed Whig and a firm Protestant. He railed against tyranny and popery, perhaps even more so than most of the other members of Parliament because his religious beliefs were so distant from Catholicism as to be regarded as heretical even within the Church of England. Newton was a follower of Arianism, meaning that he rejected the idea that Jesus is also God. The Trinity was one of the articles of faith that the Church of England inherited from Catholicism, but which Newton's extensive researches into the Bible and church history convinced him to be false. Newton had to keep this belief a secret, however, for it would have threatened his job at Cambridge University.

Newton was not a pleasant man. He had no intimate friends, and no known romantic relationships. He worked hard and dove deep, often forgetting to eat. He was humorless except when laughing at other people's stupidities. Newton didn't like sharing his scientific findings with the rest of the world. Publishing left him open to criticism, incessant public disputes, and people hogging his valuable time. Yet if someone else independently discovered something that he had already studied, he would become insanely and vindictively jealous. His acrimonious dispute with Gottfried Leibniz over the invention of calculus lasted decades. None of Newton's personality defects would be tolerable had he not also possessed a brilliant mind. None of his seemingly petty disputes would be remembered had he not also established the foundations of the modern world.

This was not Newton's first trip to London, but he used the occasion to have his portrait painted by Godfrey Kneller. It remains Newton's most famous image: Wavy graying brown hair falls to his shoulders as he looks away from the viewer with an expression that mixes total confidence and disdainful conceit.

He had a right to be proud. On July 5, 1687 — just 18 months prior to the Convention Parliament — Isaac Newton published his masterpiece, the *Philosophiæ Naturalis Principia Mathematica*, or the *Mathematical Principles of Natural Philosophy*, nicknamed by posterity the *Principia*. This is the book that brought to a triumphant close the revolution begun by Copernicus that reoriented the universe by dislodging the Earth from the center of Creation and replacing it with the Sun. In just over 500 pages of Latin text and complex geometrical diagrams, the *Principia* revealed the physical and mechanical processes that governed the workings of this new universe.

Towards the end of the *Principia*, Newton discusses how the Sun and Moon affect the rise and fall of the ocean waters in the phenomenon we know as the tides. The story of the tide-predicting machine begins with Newton.

This astronomical revolution was a long time coming. Although at least one Ancient Greek astronomer believed that the Earth revolved around the Sun[7], the dominant cosmology — as well as the dictates of common sense — positioned a stationary spherical Earth in the center of the universe. Earth is surrounded by the concentric orbits of the Moon, Mercury, Venus, the Sun, Mars, Jupiter, Saturn, and finally, the dome of the stars. These eight celestial objects revolve around the Earth, rising each day from the east to sweep across the sky and set in the west.

These eight orbits all proceed at different rates, which means that the Sun, Moon, and planets all seem to move relative to the background of the stars. Over the course of the year the Sun seems to move from west to east through the twelve constellations of the zodiac. The Moon also moves eastward relative to the stars but much quicker, completing its journey through the zodiac in under than 28 days.

If these celestial objects all orbited the Earth in perfect circles, the mathematics of astronomy would be trivial. But they do not. Most problematic are the planets. The planets generally move at different rates eastward through the zodiac, the outer planets slower than the inner planets. When viewed against the background of the stars, however, the planets sometimes seem to slow down and reverse direction to move westward. This retrograde motion is what gives planets their name: the word *planet* means *wanderer*.

When the ancient Greek and Egyptian astronomers began tracking planets using mathematics, they also discovered that the center of their orbits is not exactly the Earth, but a point somewhat offset from the Earth called the deferent that itself moves in a circle. And instead of the planets orbiting in circles, they orbit in circles modified by complex patterns called epicycles, which are little circular loops around the big circular orbit. As each planet orbits the Earth, it also makes smaller loop-the-loops. This is what gives planets their retrograde motion.[8]

Thus is the universe described in the complex mathematics compiled in a book known today as the *Almagest*, written by the 2nd century AD Egyptian astronomer Claudius Ptolemy (not related to the earlier Ptolemaic dynasty that included Cleopatra).

Ptolemy's mathematical astronomy was based on the more conceptual cosmology of the 4th century BC philosopher Aristotle, who believed the orbits of the heavenly bodies to be guided by concentric crystalline spheres. In the 13th century, Catholic theologians such as Thomas Aquinas found much to admire in Aristotle and began incorporating his philosophy into Catholic belief. In the process, the more empirical spirit of Aristotle's science was lost as his writings hardened into inflexible dogma.[9]

This was how a pagan geocentric (Earth-centered) cosmology became woven into medieval Catholic theology. Above the Earth is the purity and divinity of the crystalline spheres, but Earth itself is the realm of corruption, decay, and sin. In Dante's *Divine Comedy*, the nine circles of hell that bore deeper into the Earth symbolically mirror the nine crystalline spheres established by Catholic theologians based on a combination of Aristotle's cosmology, Ptolemy's astronomy, and a ninth sphere added by Muslim astronomers.[10] Man is poised precisely between the terrestrial and celestial realms, with a body bound to Earth but a soul that belongs to God.

Nicholas Copernicus, a Polish mathematician and astronomer and canon in the Catholic Church, seems to have begun working out an alternative to this geocentric model of the universe sometime around 1510.

It is tempting to see a causal relationship between the formative years of the Protestant Reformation and the development of heliocentric (Sun-centered) astronomy, but these two profound events of the 16th century don't seem to have influenced each other. In 1514, when Copernicus published an outline of his new system, Martin Luther had yet to post his 95 Theses and Henry VIII was still attempting to foster an heir with his first wife. But Copernicus had lots of other work in his life, and the mathematics of astronomy are very hard. He wanted his argument to be complete and indisputable, so it was not until 1543 (the year that Henry VIII married his sixth wife) that Copernicus completed his book, *De revolutionibus orbium coelestium* (*On the Revolution of the Heavenly Spheres*). Legend has it that he was brought one of the first printed copies as he lay on his deathbed.

In Copernicus's revamping of Ptolemy's cosmology, the stars and Sun are fixed in space. The Earth is one of six planets that revolve around the Sun, and only the Moon continues to revolve around the Earth. Copernicus identified three types of Earthly movement: First, the Earth rotates daily on its axis; this is what causes the Sun, stars, and planets to sweep across the sky from east to west every day. The Earth also revolves around the Sun like the other planets; a full revolution of the Earth requires one year. Copernicus also introduced a third movement of the Earth that shifts the Earth's axis in a yearly cycle to account for the change in seasons.

Copernicus continued to require many of Ptolemy's mathematical adjustments to fit the actual orbits into circular patterns, but the epicycles required for the planetary loop-the-loops disappeared. The apparent retrograde motion that so puzzled ancient astronomers was revealed to be an optical illusion as a planet circling the Sun moves past the Earth in its orbit. Despite that revelation, expressions such as "Mars is in retrograde" continue to this day to be used in astrological circles.

Astronomers capable of following Copernicus's obtuse mathematics found much to admire in his reorganization of the universe. It certainly simplified astronomical calculations. But for those who only read the non-mathematical introduction to his book, there was little choice but to ridicule the entire concept that the Earth could be spinning like a top and hurtling around the Sun without tossing its inhabitants into space.

The first concerted attacks came from the Protestants. To the followers of both Martin Luther and John Calvin, *On the Revolution of the Heavenly Spheres* was yet another overly rationalistic exercise in Roman Catholic scholasticism in clear contradiction to the clear and simple message of the Bible.

The first astronomers to use Copernicus's book didn't necessarily believe that the Earth revolves around the Sun. They just preferred the easier mathematics. Indeed, in 1582 the Catholic Church under Pope Gregory needed to reform the calendar because too many leap years had caused it to slip out of sync with celestial movement. They chose to use the convenient simplicity of Copernicus's system.[11] Protestant countries, however, rejected the new Gregorian calendar; England didn't switch over until 1752.

Over the decades — as old astronomers died and new ones were born — the Copernican model began attracting adherents: people who not only exploited the mathematics but also believed in its reality. This became a threat to the authority of Catholic theology.

In July 1609, Galileo Galilei, a forty-five-year-old mathematics professor at the University of Padua, heard about a device made from two lenses that caused distant images to appear larger to the eye. He quickly began building his own instrument, even grinding his own lenses and mounting them in lead tubes. By January 1610 he had constructed a telescope of forty power and likely became the first person ever to turn such a device toward the night sky.

What he saw through this tube astonished him. Galileo viewed a Moon pockmarked with mountains and valleys, quite unlike the pure and smooth celestial body implied by Aristotle's cosmology. He discovered that the Milky Way — only a vague cloud seen with the naked eye — actually consists of more stars. When he looked at Saturn he was puzzled because it didn't seem to be quite a sphere but instead was elongated in some strange way.

Turning his telescope to Jupiter, Galileo made his most revelatory discovery. He noticed three stars around Jupiter that neither he (nor anyone else) had ever seen. The next night, they were still there but in a different configuration. Soon he spotted a fourth star. Night after night, he recorded their positions and soon became convinced that these were not stars at all, but in reality satellites of Jupiter. Sometimes as he monitored their progress for several hours over a clear night, he could almost see the moons move.

