[Working paper]

William Gilbert and the Discovery of 'Electricks'

A Case Study in the History of Electricity

VERSION 2.0

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Abstract:
In William Gilbert's 1600 work *De magnete*, Gilbert presents an account of *electricks*, things which attract in the same way as amber. This is widely considered to mark the discovery of the phenomenon of static electric attraction. While scholars have studied Gilbert to understand the origins of his experimentalism, the details of his magnetic theory, or his metaphysical commitments, in this study we aim to understand what specifically enabled Gilbert to make his discovery of static electric attraction. We describe how Gilbert's sought to explain puzzling magnetic phenomena and the rotation of the Earth, and at the same time displace Aristotle, by creating a new magnetic cosmological theory. This theory made important claims about attraction and, in combination with the ambient confusion around the purported attractive powers of amber and other gems, prompted Gilbert to conduct a thorough experimental investigation of the attractive powers of various materials. This investigation led Gilbert to sift through the writings of his predecessors and make new discoveries of his own, thereby isolating the category of electricks. We proceed in roughly chronological order, starting with observations about lodestone and gem attraction in antiquity, describing the beginning of magnetic study in the Middle Ages, returning to the Renaissance as both developments continued, and describing Copernicus' challenge to Aristotle's cosmology. We then turn our attention to Gilbert, describing the causes and prompts of his magnetic cosmology, his ideas about attraction, his investigation of the purported attractive powers of many materials, and his discovery of electricks. Throughout, our focus is discovery-centric: we summarize the progress made at each stage, and focus on the details that help us answer the question "What led Gilbert to discover static electric attraction?" This study is part of our ongoing research into the nature and causes of scientific discovery.

Keywords: William Gilbert, electricks, magneticks, versorium, history of electricity, amber, lodestone, electric effluvia, electrostatic attraction

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This paper is currently being circulated for review. Please contact mindy[at]leverageresearch.org to give us feedback or get involved with our early stage science research program.

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Introduction

In 1600 CE, William Gilbert published *De magnete*, a work about magnetism and the Earth. In it, Gilbert devotes a chapter to "things which attract in the same manner as amber," which he calls *electricks*.[1] In that chapter, Gilbert gives long lists of electricks and non-electricks, states many properties of electricks, describes experiments that can be run to verify his claims, offers a theory of electricks, and presents an experimental instrument that others can use to investigate electricks. This is widely considered to constitute the discovery of static electric attraction and the beginning of serious electrical study. Others would later pick up this line of research, build on Gilbert's observations, and continue to advance the study of electricity.

What led Gilbert to discover static electric attraction? In this study we will trace the earliest elements of the recognition of the phenomenon in ancient Greece and Rome, through relevant developments in the Middle Ages, to the accumulation of knowledge in the Renaissance and the years before Gilbert. After setting the stage by describing Copernicus' challenge to Aristotle's cosmology, we then turn to Gilbert himself. We describe Gilbert's dispositions and propensities, his theories and experiments, as well as his eventual discovery. Our purpose throughout will be to illuminate the critical path to the discovery of static electric attraction, while setting the stage for future discussion and analysis.

In this introduction, we will expand on the aims of this essay, describing in greater depth what we mean by a "critical path," and what is involved in tracing one. We will then describe the elements, considered abstractly, that we would take to constitute a "discovery" of static electric attraction, and why we take Gilbert's steps forward to count as the relevant discovery. We then sketch the course our history follows, and remark on some of the limitations of our study.

Aims of this Essay

Tracing the Critical Path

In this study, we present a discovery-centric history. It is a history, in that it follows the developments that led to the discovery of static electric attraction in approximately chronological order. It is discovery-centric, in that it is focused on the question of what led Gilbert to make his discovery of static electric attraction.

Our goal with this discovery-centric history is to lay out and illuminate as best we can the *critical path* to the discovery of static electric attraction. The critical path to a discovery is the

[1] Gilbert, *On the Magnet,* vj. See Gilbert's definition of electricks under "Interpretations of certain words."

counterfactually-informed causal sequence that leads to that discovery. It includes, as best as can be ascertained, the things that enabled or caused the discovery, described at the level of abstraction and detail that best captures the causal and counterfactual causal structure, as well as supporting evidence.

In practice, it is often difficult to identify specific causal links, or parts of the surrounding counterfactual causal structure. In some cases, this is a natural limitation arising from the available historical evidence. In other cases, there are difficulties arising from complex issues, such as issues pertaining to general causal patterns in history or the inner workings of discovery. As such, in illuminating the critical path, we will seek to make the strongest claims we can support given the available evidence, while leaving the reasoning as evident as possible.

A Basis for Future Analysis

By illuminating the critical path to the discovery of static electric attraction, we hope to help create a solid foundation that will enable future discussion and analysis on the topic of scientific discovery. Understanding how a particular important discovery was made can contribute to this in several ways.

First, understanding how a particular important discovery was made may directly inform discussions on scientific methodology. Universal generalizations can be refuted by a single counterexample, and single examples can provide inspiration in the form of showing what was possible in a given case.

Second, by understanding how a particular important discovery was actually made, it then becomes possible to engage in a serious investigation of how else it perhaps could have been made, and how not. Understanding the array of possible paths to a discovery, including the details of those paths, how plausible each was, and so on, can provide further data to inform discussions of scientific methodology. Knowledge of what was possible in the past is greatly aided by knowledge of what was actual in the past, and this in turn can contribute to knowledge of what may be possible in the future.

Third, a history that illuminates the critical path to a particular discovery can be joined by other histories that illuminate the critical path to other discoveries. Together, a set of such histories could enable us to begin to draw conclusions about the scientific enterprise as a whole in a way that arguably befits that enterprise, that is to say, empirically.

There are other benefits to a history such as the one we attempt here. This list of benefits is a sample, especially of those that motivated us to undertake this study.

Defining the Discovery

Elements of the Discovery

In tracing the critical path to the discovery of static electric attraction, we will pay close attention to things that contributed to the elements of this discovery. This raises the question of what precisely counts as the discovery of static electric attraction.

Instances of static electric attraction were recognized, and distinguished from the nearby phenomenon of magnetic attraction, as early as Ancient Greece. Amber was known to the ancient Greeks to attract leaves and chaff, sometimes needed to be rubbed to exhibit this effect, and was not thought to transmit its attractive power to the leaves or chaff. Lodestone, on the other hand, was known to attract iron, did not need to be rubbed, and could transmit its attractive power to iron, enabling iron to attract further iron. Amber attraction is an instance of static electric attraction; lodestone attraction is an instance of magnetic attraction. Hence many ancient Greeks had identified instances of static electric attraction and distinguished them from instances of magnetic attraction.

These observations, however, are generally not considered to constitute the discovery of static electric attraction. First, static electric attraction is a phenomenon that can be exhibited by many things, including some gems (e.g., diamond, jet), but not all (e.g., not emerald or pearl), and some non-gems (e.g., sulfur, glass), but not all (e.g., not gold, silver, ivory, or cedar). This renders it distinct from amber attraction, which is simply an instance of it. This also renders it distinct from gem attraction, both the actual phenomenon, since some non-gems exhibit static electric attraction, and the idea that all gems attract, since some gems do not. The best writings on the topic from the Greeks, as well as the Romans after them, display at most the recognition that a few gems attract in a way similar to amber. Second, static electric attraction does not operate only on leaves or chaff, but rather all light objects including metals (e.g., small bits of iron, small bits of silver), liquids (e.g., oil, water), and things some ancient writers thought amber did not attract (e.g., basil). Some ancient writers begin to approach the recognition of the universality of the effect, but none reach it, and there is no indication that they consider the matter closely; none, for instance, seem to consider the question of whether amber or other gems can attract liquids. Finally, while many writers did distinguish amber and lodestone in a number of ways, the ancient Greeks, Romans, and others for many subsequent centuries treated amber and lodestone as being of a kind: two curiosities with visible attractive powers, more similar to one another than different. Their theories did not strongly distinguish amber and lodestone attraction, did not seem to suggest attraction by amber or other gems as especially worthy of investigation, and the evidence strongly suggests that in practice the ancients did not thoroughly investigate the phenomenon of static electric attraction in any of its manifestations.

Thus, while we can say that ancient Greeks encountered static electric attraction and identified instances of it, we would not say that they "discovered" it. Discovery intimates that one has identified the contours of an object, and has a sense of its importance. The Greeks did not achieve this.

It is of course difficult to precisely define the "contours" of a phenomenon, and static electric attraction is no exception. Gesturing at the contours, we can say that ideally we would want investigators to recognize that there was a phenomenon that was exhibited not just by amber, or amber and some other gems, but rather that there was a previously unidentified category of thing that exhibited the phenomenon, which included some but not all gems and some but not all non-gems. We would want them to recognize that these things attracted not only leaves and chaff, but all light objects without exception. We would also want them to recognize that rather than a simple power to attract, this type of attraction had many characteristics, including that it could be blocked by interposed objects, that it attracts in a straight line, that it can be generated by rubbing in accordance with the triboelectric series, and so forth. We would want the investigators to distinguish this type of attraction from nearby and related things, including the nearby phenomena of lodestone attraction and magnetic attraction, instances like amber attraction and gem attraction, and to dispel nearby natural ideas, such as the idea that all gems attract. Finally, we would want this to be done with as little admixture of inaccurate claims as possible, especially claims that might substantially mislead.

For the purposes of our study, we will track these elements, as well as the degree to which static electric attraction is recognized as an important phenomenon worthy of investigation, as we build up to its discovery.

Designating the Discovery

This leaves the question of deciding when exactly the contours of static electric attraction are delimited well enough for us to classify it as having been "discovered." In practice, we see a sequence of achievements related to static electric attraction, stretching from the ancient Greeks and Romans, up through to modern times. We look for where we and others are inclined to judge that the relevant discovery has been made, and we look to see whether that point is reached by a large, discrete step forward. If there is, then we can designate that point "the discovery of static electric attraction."

Gilbert and his predecessors make this designation relatively easy. As we will see, Gilbert identifies a long list of amber-like attractors, a long list of things that are not amber-like attractors, and gives the category a name ("electricks"). He thus identifies the category of static electric attractors. Gilbert also distinguishes the category of electricks from the nearby categories of magneticks (i.e., things that attract magnetically) and gems, and notes that not all gems attract. He thus distinguishes static electric attraction from all of the surrounding natural categories of

attraction, including lodestone attraction, magnetic attraction, amber attraction, and gem attraction, and dispels the nearby natural suggestion that all gems attract. Gilbert identifies that static electric attraction attracts all light things, attracts in a straight line, can be blocked by interposed objects, is affected by humidity, is not aided by heat, and can be destroyed by sufficient heat. He thus identifies several of its important features, and more than had been captured previously. Finally, Gilbert presents the category of electricks as a worthy object of investigation, and furnishes for future researchers an instrument, the non-magnetick versorium, to help them reproduce his findings. Gilbert does make a few errors, has a mistaken theory of how electricks work, and does not recognize all of the features of static electric attraction or its relation to other electrical phenomena. Nevertheless, at this point it seems as though the phenomenon of static electric attraction has been recognized, distinguished, and designated as important for future study, and in a way that is in fact picked up by future researchers.

This research on static electric attraction marked a large, discrete jump in the quality of treatments of the subject. The best of his predecessors, Girolamo Cardano, manages to explicitly contrast several features of amber attraction and lodestone attraction, identifies several features of amber attraction, including one new feature, and correctly identifies many gems as having attractive powers. This is itself a discrete improvement over Cardano's own predecessors, and if anyone before Gilbert deserves to be thought of as the discoverer of static electric attraction, it is Cardano. Nevertheless, Cardano makes important omissions and errors. He fails to positively identify static electric attractors as a single category, and incorrectly maintains that all gems attract. He also makes some other important related false claims, and describes an instrument for detecting silver that likely did not exist and would not have worked.

For these reasons, we concur with others in designating Gilbert as having discovered static electric attraction, and this is why we have selected Gilbert's work as the focus of this study.

Summary of this Essay

Outline of the Critical Path

As we will describe, the immediate cause of Gilbert's discovery of electricks was his thorough experimental investigation of the attractive powers of amber, other gems, and other materials, in which he sifted through and engaged with relevant claims from the writings of his predecessors and also conducted further experiments on his own. This investigation was very likely aided by the true claims that had been accumulating in the writings of his predecessors, with those claims providing leads, and the true claims among them perhaps helping Gilbert identify truths about electricks he might have not identified otherwise, or might have identified only with much more difficulty.

The character of Gilbert's investigation was a result of Gilbert's own dispositions, in particular his experimentalism, his theoretical propensities, and his propensity to respond to the writings of his predecessors. It was likely spurred on by the tractability of the object of study, and may have been aided by his non-magnetic versorium, the instrument for investigating electricks Gilbert later presents in *De magnete*.

Gilbert's investigation itself was likely prompted in some way by his theoretical views on one hand, and the commotion and confusion in the writings on the attractive powers of amber and other gems on the other. With respect to his theoretical views, Gilbert was developing or had developed a magnetic cosmological theory, according to which the Earth is a giant rotating magnet. This theory, which has magnetic effects as its centerpiece, may have directly prompted Gilbert to investigate non-magnetic attraction, in order to distinguish non-magnetic attraction from magnetic attraction. Alternatively, Gilbert's theory may have led him to posit an attractive force beyond magnetism in order to explain why the surface of the Earth did not fly apart as the Earth spun. This might then have led him to study attraction by amber and other gems, in order to better understand attraction or to reconcile the relevant phenomena with his other ideas about attraction.

With respect to the confusion and commotion in the writings of his predecessors, it seems likely that these at least helped to draw Gilbert's attention to the potential phenomenon of non-magnetic attraction. Without them, it is hard to know if he would have taken note of it. Further, the poor coverage of the phenomena, evidenced by the disagreement, lack of evidence, and apparent lack of careful treatment may have further goaded Gilbert into action, with the intention to uncover the relevant truths and set the record straight.

Gilbert may have been further spurred on to engage in his careful investigation by his degree of explanatory ambition. Gilbert intended his cosmological magnetic theory to displace Aristotle's cosmology, including Aristotelian explanations for terrestrial phenomena. For this, Gilbert would have to have been aiming to explain a wide range of phenomena, and this comprehensiveness may have increased his propensity to engage in thorough studies of objects of interest.

Of these prompts, spurs, and contributing causes, it is difficult to tell which operated, how strongly, and at which times. It seems important for the resolution of this question that Gilbert singles out electricks for special treatment. He treats many objects, though often in a quick or cursory fashion; he provides evidence of having engaged in a rigorous study only of magneticks and magnetic phenomena (which constitute the core of his theory), and electricks.

The path to Gilbert's discovery of electricks can be traced back further. His cosmological magnetic theory arose partially as an attempt to explain puzzling magnetic phenomena that were being discovered by magnetic researchers, following the lead of Peter Peregrinus, as well as compass makers and mariners. It also arose partially as an attempt to explain the rotation of the

Earth, and to displace Aristotle, in response to Copernicus' counter-Aristotelian proposal that the Earth rotates. The writings on attraction by amber and other gems had themselves been accumulating since antiquity, and form their own part of the story.

Order of the Study

Proceeding in rough chronological order, we begin this study in Ancient Greece and Rome. We examine the writings of the ancients on the topic of attraction by amber, other gems, and lodestone. We see a number of true claims, a substantial amount of misinformation, and a number of theories of lodestone and amber attraction that seem to provide the ancients with little practical help.

Next, we move forward to the Middle Ages. We briefly describe the proliferation of compasses around the turn of the millennium, and then turn to the work of Peter Peregrinus, who in 1269 CE provided the first serious study of magnetic attraction. Through Peregrinus' efforts, lodestone attraction comes to be understood thoroughly enough that it can be recognized as its own phenomenon, distinct from gem attraction, and plausibly important and worthy of study.

We next transition to the Renaissance, where Renaissance writers have picked up the tradition of making observations about materials including amber, other gems, and lodestone. We see how despite the continued inclusion of falsehoods, true claims about amber attraction and attraction due to other gems are starting to accumulate, and the distinction between magneticks and electricks beginning to emerge. This reaches its height with Girolamo Cardano, who, among other things, presents in the early 1550s the first list of contrasts between amber attraction and lodestone attraction.

Next, we return to the study of magnetic attraction. Peregrinus' work widely circulates in 1558 CE, and other researchers pick up and continue his line of research, making new discoveries. At the same time, compass makers and mariners have started to report new magnetic phenomena, which, combined with the other magnetic observations, yielded a number of puzzles.

Having completed the relevant histories of amber-like attraction and magnetic attraction, we then describe Aristotle's cosmological system and Copernicus' challenge to that system. This plausibly creates an opening for a new cosmology, and at the same time raises the question of how to explain the rotation of the Earth.

With the stage now set, we turn to William Gilbert. Seeking to develop a unified explanation of magnetic phenomena, explain the rotation of the Earth, and produce a cosmology to displace Aristotle, Gilbert develops a magnetic cosmological theory according to which the Earth is a giant rotating magnet. This theory centrally involves magnetic attraction, though Gilbert seems to find magnetic attraction insufficient by itself to explain the coherence of the Earth as it rotates.

Perhaps for the sake of distinguishing magnetic attraction from other ostensible attractive phenomena, perhaps for the sake of explaining the coherence of the Earth and/or reported attractive phenomena while retaining a simple theory of attraction, and perhaps spurred on by the wide scope of his explanatory ambitions and/or the writings of his predecessors, Gilbert then undertakes a careful experimental study of the attractive powers of amber, other gems, and other materials. This investigation, which includes Gilbert's extensive efforts to respond to previous writers, and which was likely aided by the truths they had discovered, leads Gilbert to distinguish the category of electricks.

After describing Gilbert, his relevant dispositions and propensities as a researcher, his development of his cosmological magnetic theory, his related ideas on attraction, the causes and prompts of his investigation of gem attraction, the investigation itself, and his discovery of electricks, we briefly describe Gilbert's efforts to transmit his discovery to the world. That effort succeeds, and through his successors, electricks become insulators, and serious electrical study begins to grow.

Limitations of the Study

Many of the subjects touched upon in this essay deserve a more comprehensive treatment than we have offered here. In particular, we do not offer a full examination of writings on lodestone and gem attraction in antiquity or the Renaissance, or even of the writers Gilbert had access to. Gilbert references hundreds of writers in *De magnete* alone, and so we chose to present what we take to be a relevantly representative sample, rather than a complete account. We also omit the early history of compasses, which bears on the eventual development of the study of magnetism under Peregrinus, leaving this for another time.

Early Electrical Study and the Path to Gilbert

There are three important threads to follow in the history leading up to Gilbert's discovery of static electric attraction: first, the accumulation of claims about the attractive powers of gems, especially amber; second, the development of knowledge of magnetic attraction; and third, the challenge to Aristotle's cosmological system by Copernicus.

The first of these threads, the accumulation of claims about the attractive powers of gems, and part of the second, the development of knowledge of magnetism, are contained within the writings of commentators on nature. These commentators, writing in antiquity and the Renaissance, frequently report a wide array of observations on many topics, sometimes covering amber attraction, attraction by other gems, and lodestone attraction in the process. Their reports,

as we will see, vary in quality, with more information and greater accuracy slowly developing over time.

The other parts of the second thread, on magnetic attraction, arise from interactions with compasses by mariners and compass-makers, or are contained within the writings of a few researchers who engage in an extended study of lodestone attraction and attraction by magnetized iron needles. These developments begin in the Middle Ages, prompted by the proliferation of the compass, and continue in the Renaissance.

These threads are important for a number of reasons. The thread on gem attraction contains the progress noticing and describing static electric attraction to date, and the writings themselves play a role in sparking, guiding, and contributing to Gilbert's study of the attractive powers of various materials. The thread on magnetic attraction displays the progress identifying magnetic attraction as a distinct and important phenomenon, clearly distinguishing it from amber-like attraction. It also yields the first set of phenomena—the magnetic phenomena—that Gilbert will seek to explain with the theory that helps to prompt his study of the attractive powers of various materials.

While it might be clearer in some ways to treat these two threads separately, either covering the commentators first and the serious magnetic researchers second, or covering amber-like attraction first and magnetic attraction second, each approach is somewhat cumbersome and does not proceed chronologically. Instead, we treat both together, going back and forth as one then the other predominates. This best captures the chronology and avoids repetition. The tale is more complex, but, we propose, in a way that matches the complexity of the reality.

The third thread, the advent of Copernicus' astronomical system and its challenge to Aristotelian cosmology, contributes by providing the second set of phenomena—the astronomical phenomena—that Gilbert will attempt to explain with his cosmological magnetic theory. We treat this thread after having concluded the first two.

1 Historical Study of Electricity and Magnetism

The history of Gilbert's discovery of static electric attraction is in large part the story of two curious stones, amber and lodestone. These stones are recognized in antiquity as having attractive powers, lodestone attracting iron and amber when rubbed attracting leaves and chaff. While distinguished in this way, amber and lodestone were generally treated as two species of the same genus, oddities worthy of note, but not important enough to deserve substantial attention. The history that follows sees lodestone first, and then amber, be distinguished and recognized as an important phenomenon, with its own behavior, worthy of sustained investigation.

While our primary focus in this study is static electric attraction, and hence the attractive powers of amber, some other gems, and some other materials, and not attraction due to lodestone or the magnetized iron needle, for reasons described earlier, we will spend time tracing the development of knowledge of both.

The history divides into four parts, or two alternating trends. The first and third parts are devoted to commentators on nature, the second and fourth to the independent study of magnetism.

We begin in ancient Greece and Rome, examining the observations made by commentators about the attractive powers of lodestone and gems, especially amber. We then move to the Middle Ages, where compasses begin to proliferate, and Peter Peregrinus writes a brief treatise that marks the beginning of serious magnetic study. We then return to the commentators on nature in the Renaissance, witnessing how in their writings, a distinction between magnetic attraction and amber-like attraction begins to take shape. We end with the magnetic developments arising from compass-makers, mariners, and magnetic researchers in the years just before Gilbert.

At the end of each part, we take stock, describing the progress towards the discovery of static electric attraction made by that point, as well as the challenges that remain.

Study of Electricity and Magnetism: Accumulation and Challenges, Part 1 of 2

Accumulation in Antiquity

Core Observations

The writings of the ancients on the topic of the attractive effects of gems and stones center on two key observations: that lodestone attracts iron, and that amber, when rubbed, attracts straw, leaves, and pieces of chaff.[2] These observations are made by a variety of writers. Some mention only the fact that amber and lodestone have an attractive power, while some mention specifically that lodestone attracts iron and that amber attracts straw and chaff.

For instance, in his *Natural History,* published between 77 and 79 CE, the Roman writer Gaius Plinius Secundus (Pliny the Elder) writes:

> To come to the properties that Amber hath, If it bee well rubbed and chaufed between the fingers, the potentiall faculty that lie within, is set on work, and brought into actual

[2] In addition to the passages below, see Gilbert, *On the Magnet,* 1-2, 47; Benjamin, *History of Electricity,* 47, 24; Heilbron, *Electricity in the 17th and 18th Centuries*, 169.

> operation, whereby you shall see it to draw chaffe straws, drie leaves, yeah, and thin rinds of the Linden or Tillet tree, after the same sort as loadstone draweth yron.[3]

Gaius Julius Solinus, a Roman chronicler living in the 3rd century CE, describes amber and lodestone attraction as well, writing, "it is well known that it [amber] snatches leaves and draws chaff to itself" and noting the ability of the lodestone to "snatch iron."[4]

Greek writers Plato and Theophrastus also reference the attractive powers of both stones. Plato, in his cosmological text *Timaeus*, written in 360 BC, writes of "the marvels that are observed about the attraction of amber and the Heraclean stones [lodestones]," and Theophrastus, Aristotle's successor at the Lyceum, adds, "And since amber is also a stone—for the kind that is dug up is found in Liguria—the power of attraction would belong to this too. The stone that attracts iron is the most remarkable and conspicuous example. This also is rare and occurs in few places. This stone too should be listed as having a similar power."[5] Plato and Theophrastus are joined by Epicurus, Lucretius, Dioscorides, and Aristotle (citing Thales), who also comment on these basic attractive behaviors of amber and the lodestone.[6]

Further Observations

Beyond the core observations about lodestone and amber attraction, ancient writers made a number of additional correct related observations. These were made less frequently, and thus had less *prima facie* evidential weight, but nevertheless added to the total stock of correct information available to those studying attraction.

