Chapter 12: The Scientific Revolution

During the seventeenth century, changes in how educated Europeans understood the natural world marked the emergence of a recognizably modern scientific perspective. The practical impact of that shift was relatively minor at the time, but the long-term consequences were enormous. For the first time, a culture emerged in Europe in which empirical observations served as the basis for logical conjecture about how natural laws operated, leading to the possibility of a vast range of scientific discovery.

For well over a thousand years, Europeans had looked backwards for insights into the natural world. They relied on Aristotle and accounts by other ancient authors to explain how the universe functioned, how physics operated, and how the human body regulated itself. These teachings were supplemented by Christian scholarship that sought to find the hand of God in the natural world. There was a marked absence of empirical research: observing, from a neutral and objective standpoint, natural phenomena and using those observations as the basis of informed experimentation as to their causes and operation.

Medieval and early-modern Europeans had never developed an empirical scientific culture because the point of science had never been to *discover* the truth, but to *describe* it. In other words, practically every pre-modern person already knew how the world worked: they knew it from myth, from the teachings of ancient authorities, and from religion. In a sense, all of the answers were already there, and thus empirical observation was seen as redundant. The term used at the time for "science" was "natural philosophy," a branch of philosophy devoted to observing and cataloging natural phenomena, for the most part without attempting to explain those observations outside of references to ancient authorities and the Bible.

The Scientific Process, Mentality, and Method

The Scientific Revolution grew out of Renaissance humanism. Humanistic scholars by the late sixteenth century were increasingly dissatisfied with some ancient authors, since those authors did not, in fact, explain everything. While ancient authors wrote about astronomy, for instance, they did not adequately explain the observed movements of the stars and planets. Likewise, with the explosion of new translations of classical works, it became clear that ancient scholars had actively debated and even rejected the teachings of figures like Aristotle. This suggested that it was legitimate to question even the most fundamental ancient ideas.

Even to scholars who respected and deferred to ancient authors, much of ancient astronomy was based on some fairly questionable speculations, like the idea that the Earth sits on top of a giant sea that occasionally sloshes around, causing earthquakes. Thus, the first major discoveries in the Revolution had to do with astronomy, as scholars started carrying out their own observations and advancing theories to explain what they saw happening in the heavens. This process is known as inductive reasoning: starting with disparate facts, then working toward a theory to explain them. It is the opposite of deductive reasoning, which starts with a known theory and then tries to prove that observations fit into it. The classic example of the latter was taking the idea that the Earth is the center of the universe as a given, then trying to force the observed movements of the heavenly bodies to make sense through elaborate explanations.

That being noted, deductive reasoning is still an important part of “real” science in that it allows for proofs: in mathematics, for instance, one can start with a known principle and then use it to prove more complex formulas. Mathematics itself played a key role in the Scientific Revolution, since many thinkers insisted that mathematics was part of a divine language that existed apart from, but was as nearly important as, the Bible itself. God had designed the universe in such a way that mathematics offered the possibility of real scientific certainty. The close relationship between math, physics, and engineering is obvious in the work of people like Da Vinci, Galileo, and Isaac Newton, all of whom combined an advanced understanding of mathematics and its practical applications.

That being said, it would be wrong to claim that the Scientific Revolution sparked a completely objective, recognizably “modern” form of science. What early-modern scientists hoped to do was understand the secrets of the universe. Isaac Newton was a scientist but also an alchemist, devoting considerable time and effort to trying to figure out how to “transmute” base metals like lead into gold. Likewise, many thinkers were intensely interested in the works of an ancient (and, as it turns out, fictional) philosopher and magician named Hermes Trismagistus, Hermes the “Thrice-Blessed,” who had supposedly discovered a series of magical formulas that explained the universe. There was a great deal of crossover between what we might think of as magic and spirituality on the one hand and “real” science on the other.
This is evident not only with Newton, but with other scientists of the era – many were astronomers *and* astrologers, just as many were mathematicians and engineers while also being alchemists. The point here is that, ultimately, even though it turns out that magic does not

exist, the interest in discovery piqued by the idea of probing the universe's secrets still led to genuine scientific discovery.

