Timberlane High School Science Summer Reading Assignment:

Course: Physics CCP

Instructions

Please read the following selection(s) from the book A Short History of Nearly Everything by Bill Bryson.

- Please provide written answers (short essay style) to the questions at the end of the reading

  •Questions adapted from Random House Publishing Inc.
  https://www.randomhouse.com/catalog/teachers_guides/9780767908184.pdf
- The written assignment is to be turned into your teacher by **Thursday, September 5th and Friday, September 6th,** for potential full credit. Accepted until Sept 12th with 10% deduction in grade per day. Not accepted after Sept 12th.
- This is a graded assignment worth up to 3% of your quarter 1 grade. **Grading Rubric:**

The writing will be assessed on the following 0 to 3 scales

- Each answer should be in a short essay style (minimum one paragraph).
  - 1: most answers are short one word answers.
  - 3: complete thoughts and sentences that fully convey the answers.
- Each answer should demonstrate evidence of reading to comprehension.
  - 1: answers indicate that the reading was not completed o 3: answers show clear comprehension of the reading
- Each answer should be correct, relevant to the topic, should strive for detail and completeness.
  - 1: answers are not relative to question or reading o 3: Answers demonstrate clear relevancy to passage and get to the heart of the rationale for question in relation to subject area.
- Each answer should refer to a specific statement or include a quote from the reading.
  - 1: the writing is vague, incomplete and contains little detail o 3: writing is detailed, complete and references specific statements or quotes from the reading passage.
- Each answer should be original (no plagiarism)

Tips on how to read science text for comprehension:

Break the reading into more than one session (2 to 4 pages per day). This should take about 15 minutes each time. Read slowly! Understand each sentence before reading the next. Be sure to examine unfamiliar words and concepts; try to determine meaning from the reading (or look them up). Make notes on each paragraph! It is OK to reread as you go or even reread the entire text. Read to understand, think about the ideas as you read and relate to what you already know, and what you may want to find out.

4 THE MEASURE OF THINGS

IF YOU HAD to select the least convivial scientific field trip of all time, you could certainly do worse than the French Royal Academy of Sciences' Peruvian expedition of 1735. Led by a hydrologist named Pierre Bouguer and a soldier-mathematician named Charles Marie de La Condamine, it was a party of scientists and adventurers who traveled to Peru with the purpose of triangulating distances through the Andes.

At the time people had lately become infected with a powerful desire to understand the Earth—to determine how old it was, and how massive, where it hung in space, and how it had come to be. The French party's goal was to help settle the question of the circumference of the planet by measuring the length of one degree of meridian (or 1/360 of the distance around the planet) along a line reaching from Yarouqui, near Quito, to just beyond Cuenca in what is now Ecuador, a distance of about two hundred miles.[1]

Almost at once things began to go wrong, sometimes spectacularly so. In Quito, the visitors somehow provoked the locals and were chased out of town by a mob armed with stones. Soon after, the expedition's doctor was murdered in a misunderstanding over a woman. The botanist became deranged. Others died of fevers and falls. The third most senior member of the party, a man named Pierre Godin, ran off with a thirteen-year-old girl and could not be induced to return.

At one point the group had to suspend work for eight months while La Condamine rode off to Lima to sort out a problem with their permits. Eventually he and Bouguer stopped speaking and refused to work together. Everywhere the dwindling party went it was met with the deepest suspicions from officials who found it difficult to believe that a group of French scientists would travel halfway around the world to measure the world. That made no sense at all. Two and a half centuries later it still seems a reasonable question. Why didn't the French make their measurements in France and save themselves all the bother and discomfort of their Andean adventure?

The answer lies partly with the fact that eighteenth-century scientists, the French in particular, seldom did things simply if an absurdly demanding alternative was available, and partly with a practical problem that had first arisen with the English astronomer Edmond Halley many years before—long before Bouguer and La Condamine dreamed of going to South America, much less had a reason for doing so.

* Triangulation, their chosen method, was a popular technique based on the geometric fact that if you know the length of one side of a triangle and the angles of two corners, you can work out all its other dimensions without leaving your chair. Suppose, by way of example, that you and I decided we wished to know how far it is to the Moon. Using triangulation, the first thing we must do is put some distance between us, so let's say for argument that you stay in Paris and I go to Moscow and we both look at the Moon at the same time. Now if you imagine a line connecting the three principals of this exercise-that is, you and I and the Moon-it forms a triangle. Measure the length of the baseline between you and me and the angles of our two corners and the rest can be simply calculated. (Because the interior angles of a triangle always add up to 180 degrees, if you know the sum of two of the angles you can instantly calculate the third; and knowing the precise shape of a triangle and the length of one side tells you the lengths of the other sides.) This was in fact the method use by a Greek astronomer, Hipparchus of Nicaea, in 150 B.C. to work out the Moon's distance from Earth. At ground level, the principles of triangulation are the same, except that the triangles don't reach into space but rather are laid side to side on a map. In measuring a degree of meridian, the surveyors would create a sort of chain of triangles marching across the landscape.

