Robert W. Baloh

Brain Electricity

The Interwoven History of Electricity and Neuroscience

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Robert W. Baloh
UCLA
Los Angeles, CA, USA

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To my father, "the electric man"

Preface

> By rapid averaging and other procedures, electronic computers are helping investigators to extract much new information from the complex recordings of the electrical activity of the brain.
>
> Mary "Mollie" Brazier, June 1, 1962, *Scientific American*

Electricity and neuroscience are topics that have fascinated science historians since ancient times. Each topic has a rich literary tradition with breathtaking discoveries made by colorful characters that changed the evolution of human culture. Yet, it has only been in recent times that medical science historians have appreciated the close interrelationship of these two topics. In England, Iwan Rhys Morus focused on the Victorian era and its fascination with the application of electricity to the body and brains of living beings from electrotherapy to electrocution. In America, Stanley Finger linked the application of electricity to the birth of neuroscience, and in France, Céline Cherici emphasized how the history of electricity was at the crossroads of biology and medicine.

As a researcher and practicing neurologist, I naturally have a different perspective than these eminent medical science historians, but I am indebted to them for their insights. I have had a lifelong interest in electricity dating back to my father showing me how to design an electric circuit as a child and reading articles about electricity in *Scientific America* as a teenager. I read about Thomas Edison and Nikola Tesla, and having grown up near Pittsburgh, I was fascinated by the battle of the electric currents between Edison and George Westinghouse. It was years later, however, before I became aware of the role these and other pioneers in electricity played in the developing fields of neurophysiology and neurology. During my neurology residency at UCLA, I met Mollie Brazier and became enamored with her stories and books on the history of neurophysiology.

Early researchers on static electricity had no way of measuring electricity, so they used their body as a rough indicator of the magnitude of electricity. A strong shock indicated more electricity than a weak shock. One of these investigators even noted a taste sensation after a shock to the tongue, a hint that nerves were activated by electricity. The discoveries of Luigi Galvani and Alessandro Volta marked a major turning point in the history of both electricity and neuroscience. Galvani convincingly showed that electricity could activate nerves and muscles and Volta's bimetal electrochemical battery provided a continuous source of electricity for physical and medical experiments. The discovery that electricity and magnetism were tightly interrelated soon followed.

Michael Faraday's lines of force theory of electromagnetic waves marked the beginning of the modern era of electricity, and his induction coil provided a new and better way to stimulate nerves (faradization). This in turn inspired Michael Todd's pioneering work on epilepsy and brain electrical stimulation. Emil du Bois-Reymond and Herman Helmholtz identified and measured the speed of a nerve action potential, and their student Julius Bernstein was the first to record an action potential. David Ferrier electrically stimulated the cerebral cortex in primates documenting localized function, and Charles Sherrington stimulated the spinal cord demonstrating the synapse and the integrative function of the nervous system.

James Clerk Maxwell was a pivotal figure in the fields of electromagnetism and physics. He converted Faraday's lines of force theory into mathematical equations that provided the foundation of modern physics. The equations showed how electromagnetic waves pass through space as vibrations in the all-pervasive ether. This led to discovery of wireless telegraphy and ultimately radio transmission. Curiously, it also led to belief that brain waves could travel in the ether making it possible to read minds and even communicate with the dead. Two of the most famous scientists of the latter nineteenth century, Oliver Lodge and William Crookes, were spiritualists who actively participated in psychic research along with their scientific research. In fact, Crookes attributed development of his radiometer and cathode ray tube to his studies in spiritualism.

The role of electricity in the developing medical specialty of Neurology in the nineteenth century cannot be overemphasized. Nearly all the early neurologists in Europe and America were electrotherapists. Since electricity activated nerves, nerve cells, and muscle, it seemed only natural that electrotherapy was best used for treating nerve, brain, and muscle diseases. Indeed, electrotherapy was most effective for treating two of the most common neurological diagnoses of the time, hysteria and neurasthenia. We now know that was because electrotherapy is a powerful placebo.

Throughout history, there has been a close interrelationship between new discoveries in electronics and advances in neuroscience. Vacuum tubes developed to improve wireless transmission led to oscillographs for recording nerve impulses and polygraphs for recording electroencephalography (EEG). The invention of transistors and long-lasting batteries made it possible to make implantable electric neurostimulators and advances in microelectrode technology led to intraneuronal recordings and deep brain stimulation. The discovery of nuclear magnetic resonance (NMR) made it possible to image the brain in unbelievable detail.

This book traces the interrelationship between electricity and neuroscience from ancient times to the late twentieth century, focusing on the key scientists and their contributions. I aim for a wide scientific audience but particularly students of neuroscience. The historical context of discovery provides an ideal framework for understanding modern concepts of electromagnetism and neuroscience. Furthermore, the stories of these pioneering researchers can be inspirational to those beginning their career in neuroscience.

Las Vegas, NV, USA Robert W. Baloh

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About the Author

Robert W. Baloh is well known as a leader in the field of neurotology. After completing his neurological training at UCLA in 1972, he joined the faculty at the UCLA School of Medicine with a joint appointment in Neurology and Head and Neck Surgery in 1973. Baloh became Professor in 1982, Distinguished Professor in 2002, and Emeritus professor in 2021. Author of 14 books, over 350 articles in peer-reviewed scientific journals, and over 100 book chapters, he is a pioneer in the study of the vestibular system: the inner ear/brain system which helps people to maintain their sense of balance and spatial awareness. He has trained more than 40 fellows who are now leaders in the field of vestibular research. Baloh also has a longstanding interest in the history of neurology and has written extensively on the subject. Among his many honors, Baloh received the Hallpike/Nylen Prize at the Bárány Society Meeting in Prague, Czechoslovakia, in 1992 and had an international Dizziness and Balance Symposium in his honor at the 2014 American Academy of Neurology meeting in Philadelphia. His book *Clinical Neurophysiology of the Vestibular System*, written with Vicente Honrubia, is currently in the fourth edition and is the standard in the field. His other books include *Dizziness, Hearing Loss and Tinnitus: The Essentials of Neurotology* (1984), *Neurotology* (1994), *Dizziness: Why Do You Feel Dizzy and What Will Help You Feel Better* (with Greg Whitman, 2016), and *Vertigo: Five Physician Scientists and the Quest for a Cure* (2017). Recently, he became interested in the boundary between neurology and psychology with the publication of *Havana Syndrome: Mass Psychogenic Illness and the Real Story Behind the Embassy Mystery and Hysteria* (with Robert Bartholomew, 2020) and *Medically Unexplained Symptoms: A Brain-Centered Approach* (2021). Most recently he published a book about exercise and brain health in 2022.

Chapter 1
The Mystery of Electromagnetism

A lodestone attracts only magnetic bodies, electrics attract everything. A lodestone lifts great weights; a strong one weighing two ounces lifts half an ounce or an ounce, Electrics attract only light weights: e.g., a piece of amber three ounces in weight lifts only one-fourth of a barleycorn weight.

