Timberlane High School Science Summer Reading Assignment:

Course: Physics Accelerated

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 Friday Sept. 8th for potential full credit. Accepted until Sept 13th with 10% deduction in grade per day. Not accepted after Sept 13th.
- 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
  - 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
  - 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
  - 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

$$F = G\frac{mm}{R_2}$$

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?

8 EINSTEIN'S UNIVERSE

AS THE NINETEENTH century drew to a close, scientists could reflect with satisfaction that they had pinned down most of the mysteries of the physical world: electricity, magnetism, gases, optics, acoustics, kinetics, and statistical mechanics, to name just a few, all had fallen into order before them. They had discovered the X ray, the cathode ray, the electron, and radioactivity, invented the ohm, the watt, the Kelvin, the joule, the amp, and the little erg.

If a thing could be oscillated, accelerated, perturbed, distilled, combined, weighed, or made gaseous they had done it, and in the process produced a body of universal laws so weighty and majestic that we still tend to write them out in capitals: the Electromagnetic Field Theory of Light, Richter's Law of Reciprocal Proportions, Charles's Law of Gases, the Law of Combining Volumes, the Zeroth Law, the Valence Concept, the Laws of Mass Actions, and others beyond counting. The whole world clanged and chuffed with the machinery and instruments that their ingenuity had produced. Many wise people believed that there was nothing much left for science to do.

In 1875, when a young German in Kiel named Max Planck was deciding whether to devote his life to mathematics or to physics, he was urged most heartily not to choose physics because the breakthroughs had all been made there. The coming century, he was assured, would be one of consolidation and refinement, not revolution. Planck didn't listen. He studied theoretical physics and threw himself body and soul into work on entropy, a process at the heart of thermodynamics, which seemed to hold much promise for an ambitious young man.[1] In 1891 he produced his results and learned to his dismay that the important work on entropy had in fact been done already, in this instance by a retiring scholar at Yale University named J. Willard Gibbs.

Gibbs is perhaps the most brilliant person that most people have never heard of. Modest to the point of near invisibility, he passed virtually the whole of his life, apart from three years spent studying in Europe, within a three-block area bounded by his house and the Yale campus in New Haven, Connecticut. For his first ten years at Yale he didn't even bother to draw a salary. (He had independent means.) From 1871, when he joined the university as a professor, to his death in 1903, his courses attracted an average of slightly over one student a semester. His written work was difficult to follow and employed a private form of notation that many found incomprehensible. But buried among his arcane formulations were insights of the loftiest brilliance.

In 1875–78, Gibbs produced a series of papers, collectively titledOn the Equilibrium of Heterogeneous Substances , that dazzlingly elucidated the thermodynamic principles of, well,

[1] Specifically it is a measure of randomness or disorder in a system. Darrell Ebbing, in the textbook General Chemistry, very usefully suggests thinking of a deck of cards. A new pack fresh out of the box, arranged by suit and in sequence from ace to king, can be said to be in its ordered state. Shuffle the cards and you put them in a disordered state. Entropy is a way of measuring just how disordered that state is and of determining the likelihood of particular outcomes with further shuffles. Of course, if you wish to have any observations published in a respectable journal you will need also to understand additional concepts such as thermal nonuniformities, lattice distances, and stoichiometric relationships, but that's the general idea.

nearly everything—“gases, mixtures, surfaces, solids, phase changes . . . chemical reactions, electrochemical cells, sedimentation, and osmosis,” to quote William H. Cropper. In essence what Gibbs did was show that thermodynamics didn’t apply simply to heat and energy at the sort of large and noisy scale of the steam engine, but was also present and influential at the atomic level of chemical reactions. Gibbs’s Equilibrium has been called “the Principia of thermodynamics,” but for reasons that defy speculation Gibbs chose to publish these landmark observations in the Transactions of the Connecticut Academy of Arts and Sciences, a journal that managed to be obscure even in Connecticut, which is why Planck did not hear of him until too late.