Halley was an exceptional figure. In the course of a long and productive career, he was a sea captain, a cartographer, a professor of geometry at the University of Oxford, deputy controller of the Royal Mint, astronomer royal, and inventor of the deep-sea diving bell. He wrote authoritatively on magnetism, tides, and the motions of the planets, and fondly on the effects of opium. He invented the weather map and actuarial table, proposed methods for working out the age of the Earth and its distance from the Sun, even devised a practical method for keeping fish fresh out of season. The one thing he didn't do, interestingly enough, was discover the comet that bears his name. He merely recognized that the comet he saw in 1682 was the same one that had been seen by others in 1456, 1531, and 1607. It didn't become Halley's comet until 1758, some sixteen years after his death.

For all his achievements, however, Halley's greatest contribution to human knowledge may simply have been to take part in a modest scientific wager with two other worthies of his day: Robert Hooke, who is perhaps best remembered now as the first person to describe a cell, and the great and stately Sir Christopher Wren, who was actually an astronomer first and architect second, though that is not often generally remembered now. In 1683, Halley, Hooke, and Wren were dining in London when the conversation turned to the motions of celestial objects. It was known that planets were inclined to orbit in a particular kind of oval known as an ellipse—"a very specific and precise curve," to quote Richard Feynman—but it wasn't understood why. Wren generously offered a prize worth forty shillings (equivalent to a couple of weeks' pay) to whichever of the men could provide a solution.

Hooke, who was well known for taking credit for ideas that weren't necessarily his own, claimed that he had solved the problem already but declined now to share it on the interesting and inventive grounds that it would rob others of the satisfaction of discovering the answer for themselves. He would instead "conceal it for some time, that others might know how to value it." If he thought any more on the matter, he left no evidence of it. Halley, however, became consumed with finding the answer, to the point that the following year he traveled to Cambridge and boldly called upon the university's Lucasian Professor of Mathematics, Isaac Newton, in the hope that he could help.

Newton was a decidedly odd figure—brilliant beyond measure, but solitary, joyless, prickly to the point of paranoia, famously distracted (upon swinging his feet out of bed in the morning he would reportedly sometimes sit for hours, immobilized by the sudden rush of thoughts to his head), and capable of the most riveting strangeness. He built his own laboratory, the first at Cambridge, but then engaged in the most bizarre experiments. Once he inserted a bodkin—a long needle of the sort used for sewing leather—into his eye socket and rubbed it around "betwixt my eye and the bone as near to [the] backside of my eye as I could" just to see what would happen. What happened, miraculously, was nothing—at least nothing lasting. On another occasion, he stared at the Sun for as long as he could bear, to determine what effect it would have upon his vision. Again he escaped lasting damage, though he had to spend some days in a darkened room before his eyes forgave him.

Set atop these odd beliefs and quirky traits, however, was the mind of a supreme genius—though even when working in conventional channels he often showed a tendency to peculiarity. As a student, frustrated by the limitations of conventional mathematics, he invented an entirely new form, the calculus, but then told no one about it for twenty-seven years. In like manner, he did work in optics that transformed our understanding of light and laid the foundation for the science of spectroscopy, and again chose not to share the results for three decades.

For all his brilliance, real science accounted for only a part of his interests. At least half his working life was given over to alchemy and wayward religious pursuits. These were not mere dabblings but wholehearted devotions. He was a secret adherent of a dangerously heretical sect called Arianism, whose principal tenet was the belief that there had been no Holy Trinity (slightly ironic since Newton's college at Cambridge was Trinity). He spent endless hours studying the floor plan of the lost Temple of King Solomon in Jerusalem (teaching himself Hebrew in the process, the better to scan original texts) in the belief that it held mathematical clues to the dates of the second coming of Christ and the end of the world. His attachment to alchemy was no less ardent. In 1936, the economist John Maynard Keynes bought a trunk of Newton's papers at auction and discovered with astonishment that they were overwhelmingly preoccupied not with optics or planetary motions, but with a single-minded quest to turn base metals into precious ones. An analysis of a strand of Newton's hair in the 1970s found it contained mercury—an element of interest to alchemists, hatters, and thermometer-makers but almost no one else—at a concentration some forty times the natural level. It is perhaps little wonder that he had trouble remembering to rise in the morning.