William Gilbert, 1600

Abstract To ancient civilizations, electricity and magnetism had mystical qualities suggesting some type of supernatural force. Not surprisingly, ancient physicians tried to harness this force to treat a variety of illnesses. In the mid-sixteenth century, William Gilbert made the first clear distinction between electricity and magnetism and his contemporary Roger Bacon proposed a general theory of magnetism as a force acting at a distance. Their work marked the beginning of modern scientific methodology. To deal with the conflict between religion and the new science, Rene Descartes proposed a two-universe solution, one that obeyed physical laws and the other that only God could understand. Descartes' theory on brain function led to the bizarre conclusion that animals could not feel pain because they lacked a soul localized in the pineal gland. Several early scientists including Roger Bacon saw a parallel between magnetism and gravity although Isaac Newton saw them as two different forces acting at a distance. Edmond Halley was the first to suggest that the Earth's magnetism came from forces deep below the Earth's surface.

Keywords Magnetism · Compass · Electrics · Anelectrics

When ancient people first witnessed electromagnetism, they were in awe. Lodestone attracted metal objects and amber when rubbed with fur attracted light objects. These inanimate objects seemed to possess supernatural powers. Lodestone was stronger than amber since it attracted heavier objects. Not surprisingly, physicians and faith healers at the time tried to harness these mysterious powers for treating a variety of diseases.

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Lodestone

According to Greek mythology, a shepherd noticed that his feet were sticking to the ground while herding his sheep on Mount Ida in a region of northern Greece called Magnesia [1]. It took great effort to lift his feet and he noticed that the bottom of his walking stick also stuck to the ground. Curious for an explanation, he dug into the ground and found a stone that attracted the nails in his shoes and the metal bottom of his walking stick. The phenomena became known as magnetism after Magnesia and the stone, lodestone, was composed of the mineral magnetite.

As far back as 2000 BCE, ancient cultures including Greeks, Egyptians, Hindus, Chinese and even possibly American Indians were aware of the magnetic properties of lodestone. The Chinese were the first to recognize that the Earth had a natural magnetism and that a piece of lodestone would align itself with the poles of the earth.

In his writings in the fourth century BCE, Wang Xu noted that a "south-pointer" allowed people to always know their position on the planet. The south pointer, also called a south-pointing fish, was a large spoon in the shape of a ladle made from lodestone (Fig. 1.1). When the south pointer was placed on the ground or on any flat surface so that it balanced on the bottom back half of the spoon the handle would point toward the south. This primitive compass was initially used exclusively to orient the construction of buildings and roads using the geometric principles of feng shui. These early Chinese compasses deviated up to 15 degrees from the true south depending on location which explains slightly different street orientations in different towns and villages [1].

It wasn't until around 800 CE that the Chinese began using a splinter of lodestone shaped like a tadpole floating on water as a compass. This primitive compass

Fig. 1.1 Ancient Chinese south pointer or south pointing fish. Spoon in the shape of a ladle made of lodestone. When placed on a flat surface the handle pointed south. (From Needham J. *Science and Civilization in China*. Cambridge, Cambridge University Press, 1962, volume 4, figure 344 with permission)

was an intermediate between the lodestone spoons and iron needles of later compasses. A few hundred years later, the Chinese scientist Shen Kuo described how he magnetized a needle by rubbing it against a lodestone and then hanging the needle with a single strand of silk attached at the center to produce a compass [2]. Kuo noted that sometimes the needle pointed south and sometimes north.

Although Marco Polo is often credited with bringing the compass to Europe after visiting China in the late thirteenth century, European mariners were already using the compass in the late twelfth century. One of the best early descriptions of a European compass was provided in a satirical poem by the French poet and monk Guyot de Provins around 1205. *"…there is an art which the sailors have, which cannot deceive. They take an ugly brown stone, the magnet, to which iron willingly attaches itself, and touching a needle with it, they fix the needle in straw, and float it on the surface of water, whereupon it turns infallibly to the Pole star"* [3].

At the time, the spherical Earth was thought to be the center of the Universe with the moon, planets, sun, and heavenly bodies all revolving around the Earth daily. The Earth's poles represented the axis around which all the bodies revolved. One star, the pole star was observed to be relatively fixed in the northern sky thought to be located on or near the axis of celestial rotation. To explain why the compass needle pointed toward the pole star, it was assumed that there were mountains of lodestone at the Earth's poles, the only material known to attract a compass needle at the time. Stories were told of passing ships being destroyed as their iron nails were pulled out by lodestone mountains.

Interestingly, Chinese compass needles have always been made with the prime end pointing to the south, whereas European compass needles have always been made to point to the north. This supports the likelihood that they were developed independently of each other.

Amber

Amber represents the world's first precious gemstone. Long before the silk and salt roads existed, the amber road was distributing amber for processing throughout the ancient civilizations on the European, Asian, and African continents. Amber that washed up onto the shores of the Baltic Sea was harvested and transported to jewelry workshops around the Mediterranean beginning more than 10,000 years BCE. Around 1000 BCE the Greeks began navigating the Black Sea and via the river Dnieper opened a trade route to the Baltic region.

Early theories on the origin of amber varied from the secretions of whales or giant ants to crystalized bird tears. According to Greek mythology, there once were two suns in the sky but the gods banished one into the ocean. When the sun hit the bottom of the ocean it broke up into thousands of pieces that washed ashore as amber.

We now know that amber is fossilized tree resin from pine trees of forests that covered the area prior to the formation of the Baltic Sea. The thick, sticky, resin oozed down the tree trunks, trapping tiny animals and vegetation in its path. The hardened resin ultimately made it to the developing sea by rains and flooding. Amber occurs in several colors from a common yellow to a rare bluish tinge. Red amber indicates the fossilized resin was exposed to the sun for a long time before washing into the sea. Black amber is filled with impurities and is fragile to work with but is most valuable when carved by an experienced artisan.

Around 600 BCE the first great Greek philosopher, Thales of Miletus, made the remarkable observation that when he rubbed amber with animal fur the amber developed the peculiar property of attracting nearby light objects such as thread or small pieces of cloth [4]. It could even provide a slight shock to the person holding the amber. As a party trick, women in ancient Greece would rub their amber jewelry to provide a shock to a frog. Thales felt that amber had a "soul" that accounted for its ability to attract other objects.

The Greek word for amber is "elektron." The materials that had these strange attractive properties were called "elektricks" and their attraction, "elektrick force." These terms are the forerunners of the words—electron, electricity, electric current, and electronics.

Early Theories on Electromagnetism

Much of what we know about ancient Greek and Roman scientific knowledge can be traced to the writings of the Roman scholar and historian, Pliny the Elder who spent a great deal of his life writing more than a million words in a 37-volume encyclopedia entitled *Naturalis Historia* (Natural History) in the first century CE. Pliny was enthralled with magnetism. *"What phenomenon is more astonishing? Where has nature shown greater audacity? For iron, the tamer of all substances is drawn to the magnet, following some intangible attraction, and, as it comes nearer, leaps to meet the magnet"* [5].