To Galileo these moons of Jupiter provided convincing proof that at least *some* celestial objects don't revolve around the Earth, and that probably the planets don't either. Galileo quickly wrote up his findings in a stort book entitled *Sidereus nuncios*, variously translated as *Sidereal Messenger* or *Starry Messenger*.[12] The brightest four moons of Jupiter — the innermost of which makes a complete revolution around Jupiter in less than two days — are still sometimes call the Medicean planets or Medicean stars after Cosimo II de' Medici, fourth Grand Duke of Tuscany, to whom Galileo dedicated his book, but they are now more frequently called the Galilean satellites.

Galileo's excitement and passion burst from the pages of *Starry Messenger*. With cocksure confidence, he devoted the rest of his life to a bold and aggressive promotion of Copernicanism.

It was also in 1609 that German Protestant mathematician and fervent Copernican Johannes Kepler completed a decade's worth of mathematical analysis of the orbit of Mars.

Kepler had a strong mystical streak. He was an astrologist and a numerologist, and an adherent to the Platonic concept of mathematics underlying all of nature. He believed that numbers reveal the mind of God, and he strove to find the numbers that God had used to construct the universe.

Kepler asked himself odd questions, like why are there six planets and not five or seven? He began looking for patterns in their orbits, and in one of the most audacious leaps of faith in astronomical mathematics he wondered if these orbits were somehow related to the five objects known as the Platonic solids.

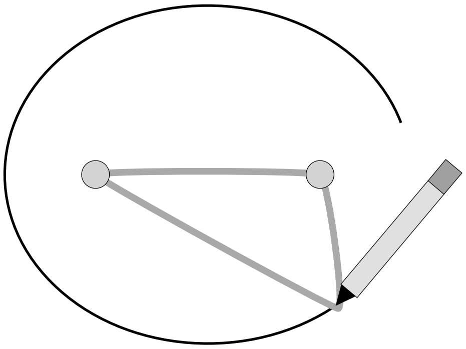
After much experimentation, Kepler found that if you mathematically construct an octahedron (an eight-sided solid made of triangles) so that it snugly encloses the orbit of Mercury, you can then fit the orbit of Venus around that octahedron. And if you then enclose the orbit of Venus within an icosahedron (twenty triangle sides), the Earth's orbit fits around that figure. And so forth with a dodecahedron (twelve pentagon sides) between the orbits of Earth and Mars, a tetrahedron (four triangle sides) between Mars and Jupiter, and finally a cube between Jupiter and Saturn.

This answered Kepler's question why there are only six planets: It is mathematically provable that there can be only five Platonic solids to fit between them. And while the fits weren't exact, the resultant system of interlocking solids was so breathtakingly beautiful that God certainly must have been a geometer to conceive of such a thing.

That was in 1596 when Kepler was only 25 years old and publishing his first book. A few years later, Kepler began working for the Danish nobleman Tycho Brahe, the most accurate naked-eye astronomer the world has ever known. Tycho Brahe had developed his own variation of the Copernican system now called the Tychonic system, in which the Sun revolves around the Earth but all the other planets revolve around the Sun. It's the exact mathematics of the Copernican system but with the comfort of a stationary Earth.

When Tycho Brahe died in 1601, Kepler got access to all his observational data and focused on analyzing the orbit of Mars. To derive the mathematics describing the orbit of Mars, Kepler also needed to derive formulas for the orbit of the Earth, because that was the vantage point from which the observations of Mars were made.

Kepler struggled to make the data fit the circles and deferents and epicycles from Ptolemy that Copernicus had continued to incorporate in his own system. Traditionally, when mathematical orbits didn't quite fit the observations, astronomers added more epicycles to compensate. But to Kepler, the actual orbits seemed more like ovals. He tried various types of ovals and then an ellipse — the figure that looks like a squashed circle than schoolchildren learn how to draw with two pins and a loop of string:



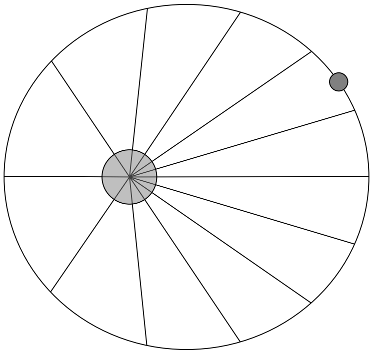
Mathematically, the two pins define the *focal points* of the ellipse. When the two focal points, are the same, the ellipse becomes a circle.

When Kepler mapped the observed orbits of the Earth and Mars to two ellipses with the Sun at one of the focal points, they fit. They fit so well that all the epicycles and deferents and other crazy mathematical adjustments accumulated from Ptolemy and Copernicus suddenly disappeared.

Since the time of the ancient Greeks and Egyptians, astronomers had been trying to fit planetary observations into circular orbits because obviously God would use perfect figures to guide the course of the planets, and the circle is the most perfect figure of all.

Kepler was the first astronomer to think outside the circle.

It had previously been assumed that the speed of a planet in its orbit was uniform. But Kepler found that the speed of each planet changed during this elliptical orbit. The nearer the planet is to the Sun is, the faster it moves, and Kepler was even able to quantify this effect. If the orbit of a planet is visualized as an elliptical pie, and the movement of a planet along its orbit each month is used to construct a pie slice cut from the Sun to the edges, then these monthly pie slices are equal in area:



The orbit describes wider but shorter pie slices when the planet is moving faster nearer the Sun, and narrower but longer pie slices when the planet is farther from the Sun and moving slower.

All of this became part of Kepler's 1609 book *Astronomia Nova*. But in a later book Kepler delved even deeper.

Just as planets move faster when their orbits bring them closer to the Sun, the closer a planet's overall orbit is to the Sun, the quicker it revolves. Mercury makes a complete orbit around the Sun in 88 Earth days. Saturn takes over 29 Earth years. In his ongoing obsessive attempts to find numerical relationships within the locations and movements of astronomical bodies, Kepler discovered that if you calculate the cube of a planet's distance from the Sun, and the square of that planet's time to orbit the Sun, the ratio of those two numbers is the same for all the planets.

It's also possible to use this rule to find relationships between pairs of planets. For example, Jupiter is about 5.2 times the distance from the Sun as the Earth. Cube that number and you get about 141. Jupiter's orbit around the Sun takes about 11.86 Earth years. Square that number and you also get 141.

Why is this? What does it mean? Kepler had no idea.

These three observations — that planets orbit in ellipses, that the orbits map out equal areas in equal times, and the relationship between a planet's distance from the Sun and the time of its orbit — became known as Kepler's Three Laws.

Exactly why is it that one celestial body revolves around another? Kepler hypothesized the existence of rays that emanate from the Sun that move each planet along a path. He called these rays *anima motrix*, or *moving force*.

To Galileo, such talk was typical superstitious astrological occultism, and Kepler was the worst offender. It was ridiculous to believe that the Sun could affect the movement of planets across the vastness of space.

Galileo believed that planets move in their orbits because that is the natural movement for planets, just as objects on Earth fall to the Earth because that is their natural movement. That tendency for objects to fall to the Earth was called *gravity*, but like Aristotle, Galileo believed gravity to be a terrestrial phenomenon, not a celestial one.

Galileo did most of his research in the terrestrial realm by analyzing falling bodies. To effectively slow down their motion, he rolled objects down inclined planes and measured how they picked up speed. He found that if an object falls 1 foot in 1 second, it falls a total of 4 feet by the end of the next second, and 9 feet by the end of the third second. The distance the object falls is proportional to the time squared.

Galileo also explored the mathematics of projectiles such as javelins. When a javelin is released from the hand it maintains the same horizontal velocity (or would in the absence of air resistance) but it also falls to the ground in the accelerating pattern that he derived. Galileo found that the combination of these two movements is a parabola. Galileo's parabola and Kepler's ellipse are both classical conic sections — mathematical siblings.

Although Galileo did comparatively little astronomical work, his confidence in the Copernican system never flagged. But an actual proof was very difficult.

A splendid proof of the Earth's passage around the Sun would have been the detection of stellar parallax in the observations of stars. If a star seemed to be in a different position in summer than in the winter, it would mean that it was being viewed from a different position — all the way over on the other side of the Sun.

To the Copernicans, the inability to detect stellar parallax became instead a demonstration of the vast reaches of space in comparison to the relatively tiny orbit of the Earth around the Sun. Not only did Copernicus dislodge the Earth from the center of the universe. He expanded the size of the universe as well. The stars are so far away that stellar parallax wasn't detected until 1838.[13]

Instead, Galileo had a whole different proof that the Earth rotated on its axis and revolved around the Sun. This proof was based on the ocean tides.

What do we know about the tides?

Anyone spending time on a coast of the Atlantic or Pacific Ocean notices first a constant lapping of waves at the shore, providing recreation for bobbers and surfers. These waves are caused by the wind.

Stick around the beach longer and you'll notice a much slower cycle of the sea as it slowly creeps up the shore and then recedes. These are the tides, and if you swim out from the shore past the waves, and you plant a long ruler into the Earth, you can actually measure the sea level as it periodically rises and falls. You will also feel the tidal currents in the water as the ocean flows from low tide to high tide, and then ebbs from high tide back to low.

Depending on the terrain and the depth of the water, the rhythm of its rise and fall can be quite complex. Different areas can exhibit very different patterns. But in the most normal and regular case, you will find that one complete cycle of the tides — from high tide to low tide and back to high tide — takes place every 12 hours and 25 minutes.

Ancient people living near the oceans recognized a bond between the tides and the Moon. When the Moon appears, the oceans swell. This connection between celestial and terrestrial activity is what makes the tides so strange and mysterious. How can the periodic movement of the oceans be seemingly governed by an object in the sky?