Quite what Halley expected to get from him when he made his unannounced visit in August 1684 we can only guess. But thanks to the later account of a Newton confidant, Abraham DeMoivre, we do have a record of one of science's most historic encounters:

In 1684 D^r Halley came to visit at Cambridge [and] after they had some time together the D^r asked him what he thought the curve would be that would be described by the Planets supposing the force of attraction toward the Sun to be reciprocal to the square of their distance from it.

This was a reference to a piece of mathematics known as the inverse square law, which Halley was convinced lay at the heart of the explanation, though he wasn't sure exactly how.

S^r Isaac replied immediately that it would be an [ellipse]. The Doctor, struck with joy & amazement, asked him how he knew it. 'Why,' saith he, 'I have calculated it,' whereupon D^r Halley asked him for his calculation without farther delay, S^r Isaac looked among his papers but could not find it.

This was astounding—like someone saying he had found a cure for cancer but couldn't remember where he had put the formula. Pressed by Halley, Newton agreed to redo the calculations and produce a paper. He did as promised, but then did much more. He retired for two years of intensive reflection and scribbling, and at length produced his masterwork: the Philosophiae Naturalis Principia Mathematica or Mathematical Principles of Natural Philosophy, better known as the Principia .

Once in a great while, a few times in history, a human mind produces an observation so acute and unexpected that people can't quite decide which is the more amazing—the fact or the thinking of it. Principia was one of those moments. It made Newton instantly famous. For the rest of his life he would be draped with plaudits and honors, becoming, among much else, the first person in Britain knighted for scientific achievement. Even the great German mathematician Gottfried von Leibniz, with whom Newton had a long, bitter fight over priority for the invention of the calculus, thought his contributions to mathematics equal to all the accumulated work that had preceded him. "Nearer the gods no mortal may approach," wrote Halley in a sentiment that was endlessly echoed by his contemporaries and by many others since.

Although the Principia has been called "one of the most inaccessible books ever written" (Newton intentionally made it difficult so that he wouldn't be pestered by mathematical "smatterers," as he called them), it was a beacon to those who could follow it. It not only explained mathematically the orbits of heavenly bodies, but also identified the attractive force that got them moving in the first place—gravity. Suddenly every motion in the universe made sense.

At Principia 's heart were Newton's three laws of motion (which state, very baldly, that a thing moves in the direction in which it is pushed; that it will keep moving in a straight line until some other force acts to slow or deflect it; and that every action has an opposite and equal reaction) and his universal law of gravitation. This states that every object in the universe exerts a tug on every other. It may not seem like it, but as you sit here now you are pulling everything around you—walls, ceiling, lamp, pet cat—toward you with your own little (indeed, very little) gravitational field. And these things are also pulling on you. It was Newton who realized that the pull of any two objects is, to quote Feynman again, "proportional to the mass of each and varies inversely as the square of the distance between them." Put another way, if you double the distance between two objects, the attraction between them becomes four times weaker. This can be expressed with the formula

$$F = \frac{Gmm}{R_2}$$

which is of course way beyond anything that most of us could make practical use of, but at least we can appreciate that it is elegantly compact. A couple of brief multiplications, a simple division, and, bingo, you know your gravitational position wherever you go. It was the first really universal law of nature ever propounded by a human mind, which is why Newton is regarded with such universal esteem.

Principia's production was not without drama. To Halley's horror, just as work was nearing completion Newton and Hooke fell into dispute over the priority for the inverse square law and Newton refused to release the crucial third volume, without which the first two made little sense. Only with some frantic shuttle diplomacy and the most liberal applications of flattery did Halley manage finally to extract the concluding volume from the erratic professor.

Halley's traumas were not yet quite over. The Royal Society had promised to publish the work, but now pulled out, citing financial embarrassment. The year before the society had backed a costly flop called The History of Fishes , and they now suspected that the market for a book on mathematical principles would be less than clamorous. Halley, whose means were not great, paid for the book's publication out of his own pocket. Newton, as was his custom, contributed nothing. To make matters worse, Halley at this time had just accepted a position as the society's clerk, and he was informed that the society could no longer afford to provide him with a promised salary of £50 per annum. He was to be paid instead in copies of The History of Fishes .

Newton's laws explained so many things—the slosh and roll of ocean tides, the motions of planets, why cannonballs trace a particular trajectory before thudding back to Earth, why we aren't flung into space as the planet spins beneath us at hundreds of miles an hour[2] —that it took a while for all their implications to seep in. But one revelation became almost immediately controversial.