The Greeks were aware that lodestone not only attracted pieces of iron and steel but that the metals themselves became magnetized so that they would attract other pieces of iron and steel. A whole chain of metal rings could be lifted and held together by a single lodestone. Pliny felt that there were two types of magnetism, one that occurred naturally such as with lodestones and another that occurred when stones like amber were rubbed with fur. The naturally occurring type was much stronger than the one that required rubbing.

The early Christian church had a different way of dealing with the mysteries of electromagnetism. Declare them a miracle. Saint Augustine summarized the current knowledge on magnetism in his masterwork *De Civitate Dei* (*The City of God*), published in 428 CE. He wrote that he was "thunderstruck" when he first saw a lodestone lift a chain of iron rings and iron flakes moved around a silver plate by a lodestone moving beneath the plate. But he was puzzled why a lodestone, unlike amber rubbed with fur, could not move even tiny pieces of straw. He concluded that man should not concern himself with such a conundrum. It was enough for a

Christian to attribute such mysteries to the *"goodness of the Creator, who is the one true God"* [5].

The first effort to explain magnetism in terms of natural phenomena is found in the poem *De Rerum Natura* (*On the Nature of Things*), written in the first century BCE by the Roman poet and philosopher Tutus Lucretius Carus [6]. The story of how this poem was rediscovered and copied by an Italian book hunter in the fifteenth century is the theme of a recent Pulitzer Prize–winning book, entitled *The Swerve* by Stephen Greenblatt. In 1417, a former papal secretary, Poggio Bracciolini discovered a copy of Lucretius' poem in a remote German monastery and reintroduced it to Western culture [7].

Lucretius was a disciple of the famous Greek philosopher, Epicurus, who in the fourth century BCE elaborated on the theory of the atom. Epicurus theorized that the universe is composed of tiny indivisible particles called atoms that are in constant motion, joining together to create objects including all living beings and eventually breaking up and returning to individual atoms. There was nothing in the Universe other than atoms and void.

In his epic poem, Lucretius emphasized that human beings are no different from any other type of matter present throughout the Universe, composed of groupings of atoms that eventually will revert to individual atoms. He "reassured" us that we should not fear death since there is nothing but atoms and void, no supernatural beings. Of course, this theory was not well received by religions either at the time or in subsequent years.

Lucretius wrote that atoms could only be set in motion by their own weight or by being propelled by some external force. Regarding magnetism, he speculated that the lodestone emitted a dense stream of atoms that bombarded and displaced the atoms in the space between the lodestone and the iron. This emission of atoms resulted in a void in the space so that the atoms of the iron slid into the void and atoms in the back on the other side of the iron pushed it toward the lodestone.

To explain why only select materials were attracted by lodestone, Lucretius suggested that some such as gold were so dense and heavy that they could not be moved while others such as wood had large spaces between the atoms that they were made of so that the atoms emitted by the lodestone passed right through. But why didn't other substances emit atoms? What was unique about lodestone?

Ancient Medical Uses of Lodestone and Amber

Ancient physicians reasoned that since lodestone had the power to attract iron, it also might have the power to attract evil spirits and illnesses from the body. As far back as 1200 BCE, Chinese physicians used lodestones on acupuncture sites to control the flow of Qi (chi) through the body and around 600 BCE Hindu physicians recommended lodestone to treat a wide range of ailments. The Greek physician Hippocrates recommended the use of loadstone to attract and remove pain associated with a variety of diseases. He advised patients with headaches to lay with their heads on a lodestone. Egyptian physicians recommended the use of lodestone bracelets to relieve the pain of arthritis. Cleopatra wore a small lodestone on her forehead to preserve youth and beauty. Many people thought that lodestone had strong aphrodisiac potency.

Ancient physicians often applied magnetite externally in a pulverized form compounded with other ingredients called Emplastrum Magneticum (magnetic plaster) to treat a variety of diseases such as arthritis, poisoning, and gout. The magnetic plaster was applied directly to an affected body part. Pliny the Elder recommended a magnetic plaster for treating burns and Galen of Pergamum compared the magnetic plaster to cathartic drugs and suggested that the plaster was useful for attracting bile and phlegm and for removing poisons.

Although amber was very popular for jewelry and decorative ornaments, it was also popular in ancient medicine, particularly for making amulets to protect the wearer from evil spirits and a wide range of diseases. A well-known Roman physician, Calistratus felt that amber amulets protected against madness and a powder of amber mixed with honey could cure ailments of the throat, stomach, eye, and ear. In Japan, red amber was thought to purify the blood and in China, a mixture of amber powder and opium was used as a tranquillizer. Amber powder has long been used as a salve to treat skin conditions and in modern times it is still used in cosmetic treatments to enhance skin elasticity and remove wrinkles.

We now know that the attractive property of amber rubbed with fur is due to static electricity, but the use of static electricity for treating medical conditions awaited the development of better techniques for generating it in the seventeenth century. Ancient healers and physicians, however, did have a source of natural electricity generated by animals. Electric rays, eels, and catfish were known to produce electricity as far back as 3000 BCE. The Egyptians called the electric catfish the "thunder of the Nile." They used the electric catfish to treat headaches and nerve pain.

Pliny the Elder described the numbing effects of the shocks of electric rays and catfish in *Naturalis Historia*. This numbing effect was used to treat a variety of painful ailments. The personal physician of the Roman Emperor Claudius, Scribonius Largus, provided a detailed medical text for treating gout affecting the feet called podagria: "*For any sort of podagria when the pain comes on, it is good for one to put a living black torpedo-fish under his feet while standing on a beach (not dry but one on which the sea washes), until he feels that his whole foot and shank are numb just up to the knees. This will both relieve the current pain and alleviate future occurrences*" [8]. The use of electric fish to treat pain became known as ichthyo-electroanalgesia and is still in use in some countries.

Magnetism and the Dark Ages

For about the next thousand years after the fall of the Roman Empire (often called the Dark Ages), there was little interest in magnetism apart from the compass for navigation. The average person's understanding of magnetism was based on ancient lore and religious teachings. For example, garlic and diamonds were thought to weaken magnets according to Pliny the Elder. Sailors who looked after the compass on board ships were warned against eating garlic or onions well into the sixteenth century. Saint Augustine used magnetism to defend the concept of miracles to skeptics who questioned their validity. If magnetic attraction can't be explained, why should we need to explain miracles.

To describe magnetism, poets often used human attributes such as love and virtue. The twelfth-century French troubadour poet Bernart de Ventadorn wrote: *"the fair lady draws me toward her like a magnet"* [9]. Guido Guinizzelli, the thirteenth-century Italian poet and originator of the dolce stil novo (sweet new style), wrote:

In what strange regions near the polar star
May the great hills of massy lodestone rise,
Virtue imparting to the ambient air
To draw the stubborn iron; while afar
From the same stone, the hidden virtue flies
To turn quivering needle to the Bear
In splendor blazing in the northern skies [10].

Replace virtue with magnetic field and one has a modern poetic description of magnetism.