And yet, the relationship between the moon and the tides is not quite that simple.

The Earth rotates on its axis every 24 hours, and that's what makes the Moon seem to rise and set. But at the same time, the Moon is orbiting the Earth every 27½ days. When the Earth completes a rotation at the end of 24 hours, the Moon has moved a bit ahead, so the Earth needs a little more time to catch up. The combination of the rotation of the Earth and the revolution of the Moon makes it seem as if the Moon orbits the Earth every 24 hours and 50 minutes.

That's not the length of the tidal cycle. That's precisely *twice* the length of the tidal cycle.

At the highest point of high tide, look up at the Moon and note its position in its arc across the sky. The Moon is likely to be at its peak — midway between rising and setting — or somewhat past that point. When the Moon next comes around to that same position 24 hours and 50 minutes later, it will coincide with high tide again. But between those two appearances of the Moon there occurs another high tide when the Moon is nowhere to be seen because it's on the other side of the Earth.

From a more global perspective, at any time there are two areas on the Earth with high tides: one on the side of the Earth facing the Moon, and the other on the opposite side of the Earth.

Longer observations of the tides reveal another odd connection with the Moon: During Full Moon and New Moon, high tides are higher and low tides are lower. The tides around these times are known as *spring tides* — in the sense of the waters "springing up."

Less extreme tides occur during the Moon's first quarter and last quarter, when the side of the Moon facing Earth is only half illuminated. These are called *neap tides*, of an obscure etymology, although it may come from the Angle-Saxon *nep*, meaning scant or lacking.[14]

Keep track of the tides for even longer periods, and you'll find that the spring tides have their most extreme peaks around the time of the spring and fall equinox, when the Sun is over the equator. They exhibit less extreme behavior during the summer and winter.

It would have been interesting to read the interpretations of the ancient Egyptian and Greek astronomers after they studied the tides. But the people of the cultures who contributed most to ancient astronomy lived on the Mediterranean Ocean, where tides are negligible. Tides simply did not affect these people, so they mostly ignored them. Aristotle barely alludes to tides. The Bible doesn't mention them at all,[15] although one of the most famous Biblical incidents — the parting of the Red Sea and the later drowning of the Egyptians — might have been a tidal phenomenon.[16]

Only when the Greeks began exploring and conquering other parts of the world did they encounter tides worthy enough to write about. But the references in the classical literature are scarce or disguised. Is the sea monster Charybdis that Odysseus encounters on his long journey home actually a treacherous whirlpool caused by an unusual thrice-daily tidal phenomenon? Alexander Pope's translation of Homer's *Odyssey* uses the very word:

> Beneath, Charybdis holds her boisterous reign
> 'Midst roaring whirlpools, and absorbs the main;
> Thrice in her gulfs the boiling seas subside,
> Thrice in dire thunders she refunds the tide.[17]

The Greek geographer Strabo describes the monthly cycle between spring tides and neap tides in his *Geography* (which dates from about 7 BC).[18] The 5th century BC historian Herodotus mentions tides in the Red Sea, and the 4th century BC explorer Pytheas of Massalia noted the relationship between the tides and the Moon.[19]

Not everybody got the message. In 55 BC, Julius Caesar led the army of the Roman Empire northward through the area he called Gaul and built a fleet of ships that crossed the English Channel into Britain. As Caesar himself picks up the story in *The Gallic War* (referring to himself in the third person),

> As it happened there was a full moon that night. On this day the Ocean tides are usually at their highest—a fact of which our men were unaware. So at one and the same time the tide had flooded the warships that Caesar had had the army ferried across, and which he had beached, and the storm began to inflict damage on the transport vessels, which were fast at anchor. Nor did our men get any chance to manœuvre them or bring them assistance. Several of the ships were wrecked, the rest had lost their ropes, their anchors, and the rest of their rigging, and were unfit to sail. The inevitable result was panic throughout the army.[20]

Of course, the claim by Caesar's naval commanders that they weren't aware of spring tides might have been an excuse for the disaster that occurred.

Precisely how the Moon affected the tides remained elusive. To the Roman philosopher Cicero, writing in *The Nature of the Gods* (c. 44 BC), the synchronicity between the Moon and the tides reveals the existence of a supreme being:

> How could the sea-tides and the confined waters in the straits be affected by the rising and setting of the moon? Or the diverse course of the stars be maintained in the single rotation of the entire heavens? What is certain is that these processes could not take place through harmonious activity in all parts of the universe, unless they were each embraced by a single divine, all-pervading, spiritual force.[21]

This is an early exposition of the argument for the existence of God based on the apparent design of the universe. The effect of the Moon on the waters of the Earth was also used to justify the reliability of astrology.[22]

Other early explanations sometimes have an animist feel, such as the tides being the breath or blood of the Earth that is expelled and retracted as the Earth breathes. Here's the 1st century AD Roman naturalist Pliny the Elder:

> Hence we may certainly conjecture that the moon is not unjustly regarded as the star of our life. This it is that replenishes the Earth; when she approaches it, she fills all bodies, while, when she recedes, she empties them.[23]

Between the Romans and the Renaissance, chroniclers of the tides focused on the practical rather than the theoretical. Tide tables first appeared in China in the 11th century and then in England a century of two later.[24] Still, catastrophes occurred. In 1216, King John of England…

> … was assembling a considerable army, with a view of fighting one great battle for his crown; but passing from Lynne to Lincolnshire, his road lay along the sea-shore, which was overflowed at high water; and not chusing the proper time for his journey, he left in the inundation all his carriages, treasure, baggage, and regalia…. and his distemper soon after put an end to his life.[25]

In the 14th century *Canterbury Tales*, Geoffrey Chaucer writes of the Shipman "But of his craft, to rekene wel his tydes."[26] Tide clocks with a hand that tracks the Moon by revolving every 12 hours and 25 minutes date from the 17th century.

For those who pilot ships, and for those who await their safe return, it was enough to know that the Moon and tides were related in their cycles without knowing why.

In the new spirit of astronomical inquiry that accompanied the wake of Copernicus, an explanation for tidal phenomena became more pressing. The English experimental scientist and magnetism enthusiast William Gilbert (contemporaneous with Queen

Elizabeth) believed that the Moon exerts a magnetic influence over the Earth that pulls up the waters of the ocean.[27] Johannes Kepler also suggested that "The orb of the attractive power in the Moon is extended all the way to the Earth, and calls the waters forth beneath the torrid zone, in that it calls them forth into its path wherever the path is directly above a place."[28]

Francis Bacon is commonly regarded as the originator of the scientific method of induction but he was not a Copernican. Bacon denied that the seeming connection between the Moon and tides implied a causal relationship. Instead, the same cause underlying the movement of the heavens from east to west also affected the seas. This motion, he said "is not properly a celestial but quite a cosmical motion."[29] The difference is that the seas encounter the obstacles of shorelines, which causes them to bounce off, and then oscillate back and forth.

The theories that posited a direct influence of the Moon over the oceans of the Earth — either by somehow pulling the waters or perhaps heating them — all had a major deficiency: They only accounted for half the high tides. Why is there another high tide on the side of the Earth away from the Moon? How can the Moon pull the waters in one direction but push them away in the opposite direction?

Perhaps for that reason, the two major explanations of the tides in the early 17th century didn't involve pulling at all.

Galileo's theory of the tides was also his proof that the Earth rotated on its axis and revolved around the Sun. He first discussed it in an essay entitled "Discorso del flusso e reflusso del mare" (Discourse on the floe and ebb of the sea) sent as a letter in 1616 to Cardinal Orsini in Rome in a futile attempt to prevent the anti-Copernican decree issued later that year.[30] It's possible that Galileo had developed this theory as early as two decades previously.[31]

Galileo intended to present this theory in his definitive book on the Ptolomaic and Copernican systems. He wanted to call it *De fluxu et refluxu maris*, but Rome did not allow that title.[32] The book became *Dialogo sopra i due massimi sistemi del mondo* (*Dialogue Concerning the Chief World Systems*), published in 1632.

Galileo believed that he could avoid seeming to promote Copernicanism by framing the arguments in the form of a dialog with both sides presented equally. *Dialogue Concerning the Chief World Systems* takes the form of four days of such conversations in Venice among Salviati (the enthusiastic Copernican), Simplicio (the advocate of the old geocentric cosmologies of Aristotle and Ptolemy), and Sagredo (the unbiased observer). On the last of the four days, Galileo uses the voice of Salviati to present his strongest case for the physical evidence that the Earth rotates on its axis and revolves around the Sun.

Salviati (speaking for Galileo) reminds his friends about the barges that carry barrels of fresh water from Fusina to Venice. If a barge hits an obstacle or gains speed, the water in the barrels responds by moving backward or forward, and then oscillating.[33]

Similarly, if the Copernican theory is correct, then at any time, half the Earth's surface is facing the Sun and half is turned away from the Sun. As the Earth rotates on its axis, the sunny side of the Earth moves contrary to the Earth's orbit around the Sun while the dark half moves in the same direction as the Earth's orbit. As the Earth spins on its axis, the Earth's surface is constantly changing velocity, moving faster when the rotation is in the same direction as the Earth's orbit, and slower when the rotation is opposite the Earth's orbit. This daily acceleration and deceleration causes the ocean waters to slosh around just as in the barrels of water on those barges to Venice.