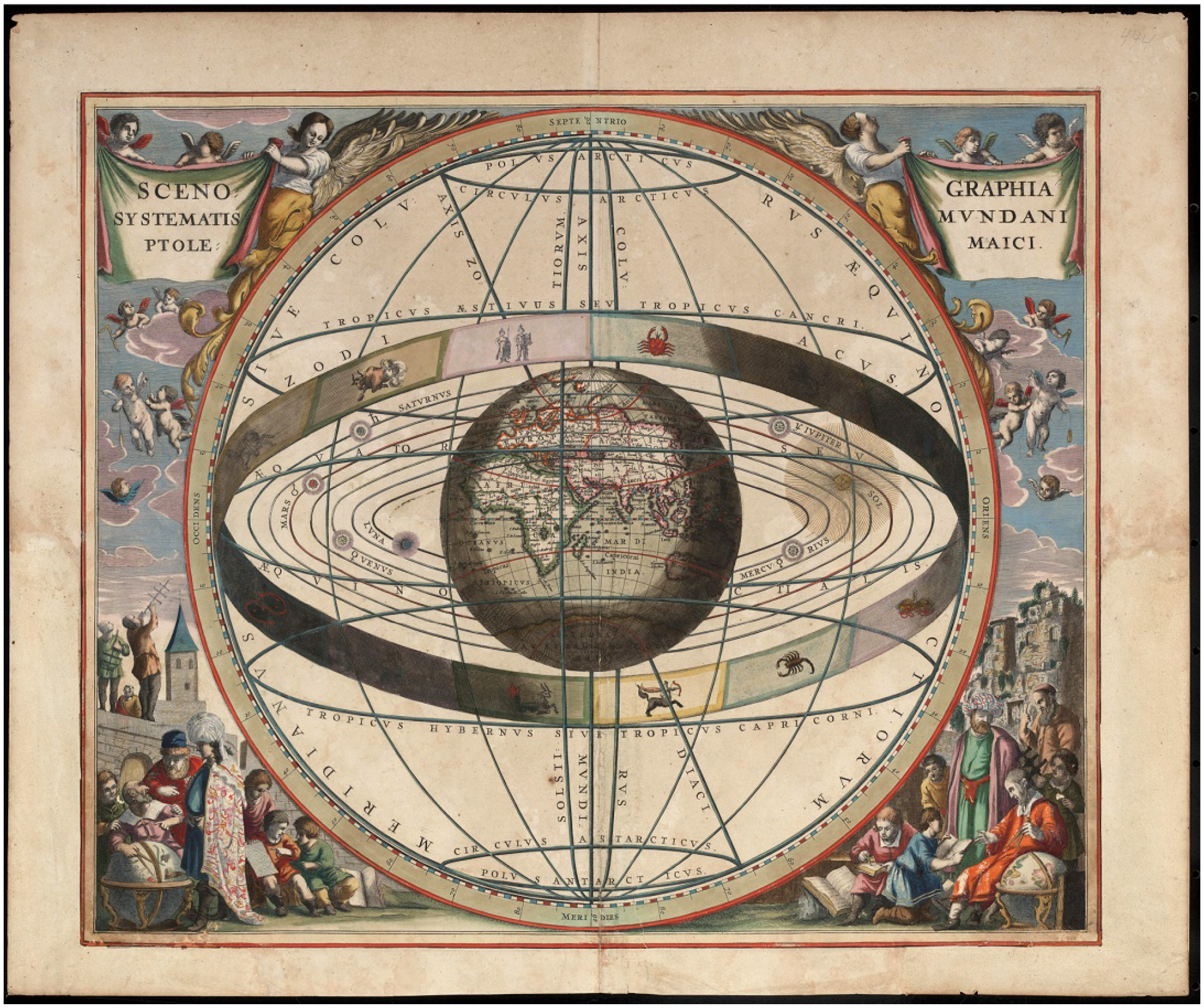
The major figure in codifying and popularizing the new empirical, inductive process was Francis Bacon (1561 – 1626), an English nobleman. Bacon is best remembered for "creating" the scientific method: advancing a hypothesis to explain observed data, but then trying to disprove the hypothesis rather than trying to force the facts to prove it. In this way, the best that could be hoped for was a highly likely, not-yet-disproven theory, rather than a flimsy, vulnerable theory that needed artificial defenses. Over time, the scientific method came to include a corollary requirement: the results of an experiment had to yield the same results consistently in order for a hypothesis to be considered viable.