In his canzone on love, Guinizzelli wrote: *"love has a home in a gently noble heart, like, in the same manner, adamas* [medieval word for magnet] *has home in an iron mine"* [9]. Medieval poets took advantage of the phonetic resemblance of the words for lover (amans) and magnet (adamas). William Shakespeare used *adamant,* another word for magnet, in Midsummer Night's Dream: *"You draw me, you hard-hearted adamant, but yet you draw not iron; for my heart is true as steel."*

Peter the Wanderer

Into the vacuum of critical thinking in the Dark Ages stepped a little-known French engineer Pierre Pelerin de Maricourt, better known as Petrus Peregrinus or Peter the Wanderer. He acquired the name Peregrinus or Pilgrim after visiting the Holy Land. His *Epistola de Magnete* (*Letter on the Magnet*) is considered one of Europe's earliest scientific reports [11]. A contemporary, the English Franciscan friar and philosopher Roger Bacon, called it the definitive work on magnets and lauded Peregrinus for his mathematical and experimental skills. The letter, dated August 8, 1269, was composed during the siege of Lucera in southern Italy and provided Peregrinus time to reflect on experiments he had carried out earlier. He was part of the army of Charles I, Duke of Anjou and King of Sicily, who was besieging Lucera at the behest of the Pope. Peregrinus' job was to design and build machines for heaving stones and fireballs into Lucera [9].

The letter consisted of two parts: a first part providing a description of the polarity of magnets, how to determine the north and south poles and the attraction and repulsion between poles. The second part described instruments that utilized magnetism, the floating compass and a new pivoted compass and ended with wild speculation about a magnetic clock and a perpetual motion machine.

Peregrinus was the first to make a clear distinction between the north and south poles of a magnet. In his experiments, he made a sphere of lodestone and observed that when a compass needle was placed at different points around the globe, there were two unique locations where the needle aligned itself perpendicular to the surface of the globe. When the compass needle was placed at other positions around the globe, the needle outlined a series of meridians all of which came together at the two opposite poles. Peregrinus recognized the similarity of his magnetized globe, which he called the "terrella" (little Earth), to the Earth's magnetism. He proposed that the Earth's north and south poles were on the axis around which all of Creation revolved.

Peregrinus made several other observations that had eluded the ancient philosophers. He showed that the north pole of a magnet attracted the south pole of another magnet, whereas the north poles of different magnets repelled each other. He also observed that breaking a lodestone into multiple smaller pieces resulted in each piece having its own north and south poles. "*You will also notice that the ends of the two stones which before their separation were together, after breaking will become one a north pole and the other a south pole. If now these same broken portions are brought near each other, one will attract the other, so that they will again be joined…"* [11].

Peregrinus then addressed the question of why the compass needle points to the north pole. He dismissed the prevailing notion that there were mountainous deposits of lodestone at the north pole attracting the needle since there were lodestone deposits at other locations around the Earth, yet these deposits had minimal effect on the direction of the compass needle. He also observed that the Pole Star was not fixed at the celestial north pole but rather slightly moved around it and that the compass needle did not follow the movement. Considering the symmetrical pattern of the compass needle around his small lodestone globe, he reasoned that the Earth's magnetism was also symmetrical, a basic property of the Universe unrelated to any local deposits of lodestone on the Earth or position of celestial bodies, "*…the poles of the lodestone derive their virtue from the poles of the heavens*" [11].

The notion that the Earth was the center of the Universe with all celestial bodies rotating about it was engrained in religious doctrine at the time. A staunch Catholic such as Peregrinus did not consider questioning the doctrine.

The ancient Greek astronomer, Aristarchus of Samos, proposed a heliocentric model of the solar system as far back as the third century BCE with the Earth revolving about the Sun once a year and rotating about its axis once a day. However, Aristotle, Plato, and Ptolemy favored the geocentric model of the solar system, and this model was accepted by the developing Christian religion and remained dominant throughout the Middle Ages. Even after Nicholas Copernicus, the German astronomer and Catholic Cannon provided a strong scientific defense of the heliocentric model in the sixteenth century, the Inquisition of 1615 concluded that the heliocentric model was absurd and heretical because it contradicted the Holy Scripture. Galileo Galilei, the Italian astronomer and polymath who championed

Copernicus' heliocentric model, was tried by the Inquisition and spent the remainder of his life under house arrest [12].

Peregrinus ended his *Letter* by proposing a perpetual motion machine consisting of a toothed wheel powered by a magnet. A small, rounded weight made of brass or silver was located between two of the teeth. Peregrinus indicated that the metallic ball "*seeks the center of the earth in virtue of its weight, thereby aiding the motion of the teeth*" [11]. Several versions of Peregrinus' perpetual motion machine were subsequently made but unsurprisingly none of them worked. Although the notion of perpetual motion had great appeal during the Middle Ages, modern thermodynamic theories show that it is impossible to produce such devices.

Magnetism in Medieval Medicine

Magnets and magnetite plasters and concoctions played a large role in medieval medicine [13]. The earliest use of lodestone in medicine was to aid surgeons in removing an iron arrow tip from the body. As far back as 600 BCE, the Hindu surgeon Sucruta described how he used a magnet to help extricate an arrow tip. He noted that the magnet worked best if the arrow tip did not have barbs and if there was a wide opening parallel to the fibers of the tissue. In the thirteenth century, the English physician Gilbertus Anglicus wrote in his *Compendium Medicinae* that a magnet could help the surgeon localize and extract iron concealed in the flesh. More bizarre were reports of successful treatment of hernias after having the patient swallow iron fillings and using a magnet to draw in and restore the protruding intestine. Others reported successful extraction of metal particles from the eye using a magnetic plaster spread over the eye.

Magnets applied to the head were common for treating a wide range of neurological and psychiatric disorders. In the sixth century, Aetius of Amida recommended the application of a magnet as the treatment of choice for hysteria and muscle spasms. Magnets were used to draw epileptic seizures from the brain. The twelfth-century nun and mystic Hildegard of Bingen wrote about religion and philosophy but also wrote a treatise on plants and minerals for medical purposes. Because of this, she is often considered the first German woman doctor. Magnetism was at the center of her healing process. She followed the usual practices of the time but also went a bit further recommending placing a lodestone in the patient's mouth to treat fits of rage and anger and to prevent lies and malicious gossip. She also felt that holding a lodestone in the mouth could make fasting more bearable.

Although most uses of magnetite in medieval medicine were external, it was also common to pulverize magnetite and mix it with milk for internal application. The eleventh-century Persian philosopher and physician Avicenna recommended this concoction for accidental poisoning with rusted iron suggesting that the poison would be attracted to the magnetite and speed up the excretion from the intestines. Others recommended the mixture for treating a variety of poisonings. This may have worked by inducing vomiting. The thirteenth-century German Dominican friar and philosopher Albertus Magnus, who was later canonized as a Catholic saint, recommended a milk/magnetite mixture for treating heart failure and edema in his book *Mineralia*.

Paracelsus, Doctor, and Mystic

The culmination of medieval fascination with magnets in medicine occurred with the enigmatic Theophrastus Bombast von Hohenheim, better known as Paracelsus, a physician and alchemist born in Switzerland in 1493. Paracelsus developed an elaborate theory on how magnets cure disease and introduced the concept of "animal magnetism," a forerunner of mesmerism and hypnosis.