To Galileo, this was the only possible explanation for the tides, and therefore a confirmation of the Copernican theory. Salviati flatly denies any connection between the tides and the Moon. The idea that the Moon has some kind of occult power over the ocean waters is an ancient superstition akin to astrology, and Galileo can't resist taking a potshot at Kepler (who had died two years earlier) for his reliance on the Moon's action at a distance:

> I am more astonished at Kepler than any other. Despite his open and acute mind, and though he has at his fingertips the motions attributed to the Earth, he has nevertheless lent his ear and his assent to the moon's dominion over the waters, to occult properties, and to such puerilities.[34]

The Roman church was not convinced by Galileo's argument. Or perhaps they didn't appreciate Catholic orthodoxy advocated by a character named Simplicio. Several decades earlier, Galileo might have gotten away with it. But by the time of the publication of *Dialogue Concerning the Two Chief World Systems*, the Catholic Church had ramped up the Counter-Reformation to strengthen Rome against the Protestants. No questioning of its authority could be tolerated. In 1633 Galileo was tried for heresy and found guilty. He spent the rest of his years under house arrest until his death in 1642.

As the news of Galileo's conviction spread across Europe, one budding scholar and convinced Copernican was stopped dead in his tracks. Thirty-seven-year-old René Descartes — born in France, Jesuit educated, a veteran on the Catholic side of the still ongoing Thirty Year's War— desired little more than to pursue a life of the mind. He had secluded himself in Amsterdam and was working on what he hoped to be his first book. Upon hearing that Galileo had been convicted and Galileo's book had been burned, he wrote to a friend:

> I was so surprised by this that I nearly decided to burn all my own papers, or at least let no one see them. For I couldn't imagine that he — an Italian and, I believe, in favor with the Pope — could have been made a criminal, just because he tried, as he certainly did, to establish that the Earth moves…. I must admit that if this view is false, then so too are the entire foundations of my philosophy, for it can be demonstrated from them quite clearly. And it is such an integral part of my treatise that I couldn't remove it without making the whole work defective. But for all that, I wouldn't want to publish a discourse which had a single word that the Church disapproved of; so I prefer to suppress it rather than publish it in a mutilated form.[35]

It was not so much that Descartes feared prosecution. He was always a safe distance from Rome. Despite the often radical nature of the philosophy he had formulated, Descartes continued to feel a strong connection with the church. Writes one biographer, "All his life he was loyal to the Jesuits, and not only painfully careful to avoid offending them but actively keen to have their approval, most especially in his writings, which he wished them to adopt as textbooks in their schools."[36]

Over the next several years Descartes cannibalized his abandoned book[37] and elaborated on the philosophical arguments. These became his most famous and enduring works: the *Discourse on the Method* (1637) and *Meditations on First Philosophy* (1641).

Descartes eventually realized how he could present Copernican astronomy in a manner that couldn't possibly be objectionable. He wrote his *Principia philosophiae* (*Principles of Philosophy*) as a complete and comprehensive exposition of his philosophy and cosmology, hoping it would become a Jesuit textbook. The book, published in 1644, consists of a series of just over 500 titled paragraphs divided into four parts that take the reader step-by-step from basic philosophy to a knowledge of the complex mechanisms behind the workings of the universe.

Descartes begins his *Principles of Philosophy* by attempting to strip away everything we think we know. How can we trust our perceptions and preconceptions? Our senses often deceive us. Sometimes we can't even tell whether we're awake or dreaming. As we increasingly doubt how little we can believe, we become aware that our minds have been working the entire time. The very existence of this contemplating mind is the one thing we can trust with absolute certainty: In Latin, *cogito ergo sum*; in French, *je pense, donc je suis*; in English, *I think, therefore I am*.

From these modest beginnings, Descartes infers that our minds could only have been a gift from a benevolent God, who created us to be innately alert to His existence. God has (as Descartes wrote in his *Meditations*) "inscribed this idea within me, to serve, so to speak, as the mark by which the craftsman makes himself known in his handiwork."[38] Our minds are connections to God, who would not have fashioned such a marvel to trick us. We cannot be deceived if we train our minds to think in a clear and distinct manner using mathematics as a model. This ability is also innate.

And use his mind he does. Descartes conceives the mind with its divine connections to be quite distinct from the material world. The word of physical objects — including the stuff that makes up human bodies and the soulless automata we call animals — functions entirely in a mechanistic manner. These mechanical principles dictate that nothing can cause anything else to move except by direct physical contact.

This premise doesn't seem promising for describing how celestial objects move through a cosmic void, but Descartes doesn't think there is such a void. Descartes believes a vacuum to be logically impossible. In the terminology of the era, *substance* is equivalent to *extension*. By extension is meant a width, height, and depth in space, and if there is no void, then every extension is occupied by some kind of substance.

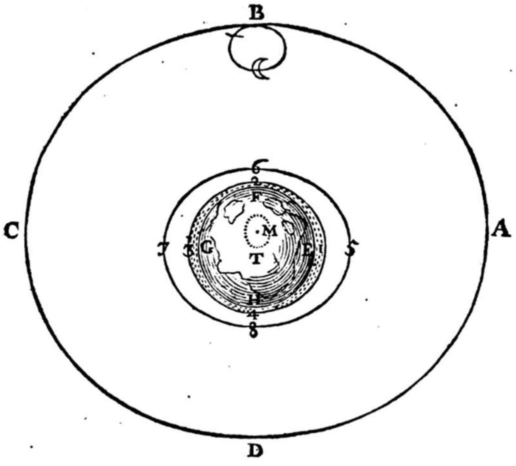
The vast reaches of the cosmos are filled with a primary fluid-like substance that Descartes tends to call *materia cœlestis* or "heavenly matter."[39] This concept is known as a *plenum*, from the Latin world for *full*. Descartes' plenum is not static, however. It is energized with circular vortexes set in motion by God that carry the planets in their orbits like leaves in the whirlpools of a turbulent river.

The vortex that surrounds the Earth pushes down towards the Earth from all directions. This is the physical cause that keeps the matter that makes up the Earth cohered in a sphere, and which results in objects having weight and the tendency for them to fall. Gravity is the direct physical contact of the heavenly matter of the plenum with the more visible matter of our world.

All motion in Descartes' system is relative. A planet doesn't move relative to the vortex that carries it. Because the Earth is stationary relative to its vortex, Descartes clearly denies any heretical movement of the Earth, and just to make sure he concludes the *Principia philosophiae* with the following disclaimer:

> Nevertheless, mindful of my insignificance, I affirm nothing: but submit all these things both to the authority of the Catholic Church and to the judgment of men wiser than I; nor would I wish anyone to believe anything except what he is convinced of by clear and irrefutable reason.[40]

Descartes would have been derelict in his philosophical duties if he failed to take on the challenge of the tides, and much of the latter part of *Principia philosophiae* leads up to this discussion. Here is Descartes' original diagram[41]:



The Earth is in the center. The outer circle (ABCD) is the vortex that causes the Earth to rotate, and which also carries the Moon (the small circle at top) it its orbit around the Earth. For purposes of simplicity, the Earth is entirely covered with water (the dotted area) and the seas are covered by the atmosphere (the numbered circle around the Earth).

Without the presence of the Moon, the center of the Earth would sit at the center of the vortex. But the Moon unbalances the vortex, and causes the Earth to shift slightly away from the Moon, and also from the vortex center. This Moon and shifted Earth cause the vortex to exert more pressure on the Earth at the top and bottom (in this diagram) than on the left and right, and that is what causes low and high tides at different areas around the world.

It's easy to see how the low and high tides shift around the Earth as the Earth rotates on its axis. Descartes also demonstrates that the vortex ABCD is not quite a circle but morphs slightly in shape based on the relative angles of the Moon and Sun relative to Earth. This is what causes more extreme tides at New Moon and Full Moon.

The vortex theory accounts for all the observed periodicity in the tides but compels the time of low tide to coincide with the Moon being directly overhead. This is not quite what observations reveal. Depending on the depth of the sea and irregularities in the shoreline, high tide can occur when the Moon is directly overhead, or up to six hours later. Descartes' explanation indicates that high tide is *always* six hours after the Moon has reached its overhead peak.

Both Galileo and Descartes were skilled mathematicians. Descartes is credited with combining geometry and algebra in what we now call analytic geometry.[42] The Cartesian coordinate system is named in his honor. Yet neither Galileo nor Descartes attempted to apply mathematics to their models of the cosmos. Both men were familiar with Kepler's work (Galileo probably more so), but neither man could mathematically demonstrate how or why the movements of the planets were governed by Kepler's Three Laws.

Despite this omission, Descartes' vortex theory was the first comprehensive mechanistic description of the universe. Except in its genesis, Descartes' universe requires no supernatural intervention. The mechanical philosophy as Descartes presented it remained quite compelling for decades after his death in 1650.

But not for Catholics. In 1663, all of Descartes' writings were added to the *Index Librorum Prohibitorum*, where they joined the work of Copernicus, Galileo, and Kepler.

Isaac Newton — born on Christmas Day in 1642, the same year that Galileo died — once said in an uncharacteristically gracious moment, "If I have seen further it is by standing on the shoulders of giants."[43] Three of those shoulders belonged to Galileo Galilei, Johannes Kepler, and René Descartes, but it was up to Newton to work out the mechanics of planetary orbits and crack the mystery of the tides.