Transmission of Lodestone Attraction Through Iron

Several thinkers mention the fact that lodestones can cause iron to attract further pieces of iron. In the *Ion*, for instance, Plato writes:

> ...like that contained in the stone which Euripides calls a magnet, but which is commonly known as the stone of Heraclea [lodestone]. This stone not only attracts iron rings, but also imparts to them a similar power of attracting other rings; and sometimes you may

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[3] Gilbert, *On the Magnet,* under "Notes," 37-38. This quote begins: "Hee [Niceas] writeth also, that in Aegypt it [amber] is engendered… Semblably in Syria, the women (saith hee) make wherves of it for their spindles, where they use to call it Harpax, because it will catch up leaves, straw, and fringes hanging to clothes."
[4] Solinus, *Polyhistor,* 20.12, 52.53.
[5] Plato, *Timaeus,* 502; Theophrastus, *On Stones,* 51.
[6] Chalmers, "Lodestone and the Understanding of Matter," 79; Gilbert, *On the Magnet,* 61; Lucretius, *Nature of Things* (1910), loc. 378, loc. 384; Dioscorides, *Materia Medica,* 819; Aristotle, *Complete Works,* 409a19-409a21. Epicurus writes on both, and Lucretius, Dioscorides, and Aristotle on the magnet. Dioscorides: "That lodestone which draws iron easily is the best, with an azure colour [blue], and thick but not too heavy. It is able to draw out thick fluids if thirty grains are given with honey and water." Aristotle: "Thales, too, to judge from what is recorded about him seems to have held soul to be a motive force, since he said that the magnet has a soul in it because it moves the iron."

> see a number of pieces of iron and rings suspended from one another so as to form quite a long chain: and all of them derive their power of suspension from the original stone.[7]

Lucretius mentions this fact as well in his *De Rerum Natura*.[8]

Gemstones' Attractive Powers

Several writers also identify that the attractive power of gems extends beyond the basic power of amber to attract leaves and chaff. Pliny notes that ruby and garnet attract leaves, chaff, and straw:

> Over and besides, I find other sorts of Rubies different from those above named;... which being chauged in the Sun, or otherwise set in a heat by rubbing with the fingers, will draw unto them chaffe, straws, shreds, and leaves of paper. The common Grenat also of Carchedon or Carthage, is said to doe as much, although it be inferior in price to the former.[9]

Pliny and St. Isidore "speak of a certain stone, *lychnis*, of a scarlet or flame colour, which, when warmed by the sun or between the fingers, attracts straw or leaves of papyrus."[10]

Solinus, observing that jet attracts like amber, writes, "if the power, rubbe it [Geat] till it be warme, and it holdeth such things as are laide to it; as Amber doth."[11]

Theophrastus, speaking of lyncurium, notes not only its similarity to amber, in that it attracts "Straws and small pieces of Sticks," but also that it attracts thin pieces of copper and iron[12]:

> It [emerald] is, however, excellent, in its Virtues, as is also the *Lapis Lyncurious,* which is likewise used for engraving Seals on, and is of a very solid Texture, as Stones are; it has also an attractive Power, like that of Amber, and is said to attract not only Straws and small pieces of Sticks, **butt even Copper and Iron, if they are beaten to thin pieces**. This Diocles affirms.[13]

Plutarch says of amber that it attracts almost everything light.[14]

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[7] Plato, *Ion,* 13.
[8] Lucretius, *Nature of Things* (1910), loc. 378.
[9] Gilbert, *On the Magnet,* under "Notes," 39.
[10] Gilbert, *On the Magnet,* under "Notes," 39; Pliny, *Natural History* (2004), bk. 37, chap. 29. Lychnis may refer to red tourmaline.
[11] Gilbert, *On the Magnet,* under "Notes," 37.
[12] Lyncurium may be tourmaline, jacinth, belemnite, or amber. John M. Riddle argues that it is amber; Thompson reports that others believe it is tourmaline, jacinth, or belemnite; Paul Fleury Mottelay supposes it is tourmaline. Riddle, "Amber in Ancient Pharmacy," 5; Gilbert, *On the Magnet,* under "Notes," 38; Mottelay, *History of Electricity and Magnetism,* 18.
[13] Gilbert, *On the Magnet,* 38. Emphasis added. Also translated as: "It [emerald] is remarkable in its powers, and so is the *lyngourion [lyncurium];* for seals are cut from this too, and it is very hard, like real stone. It has the power of attraction, just as amber has, and some say that it not only attracts straws and bits of wood, but also copper and iron, if the pieces are thin, as Diokles used to explain." Theophrastus, *On Stones,* 28.
[14] Plutarch, *Quaestiones Convivales,* 647b.

These observations, in addition to the core observations about lodestone and amber, were steps towards the recognition of static electric attraction as a single phenomenon, distinct from magnetic attraction. The similarities between amber and other gemstone attraction suggest that there might be a similar causal mechanism at work in both cases. The fact that some gems have broader attractive powers, not just the ability to attract leaves and chaff, indicates that the phenomenon of amber-like attraction might be something more universal. The fact that lodestone can transmit its attractive effect through iron to other pieces of iron, while amber was not observed to do something similar, potentially indicates an important distinction between the two.

Unfortunately, as we will see, these suggestions were difficult to recognize and pursue, at least in part because as accurate observations accumulated, so too did substantial misinformation.

Challenges in Antiquity

Misinformation

In addition to a number of true claims about lodestone and gem attraction, ancient texts were replete with misinformation. In the context of such misinformation, it was difficult for anyone to straightforwardly extract truths about the attractive powers of stones and gems from the writings of the ancients. The core observations about amber and lodestone were repeated frequently and by many sources, but there were few other claims consistent enough to be relied upon.

This misinformation appears in a variety of forms. First, there are straightforwardly mistaken observational claims. Such claims are sometimes made boldly, with vivid descriptions or assurances of their obviousness. Solinus, for instance, vividly claims that diamond can cancel the attractive power of lodestone:

> ...if the diamond is placed near, it does not allow the lode-stone to snatch iron. Or if the lode-stone has already drawn iron to itself, the diamond snatches it away and steals it, as though it were booty.[15]

Plutarch, in his *Convivales Quaestiones*, claims it is "very evident" that amber cannot attract basil and that lodestone does not attract iron that has been rubbed by garlic:

> ...amber draws all light things to it, except basil and such as are dipped in oil; and a loadstone will not draw a piece of iron that is rubbed with garlic. Now all these, as to matter of fact, are very evident; but it is hard, if not altogether impossible, to find the cause.[16]

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[15] Solinus, *Polyhistor,* 52.56; Gilbert, *On the Magnet,* under "Notes," 4. This myth became popular and was propagated up through Gilbert's time. The diamond might have attracted the iron electrically, though it is unlikely that it generally disrupted lodestone attraction.

[16] Plutarch, *Quaestiones Convivales,* 647b; Gilbert, *On the Magnet,* under "Notes," 42.

There are also dubious medical claims. Dioscorides, in his *De Materia Medica*, for instance, attributes to the lodestone an effect certainly beyond its powers:

> That lodestone which draws iron easily is the best, with an azure color [blue], and thick but not too heavy. It is able to draw out thick fluids if thirty grains are given with honey and water.[17]

In addition, there are also substantial fabrications, complete with purported eyewitnesses. Philostratus, in *The Life of Apollonius of Tyana*, describes a stone called a "pantarbe," which seems to combine and exaggerate the attractive and repulsive effects of the lodestone and some of the features of attractive gems, adding mystical rites and a purported public demonstration for good measure:

> "However about the stone which attracts and binds to itself other stones you must not be skeptical; for you can see the stone yourself if you like, and admire its properties. For the greatest specimen is exactly of the size of this finger nail," and here he pointed to his own thumb, "and it is conceived in a hollow in the earth at a depth of four fathoms; but it is so highly endowed with spirit, that the earth swells and breaks open in many places when the stone is conceived in it. But no one can get hold of it, for it runs away, unless it is scientifically attracted; but we alone can secure, partly by performance of certain rites and partly by certain forms of words, this pantarbe, for such is the name given to it.
>
> Now in the night-time it glows like the day just as fire might, for it is red and gives out rays; and if you look at it in the daytime it smites your eyes with a thousand glints and gleams. And the light within it is a spirit of mysterious power, for it absorbs to itself everything in its neighborhood. And why do I say in its neighborhood? Why you can sink anywhere in river or in sea as many stones as you like, and these not even near to one another, but here there; and everywhere; and then if you let down this stone among them by a string it gathers them all together by the diffusion of its spirit, and the stones yield to its influence and cling to it in bunch, like a swarm of bees."
>
> And having said this he showed the stone itself and all that it was capable of effecting.[18]

If there had simply been an occasional false claim, or if authors had been careful to state the provenance of their claims, or honestly provide their evidence, it might have been easier to discern the false claims from the true. Unfortunately, false claims were common. Indeed, in some cases, writers would make many claims, back-to-back, with little or no justification. In this way, ancient writings were often repositories of things heard and possibly seen, rather than a repository of carefully curated observations. The following page from Pliny's *Natural History* illustrates this well:

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[17] Dioscorides, *De Materia Medica,* 819.
[18] Philostraphutus, *Life of Apollonius,* 329-331.

Book XXXVI

inscribed in it on earthenware is indelible. When it is burnt it gives off a smell like that of sulphur. What is remarkable is that it is ignited by water and quenched by oil.[a] The kindling of jet drives off snakes and relieves suffocation of the uterus. Its fumes detect attempts to simulate a disabling illness or a state of virginity. Moreover, when thoroughly boiled with wine it cures toothache and, if combined with wax, scrofulous tumours. The Magi are said to make use of it in what they call 'divination by axes'; and they assert it will not burn away completely if a wish is destined to come true.[b]

XXXV. Sponge stones are found in sponges, and therefore belong to the sea.[c] They are sometimes called in Greek 'stone-solvents' because they cure affections of the bladder and break up stone in it if they are taken in wine.

XXXVI. Phrygian stone is so called from the people of that name and occurs as porous lumps.[d] After being soaked in wine it is roasted, and bellows are used to fan it until it turns red, whereupon it is quenched with sweet wine, and the process is repeated three times on each occasion. It is of use only in dyeing garments.

XXXVII. 'Schistos' and haematite are closely related. Haematite *Haematite.*
is found in mines, and when roasted reproduces the colour of red-
lead. It is roasted in the same way as the Phrygian stone, § 143.

Figure 1. A representative excerpt from Pliny's *Natural History*.[19]

Gilbert chastised ancient writers for their inaccuracy, accusing them of failing to check their claims against their own experience:

> But that the story of the lodestone might not appear too bare and too brief [had the ancients only reported the lodestone merely attracted iron], to this singular and sole known quality were added certain figments and falsehoods, which in the earliest of times, no less than nowadays, used to be put forth by raw smatterers and copyists to be swallowed by men.
>
> As for instance, that is a loadstone be anointed with garlick, or if a diamond be near, it does not attract iron. Tales of this sort occur in Pliny, and in Ptolemy's *Quadripartitum*; and the errors have been seduously propagated, and have gained ground (like ill weeds that grow apace) coming down even to our day, through the writings of a host of men, who, to fill put their volumes to proper bulk, write and copy out pages upon pages on this, that, and the other subject, of which they know almost nothing for certain of their own experience.[20]

The problems with misinformation no doubt plagued the ancient writers and thinkers themselves, and the misinformation from the ancients' texts would survive until Gilbert's time. In the end, it

[19] Pliny, *Natural History* (1938), 115.
[20] Gilbert, *On the Magnet,* 2.

would require Gilbert's substantial experimental effort to examine the claims of the ancients carefully and distinguish the true from the false.

Misleading Theories

While the problem of misinformation is almost certainly the largest difficulty arising from the ancients' texts, it is also worth noting the potential effects of the ancients' theories. Theories can make it easier or harder to make discoveries: as we will later see, the use of the doctrine of similitudes among Renaissance physicians may have made it harder for them to recognize the distinction between lodestone and amber-like attraction, while Gilbert's magnetic theory of the Earth likely helped to impel him to investigate it.

There is little evidence of the direct impacts of the ancients on the study of lodestone or amber-like attraction. Nevertheless, it is worth noting that the theories of the ancients, if they had any effect at all, might seem to incline thinkers who held them against engaging in a thorough experimental study of lodestone or amber-like attraction. They were, in that subtle sense, misleading.

We will first review some of the theories of the ancients, those of Epicurus, Lucretius, Plato, Galen, and Thales. We will then make some general, albeit speculative comments.

Epicurus tried to explain attraction in terms of a well-understood mechanism: pulling. If lodestones, for instance, were somehow mechanistically pulling iron to them, the phenomenon would be explained and the puzzle resolved. In particular, he claimed that lodestone exudes atoms, which hook onto the iron and draw it back.[21]

Lucretius tried to explain attraction in terms of a previously understood phenomenon: the vacuum. If the lodestone somehow created a vacuum between it and the iron, this might cause the iron to be drawn towards the vacuum and hence to the lodestone. Advancing this view, he proposed that lodestone spews seeds towards iron, leaving a vacuum, and that iron atoms are then pulled into the vacuum, pulling the rest of the iron with them towards the lodestone.[22]

Plato suggested a related mechanism, motion in a plenum. On this hypothesis, all space is filled. Motion is then possible if when A moves into B's place, B moves into C's place, C moves into

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[21] Chalmers, "Understanding of Matter," 79.

[22] Chalmers, "Understanding of Matter," 79. Lucretius writes, "Wherefore, when all these things have been surely established and settled for us, laid down in advance and ready for use, for what remains, from them we shall easily give account, and the whole cause will be laid bare, which attracts the force of iron. First of all it must needs be that there stream off this stone very many seeds or an effluence, which, with its blows, parts asunder all the air which has its place between the stone and the iron. When this space is emptied and much room in the middle becomes void, straightway first-beginnings of the iron start forward and fall into the void, all joined together; it comes to pass that the ring itself follows and advances in this way, with its whole body." Lucretius, *Nature of Things* (1910). Also see corresponding passage in Lucretius, *Nature of Things* (2008).

D's place, and so on back to A, as with a solid spinning disk. In the *Timaeus*, Plato suggests that lodestone and amber attraction will ultimately be explained in this way, without suggesting a more specific mechanism:

> the marvels that are observed about the attraction of amber and the Heraclean stones [lodestones], —in none of these cases is there any attraction; but he who investigates rightly, will find that such wonderful phenomena are attributable to the combination of certain conditions—the non-existence of a vacuum, the fact that objects push one another round, and that they change places, passing severally into their proper positions as they are divided or combined.[23]

Rather than trying to explain attraction in terms of the movement of small particles, Galen proposed that everything had an attractive power that caused it to attract something in particular. On this, he wrote, "[e]verything which exists, possesses a faculty by which it attracts its proper quality."[24] Applying this to lodestone attraction, he wrote, "that by which a vacuum becomes refilled and that caused by appropriateness of quality; air is drawn into the bellows in one way, and iron by the lodestone in another."[25] If everything has an attractive power that causes it to attract something in particular, then it is much less noteworthy that lodestone attracts iron.

Finally, it appears that Thales tried to explain attraction by postulating an entity as the cause of attraction. The idea behind this sort of explanation is that if an entity exists that explains a phenomenon, then it is no longer the case that that phenomenon needs to be explained. Thus on the topic of lodestone attraction, Aristotle reported that Thales claimed that lodestones had souls in them, and these were the cause of the iron's movement.[26] (Aristotle himself did not offer a specific explanation for amber or lodestone attraction.)

Among the different attributes of these theories, each suggests where to look next for a more thorough explanation of the phenomena of lodestone attraction or amber attraction. Epicurus' theory depends on microscopic mechanical causes; to learn more about how those work, one might investigate magnification, to magnify the hooks that the lodestone's atoms use to draw in the iron. Alternatively, one might investigate whatever physical phenomena yielded the most insight into the general operation of microscopic mechanical causes, with the idea that one might then use that knowledge to understand the lodestone better. One might think to try testing Epicurus' theory directly by interposing solid objects and seeing whether they diminished the lodestone's attractive power. But a proponent of Epicurus' theory would likely have already had to postulate that atoms can penetrate seemingly solid objects, and so might not be surprised if an interposed object did not diminish the lodestone's attractive power. Notably, direct

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[23] Plato, *Timeus,* 502.
[24] Galen, *Natural Faculties,* bk. I, chap. XIV.
[25] Galen, *Natural Faculties,* bk. III, chap. XV.
[26] Aristotle, *Complete Works,* 409a19-409a21. See also footnote 6 of this text.

experimentation with lodestone and amber in an attempt to find patterns in their attractive effects was not naturally suggested.

A similar dynamic applies to Lucretius' and Plato's theories. For Lucretius, one might want to investigate vacuums, and for Plato, one might want to investigate the sorts of patterns of motion that can exist in a plenum. Both theories would be likely to resist direct testing, and neither seems to suggest engaging in a thorough experimental study of lodestone or amber.

Galen's theory is not much better. Galen postulates that lodestone attraction and amber attraction are themselves unremarkable: the surprising phenomenon to be explained is why other objects do not seem to attract, since it is proposed that they do. This directs the researcher away from looking at lodestone or amber and towards looking at other objects.

Perhaps surprisingly, Thales' theory might be the best of the theories mentioned here for keeping a researcher's interest on lodestone (and amber, if he had a similar theory of amber). Rather than explaining lodestone in terms of a universal mechanism, as the others did, Thales seems to have proposed that lodestone was special, in that lodestones had souls. This keeps our attention on lodestones, raising the question of why lodestones have souls and other stones do not. Unfortunately though, this also seems unlikely to incline researchers to engage in a thorough experimental study, since such a study presumably would not help us ascertain the cause of the lodestones having souls.

This reflection is not definitive proof that the theories of the ancients were counterproductive with respect to progress towards the identification of static electric attraction, but it does make a *prima facie* case. At the very least, these theories will stand in sharp contrast to Gilbert's own magnetic theory of the Earth, which may have propelled him to investigate amber-like attraction closely and attempt to distinguish it from lodestone attraction.

Progress to this Point

The ancient Greeks and Romans left for later generations a collection of writings on the attractive effects of lodestone and gems of distinctly variable quality. Some of the claims were true. These true claims include: lodestone attracts iron; amber attracts leaves, straw, and pieces of chaff; lodestone can pass its attractive power through iron to other pieces of iron; a variety of gems other than amber exhibit an attractive power analogous to amber; amber can attract (almost) everything light; at least one gem other than amber can attract iron and copper. In these claims, it is possible to make out the outlines of a category of amber-like attractors with attractive powers that affect many things, and to make out a distinction between that category of attraction and lodestone attraction. This would become the distinction between electricks and magneticks, between static electric attractors and magnetic attractors.

Many of the claims, however, were false, and the prevalence of misinformation made it difficult to tell which claims to believe without an extended independent investigation. The theories of the ancients were not helpful. The things that may have motivated Gilbert to push further, including the identification of magnetic poles, the drawing of the analogy between the lodestone and the Earth, the recognition of a more thorough contrast between lodestone attraction and amber-like attraction, and so on, had not yet been observed, and the theories that would help had not yet been invented.

Study of Magnetism: Independent Developments, Part 1 of 2

The First Compasses

Many centuries after Greek and Roman writers recorded their observations and claims about lodestone and gem attraction, a new understanding of lodestone attraction began to develop independently.

The first part of this independent development involved the start and spread of compass use after the turn of the millennium. While there is scattered evidence of earlier compass use in China, ancient Greece and Rome, and Sumer, the first clear descriptions of compasses and their use in marine navigation appeared in Europe, China, and the Arab world in the 11th and 12th centuries CE.[27] References to the compass in Europe then became more frequent between the 12th and 13th centuries, including mentions in the work of French poet and writer Guiot de Provins between 1190 and 1205 CE, the description of the lodestone as a 'shipman's stone' by Mandeville in the early 12th century, the writings of the cardinal and crusader Vitry in Syria between 1200 and 1220 CE, the letter from Peter Peregrinus on the study of the compass in 1269 CE, and the work of Lully of Majorca in describing seamen's instruments in 1272, 1286, and 1295 CE.[28]

The spread of these magnetic compasses provided evidence that magnetized iron and lodestones rotate to point towards the north star. While a simple observation, this provided a glimpse into a

[27] May, "Compasses Used in Antiquity," 415, 416; Bromehead, "Alexander Neckam." These compasses featured floating, rotating magnetic fishes of iron and wood and a pivoted iron needle magnetized by striking it with a lodestone. In China, the early references are made by Tsêng Kung-Liang in *Wu Ching Tsung Yaa* and Chu Yu in *Phing-Chou Kho.* In the Arab world in 1220 CE, Awfi mentions the compass's marine use. Alexander Neckham is widely credited with the first reference in the European world. See May, "Compasses in Antiquity," 416-420 and Mottelay, *History Of Electricity and Magnetism*, 1-29 (including Frode the Wise on 28) for descriptions of possible earlier compass use.

[28] May, "Compasses Used in Antiquity," 414; Bromehead, "Alexander Neckam," 2; Mottelay, *History of Electricity and Magnetism,* 30-32; Chalmers, "Understanding of Matter," 80.

new and distinguishing feature of lodestone attraction that would soon be substantially expanded upon.

Peregrinus' Magnetic Research

Writing in 1269 CE, Magister Petrus de Maharne-Curia, or Peter Peregrinus, composed a treatise on lodestone attraction called *Epistola de Magnete*.[29] The *Epistola* constituted a substantial advance in the understanding of magnetic attraction and would also later spark a tradition of researchers who would continue to advance magnetic research. It was thus a further step in the development of an independent understanding of magnetic attraction.

Little is known about Peregrinus himself, including the origin of his sobriquet, "Peregrinus," which is often translated "pilgrim." He is sometimes said to have fought in the crusades, and his title "magister" indicates his achievement of scholastic honors.[30] His *Epistola* appeared in the context of the proliferation of compass use, but had no clear immediate predecessor among works on lodestone attraction, either in length, precision, style, content, method, or importance.[31]

In his *Epistola*, Peregrinus identifies several important features of lodestone attraction, provides clear, simple, reliable instructions for reproducing his observations, and provides future researchers with what is essentially a toolkit for experimental lodestone study. With respect to observations, he identifies a new central phenomenon of lodestones: pole behavior. With respect to providing others with the ability to replicate his experiments and reproduce his observations, he provides clear, simple, step-by-step instructions, as well as instructions for how to create a specially formed lodestone for use in the experiments. At the end of his treatment of lodestone attraction, Peregrinus also provides a theory of lodestone attraction, as well as an important erroneous claim.

Due to its clear departure from the style of the ancients, its substantial influence on subsequent magnetic study, and its substantial influence on Gilbert, it is useful to describe Peregrinus' *Epistola* and its contents in some degree of depth.

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[29] *Epistola de Magnete* is also called *Epistola ad Sigerum,* a letter to his countryman Sigerus. Benjamin argues that Sigerus was Peregrinus' next-door neighbor. Benjamin, *History of Electricity*, 165-168; Peregrinus, *Letter of Peter Peregrinus,* xvi.

[30] Benjamin, *History of Electricity,* 165-168.

[31] Peregrinus had a few contemporaries who also noticed pole behavior, though their research largely did not rival his. One was Albertus Magnus, a German Saint living between 1200 and 1280 CE, who also noticed some pole phenomena. Magnus maintained that there were two types of lodestone, one that rotates to the South and one that rotates to the North. Gilbert, *On the Magnet,* 7, under "Notes," 18-19. Another, as we shall see, was Alexander Neckam, who described the compass and theorized on pole behavior using the doctrine of similitudes.

Epistola de Magnete

The *Epistola* is divided into two parts, with Part 1 devoted to lodestone attraction and Part 2 devoted to the construction and use of compasses. In the first part, Peregrinus covers the purpose of his work (Chapter 1) and the qualifications of an experimenter (Chapter 2), describes how to select a lodestone (Chapter 3), explains how to craft a special lodestone for use in experimental study (Chapter 4), and then describes a series of experiments and the observations that are demonstrated through them (Chapters 4-9). He ends by stating a theory of how lodestone attraction works.

The style and content of the *Epistola* are suggested by the section headings of Part 1:

Chapter 1: Purpose of the work
Chapter 2: Qualifications of the experimenter
Chapter 3: Characteristics of a good lodestone
Chapter 4: How to distinguish the poles of a lodestone
Chapter 5: How to discover the poles of a lodestone and how to tell which is north and which is south
Chapter 6: How one lodestone attracts another
Chapter 7: How iron touched by a lodestone turns towards the poles of the world
Chapter 8: How a lodestone attracts iron
Chapter 9: Why the north pole of a lodestone attracts the south pole of another and vice versa
Chapter 10: An inquiry into the cause of the natural virtue of the lodestone[32]

Observations and Apparatus

After commenting on introductory matters, Peregrinus explains how to create a special lodestone for use in experimental study. He explains how to select a good lodestone, and then instructs the reader to round their lodestone into a sphere and polish it. He writes: "With an instrument with which crystals and other stones are rounded let a lodestone be made into a globe and then polished."[33]

Peregrinus does not name his experimental tool; Gilbert would later call it a "terrella."

After giving instructions for constructing a terrella, Peregrinus describes methods for identifying its poles. He gives two different sets of instructions. The first involves placing iron needles on the terrella, letting the needles come to rest naturally, and then extending lines from the needles to find their points of intersection:

[32] Peregrinus, *Letter of Petrus Peregrinus*.
[33] Peregrinus, *Letter of Petrus Peregrinus,* 7.