This was the suggestion that the Earth is not quite round. According to Newton's theory, the centrifugal force of the Earth's spin should result in a slight flattening at the poles and a bulging at the equator, which would make the planet slightly oblate. That meant that the length of a degree wouldn't be the same in Italy as it was in Scotland. Specifically, the length would shorten as you moved away from the poles. This was not good news for those people whose measurements of the Earth were based on the assumption that the Earth was a perfect sphere, which was everyone.

For half a century people had been trying to work out the size of the Earth, mostly by making very exacting measurements. One of the first such attempts was by an English mathematician named Richard Norwood. As a young man Norwood had traveled to Bermuda with a diving bell modeled on Halley's device, intending to make a fortune scooping pearls from the seabed. The scheme failed because there were no pearls and anyway Norwood's bell didn't work, but Norwood was not one to waste an experience. In the early seventeenth century Bermuda was well known among ships' captains for being hard to locate. The problem was that the ocean was big, Bermuda small, and the navigational tools for dealing with this disparity hopelessly inadequate. There wasn't even yet an agreed length for a nautical mile. Over the breadth of an ocean the smallest miscalculations would become magnified so that ships often missed Bermuda-sized targets by dismaying margins. Norwood, whose first love was trigonometry and thus angles, decided to bring a little mathematical rigor to navigation and to that end he determined to calculate the length of a degree.

Starting with his back against the Tower of London, Norwood spent two devoted years marching 208 miles north to York, repeatedly stretching and measuring a length of chain as he went, all the while making the most meticulous adjustments for the rise and fall of the land and the meanderings of the road. The final step was to measure the angle of the Sun at York at the same time of day and on the same day of the year as he had made his first measurement in London. From this, he reasoned he could determine the length of one degree of the Earth's meridian and thus calculate the distance around the whole. It was an almost ludicrously ambitious undertaking—a mistake of the slightest fraction of a degree would throw the whole thing out by miles—but in fact, as Norwood proudly declaimed, he was accurate to "within a scantling"—or, more precisely, to within about six hundred yards. In metric terms, his figure worked out at 110.72 kilometers per degree of arc.

In 1637, Norwood's masterwork of navigation, The Seaman's Practice , was published and found an immediate following. It went through seventeen editions and was still in print twenty-five years after his death. Norwood returned to Bermuda with his family, becoming a

[2] How fast you are spinning depends on where you are. The speed of the Earth's spin varies from a little over 1,000 miles an hour at the equator to 0 at the poles.

successful planter and devoting his leisure hours to his first love, trigonometry. He survived there for thirty-eight years and it would be pleasing to report that he passed this span in happiness and adulation. In fact, he didn't. On the crossing from England, his two young sons were placed in a cabin with the Reverend Nathaniel White, and somehow so successfully traumatized the young vicar that he devoted much of the rest of his career to persecuting Norwood in any small way he could think of.

Norwood's two daughters brought their father additional pain by making poor marriages. One of the husbands, possibly incited by the vicar, continually laid small charges against Norwood in court, causing him much exasperation and necessitating repeated trips across Bermuda to defend himself. Finally in the 1650s witch trials came to Bermuda and Norwood spent his final years in severe unease that his papers on trigonometry, with their arcane symbols, would be taken as communications with the devil and that he would be treated to a dreadful execution. So little is known of Norwood that it may in fact be that he deserved his unhappy declining years. What is certainly true is that he got them.

Meanwhile, the momentum for determining the Earth's circumference passed to France. There, the astronomer Jean Picard devised an impressively complicated method of triangulation involving quadrants, pendulum clocks, zenith sectors, and telescopes (for observing the motions of the moons of Jupiter). After two years of trundling and triangulating his way across France, in 1669 he announced a more accurate measure of 110.46 kilometers for one degree of arc. This was a great source of pride for the French, but it was predicated on the assumption that the Earth was a perfect sphere—which Newton now said it was not.

To complicate matters, after Picard's death the father-and-son team of Giovanni and Jacques Cassini repeated Picard's experiments over a larger area and came up with results that suggested that the Earth was fatter not at the equator but at the poles—that Newton, in other words, was exactly wrong. It was this that prompted the Academy of Sciences to dispatch Bouguer and La Condamine to South America to take new measurements.

They chose the Andes because they needed to measure near the equator, to determine if there really was a difference in sphericity there, and because they reasoned that mountains would give them good sightlines. In fact, the mountains of Peru were so constantly lost in cloud that the team often had to wait weeks for an hour's clear surveying. On top of that, they had selected one of the most nearly impossible terrains on Earth. Peruvians refer to their landscape as muy accidentado —"much accidented"—and this it most certainly is. The French had not only to scale some of the world's most challenging mountains—mountains that defeated even their mules—but to reach the mountains they had to ford wild rivers, hack their way through jungles, and cross miles of high, stony desert, nearly all of it uncharted and far from any source of supplies. But Bouguer and La Condamine were nothing if not tenacious, and they stuck to the task for nine and a half long, grim, sun-blistered years. Shortly before concluding the project, they received word that a second French team, taking measurements in northern Scandinavia (and facing notable discomforts of their own, from squelching bogs to dangerous ice floes), had found that a degree was in fact longer near the poles, as Newton had promised. The Earth was forty-three kilometers stouter when measured equatorially than when measured from top to bottom around the poles.