Undaunted—well, perhaps mildly daunted—Planck turned to other matters.[2] We shall turn to these ourselves in a moment, but first we must make a slight (but relevant!) detour to Cleveland, Ohio, and an institution then known as the Case School of Applied Science. There, in the 1880s, a physicist of early middle years named Albert Michelson, assisted by his friend the chemist Edward Morley, embarked on a series of experiments that produced curious and disturbing results that would have great ramifications for much of what followed.

What Michelson and Morley did, without actually intending to, was undermine a longstanding belief in something called the luminiferous ether, a stable, invisible, weightless, frictionless, and unfortunately wholly imaginary medium that was thought to permeate the universe. Conceived by Descartes, embraced by Newton, and venerated by nearly everyone ever since, the ether held a position of absolute centrality in nineteenth-century physics as a way of explaining how light traveled across the emptiness of space. It was especially needed in the 1800s because light and electromagnetism were now seen as waves, which is to say types of vibrations. Vibrations must occur in something; hence the need for, and lasting devotion to, an ether. As late as 1909, the great British physicist J. J. Thomson was insisting: “The ether is not a fantastic creation of the speculative philosopher; it is as essential to us as the air we breathe”—this more than four years after it was pretty incontestably established that it didn’t exist. People, in short, were really attached to the ether.

If you needed to illustrate the idea of nineteenth-century America as a land of opportunity, you could hardly improve on the life of Albert Michelson. Born in 1852 on the German–Polish border to a family of poor Jewish merchants, he came to the United States with his family as an infant and grew up in a mining camp in California’s gold rush country, where his father ran a dry goods business. Too poor to pay for college, he traveled to Washington, D.C., and took to loitering by the front door of the White House so that he could fall in beside President Ulysses S. Grant when the President emerged for his daily constitutional. (It was clearly a more innocent age.) In the course of these walks, Michelson so ingratiated himself to the President that Grant agreed to secure for him a free place at the U.S. Naval Academy. It was there that Michelson learned his physics.

Ten years later, by now a professor at the Case School in Cleveland, Michelson became interested in trying to measure something called the ether drift—a kind of head wind produced by moving objects as they plowed through space. One of the predictions of Newtonian physics was that the speed of light as it pushed through the ether should vary with

---

[2] Planck was often unlucky in life. His beloved first wife died early, in 1909, and the younger of his two sons was killed in the First World War. He also had twin daughters whom he adored. One died giving birth. The surviving twin went to look after the baby and fell in love with her sister's husband. They married and two years later she died in childbirth. In 1944, when Planck was eighty-five, an Allied bomb fell on his house and he lost everything-papers, diaries, a lifetime of accumulations. The following year his surviving son was caught in a conspiracy to assassinate Hitler and executed.

respect to an observer depending on whether the observer was moving toward the source of light or away from it, but no one had figured out a way to measure this. It occurred to Michelson that for half the year the Earth is traveling toward the Sun and for half the year it is moving away from it, and he reasoned that if you took careful enough measurements at opposite seasons and compared light's travel time between the two, you would have your answer.

Michelson talked Alexander Graham Bell, newly enriched inventor of the telephone, into providing the funds to build an ingenious and sensitive instrument of Michelson's own devising called an interferometer, which could measure the velocity of light with great precision. Then, assisted by the genial but shadowy Morley, Michelson embarked on years of fastidious measurements. The work was delicate and exhausting, and had to be suspended for a time to permit Michelson a brief but comprehensive nervous breakdown, but by 1887 they had their results. They were not at all what the two scientists had expected to find.

As Caltech astrophysicist Kip S. Thorne has written: "The speed of light turned out to be the same inall directions and at all seasons." It was the first hint in two hundred years—in exactly two hundred years, in fact—that Newton's laws might not apply all the time everywhere. The Michelson-Morley outcome became, in the words of William H. Cropper, "probably the most famous negative result in the history of physics." Michelson was awarded a Nobel Prize in physics for the work—the first American so honored—but not for twenty years. Meanwhile, the Michelson-Morley experiments would hover unpleasantly, like a musty smell, in the background of scientific thought.