> First, place an iron needle atop the spherical lodestone. Let the needle pivot to point in its natural direction. Extend the line of the needle around the globe, dividing it into two parts. Then, place a needle on another part of the lodestone and let the needle pivot. Again, extend the line of the needle around the globe. Find the intersection points of the lines you have drawn. These will correspond to the poles of the lodestone.[34]

The second method involves finding the places on the terrella where small pieces of iron stand upright:

> Second, select a small thin piece of iron about the length of two fingernails, or break a small piece off our iron needle. Place the piece of iron on the stone, and move it until it stands vertically upright. This will mark one of the poles above. Then, take a similar piece of iron and perform the same operation at the other end of the lodestone to find the opposite pole.[35]

The points of intersection for the needles, or the places on the terrella where small pieces of iron stand upright, are the poles of the terrella.

After he has explained how to identify a terrella's poles, Peregrinus explains how to demonstrate that the poles of a terrella turn to face the poles of the heavens. He instructs the reader to place a terrella into a floating dish, making sure that the dish does not touch the sides of the larger container it is in. He notes that when one does this, the dish will rotate in the water until one of the terrella's poles point to the north pole of the heavens (marked by the north star), and the other pole points to the south pole of the heavens.[36] He writes: "Since the north and south parts of the heavens are known, these same points will then be easily recognized in the stone because each part of the lodestone will turn to the corresponding part of the heaven."[37] Peregrinus notes further that when one turns the dish so that the poles of the terrella no longer point at the poles of the heavens, the dish will "return thereto a thousand times, as by natural instinct."[38]

Peregrinus next tells the reader to hold one terrella in each hand and try to bring them together, thereby demonstrating the ways magnetic poles attract and repel one another.[39] He later affirms that iron touched by a lodestone mimics a lodestone in having poles, turning towards the poles of the world, and attracting opposite poles of lodestone.[40]

These observations demonstrate a new and important aspect of magnetic attraction, which we will call pole phenomena or pole behavior. This distinctive behavior of poles is comprised of three core elements: the existence of poles of magnets (including in lodestones and magnetized

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[34] Peregrinus, *Letter of Petrus Peregrinus,* 7.
[35] Peregrinus, *Letter of Petrus Peregrinus,* 7-8.
[36] Peregrinus, *Letter of Petrus Peregrinus,* 8-9.
[37] Peregrinus, *Letter of Petrus Peregrinus,* 8-9.
[38] Peregrinus, *Letter of Petrus Peregrinus,* 8-9.
[39] Peregrinus, *Letter of Petrus Peregrinus,* 10-11.
[40] Peregrinus, *Letter of Petrus Peregrinus,* 12-13.

iron), the attraction of opposite poles and repulsion of similar poles of magnets, and the tendency for magnetic poles to rotate towards the poles of the world.

Peregrinus' Theory

In the final chapter of Part 1 of the *Epistola*, after presenting the preceding experiments and observations, Peregrinus proposes a theory to explain the observations. He argues that because the poles of a lodestone point to the poles of the heavens, the powers of the poles of a lodestone are derived from the poles of the heavens. He writes:

> Since the lodestone points to the south as well as to the north, it is evident from the foregoing chapters that we must conclude that not only from the north pole but also from the south pole rather than from the veins of the mines virtue flows into the poles of the lodestone. This follows from the consideration that wherever a man may be, he finds the stone pointing to the heavens in accordance with the position of the meridian; but all meridians meet in the poles of the world**; hence it is manifest that from the poles of the world, the poles of the lodestone receive their virtue**. Another necessary consequence of this is that the needle does not point to the pole star, since the meridians do not intersect in that star but in the poles of the world. In every region, the pole star is always found outside the meridian except twice in each complete revolution of the heavens. From all these considerations, **it is clear that the poles of the lodestone derive their virtue from the poles of the heavens.**[41]

Peregrinus adds further that this is true not only of the poles of the lodestone, but of the entire lodestone, so that the entire lodestone derives its powers from the entire heavens:

> As regards the other parts of the stone, the right conclusion is, that they obtain their virtue from the other parts of the heavens, so that we may infer that not only the poles of the stone receive their virtue and influence from the poles of the world, but likewise also the other parts, or the entire stone from the entire heavens.[42]

This theory of the behavior of the lodestone differs from theories of the ancients and has at least two virtues. First, it provides an explanation for the fact that lodestones and magnetized needles turn to face the poles of the heavens. Second, as we will later see, it is one adjustment away from Gilbert's later claim that lodestones are responding to the poles of the Earth, rather than the poles of the heavens; in fact, Gilbert's claim is naturally suggested by Peregrinus' theory, when Peregrinus' theory is confronted with the observations of magnetic dip and variation that would be made several centuries later.

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[41] Peregrinus, *Letter of Petrus Peregrinus,* 19-20. Emphasis added.
[42] Peregrinus, *Letter of Petrus Peregrinus,* 19-20.

An Erroneous Claim

There is one last part of Peregrinus' *Epistola* upon which we must remark. At the end of Part 1, in support of his claim that the entire lodestone derives its powers from the entirety of the heavens, Peregrinus describes a more complex experiment involving placing a terrella on pivots and aligning it with a meridian:

> You may test this in the following manner: A round lodestone on which the poles are marked is placed on two sharp styles as pivots having one pivot under each pole so that the lodestone may easily revolve on these pivots. Having done this, make sure that it is equally balanced and that it turns smoothly on the pivots. Repeat this several times at different hours of the day and always with the utmost care. Then place the stone with its axis in the meridian, the poles resting on the pivots. Let it be moved after the manner of bracelets so that the elevation and depression of the poles may equal the elevation and depressions of the poles of the heavens of the place in which you are experimenting. If now the stone be moved according to the motion of the heavens, you will be delighted in having discovered such a wonderful secret...[43]

Peregrinus claims that in such a configuration, a terrella will rotate along with the heavens. He adds, "...but if not, ascribe the failure to your own lack of skill rather than to a defect in nature."[44]

Unfortunately, this experiment does not work, Peregrinus' admonition notwithstanding. Gilbert himself tried to repeat it, and not observing the terrella rotate, wrote:

> I omit what Peter Peregrinus constantly affirms, that a terrella suspended above its poles on a meridian moves circularly, making an entire revolution in 24 hours: which, however, it has not happened to ourselves as yet to see.[45]

It is hard to explain why Peregrinus would include this erroneous claim, especially given the accuracy and care he displays elsewhere in the first book of his treatise. It is perhaps even more surprising that, despite Gilbert's failure to reproduce Peregrinus' result, Gilbert ended up proposing a theory of magnetism that accorded with that result.

Peregrinus' Contributions

The *Epistola* would later contribute to the study of magnetic attraction both directly and indirectly. It contributed directly to the understanding of magnetic attraction through the identification of the pole behavior of magnets. Peregrinus showed that lodestones have poles, that they rotate to face the poles of the heavens, that their poles attract and repel one another, and that needles magnetized by lodestones also turn to face the poles of the heavens.

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[43] Peregrinus, *Letter of Petrus Peregrinus,* 20-21.
[44] Peregrinus, *Letter of Petrus Peregrinus,* 21.
[45] Gilbert, *On the Magnet,* 223.

Peregrinus' work contributed indirectly by providing future researchers with an instruction manual, complete with an experimental tool (the terrella) and simple, reliable instructions for replicating important basic experiments. This would allow future researchers to build on Peregrinus' results, thereby contributing even further to the understanding of magnetic attraction.

Unfortunately, the fruit of Peregrinus' research would have to wait almost three centuries before being received. Although the *Epistola* was written in 1269 CE, it was not printed and widely circulated until 1558 CE. After that point, multiple researchers, including Sarpi, Norman, Porta, and Gilbert himself, would build on what Peregrinus had discovered.

Progress to this Point

With the findings of Peregrinus, presaged by the basic observation about magnetism provided by the compass, investigators were now substantially better positioned to draw the distinction between static electric attraction and magnetic attraction. This was first through the advances in the understanding of magnetic attraction as a distinct phenomenon, second through the buildup of magnetic knowledge that Gilbert would rely on in constructing the magnetic cosmological theory that would precipitate his investigation of gem attraction, and third through the improved prospects for future magnetic study, which would contribute to both of these.

With respect to the understanding of magnetic attraction, the identification of pole phenomena made it very plausible that lodestone attraction was a unified phenomenon, distinct from other phenomena. Amber and other gemstones did not clearly exhibit anything similar, as researchers would gradually discover.

With respect to the accumulation of magnetic knowledge that would help enable Gilbert to develop his magnetic theory of the Earth, several steps had been made. Apart from the identification of pole phenomena, Peregrinus' theory of lodestone attraction, his erroneous claim about the rotation of the terrella in concert with the heavens, and even the terrella itself (as the source of a potential analogy between the terrella and the Earth) would later help to suggest Gilbert's magnetic theory.

On the prospects for future magnetic study, there was the contribution of Peregrinus' *Epistola*, which provided a natural starting point for future researchers, aiding them in multiple ways. There was also the fact that lodestone attraction was much more plausibly an important phenomenon, worthy of direct study. Before the spread of compass use and the work of Peregrinus, lodestone attraction might have been dismissed as a curiosity. Now there was a link between lodestone attraction and the heavens, and this link was relied on in the everyday practice of mariners. This may have made the phenomenon of lodestone attraction appear more important, for both theoretical and practical purposes.

Most of these benefits would have to wait until the later publication of the *Epistola* to come to fruition. In the meantime, progress towards the discovery of electricks took the form of new observations collected by writers in the Renaissance.

Study of Electricity and Magnetism: Accumulation and Challenges, Part 2 of 2

Accumulation and Challenges in the Renaissance

Observations and Compilations

Starting in the first half of the 16th century CE, writers again took up the challenge of describing lodestone attraction and gem attraction.[46] These authors frequently wrote lengthy treatises in natural philosophy, mineralogy, or medicine, covering many topics and sometimes building on the writings of the ancients. In the course of these treatises, they touched on various aspects of magnetic and electric behavior.

In this section, we will discuss some of Gilbert's most relevant predecessors. We will first cover the most important three, Agricola, Fracastoro, and Cardano. For each, we will briefly describe their backgrounds, note their accurate and inaccurate claims about lodestone and gem attraction, and comment on how they contributed to the clarification or obscuration of the emerging distinction between lodestone and amber-like attraction. We will then discuss a few others, illustrating how, despite the contributions of Agricola, Fracastoro, and Cardano, false claims and confusion continued to arise.

Georg Agricola

Background — Georg Agricola was a physician and mineralogist. In 1544, he published *De natura fossilium*, a lengthy mineralogical text outlining the names and etymology, history, composition, sources, properties, and local uses of various stones and rocks. In nearly every section of *De natura fossilium,* Agricola provides an extensive overview of the views of his

[46] It is obviously not the case that no writers commented on amber and lodestone attraction between the ancient period and the Renaissance. However, on the whole, we have notably fewer records of novel contributions from this period (either due to a paucity of surviving texts or a decline in its study). A brief sampling of surviving claims from this period: Gilbert credits the Persian scholar Avicenna (980-1037 CE), called Abohalis at one point in text, with reporting that amber (called *carabe*) attracted chaff, while also perilously recommending a drachum's weight of lodestone dissolved in juice to cure iron poisoning. Gilbert, *On the Magnet,* 47, 35. Aldhelm (639-709 CE) also continued to propagate the myth that diamond interrupts magnetism. Rusche, *Aldhelm Scholia,* 439; Benjamin, *History of Electricity,* 115. For an interesting instance of novel observation mixed with misinformation, consider Albertus Magnus' proposal that there are two kinds of lodestone, one that points north and one that points south. This was an early record of the lodestone's affinity for poles, but incorrectly postulated two lodestone variants. Gilbert, *On the Magnet,* 7, under "Notes," 18-19. See also St. Isidore and Marbode of Rennes for further mentions of amber and the magnet in medieval scholarship.

historical predecessors. Agricola's work includes a section on amber (Book IV), a section on the lodestone (Book V), and a brief comment on jet's attractive behaviors.[47]

His section on amber, Book IV, is long and thorough. In it, he discusses amber's etymology, possible colors and shapes, differences from similar gems in appearance and name, uses (such as in jewelry and medicine), composition and origin in trees, and differences in appearance and property based on geographic region, and thoroughly recounts the views of the ancients on amber's properties and attractive powers.

Accurate claims — Agricola affirms the basic attractive effects of amber and the lodestone, and repeats Plato's observation that the lodestone transmits its power through iron rings.[48] He then combines Plutarch and Theophrastus' claims, stating that amber attracts all light objects including small pieces of metal.[49] Agricola also claims that jet attracts like amber, saying "amber and jet will attract chaff, hair, and straws."[50]

Inaccurate claims — Agricola claims that lodestone's attraction is canceled by garlic and diamond, repeating inaccuracies stated by the ancients.[51] He adds some inaccurate claims of his own, including that in a recent case, gray amber rubbed with iron attracted leaves from two feet away.[52] Agricola also affirms the ancient myth that there exists a counterpart to lodestone, theamedes, which repels iron, and joins the ancients in claiming that theamedes and lodestone are sometimes found in the same stone.[53]

Contributions — Agricola is the first writer we have found to identify that amber attracts everything light. He also recognizes the similarity between amber and jet. Agricola was stably referenced by later thinkers, including Cardano and Gilbert, both of whom affirm his claim that

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[47] Agricola, *De natura fossilium.*
[48] Agricola, *De natura fossilium,* loc. 387, loc. 1862.
[49] Agricola, *De natura fossilium,* loc. 1726. "Having been warmed by rubbing amber will draw and support feathers, chaff, balls, leaves and other small light substances in the same manner as lodestone attracts iron."
[50] Agricola, *De natura fossilium,* loc. 387. This quote ends "while some even acts as lodestone and will pick up light objects." This could be interpreted as an additional ambiguity, although "acts as lodestone" could also be taken to generally reference attraction.
[51] Agricola, *De natura fossilium,* loc. 1881, loc. 1890. "Lodestone will not attract iron that is covered with rust, impure iron or iron that has been smeared with the juice of onion or garlic" and "To no less degree, diamond resists its power. If a diamond is placed next to iron a lodestone cannot draw it or if iron has been attracted to the stone as soon as a diamond is placed along side of it the iron will drop."
[52] Agricola, *De natura fossilium,* loc. 1731. "Recently some gray amber was dug up on the beach near Puceca on this side of the Vistula which, when rubbed with iron, would draw leaves that had fallen to the ground even when held in the hand a distance of two feet above them." We presume that this did not occur as described, unless the electrical effect was unusually strong.
[53] Agricola, *De natura fossilium,* loc. 387, 1896, 1901; Sander, "Magnetism and Theamedism." "Lodestone attracts iron while theamedes repels it," "Theamedes has the opposite power to lodestone since the latter attracts iron, the former repels it," and "Even today stones are found composed in part of lodestone, in part of theamedes." The invention of theamedes might have been used to explain the lodestone's repulsive effects.

amber attracts all light things.[54] It is plausible that Agricola's work also helped future researchers by making it easier for them to correctly distinguish amber from other gemstones in nature and in previous author's texts.

Girolamo Fracastoro

Background — Girolamo Fracastoro was a physician and scholar. He taught logic and anatomy at the University of Padua, wrote medical poetry (publishing the famous *Syphils sive Morbus Gallicus* in 1530), and studied astronomy (publishing *Homocentrica* in 1538).[55] His other works feature biblical poetry, a description of a rudimentary telescope, and analyses of sedimentary rocks, plants, the temperature of wines, the rise of the Nile, and the nature of the mind and soul.[56]

In 1546, Fracastoro published *De contagione et contagiosis morbis*, a medical text on contagious disease and syphilis.[57] As a preface to this work, he included *De sympathia et antipathia rerum* (On Sympathy and Antipathy), a 41-page description and theory of attractive behavior.[58]

Accurate claims — Fracastoro correctly identifies that diamond attracts like amber.[59] He also identifies that amber attracts small bits of amber: "moreover, [rubbed] amber snatches up little pieces of amber."[60] This matches the correct position that amber attracts all small objects, not just leaves and chaff.

Inaccurate claims — Fracastoro claims that lodestone attracts silver.[61] He also claims that lodestones are attracted by magnetick mountains, rather than rotating to face the poles of the Earth or the heavens.[62] Finally, Fracastoro makes the misleading claim that "[rubbed] amber

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[54] Gilbert references Agricola seven times in *De magnete.* Cardano references him 18 times in *De Subtilitate.*
[55] Pesapane, Marcelli, and Nazzaro, "Hiieronymi Fracastorii."
[56] Winslow, *The Conquest of Epidemic Disease,* 127.
[57] *Syphils* and *De Contagione* were central to Fracastoro's studies. *De Contagione* includes the theory that many diseases are caused by chemical *seeds* (or germs, without the connotation of living organisms) transmitted from person to person, with each disease having a different seed and different seeds being weakened to different degrees by environmental conditions. These seeds cause chemical (putrefactive) change in the receiving person's physical tissue, thereby causing the disease symptoms. Fracastoro's theory also touched on different contagion conditions for different diseases, and suggested that some diseases require an "analogy" in the physical tissue of the receiver to take root. Winslow characterizes this theory as "the first really philosophical statement of the contagionistic theory of disease—a mountain peak in the history of etiology perhaps unequalled by any writer between Hippocrates and Pasteur." Winslow, *The Conquest of Epidemic Disease,* 142-143.
[58] Counted from Fracastoro, *De sympathia et antipathia rerum* (1574).
[59] Gilbert, *On the Magnet,* 50; Fracastoro, *De sympathia et antipathia rerum* (1574), C.
[60] Fracastoro, *De sympathia et antipathia rerum* (1574), 62C-D; Assis, *Foundations of Electricity,* 1:34. This position may have also generated confusion, leading readers to believe that amber attracts itself in a way analogous to how lodestone attracts itself.
[61] Gilbert, *On the Magnet,* 110.
[62] Gilbert, *On the Magnet,* 5.

attracts to itself not only straws and chaff, but also silver."[63] Rubbed amber can attract small bits of silver, but not pieces of silver in general.

Contributions — Fracastoro is the first writer we found who observes that diamond attracts like amber. This added to the growing list of accurate reports of gems with amber-like attractive effects that Gilbert had access to, and was repeated by Gartias da Orto and Levinus Lemnius.[64]

Other — In addition to his above contribution, Fracastoro invented an instrument called the *perpendiculo*, which may have aided research into amber-like attraction. Fracastoro also held the doctrine of similitudes; we will discuss both of these things in the sections below.

Girolamo Cardano

Background — Girolamo Cardano had wide-ranging talents and has aptly been described as a physician, astrologer, natural philosopher, and mathematician.[65] In the 1550s, he published *De subtilitate* and *De rerum varietate*. These texts cover a wide range of topics, including astronomy, geometry, earthly elements, animals, metals, stones, light, plants, psychology, the soul and intellect, occult phenomena, demons, and God.[66] In the course of covering these topics, Cardano devotes a few pages to the behavior of lodestone, amber, and other gems.

Accurate claims — Cardano cites and affirms Agricola's claim that amber attracts everything light. Cardano writes, "it attracts everything light—straws, stalks, thin metal scrapings, and leaves of basil," which specifically denies Plutarch's ancient myth that amber does not attract basil.[67] He describes the pole behavior of lodestones, notes that lodestones do not rotate to face true north, and uses pole behavior to explain the repulsive power of lodestones.[68] He also denies the existence of theamedes, and denies the ancient myths that onion, garlic, and diamond can cancel the lodestone's power.[69]

Cardano later explicitly distinguishes amber and lodestone behaviors in a rapid-fire list of contrasts, writing:

> The lodestone and amber do not in fact attract on the same basis; amber attracts anything light, the lodestone only attracts iron. When something is in between, amber does not

[63] Fracastoro, *De sympathia et antipathia rerum* (1574), 62C; Assis, *Foundations of Electricity,* 1:34.
[64] Gilbert, *On the Magnet,* 50, under "Notes," 39. For Lemnius' comment, Thompson points to *Occulta naturæ miracula* (English edition, London, 1658, p. 199), which was first published in 1559, 13 years after Fracastoro wrote.
[65] Cardano, *De Subtilitate* (2013), under "Introduction," xi.
[66] Cardano, *De Subtilitate* (1550); Cardano, *De Subtilitate* (2013); Cardano, *De rerum varietate* (1558).
[67] Cardano, *De Subtilitate* (2013), 1:306.
[68] Cardano, *De Subtilitate* (2013), 1:412-413. Cardano notes magnetic variation here, a topic we will revisit when studying magnetic development. He proposes that compass needles point five degrees away from geographic north.
[69] Cardano, *De Subtilitate* (2013), 1:414, 412. From 412, he writes, "And, contrary to the fables, it is not obstructed by garlic or onions, much less by diamond."

> move a straw, but a lodestone does move iron. Amber is not attracted in turn by a straw, but lodestone is attracted by the iron too. A straw is not moved in a particular direction, but on contact with a lodestone, iron makes now for the north and now for the south. Finally, amber's attraction is much assisted by warmth and friction, but a lodestone's only by a portion of the lodestone being made purer.[70]

These claims are largely true.[71] Lastly, Cardano claims that amber attracts after being rubbed with wool or linen, while other gemstones attract after being rubbed with wool but not with linen.[72] This claim may be true, depending on the details of the materials to which Cardano was referred.[73]

Inaccurate claims — Cardano incorrectly asserts that every gemstone attracts chaff, writing, "The evidence is that every gemstone when rubbed with a woolen cloth attracts both straws and dry leaves to itself."[74] As Gilbert would later establish, it is not true that every gemstone attracts when rubbed. Cardano argues that fire has an attractive effect, and amber's attraction is due to heat, just like fire.[75] Gilbert later disputes the claim that fire has an attractive effect.[76] Cardano also repeats the likely false claim of Agricola's about gray amber.[77]

Contributions — Cardano appears to be the first of Gilbert's sources to contrast lodestone attraction and amber attraction directly and at length, carefully distinguishing their opposing

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[70] Cardano, *De Subtilitate* (2013), 1:306.

[71] There are some inaccuracies in this list, though they are relatively minor. First, amber is in fact mutually attracted by chaff, though it will be many years before this is realized. Gilbert also makes this mistake. Second, Cardano is correct about the lodestone's attractive behavior with respect to the materials that were known to scholars at the time, though there are other things that lodestone attracts, such as nickel, that were not yet known.

[72] Cardano, *De Subtilitate* (2013), 1:306. He also offers a theory to explain the differences: "The reason for this [amber attracting light objects] is that moistness has fatness and stickiness, and when that is sent out, the moistness moves towards anything light, as fire too does to fuel; hence if it [amber] is rubbed, it attracts rather vigorously, on account of the heat too. The evidence is that every gemstone when rubbed with a woolen cloth attracts both straws and dry leaves to itself; when they have stuck, they are in motion; because the fattiness lurking in the wool is attached to the gemstone and warms up with rubbing; but in amber it is dissolved. Hence gemstones do not attract on rubbing with linen, but amber does."

[73] This depends on the triboelectric rankings of the materials to which he was referring. For more on triboelectric rankings, see Appendix C. Possible rankings that might display this effect, positive (left) to negative (right), include: (1) Linen, Gemstones, Wool, Amber; (2) Gemstones, Linen, Wool, Amber. Given the knowledge at the time, the results of rubbing with different materials was likely confusing. No previous thinker had delved into this, and the first triboelectric ranking was not produced until 1757 CE by John Wilcke.

[74] Cardano, *De Subtilitate* (2013), 1:306.

[75] Cardano, *De Subtilitate* (2013), 1:306-7. "...The conclusion?—The attraction of amber is surely like that exerted by a cupping glass from the fire and other hot things, because of that well-known innate heat, which sticks to room walls, as I said, and makes rooms smell nice even till the third day. In every bitumen there is actually the fatty hot moistness, which makes it burn readily too. But for attracting, choose amber among the bitumens..."

[76] Gilbert, *On the Magnet,* 49-50.

[77] Cardano, *De Subtilitate* (2013), 1:307. "But for attracting, choose amber among the bitumens, and the ash-colored amber among the kinds of amber, the one that is dug out on the mouth of the Vistula at Puceca on the seashore; it, as Agricola reports, when rubbed with iron attracts leaves from the ground to itself two feet up in the air."

features.[78] He appears to be the first to explicitly point out that interposing something will block the amber's attractive effects, but not the attractive effects of the lodestone. Gilbert was familiar with these claims.[79]

Other — Apart from the above contributions, Cardano also invented an instrument, a magnetized silver needle, which may have aided his research into amber attraction and attraction by other gems. We will examine this more in the next section.

After Cardano

Between Cardano and Gilbert, writers continued to add new claims, some true and some false, while largely ignoring Cardano's list of differences between amber and lodestone attraction.

One such writer was Julius Scaliger, a physician and defender of Aristotle. Scaliger published a critique of Cardano in 1557 entitled *Exotericarum exercitationum liber XV, de subtilitate, ad hieronymum cardanum*. In its 1,129 pages devoted to Cardano, Scaliger does not mention Cardano's observations about lodestone and amber or make useful observations about them himself. He instead adds a misleading, but perhaps true, claim of his own: that diamond attracts iron.[80] (Diamond only attracts small bits of iron; Scaliger does not mention this.)