Bouguer and La Condamine thus had spent nearly a decade working toward a result they didn't wish to find only to learn now that they weren't even the first to find it. Listlessly, they completed their survey, which confirmed that the first French team was correct. Then, still not speaking, they returned to the coast and took separate ships home.

Something else conjectured by Newton in the Principia was that a plumb bob hung near a mountain would incline very slightly toward the mountain, affected by the mountain's gravitational mass as well as by the Earth's. This was more than a curious fact. If you measured the deflection accurately and worked out the mass of the mountain, you could calculate the universal gravitational constant—that is, the basic value of gravity, known as G—and along with it the mass of the Earth.

Bouguer and La Condamine had tried this on Peru's Mount Chimborazo, but had been defeated by both the technical difficulties and their own squabbling, and so the notion lay dormant for another thirty years until resurrected in England by Nevil Maskelyne, the astronomer royal. In Dava Sobel's popular book Longitude, Maskelyne is presented as a ninny and villain for failing to appreciate the brilliance of the clockmaker John Harrison, and this may be so, but we are indebted to him in other ways not mentioned in her book, not least for his successful scheme to weigh the Earth. Maskelyne realized that the nub of the problem lay with finding a mountain of sufficiently regular shape to judge its mass.

At his urging, the Royal Society agreed to engage a reliable figure to tour the British Isles to see if such a mountain could be found. Maskelyne knew just such a person—the astronomer and surveyor Charles Mason. Maskelyne and Mason had become friends eleven years earlier while engaged in a project to measure an astronomical event of great importance: the passage of the planet Venus across the face of the Sun. The tireless Edmond Halley had suggested years before that if you measured one of these passages from selected points on the Earth, you could use the principles of triangulation to work out the distance to the Sun, and from that calibrate the distances to all the other bodies in the solar system.

Unfortunately, transits of Venus, as they are known, are an irregular occurrence. They come in pairs eight years apart, but then are absent for a century or more, and there were none in Halley's lifetime.[3] But the idea simmered and when the next transit came due in 1761, nearly two decades after Halley's death, the scientific world was ready—indeed, more ready than it had been for an astronomical event before.

With the instinct for ordeal that characterized the age, scientists set off for more than a hundred locations around the globe—to Siberia, China, South Africa, Indonesia, and the woods of Wisconsin, among many others. France dispatched thirty-two observers, Britain eighteen more, and still others set out from Sweden, Russia, Italy, Germany, Ireland, and elsewhere.

It was history's first cooperative international scientific venture, and almost everywhere it ran into problems. Many observers were waylaid by war, sickness, or shipwreck. Others made their destinations but opened their crates to find equipment broken or warped by tropical heat. Once again the French seemed fated to provide the most memorably unlucky participants. Jean Chappe spent months traveling to Siberia by coach, boat, and sleigh, nursing his delicate instruments over every perilous bump, only to find the last vital stretch blocked by swollen

[3] The next transit will be on June 8, 2004, with a second in 2012. There were none in the twentieth century.

rivers, the result of unusually heavy spring rains, which the locals were swift to blame on him after they saw him pointing strange instruments at the sky. Chappe managed to escape with his life, but with no useful measurements.

Unluckier still was Guillaume Le Gentil, whose experiences are wonderfully summarized by Timothy Ferris in Coming of Age in the Milky Way . Le Gentil set off from France a year ahead of time to observe the transit from India, but various setbacks left him still at sea on the day of the transit—just about the worst place to be since steady measurements were impossible on a pitching ship.

Undaunted, Le Gentil continued on to India to await the next transit in 1769. With eight years to prepare, he erected a first-rate viewing station, tested and retested his instruments, and had everything in a state of perfect readiness. On the morning of the second transit, June 4, 1769, he awoke to a fine day, but, just as Venus began its pass, a cloud slid in front of the Sun and remained there for almost exactly the duration of the transit: three hours, fourteen minutes, and seven seconds.

Stoically, Le Gentil packed up his instruments and set off for the nearest port, but en route he contracted dysentery and was laid up for nearly a year. Still weakened, he finally made it onto a ship. It was nearly wrecked in a hurricane off the African coast. When at last he reached home, eleven and a half years after setting off, and having achieved nothing, he discovered that his relatives had had him declared dead in his absence and had enthusiastically plundered his estate.