Bacon took the radical step of breaking even with the Renaissance obsession with ancient scholarship by arguing that ancient knowledge of the natural world was all but worthless and that scholars in the present should instead reconstruct their knowledge of the world based on empirical observation. Bacon was a kind of prophet of the movement, not a scientist himself – he was fired as the Lord Chancellor of King James I after accepting bribes, and he died after catching a cold stuffing snow into a dead chicken as some kind of ill-conceived biological experiment. Regardless, he codified the new methodology and worldview of the Scientific Revolution itself.

Scientific Discoveries

Astronomy

The most influential ancient sources of scientific knowledge were Ptolemy, a Greek astronomer and mathematician, and Aristotle. Both argued that the Earth was at the center of the universe, which consisted of a giant crystal sphere studded with the stars. That sphere slowly rotated, while the sun, moon, and planets were suspended above the earth within the sphere and also rotated around the Earth. Ptolemy, who lived centuries after Aristotle, elaborated on the Aristotelian system and claimed that there were not just one but close to eighty spheres, one within the other, which explained the fact that the different heavenly bodies did not all move in the same direction or at the same speed. The idea that the earth is at the center of the universe is known as *geocentrism*.



The geocentric universe illustrated, with the sun and planets revolving around the Earth. Interestingly, the illustration above was created in 1660, a few decades after Galileo popularized the fact that heliocentrism was completely inaccurate.

In this model of the universe, the earth was distinct from the other heavenly bodies. The earth was imperfect, chaotic, and changing, while the heavens were perfect and uniform. Thus, Christian thinkers embraced the Aristotelian model in part because it fit Christian theology so well: God and the angels were on the outside of the most distant crystal sphere in a state of total perfection, while humans and the devil were on, or inside in the case of Satan, the imperfect world. This Christianized version of an ancient Greek model of the universe is where the concept that God and heaven are "up in the sky" and hell is "below the ground" originated. When the astronomers of the Scientific Revolution started detecting irregularities in the heavens, this totally contradicted how most learned people thought about, and had thought about, the essential characteristics of the universe.

The problem with this model is that it did not match the observed paths taken by the stars and, especially, the planets, which do not follow regular, circular orbits. Medieval astronomers tried to account for these differences by ever-more-elaborate caveats and modifications to the idea of simple perfect orbits, positing the existence of hugely complex paths supposedly taken by various heavenly objects. A Polish priest, Nicolaus Copernicus (1473 – 1543), was the first to argue in a book published just before his death that the whole system would match reality if the sun was at the center of the orbits instead of the earth: this concept is called heliocentrism. He retained the idea of the crystal spheres, and he also used Ptolemy's calculations in his own work, but his was nevertheless the first work to propose the concept of a heliocentric universe. Copernicus himself was a quintessential Renaissance man; he was a medical doctor, an accomplished painter, fluent in Greek, and of course, as an astronomer.

Copernicus's theory was little known outside of astronomical circles, with most astronomers expressing dismay and skepticism at the idea of heliocentrism. A Danish astronomer named Tycho Brahe (1546 – 1601) tried to refute the Heliocentric theory by publishing a massive work of astronomical observations and corresponding mathematical data that attempted to demonstrate that the Earth was indeed at the center of the universe but that the heavenly bodies followed monstrously complex orbits. He spent twenty years carefully observing the heavens from his castle on an island near Copenhagen. The major importance of Brahe's work for posterity was that it provided a wealth of data for later astronomers to work from, even though his central argument turned out to be inaccurate.