Newton grew up during the Civil War and the rule of Oliver Cromwell. He was 17 years old in 1660 when the Restoration put Charles II on the throne. Later that year, a group of academics, physicians, and gentlemen scholars founded an organization they called the Royal Society of London dedicated to investigations of nature and mathematics, later called the Royal Society of London for Improving Natural Knowledge. Among the names associated with the early Royal Society were Christopher Wren, Robert Boyle (remembered today for his pioneering work in chemistry), and Robert Hooke, who explored the sky with telescopes and the minutiae of living things with microscopes. All these men were to play a role in Newton's future life.

In 1661, Newton began attending Trinity College in Cambridge, where he was generally regarded by his schoolmates as weird and unsociable. He soon earned a reputation for absent-mindedness. Many of the stories later told about Newton concerned his propensity for becoming so involved in his work that he would often forget to eat.

Newton soon abandoned the Aristotle-rich curriculum of Trinity to embark on his own program of self-study. He read Galileo and all of Descartes, and took some ideas from both writers, but rejected many others. He would spend much time scribbling mathematics and diagrams on paper, but he also built things. Newton constructed the first successful reflecting telescope, a type of telescope that collects light on a curved mirror and focuses it on another mirror in an eyepiece. He experimented, sometimes even on his own body, and more than once came close to blinding himself.[44]

Newton had already made some crucial headway in mathematics and celestial mechanics when the Great Plague hit England in 1665. What's now known as bubonic plague was spread by bites from fleas that lived on rats, and the 1665 epidemic eventually killed over 100,000 people in England. For their own welfare, all the students at Cambridge were sent home and the college was shut down for almost two years. Newton was not the type of person to treat this break as a vacation. If anything, it gave him more study time without the distractions of a formal education. If his later testimony is to be believed, Newton made several intellectual breakthroughs during this period, including the development of calculus and the concept of universal gravity. It is not entirely inconceivable that an apple falling from a tree at his family home played a role in his thoughts.

By 1666, the 23-year-old Isaac Newton "had become the leading mathematician in Europe,"[45] but the only person who knew this was himself. He had a lifelong neurotic adversity to publishing his work. He didn't want the attention that would draw him away from his studies, and he didn't want to waste time engaged in defending controversial ideas. It wasn't until nearly two decades later when Newton told the younger Edmund Halley that he had already solved the crucial problems involved in planetary motion that he was persuaded write a book.

The title that Newton chose — *Philosophiæ Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy*) — was deliberately intended to evoke memories of Descartes' *Principia philosophiæ* — but the additional adjectives signal a profound difference.

The old term *natural philosophy* encompassed subjects that today would be divided into the myriad fields of astronomy, physics, electricity, chemistry, and even biology. It is tempting to treat natural philosophy as simply a quaint term for a familiar classroom. But in Newton's day, natural philosophy had a religious element that was crucial to its practice:

> [O]ver and above any other defining feature which marks natural philosophy off from modern science — for instance, that it was philosophy, and therefore primarily for the purposes of contemplation rather than action — natural philosophy was *about God* and *about God's universe*. Indeed, this was the central pillar of its identity as a discipline, both with respect to its subject-matter and to its goals, its purposes, and the function

> it served. This is what, more than anything else, distinguishes it from our modern science.[46]

Even when more modern terms became available in the 19th century, some scientits preferred the older appellations. The 1867 book that William Thomson (Lord Kelvin) coauthored was titled *A Treatise on Natural Philosophy*.

Despite the underlying implications of natural philosophy, Newton makes nearly no allusion to God, religion, or metaphysics in the first edition of the *Principia*. This was deliberate. As he famously stated at the outset of Book 3, "No more causes of natural things should be admitted than are both true and sufficient to explain their phenomena."[47]

If Descartes' *Principia* is structured like a Jesuit schoolbook, Newton's *Principia* takes the form of a mathematics text: It begins with definitions and axioms and then proceeds with mathematical proofs. Rather than using the powerful tools of the calculus he had developed, Newton chose instead to present these proofs with more archaic and complex geometric diagrams. Three centuries later, Nobel prize-winning physicist Subrahmanyan Chandrasekhar translated these diagrams into more modern mathematics in a book he called *Newton's Principia for the Common Reader*, but by "common reader" he meant someone fluent in differential equations.

Despite the difficult presentation, the laws of motion established in the *Principia* have become well-known and deeply embedded in our culture. These laws begin with the concept of inertia that Newton got from Descartes: A body remains at rest or in motion travelling in a straight line with a constant velocity unless acted upon by a *force*.

Newton's force is anything that causes the body to accelerate, which means to change either its speed or its direction. In the metric system used today, force is measured in units of *newtons*. A newton is the force required to accelerate a kilogram mass by one meter per second squared, meaning that every second the force is applied, the mass's velocity increases by one meter per second. The most fundamental formula in physics is Force equals Mass times Acceleration, $F = ma$.

Very early in the *Principia* (Definition 5 on page 3 of the original Latin edition[48]), Newton invents a new word:

> Centripetal force is the force by which bodies are drawn from all sides, are impelled, or in any way tend, toward some point as to a center.[49]

The word *centripetal* means *center seeking*, and this word was needed because one did not exist.

The slightly different word *centrifugal* existed prior to the *Principia*; that word was coined by Dutch mathematician Christiaan Huygens in 1659. Centrifugal — literally, *center fleeing* — is the force that extends *out* or *away* from a center of rotation, and it's very common to our direct experience. We feel centrifugal force when we swing something in a circle, or take a sharp turn in a moving vehicle. But the use of the word *force* here is not quite right. Centrifugal force is really a manifestation of inertia.

If you tie a string to a ball and swing it around your head, the ball acquires inertia. This inertia tends to keep the ball moving in a straight line tangent to its orbit, as you can easily determine if you let go of it. If you don't let go, it remains moving in a circle because of the string's molecular forces (unknown in Newton's time) pulling the ball towards the center. Those molecular forces constitute the centripetal force — the force pulling the ball towards the center. What we call the centrifugal force is actually the difference between the inertia and the centripetal force.

At first, Newton explores centripetal force very abstractly. After developing some mathematical tools, he begins determining what the characteristics of this centripetal force must be for elliptical orbits, for objects in free fall, and later for pendulums. Newton progressively establishes exactly what type of centripetal force is consistent with Galileo's analysis of falling objects and Kepler's discovery of elliptical orbits.

Newton finds that for consistency with Galileo and Kepler, the centripetal force must follow an *inverse-square law*. What this means is that the centripetal force decreases as two objects get farther apart (which seems reasonable), but that the decrease is based not on the distance but the *square* of the distance. Double the distance between two objects, and the centripetal force drops to one-quarter (one divided by two squared). Triple the distance and the centripetal force becomes one-ninth of the original.

It's almost as if centripetal force spreads out like light. If you shine a light on a wall from a distance of 10 feet, an area of the wall is illuminated. If you step back 20 feet from the wall, the illuminated area doubles both horizontally and vertically, which means that the illuminated area increases by a factor of four. Overall it's the same amount of light, so the light hitting any particular spot decreases to one-quarter. That's the inverse-square law.

It's possible to imagine centripetal force behaving in something other than an inverse-square law, but the mathematical implications of the inverse-square law are profound. This is precisely the type of force that causes objects to orbit in ellipses.

Kepler also found that during an elliptical orbit, a planet moves faster when it's nearer the Sun than farther away. Newton proves that the inverse-square law causes precisely that effect. Kepler's third law involved the relationship between the distance of planets from the Sun and the time of their orbits, and Newton proves that's a result of the inverse-square law as well. In 1687, no one but Newton had the mathematical chops to prove these things.

It is only much later in the *Principia* — after Book 2 explores objects moving through a resistive medium with an agenda of demonstrating the mathematical impossibility of Descartes' vortexes — that Newton equates this centripetal force with gravity. Newton's big conceptual leap was in identifying a gravitational attraction between *any* two masses. Gravity is universal: the same force that causes an apple to fall from a tree also keeps the Moon in its orbit around the Earth.

The gravitational force between two objects is proportional to their masses. Bigger masses have greater attraction than smaller masses. The force of gravity is what causes a mass to have weight. In fact, the unit of weight in the metric system is the same as the unit of force: the newton. Although people commonly use grams and kilograms to express weight, those are more properly units of mass. A one kilogram mass weighs 9.8 newtons on the Earth but about 1.64 newtons on the Moon.

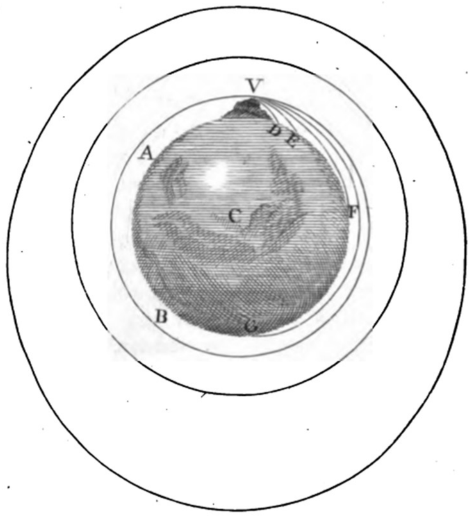
Every little particle that makes up the Earth has a gravitational attraction to every other little particle. This is what holds the Earth together. Similarly, the mutual gravitation of all the particles that make up the Moon is what holds the Moon together. But what is the gravitational attraction between the Earth and the Moon as entire entities? Doesn't the calculation of this mutual gravity get inordinately complex if we must take account of all these individual particles?