Another such writer was Garcia da Orto, a Portuguese Jewish doctor who studied for thirty years in India. In his *Historia dei Semplici Aromati*, a treatise published in 1563 on the medicinal use of plants, da Orto reiterates Fracastoro's true claim that diamond attracts straw when rubbed, but adds the false claim that two diamonds, when joined together, cannot be separated.[81]

A third was Giambattista della Porta. Porta was an Italian natural philosopher who wrote a twenty-book treatise called *Magiae Naturalis*, originally published in 1558 when Porta was sixteen years old, and later extended in 1589.[82] Porta's work is important primarily for his work on lodestone attraction, attempting to extend Peregrinus' research. He does touch on the

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[78] For an earlier suggested contrast between lodestone and amber attraction, see Ficino, *Book of Life*, 133: "We see how sailors on watch use a magnet with a needle balanced to move to the Bear Star as an indication where the Pole is, the magnet drawing them there, because the power of the Bear Star is still in this stone. It is transferred into the iron, drawing both back to the Bear Star. This power is infused into it from the beginning, but it is also continuously fed by the rays of the Bear Star… Amber, perhaps, does the same for the other Pole." However, Ficino's passage does not reveal much commitment to the distinction, nor any relevant observation.
[79] Gilbert, *On the Magnet,* 49-50. Gilbert summarizes the theories Cardano gives immediately before and after his list of differences between amber and the magnet, providing strong indication that he knew of Cardano's list.
[80] Gilbert, *On the Magnet,* 112.
[81] Gilbert, *On the Magnet,* under "Notes," 38. Thompson writes that on page 200 of the Venetian 1616 edition of *Historia*, da Orto says: "Questo si bene ho sperimentato io più volte, che due Diamanti perfetti fregati insieme, si vniscono di modo insieme, che non di leggiero li potrai separare. Et ho parimente veduto il Diamante dopo di esser ben riscaldato, tirare à se le festuche, non men, che si faccia l'elettro."
[82] Benjamin, *History of Electricity,* 230.

foregoing topics though, correctly denying the myth that garlic destroys lodestone attraction, while falsely claiming that diamond can magnetize iron.[83]

These additions simultaneously clarified some aspects of gemstone attraction, while adding misinformation that obfuscated the distinction between magnetick and electrick attraction.

Suggestions of Instruments

As some writers made progress collecting correct observations about lodestone attraction and amber-like attraction, and working to distinguish the two, another type of progress was accumulating: progress on instruments that could suggest the possibility of an instrument for detecting the attractive powers of amber and other materials. These hints of electrical instruments may have inspired Gilbert's creation of his own instrument for detecting electric effects: the versorium, a pivoted needle that spins toward rubbed electricks.

We will briefly discuss two such instruments, Fracastoro's *perpendiculo* and Cardano's purported magnetized silver rod. Gilbert himself did not have access to either instrument and instead was relying on Fracastoro's and Cardano's descriptions. Those descriptions were themselves either ambiguous or dubious, at best suggesting the possibility of an instrument that would detect amber attraction. We will also briefly remark on the compass and how it too might naturally have suggested such an instrument.

Perpendiculo

In his *De sympathia et antipathia rerum*, Fracastoro mentions using an instrument called a *perpendiculo* in his experiments. He describes this in a single ambiguous passage:

> In fact we, in the presence of several of our medical doctors, have made experiments of many things with a perpendiculo which is well adapted as in a marine compass, and have observed how a magnet attracts another magnet, [magnetized] iron [attracts] iron, due to the fact that a magnet attracts iron and the iron [attracts] the magnet; moreover, [rubbed] amber snatches up little pieces of amber... and, likewise, [rubbed] amber attracts to itself not only straws and chaff, but also silver.[84]

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[83] Porta, *Natural Magick,* bk. 7:chap. XLVIII, LV; Gilbert, *On the Magnet,* 143; Benjamin, *History of Electricity,* 297.

[84] Fracastoro, *De sympathia et antipathia rerum* (1574), 62C-D; Fracastoro, *De Sympathia et antipathia rerum (*1550), 69-70; Assis, *Foundations of Electricity,* 1:34; translation and original passage from *Foundations and Electricity* and modified by J. L. Heilbron in personal correspondence in March 2020. Original: "Nos enim praesentibus multis è nostris medicis experientiam multorum fecimus, perpendiculo bene & concinne aptato, quale est in nauigatoria pyxide, ac manifeste vidimus magnetem trahere magnete, ferrum ferrum, tum magnetem trahere ferrum, ferrum magnetem. porro electrum parua electri frustula rapere, argentum attrahere argentum, &, quod valde mirati fuimus, magnetem vidimus argentum trahere: item Electrum non solum surculos & paleas mouere ad se, sed & argentum."

Scholars have interpreted this passage in a variety of ways. Given the Latin meaning of the word perpendiculo ("perpendicular") and Fracastoro's description, some propose that the perpendiculo functioned like a plumb-line.[85] On this interpretation, a test object would be placed on a vertical thread and allowed to move towards rubbed amber brought in its vicinity; if the object on the thread moved, it was attracted by the rubbed amber.

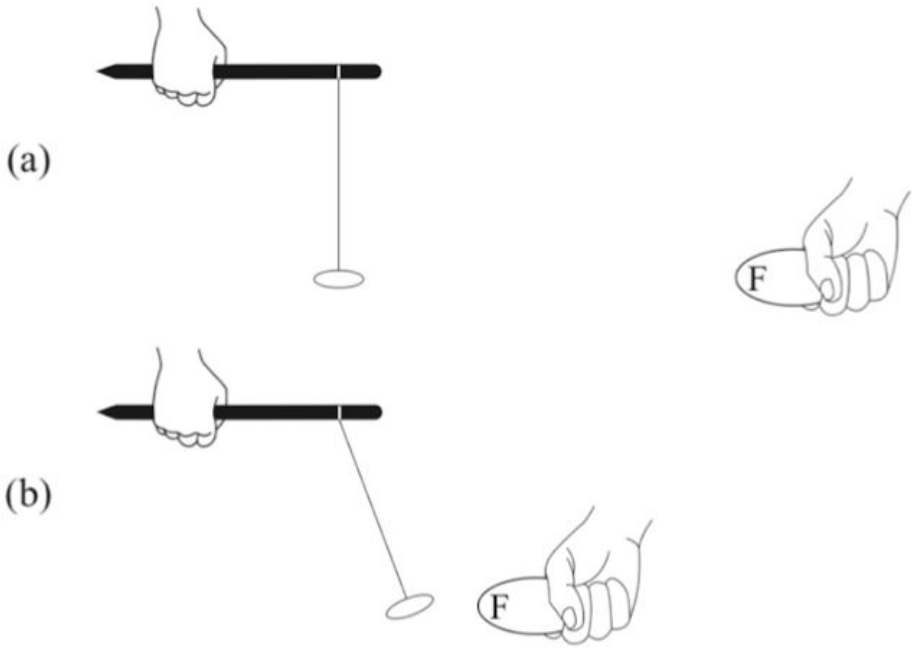

Figure 2. Assis' depiction of Fracastoro's *perpendiculo*.[86]

This interpretation leaves puzzling why Fracastoro describes the perpendiculo as "well adapted as in a mariner's compass." Plumb-lines did not appear in mariners' compasses, which function instead by a pivoted needle magnetized by a lodestone.[87]

Another proposal is that the perpendiculo is a horizontal metal needle, hung from a plumb-line.[88] This interpretation retains the straightforward interpretation of perpendiculo as a plumb-line and explains the phrase "which is well adapted as in a mariner's compass" by reference to the posited horizontal metal needle. This interpretation leaves it unclear why Fracastoro used a plumb-line, rather than simply creating a pivoted needle, like a compass. Additionally, when Fracastoro

[85] Assis, *Foundations of Electricity,* 34; Saslow, *Magnetism, Electricity, and Light,* 68. A plumb-line is a vertical hanging thread with a weight at the bottom.
[86] Assis, *Foundations of Electricity,* 1:35.
[87] May, "History of the Magnetic Compass," 211-214. For a description of how to make a mariner's compass, see Peregrinus' compass instructions.
[88] J. L. Heilbron, personal correspondence to the author, March 17, 2020.

mentions amber in the passage, he writes: "moreover, [rubbed] amber snatches up little pieces of amber… and likewise, [rubbed] amber attracts to itself… straws and chaff." If the passage is to be understood as relating the perpendiculo to these claims, it seems the perpendiculo should be used to detect amber snatching up little pieces of amber. It is unclear how a horizontal metal needle on a plumb-line would do this.

The perpendiculo might also be understood to be simply a metal pivoted needle, as in a mariner's compass, but used to detect amber attraction.[89] This is in fact the design of Gilbert's *versorium*, leading some scholars to propose that Gilbert copied the versorium from Fracastoro. Gilbert was extensively familiar with Fracastoro's work and, in *De magnete*, quotes a passage from the same page in which Fracastoro mentions the perpendiculo.[90] This interpretation, however, leaves the use of the word *perpendiculo* unexplained and still does not show how the instrument might detect amber's ability to attract amber or small bits of chaff.

A final possibility is that Fracastoro used a magnetized needle to detect lodestone attraction only, and not amber attraction. On this interpretation, Fracastoro's description of amber attraction is the beginning of a new comment, rather than a continuation of the previous comment. If this is correct, the perpendiculo was not actually used to detect amber attraction at all.

On some of these interpretations, Fracastoro had designed a special instrument for the detection of amber attraction. On others, Fracastoro had not, and instead had merely left behind an ambiguous text. Even an ambiguous text, however, might have suggested to Gilbert and other readers of *De sympathia et antipathia rerum* the possibility of using an instrument to detect amber attraction. If Fracastoro had an instrument for detecting amber attraction and word of this somehow reached Gilbert, or if Gilbert spent time trying to interpret Fracastoro's text, the perpendiculo may have suggested to him the idea to create an instrument for detecting amber attraction.

Magnetized Silver Rod

Whereas Fracastoro's description was ambiguous, Cardano's seems to be false. He writes:

> There is a certain kind of magnet which attracts silver: if therefore a little rod of silver has been affected by this [kind of magnet], and has been placed where it can rotate, it will be turned towards silver, especially a lot of it, even though buried.[91]

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[89] Heilbron, *Electricity in the 17th and 18th Centuries,* 175.

[90] Fracastoro, *De sympathia et antipathia rerum* (1574)*,* 62; Fracastoro, *De sympathia et antipathia rerum* (1550)*,* 69-70; Gilbert, *On the Magnet,* 50. The passage introducing the perpendiculo is from page 62 section C-D of *De sympathia et antipathia rerum (*1574); Gilbert criticizes Fracastoro's passage on amber, diamond, and sympathies, which appears on page 62 section C of the same.

[91] Cardano, *De rerum varietate*, 783. Translated by John Henry in personal correspondence in September 2020. The original Latin: "Est autem magnetis quoddam genus, quod argentum trahit: si ergo tenuis virgula ex argento eo infecta fuerit, ubi versatilis constituerit, ad argentum, praesertim multum, licet sepultum, convertetur." Or: "So

This passage describes a silver rod magnetized by a silver-attracting lodestone that would turn towards large quantities of silver.

Unfortunately, we know of no such silver-attracting lodestone, and a silver rod struck with a typical lodestone would not work to detect buried silver by an electrical or magnetic mechanism. Electric attraction would likely have a very limited range, would only work if the target deposit of silver had acquired and retained excess charge, and would render the magnetization by the lodestone superfluous. Magnetic attraction would also not work, as silver is not ferromagnetic and would not magnetize.[92]

While Cardano's description is dubious, it does still suggest the idea of a pivoted instrument that could be used to detect something other than poles, lodestone, or iron. It thus is a second description of a device that might have prompted the idea of an instrument for detecting amber attraction.

Compasses

In addition to the above instruments, Gilbert was also familiar with compasses. Compasses had become widespread, and Gilbert used them in his own magnetic research. While no previous thinker reports approaching amber or other gems with a compass, the prevalence of compasses, as well as the use and usefulness of compasses in magnetic experiments, certainly may have suggested to Gilbert the idea of an instrument that could detect amber attraction.

So, the list of instruments with potential correlates for detecting electrical effects grew.

Doctrine of Similitudes

While true claims and promising leads in electrical study had begun to accumulate, there were a number of factors that muddied the water. In addition to the continuing misinformation, the theoretical views held at the time also sometimes posed problems. One theory in particular stands out as a potential source of trouble: the doctrine of similitudes, or doctrine of signatures.

This doctrine had a long history in medicine, with early mentions dating back to China and India prior to 2000 BC. In ancient Greece and Rome, hints of the doctrine are visible in Pliny, Dioscorides, and Galen.[93] In the century before Gilbert, it was held by notable magnetic and

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Cardan (perhaps deceived by others) says that there is a certain kind of loadstone which draws silver; he adds a most foolish test of this: 'If therefore' (he says) 'a slender rod of silver be steeped in that in which a versatory needle has stood, it will turn toward silver (especially toward a large quantity) although it be buried.'" Gilbert, *On the Magnet,* 110.

[92] See Appendix C for a summary of the relevant science.

[93] Bennett, "Doctrine of Signatures," 248.

electric theorists like Fracastoro and Porta, and Gilbert devotes several paragraphs of his introduction of electricks to its refutation.[94]

Originally, the doctrine of similitudes held that the appearance or properties of particular plants reveal their medicinal function, perhaps by mimicking the organs or other physical parts they influence. For instance, a red plant might influence the blood.[95] In Renaissance attractive theory, the doctrine was expanded to propose that in general, like attracts like. This version was applied to evident attractions, and a similarity between the two bodies involved was then sought. During this process, the doctrine was sometimes taken to rely on visible similarity and sometimes appealed to underlying similarity of composition, predisposition, or form. For example, after Fracastoro noticed that diamond and amber attracted hair, he proposed an underlying hidden similarity between all three.[96]

Ideally, if a theorist espousing the doctrine postulated that two objects attracted on the basis of their internal wetness, they might search surrounding objects for internal wetness and predict attraction in those cases. If such attraction was not found, this might lead them to refine the theory. Instead, in some cases, thinkers using the doctrine of similitudes would propose axes of similarity whereby objects might attract, and then seem not to test predictions on the basis of the posited similarities and perhaps later offer incompatible explanations in the same text.[97] This less structured application of the doctrine may have stopped these thinkers from accumulating a thorough catalog of attractive behaviors and developing a crisp set of underlying distinctions between attractive forces. A wider analysis of the application of the doctrine of similitudes in Renaissance magnetic study would be fruitful for understanding how common this application of the doctrine was, as well as the degree to which its use posed problems in practice.

Progress to this Point

Through the efforts of a few writers, the distinction between static electric attraction and magnetic attraction was now coming into view. Some noted the attractive effects of additional gems, and the claim that amber attracts all light objects had begun to gain acceptance. Cardano specifically distinguished the different behaviors of amber attraction and lodestone attraction, contrasting them along several dimensions and adding important new descriptions; this research

[94] Gilbert, *On the Magnet,* 50; Fracastoro, *De sympathia et antipathia rerum* (1574), 62C; Lev, "Doctrine of Signatures," 14; Bennett, "Doctrine of Signatures," 248.
[95] Bennett, "Doctrine of Signatures," 246.
[96] Gilbert, *On the Magnet,* 110.
[97] Potential instances are visible in Fracastoro, Porta, and Neckam's magnetic work. See Gilbert, *On the Magnet,* 110, 63 and Benjamin, *History of Electricity,* 127-128, 241.

arguably marked the high point of the efforts of all observers to date to recognize and compare the properties of lodestone and amber.[98]

Beyond the accumulation of observations and the new focus on distinguishing the types of attraction, there was also progress in the development of instruments, or in the reports of such developments. Two new instruments, the perpendiculo and the purported magnetized silver rod, joined the compass in potentially suggesting the idea of creating an instrument for detecting attraction by amber or other gems.

Despite this progress, there were still difficulties. Possibly aided in part by the doctrine of similitudes, false claims continued to circulate, and new myths were invented even as old myths were struck down. As we saw above, for instance, Fracastoro proposes that lodestone and rubbed amber can attract silver (implying in the case of amber that this is not just for small bits of silver), Cardano says that every gemstone attracts chaff, da Orto claims that diamonds when joined cannot be separated, Scaliger claims that diamond attracts iron, and Porta claims that diamond can magnetize iron. In addition to decreasing the perceived trustworthiness of any of the claims of the authors, these false claims directly confounded the distinction between magnetick and electrick attraction: what was being uncovered was, at the same time, being covered back up.

On this background of promise and confusion, with Cardano at its peak, the next steps in electrical development came from further progress in the independent study of magnetism rather than the combined study of amber, lodestone, and other gems.

Study of Magnetism: Independent Developments, Part 2 of 2

The Spread of Peregrinus' Research Program

Although Peregrinus' *Epistola de Magnete* was written in 1269 CE, it was not published during his lifetime and was not well known. Centuries later, in 1558 CE, Achilles Gasser published the *Epistola*, and it widely circulated. This sparked a new phase in the development of knowledge of lodestone attraction, including three primary contributors: Robert Norman, Fra Paolo Sarpi, and Giambattista della Porta. These writers helped to solidify magnetism as an independent field of study while accumulating further observations about the behavior of the lodestone.

[98] This was not yet a distinction between electricks and magneticks, as Cardano distinguished amber attraction and attraction due to other gems, and also had not yet recognized that not all gems attract. He also did not postulate two distinct categories; he simply described and contrasted amber and lodestone behavior. This meant that he had not successfully identified amber-like attraction as the key phenomenon, and counterposed it to magnetic attraction.

Robert Norman

Robert Norman was a mariner and compass maker, who greatly helped the study of the magnet. He replicated and expanded an experiment of Peregrinus, and identified two important new magnetic phenomena.[99] He published the results of his work in 1576 in a book entitled *The Newe Attractive*. This work was well received: prior to Gilbert's publication of *De magnete* in 1600, *The Newe Attractive* was reprinted three times.[100] Gilbert himself, not one to give praise lightly, refers to Norman as "a skilful seaman and ingenious artificer," and refers to his work five times in *De magnete*.[101]

Here, we will discuss Norman's discovery of magnetic dip, his identification of the magnetic verticity, and his theory of the *point respective*.[102]

Magnetic Dip

Given the evidence available at the time, one might expect that a magnetized compass needle would rotate to face the poles, remaining tangent to the Earth's surface as it did. In his work making compasses, Norman found instead that magnetized compass needles, once magnetized, would tilt downward. The effect was sufficiently large to affect the design of the compasses he was working on:

> Havying made many and divers compasses and using alwaies to finish and ende them, before I touched the needle, I found continually, that after I had touched the Irons with the Stone, that presently the North poinct thereof would bende or *Decline* downwards under the Horizon in some quantitie: in so much that to the Flye of the Compasse, which before was made equall, I was stil constrained to put some small peece of Ware in the South part thereof, to counterpoise this *Declining*, and to make it equall againe.[103]

This phenomenon is now known as magnetic dip or magnetic inclination. After ignoring the discovery for a period of time, Norman was commissioned to build a compass needle "sixe ynches long." At this length, the dip was noticeable and problematic. Norman attempted to trim

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[99] Porta's work includes a similar experiment, likely also taken from Peregrinus; Norman may have been inspired by Porta's version rather than Peregrinus'.
[100] Henry, "Animism and Empiricism," 100.
[101] Gilbert, *On the Magnet,* 5, 8, 153, 161-162.
[102] Magnetic dip may have been noticed earlier by Georg Hartman in 1544; see Benjamin, *History of Electricity,* 211. Norman makes no reference of Hartman in his text, however, and describes stumbling upon the phenomena independently. Gilbert also does not reference Hartman, and credits Norman with the discovery of dip; Gilbert, *On the Magnet,* 8.
[103] Henry, "Animism and Empiricism," 104.

the needle down to correct it, which ended up spoiling the whole work. Upset by this ("strochen into some color"), Norman set himself the task of explaining the effect.[104]

To investigate the phenomenon, he designed an experiment. He modified an iron needle so it could move in a vertical plane, like the hand on a mounted clock. He overlaid a 360-degree marked vertical circle, and measured how far below or above the horizontal his needle moved when magnetized. While located in London, the needle dipped to 71 degrees and 50 minutes below the horizontal, confirming the reality of the phenomenon.[105]

Magnetic Verticity

Extending Peregrinus' experiment with the rotating dish, Norman placed a magnetized needle on a floating cork in a round tub and let it rotate in the water. He then observed that while the cork rotates to face north, it does not move north.[106] The needle pivots to change its angle, but does not change its position in the tub. From this, Norman concluded that poles do not attract lodestone or magnetized iron, but instead have a rotational effect. (Gilbert would refer to this as the verticity of the magnet.)[107]

Pointe Respective

Norman attempts to explain the phenomenon of magnetic dip and the rotational behavior of magnetized needles by postulating a *pointe respective*, a point that magnetized needles turn to point towards, both horizontally and vertically.[108] On this theory, one could conceivably use measurements of dip and needle rotation to locate the *pointe respective*.

These observations further clarified magnetic behavior and differentiated it from amber attraction, while also, as we will see, inspiring Gilbert's magnetic cosmological theory. Norman's work was soon followed by others, who continued to expand on Peregrinus' basic discoveries and develop a picture of magnetic phenomena.

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[104] Henry, "Animism and Empiricism," 104.
[105] Henry, "Animism and Empiricism," 110.
[106] Peregrinus observed that the magnet rotated north, but, unlike Norman, did not take care to note that it did not move closer to the northern end of the water-filled vessel. As a result, Peregrinus did not clearly distinguish attraction from rotation towards the poles.
[107] Gilbert, *On the Magnet,* vj, 132, 162-163. Verticity: polar vigor, a turning tendency. See also Gilbert's disponent power of the magnet.
[108] Henry, "Animism and Empiricism," 110; Gilbert, *On the Magnet,* 5, 153, 162, under "Notes," 56. Thompson quotes Norman: "Your reason towards the earth carrieth some probabilitie, but I prove that there be no *Attractive*, or drawing propertie in neyther of these two partes, then is the *Attractive* poynt lost, and falsly called the poynt *Attractive*, as shall be proved. But because there is a certayne point that the Needle alwayes respecteth or sheweth, being voide and without any *Attractive* propertie: in my judgment this poynt ought rather to bee called the point Respective ... This Poynt *Respective*, is a certayne poynt, which the touched Needle doth alwayes *Respect* or shew …"

Fra Paolo Sarpi

Fra Paolo Sarpi was a historian, natural philosopher, statesman, canon lawyer, and monk in the Augustinian Servite order, who made important discoveries on the circulation of blood, the uvea of the eye, refraction, heat, similarities of the sun and stars, and more.[109] Working in the second half of the 16th century, Sarpi apparently studied both magnetic phenomena and other natural phenomena extensively. The works attributed to him include a treatise with 140 individual propositions on the lodestone, along with some scattered notes and a treatise on natural philosophy with 674 propositions on a variety of natural phenomena.[110]

Unfortunately, Sarpi's work on the lodestone was lost when the monastery that stored it burned down.[111] According to a report, it is plausible that Sarpi had access to Peregrinus' *Epistola* as well as Norman's discoveries, and had himself discovered a number of new and important phenomena about lodestone attraction. These included: that the attractive power of a lodestone increases with size, that fire destroys lodestone's attractive power, and that there is an "atmosphere" of magnetic activity around the poles of a lodestone (indicating a first recognition of magnetic force lines).[112]

What little evidence survives of Sarpi's work indicates that he too contributed to magnetic study, developing the understanding of the magnet separate from its amber counterpart. Sarpi's work may have also concretely influenced later magnetic researchers, including Gilbert, who was himself in personal contact with Sarpi and so may have learned of these discoveries, and Porta, who acknowledges Sarpi's research in the introduction to his book on magnetism.[113]

Giambattista della Porta

Giambattista della Porta was a natural philosopher and playwright who ran a secret scholarly society called Accademia dei Segreti (or Otiosi), whose membership required publishing an original work in philosophy or medicine.[114] Like Sarpi, he worked in the second half of the 16th century, compiling and extending the works of many researchers, and authoring a massive volume entitled *Natural Magick*. This work was 20 books long, the seventh of which was

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[109] Benjamin, *History of Electricity,* 225.
[110] Benjamin, *History of Electricity,* 225. The contents of Sarpi's works are reported in a biography of Sarpi written by Griseliui in 1760 CE.
[111] Benjamin, *History of Electricity,* 225. Sarpi's works were housed at the Servite Monastery, where they had been catalogued and arranged in order by Guiseppi Bergantini. The monastery burned down in 1766. Sarpi's religious and political texts survived, as apparently did a copy of his book on natural phenomena.
[112] Benjamin, *History of Electricity,* 226-228. Benjamin describes a copy of Sarpi's book on natural phenomena that survived and was located at the Library of St. Mark in Venice. Benjamin was writing in the late 19th century; we have thus far been unable to confirm the continued existence of this copy.
[113] Gilbert, *On the Magnet,* under "Notes," 16-17; Porta, *Natural Magick,* bk. 7:"The Proeme".
[114] Benjamin, *History of Electricity,* 230-231.

entitled *The Wonders of the Lodestone*. In its 56 short chapters, Porta extends Peregrinus' and Sarpi's work, including many claims and some experimentation.[115]

Porta's work on the lodestone includes a number of correct claims, interesting experiments, and important errors. Some were original, and some were drawn from others. He affirms the lodestone's pole behavior, repeats Peregrinus' instructions for finding a lodestone's poles, acknowledges the lodestone's basic attractive and repulsive properties, repeats Sarpi's observation that large lodestones typically attract more strongly, and repeats Plato's observation that the lodestone transfers its virtue to create strings of iron.[116] He measures the strength of lodestone attraction with distance, suspends magnets and causes iron anchored with thread to levitate, uses iron filings to investigate the magnetic atmospheres around poles, splits lodestones to understand the strength of the pole behavior of their parts, and so forth.[117] In addition to these correct claims and new experiments, his work also included a number of inaccuracies, which Gilbert responds to in detail.[118] These may have arisen from Porta himself, or from others whose conclusions he was compiling.