Paracelsus was a paradoxical character who was either loved or hated by his medical peers. He regularly criticized his fellow physicians and apothecaries and displayed contempt for Galen and Avicenna, the two ancient physicians considered the pillars of medieval medicine. He famously burned Avicenna's massive medical text *Canon of Medicine* in the Basel Market Square in 1527. He wrote and taught in German rather than the traditional Latin, and he preached that the only way to learn the art of medicine was to practice it on patients. He was known for his abusive language and heavy drinking, and he ridiculed physicians with pompous titles.

Regarding Paracelsus' own titles, there are conflicting reports. Some questioned his descent from the Swabian noble family Bombast von Hohenheim suggesting that he invented the title and that his father, who was also a physician, was born a commoner. The title Paracelsus is even more controversial since it seems inconsistent with his distaste for Latinized names. In Latin, it means literally surpassing Celsus, the first-century Roman author of *De Medicina*, the best surviving treatise on ancient medicine. Some suggested that his circle of friends honored him with the name, while others suggested that his enemies used it as ridicule and that he later accepted it for spite. Regardless, he first used it in medical publications in 1536 and regularly thereafter.

Paracelsus despised the ancient "humoral theory," replacing it with an equally speculative theory based on astronomy and alchemy. The human body was a microcosm of the solar system. The sun was the heart, the moon the brain, Jupiter the liver, Saturn the spleen, and Venus the kidneys. From the constellation of the planet diseases arose. He described what he called a "life force" in the human body that when depleted resulted in disease. The "life force" could be replenished with herbs and foods and with chemicals such as sulfur and mercury. Magnets could energize the body's "life force" and thereby start the healing process.

Since magnets had the mysterious power to attract iron, Paracelsus felt that they could also attract diseases from the body. The magnetically extracted disease could be "inoculated" into the ground, a plant, or even another person. He described detailed procedures for transplanting diseases from the body using a magnet. For example, to treat epilepsy, which he felt was due to too much nervous fluid in the brain, he applied the repulsing pole of a magnet to the head and spine and the attracting pole to the abdomen.

Paracelsus also considered the human body to possess magnetic properties. *"Man possesses a magnetic power by which he can attract certain effluvia of a good or evil quality in the same manner as a magnet will attract particles of iron… A magnet may be prepared from iron that will attract iron, and a magnet may be prepared out of some vital substance* (for example urine or blood) *that will attract vitality… If such a magnet is applied to a part of the patient's body, it attracts and absorbs vitality from that part in the same manner as a sponge absorbs water, and it will thereby allay the inflammation existing in such a part, because it attracts the superabundance of magnetism carried to that place by the rush of the blood"* [14].

This "animal magnetism" not only had the power to influence disease but also human interactions. *"In this way diseases can be cured in one person and caused to appear in another; love between two persons of the opposite sex may thus be created, and magnetic links be established between persons living at distant places, because there is only one universal principle of life, and by it all beings are sympathetically connected together"* [14].

There is a spiritual quality to Paracelsus' writings and like most medieval physicians he was deeply religious. In the end, it was God's will that diseases occurred and only through God's will could physicians heal the patient. As with Saint Augustine, Paracelsus felt that ultimately only God could understand the complex nature of disease.

Problems with the Compass

Even though Peregrinus described what he considered a symmetrical magnetism aligned with the Earth's celestial north pole, navigators were already noticing that compass needles often deviated from the true north [1]. Initially, the discrepancies were attributed to defective needles or carelessness but after these possibilities were refuted, the phenomena became known as "declination," a tilting of the magnetic pole from the north pole. Systematic measurements of compass needle declination in Europe in the mid-fifteenth century identified an 11–12 degrees deviation to the east of the true north.

In the late fifteenth century, at the beginning of the great Portuguese and Spanish voyages of discovery, it became more and more apparent that the compasses being used could not provide reliable measurements of longitude at sea. During his voyage to the Americas, Christopher Columbus was alarmed that his compass needle deviated a good amount from the Pole Star. Columbus suggested to his crew that this was probably due to the previously undetected movement of the Pole Star. However, in the mid-sixteenth century, the Neapolitan scholar John Baptista Porta suggested that the declination of the compass needle changed as Columbus moved across the Atlantic Ocean, from about 10 degrees east of north in Europe to about

10 degrees west of north in the Caribbean islands. The meridian with approximately zero declination was at the Azure Islands.

Around this time, the Flemish cartographer, Gerardus Mercator, concluded that declination resulted from the fact that the magnetic axis of the Earth was tilted from the rotational axis. The magnetic meridians intersected at the magnetic poles, not the geographic poles. Like Porta, Mercator noted that declination was zero at the Azures. Declination explained many of the distortions of coastlines on contemporary maps. Mercator speculated on a map of the Artic region (since no one had ever been there) depicting both poles as magnetic islands (presumably adhering to the lodestone mountain theory of the Earth's magnetism). Remarkably, California recently claimed by Spain was located north of the Arctic Circle on his map.

Another phenomenon the navigators noticed as ships explored more and more of the Earth's seas was a property of the compass initially called "dip," later called "inclination." The compass needle balanced on a pivot would tilt up or down vertically depending on the latitude of the ship, the further north or south of the equator, the greater the inclination. When a compass designed for the northern hemisphere was used in the southern hemisphere, the north end of the needle was pulled upward, and the south end was pulled downward. Whereas a compass designed for the southern hemisphere showed the opposite effect.

Initially, this "bothersome" effect was corrected by counterbalancing with weight to make the needle swing primarily in the horizontal plane for its area of use. However, others saw inclination as a potentially useful way to estimate latitude. The English compass maker, Robert Norman, published a pamphlet in 1581, in which he described two versions of a compass for measuring inclination. The first version was reminiscent of the original floating compass, a magnetized needle in cork that was designed to have neutral buoyancy in a container of water. With this devise, he could measure both declination and inclination although not very accurately. For a more accurate measurement of inclination, he constructed a vertical compass with a central pivot so that the needle settled at the angle of inclination. With these devices, navigators observed that the angle of inclination gradually increased from almost zero at the equator to almost one as one approached the poles. Any theory on the Earth's magnetism had to account for declination and inclination.

William Gilbert and *De Magnete*

William Gilbert was born in Colchester, England in 1544, the eldest of 11 children [15, 16]. He was a brilliant student and entered St. Johns College, Cambridge to study mathematics at age 14. Over time his interests turned to medicine, and he graduated as a Doctor of Medicine in 1569. After touring the continent and visiting the best medical schools, Gilbert developed a medical practice in London with a reputation as an expert in maritime diseases. Having an inquiring mind, Gilbert expanded his interests beyond medical practice to a wide range of scientific inquiries. He began with experimental chemistry but was soon drawn to the strange phenomena of magnetic and electric attractions. Gilbert hosted small groups of amateur scientists in his house where they discussed scientific advancements and performed experiments on their own.