A German astronomer, Johannes Kepler (1571 – 1630), who had been Brahe's assistant late in his life, ended up using Brahe's data to argue against Brahe's conclusion, demonstrating that the data actually proved that the sun was indeed at the center of the universe. Kepler also noticed that there was some kind of force emanating from the sun that seemed to hold the planets in orbit; based on the recent work of another scientist concerning magnets, Kepler concluded that some form of magnetism was likely the cause (in fact, Kepler had noticed the role of gravity in space). Interestingly, Kepler did his work while holding a position as the official imperial mathematician of the Holy Roman Emperor Rudolph II, who overlooked the fact that Kepler was a Protestant because he (Rudolph) was so interested in science - and this was against the backdrop of the Thirty Years' War, no less!

In the end, the most significant publicist of heliocentrism was an Italian, Galileo Galilei (1564 - 1642). Galileo built a telescope based on a description he had heard and was delighted to discover previously unknown aspects of the heavenly bodies, such as the fact that the moon and sun did not have smooth, perfect surfaces, and that Jupiter had its own moons. He publicly demonstrated his telescope and quickly became well known among educated elites across Europe. His first major publication, *The Starry Messenger* in 1610, conclusively demonstrated that the heavens were full of previously unknown objects (e.g. the moons of Jupiter) and that planets and moons appeared to be "imperfect" in the same manner as the earth.

In 1632 he published a work, the *Dialogue*, that used the work of earlier astronomers and his own observations to support the heliocentric view of the universe; this work quickly became much better known than had Copernicus's or Kepler's. The Dialogue consisted of two imaginary interlocutors, one of whom presented the case for heliocentrism, the other for geocentrism. The supporter of heliocentrism wins every argument, and his debate partner, "Stupid" (*Simplicio*) is confounded. In publicizing his work, Galileo undermined the idea that the heavens were perfect, that the earth was central, and by extension, that ancient knowledge was reliable. Few things could have been more disruptive.

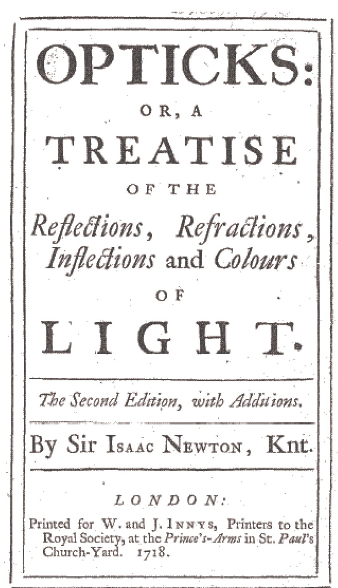
Galileo was tried by the Inquisition in 1633, in part because his former patron, the pope Urban VIII, thought that Galileo had been mocking him personally by naming the imaginary defender of the Ptolemaic view Stupid. Specifically, Galileo was accused of supporting a condemned doctrine, heliocentrism, not of heresy per se. Galileo was forced to recant and his book was placed on the Catholic *Index* of banned books, where it would remain until 1822. Much of the explanation for this persecution can be found in the fact that his work was published against the backdrop of religious war then engulfing Europe; the Catholic Church was not in a tolerant mode in the seventeenth century.

Galileo is less well remembered for his work in physics, but his work there was as important as his astronomy. Six years after the Dialogue was put on the Index, he published another work, *Two New Sciences of Motion and Mechanics*, that provided a theory and mathematical formulas of inertia and aspects of gravity. These theories refuted Aristotelian physics, which had claimed that objects only stay in motion when there is direct impetus; Galileo demonstrated through experiments the principles of inertia and acceleration and began the task of defining their operation mathematically.