In many ways, Porta serves much the same role as Sarpi in the development of magnetism prior to Gilbert—he too accumulates magnetic observations and evidences the birth of the dedicated field of magnetic study. The attention he paid to lodestone and iron alone helped expand and solidify the picture of magnetic phenomena begun by Peregrinus, and enabled Gilbert to contrast magnetism and amber-like attraction.

Mariners' Data

By the 16th century, compasses saw widespread use by mariners, shipmen, and those studying navigation.[119] Gilbert was in contact with a number of these men, having spoken with famous mariners Sir Francis Drake and Thomas Cavendish, studied the work of navigational theorists

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[115] Porta, *Natural Magick,* bk. 7. Some modern scholars propose Porta was a student of Sarpi. At minimum, from the introduction to Porta's book on magnetism, we learn that Porta knew of, studied, and may have communicated with Sarpi for seven years prior to the publication of Porta's book, during which time topics of nature and magnetism were almost certainty discussed. Porta, *Natural Magick,* bk. 7:"The Proeme"; Benjamin, *History of Electricity,* 223.
[116] Porta, *Natural Magick,* bk. 7:chap. III, XV, XVIII, X, XI, XLVIII.
[117] Gilbert, *On the Magnet,* 92, under "Notes," 48; Porta, *Natural Magick,* bk. 7:chap. XLVII, XXVII. Thompson quotes Porta referencing Peregrinus when describing one of these experiments: "Petrus Pellegrinus saith, he shewed in another work how that might be done: but that work is not to be found. Why I think it extream hard, I shall say afterwards. But I say it may be done, because I have now done it, to hold it fast by an invisible band, to hang in the air; onely so, that it be bound with a small thread beneath, that it may not rise higher: and then striving to catch hold of the stone above, it will hang in the air, and tremble and wag itself."
[118] Gilbert points out a number of these errors. See for instance Gilbert, *On the Magnet,* 63, 66, 138, 102, 138, 143, 144, 149, 166-167.
[119] Lane, "Invention of the Compass," 606-614; Gilbert, *On the Magnet,* 7-8.

William Barlowe and Edward Wright, interviewed other shipmen, and been a doctor in the English navy.[120]

The years between the first mentions of compasses and this wider adoption had given plenty of time for mariners in their adventures around the globe to test the worthiness of the compass as an instrument of navigation. This yielded two primary findings, one from the continued and increasing use of the compass, and the other from the reports of mariners, navigational theorists, and other shipmen.

The continued use of the compass served to solidify the simple point that compass needles at many different points around the globe point approximately to the geographic poles. As such, the notion of a relationship between the magnetism and the poles of the world (argued for by Peregrinus) saw stable acceptance in the compass.

The reports from mariners also provided an important amendment: while magnetized compass needles do point approximately north, they do not point exactly to the poles of the Earth or the heavens.[121] Rather, there is a systematic deviation, which is now known as magnetic variation. On this phenomenon, Gilbert writes, "Some learned men there are who in the course of long voyages have observed the differences of magnetick variation: the most scholarly Thomas Hariot, Robert Hues, Edward Wright, Abraham Kendall, all Englishmen," and defines magnetic variation as "Variation, a deflexion from the meridian, which we call a perverted movement."[122]

Together, these observations solidified previous knowledge about the behavior of magnetized compass needles and provided a new phenomenon, magnetic variation, for investigators of magnetic phenomena to explain. These added to the now growing collection of information and puzzles that constituted the cutting edge of the understanding of magnetic attraction, with which Gilbert was intimately concerned.

Progress to this Point

By the time of Gilbert's research, the study of magnetic attraction was burgeoning. Building on the work of Peregrinus, and sometimes importing knowledge from the craft of compass-making, there was now a clear research tradition accumulating knowledge about lodestones and magnetized needles. Beyond pole behavior, researchers had now identified magnetic dip, the

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[120] Gilbert, *On the Magnet,* iiij, 117; Pumfrey, "William Gilbert," 8-9. Gilbert was determined to be a "fytt persons to be employed in the said Navye to have care of the helthe of the noblemen, gentlemen and others in that service." He also collaborated closely with Wright, who wrote the preface to *De magnete*, potentially relying on him for both compass data and navigational theory.
[121] Ash, "Navigation Techniques and Practices"; Gilbert, *On the Magnet,* iiij, 7-8, 117.
[122] Gilbert, *On the Magnet,* 7, 46.

rotational power or verticity of magnets, the fact that magnetic attraction varies with distance, that fire can cause lodestones to lose their attractive power, and so forth.

At the same time, mariners were accumulating data about the behavior of compasses at different points on the Earth's surface, and this was yielding strong evidence for magnetic variation in addition to the pole affinity of magnetized iron initially noted by Peregrinus.

These advances contributed to the impending discovery of static electric attraction in two ways. First, they continued to build the already solid case that lodestone attraction was a distinct phenomenon from amber-like attraction. Magnetic attraction had been described; it now remained to identify electricks.

Second, they helped to set the stage for Gilbert's development of his magnetic theory of the Earth. As we will see, magnetic dip, magnetic variation, and the rotational properties of magnetic attraction might have inspired some components of Gilbert's theory and were observations or pieces of data to which he would reconcile his theory. Gilbert would also respond to Norman's *pointe respective*, which had already taken the conceptual step of moving the locus of terrestrial lodestone attraction out of the heavens and towards the Earth.

Combined with the advances in the understanding of attraction by amber and other gems, especially from Cardano, Gilbert was favorably positioned. The primary missing pieces were a thorough experimental investigation of amber-like attraction and the impetus for such an investigation.

2 Copernicus' Challenge to Aristotle

In the centuries leading up to Gilbert, the most widely accepted description of the cosmos in the Western world had been given by Aristotle.[123] In 1543 CE, the year of Copernicus' death and the year before Gilbert's birth, Copernicus published *De revolutionibus orbium coelestium libri vi*, presenting an alternative description of the heavens and the location and motion of the Earth within it. This left an opening for a bold thinker to produce a modified theory of the cosmos, explaining the Earth's new role in the solar system.

Gilbert seized this opportunity, with the aim of his research being to create a new theory of the elements, the Earth, and planetary behaviors. To complete our review of the background to Gilbert, we will now briefly review Aristotle's theory and Copernicus' challenge.

[123] Lohr, "The Medieval Interpretation of Aristotle," 80-98; Lohr, "Aristotelian Division of Speculative Sciences," 49-58; Falcon, "The Reception of Aristotle in Antiquity," 1-19; Grant, "Terms 'Aristotle' and 'Aristotelianism,'" 335-358; Del Soldato, *Early Modern Aristotle;* Heilbron, *Electricity in the 17th and 18th Centuries,* 35-38; Costello, *Scholastic Curriculum*; Janiak, *Newton as Philosopher,* 102-103.

Aristotle's Cosmological Theory

Aristotle proposed that there were four terrestrial elements, Earth, Water, Air, and Fire, each with a natural place in the cosmos. Earth and Water were heavy and thus went down. Air and Fire were light and thus went up.[124] Our planet was spherical and made of Earth. Surrounding it was a spherical shell of Water. Beyond that, there was a spherical shell of Air, and beyond that, a spherical shell of Fire. Together these constituted the terrestrial or earthly sphere.[125] The Earth, at the center, did not move or rotate.[126]

Outside the terrestrial sphere, there were further shells, each composed of a fifth element: Aether. Aether moved in a circular motion around the terrestrial sphere. The celestial bodies, including the sun, moon, and planets, were themselves made of Aether and existed in different shells. In the outermost shell were the fixed stars. The shells rotated at different speeds; together, they constituted the celestial or heavenly sphere.[127]

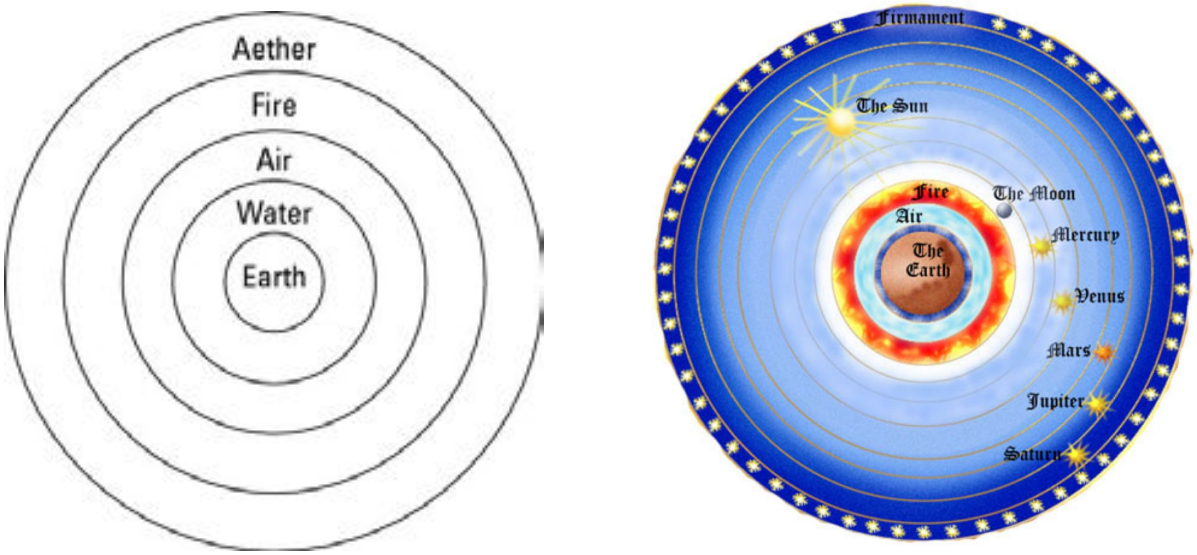

Figure 3. Aristotelian cosmology — the relative placement of the elements (left) and the terrestrial and celestial spheres (right).[128]

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[124] Aristotle, *Complete Works,* 309b, 312a25-313a14; Rovelli, "Aristotle's Physics," 2.
[125] Aristotle, *Complete Works,* 287a30-287b21, 309b, 312a25-313a14, 341b12-341b20, 391b14-392a31; Rosen, "Solid Celestial Spheres," 13; Konstantinos, Theodosiou, and Dimitrijevic, "Aristotelian Aether," 136.
[126] Aristotle, *Complete Works,* 296a24-297a7.
[127] Aristotle, *Complete Works,* 391b9-392a31; Rosen, "Solid Celestial Spheres," 13, Konstantinos, Theodosiou, and Dimitrijevic, "Aristotelian Aether," 137-8; Rovelli, "Aristotle's Physics," 2.
[128] Rovelli, "Aristotle's Physics," 137; Sidoli, "Aristotle's Natural Philosophy," slide 14.

For all of its imperfections, this theory provided a simple, basic explanation of why most things were located where they were and generally moved as they did. It was then possible on this basis to inquire into the specific causes of phenomena that were not yet explained, such as winds, comets, shooting stars, and more.[129]

Copernicus' Challenge

Copernicus proposed three important changes to the Aristotelian system. First, he proposed that the Earth and other planets revolve around the Sun, and that only the Moon revolves around the Earth. Second, he proposed that the Earth itself rotates on an axis. Third, he proposed that the Earth is tilted on its axis of rotation.

Copernicus used these proposals to explain a number of astronomical phenomena that had forced Aristotelians to add complexity to their theories. These included that planets had been observed to move forward and then back relative to other astronomical bodies, that planets appear to change their distances from the Earth, that the day is of different lengths during different seasons, and that some planets appear to have a much greater range of motion relative to the Sun than others.[130]

These explanations and the proposal they accompanied importantly disagreed with Aristotle's description of the arrangement of the celestial sphere. In response, one option was to deny Copernicus' astronomical system; another was to affirm his system while still accepting Aristotle's explanations of earthly phenomena. But if one accepted some of Copernicus' propositions and found them to be in conflict with or Aristotle's explanations of earthly phenomena, one would then need a new explanation of the terrestrial sphere.

Gilbert would later find himself in exactly this position. Copernicus affirmed that the Earth rotated on its axis, and Gilbert agreed. But what was the cause of the Earth's rotation? It was hard to see how Earth, Fire, Water, or Air could afford an adequate explanation. This suggested the need for a new theory of the terrestrial sphere that would explain the earth's motion in the cosmos.[131]

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[129] In Aristotle's system, comets and shooting stars are found in the sphere of fire. Aristotle, *Complete Works,* 341b17-341b35, 344a5-345a10.
[130] Copernicus, *De Revolutionibus* (1978).
[131] In "Animism and Empiricism: Copernican Physics and the Origins of William Gilbert's Experimental Method," Henry draws a distinction between Copernicus and "philosophizing astronomers" (including Gilbert). Where Copernicus was content with a mathematical justification for his astronomy, the philosophizing astronomers (in the tradition of natural philosophy) wanted an explanation for the Earth's proposed motion. Henry, "Animism and Empiricism," 107. Aristotle's theory provided no such explanation, leaving a gap for Gilbert to fill.

Gilbert's Discovery of *Electricks*

William Gilbert was a physician, grand theorist, and experimentalist, born in Colchester, England in 1544.

Gilbert attended St. John's College at the University of Cambridge from 1558 to 1561, where he studied mathematics, astronomy, dialectics, and Aristotelian philosophy, including ethics, metaphysics, and physics.[132] By 1569, Gilbert had completed an M.A. and an M.D., and went on to pursue a successful career in medicine. After moving to London, Gilbert became court physician to Queen Elizabeth I and president of the Royal College of Physicians.[133]

During his time at court, Gilbert worked on two treatises, *De magnete, magneticisque corporibus, et de magno magnete tellure* (English: "On the Magnet and Magnetic Bodies, and on the Great Magnet the Earth," henceforth: "*De magnete*") and *De mundo nostro sublunari philosophia nova* (English: "New Philosophy about our Sublunary World," henceforth: "*De mundo*").[134] In these treatises, Gilbert presents a cosmological theory in which the Earth is a giant magnet and there exists a single terrestrial element, Earth, with magnetic properties. In *De magnete*, published in 1600, Gilbert presents his theory, extends previous magnetic researchers' investigations of magnetic attraction, and carefully distinguishes two categories of things, *electricks* and *magneticks*, each with its own type of attractive power. In *De mundo*, published posthumously from a compilation of his notes and manuscripts in 1651, he attempts to reconcile his magnetic cosmological theory with the large number of topics covered by Aristotelian physics.[135]

Today, Gilbert is remembered for his contributions to magnetic knowledge and for the isolation of static electric attraction as a distinct physical phenomenon. The distinction between electricks and magneticks presented in *De magnete*, along with Gilbert's descriptions of experiments and the *versorium* (a tool for measuring static electric attraction), form the basis of the study of static electric attraction that would follow in the 17th century.

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[132] Heilbron, *Electricity in the 17th and 18th Centuries,* 170; Pumfrey, "William Gilbert," 7-8. His surviving book collection includes two works of Galen, Mathioli's *Materia medica*, and a book of Aristotle's natural philosophy.
[133] Heilbron, *Electricity in the 17th and 18th Centuries,* 170.
[134] Unfortunately, there is currently no English translation of *De mundo.* We have instead relied on Sister Suzanne Kelly's thorough summary and analysis accompanying her presentation of the Latin text. Stephen Pumfrey is currently working on such a translation, which we will use to update this analysis upon its completion, if applicable.
[135] After Gilbert's death, *De mundo* was compiled from notes and gifted to Prince Henry (James I's son) by Gilbert's brother, William Gilbert of Melford. *De mundo* eventually made its way to Thomas Harriot and Francis Bacon. After Bacon's death, as Isaac Gruter was preparing his manuscripts for print (having received copies from William Boswell's Library after Boswell's death), Gruter found two copies of *De mundo*, presumably amongst Bacon's papers. In 1651, Gruter combined and published them, creating the first printed edition of *De mundo.* Kelly, *De Mundo*, 1:13, 16, 17.

In what follows, we will look at why Gilbert chose to investigate the phenomena of attraction by amber and other gems, and how he identified the category of electricks. We will consider Gilbert's dispositions, things that may have prompted Gilbert's magnetic cosmological theory, Gilbert's theory itself, how that theory led him to engage in his thorough investigation of amber and gem attraction, his investigation, and the resulting discovery of electricks.

1 Gilbert's Dispositions

Gilbert had a number of dispositions that might have helped to position him to develop his magnetic theory, recognize the problem posed by non-lodestone attraction, and engage in a thorough investigation of attraction by amber of other gems. We will briefly describe Gilbert's tendency to engage with other writers, his experimentalism, and the role of theory in his research.

Engagement with Predecessors

Gilbert was extremely familiar with the views of other writers. He references over a hundred thinkers by name in *De magnete* alone and a number more in *De mundo*.[136] In doing this, he does not engage in a merely performative way with previous writers or respond only to claims that help him advance his theory—rather, he diligently catalogs the relevant views on each topic he discusses, accurately summarizes them (for the most part), and offers short (though sometimes suspicious) refutations.[137] While he is often dismissive of his predecessors and sometimes discards their views without response, he nevertheless consistently and thoroughly describes their views and displays more than a cursory understanding of them.[138]

The following is a characteristic passage where he summarizes and engages closely with one theory:

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[136] Gilbert, *On the Magnet.* Among those he references are Josephus Acosta, Affaytatus Fortunius, Agricola, Albertus Magnus, Aristotle, Thomas Aquinas, Roger Bacon, Porta, William Barlowe, Tycho Brahe, Sebastian Cabot, Thomas Cavendish, Cardano, Giulio Cesare, Copernicus, Cornelius Agrippa, Cornelius Tacitus, Alfonso Diego, Dioscorides, Sir Francis Drake, Empedocles, Epicurus, Thomas Erastus, Ficino, Sarpi, Fracastoro, Galen, Garcia da Orto, Hugo Grotius, Hero of Alexandria, Hippocrates, Scaliger, Abraham Kendall, Livio Sanuto, Lucretius, Olaus Magnus, Marbode, Marc Polo, Martin Cortes, Serapio, Norman, Paracelsus, Parmenides, Peregrinus, Philostratus, Plato, Pliny, Plutarch, Ptolemy, Gulielmus Puteanus, Pythagoras, Franciscus de la Rue, Simon Stevinus, Solinus, Strabo, Joannes Taisner, Thales, Theophrastus, Arnaldus de Villa Nova, and Zoroaster.

[137] These refutations are characteristically medieval rather than modern in style. On the whole, Gilbert's refutations are not as strong as his summaries and demonstrated understanding of the texts. For a sense of the accuracy of Gilbert's summaries and references, see Thompson's notes, which quote relevant sections of many primary source texts Gilbert mentions.

[138] It is also fruitful to compare Gilbert's style to those of his contemporaries. Where others would repeat some claims, affirm some without testing, and refute a sample, Gilbert is more consistent and more discerning. He often puts claims to the test, and gets closer to including an exhaustive catalogue of authors' views on each topic.

> To Baptista Porta the loadstone seems a sort of mixture of stone and iron, in such a way that it is an iron stone or stony iron. 'But I think' (he says) 'the Loadstone is a mixture of stone and iron, as an iron stone, or a stone of iron. Yet do not think the stone is so changed into iron, as to lose its own Nature, nor that the iron is so drowned in the stone, but it preserves itself; and whilst one labours to get the victory of the other, the attraction is made by the combat between them. In that body there is more of the stone than of iron; and therefore the iron, that it may not be subdued by the stone, desires the force and company of iron; that being not able to resist alone, it may be able by more help to defend itself.... The Loadstone draws not stones, because it wants them not, for there is stone enough in the body of it; and if one Loadstone draw another, it is not for the stone, but for the iron that is in it.' As if in the loadstone the iron were a distinct body and not mixed up as the other metals in their ores! And that these, being so mixed up, should fight with one another, and should extend their quarrel, and that in consequence of the battle auxiliary forces should be called in, is indeed absurd. But iron itself, when excited by a loadstone, seizes iron no less strongly than the loadstone. Therefore those fights, seditions, and conspiracies in the stone, as if it were nursing up perpetual quarrels, whence it might seek auxiliary forces, are the ravings of a babbling old woman, not the inventions of a distinguished mage.[139]

Likewise, here is a characteristic passage where he describes a cluster of views on a topic in a rapid-fire sequence:

> [After summarizing and dismissing magnetic mountains as the cause of magnetic variation...] But the cogitations of others are still more vain and trifling, such as that of Cortes about a moving influence beyond all the heavens; that of Marsilius Ficinus about a star in the Bear; that of Peter Peregrinus about the pole of the world; that of Cardan, who derives it from the rising of a star in the tail of the Bear; of Bessardus, the Frenchman, from the pole of the Zodiack; that of Livio Sanuto from some magnetick meridian; that of Franciscus Maurolycus from a magnetical island; that of Scaliger from the heavens and mountains; that of Robert Norman, the Englishman, from a point respective. Leaving therefore these opinions, which are at variance with common experience or by no means proved, let us seek the true cause of the variation.[140]

Reading, summarizing, and sorting through many views in this way may have contributed to Gilbert's development of his large set of explanations for natural phenomena, and in combination with his experimentalism, seems to have allowed Gilbert to sift out many of the accurate observations that previous authors had made.

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[139] Gilbert, *On the Magnet,* 63.
[140] Gilbert, *On the Magnet,* 152-153.

Experimentalism

Much has been written on the origin of Gilbert's experimentalism, including its uniqueness and the sociological and cultural factors involved.[141] For our purposes, we will focus on Gilbert's experimentalism only insofar as it helps to explain his discovery of electricks.

It is clear that Gilbert was highly experimental. He conducts an astonishing number of extremely varied magnetic and electrical experiments throughout *De magnete.*

Of his magnetic experiments, some were original and some were modeled on the experiments of Peregrinus.[142] He placed compass needles all along the edges of a terrella to find they imitated pole behavior, split lodestones and placed compass needles between them, moved compass needles further and further away from the surface of the lodestone to see the lodestone's effect at a distance (discovering the "orb of virtue" around a lodestone), created uneven lodestone surfaces to discover the effects of an uneven magnetic surface on the direction of a compass needle, described compass behavior, and more. He also tested the behavior of lodestones wrapped in iron in a way designed to increase their magnetic effect ("armed lodestones"), studied the effect of putting silk between two lodestones, expanded an experiment inspired by Porta's hanging magnets, investigated whether a nearby lodestone will cause two pieces of iron to attract, examined whether heat causes the magnetization of iron, and examined the strength of corrupted and eroded lodestone.

Gilbert was thorough in his electrical experiments as well, famously testing Porta's claim that a diamond could magnetize iron 70 times.[143]

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[141] Many researchers have studied the origin and extent of Gilbert's experimentalism as part of an attempt to understand the origin and nature of the Scientific Revolution. See Zilsel, "Origins of William Gilbert's Scientific Method"; Henry, "Animism and Empiricism"; Gaukroger, *The Emergence of a Scientific Culture.*

[142] Gilbert's magnetic experiments, excluding his claims about the navigational behavior of a compass at sea and records of astronomic behavior, can be found on pages 13, 16, 30, 31, 72-75, 76, 77, 82, 84, 84-86, 87, 87-80, 91, 91-92, 93-94, 95-96, 96, 97-98, 98, 99, 100-103, 103-105, 105-108, 108, 109, 115-116, 117-119, 119-123, 124-126, 126-129, 130-131, 131-132, 132, 133, 134-138, 137-138, 138, 140-141, 144, 144-146, 146, 147-151, 151, 155-159, 159-160, 162-163, 164, 173-174, 188-189, 190-191, 192-193, 194, 195-196, 196-198, 198-199, 200-202, 202-204, 205-207, and 222-223 of *On the Magnet*. Our apologies to Gilbert for any we have missed.

[143] Gilbert, *On the Magnet,* 143. See "Gilbert's Investigation of Gem Attraction" and "The Discovery of Elecricks" later in this text for a sampling of Gilbert's other electrical experiments.