Over time, Gilbert's reputation as a physician and experimenter solidified leading to his selection as President of the Royal College of Physicians in 1600. This year was of particular significance since it was also the year that Gilbert published his monumental work on magnetism and static electricity, *De Magnete,* and the year he was called to court and appointed physician to Queen Elizabeth I. His service to the Queen was short-lived since she died in early 1603, and Gilbert died later in the same year during the great plague epidemic.

De Magnete, with the full translated title "*On the magnet, Magnetick Bodies also, and on the great magnet the Earth; a new Philosophy demonstrated by many arguments and experiments*" was the first book to establish magnetism and electricity as a science [17]. The work is often considered key in the evolution of science from the ancient to the modern. It was initially published in Latin with several editions in the early seventeenth century and was first translated into English in the late nineteenth century.

De Magnete was divided into six books and 115 chapters although many of the chapters were short, not much more than an outline. The focus of the book was on magnets, much of which reiterated and expanded the work of Peregrinus. Even though the title page listed the author as William Gilbert M. D.—Electrician, there was only a single chapter devoted to amber and static electricity. However, in many ways, this chapter was the most impactful of all the chapters.

Gilbert's work on magnetism can be divided into three broad areas, his work on lodestone and the Earth's magnetism, the problems with the compass and navigation. and the relevance of magnetism in the heliocentric model of the solar system. Like Peregrinus, Gilbert concluded that the Earth was a giant magnet but unlike Peregrinus, Gilbert had additional information including measurements of declination and inclination of the Earth's magnetic field and overwhelming evidence for the heliocentric model of the solar system.

In experiments very similar to those of Peregrinus, Gilbert made a lodestone sphere which he also called a terrella (little Earth) and he measured the orientation of small pieces of wire (~1 cm) placed at locations all over the terrella. He noted that the angles these tiny pieces of wire made with the surface of the terrella were the same as the measurements of inclination observed at different latitudes on Earth. He concluded that the magnetism of the terrella was due to the magnetized iron of the lodestone so the Earth's magnetism must be due to the magnetism within the planet itself and not due to mountains of lodestone at the poles, the Pole Star, or the celestial pole as proposed by Peregrinus.

Gilbert proposed that magnetism was spread through the whole substance of the Earth and it was symmetrical about the Earth's axis of rotation. To explain declination, he suggested that although the compass needle was mainly influenced by the magnetism of the globe it was also influenced to a lesser degree by magnetic rocks located on the continents. He speculated that in the middle of an ocean equally distant from land, the compass needle would point directly north. To test this hypothesis, he made terrellas with lumps of lodestone protruding from the surface to represent mountainous continents and gouged out areas to represent ocean basins. He reported that the models supported his hypothesis in that when a compass needle was near a lump it deviated from the pole of the terrella whereas a compass needle near a basin pointed toward the pole.

Although he believed that the operation of the Universe was outside of experimental proof, he had praise for Copernicus and his sun-centered solar system. He reasoned that the distance to the other stars must be enormous so that it would be impossible for them to rotate about the Earth daily. The stars near the equator would have to be moving at unimaginable speeds whereas those close to the poles would hardly move at all.

Gilbert speculated that magnetism was key to generating the Earth's rotation and the orbital rotation of other planets and stars. But his explanation for how magnetism achieved this effect borders on the bizarre. Despite forward thinking on the origin of the Earth's magnetism, he still believed in the ancient notion that magnets had souls and moved themselves. Furthermore, he objected to the term "magnetic attraction" preferring what he called magnetic "coition." He used this animistic term in its literal sense, meaning to mate or join. *"Coition, we say, not attraction for the term attraction has wrongfully crept into magnetic philosophy, through the ignorance of the Ancients"* [17].

There was no physical force acting between magnets and iron but rather a coming together like two people might approach one another. *"Thus, the magnetic coition is the act of the lodestone and of the iron, not one of them alone"* [17]. Since the Earth is a magnet, it can move itself, rotating on its axis and circle the sun. Other heavenly bodies moved themselves without any force acting between them, no action at a distance as some suggested.

Fortunately, Gilbert published his heliocentric theory in a reformed England. Expressing similar views in Catholic Europe would likely have led to being burned at the stake. In the same year (1600), the Italian philosopher and former priest Giordano Bruno was burned at the stake for supporting a heliocentric model of the solar system.

In his chapter on "electrics," Gilbert made a clear distinction between lodestone and amber for the first time. He demonstrated that the attractions of these two substances had entirely different properties. "*A lodestone attracts only magnetic bodies, electrics attract everything. A lodestone lifts great weights; a strong one weighing two ounces lifts half an ounce or an ounce, Electrics attract only light weights:* e.g.*, a piece of amber three ounces in weight lifts only one-fourth of a barleycorn weight"* [17].

Gilbert made a device he called a versorium (Latin for "turn around"), a kind of electroscope to test for the presence of an electric charge. The versorium consisted of a thin light-weight needle balanced on a pivot (like a compass but the needle was not magnetized). It would move toward a nearby object if was electrically charged (Fig. 1.2). His versorium was much more sensitive to the weak forces of electric attraction than bits of thread or scraps of paper. With this more sensitive instrument, he found that many other materials exhibited an amber-like effect. A wide variety of

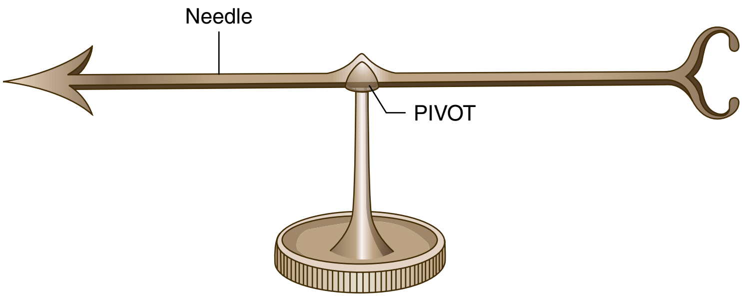

Fig. 1.2 Gilbert's versorium. Light-weight needle balanced on a pivot like a compass, but the needle was not magnetized. The needle turned toward a nearby object that was charged with electricity. (Redrawn from Gilbert W. *De Magnete*, 1600)

gemstones as well as fake gemstones made of glass or crystal attracted the needle when rubbed. Substances that attracted the needle were called "electrics" and those that did not anelectrics.

Several factors were unique to "electric" materials. Gilbert found that the attractive properties of electrics were particularly sensitive to moisture. Condensation of water on the surface of the material inhibited the attraction so the experiments were difficult to perform in humid weather. Some liquids such as alcohol inhibited attraction, whereas others such as olive oil had no effect. Extreme heat markedly inhibited electric attraction. None of these factors altered the attractive properties of lodestone.

Gilbert proposed that the attraction of electrics was caused by an "electric effluvium" (from the Latin effluere, meaning to flow out) that was emitted when the materials were rubbed. *"For as no action can be performed by matter save by contact, these electric bodies do not appear to touch, but of necessity something is given out from the one to the other to come into close contact therewith and be a cause of incitation to it"* [17]. The effluvia from the electric somehow reaches out to a nearby object, attaches itself to the object, and then pulls it back to the electric. The effluvia act like "material rods" attaching to nearby objects and holding on to them until the force is spent and the objects are released and fall way.