Isaac Newton

Perhaps the single most important figure of the Scientific Revolution was Sir Isaac Newton, an English mathematician (1642 – 1727). Newton was, simply put, a genius. He was a chaired professor of mathematics at Cambridge University at the age of 27 and was renowned within his own lifetime for being one of the great minds of his age. In 1687 he published the *Mathematical Principles of Natural Philosophy*, which posited a single universal law of gravitation that applied equally to enormous objects like the planet Earth and tiny objects that could barely be detected by human senses. The entire system of physics was mapped out and described in precise, and accurate, mathematical formulas in the Mathematical Principles. It was one of the single greatest works of science of all time: its importance was not just in being "right," but in providing a comprehensive system that could replace the work of ancient authors like Aristotle. Following Newton, figures like Aristotle and Ptolemy were increasingly regarded in the manner they are today: important individuals in the history of thought, especially philosophy, but not sources of accurate scientific information.

Newton was one of the great intellectual over-achievers of all time. He correctly calculated the relative mass of earth and water, deduced that electrical impulses had something to do with the nervous system, and figured out that all colors are part of the larger spectrum of light. He personally designed and built a new and more effective kind of telescope, and wrote the founding paper of the modern science of optics.



OPTICKS:
OR, A
TREATISE
OF THE
Reflections, Refractions, Inflections and *Colours*
OF
LIGHT.

The Second Edition, with Additions.

By Sir ISAAC NEWTON, Knt.

LONDON:
Printed for W. and J. INNYS, Printers to the Royal Society, at the *Prince's-Arms* in St. *Paul's* Church-Yard. 1718.

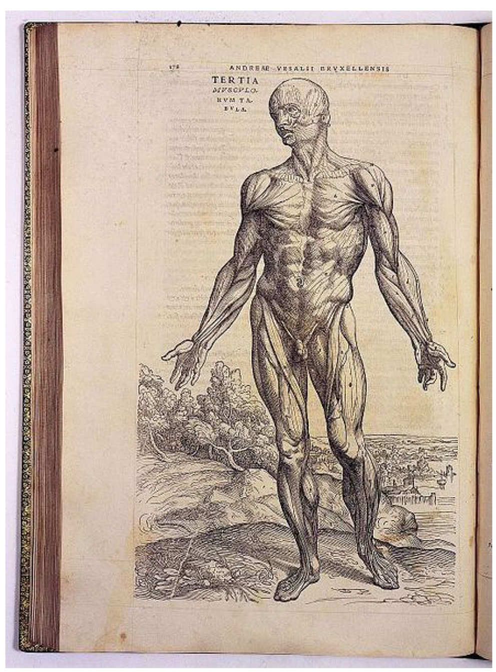
Newton's treatise on the properties of light, the founding document of optics.

Newton, personally, was a humorless curmudgeon. While he was famous in his own lifetime, ultimately being knighted by King William and serving as the chair of Britain's first scientific society, he only reluctantly published his work, and that only after fearing that his self-understood "rivals" would steal it if he did not. He was also completely chaste his entire life and had what might charitably be described as a "disagreeable" temperament.

Medicine

While astronomy and physics advanced by leaps and bounds during the period of the Scientific Revolution, other scientific disciplines such as medical science and biology advanced much more slowly. At the time there were a host of received notions and prejudices, especially against work on human cadavers, that prevented large-scale experimentation. Instead, most doctors continued to rely on the work of the Greek physician Galen, who in the second century CE had elaborated on the Aristotelian idea of the four "humors" that supposedly governed health: blood, phlegm, yellow bile, and black bile. According to that theory, illness was the result of an overabundance of one humor and a lack of another - hence the centuries-old practice of bleeding someone who was ill in hope of reducing the "excess" blood.

While belief in humors continued to hold sway in the absence of more compelling theories, important advances did occur in anatomy. The Italian doctor Andreas Vesalius (1514 – 1564) published a work on anatomy based on cadavers. Another doctor, William Harvey (1578 – 1657), conclusively demonstrated that blood flows through the body by being pumped by the heart, not emanating out of the liver as had been believed before. Shortly after his death, other doctors used a new invention, the microscope, the detect the capillaries that connect arteries to other tissues. Increasingly, physicians began to consider the human body as an item written into the Book of Nature as well.



One of Vesalius's illustration, in this case of human musculature.