Gilbert also chastised his predecessors for their frequent failure to test their claims experimentally.[144] He not infrequently describes his less experimental colleagues as "foolish," "idle," "ridiculous," and "superstitious."[145]

In combination with his propensity to respond to other authors, Gilbert's experimentalism likely helped him to be able to sift through the claims of the past, allowing him to identify and collect true claims while recognizing and separating out the myths. Gilbert's experimentalism also seems to have been crucial in the actual identification of electricks, as distinguishing the categories of amber-like attraction from amber attraction and gem attraction required thoroughly testing many different materials, as well as learning to control for ambient conditions like the weather.

Theory

Finally, Gilbert was a theorist. His theoretical tendencies led him to not only develop theories and explanations for many natural phenomena, but also to combine those theories into a single grand theory meant to explain the functioning of the universe.

Gilbert's theoretical propensities are on display in both of his works. *De magnete,* ostensibly Gilbert's less theoretical work, is structured around Gilbert's core theory, each chapter helping to build the argument that the Earth is a giant magnet. *De mundo* is structured in scope like Aristotle's physics, with Gilbert providing theories of a wide range of terrestrial and celestial phenomena, including comets, rainbows, moon lakes (craters), tides, winds, clouds, light, the origin of springs and rivers, the Milky Way, and vacuums.[146]

While Gilbert's experimentalism has been widely recognized and touted, it seems that his theoretical propensities were critical as well. Without them, it is hard to imagine how he would have chosen attraction by amber and other gems in particular as an object of study, given the vast number of things in the natural world to which an experimentalist could have applied their talents.

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[144] For instance, see Gilbert, *On the Magnet,* 48, 8. "Our own age has produced many books about hidden, abstruse, and occult causes and wonders, in all of which amber and jet are set forth as enticing chaff; but they treat the subject in words alone, without finding any reasons or proofs from experiments, their very statements obscuring the thing in a greater fog, forsooth in a cryptic, marvellous, abstruse, secret, occult, way. Wherefore also such philosophy produces no fruit, because very many philosophers, making no investigation themselves, unsupported by any practical experience, idle and inert, make no progress by their records, and do not see what light they can bring to their theories," and "with such idle tales and trumpery do plebeian philosophers delight themselves and satiate readers greedy for hidden things, and unlearned devourers of absurdities."
[145] See Gilbert, *On the Magnet,* ij, iij, 7, 32, 46, 61, 111, 114, 116, 138, 142, 144, 169, 225, 227.
[146] Kelly, *De Mundo.*

With regard to the relation between Gilbert's disposition to respond to other authors, his experimentalism, and his theoretical propensities, it is most natural to think of each of these working together, with none predominating. It is easy to see how Gilbert used experiments to overturn testimony and refute theory. But in at least one central case, Gilbert also seems to have relied on theory and testimony over the results of direct experimentation. In particular, Gilbert's magnetic theory predicts that terrellas should spin on their own, mimicking the Earth's rotation, as a result of their own magnetic power. This claim was also erroneously affirmed by Peregrinus. Gilbert tested this, found that the terrella did not spin, and reported in *De magnete*, "I omit what Peter Peregrinus constantly affirms, that a terrella suspended above its poles on a meridian moves circularly, making an entire revolution in 24 hours: which, however, it has not happened to ourselves as yet to see."[147] Nevertheless, Gilbert stuck to his theory and asserted that the Earth's magnetism was responsible for its diurnal rotation.[148]

As we describe Gilbert's identification of electricks, we will see how his tendency to respond to other writers, his experimentalism, and his use of theory helped to guide and shape his research.

2 Gilbert's Research

Prompts for Gilbert's Cosmological Theory

The Need for a New Cosmology

We previously saw how Copernicus called into question the basic structure of the Aristotelian universe. This left an opening for theorists who accepted at least some of Copernicus' claims and wanted to reconcile them with an understanding of the terrestrial sphere.

There is substantial reason to believe that Gilbert took up this challenge. With respect to Copernicus, Gilbert accepted the claim that the Earth rotated, devoted a chapter in *De magnete* to arguments by Copernicus about the speed of heavenly rotation, and developed a magnetic theory that aimed specifically to explain the rotation of the Earth.

(It is possible that Gilbert was also motivated by Copernicus' other claims. Gilbert was at least aware of them, diagramming in *De mundo* Copernicus' proposed heliocentric universe and displaying its clear deviation from Aristotle.[149] Gilbert though was careful to distinguish his

[147] Gilbert, *On the Magnet,* 223.
[148] In the context of the rest of Gilbert's evidence and his belief in the rotational power of the magnet, this may have been a reasonable position. Gilbert had solid evidence for the magnetic properties of the Earth, a relation between rotation and magnetism (see Georgescu, "Disponent Power"), was well-familiar with the finickiness of experiments (see his knowledge of the weather's effect on chaff, for example), and had generally found Peregrinus' results reliable.
[149] Kelly, *De Mundo,* 1:38, 41-42.

theory from Copernicus', neither affirmed nor denied heliocentrism, and created a theory that was compatible with both geocentrism and heliocentrism.[150] It is possible that Gilbert accepted Copernicus' claims about the revolution of the Earth around the Sun and the tilting of the Earth on its axis and was simply aiming to avoid conflict with the Catholic Church. It is also conceivable that Gilbert remained agnostic on the questions.)

With respect to Aristotle, there is substantial evidence that Gilbert aimed to unseat Aristotle and replace his cosmology with one based on a single element, magnetic Earth. Gilbert's work *De mundo* is divided into two parts, "Physiologiae nova contra Aristotelem" (English: "New physiology against Aristotle) and "Nova meteorologia contra Aristotelem" (English: "New meteorology against Aristotle). Gilbert's "Physiologiae" is composed of two books and describes his system of cosmology and views on astronomy. His "Meteorologia" is composed of three books and gives his explanation of other natural phenomena.[151] This mimics Aristotle's original *Meteorologica*, which has the same structure and covers the same topics (though Gilbert leaves out several topics pertaining to the weather).[152] It also follows the Aristotelian trend of building an understanding of the world and cosmology founded on an understanding of the basic earthly elements and their interaction, replacing Earth, Fire, Water, and Air with a magnetic version of Earth.

De mundo also includes a number of detailed, though somewhat uncharitable refutations of Aristotle's perspectives, followed by the presentations of Gilbert's own theories. In "Physiologiae," for instance, Gilbert extensively criticizes the four basic earthly elements and their postulated natural places.[153]

With works that mimic Aristotle's in style and topic selection, and a theory that plays the same role, it seems clear that Gilbert was attempting to produce a picture of the cosmos that explained Copernicus' claim about the rotation of the Earth with a theory that retained the scope and exhaustiveness of Aristotelian physics.

Evidential and Theoretical Landscape

Beyond the dispositions and motivations that may have set Gilbert on his course, we can also describe important parts of the evidential and theoretical landscape at the time before Gilbert's investigation. In particular, since the time of Peregrinus' investigation of magnetism, new

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[150] Kelly, *De Mundo,* 1:38, 41-42*;* Gilbert, *On the Magnet,* 214-221. In *De magnete,* after describing the Earth's diurnal rotation, he writes: "I pass over the reasons of the Earth's remaining motions, for at present the only question is concerning its diurnal movement."
[151] Kelly, *De Mundo,* 1:11, 25-37, 45-55.
[152] Kelly, *De Mundo,* 1:45.
[153] Kelly, *De Mundo,* 1:25-37.

observations, phenomena, and puzzles had emerged at the intersection of magnetism and astronomy, any or all of which might have suggested a magnetic cosmology like Gilbert's.

Of these, we will briefly describe three: pole phenomena in general, the relation between pole phenomena and magnetic variation and dip, and the question of the cause of the rotation of Earth.

Pole Phenomena

Peregrinus had discovered a link between magnets and the heavens: both had two points of interest, and the points of interest in each related to one another. These points of interest and the relation between them, summarized with the term "pole phenomena," suggested that there was some important relation between magnets and the heavens.

The nature of this relation was unclear, however. Peregrinus had shown that the poles of lodestones attracted and repelled one another and that the poles of lodestones also turned to face the poles of the world. Norman had clarified that the poles of lodestones are not attracted by the poles of the heavens, but instead merely rotate. Poles were clearly important, but why they related to each other as they did was unclear.

Magnetic Dip and Variation

Peregrinus' theory of pole phenomena was that the poles of the heavens imbued lodestones with their power, thereby relating the poles of the lodestone to the poles of the heavens. However, there were now two reasons to doubt the immediate relation between the poles of the lodestone and the poles of the heavens: magnetic dip and magnetic variation.

Magnetic dip, identified by Norman, is the phenomenon whereby magnetized compass needles do not rotate on a flat plane, perpendicular to the Earth's surface, but instead point downward to different degrees in different places. This presented a challenge to the view that magnets (lodestones and magnetized needles) were responding immediately to the poles of the heavens. If lodestones received their powers from the heavens, and this was why lodestones turned to face the poles of the heavens, why would magnetized needles point downward? Since the poles of the heavens were up, not down, magnetic dip suggested that magnets were responding to something other than the poles of the heavens.

Magnetic variation, identified by mariners in Gilbert's time and referred to previously by Cardano, is the phenomenon whereby lodestones and magnetized needles did not point directly towards the poles of the heavens, but instead pointed in directions that deviated from this. This was a further challenge: if lodestones and magnetized needles were responding to the poles of the heavens, why were they not rotating to face those poles

directly? This too suggested that magnets were responding to something other than the poles of the heavens.

Norman postulated a *pointe respective*, a special point to which magnetized needles pointed. (Gilbert rejected this proposal; see Appendix D.) This suggestion at least took the conceptual step of looking for a locus of magnetic behavior other than the poles of the heavens. But it left the puzzle of what exactly magnets were pointing to and why.

The Rotation of the Earth

In addition to reconciling pole behavior with magnetic dip and variation, a further difficulty was explaining the rotation of the Earth. Copernicus had proposed that the Earth rotates on its axis, and Gilbert accepted this. But if the Earth rotated, what was the cause? All observed rotation required a constant cause in order to persist; without a constant cause, the Earth would stop rotating.

Norman had drawn a link between magnets and rotation, showing that magnets are rotating in response to the poles of the heavens (or the *pointe respective*, or whatever the actual cause), rather than being attracted. In addition, Peregrinus had erroneously stated that the terrella spun on its own in accordance with the heavens. These observations (even if one was false) opened up the possibility that magnets were, in some way, involved in the rotation of the Earth.

These phenomena, observations, and puzzles helped to create a backdrop against which a new magnetic cosmological theory could emerge.

Gilbert's Magnetic Cosmology

In contrast to Aristotle's four terrestrial elements, Fire, Water, Earth, and Air, Gilbert postulates a single terrestrial element, Earth, and attributes magnetic properties to it. Gilbert then proposes that the Earth is a giant spherical magnet, and that magnets by their nature rotate. He claims that the Earth is neither a perfect magnet nor perfectly spherical, but rather that its surface is corrupted, degraded, and slightly non-uniform in shape. He then uses the magnetic nature of the Earth, as well as its surface corruption, to attempt to explain a large number of observable phenomena.[154]

Gilbert presents this view as follows:

> The loadstone derives temporary properties, and acquires its verticity from the earth, and iron is affected by the verticity of the globe even as iron is by a loadstone: Magneticks are conformable to and are regulated by the earth, and are subject to the earth in all their

[154] For a more complete description of Gilbert's magnetic theory, see Appendix B.

> motions. All its movements harmonize with, and strictly wait upon, the geometry and form of the earth, as we shall afterwards prove by most conclusive experiments and diagrams; and the chief part of the visible earth is also magnetical, and has magnetick motions, although it be disfigured by corruptions and mutations without end… But we maintain that the true earth is a solid substance, homogeneous with the globe, closely coherent, endowed with a primordial and (as in the other globes of the universe) with a prepotent form; in which position it persists with a fixed verticity, and revolves with a necessary motion and an inherent tendency to turn, and it is this constitution, when true and native, and not injured or disfigured by outward defects, that the loadstone possesses above all bodies apparent to us, as if it were a more truly homogenic part taken from the earth.[155]

This view enabled Gilbert to reconcile many of the observations that had been made by magnetic researchers, as well as explain Copernicus' postulated rotation of the Earth.

Explaining Pole Phenomena

Gilbert's theory offers a new explanation for pole behavior. According to his theory, both the lodestone and the core of the globe are made of the element Earth, which has magnetic properties. As a result, both lodestones and the Earth are magnets, so the poles of a lodestone respond to the poles of the Earth.

Explaining Magnetic Dip

On Gilbert's theory, since the Earth is a giant spherical magnet, essentially a giant terrella, lodestones and magnetized needles respond to the Earth in the same way that iron needles on a terrella respond to the terrella. Gilbert experimentally demonstrates how the needles on a terrella respond and shows that this is similar to the phenomenon of magnetic dip. He writes in *De magnete*, "The magnetick dip (which is the wonderful turning of magnetick things to the body of the terrella) in systematick course, is seen in clearer light to be the same thing upon the earth," and presents the following diagram:[156]

[155] Gilbert, *On the Magnet,* 42.
[156] Gilbert, *On the Magnet,* 212.

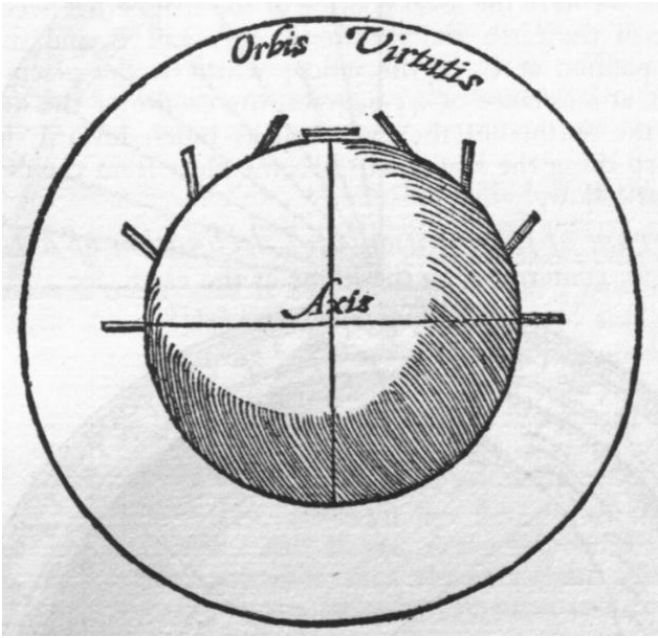

Figure 4. Dip in a terrella, as captioned by Gilbert: Variety in the declinations of iron spikes at various latitudes of a terrella.[157]

Note that the iron filings on the left and right of the terrella point increasingly downwards, similar to magnetic dip.

Explaining Magnetic Variation

According to Gilbert, while generally spherical, the surface of the Earth is not entirely uniform. He uses this to explain why magnetized needles do not point exactly to the poles of the Earth. In *De magnete*, Gilbert writes:

> The great magnet or terrestrial globe directs iron (as I have said) toward the north and south; and excited iron quickly settles itself toward those termini. Since, however, the globe of the earth is defective and uneven on its surface and marred by its diverse composition, and since it has parts very high and convex (to the height of some miles), and those uniform neither in composition nor body, but opposite and dissimilar: it comes to pass that the whole of that force of the earth diverts magnetical bodies in its periphery toward the stronger and more prominent connected magnetick parts.
>
> ...But the variation does really take place, not so much because of the more prominent and imperfect terrestrial parts and continent lands as because of the

[157] Gilbert, *On the Magnet,* 191. The image is included in Gilbert's chapter on dip, referred to by him as *magnetic declination.* Note the apparent ambiguity with modern usage of the term *declination*.

> inæquality of the magnetick globe, and because of the real earth, which stands out more under the continent lands than under the depths of the seas.[158]

With a non-uniform earth, slight variations in the direction of a magnetic compass from the poles of the Earth might be expected.

Explaining the Rotation of the Earth

According to Gilbert's theory, the Earth is a magnet and magnets naturally rotate. This straightforwardly explained the postulated rotation of the Earth.[159]

Through these explanations, Gilbert used his magnetic theory to reconcile Copernicanism, magnetic observations, and navigational data.

Gilbert also used his theory to attempt to explain many terrestrial and celestial phenomena.[160] Gilbert uses the previously mentioned corruption of Earth to explain some of these terrestrial phenomena, including why most everyday objects are not magnetic and why some lodestone and iron are only weakly magnetic.[161]

He also introduced *humours* to help him explain springs and rivers, metals, and electricks, as we shall see, in addition to the phenomena explained by the Earth's magnetism. According to Gilbert, these humours are exuded by the basic element Earth, can be moist, and are not their own elements.[162] He writes:

> The earth emits various humours, not begotten of water nor of dry earth, nor from mixtures of these, but from the substance of the earth itself: these humours are not distinguished by contrary qualities or substance, nor is the earth a simple substance, as the Peripateticks dream. The humours proceed from vapours sublimated from great depths; all waters are extracts and, as it were, exudations from the earth.[163]

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[158] Gilbert, *On the Magnet,* 153. See also Georgescu's "The Disponent Power in Gilbert's *De Magnete.*" Georgescu argues that the *disponent power* of magnets underlies Gilbert's magnetic theory and bolsters his belief in the daily rotation of the magnet and the Earth. On page 170, she also describes the limitations Gilbert confidence in Copernicus' phenomena and his explanation thereof.
[159] Gilbert, *On the Magnet,* 215, 223-224, 231. Gilbert also argues for the role of the sun in animating the Earth's daily rotation.
[160] We will focus less on celestial phenomena here, as they are less related to Gilbert's discovery of electricks.
[161] Gilbert, *On the Magnet,* 37-38, 42-44, 65, 96, 142-143.
[162] Gilbert, *On the Magnet,* 19-20, 39-44. One might ask how Earth excluded humours with different properties (sometimes moist, non-magnetic), if there only exists a single element, and whether these humours are linked to corruption in any way. It is not clear from the text how Gilbert answers these questions, though there are a number of subtle indications that humours cause corruption. For example, pages 43-44 of *On the Magnet* indicate that some corruptions are fatty and fluid, linking humours to corruption. See also pages 142-143.
[163] Gilbert, *On the Magnet,* 20.

With his theory of magnetic Earth and its corruptions and humours in hand, it was then possible for Gilbert set about trying to explain the vast number of phenomena that others like Aristotle had tried to explain.

The Cause of Gilbert's Investigation of Electric Attraction

With Gilbert seeking to explain so many things, there arises the question of why Gilbert decided to focus special energy on the topic of amber attraction. He devotes an entire chapter to the results of his investigation in *De magnete*, and his investigation has a level of quality much akin to his study of magnetic phenomena and superior to his study of other things.[164] Some causes seem more likely, others less so. Since we do not have direct evidence, we will simply comment on several different possible causes and highlight one that is especially plausible.

It is tempting to want to explain Gilbert's thorough investigation on the basis of his experimentalism. However, given the substantial scope of his project and the wide range of phenomena available to be studied electrically, it seems likely that experimentalism alone would be insufficient. Even an experimentalist challenger to Aristotle could choose to focus their experimentalism on any number of different things, and restricting oneself only to things explained by Aristotle would not be much of a restriction.

It also seems difficult to explain Gilbert's investigation solely or primarily by reference to his attempt to unseat Aristotle, as Aristotle himself did not comment on gem attraction and so there was no specific theory to overturn.

Finally, it is challenging to explain Gilbert's electrical investigation solely on the basis of his desire to respond to his contemporaries—neither Agricola, Cardano, Gilbert, Porta, Scaliger, da Orto, nor the ancient writers Gilbert mentions primarily wrote on amber-like attraction; instead, their electrical claims were buried in much broader works, many parts of which Gilbert disregarded.

It is still possible that Gilbert was uniquely inspired by a particularly promising idea from one of these authors, or even stumbled upon the topic of amber-like attraction by chance. However, it seems more plausible that Gilbert's interest in amber-like attraction was sparked in one way or another by his cosmological theory. This could have been in a number of ways; we will note the two most plausible here.

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[164] Our estimation of the detail of Gilbert's other investigations comes from Sister Suzanne Kelly's summaries, especially Kelly, *De Mundo*, 1:chap. 2, chap. 3. We hope to compare Gilbert's different investigations further on the basis of Pumfrey's soon-to-be-released English translation of *De mundo.* Gilbert did also thoroughly investigate several other phenomena besides electricks and magneticks, producing detailed observations on comets and charts on the wind. Kelly, *De Mundo,* 1:46, 49.

First, in his theory, Gilbert tried to explain the behavior of the Earth and cosmos in terms of magnetic attraction. This involved the systematic exploration of lodestone attraction and a thorough attempt to explain related magnetic and astronomical behaviors in terms of his theory. At the time, properties of gem attraction were frequently confused with those of lodestone attraction; diamond was said to magnetize iron, certain gems were said to attract themselves and iron, and both amber and lodestone were wrongly said to attract silver of non-trivial weight. As a result, a systematic treatise with the lodestone as its centerpiece that did not comment on gem attraction might appear to Gilbert to have an important gap. This would explain why Gilbert chose to include his treatment of electricks in *De magnete*, where he stated and argued for his cosmological theory, rather than in *De mundo*, where he describes a much wider range of topics (e.g., rainbows, types of bodies of water, light).

Alternatively, it is possible that Gilbert was driven to study non-magnetic attractive effects by his attempt to explain the coherence of the Earth. Gilbert accepts that the Earth rotates on its axis. This raises the question of why the surface of the Earth does not come apart as the Earth spins. Gilbert himself discusses this question in *De magnete*, and while he attributes some of the Earth's coherence to magnetic attraction, he attributes some to electrick attraction as well.[165] It is possible that after accepting the rotation of the Earth, Gilbert found it necessary to explain its continued coherence. Concluding that magnetic attraction was insufficient, perhaps because much of the surface of the Earth is evidently non-magnetic, he may then have found it necessary to postulate another form of attraction. This then may have motivated him to investigate other forms of attraction, in order that his theory of the coherence of the Earth, despite its rotation, be adequately justified.

Both of these routes proceed in one way or another from his magnetic cosmological theory. Thus motivated to investigate the attractive powers of amber and other gems, Gilbert's experimentalism and responsiveness to his contemporaries may then have become relevant. Spurred on to clarify the area, his engagement with the views of others, the accumulation of true claims in their texts, and his experimentalism would have set him up well to understand the nature of electricks.

Gilbert's Investigation of Attraction by Various Materials

Gilbert's actual investigation of the attractive powers of various materials made use of three important pieces. We will now describe his study, touching on what may have given him leads and helped to direct his attention, as well as the instrument he may have used.

[165] Gilbert, *On the Magnet*, 217, 218, 60.

Texts on Lodestone and Gem Attraction

As he reveals in *De magnete*, Gilbert studied a large number of writers' commentaries on lodestone and gem attraction, including Lucretius, Pliny, Plutarch, Solinus, Galen, Agricola, Cardano, Fracastoro, da Orto, Scaliger, Porta, and Norman. These writers may have given Gilbert a substantial head start by providing him with a large number of leads to investigate, including many claims that would turn out to be true.

In particular, Cardano had recently listed a number of properties of amber attraction and distinguished amber attraction from lodestone attraction. Magnetic behavior had also been described clearly enough that such a contrast was possible. Various writers had also suggested that amber attracted all light objects and that other gems attracted like amber. Cardano had suggested, incorrectly but perhaps fruitfully, that all gems had attractive effects. Gilbert was aware of all of these claims, or at least the texts in which they appeared, and specifically commented on many of them.

While these texts may have provided Gilbert with leads, they would not have made the distinction between electricks and magneticks clear at the outset. The best previous writer on attraction due to amber and other gems, and on their distinction from lodestone attraction, was Cardano. But Cardano himself distinguished amber attraction from the attraction due to other gems, and his correct claims were buried within a larger mass of much less reliable claims from other authors, including claims which blurred the distinction between electricks and magneticks by attributing magnetic effects to electricks.

Gilbert's Electrical Experiments

Gilbert would make the most progress, and sift through the claims of previous authors, through the vast number of experiments he conducted himself. He tested all of the observational claims by previous authors, excepting medicinal claims and claims of occult powers. He also tested many possibilities not mentioned by previous writers. Gilbert tested materials like mica, bones, ivory, alabaster, coral, muscovy stone, sulfur, amethyst, and others for attractive effects. He tested and compared gemstones to metals and to materials that easily crumble.[166] He rubbed materials at different levels of vigor to determine how much rubbing was needed to produce attraction.[167] He designed an experiment to determine whether rubbed amber attracts water.[168] He rubbed amber in the vicinity of a flame to determine whether attraction works by drawing the air surrounding chaff.[169]

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[166] Gilbert, *On the Magnet*, 51, 52.
[167] Gilbert, *On the Magnet,* 56.
[168] Gilbert, *On the Magnet,* 48, 51, 55.
[169] Gilbert, *On the Magnet,* 55. He concluded it did not, as the air was not disturbed.