Although Gilbert understood that poles of a magnet repel other like poles while unlike poles attracted unlike poles, he was unaware that electric materials could also attract and repel each other. His electric effluvia only explained the attraction between electric materials. He did observe that objects fell off an electric once they had touched it, but he attributed that to a loss of the effluvia force.

Francis Bacon and Force Acting at a Distance

Another Englishman who took advantage of the relative safety of a reformed Elizabethan England at the turn of the seventeenth century was Francis Bacon, a natural philosopher and statesman who served for a period as Lord Chancellor of

England. A contemporary of Gilbert, Bacon would take the experimental method introduced by Gilbert to another level defining the process of scientific induction that became known as "Baconism." He is often considered the father of modern science. Paradoxically, Bacon, a staunch Anglican, believed in an Earth-centered Universe despite compelling evidence to the contrary.

Bacon entered Cambridge University at age 12 where his education was conducted largely in Latin and heavily focused on Aristotelian metaphysical philosophy. Although Bacon admired Aristotle, he felt that his methods were argumentative and arbitrary often leading to wrong conclusions. Like Gilbert, he saw a new method, the experimental method. Bacon felt that all knowledge is derived from inductive reasoning—a method of reasoning whereby a series of experimental observations are synthesized to come up with a general principle. *"Once these particulars have been gathered together, the interpretation of Nature proceeds by sorting them into a formal arrangement so that they may be presented to the understanding*" [18].

Bacon avidly read Gilbert's *De Magnete* and though he was impressed with his experimental observations he ridiculed Gilbert's explanations of magnetic force and gravity [19]. Unlike Gilbert, who believed that bodies could influence other bodies only through physical contact, Bacon had no problems with suggesting force acting at a distance. In Aphorism 45, Bacon wrote, *"Again, if there be any magnetic power which operates by consent between the Earth and heavy bodies, between the globe of the Moon and the seas (which seems very likely in the half-monthly tidal cycle), or between the stellar heavens and the planets by which the latter are summoned and drawn to their apogees, then all these operate at very long distances indeed"* [20]. Bacon pointed out that an obvious example of the magnetic force acting at a distance is magnetism deep within the Earth acting on a compass needle on the surface of the Earth.

Bacon felt that there was a definite link between the Earth's gravity and magnetism. The same magnetic force that draws iron to a magnet draws heavy bodies to the Earth. He noted that gravity and magnetism shared a common property—*"the closer heavy bodies get to the Earth, the more strongly and vigorously they are carried toward it, and the further away the more weakly and slowly (as happens in magnetic attractions)"* [21]. Magnetism not only explained attraction at a distance but also an attraction at small distances, such as when *"amber and jet attract straws; bubbles merge when they come together; certain purgative medicines draw humours down from above; and things of that kind"* [20].

Bacon considered magnetism the universal force that explained the movement of the heavenly bodies, the Earth's gravity, and electrical attraction. But what was this magnetic force? In his essay *Pan, or Nature,* Bacon described how the universal force might work. *"The body of Nature is most elegantly and truly represented as covered with hair; in allusion to the rays which all objects emit; for rays are like the hairs or bristles of nature; and there is scarcely anything which is not more or less radiant. This is very plainly seen in the power of vision, and not less so in all kinds of magnetic virtue, and in every effect which takes place at a distance. For whatever produces an effect at a distance may be truly said to emit rays. But Pan's hair is* *longest in the beard, because the rays of the celestial bodies operate and penetrate from a greater distance than any other"* [22].

In this remarkably prescient paragraph, Bacon suggests that there is a unifying concept in nature that can explain forces acting from afar and near and that these forces result from rays emitted by objects. Examples of the rays are light (vision) and magnetism. It would be many centuries before light rays were shown to be electromagnetic waves and scientists are still searching for a unifying concept of gravity and electromagnetism.

It is important to recognize that Bacon's idea of force acting at a distance was a paradigm shift in how scientists viewed the Universe. From the ancient philosophers through Gilbert, there was a consensus that physical bodies could influence other physical bodies only through direct contact. Of course, this is why magnets were assumed to have animate souls. There was a mystical quality to Bacon's explanation for the force acting at a distance, but he did suggest a possible mechanism—rays emitted by physical bodies.

Magnetic Cosmology

Although Gilbert and Bacon were the first to suggest that magnetism could explain the movement of the heavenly bodies, they each had critical flaws in their basic premises. Gilbert believed that magnetic bodies had a soul to explain their movement, whereas Bacon believed in an Earth-centered universe with all heavenly bodies circling the Earth. These religious beliefs dominated their scientific endeavors. A contemporary of Gilbert and Bacon, the German mathematician and astronomer, Johannes Kepler, also struggled with conflicts between religion and science but he reconciled the conflict by proposing that God created the world according to an intelligible plan and that plan should be accessible to man. Despite this arrangement, religious zealots hounded him through much of his scientific career.

After extensive measurements of planetary movement, Kepler confirmed the Copernican heliocentric model and concluded that the planets moved in an elliptical orbit rather than a circular orbit around the sun. He completely rejected the animistic model of Gilbert. Since the pull on the planets grew weaker the further they were from the sun, Kepler concluded that there must be a "corporeal" force between the planets and the sun acting at a distance [23].

Kepler speculated that the sun generated "rods" of magnetic force as it rotated on its axis and in turn these rods of magnetic force swept the planets around the sun. To explain the elliptical orbits of the planets, he proposed that the magnetic force of the sun alternately attracted and repelled the planets based on the alignment of the planetary poles with the sun's monopole. Unlike Bacon, Kepler made no attempt to explain the nature of the magnetic force acting at a distance but rather described the universe in spiritual terms with the sun corresponding to the Father, other heavenly bodies to the Son and the space in between to the Holy Spirit.

Christianity and Medieval Science

The early Christian church had a paradoxical relationship with the teachings of the ancient Greek philosophers Plato and Aristotle. Many early Christians followed the stoic philosophy as taught by Plato and Aristotle but there were fundamental aspects of stoicism that were incompatible with Christianity. Like the Christians, Stoics believed that material wealth and status were of no importance and that virtue was the key to happiness. But unlike the Christian God who had human qualities and cared for the human condition, the stoic God was an all-powerful and pervasive force in the Universe, equivalent to what we call "nature." The stoic God had little interest in the human condition possibly even unaware of it.

Although Plato influenced the early Christian church, it wasn't until the twelfth and thirteenth centuries that Aristotle became such an influential figure in Christian doctrine. At that time, his works on metaphysics and ethics were rediscovered and translated into Latin and thereby became available to medieval Christian scholars. Saint Thomas Aquinas, often considered the greatest medieval Christian thinker, played a key role in incorporating Aristotle's teachings into Christian theology. Aquinas was particularly influenced by Aristotle's notion that knowledge is not innate but rather is obtained through one's senses and from logical inference of self-evident truths.

Through Aquinas, Aristotle's teachings became deeply embedded in Christian theology. To doubt Aristotle was considered heretical. A good example is Aristotle's belief in an Earth-centered model of the Universe. Despite compelling evidence against the model that developed in the fifteenth to seventeenth centuries, the Christian hierarchy would have none of it.