In comparison, the disappointments experienced by Britain's eighteen scattered observers were mild. Mason found himself paired with a young surveyor named Jeremiah Dixon and apparently they got along well, for they formed a lasting partnership. Their instructions were to travel to Sumatra and chart the transit there, but after just one night at sea their ship was attacked by a French frigate. (Although scientists were in an internationally cooperative mood, nations weren't.) Mason and Dixon sent a note to the Royal Society observing that it seemed awfully dangerous on the high seas and wondering if perhaps the whole thing oughtn't to be called off. In reply they received a swift and chilly rebuke, noting that they had already been paid, that the nation and scientific community were counting on them, and that their failure to proceed would result in the irretrievable loss of their reputations. Chastened, they sailed on, but en route word reached them that Sumatra had fallen to the French and so they observed the transit inconclusively from the Cape of Good Hope. On the way home they stopped on the lonely Atlantic outcrop of St. Helena, where they met Maskelyne, whose observations had been thwarted by cloud cover. Mason and Maskelyne formed a solid friendship and spent several happy, and possibly even mildly useful, weeks charting tidal flows.

Soon afterward, Maskelyne returned to England where he became astronomer royal, and Mason and Dixon—now evidently more seasoned—set off for four long and often perilous years surveying their way through 244 miles of dangerous American wilderness to settle a boundary dispute between the estates of William Penn and Lord Baltimore and their respective colonies of Pennsylvania and Maryland. The result was the famous Mason and Dixon line, which later took on symbolic importance as the dividing line between the slave and free states. (Although the line was their principal task, they also contributed several astronomical surveys, including one of the century's most accurate measurements of a degree of meridian—an achievement that brought them far more acclaim in England than the settling of a boundary dispute between spoiled aristocrats.)

Back in Europe, Maskelyne and his counterparts in Germany and France were forced to the conclusion that the transit measurements of 1761 were essentially a failure. One of the problems, ironically, was that there were too many observations, which when brought together often proved contradictory and impossible to resolve. The successful charting of a Venusian transit fell instead to a little-known Yorkshire-born sea captain named James Cook, who watched the 1769 transit from a sunny hilltop in Tahiti, and then went on to chart and claim Australia for the British crown. Upon his return there was now enough information for the French astronomer Joseph Lalande to calculate that the mean distance from the Earth to the Sun was a little over 150 million kilometers. (Two further transits in the nineteenth century allowed astronomers to put the figure at 149.59 million kilometers, where it has remained ever since. The precise distance, we now know, is 149.597870691 million kilometers.) The Earth at last had a position in space.

As for Mason and Dixon, they returned to England as scientific heroes and, for reasons unknown, dissolved their partnership. Considering the frequency with which they turn up at seminal events in eighteenth-century science, remarkably little is known about either man. No likenesses exist and few written references. Of Dixon the Dictionary of National Biography notes intriguingly that he was "said to have been born in a coal mine," but then leaves it to the reader's imagination to supply a plausible explanatory circumstance, and adds that he died at Durham in 1777. Apart from his name and long association with Mason, nothing more is known.

Mason is only slightly less shadowy. We know that in 1772, at Maskelyne's behest, he accepted the commission to find a suitable mountain for the gravitational deflection experiment, at length reporting back that the mountain they needed was in the central Scottish Highlands, just above Loch Tay, and was called Schiehallion. Nothing, however, would induce him to spend a summer surveying it. He never returned to the field again. His next known movement was in 1786 when, abruptly and mysteriously, he turned up in Philadelphia with his wife and eight children, apparently on the verge of destitution. He had not been back to America since completing his survey there eighteen years earlier and had no known reason for being there, or any friends or patrons to greet him. A few weeks later he was dead.

With Mason refusing to survey the mountain, the job fell to Maskelyne. So for four months in the summer of 1774, Maskelyne lived in a tent in a remote Scottish glen and spent his days directing a team of surveyors, who took hundreds of measurements from every possible position. To find the mass of the mountain from all these numbers required a great deal of tedious calculating, for which a mathematician named Charles Hutton was engaged. The surveyors had covered a map with scores of figures, each marking an elevation at some point on or around the mountain. It was essentially just a confusing mass of numbers, but Hutton noticed that if he used a pencil to connect points of equal height, it all became much more orderly. Indeed, one could instantly get a sense of the overall shape and slope of the mountain. He had invented contour lines.

Extrapolating from his Schiehallion measurements, Hutton calculated the mass of the Earth at 5,000 million million tons, from which could reasonably be deduced the masses of all the other major bodies in the solar system, including the Sun. So from this one experiment we learned the masses of the Earth, the Sun, the Moon, the other planets and their moons, and got contour lines into the bargain—not bad for a summer's work.