Gilbert's experiments were patient and careful. Static electric effects can be subtle and finicky to detect; they are affected by the weather, obfuscated by gravity, and jumbled by variation in the insulating properties and triboelectric rankings of what seem to be the same materials (for example, glass with different compositions, or variations in jet). In the course of his experiments, he came to be sensitive to the effect of temperature and humidity on his materials, as well as the different compositions of his materials on his results.[170]

In addition, he may have also used a specially designed instrument, the *versorium,* for the purpose of increasing the accuracy of his detection of electrostatic attraction—in his writings on the versorium, he notes, "But in order that you may be able clearly to test how such attraction occurs, and what those materials are which thus entice other bodies (for even if bodies incline towards some of these, yet on account of weakness they seem not to be raised by them, but are more easily turned), make yourself a versorium of any metal you like."[171] Unfortunately, it is not evident from Gilbert's writings or other available biographical information whether he relied on this instrument in his experiments or designed it afterward as part of his attempt to communicate his results.

Gilbert's Magnetic Theory

Finally, it is worth noting that since the likely purpose of Gilbert's investigation was to reconcile gem attraction with his magnetic theory of the universe, it is not unlikely that Gilbert's attention in his research was directed to the question of whether gem attraction was the same or different from magnetic attraction, and either way, how it could be reconciled his with general magnetic theory. This stands in contrast to previous theories that might have been used to try to explain gem attraction, as we have noted that those theories were (if anything) more likely to direct researchers away from a focus on experimentally determining the relation between lodestone attraction and gem attraction, rather than propel researchers to distinguish them.

The Discovery of *Electricks*

Gilbert's investigation led him to discover many features of amber-like attractors and sharply separate the phenomenon of amber-like attraction from that of lodestone attraction.

To the list of known amber-like attractors, he added sapphire, carbuncle, iris, mastic, and others, while solidifying the role of diamond:

> For it is not only amber and jet (as they suppose) which entice small bodies; but Diamond, Sapphire, Carbuncle, Iris gem, Opal, Amethyst, Vincentina, and Bristolla (an English gem or spar), Beryl, and Crystal do the same. Similar powers of attraction are

[170] Gilbert, *On the Magnet,* 55, 56.
[171] Gilbert, *On the Magnet,* 48.

> seen also to be possessed by glass (especially when clear and lucid), as also by false gems made of glass or Crystal, by glass of antimony, and by many kinds of spars from the mines, and by Belemnites. Sulphur also attracts, and mastick, and hard sealing-wax compounded of lac tinctured of various colours. Rather hard resin entices, as does orpiment, but less strongly; with difficulty also and indistinctly under a suitable dry sky, Rock salt, muscovy stone, and rock alum.[172]

Several of these were not gems, thereby distinguishing amber-like attractors from gems. He also determined that many gems were not attractors, refuting Cardano's proposal that all gemstones attract and distinguishing gems from amber-like attractors:

> On the other hand many gems, as well as other bodies, are polished, yet do not allure, and by no amount of friction are they aroused; thus the emerald, agate, carnelian, pearls, jasper, chalcedony, alabaster, porphyry, coral, the marbles, touchstone, flint, bloodstone, emery, do not acquire any power; nor do bones, or ivory, or the hardest woods, as ebony, nor do cedar, juniper, or cypress; nor do metals, silver, gold, brass, iron, nor any loadstone, though many of them are finely polished and shine.[173]

He went further, testing many other objects that he determined did not have amber-like attractive effects:

> But the dross of metals, as also metals, stones, rocks, woods, contain earth rather, or are mixed with a good deal of (*) earth; and therefore they do not attract.
>
> ...But those substances which are more mixed of water and earth, and are produced by the equal degradation of each element (in which the magnetick force of the earth is deformed and remains buried; while the watery humour, being fouled by joining with a more plentiful supply of earth, has not concreted in itself but is mingled with earthy matter), can in no way of themselves attract or move from its place anything which they do not touch. On this account metals, marbles, flints, woods, herbs, flesh, and very many other things can neither allure nor solicit any body either magnetically or electrically.
>
> ...But substances consisting mostly of humour, and which are not very firmly compacted by nature (whereby do they neither bear rubbing, but either melt down and become soft, or are not levigable, such as pitch, the softer kinds of resin, camphor, galbanum, ammoniack, storax, asafœtida, benzoin, asphaltum, especially in rather warm weather) towards them small bodies (*) are not borne.[174]

Having separated the materials that attract like amber from those that do not, he named his new category of attractive materials: *electricks.*

In identifying the basic behaviors of electric attraction, he added to and reaffirmed the list of simple descriptions of amber-like attraction and contrasted it with magnetic attraction. He notes

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[172] Gilbert, *On the Magnet,* 48.
[173] Gilbert, *On the Magnet,* 52.
[174] Gilbert, *On the Magnet,* 52-53.

that electricks attract all things (including water and oil), intervening objects disrupt electrical attraction, and different electricks attract at different strengths and with different amounts of rubbing.[175] He writes:

> If indeed either a sheet of paper or a piece of linen be interposed, there will be no movement. But a loadstone, without friction or heat, whether dry or suffused with moisture, as well in air as in water, invites magneticks, even with the most solid bodies interposed, even planks of wood or pretty thick slabs of stone or sheets of metal. A loadstone (*) appeals to magneticks only; towards electricks all things move. A loadstone raises great weights; so that if there is a loadstone weighing two ounces and strong, it attracts half an ounce or a whole ounce. An electrical substance only attracts very small weights.[176]

The vast majority of Gilbert's classifications of materials and basic descriptions of static electric attraction hold.[177] Having recognized, clearly delineated, and described the category of electricks accurately enough, and having sharply distinguished it from the category of magneticks, it is correct to say that Gilbert had now discovered static electric attraction.

Having distinguished electricks and magneticks, Gilbert proposed a theory of electricks involving *effluvia*:

> Therefore an effluvium resulting from a non-fouling friction, and one which is not changed by heat, but which is its own, causes union and coherency, a prehension and a congruence towards its source, if only the body to be attracted is not unfitted for motion, either by the surroundings of the bodies or by its own weight. To the bodies therefore of the electricks themselves small bodies are borne. The effluvia extend out their virtue—effluvia which are proper and peculiar to them, and *sui generis*, differing from common air, being produced from humour, excited by a calorifick motion from attrition and attenuation. And as if they were material rays, they hold and take up chaff, straws, and twigs, until they become extinct or vanish away: and then they (the corpuscles) being loosed again, attracted by the earth itself, fall down to the earth.[178]

In brief, Gilbert attempts to explain electricks using moisture. As we have seen, Gilbert proposed that Earth releases moisture in the form of humours. Here, he adds that electricks are substances of compacted moisture. When rubbed, they release the moisture trapped inside them in the form of vapors, called *effluvia.* Because water attracts, small objects stick to these vapours and are

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[175] Gilbert, *On the Magnet,* 55, 56, 59.
[176] Gilbert, *On the Magnet,* 53.
[177] Electricks must be insulators to attract; materials, such as amber or jet, that are typically insulators can instead sometimes be conductors. As a result, materials justly included in Gilbert's list of electricks will vary. However, his list is substantially more accurate, on average, than anything that had come before.
[178] Gilbert, *On the Magnet,* 61.

pulled towards the electricks.[179] Magneticks were thus explained by the element Earth, and electricks were explained by moist effluvia. Summarizing this view, Gilbert writes:

> But now at length we must understand why small bodies turn towards those substances which have drawn their origin from water; by what force and with what hands (so to speak) electricks seize upon kindred natures. In all bodies in the world two causes or principles have been laid down, from which the bodies themselves were produced, matter and form. Electrical motions become strong from matter, but magnetick from form chiefly; and they differ widely from one another and turn out unlike, since the one is ennobled by numerous virtues and is prepotent; the other is ignoble and of less potency, and mostly restrained, as it were, within certain barriers; and therefore that force must at times be aroused by attrition or friction, until it is at a dull heat and gives off an effluvium and a polish is induced on the body.[180]

In addition to his new category and his theory, Gilbert develops an instrument for the detection of electrical effects: the *versorium.* The versorium is a pivoted metal needle, as in a compass, that spins towards rubbed electrick bodies. Gilbert describes it as follows:

> But in order that you may be able clearly to test how such attraction occurs, and what those materials are which thus entice other bodies (for even if bodies incline towards some of these, yet on account of weakness they seem not to be raised by them, but are more easily turned), make yourself a versorium of any metal you like, three or four digits in length, resting rather lightly on its point of support after the manner of a magnetick needle, to one end of which bring up a piece of amber or a smooth and polished gem which has been gently rubbed; for the versorium turns forthwith. Many things are thereby seen to attract, both those which are formed by nature alone, and those which are by art prepared, fused, and mixed.[181]

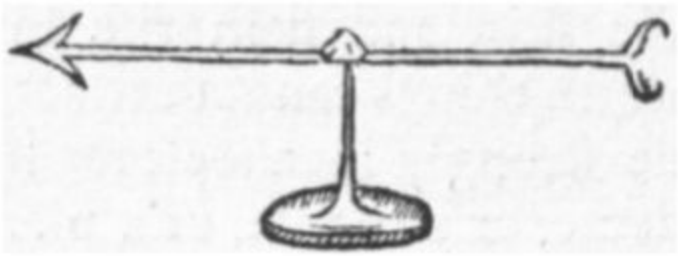

Figure 5. Gilbert's diagram of the versorium.[182]

[179] Gilbert offers water droplets congealing and rods being pulled together in the ocean as evidence for the claim that water allures. Gilbert, *On the Magnet,* 57-58.
[180] Gilbert, *On the Magnet,* 52-53.
[181] Gilbert, *On the Magnet,* 48-49.
[182] Gilbert, *On the Magnet,* 49.

If the versorium is small and light, in the presence of a rubbed electrick the versorium will be attracted and rotate to point towards the electrick. As a result, the versorium can detect static electric attraction. Because the versorium's movement is not opposed by gravity (like chaff, straw, or leaves would be), it allows for more precise detection of electrical effects.

Having discovered electricks, produced a theory to explain them, and created an instrument to detect them, Gilbert's next task was to present his results to the world.

The Presentation of *Electricks*

Gilbert introduces electricks in Book II, Chapter 2 of *De magnete.* His presentation of electricks differs from the writings of his predecessors in several ways and features a number of elements that may have disposed his new category to adoption. We will review those elements here to explain why Gilbert's work may have been adopted by later scientists, rather than simply passed over.

It would be easy to assume that the accuracy of Gilbert's distinction alone garnered adoption. However, the history of the study of lodestone and gem attraction preceding Gilbert suggests otherwise. Writers in ancient Greece and Rome made accurate observations that were not adopted, and Cardano, just fifty years previously, accurately distinguished amber from magnetic attraction and identified several important properties of static electric attraction and yet was largely ignored.

When considering how Gilbert's work differed, it is useful to consider the challenges to adoption faced by prior thinkers and how Gilbert's work addressed them.

Prior to Gilbert, a mix of accurate and inaccurate claims, theories, and observations circulated about amber and lodestone attraction. Even if an accurate claim was added, these claims were not easy to pick apart from the false claims. Frequently, justification relied on testimony or no justification was given at all. To make matters worse, these claims were often buried in small paragraphs in gigantic bodies of surrounding literature. These factors helped make it easy for new truths to fail to reach wider adoption.

By contrast, Gilbert much more clearly identifies and describes his electricks and provides substantially clearer evidence. He gives enough examples to demonstrate the existence of a category, rather than an isolated phenomenon, and enough examples and non-examples to distinguish it from any other known category. He allocates an entire chapter to electricks and gives them an evocative name. He demonstrates thorough command of the area, displaying extensive familiarity with the claims of previous thinkers and refuting many of them. Further, the essence of his claim is simple ("there are two categories") and easy to understand. He provides enough detail to show that he has investigated thoroughly, and he provides an instrument so the

reader might check for themselves (which proves persuasive, whether or not the instrument is used).

Gilbert's work also tacitly provided a relatively clear path for continued investigation. The more theoretically inclined would go on to dispute many parts of his explanation of the novel phenomenon, including his effluvia theories, his magnetic theories, and his cosmological theories. The more experimentally inclined would go on to copy his methodology to expand the list of electricks and electric behavior. While other thinkers, like Cardano, included some steps of this type (one could expand on Cardano's list of differences between magnetic and amber attraction, as Gilbert likely did), the paths offered by Gilbert were much clearer. A thinker copying Cardano is left no experimental guide, whereas the disciple of Gilbert receives an entire research program, complete with an instrument and initial findings to reproduce. In this way, Gilbert imitates Peregrinus, whose work was also adopted and extended by magnetic thinkers after its publication in 1558.

The Adoption of Electricks in Electrical Study

Whether for their truth or the persuasiveness of Gilbert's presentation, Gilbert's electricks slowly began to see adoption among electrical researchers. By the mid to late 1600s, his category of electricks was widely recognized, and the electric effects he reported were well-known. In the years between 1620 and 1680, researchers copied Gilbert's experimental style, elaborated on and challenged his effluvia theory of electric attraction, invented new instruments, and added to his list of electricks. This line of discovery led multiple researchers to encounter electric repulsion, and eventually set the stage for the discovery of electric light and the distinction between conductors and insulators.[183]

We will offer a few examples to demonstrate the pattern of engagement and adoption Gilbert's work saw, though we will leave a thorough investigation of the later evolution of electric theory in the years after Gilbert to another study.

Robert Boyle (first published in 1660) specifically references using a pivoted needle to detect electric effects, adds turpentine gum, white sapphires, emerald (contradicting Gilbert), English amethysts, and carnelian to the list of electricks, but explicitly denies Gilbert's hypothesis that magnetism arises from the magnet's form.[184] Gilbert's magnetic cosmological theory was also discussed by Otto Von Guericke, who went on to claim instead that the Earth was a giant electrick and to invent the equivalent of an electrical terrella (a sulfur globe) to mimic Gilbert's magnetic experiments.[185]

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[183] Heilbron, *Electricity in the 17th and18th Centuries,* 197-205, 229-260.
[184] Benjamin, *History of Electricity,* 416, 418, 419.
[185] Heilbron, *Electricity in the 17th and 18th Centuries,* 215-217.

Gilbert's electric effluvia theory also went on to spark years of direct responses from Jesuit researchers, especially by Niccoló Cabeo, Gaspar Schott, and Francesco Lana.[186] Cabeo in particular examined Gilbert's electrical phenomena and floating lodestone experiments in depth, incorporating them into books published in 1629.[187]

By the first decades of the 1700s, as seen in the work of thinkers like Francis Hauksbee, Stephen Gray, and Charles François de Cisternay DuFay, electricity was no longer paired with magnetism and had visibly evolved into a field of its own. Through their research, Gilbert's electricks became insulators, and the attractive properties of like and unlike charge were discovered. Over the next 150 years, electrical research continued to evolve until electromagnetic theory, developed by Hans Christian Ørsted, Michael Faraday, and James Clerk Maxwell, reunified the fields of electricity and magnetism.

Conclusion

Having completed our discovery-centric history, it is worthwhile to summarize its course, noting what we take to be elements of the critical path to the discovery of static electric attraction, to raise a number of questions that arise from reflecting on that path, and to tie this study to the larger project of better understanding science.

Summary of the History

The first beginnings of the study of the phenomenon of static electric attraction began in ancient Greece and Rome, where commentators on nature reported observations about two curiosities, amber and lodestone. Many noted that amber, when rubbed, attracts leaves and chaff, and that lodestone attracts iron. Some made further claims as well, including some accurate claims about the attractive powers of gems besides amber. Along with the true claims, there were many false claims, and it was hard to distinguish them. Ancient theories of lodestone or amber attraction provided little help, and while the ancients themselves made little progress, through their efforts the stock of claims that would later be available to Gilbert about the attractive powers of various materials began to accumulate.

In the 11th and 12th centuries, the use of the compass became widespread. Writing in 1269 CE, Peter Petergrinus produced a short treatise on magnetism and compass-making. In his treatise, Peregrinus identified many important but hidden features of lodestone attraction, tied the phenomenon of lodestone attraction to the cosmos, showed how to select and craft a lodestone to

[186] Heilbron, *Electricity in the 17th and 18th Centuries,* 180-183, 188, 190-191.
[187] Heilbron, *Electricity in the 17th and 18th Centuries,* 180-182.

make it easier to study, and presented what was in essence a magnetic research program that others could easily follow. The world would then wait for three centuries for this work, which isolated and distinguished the nearby phenomenon of magnetic attraction, and contributed input into and inspiration for Gilbert's magnetic cosmological theory, to be published.

Entering the Renaissance, and the mid-to-late 16th century, the tradition of commentators on nature resumed. Writers began to undertake more direction examinations of amber and other gems. More and more accurate observations were compiled, and Giralamo Cardano in particular contrasted amber attraction and lodestone attraction, correctly noting many distinguishing features of each. False claims persisted, however, and these continued to blur the lines between magnetic attraction and amber-like attraction. These reports joined the claims of the ancients, providing further truths about amber-like attraction Gilbert could identify as he sifted through and tested the claims of his predecessors, and may have provided suggestions of the possibility of an instrument for studying amber-like attraction.

In 1558 CE, Peregrinus' magnetic treatise was published. Other researchers followed in Peregrinus' footsteps, identifying more facts about magnetic attraction. At the same time, observations were being made about the surprising behavior of magnetized needles by both compass-makers and mariners. Some of these new magnetic observations, especially magnetic dip and magnetic variation, seemed to be at odds with Peregrinus' picture of lodestones as responding to the poles of the heavens, and raised the question of what exactly lodestones were responding to.

This story had been unfolding against the backdrop of a widespread acceptance of Aristotle's cosmological system, and a new challenge to that system. In 1543 CE, Copernicus published his astronomical treatise, in which he claimed that the Earth revolved around the Sun, and that the Earth rotated. This challenged the Aristotelian picture of the Earth and the role of the Earth in the cosmos, and helped to create an opening for a new picture of the world.

Enter William Gilbert, experimentalist and theorist. Gilbert was convinced of Copernicus' claim that the Earth rotates, and was also aware of the puzzling magnetic phenomena, from both the writing of compass-maker Robert Norman, who identified magnetic dip, and his conversations with mariners, who identified magnetic variation. Seeking to explain these phenomena, and at the same time displace Aristotle, Gilbert constructed a magnetic cosmological theory, centered on a theory of magnetic behavior and the claim that the Earth is a giant magnet.

Gilbert used his theory to resolve the difficulties that had arisen in the field of magnetic study, and to attempt to explain the rotation of the Earth. These explanations include an explanation of why the Earth retains its integrity while spinning, and for that, Gilbert felt it necessary to rely on an attractive force other than magnetism. By one or another means, this system of explanations, as well as the commotion other writers had been making on the topic, helped lead Gilbert to

identify attraction by amber, other gems, and other materials as a worthy object of extended study.

Taking the writings of his predecessors on the attractive powers of amber, other gems, and related phenomena as an input, Gilbert then set out to thoroughly investigate the attractive power of various materials. He learned to control experimental conditions, ran a very large number of experiments, thoroughly checked the claims of his predecessors, and may have used an experimental instrument, the non-magnetick versorium, which could be used to detect subtle static electric effects. Through this study, Gilbert identified a long list of amber-like attractors, identified a long list of things that were not amber-like attractors, identified many features of these amber-like attractors, and showed that the category of amber-like attractors was importantly distinct from any other known category. He gave this new category of object a name: *electricks*. This constituted his discovery of static electric attraction.

Gilbert wrote up his results in a chapter of *De magnete*, his treatise on magnetism and the magnetic Earth. He stated his results, gave descriptions of experiments that could be run to verify his claims, and included a description and picture of the non-magnetick versorium.

De magnete was published in 1600 CE. Over the following several decades, Gilbert's discoveries were recognized and added to by others. These later researchers tested Gilbert's claims, added more entries to his list of electricks, and disputed his theories. Following Gilbert, it was now possible to study and expand the understanding of static electric attraction, entirely apart from the study of magnetism. Electrical study had begun.

Alternate Paths to the Discovery

The foregoing history raises a number of interesting questions. We will remark on a few of those questions, in particular those concerning the viability of alternate paths to the discovery of static electric attraction. The answers to these questions will shed further light on the relative importance of each element of Gilbert's critical path and help us understand the general abstract factors that can help and hinder discovery. We would be excited to see these questions answered in further analyses.

A first question to consider is why the ancients did not themselves isolate static electric attraction or assign it greater importance. Did there need to be a plausible theory that designated attraction by amber and other gems as a worthwhile object of study? To what degree did observations about amber-like attraction need to build up by happenstance over time?

A related matter is whether the commentators on nature in the Renaissance would have eventually clearly identified static electric attraction on their own, without any intervention from an experimentalist and bold theorist, and if so, how long this might have taken. On one hand,

there was a trend towards increasing clarity. Writers were dispelling myths, and Cardano in particular made important steps forward, including his list of contrasts between lodestone and amber attraction. On the other hand, as encouraging as these signs may be, Cardano's observations on amber attraction and attraction by other gems were largely ignored, and after him the stream of lower quality commentary continued. There was still an appreciable distance to go to reach a clear identification of static electric attraction, and it is not immediately obvious that more commentary of the same type would have been sufficient.

Another question is the degree to which it was feasible to identify static electric attraction without the aid that came from an understanding of magnetic attraction. Put pithily, could static electric attraction have come first? It is certainly conceivable that static electric attraction could have been discovered without much progress on magnetism. Nevertheless, it is remarkable, and perhaps important, the degree to which knowledge of magnetism, and the various related contributions of Peregrinus, in fact helped Gilbert make his discovery.

Of Gilbert himself and the elements of his research process, we might ask: Is static electric attraction too finicky to have been identified without a substantial experimental effort? Were amber and its companions too obscure to have been selected for extended study without being designated as important by a theory? If so, were there candidates for theories besides those that covered what we might think of as the other half of attraction (i.e., magnetic attraction)? Could Gilbert, or someone in his place, have succeeded with a much less explanatorily ambitious research program?

The answers to these questions are likely to be matters of degree, though extended analysis may yield sharper conclusions. There are also, of course, many other important questions to answer and adjacent topics to be examined.

Towards a Better Understanding of Science

This history told the story of Gilbert's discovery of static electric attraction. In it, we saw a role for observation, experiment, theory, previous research, breakthroughs in seemingly unrelated domains, challenges to previous theory, and the attempted unification of multiple domains. We confronted the obstacles of misinformation and unilluminating theories, both in the context of an initially obscure object of study.

This study provides a data point about scientific discovery. It provides a basis from which to answer further questions about the discovery of static electric attraction, will likely shed light on the dynamics of other historical discoveries, and may contribute directly to an understanding of scientific methodology. By knowing how science worked at one point in history, perhaps we can understand better how science does and can function today.

The discovery of static electric attraction is but one of a very large number of important discoveries that together constitute the successful history of science. By carefully studying these discoveries, and determining how they happened, there can come to exist a more complete foundation for the understanding of science.

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Appendices

Appendix A: Gilbert's Electrical Discoveries

Gilbert's electrical discoveries include the list of electricks he identifies, the list of non-electricks he identifies, the invention of the non-magnetic versorium, and a number of further observations and general claims.

Gilbert lists the following electricks: amber, jet, diamond, sapphire, carbuncle, iris stone, opal, amethyst, vincentina, the English gem or Bristole stone, beryl, rock crystal, glass, false gems made of crystal or paste glass, fluor spars, antimony glass, belemnites, sulfur, mastic, lac sealing wax, hard resin, orpiment, rock salt, mica, and rock alum.[188]

He lists the following non-electricks: emerald, agate, carnelian, pearls, jasper, chalcedony, alabaster, porphyry, coral, the marbles, touchstone, flint, bloodstone, emery, bone, ivory, ebony, cedar, juniper, cypress, silver, gold, brass, iron, lodestone, flesh, pitch, the softer kinds of resin, camphor, galbanum, ammoniack, storax, asafœtida, benzoin, asphaltum (especially in warmer weather). Gilbert also lists the following general categories of things as non-electrick: the dross of metals, metals, stones, rocks, woods, marbles, flints, herbs, and "very many other things."[189]

Regarding Gilbert's discoveries, and his invention of the non-magnetic versorium, Silvanus P. Thompson provides the following helpful list in the notes to his translation of *De magnete*:

1. The generalization of the class of *Electrics*.
2. The observation that damp weather hinders electrification.
3. The generalization that electrified bodies attract everything, including even metals, water, and oil.
4. The invention of the non-magnetic *versorium* or electroscope.
5. The observation that merely warming amber does not electrify it.
6. The recognition of a definite class of *non-electrics*.
7. The observation that certain electrics do not attract if roasted or burnt.
8. That certain electrics when softened by heat lose their power.
9. That the electric effluvia are stopped by the interposition of a sheet of paper or a piece of linen, or by moist air blown from the mouth.
10. That glowing bodies, such as a live coal, brought near excited amber discharge its power.

[188] Gilbert, *On the Magnet,* 48.
[189] Gilbert, *On the Magnet,* 52-53..