The Jesuits, a Catholic order founded in 1534, nicely illustrates the paradoxical relationship of the Roman Catholic Church and science. The Jesuits were accepting of the scientific experimental method for understanding the workings of nature, but they rigidly upheld the belief of an immobile Earth at the center of the Universe.

Niccolo Cabeo was a Jesuit monk who read Gilbert's *De Magnete* with great interest and published his own experiments and critique entitled *Philosophia Magnetica* in 1629. Cabeo estimated that Gilbert's lodestone model of the Earth was about 10 cm in diameter and that the elevations of the mountains and depressions at the base of the oceans would be no more than a tenth of a millimeter if constructed to scale [24]. Using his own terrella (Little Earth) he showed that these tiny irregularities in the Earth's surface had little effect on a compass needle and thus could not explain declination. In his writing, however, Cabeo was more interested in defending the Earth-centered model of Creation than explaining why a compass needle might deviate from the true north.

Despite Gilbert's extensive experiments on static electricity, he described only the attractive forces and failed to mention repulsive forces. His effluvium theory accounted only for electrical attraction. Niccolo Cabeo, on the other hand, noted that when he rubbed amber, it would first attract the versorium needle and bits of paper but if they touched the amber, they would suddenly be repelled and fly away from the amber [25]. The amber could have both attractive and repulsive qualities. It would be more than a century before the American, Benjamin Franklin, described the positive and negative charges of static electricity.

Rene Descartes and the Dual Universe Solution

The French mathematician and philosopher, Rene Descartes, came up with a clever solution to the science/God problem—two separate universes, a physical universe and a spiritual universe. There was the nonthinking universe that followed straightforward physical laws and the thinking universe occupied by God and humans that was understandable only by God. This construct allowed him to speculate on the laws of the physical universe hopefully without offending the church censors.

Descartes, a mathematician and philosopher like the ancient philosophers Plato and Aristotle, relied on logic rather than experimentation to understand the physical universe. His use of logic is illustrated by the famous statement known as his most certain proposition—"*I think, therefore I am.*" Just as Gilbert and Bacon represented the new scientific approach, Descartes represented the old philosophical approach. Descartes' view of the physical universe was a version of the atom theory of Epicurus and Lucretius discussed earlier in the chapter. But Descartes believed that there was no empty space; the space between masses was filled with tiny atoms like a gas, that he called ether [aether in Latin]. Movement of the ether resulted in movement of masses present within the ether.

Descartes explained the orbit of the Earth and other planets around the sun as due to the Earth and planets being "pushed" by ether as it moved about the sun in a large vortex [26, 27]. The vortex of ether could move some matter to its outside while other matter could move toward its center explaining the Earth's gravity. All bodies must occupy some space and no two bodies could occupy the same space. However, a large body could contain spaces that smaller bodies or thin fluids could enter and pass through.

Recall that Lucretius explained the pull of iron toward a magnet by postulating that the magnet emitted streams of atoms that bombarded and displaced atoms in the space between the magnet and the iron. This produced a void and the iron slid into the void toward the magnet. There was no possibility of a void in Descartes' ether model, so he proposed an elaborate scheme of left- and right-handed corkscrew-shaped atoms that moved in the ether about a magnet and worked like a corkscrew wine bottle opener. These atoms entered tiny channels in the magnet and the iron attracted or repelled the iron from the magnet depending on the direction of the corkscrews.

Descartes' drawing of the corkscrew particles moving about a large sphere of lodestone (comparable to Gilbert's terrella) in his *Principia Philosophiae* published in 1644 is often described as the first illustration of the concept of a magnetic field (Fig. 1.3). On superficial inspection, this may seem the case, but on a closer look, there are major differences between Descartes' illustration and our current concept

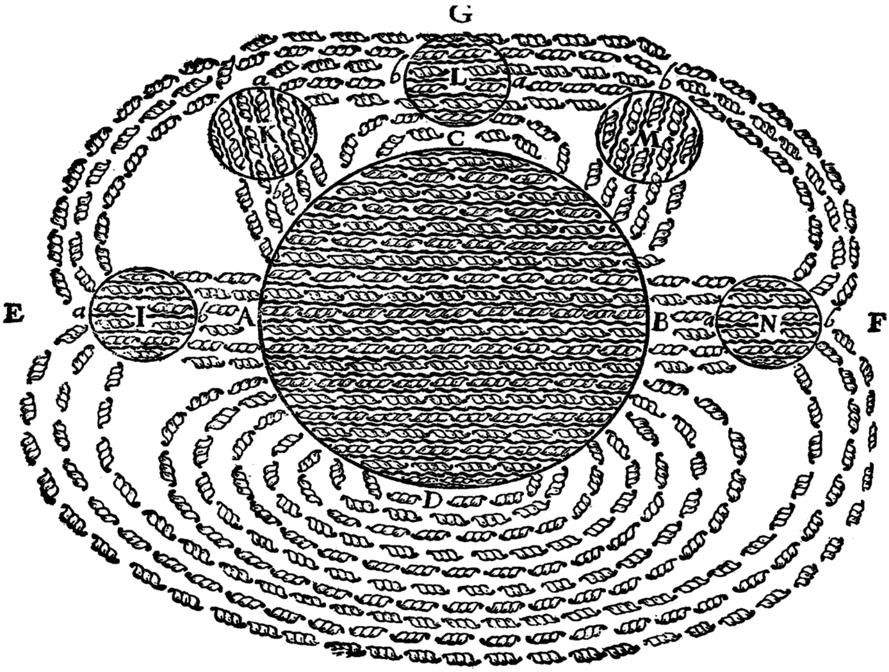

Fig. 1.3 Descartes theory of magnetism published in 1644. Left and right-handed corkscrew-shaped atoms moved in the ether around a magnet. The corkscrew atoms worked like a wine bottle opener pulling objects toward the magnet. (From Descartes R. *Principia Philosophiae*, 1644, p. 271, free Google eBook)

of a magnetic field. For one, the scheme requires that the channels in the lodestone and iron in the "magnetic field" be exactly aligned so that the corkscrew atoms can flow between the two structures. This is obviously not the case with a magnetic field. Descartes did not even attempt to explain the orientation of a compass needle with the magnetic field.

The physical universe as described by Descartes was a mechanical clockwork universe composed of matter with no empty space and no energy outside of the kinetic energy of matter in motion. On the other hand, his spiritual universe composed of God and human souls was immaterial and unable to be described in physical terms. The human brain was at a key crossroads in his dual model since it housed the machinery for control of the automatic workings of the body and the soul for thinking and self-awareness like God.

Descartes considered nerves to be hollow tubes that were connected to the fluid-filled compartments in the brain called ventricles. For reflex behavior, such as withdrawing from a painful stimulus, he postulated that thin filaments within each nerve tube controlled tiny valves in the ventricles of the brain that controlled the flow of animal spirits into the nerves. Painful pressure or heat against the skin would move the filaments (like pulling on a rope to ring a bell), open the valves, and release