Not everyone was satisfied with the results, however. The shortcoming of the Schiehallion experiment was that it was not possible to get a truly accurate figure without knowing the actual density of the mountain. For convenience, Hutton had assumed that the mountain had the same density as ordinary stone, about 2.5 times that of water, but this was little more than an educated guess.

One improbable-seeming person who turned his mind to the matter was a country parson named John Michell, who resided in the lonely Yorkshire village of Thornhill. Despite his remote and comparatively humble situation, Michell was one of the great scientific thinkers of the eighteenth century and much esteemed for it.

Among a great deal else, he perceived the wavelike nature of earthquakes, conducted much original research into magnetism and gravity, and, quite extraordinarily, envisioned the possibility of black holes two hundred years before anyone else—a leap of intuitive deduction that not even Newton could make. When the German-born musician William Herschel decided his real interest in life was astronomy, it was Michell to whom he turned for instruction in making telescopes, a kindness for which planetary science has been in his debt ever since.[4]

But of all that Michell accomplished, nothing was more ingenious or had greater impact than a machine he designed and built for measuring the mass of the Earth. Unfortunately, he died before he could conduct the experiments and both the idea and the necessary equipment were passed on to a brilliant but magnificently retiring London scientist named Henry Cavendish.

Cavendish is a book in himself. Born into a life of sumptuous privilege—his grandfathers were dukes, respectively, of Devonshire and Kent—he was the most gifted English scientist of his age, but also the strangest. He suffered, in the words of one of his few biographers, from shyness to a "degree bordering on disease." Any human contact was for him a source of the deepest discomfort.

Once he opened his door to find an Austrian admirer, freshly arrived from Vienna, on the front step. Excitedly the Austrian began to babble out praise. For a few moments Cavendish received the compliments as if they were blows from a blunt object and then, unable to take any more, fled down the path and out the gate, leaving the front door wide open. It was some hours before he could be coaxed back to the property. Even his housekeeper communicated with him by letter.

Although he did sometimes venture into society—he was particularly devoted to the weekly scientific soirées of the great naturalist Sir Joseph Banks—it was always made clear to the other guests that Cavendish was on no account to be approached or even looked at. Those who sought his views were advised to wander into his vicinity as if by accident and to "talk as

[4] In 1781 Herschel became the first person in the modern era to discover a planet. He wanted to call it George, after the British monarch, but was overruled. Instead it became Uranus.

it were into vacancy." If their remarks were scientifically worthy they might receive a mumbled reply, but more often than not they would hear a peeved squeak (his voice appears to have been high pitched) and turn to find an actual vacancy and the sight of Cavendish fleeing for a more peaceful corner.

His wealth and solitary inclinations allowed him to turn his house in Clapham into a large laboratory where he could range undisturbed through every corner of the physical sciences—electricity, heat, gravity, gases, anything to do with the composition of matter. The second half of the eighteenth century was a time when people of a scientific bent grew intensely interested in the physical properties of fundamental things—gases and electricity in particular—and began seeing what they could do with them, often with more enthusiasm than sense. In America, Benjamin Franklin famously risked his life by flying a kite in an electrical storm. In France, a chemist named Pilatre de Rozier tested the flammability of hydrogen by gulping a mouthful and blowing across an open flame, proving at a stroke that hydrogen is indeed explosively combustible and that eyebrows are not necessarily a permanent feature of one's face. Cavendish, for his part, conducted experiments in which he subjected himself to graduated jolts of electrical current, diligently noting the increasing levels of agony until he could keep hold of his quill, and sometimes his consciousness, no longer.

In the course of a long life Cavendish made a string of signal discoveries—among much else he was the first person to isolate hydrogen and the first to combine hydrogen and oxygen to form water—but almost nothing he did was entirely divorced from strangeness. To the continuing exasperation of his fellow scientists, he often alluded in published work to the results of contingent experiments that he had not told anyone about. In his secretiveness he didn't merely resemble Newton, but actively exceeded him. His experiments with electrical conductivity were a century ahead of their time, but unfortunately remained undiscovered until that century had passed. Indeed the greater part of what he did wasn't known until the late nineteenth century when the Cambridge physicist James Clerk Maxwell took on the task of editing Cavendish's papers, by which time credit had nearly always been given to others.