11. That the heat of the sun, even when concentrated by a burning mirror, confers no vigour on the amber, but dissipates the effluvia.
12. That sulphur and shell-lac when aflame are not electric.
13. That polish is not essential for an electric.
14. That the electric attracts bodies themselves, not the intervening air.
15. That flame is not attracted.
16. That flame destroys the electrical effluvia.
17. That during south winds and in damp weather, glass and crystal, which collect moisture on their surface, are electrically more interfered with than amber, jet and sulphur, which do not so easily take up moisture on their surfaces.
18. That pure oil does not hinder production of electrification or exercise of attraction.
19. That smoke is electrically attracted, unless too rare.
20. That the attraction by an electric is in a straight line toward it.[190]

We consider Gilbert's primary contributions to electrical study to be:

(1) **New category:** The identification of a category of object ("electricks") that exhibits amber-like attraction and does not match any previously identified natural category, including the category of gems.
(2) **Central feature:** The observation that all electricks attract all light bodies.
(3) **Distinction from nearby phenomena:** The explicit distinction between magnetic and electric attraction, distinguishing them on the basis of behavior, underlying mechanism, and which objects exhibit each.
(4) **Instrument:** The invention of the non-magnetick versorium, to identify subtle electrical effects.

Appendix B: Gilbert on Basic Magnetic Behaviors

Gilbert claims that magnets exhibit the following basic behaviors:[191]

- (a) **Magnetic coition:** "incitement to magnetick union" — magnets exhibit coition or blending together (attraction), especially when close. This force exists in an orb of magnetic coition. Once an object is within the orb of magnetic coition (within the orb of magnetic virtue), it will move.

- (b) **Magnetic verticity:** "direction towards the poles of the earth, and the verticity and continuance of the earth towards the determinate poles of the world" — magnets have a verticity, directive force, or turning power; a magnetized needle or lodestone will rotate

[190] Gilbert, *On the Magnet,* under "Notes," 42.
[191] Gilbert, *On the Magnet,* 46; Georgescu, "Disponent Power," 153.

towards the poles in the vicinity of the globe or a terrella, rather than move physically closer. This force exists from all parts of a magnet but is strongest at the poles. It is often a precursor to coition, acting to arrange magnets so they may attract.

- (c) **Magnetic dip ("declination"):** "a descent of the magnetic pole below the horizon" — the deviation of a magnetized needle from the expected magnetic north in the vertical plane. Declination is especially noticeable in the downward movement of needles near the north pole.
- (d) **Magnetic variation:** "a deflexion from the meridian, which we call a perverted movement" — the deviation of a magnetized needle from the expected magnetic north in the horizontal plane. Variation is caused by Earth's uneven and corrupt terrain.
- (e) **Magnetic rotation ("revolution"):** "circular motion" — magnets rotate on their axes.

Note: Gilbert objects to the word "attract," as he thinks it indicates non-mutuality. In this text, we do not follow Gilbert's usage, regularly using "attract" without the connotation of non-mutuality.

Appendix C: Modern Explanations of Attraction

To understand Gilbert and his contemporaries' discoveries, it is helpful to understand modern explanations for magnetic and static electric attraction. As a result, we shall provide a brief summary, such as might be taught at the high school or early-collegiate level.[192] We will cover magnetic attraction first, and then static electric attraction, as this was the historical order in which each first came to be better understood.

Magnetism and Lodestone Attraction

Magnetic Behavior and Magnetic Fields

Lodestones are typically made of magnetite (Fe_3O_4), a naturally occurring and permanently magnetic mineral. As a result, lodestones are magnets.

Magnets have magnetic poles and magnetic fields and can exert magnetic force. Magnetic fields can be represented by magnetic field lines. Magnetic field lines indicate the direction of the magnetic force on a northern monopole (either a single electric charge or a hypothetical isolated northern magnetic pole) at a given location in the vicinity of the magnet. By convention, the field

[192] Material primarily summarized on the basis of Assis' *The Experimental and Historical Foundations of Electricity*, Thompson and Oldfield's "Magnetic Properties of Solids," and Knight's *Physics for Scientists and Engineers*.

lines point outward from the *north* pole and inward toward the *south* pole. The following figure depicts a standard bar magnet and its magnetic field lines:

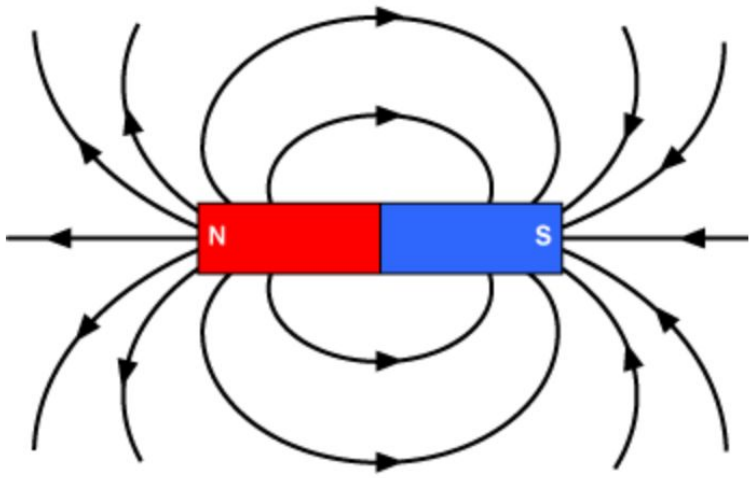

Figure 6. Magnetic field lines of a bar magnet.[193]

The field lines in this diagram indicate that a hypothetical monopole placed directly in front of the northern end of the bar magnet would experience a repulsive force away from that pole.

When the northern poles of two magnets are moved together, the magnets experience a repulsive force. The resultant magnetic field lines are shown below:

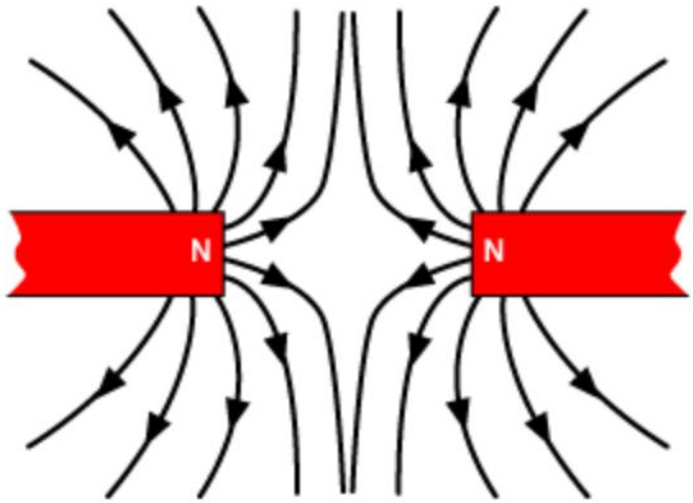

Figure 7. Magnetic field lines of approaching like-magnetic poles.[194]

[193] Museum of Science in Boston and Northeastern University, "How Magnets Work."
[194] Museum of Science in Boston and Northeastern University, "How Magnets Work."

The same behavior holds when two southern magnetic poles approach one another. In other words, similar magnetic poles repel.

When the northern and southern poles of two magnets are moved together, they attract. The resultant magnetic field looks like this:

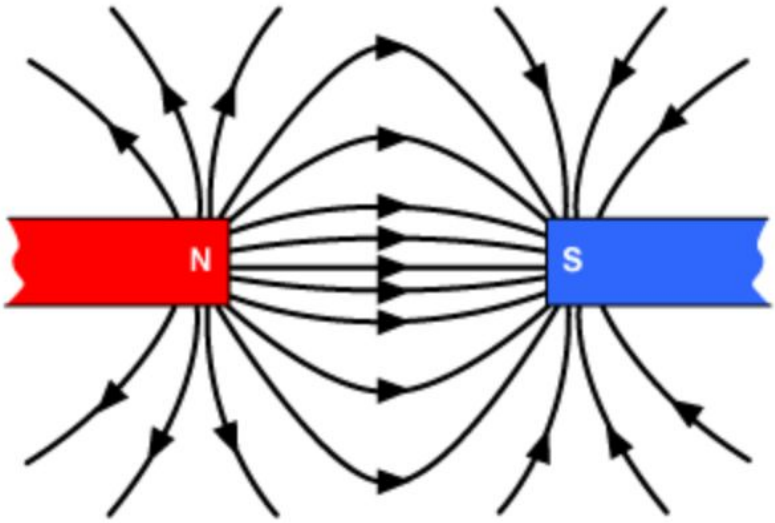

Figure 8. Magnetic field lines of approaching unlike-magnetic poles.[195]

Magnetic fields are produced by the motion of electric charge. Permanent magnetic materials, like the lodestone, gain magnetic properties from the motion of electrons within the material.

Ferromagnetic Materials

In Gilbert's time, the lodestone was known to attract iron and other lodestones. Magnets also attract a larger set of substances called ferromagnetic materials. Ferromagnetic materials include metals such as nickel, cobalt, and steel, in addition to iron.

When ferromagnetic materials like iron are placed in the vicinity of a magnetic field at the right temperature, the magnetic field reorients the dipoles within the ferromagnetic material. After the original magnetic field is removed, the newly arrayed dipoles in the material give rise to a magnetic field of their own. This behavior allows iron to exhibit magnetic properties; magnetized iron attracts other pieces of iron, has its own magnetic poles, and behaves, in the vicinity of bar magnets, like another bar magnet.

Non-ferromagnetic materials are also affected by magnetic fields, though the magnetic force is not typically strong enough to produce visible motion. Non-ferromagnetic materials include

[195] Museum of Science in Boston and Northeastern University, "How Magnets Work."

paramagnetic, diamagnetic, ferrimagnetic, antiferromagnetic, and imperfect antiferromagnetic materials. These materials differ in how strongly they are attracted by magnets, whether they retain their magnetic properties after the removal of a magnetic field, and the arrangements of the magnetic moments within the material.[196]

Compass Behavior

At the center of magnetic compasses, there is a horizontally rotating iron needle. These iron needles are ferromagnetic. When rubbing or striking the needle with a magnet, the needle's dipoles reorient, and the iron needle is magnetized, developing its own magnetic field and corresponding magnetic poles. When a magnetized needle is moved toward the southern end of a fixed bar magnet, the needle will rotate until its northern polar end points towards the southern pole of the bar magnet. If the needle is moved in a circle around the bar magnet, its northern end will follow the bar magnet's field lines (pointing outward from the bar magnet's northern pole) as shown below:

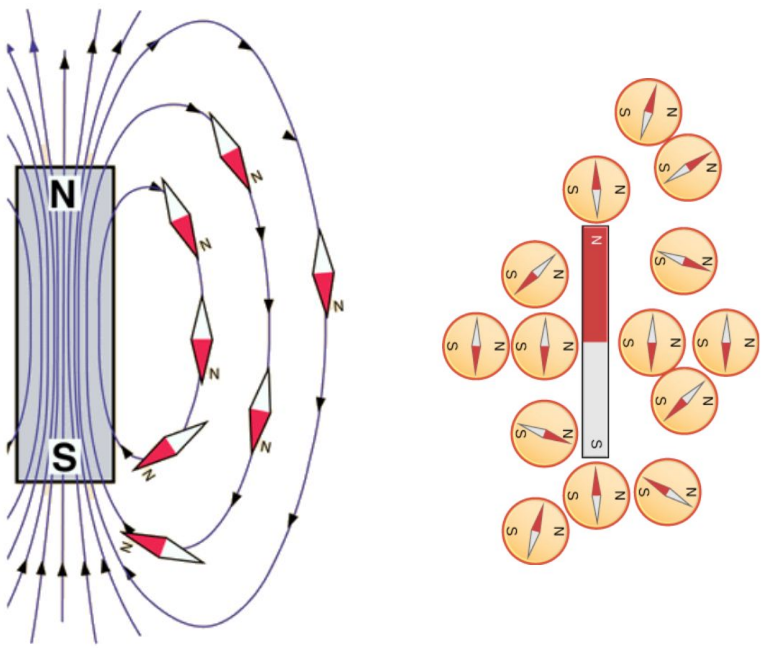

Figure 9. Compass needles in the vicinity of a bar magnet.[197]

The Earth's Magnetic Field and Compass Navigation

Just as a magnetized needle rotates in the vicinity of a fixed bar magnet, a compass needle will rotate in the presence of the Earth's magnetic field. The Earth's magnetic field is caused by

[196] Thompson and Oldfield, "Magnetic Properties of Solids," 3-5.
[197] Georgia State University, "Magnets and Electromagnets"; OpenStax, "Ferromagnets and Electromagnets."

currents of molten iron and nickel flowing rapidly within its core. These currents include rapidly moving charge, and thus exhibit electromagnetic behavior that gives rise to the Earth's magnetic field. The magnetic field generated by these currents has a particular orientation with respect to the Earth's surface—the magnetic north pole of the Earth is located near the Earth's geographic pole, offset by about 11 degrees. The following diagram shows the position of the Earth's magnetic field and corresponding direction of a compass needle:

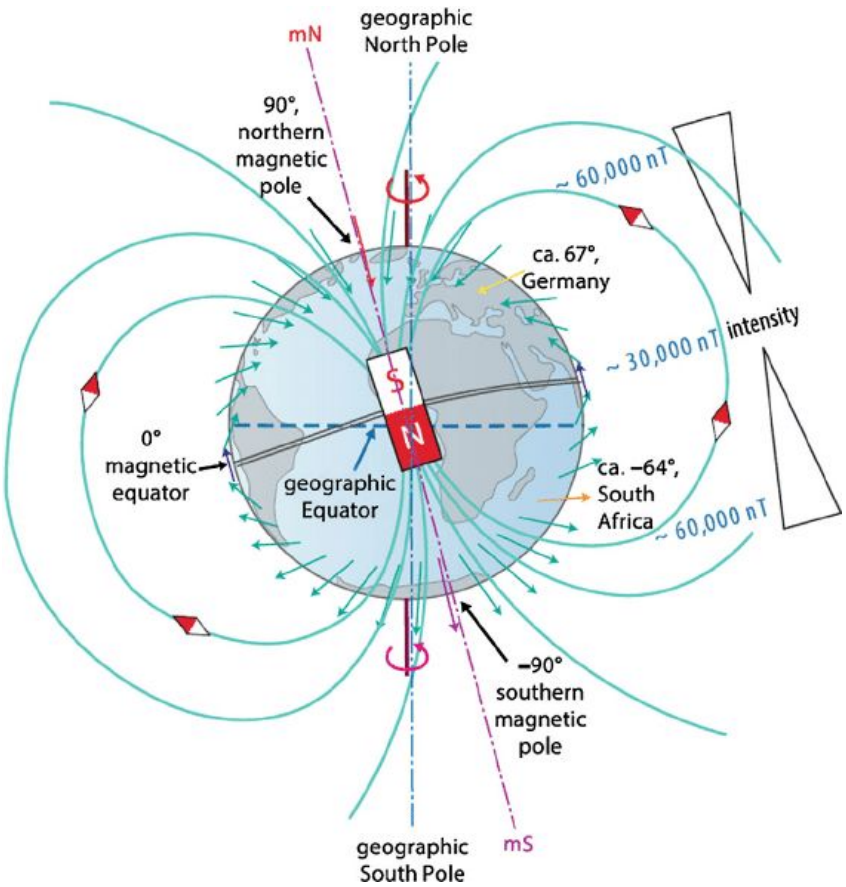

Figure 10. The orientation of the Earth's magnetic field.[198]

As a result of this magnetic behavior, compass needles rotate north and south on the Earth's surface and can be used in navigation.

Static Electricity and Amber Attraction

Some materials, when rubbed, attract light objects. We will briefly describe how this attraction works.

[198] Mouritsen, "Magnetoreception."

The Triboelectric Series

When a bit of wool is rubbed back and forth against a piece of amber, the friction from this rubbing motion causes a transfer of charge between the amber and the wool. This results in a negative charge on the amber and a positive charge on the wool. Though there is some dispute as to the details of the mechanism of transfer of charge, it is generally accepted that the resulting charge on the amber explains its attractive power.[199]

The molecular structure of any given two materials determines which of them, when they are rubbed together, will acquire negative charge and which will acquire positive charge. The *triboelectric series* (a ranked list of materials) documents which materials will gain which charge. When a given material listed in a triboelectric series is rubbed against a material listed lower than it in the same series, the higher material will gain positive charge and the lower material negative charge. Triboelectric rankings of materials are determined empirically by testing each material. These tests can be done using relatively simple instruments to distinguish positive from negative charge on a given material.[200]

Not all triboelectric series are the same—there is variation in which materials are included in each series, as well as the order of materials, even in series that list the same materials. The variation in triboelectric rankings arises from different experimenters including different materials, and from there being different compositions of what are listed as the same materials. From these rankings, we see that when amber is rubbed with wool, the amber often acquires a negative charge and the wool a positive charge.[201] This resulting charge on amber is the basis for its ability to attract chaff, leaves, straw, and other light materials.

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[199] A simple theory underlying the triboelectric series is that materials contain freely or loosely floating electrons that transfer between materials that are rubbed together. Materials with more relative freedom of electrons will release electrons when rubbed against a material whose electrons are more tightly held. Modified versions of this theory have been entertained for many years and often appear in textbooks. Some researchers strongly advocate this theory, including that electrons transfer and that the measured starting polarity of a material is a very good predictor of its triboelectric ranking. In contrast, however, some argue that this theory, when paired with our understanding of each material's atomic and molecular structure, does not readily predict the triboelectric ranking of materials. Some researchers have also expressed confusion about why this transfer would take place against the charge's typical attractive force patterns, and how insulators, whose charge is otherwise relatively fixed within itself, would transfer charge across materials. As a result of these and other uncertainties, there is still disagreement among triboelectric researchers as to whether the acquisition of positive and negative charge arises from the transfer of electrons at all. Shaw and Barton, "Experiments on Tribo-Electricity," 27; Assis, *Foundations of Electricity,* 2:272; Lee and Orr, "The Triboelectric Series."

[200] For instructions on how to perform these experiments and create a triboelectric ranking, see Assis, *Foundations of Electricity,* 1:111-123.

[201] Shaw and Barton, "Experiments on Tribo-Electricity," 32.

Conductors, Insulators, Polarization, and Electrostatic Attraction

To understand why excess charge allows amber to attract light objects, we will briefly explain conductors and insulators. Inside conductors, charge moves much more freely than inside insulators. Insulators still permit some charge mobility, allowing charge to move within a given molecule.

Like charges repel and unlike charges attract. As a result, when a charged material is moved toward another material, the charge in that other material is attracted or repelled.

In conductors, the charge within a material redistributes across the entire material to maximize the distance between like charges. When an electrically neutral conducting material is approached by a negatively charged material, the charges in the conducting material move as follows (conductor on the right):

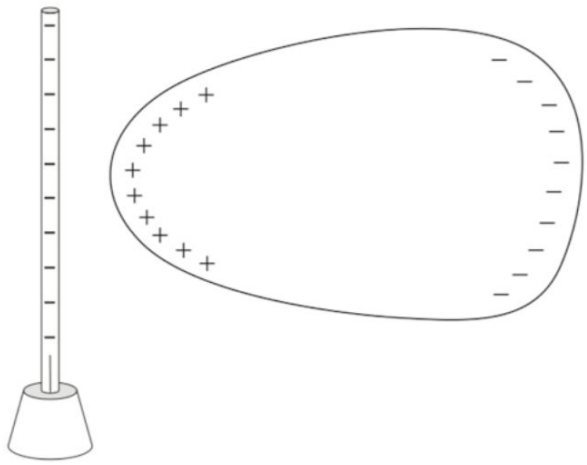

Figure 11. Assis' diagram of a conductor in the vicinity of a negatively charged object.[202]

This behavior creates a net charge on each end of the conductor.

In contrast, the motion of charge in insulators due to repulsion and attraction stays within each molecule. The polarization of all the molecules still creates a net charge across the whole insulator, though distinctly smaller in magnitude than in a conductor.

[202] Assis, *Foundations of Electricity,* 1:200.

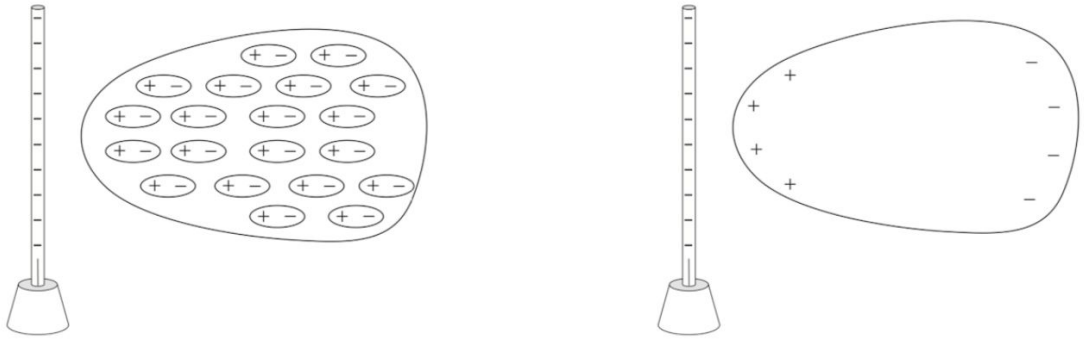

Figure 12. Assis' diagram of an insulator (left) and a conductor (right) near a negatively charged object.[203]

In both conductors and insulators, the approach of another object that is charged will yield a redistribution of charge within the original object, yielding a net charge on each end of the object.

According to Coulomb's law, attraction decreases with distance. While the negative charge of the polarized object will repel the negative charge on the original negatively charged insulator, this repulsive force will be weaker than the attractive force from the closer positive end of the polarized object. As a result, the original charged object and the newly polarized object will attract. When the repulsive force of the two negatives and the attractive force of the positive and negative become equal, then the system is in equilibrium, and the objects stop attracting. In polarized conductors, this attraction effect is the strongest. In polarized insulators, the effect still occurs, but less strongly.

Amber itself is typically an insulator. When rubbed by wool, it frequently acquires a negative charge, thereby becoming a negative insulator. If it is then brought near to electrical neutral objects, such as bits of paper, the negative charge in the amber repels the negative charge within each bit of paper, and attracts the positive charge. This causes the portion of each bit of paper closest to the amber to become net positive and the portion farthest from the amber to become net negative, creating a net polarization. If the attractive force between the amber and the positive end of a bit of paper is stronger than the repulsive force between the amber and the negative end of that bit of paper, as well as other relevant forces such as gravity, then that bit of paper will rise toward the amber.

The fact that amber is typically an insulator is crucial to this effect. When it is an insulator, amber maintains its negative charge from being rubbed with wool even when held in an experimenter's hand. By contrast, a conductor would pass that charge through the user's hand,

[203] Assis, *Foundations of Electricity,* 1:201.

which also conducts, and down to the ground, removing the added charge needed for the amber to polarize and attract the bits of paper. When a piece of amber acts as a conductor rather than an insulator, which does sometimes happen, the amber does not exhibit attractive effects.

This description also applies to rubbed insulating materials other than amber. Whether a rubbed insulator acquires a positive or negative charge, it will polarize and attract electrically neutral objects. As a result, any insulating material that is rubbed by an element higher or lower on the triboelectric series can acquire charge and exert attractive force. This can enable those materials to attract light objects, just like amber does with small bits of paper.

Several related phenomena also affect the attractive behaviors seen in static electric contexts and add complexity to the basic behaviors we have described. The conditions of attraction and objects' rankings in the triboelectric series can be affected by environmental factors like temperature and humanity. Further, polarization and subsequent attractive forces can exist when the light objects are not electrically neutral or when amber is replaced with a conducting material surrounded by insulators. Additionally, after objects attract, they sometimes repel.

However, to understand the development of insights into static electric attraction up through Gilbert, the details of these mechanisms can be put aside. It is enough to understand that (1) rubbed insulators attract light objects in static electric contexts, (2) there exists complexity and variation stemming from the different compositions of materials as related to their position in the triboelectric series and whether they behave as conductors or insulators, and (3) attractive behaviors are influenced by other phenomena environmental conditions, the original charges of small materials being attracted, and repulsion following attraction.

Appendix D: Treatment of References

Thompson's Notes

With a group of ten collaborators and translators over the course of ten years, Silvanus P. Thompson sought to translate *De magnete* and verify the primary sources Gilbert cites.[204] His notes offer an incredibly extensive catalog of authors and primary source excerpts to match Gilbert's (uncited) claims about the views of ancient, medieval, and Renaissance thinkers.

After checking a number of Thompson's citations to verify reliability, we concluded that his notes are thorough and clear on the extent of their coverage, and the translations and excerpts given are usually accurate. We thus felt it was safe to rely on these notes in this essay. In many

[204] Roller, "On the Magnet," 172-173; Gilbert, *On the Magnet,* under "Notes." The group was called the Gilbert Club.

cases we cite Thompson's notes directly; in cases where we dig deeper, we cite the relevant original sources.

Gilbert's References

Gilbert summarizes and quotes the views of many thinkers. Unfortunately, Gilbert often does not cite their texts, leading to some concern about the accuracy of his reports. From the sources we were able to verify, Gilbert is often overly critical or hard to interpret, but not typically prone to fully mischaracterizing ideas. As a result, we consider Gilbert's account somewhat but not totally reliable, and a shame to exclude entirely due to its exhaustiveness. As a result, we rely on his translations and renditions of others' claims only where we could not find other sources.