In the *Principia*, Newton proves that the overall gravitational attraction of a body such as the Earth or the Moon is the same as if the entire mass of the object were concentrated in its center. This simplifies the calculations enormously.

For example, the center of the Earth is about 4,000 miles below the Earth's surface. If you weigh 160 pounds on the Earth's surface, at 4,000 miles above the Earth's surface you'd weigh one-quarter of that, or 40 pounds. That's the inverse-square law: Double the distance, quarter the weight. At 8,000 miles above the Earth's surface, your weight drops to one-ninth, and at 12,000 miles up (16,000 miles from the center) it drops to one-sixteenth, or 10 pounds.

In Newton's analysis, gravity causes a celestial body to remain in orbit in the same way that gravity causes an object to fall to the Earth. Recall Galileo's javelin: The javelin thrower's arm accelerates the javelin to a particular velocity. When the javelin is released by the thrower's hand, it travels horizontally at a constant speed due to inertia. At the same time, the force of gravity pulls the javelin to the Earth. The javelin accelerates as it falls. The combination of these two movements causes the javelin to make a curve in the air until it hits the ground. This curve, Galileo proved, is a parabola.

An orbit is analogous. In a thought experiment that Newton originally wrote for the *Principia* but which wasn't published until after his death, he presents a more intuitive demonstration. Newton asks us to imagine carting a cannon to the top of a mountain, and shooting a cannonball from point V as shown in this original diagram:[50]



As we know from Galileo's javelin, the cannonball falls to the Earth in a parabola and lands at position D. Now load up the cannon with somewhat more gunpowder and try it again. The cannonball exits the cannon with a greater velocity and travels farther before it drops at position E.

Now keep ramping up the firepower. At some point — in theory, or course, because this is merely a thought experiment — the curvature of the Earth will start to affect where the cannonball lands. As the Earth curves away from the falling cannonball, the cannonball travels farther because it has farther to fall, and lands at positions F and G.

With a very, very high velocity no air resistance the cannonball never reaches the Earth. It keeps falling and falling towards the Earth but its horizontal velocity keeps it moving to a place where the Earth has curved away.

The cannonball is now in a low orbit around the Earth. The cannonball is continuously falling to the Earth but it never reaches the Earth's surface because the inertia of the cannonball also continuously carries it forward.

This is the conceptual leap of universal gravity: The Moon orbits the Earth because the Moon is falling to the Earth, and planets orbit the Sun because they're falling to the Sun.

In Aristotle's cosmology, gravity was the tendency for terrestrial objects to fall to Earth. Even to Galileo, gravity was limited to terrestrial objects. But in Newton's *Principia*, gravity becomes universal and the age-old distinction between the terrestrial and celestial vanishes.

The concept of universal gravity and the inverse-square law were certainly in the air in the 1680s. Indeed, in 1684, Robert Hooke told Christopher Wren and Edmund Halley that he had derived an inverse-square law from Kepler's Laws, and Halley himself had figured it out for circular orbits. Hooke couldn't produce the mathematical proof, however. This is the encounter that eventually led to Newton writing the *Principia*.

Although the first edition of the *Principia* approached the subject of comets, it wasn't known for sure that comets also often orbit the Sun. But in 1705 Edmund Halley used Newton's mathematics to establish that three comet sightings recorded over a 151-year period were actually the same comet orbiting in an extremely elongated ellipse, whipping around the Sun during the brief time that it's visible and then spending much of the rest of its 75-year orbit in a slow arc far beyond the range of sight.

At one time Newton considered including a justification of the Copernican model of the solar system in the *Principia*, but he later found it to be unnecessary. By the 1680s it was pretty much accepted among astronomers, and particularly those living in a Protestant country like England a thousand miles from Rome.

The heliocentric model is actually implied by Newton's laws of motion. Smaller masses always tend to revolve around larger masses because the more massive bodies are more resistant to the forces required for them to orbit. More precisely, two objects orbit each other around at a point sometimes referred to as the center of gravity, but is more correctly termed the center of mass or *barycenter*. The Moon and the Earth spin around their mutual center of gravity, and the Earth and Moon together orbits the Sun around their center of gravity.

Isaac Newton would have loved to tell the world exactly what gravity was and how it worked, and how two masses can attract each other across the vastness of space. He could not. This is why he called his book the *Mathematical Principles of Natural Philosophy* rather than just the *Principles of Natural Philosophy*. In the *Principia*, gravity is little more than a mathematical construct: The force of gravity is necessary and sufficient to mathematically derive everything we know about terrestrial and celestial motion, but Newton wasn't willing to speculate further. Several decades were required before gravity could shake the stigma of an occult property, and the acceptance occurred much slower in France than in England. Gravity remained unfathomable for over two centuries after the *Principia* until Einstein's theory of general relativity in 1915, and even then, many mysteries remain.

In Book 3 of the *Principia*, entitled "The System of the World," Newton uses everything he's proved to take on some real-life problems. For example, the Earth itself is deformed because of centrifugal force. Newton demonstrates[51] that as the Earth spins on its axis, centrifugal force causes the Earth to bulge at the equator and flatten near the poles. A cross section of the Earth sliced from the north pole to the south would resemble an ellipse.

No book as lengthy as the *Principia*, or which plunged deeper into the workings of the universe, could have ignored the subject of the tides.

To Galileo, the tides were caused by the interaction between the Earth rotating on its axis and revolving around the Sun. The daily shifts in direction causes the oceans to slosh around like water in a barrel aboard a barge. To Descartes, the tides were caused by the same celestial vortex that kept the Moon in its orbit around the Earth. As the Moon orbits, the vortex shifts, pushing down on the seas and causing low tides.

When Newton was still a teenager, Christopher Wren suggested to Robert Boyle an experiment involving the barometer that Boyle had been exploring…

> … in order to examine Monsieur des Cartes's Hypothesis, Whether the passing by of the Body of the Moon did press upon the Air, and consequently also the Body of the Water.

The subsequent experiments were apparently the first systematic measurements of atmospheric air pressure.

> The Time, when these Observations were made, was about the year 1658, or 59; at which Time Mr. Boyle having a Barometer fixed up, for observing the Moon's influence upon the Waters, happened to discover the use of it in relation to the Weather…[52]

Although atmospheric air pressure correlated with weather changes, it didn't seem to have anything to do with the Moon's position in the sky.

Newton's analysis of the tides is now sometimes called the static or equilibrium theory because it doesn't take into account the complex hydrodynamics that result from the division of the Earth into sea and land, the shape of irregular shorelines, and the varying depth of the oceans. Newton's theory assumes that the Earth is entirely covered with water, or that the water is confined to a channel around the Earth.

Common observations establish that the high tide comes every 12 hours and 25 minutes, but only half the high tides coincide with the Moon begin overhead. Viewed from afar, the Earth (on the left in the following diagram covered with water) has one high tide on the side of the Earth facing the Moon (on the right) and another high tide on the other side of the Earth facing away from the Moon:

Obviously this diagram is not to scale and the tidal effect is greatly exaggerated!

Every 24 hours, as the Earth rotates on its axis (counter-clockwise if we're looking at the northern hemisphere), the locations of those high tides change. The Moon revolves around the Earth (also counter-clockwise from this perspective) about 12.5 degrees a day, so for any particular location on the Earth, the Moon appears 24 hours 50 minutes later every day, and the high tides come every 12 hours and 25 minutes.

After Newton establishes gravitational attraction, the simple explanation for the two bulges is that the attraction by the Moon "of the nearer water will be greater and that of the more distant water will be smaller"[53] than the overall attraction between the Earth and the Moon. That's why there are two bulges.

That explanation might still be puzzling, and the diagram doesn't help. Even if it's believable that the Moon is pulling the waters on the side of the Earth that's closest to it, it still seems as if the waters on the other side are being pushed away. What is it that cause those waters to bulge?

The problem is that we tend to imagine the Earth and Moon in that diagram as static and somehow fixed in space. They are not. If the Earth and Moon were not moving, they would attract each and collide. They don't do that because the Earth and Moon are revolving around each other at their barycenter. The distance between them is governed by the speed of that rotation and their mutual gravitational attraction. In that sense, the attraction between the Earth and Moon is in a state of equilibrium. The gravitational attraction between the Moon and the oceans must therefore be interpreted as *relative to* the overall attraction between the Earth and the Moon. That relative attraction of the oceans to the Moon is a positive quantity on the side facing the Moon and a negative quantity on the side away from the Moon.

Another way to think about it is to consider centrifugal force. (Physics purists dislike this approach. They tend to prefer analyses without fictitious forces, and for good reason.)

The Earth is about 80 times the mass of the Moon, and the two bodies are about 240,000 miles apart. That puts the barycenter about 3,000 miles from the center of the Earth and about a thousand miles below the Earth's surface. This diagram of the Earth and Moon *is* to scale and shows the barycenter as a tiny dot inside the Earth:

That barycenter is not a fixed place in the Earth. The Earth rotates on its axis once a day as the Earth and Moon are revolving around the barycenter every four weeks or so, so the physical location of the barycenter is continuously changing, just as the locations of the high tides relative to the Earth are continuously changing.

The water on the surface on the Earth that faces the Moon experiences more of the Moon's gravity, but as the Earth and Moon revolve around their barycenter, the waters on the opposite side of the Earth experience less gravity from the Moon, and are thrown away from the Earth due to centrifugal force:

It's similar to the effect that causes the rotating Earth itself to have a bulge at its equator.