Many medical advances would not have been possible without Renaissance-era advances in other fields. Renaissance artistic techniques made precise, accurate anatomical drawings possible, and print ensured that works on medicine could be distributed across Europe rapidly after their initial publication. Thus, scientists and doctors were able to contribute their discoveries to a growing body of work, all of which led to a more widespread understanding of how the body worked. Even though the concept of the humors (as well as other ideas like miasmas causing disease) remained prevalent, doctors now had a better idea of how the body was designed and what its constituent parts actually did.

Unfortunately for the health of humankind, the new understanding of anatomy did not lead to an understanding of contagion. The Dutch scientist Antonie Van Leeuwenhoek (1632-1723) invented the microscope, and in the 1670s he was able to identify what were later referred to as bacteria. Unfortunately, he did not deduce that bacteria were responsible for illness; it would take until the 1860s with the French doctor and scientist Louis Pasteur for definitive proof of the relationship between germs and sickness to be established.

Science and Society

Women

An often-overlooked facet of the Scientific Revolution was the participation of aristocratic women. Noblewomen were often the collaborators of their husbands or fathers – for example, it was a husband and wife team, the Lavoisiers, in France that invented the premises of modern chemistry in the eighteenth century. In some cases, such as the early entomologist Maria Sibylla Merian, women struck out on their own and conducted experiments and expeditions – Merian took a research trip to South America and did pioneering work on the life cycles of various insect species.

One of Merian's illustrations, depicting the life cycle of butterflies and moths.

A few male theorists supported a proto-feminist outlooks as well. The French scholar François Poulain de la Barre (1647-1725) concluded that empirical observation demonstrated that the custom of male dominance in European society was just that: a custom. Nothing about pregnancy or childbearing made women inherently unsuitable to participate in public life. De la Barre applied a similar argument to non-European peoples, arguing that there were only cosmetic differences between what would later be called "races." His work was almost unprecedented in its egalitarian vision, anticipating the ideas of human universalism that only really came of age in the nineteenth century, and only became dominant views in the twentieth.

Despite the existence of highly-qualified and educated women scientists, informal rules banned them from joining scientific societies or holding university positions. In general, in one of the most obvious failures of the Scientific Revolution to overcome social prejudices was in the marked tendency of male scientists to use the new science to reinforce rather than overthrow sexist stereotypes. Anatomical drawings drew attention to the fact that women had wider hips than did men, which supposedly "destined" them for a primary function of childbearing. Likewise, they (inaccurately) depicted women as having smaller skulls, supposedly implying lower intelligence. In fields in which women had held very important social roles in the past, such as midwifery, male scientists and doctors increasingly pushed them to the side, insisting on a male-dominated "scientific" superiority of technique. In short, it proved easier to overthrow the entire vision of the universe than to upset sexual roles and stereotypes.

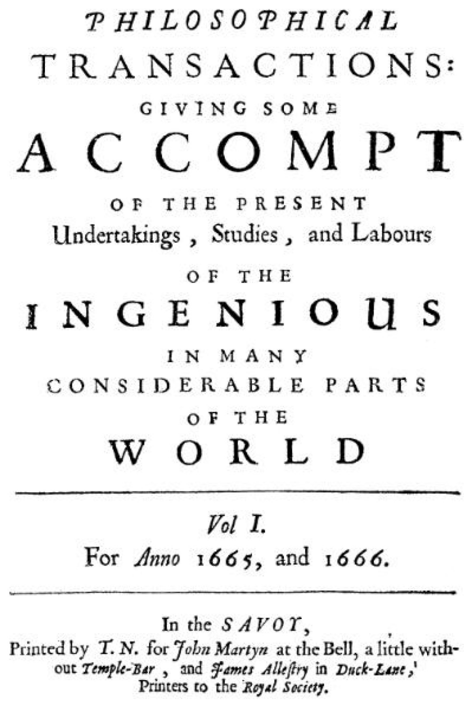
Scientific Institutions and Culture

Many developments in the early part of the Scientific Revolution occurred in Catholic countries such as Italy, but over time the center of scientific development shifted north and west. While many Protestants, including Luther himself, were just as hostile as were Catholics to new scientific ideas at first, in the long term Protestant governments proved more tolerant of ideas that seemed to violate the literal truth of the Bible. This had less to do with some kind of inherent tolerance in Protestantism than to the fact that Protestant institutions were less powerful and pervasive than was the Roman church in Catholic countries.