Remarkably, and despite his findings, when the twentieth century dawned Michelson counted himself among those who believed that the work of science was nearly at an end, with "only a few turrets and pinnacles to be added, a few roof bosses to be carved," in the words of a writer in Nature.

In fact, of course, the world was about to enter a century of science where many people wouldn't understand anything and none would understand everything. Scientists would soon find themselves adrift in a bewildering realm of particles and antiparticles, where things pop in and out of existence in spans of time that make nanoseconds look plodding and uneventful, where everything is strange. Science was moving from a world of macrophysics, where objects could be seen and held and measured, to one of microphysics, where events transpire with unimaginable swiftness on scales far below the limits of imagining. We were about to enter the quantum age, and the first person to push on the door was the so-far unfortunate Max Planck.

In 1900, now a theoretical physicist at the University of Berlin and at the somewhat advanced age of forty-two, Planck unveiled a new "quantum theory," which posited that energy is not a continuous thing like flowing water but comes in individualized packets, which he called quanta. This was a novel concept, and a good one. In the short term it would help to provide a solution to the puzzle of the Michelson-Morley experiments in that it demonstrated that light needn't be a wave after all. In the longer term it would lay the foundation for the whole of modern physics. It was, at all events, the first clue that the world was about to change.

But the landmark event—the dawn of a new age—came in 1905, when there appeared in the German physics journal Annalen der Physik a series of papers by a young Swiss bureaucrat who had no university affiliation, no access to a laboratory, and the regular use of no library greater than that of the national patent office in Bern, where he was employed as a technical examiner third class. (An application to be promoted to technical examiner second class had recently been rejected.)

His name was Albert Einstein, and in that one eventful year he submitted to Annalen der Physik five papers, of which three, according to C. P. Snow, “were among the greatest in the history of physics”—one examining the photoelectric effect by means of Planck’s new quantum theory, one on the behavior of small particles in suspension (what is known as Brownian motion), and one outlining a special theory of relativity.

The first won its author a Nobel Prize and explained the nature of light (and also helped to make television possible, among other things).[3] The second provided proof that atoms do indeed exist—a fact that had, surprisingly, been in some dispute. The third merely changed the world.

Einstein was born in Ulm, in southern Germany, in 1879, but grew up in Munich. Little in his early life suggested the greatness to come. Famously he didn’t learn to speak until he was three. In the 1890s, his father’s electrical business failing, the family moved to Milan, but Albert, by now a teenager, went to Switzerland to continue his education—though he failed his college entrance exams on the first try. In 1896 he gave up his German citizenship to avoid military conscription and entered the Zurich Polytechnic Institute on a four-year course designed to churn out high school science teachers. He was a bright but not outstanding student.

In 1900 he graduated and within a few months was beginning to contribute papers to Annalen der Physik. His very first paper, on the physics of fluids in drinking straws (of all things), appeared in the same issue as Planck’s quantum theory. From 1902 to 1904 he produced a series of papers on statistical mechanics only to discover that the quietly productive J. Willard Gibbs in Connecticut had done that work as well, in his Elementary Principles of Statistical Mechanics of 1901.

At the same time he had fallen in love with a fellow student, a Hungarian named Mileva Maric. In 1901 they had a child out of wedlock, a daughter, who was discreetly put up for adoption. Einstein never saw his child. Two years later, he and Maric were married. In between these events, in 1902, Einstein took a job with the Swiss patent office, where he stayed for the next seven years. He enjoyed the work: it was challenging enough to engage his mind, but not so challenging as to distract him from his physics. This was the background against which he produced the special theory of relativity in 1905.