Among much else, and without telling anyone, Cavendish discovered or anticipated the law of the conservation of energy, Ohm's law, Dalton's Law of Partial Pressures, Richter's Law of Reciprocal Proportions, Charles's Law of Gases, and the principles of electrical conductivity. That's just some of it. According to the science historian J. G. Crowther, he also foreshadowed "the work of Kelvin and G. H. Darwin on the effect of tidal friction on slowing the rotation of the earth, and Larmor's discovery, published in 1915, on the effect of local atmospheric cooling . . . the work of Pickering on freezing mixtures, and some of the work of Rooseboom on heterogeneous equilibria." Finally, he left clues that led directly to the discovery of the group of elements known as the noble gases, some of which are so elusive that the last of them wasn't found until 1962. But our interest here is in Cavendish's last known experiment when in the late summer of 1797, at the age of sixty-seven, he turned his attention to the crates of equipment that had been left to him—evidently out of simple scientific respect—by John Michell.

When assembled, Michell's apparatus looked like nothing so much as an eighteenth-century version of a Nautilus weight-training machine. It incorporated weights, counterweights, pendulums, shafts, and torsion wires. At the heart of the machine were two 350-pound lead balls, which were suspended beside two smaller spheres. The idea was to measure the gravitational deflection of the smaller spheres by the larger ones, which would allow the first measurement of the elusive force known as the gravitational constant, and from which the weight (strictly speaking, the mass)[5] of the Earth could be deduced.

Because gravity holds planets in orbit and makes falling objects land with a bang, we tend to think of it as a powerful force, but it is not really. It is only powerful in a kind of collective sense, when one massive object, like the Sun, holds on to another massive object, like the Earth. At an elemental level gravity is extraordinarily unrobust. Each time you pick up a book from a table or a dime from the floor you effortlessly overcome the combined gravitational exertion of an entire planet. What Cavendish was trying to do was measure gravity at this extremely featherweight level.

Delicacy was the key word. Not a whisper of disturbance could be allowed into the room containing the apparatus, so Cavendish took up a position in an adjoining room and made his observations with a telescope aimed through a peephole. The work was incredibly exacting and involved seventeen delicate, interconnected measurements, which together took nearly a year to complete. When at last he had finished his calculations, Cavendish announced that the Earth weighed a little over 13,000,000,000,000,000,000,000 pounds, or six billion trillion metric tons, to use the modern measure. (A metric ton is 1,000 kilograms or 2,205 pounds.)

Today, scientists have at their disposal machines so precise they can detect the weight of a single bacterium and so sensitive that readings can be disturbed by someone yawning seventy-five feet away, but they have not significantly improved on Cavendish's measurements of 1797. The current best estimate for Earth's weight is 5.9725 billion trillion metric tons, a difference of only about 1 percent from Cavendish's finding. Interestingly, all of this merely confirmed estimates made by Newton 110 years before Cavendish without any experimental evidence at all.

So, by the late eighteenth century scientists knew very precisely the shape and dimensions of the Earth and its distance from the Sun and planets; and now Cavendish, without even leaving home, had given them its weight. So you might think that determining the age of the Earth would be relatively straightforward. After all, the necessary materials were literally at their feet. But no. Human beings would split the atom and invent television, nylon, and instant coffee before they could figure out the age of their own planet.

To understand why, we must travel north to Scotland and begin with a brilliant and genial man, of whom few have ever heard, who had just invented a new science called geology.

[5] To a physicist, mass and weight are two quite different things. Your mass stays the same wherever you go, but your weight varies depending on how far you are from the center of some other massive object like a planet. Travel to the Moon and you will be much lighter but no less massive. On Earth, for all practical purposes, mass and weight are the same and so the terms can be treated as synonymous. at least outside the classroom.

Chapter 4: The Measure of Things

Discussion Questions

1. Summarize the accomplishments of Edmond Halley. Why do you think his scientific contributions were so diverse compared to today's scientists?

2. What are Newton's three laws of motion? What is the formula representation of his law of universal gravitation?

3. Of what significance is it to navigators if the Earth is not a perfect sphere?

4. What was Richard Norwood's main contribution to science? Why can we say, with a great deal of confidence, that Norwood was a very careful worker?

5. Describe one way to determine the mass of the earth.

6. What was history's first cooperative scientific venture?

7. How did the discovery of contour lines relate to determining the mass of the Earth?

8. Who was "the most gifted English scientist of his age"? Provide evidence of why this person was awarded that "title".

9. Describe the chain of events leading from a wager to the foundation of modern physics: Newton's *Principia.*

10. What does an "inverse square law" mean? How does it apply to the motion of planets?

11. Describe two efforts to measure the size of the earth.

12. What complicating factor (or invalid assumption) made precise navigation difficult?

13. Describe the strategy proposed by Edmund Halley to measure the distance between the earth and sun.

14. What is the link between the effort to carry out Halley's proposed measurement and the informal name for the southern U.S. states?