Although it's convenient to think of the Moon pulling up the waters of the Earth, that's not exactly what happens. The Moon's gravity doesn't have enough strength to pull the waters straight up. But the Moon has a gravitational influence over much of the entire hemisphere of water facing the Moon, and it does have enough strength to pull the waters sideways, just as it's usually easier to push or pull something than to lift it. The waters tend to move toward the area coinciding with the Moon's position, and that's what creates the bulge of high tide. Similarly, centrifugal force tends to throw the waters off in the opposite direction, and those waters accumulate to have the highest bulge at a point opposite the Moon.

If there were no Moon we'd still have tides from the effect of the Sun but they'd be only about 45% of the intensity of the lunar tides. Although the Sun is much more massive than the Moon (about 27 million times more massive) it is also a farther distance away from the Earth — about 93 million miles, or about 390 times the distance from the Earth to the Moon. Interestingly, the tidal force obeys an inverse *cube* law. It's proportional to the mass but decreases as the *cube* of the distance. Divide 27 million by 390 cubed, and that's the 45%.

The Sun also causes two tidal bulges — one towards the Sun because of the Sun's gravity, and the other way from the Sun because of the centrifugal force of the Earth's orbit around the Sun:

The Earth rotates on its axis relative to the Sun every 24 hours, so the cycle of solar tides is only 12 hours long.

The peculiar title cycle that we experience — big spring tides during New Moon and Full Moon and lesser neap tides in between — is due to the interaction of the solar and lunar tides.

At New Moon, the Moon sits roughly between the Sun and the Moon and the effects of the solar and lunar tides are combined in this exaggerated diagram:

Two bodies lining up on one side of the Earth is known as a *conjunction*.

Similarly, at Full Moon the Earth is roughly between the Sun and Moon and the effect is similar:

This configuration is known as an *opposition*. Both conjunction and opposition are examples of *syzygy* — three astronomical bodies lining up. Eclipses can only occur during the syzygy.

But at first quarter and last quarter, the Sun and Moon are in a configuration known as a *quadrature*. They pull the waters contrary to each other, The Sun partially compensates for the Moon’s gravity, which lessens the overall effect of the tides, but the lunar tides dominate and the tidal cycle is still 12 hours 25 minutes:

Or as Newton described the effect,

> [T]he two motions which the two luminaries [the Sun and the Moon] excite will not be discerned separately but will cause what might be called a mixed motion. In the conjunction or opposition of the luminaries their effects will be combined, and the result will be the greatest ebb and flow. In the quadratures the Sun will raise the water while the moon depresses it and will depress the water while the moon raises it; and the lowest tide of all will arise from the difference between these two effects.[54]

In the simplest analysis, the rise and fall of the ocean waters is a combination of three cycles:

- Two solar tides during the Earth's rotation on its axis every 24 hours
- Two lunar tides during the Moon's apparent revolution around the Earth of 24 hours 50 minutes
- The varying interaction of the Sun and the Moon over a 29½ day cycle of the phases of the Moon.

Overall, the tides have a semi-diurnal (meaning half a day) cycle.

Various other cycles of the Earth, Moon, and Sun complicate this:

Orbits are elliptical. The closest distance that the Moon comes to the Earth is known as the *perigee* and the farthest distance is the *apogee*. The Moon goes through one of these elliptical cycles during its orbit of 27.3 days. (This is shorter than the time between New Moons, which is 29.5 days, because that period is also affected by the Earth's rotation around the Sun.) Lunar tides are somewhat intensified at perigee, though the effect is not nearly as great as that of the Full Moon and New Moon.

The terms are different for the elliptical orbit of the Earth rotating around the Sun. The shortest distance between the Earth and Sun is the *perihelion* (which occurs around January 3) and the longest distance is the *aphelion* (about July 4). This also affects the tides.

No mention has been made yet of the Earth's 23.4° tilt on its axis. This tilt causes the seasons and affects the tides as well. At summer solstice (about June 21), the northern hemisphere experiences its maximum tilt towards the Sun, as the axis indicates:

The curved line across the center of the Earth represents the equator. The main effect of the Sun's gravity is on the northern hemisphere, and the maximum effect is at a latitude of 23.4° north, known as the Tropic of Cancer. But the opposite high tide is in the southern hemisphere, and has a maximum effect at the Tropic of Capricorn. This means that the two solar tides in these regions are unequal. As the Earth rotates on it axis, the northern hemisphere gets one intense solar tide when the Sun is overhead and a lesser solar tide in the middle of the night. In the southern hemisphere, the lesser solar tide is during the day and the larger solar tide is in the night. The effect is opposite at winter solstice (about December 21).

The orbit of the Earth around the Sun, and the orbit of the Moon around the Earth are roughly in the same plane. There's only about a 5° difference, which means that this same seasonal effect also occurs with lunar tides. However, during the 28.5-day cycle of the phases of the Moon, the interaction becomes more complex. At summer solstice, when the Sun and Moon are in opposition, the northern hemisphere gets its maximum solar tide when the Sun is directly overhead while the southern hemisphere is experiencing its maximum lunar tide:

This effect is known as the *diurnal inequality* of the tides, and it has both a yearly and a monthly cycle.

At the equinoxes (about March 21 and September 21), the Sun is directly overhead the equator, so there is no diurnal inequality due to the solar tides, but the equatorial area experiences the most extreme tides. The Moon is also over the equator during Full Moon and New Moon, contributing to the effect. These are known as *equinoctial tides*.

Fortunately, it's not necessary to take any of the other planets into account; they have a negligible effect on Earth tides.

But keep in mind that Newton's analysis of the tides is an unrealistic simplification that assumes the Earth is entirely covered by water, or the waters are confined to a channel circling the Earth. In real life, tides interact with very irregular shorelines and shore beds, which causes the tides to resonate in complex ways. Getting a feel for these interactions requires taking hydrodynamics into account.

In his explication of the tides, Newton established the basic mechanics but also left plenty of work for his successors.

Newton's *Principia* represented a foundational break with earlier 17th century theories. In 1650, the young Robert Boyle coined the term *mechanical philosophy* to describe the common elements of the various systems of natural philosophy developed by Descartes, the Frenchman Pierre Gassendi, and the Englishman Thomas Hobbes. In a system based on a mechanical philosophy, all natural phenomenon derives from direct interactions of particles of inert matter.

With Newton's concept of universal gravity, the basic tenet of the mechanical philosophy was thrown askew. All matter now has a property of attraction to all other matter in a mysterious way and without any apparent connection. Neither Newton nor anyone else had any explanation for how this worked, and yet, the mathematics of this attraction were capable of accurately describing for the first time all the fundamental phenomena of the universe.

It's useful to recall Newton's statement at the outset of Book 3 of the *Principia*, "No more causes of natural things should be admitted than are both true and sufficient to explain their phenomena." The result was that the first edition of the *Principia* didn't ascribe anything in the natural world to the effect of a Creator. It was only in the second edition (published in 1713) that Newton added a final General Scholium that devotes a few paragraphs to the existence of God and the evidence of His design in the structure and nature of the universe.

Newton's *Principia* had a profound influence on western civilization that went far beyond establishing basic laws of motion and the principle of universal gravity. Its impact was felt in British (and later, Continental and American) philosophy, religion, and society. Newtonians treated the existence of natural laws — with their consequent effect on the order, harmony, and regularity of the universe — as clear evidence of intelligent design. Newtonians used this natural theology to advocate for a big-tent latitudinarian approach to religion with "broad principles, based on the operation of nature, which would appeal to reasonable and sober men, regardless of their particular version of Protestantism."[55]

A natural theology based on Newton, however, contained the seeds of its own destruction. Some thinkers "perceived that in the heart of Newtonian science lurked an entirely naturalistic, secular way of explaining the natural world."[56] The natural laws themselves became substitutes for God. Because Newton's clockwork universe runs by itself, it requires no divine interaction except possibly to set it going in the first place. Miracles were increasingly doubted because they represented improbable violations of God's (or nature's) own laws. There is a direct line from the *Principia* to the deists, skeptics, and Unitarians of the 18th century Enlightenment — to British writers David Hume and Edward Gibbon, French *philosophes* Denis Diderot and Voltaire, and American revolutionaries Thomas Paine, Thomas Jefferson, and Benjamin Franklin. But the pious Newton would have been appalled by this trend.

French and American revolutionaries of the 18th century were also inspired by the political events in England in 1688 and 1689. This was a revolution that occurred largely in the halls of Parliament. Before the Convention Parliament agreed that James II had effectively abdicated, and that William and Mary should become co-monarchs to succeed him, they drafted a Declaration of Rights that spelled out the limitations of the new sovereigns. Many of these limitations had long histories in English tradition and law, but Charles II and James II had both violated them, and the Declaration made it clear that this would no longer be tolerated.

After William and Mary became King William III and Queen Mary II, the Convention Parliament became an actual Parliament, the Declaration of Rights became a Bill of Rights, and Isaac Newton and the other members of Parliament settled down to work that occupied them for much of the rest of the year. The relationship between Parliament and the monarchy had already fundamentally changed. Parliament established a dominance that would never be diminished. Prior to 1689, Parliaments sat only when the sovereign summoned them. Since 1689, Parliament has met every year regardless.[57]

By the end of 1689, these events had become known as the Glorious Revolution. It is also known as the Bloodless Revolution, but rather less accurately, for there were battles in Ireland and Scotland, and a nine-year war with France that spread to North America, where it was called King William's War, and resulted in France giving up its territories east of the Mississippi River.