In the Netherlands and England in particular it was possible to openly publish and/or champion scientific ideas without fear of a backlash; in the case of Newton, it was possible to be outright famous. In general, Protestant governments and elites were more open to the idea that God might reveal Himself in nature itself, not just in holy scripture, and thus they were sympathetic to the piety of scientific research. Ultimately, this increased tolerance and support of science would see the center of scientific innovation in the northwest of Europe, not in the heart of the earlier Renaissance in Italy.

That being noted, France was not to be underestimated as a site of discovery, due in part to the cosmopolitanism of Paris and the traditional power of the French kings in holding the papacy at arm's length. The Royal Academy of Sciences in France was opened in the same year as its sister organization, the Royal Society, in England (1662). Both funded scientific efforts that were "useful" in the sense of serving shipping and military applications as well as those which were more purely experimental, as in astronomy. The English Royal Society was particularly focused on military applications, especially optics and ballistics, setting a pattern of state-funded science in the service of war that continues to this day.

The English and French scientific societies were important parts of the development of a larger "Republic of Science," the predecessor to present-day "academia." Learned men (and some women) from all over Europe attended lectures, corresponded, and carried out their own scientific experiments. Newton was the president of the Royal Society, which published Philosophical Transactions of the Royal Society, the forerunner to academic journals that remain the backbone of scholarship today.


PHILOSOPHICAL
TRANSACTIONS:
GIVING SOME
ACCOMPT
OF THE PRESENT
Undertakings, Studies, and Labours
OF THE
INGENIOUS
IN MANY
CONSIDERABLE PARTS
OF THE
WORLD

Vol I.
For *Anno* 1665, and 1666.

In the *SAVOY*,
Printed by *T. N.* for *John Martyn* at the Bell, a little without *Temple-Bar*, and *James Allestry* in *Duck-Lane*,
Printers to the *Royal Society*.

The cover of the first volume of the Philosophical Transactions, arguably the first formal academic journal in history.

The importance of the Republic of Science cannot be overstated, because the ongoing exchange of ideas and fact-checking among experts allowed science to progress incrementally and continually. In other words, no scientist had to "start from scratch," because he or she was already building on the work of past scholars. Rather than science requiring an isolated genius like Da Vinci, now any intelligent and self-disciplined individual could hope to make a meaningful contribution to a scientific field. Newton explicitly acknowledged the importance of this incremental growth of knowledge when he emphasized that “If I have seen further it is by standing on the shoulders of giants.”

The Republic of Science also inaugurated a shift away from the use of Latin as the official language of scholarship in learned European culture. Scientific essays were often written in the vernacular by scientists like Kepler and Galileo in part because they wanted to differentiate their work from church doctrine (which, of course, was traditionally written in Latin). Newton initially wrote in Latin so that it could be read by his peers on the continent, but his later works were in English. Over the course of the eighteenth century, Latin steadily declined as the practical language of learning, replaced by the major vernaculars, especially French and English.

The Philosophical Impact of Science

One of the effects of the scientific discoveries of the sixteenth century was a growing belief that the universe itself operated according to regular, predictable, "mechanical" laws that could be described through mathematics. This outlook lent itself to one in which God could be seen as a great scientist or clockmaker: the divine intelligence who created a perfect universe and then set it in motion. In this sense, then, the new scientific discoveries in no way undermined religious belief at the time, despite the fact that they contradicted certain specific passages of the Bible. This kind of religious outlook became known as *deism*, and its proponents deists, people who believed that God did not intervene in everyday life but instead simply set the universe in motion, then stepped back to watch.