Although there seems to be evidence that Isaac Newton took a radical pro-Parliament and anti-Catholic Whig stance on the issues that Parliament faced, the records of the time don't indicate that he actually participated in the debates. According to one anecdote (taken seriously by Newton's most insightful biographer), Newton spoke up only once, and that was to ask an usher to close a window because he felt a draft.[58]

To justify the replacement of one sovereign with another, several interpretations of the Glorious Revolution developed. The Tories tended toward a theory related to conquest.[59] Just as Henry Tudor defeated Richard III in the Battle of Bosworth in 1685, William defeated James II in 1688, even though they were never on the same battlefield.

The Whigs, however, tended to favor a contract theory for the Glorious Revolution. James II had violated his implicit contract with the people of England, who responded by deposing him and selecting a new sovereign, because this was the people's right.

Very much in favor of the contract theory (which he called a *compact*) was 56-year-old philosopher John Locke. Locke had been in exile in Europe since 1683, when he was identified as having some contact with the men involved in the Rye House Plot to assassinate Charles II and his brother James. Locke returned to England about the same time that Mary joined her husband William following the approval of the Declaration of Rights by the Convention Parliament. Some historians even believe they travelled to England on the same ship.[60]

Before the end of 1689, John Locke published the three books that established his philosophical legacy.

In April, *Epistola de Tolerantia* was published anonymously in Holland, later translated into English as *A Letter Concerning Toleration*, which dealt with how a country might deal with a wide spectrum of religious belief. Locke appealed to the charity of Christianity itself to declare tolerance for other Christian sects, and to separate religion from government:

> I esteem it above all thing necessary to distinguish exactly the Business of Civil Government from that of Religion, and to settle the just Bounds that

> lie between the one and the other. If this be not done, there can be no end put to the Controversies that will be always arising, between those that have, or at least pretend to have, on the one side, a Concernment for the Interest of Mens Souls, and on the other side, a Care of the Commonwealth.[61]

However, Locke did not feel that this tolerance should be extended to Roman Catholics, who were widely believed to value Roman authority over the civil government. Nor do atheists get a pass, for they could not be trusted to comply with any promises, covenants, or oaths.

In November, Locke's *Two Treatises of Government* appeared, also anonymously. The first treatise is a takedown of a book published in 1680 that argued for absolute rule and the divine right of kings through the Biblical analogy of Adam and parentage. The second treatise explores the characteristics of a government that protects lives, liberties, and property with the consent of the governed:

> I affirm, *viz.* That the *Beginning of politick Society* depends on the Consent of the Individuals, to joyn into, and make one Society; who, when they are thus incorporated, might set up what Form of Government they thought fit. And tis not without Reason, that he seeks out, and is willing to joyn in Society, with others, who are already united, or have a Mind to unite, for the mutual *Preservation* of their Lives, Liberties, and Estates, which I call by the general Name, *Property*.[62]

The Tories preached non-resistance to the monarchy. Locke outlined a political philosophy to justify revolution if necessary to secure the rights of the people.

A month later, in December 1689, John Locke published his big book, *An Essay Concerning Human Understanding*, which he had been working on for nearly two decades. Unlike the two earlier publications of 1689, Locke's name appeared between the covers.

As the title indicates, Locke's *Essay* concerns how the mind obtains information about the outside world and formulates ideas. In response to the assumption of Descartes and others that our minds provide a connection to God, Locke boldly titles his second and third chapters "No innate Principles in the Mind" and "No innate practical Principles." Instead, the mind at birth is "a white Paper, void of all Characters, without any *Ideas*"[63] — a *tabula rasa* that is ready to process sensory experience and accumulate knowledge.

> *Knowledge* then seems to me to be nothing but *the perception of the connexion and agreement, or disagreement and repugnancy of any of our Ideas*. In this alone it consists. Where this Perception is, there is Knowledge, and where it is not, there, though we may fancy, guess, or believe, yet we always come short of Knowledge.[64]

As crucial as knowledge itself is our awareness of the limitations of knowledge. Our ultimate uncertainty requires us to use probabilities to evaluate the validity of potential truths[65], and set boundaries between faith and reason.[66] Locke is actually pessimistic about the program of natural philosophy because he doesn't feel that we can ever discover the underlying causes of natural phenomena beyond what we can detect with our senses.[67] This is quite in contrast to Descartes, who believed that he could figure out the universe entirely through clear and distinct contemplation.

John Locke and Isaac Newton met sometime in 1689 and discovered some affinities. It is likely they discussed their unorthodox religious beliefs.[68] Although the *Principia* was quite beyond his mathematical abilities, Locke recognized the importance of the book and strove to understand it. One scholar writes how Locke viewed the importance of the Newton's work:

> The only way in which natural philosophy could be advanced was by the methods of observation and deduction and, although there were definite limits to what could be learnt by the application of such techniques, Newton had shown that they were, nevertheless, capable of producing the most wonderful results. The *Principia* was for Locke the vindication of a general methodological approach to which he had subscribed for perhaps twenty years.[69]

Newton likewise seemed to take something from Locke's epistemology — a certain clarity concerning the way in which we obtain information about the natural world through our senses and how we can formulate knowledge from it. Locke's influence seems very strong in this abandoned draft of a preface that Newton wrote for a later edition of the *Principia*:

> What is taught in metaphysics, if it is derived from divine revelation, is religion; if it is derived from phenomena through the five external senses, it pertains to physics; if it is derived from knowledge of the internal actions of our mind through the sense of reflection, it is only philosophy about the human mind and its ideas as internal phenomena likewise pertain to physics. To dispute about the objects of ideas except insofar as they are phenomena is dreaming. In all philosophy we must begin from phenomena and admit no principles of things, no causes, no explanations, except those which are established through phenomena. And although the whole of philosophy is not immediately evident, still it is better to add something to our knowledge day by day than to fill up men's minds in advance with the preconceptions of hypotheses.[70]

The publication of the *Principia* seemed to allow Newton to emerge from a shell of isolation. In the years following, he became somewhat more gregarious. His service during the Glorious Revolution also led to a major government job running the Royal Mint.

Despite the relative bloodlessness of the Glorious Revolution (at least in England) the upheaval proved to be difficult for those citizens who had made a commitment to Roman Catholicism or to James II. The poet laureate for the previous twenty years, John Dryden, refused to take the oaths of allegiance to the new sovereigns and was replaced by Thomas Shadwell.

Others took the transition more in stride. Henry Purcell — born in 1659 on the eve of the Restoration who eventually became one of the court's favorite composers — navigated the regime change more smoothly. After three years of composing annual Welcome Odes for James II from 1685 to 1687, he wrote his first Birthday Ode for Queen Mary II in 1689, and then for the next five years as Mary's April 30th birthday became a national day of celebration.[71]

The Birthday Ode of 1694 was the last, however. By year-end, Queen Mary II was dead from smallpox at the age of 32, and Henry Purcell was called upon to write the music for her funeral. The slow march for timpani and a quartet of trumpets remains one of his most recognizable compositions. Over three centuries later, Purcell's mournful music captures the ache that England felt for their much-loved Queen who defied her father and joined her husband in helping to rescue England from tyranny.

But it is Isaac Newton, who lived to the age of 84, who has by far the most prominent memorial in Westminster Abbey. The inscription in Latin begins "Here is buried Isaac Newton, Knight, who by a strength of mind almost divine, and mathematical principles peculiarly his own, explored the course and figures of the planets, the paths of comets, the tides of the sea…"[72]

Alexander Pope, born in the watershed year of 1688, composed a more succinct epitaph: "Nature and Nature's laws lay hid in night: God said, Let Newton be! And all was light."

Living in London in 1727 at the time of Newton's funeral was a 32-year-old wit and gadfly in exile from his native France who wrote under the name of Voltaire. This was his first visit to England and the more he saw, the more he liked. He admired England's freedoms, its religious tolerance, its literature, and its advanced intellectual progress.

A few years later, Voltaire's book *Letters Concerning the English Nation* sings his enthusiasms, and shows a surprising interest in Newton's science of an intensity and depth that we no longer expect from humanist authors. Of the 24 letters in the first edition, Voltaire devotes three to Newton, another to Locke, and an introductory letter contrasting Newton and Descartes in which he refers to the works of Descartes as "useless"[73] and heralds Isaac Newton as "this Destroyer of the Cartesian System."[74]

> A Frenchman who arrives in *London*, will find Philosophy, like every Thing else, very much chang'd there. He had left the World a *plenum*, and he now finds it a *vacuum*. At *Paris* the Universe is seen, compos'd of Vortices of subtile Matter; but nothing like it is seen in *London*. In *France*, 'tis the Pressure of the Moon that causes the Tides; but in *England* 'tis the Sea that gravitates towards the Moon…
>
> The very Essence of Things is totally chang'd. You neither are agreed upon the Definition of the Soul, nor on that of Matter. *Descartes* … maintains that the Soul is the same Thing with Thought, and *Mr. Locke* has given a pretty good Proof of the contrary.[75]

Voltaire's *Letters Concerning the English Nation* (also known as the *Philosophical Letters*) is now regarded as one of the seminal writings of the French Enlightenment.

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