Some thinkers, most notably the French philosopher Rene Descartes (1596 – 1650), tried to apply this new logical outlook to theology itself. Descartes tried to subject belief and doubt to a thorough logical critique, asking what he could be absolutely sure of as a philosophical starting-point. His conclusion was that the only thing he really knew was that he doubted, that there was something thinking and operating skeptically, which in turn implied that there was a thing, himself, capable of thought. This led to his famous statement "I think, therefore I am." Descartes went on to follow a series of logical "proofs" from this existing, thinking being to "prove" that God Himself existed, as the original source of thought. This was a philosophical application not just of the new mechanical and mathematical outlook, but of deductive reasoning. Descartes, personally, embraced the view that God was a benevolent and reasonable power of creation, but one who did not lower Himself to meddle in the universe.

Perhaps the most important cultural change that emerged from the Revolution was the simple fact that science acquired growing cultural authority. The results of the new science were demonstrable; Galileo delighted onlookers by allowing them to use his telescope not just to look at the sky, but at buildings in Rome, thereby proving that his invention worked. The possibility that science could, and in fact already had, disproved claims made in the Bible laid the foundation for a whole new approach to knowledge that threatened a permanent break with a religiously-founded paradigm. In other words, scientific advances inadvertently led to the growth in skepticism about religion, sometimes up to and including outright atheism: the rejection of the very idea of the existence of God.

The most extreme figure in this regard was Baruch Spinoza (1632 – 1677), a Sephardic Jew who was born and raised in Amsterdam in the Netherlands. Spinoza took the insights of the era and applied them wholeheartedly to religion itself, arguing that the universe of natural, physical laws was synonymous with God, and that the very idea of a human-like God with a personality and intentions was superstitious, unprovable, and absurd. He was excommunicated from Judaism itself when he was only twenty-four but went on to continue publishing his works, in the process laying the groundwork for what were later known as “freethinkers” – people who may or may not have been actual atheists, but who certainly rejected the authority of holy writings and churches.

Spinoza’s work was controversial enough that he was condemned as an atheist not only by the Jewish community, but by both the Catholic church and various Protestant churches as well. One of the things about his thought that infuriated practically everyone was that Spinoza claimed that there was no such thing as “spirit” or “the soul” – all of the universe was merely matter, and the only way to truly learn about its operation was to combine empirical experimentation with mathematics. This “materialism” as it was called at the time was so close to outright atheism as to be almost indistinguishable.

The other side of skepticism was a kind of cynical version of religious belief that dispensed with the emotional connection to God and reduced it to a simple act of spiritual insurance: the French mathematician Blaise Pascal (1623 – 1662), inventor of the field of probability, postulated “Pascal’s Wager.” In the Wager, Pascal argued that either God does or does not exist, and each person can choose either to acknowledge Him or not. If He does exist, and one acknowledges Him, then one is saved. If He does exist, and one rejects Him, then one is damned. If He does not exist and one acknowledges Him, nothing happens, and if He does not exist and one does not acknowledge Him, nothing happens either. Thus, one might as well worship God in some way, since there is no negative fallout if He does not exist, but there is (i.e. an eternity of torment in hell) if He does.

Pascal applied an equally skeptical view to the existing governments of his day. He noted that “We see neither justice nor injustice which does not change its nature with change in climate. Three degrees of latitude reverse all jurisprudence; a meridian decides the truth. Fundamental laws change after a few years of possession...a strange justice that is bounded by a river! Truth on this side of the Pyrenees, error on the other side.” In other words, there was no fixed or eternal or God-given about royal decrees and laws; they were arbitrary customs enforced through the state.

Conclusion

The Scientific Revolution, while it certainly achieved many important breakthroughs and discoveries, was as much about a cultural and intellectual shift as the discoveries themselves. It was not, for example, accompanied by technological advances of note with a few exceptions like telescopes. Instead, its importance lay in the fact that, first, educated people came to believe that the workings of the universe could be discovered through inquiry and experimentation, and second, that the universe itself was structured along rational lines. Those conclusions would in turn lead to a monumental movement of philosophy and thought during the eighteenth century: the Enlightenment.

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