Called “On the Electrodynamics of Moving Bodies,” it is one of the most extraordinary scientific papers ever published, as much for how it was presented as for what it said. It had no footnotes or citations, contained almost no mathematics, made no mention of any work that had influenced or preceded it, and acknowledged the help of just one individual, a

---

[3] Einstein was honored, somewhat vaguely, "for services to theoretical physics." He had to wait sixteen years, till 1921, to receive the award-quite a long time, all things considered, but nothing at all compared with Frederick Reines, who detected the neutrino in 1957 but wasn't honored with a Nobel until 1995, thirty-eight years later, or the German Ernst Ruska, who invented the electron microscope in 1932 and received his Nobel Prize in 1986, more than half a century after the fact. Since Nobel Prizes are never awarded posthumously, longevity can be as important a factor as ingenuity for prizewinners.

colleague at the patent office named Michele Besso. It was, wrote C. P. Snow, as if Einstein “had reached the conclusions by pure thought, unaided, without listening to the opinions of others. To a surprisingly large extent, that is precisely what he had done.”

His famous equation, $E = mc^2$, did not appear with the paper, but came in a brief supplement that followed a few months later. As you will recall from school days, E in the equation stands for energy, m for mass, and c^2 for the speed of light squared.

In simplest terms, what the equation says is that mass and energy have an equivalence. They are two forms of the same thing: energy is liberated matter; matter is energy waiting to happen. Since c^2 (the speed of light times itself) is a truly enormous number, what the equation is saying is that there is a huge amount—a really huge amount—of energy bound up in every material thing.[4]

You may not feel outstandingly robust, but if you are an average-sized adult you will contain within your modest frame no less than 7×10^{18} joules of potential energy—enough to explode with the force of thirty very large hydrogen bombs, assuming you knew how to liberate it and really wished to make a point. Everything has this kind of energy trapped within it. We’re just not very good at getting it out. Even a uranium bomb—the most energetic thing we have produced yet—releases less than 1 percent of the energy it could release if only we were more cunning.

Among much else, Einstein’s theory explained how radiation worked: how a lump of uranium could throw out constant streams of high-level energy without melting away like an ice cube. (It could do it by converting mass to energy extremely efficiently à la$E = mc^2$.) It explained how stars could burn for billions of years without racing through their fuel. (Ditto.) At a stroke, in a simple formula, Einstein endowed geologists and astronomers with the luxury of billions of years. Above all, the special theory showed that the speed of light was constant and supreme. Nothing could overtake it. It brought light (no pun intended, exactly) to the very heart of our understanding of the nature of the universe. Not incidentally, it also solved the problem of the luminiferous ether by making it clear that it didn’t exist. Einstein gave us a universe that didn’t need it.

Physicists as a rule are not overattentive to the pronouncements of Swiss patent office clerks, and so, despite the abundance of useful tidings, Einstein’s papers attracted little notice. Having just solved several of the deepest mysteries of the universe, Einstein applied for a job as a university lecturer and was rejected, and then as a high school teacher and was rejected there as well. So he went back to his job as an examiner third class, but of course he kept thinking. He hadn’t even come close to finishing yet.

When the poet Paul Valéry once asked Einstein if he kept a notebook to record his ideas, Einstein looked at him with mild but genuine surprise. “Oh, that’s not necessary,” he replied. “It’s so seldom I have one.” I need hardly point out that when he did get one it tended to be good. Einstein’s next idea was one of the greatest that anyone has ever had—indeed, the very greatest, according to Boorse, Motz, and Weaver in their thoughtful history of atomic science.

---

[4] How c came to be the symbol for the speed of light is something of a mystery, but David Bodanis suggests it probably came from the Latin celeritas, meaning swiftness. The relevant volume of the Oxford English Dictionary, compiled a decade before Einstein's theory, recognizes c as a symbol for many things, from carbon to cricket, but makes no mention of it as a symbol for light or swiftness.

“As the creation of a single mind,” they write, “it is undoubtedly the highest intellectual achievement of humanity,” which is of course as good as a compliment can get.

In 1907, or so it has sometimes been written, Albert Einstein saw a workman fall off a roof and began to think about gravity. Alas, like many good stories this one appears to be apocryphal. According to Einstein himself, he was simply sitting in a chair when the problem of gravity occurred to him.

Actually, what occurred to Einstein was something more like the beginning of a solution to the problem of gravity, since it had been evident to him from the outset that one thing missing from the special theory was gravity. What was “special” about the special theory was that it dealt with things moving in an essentially unimpeded state. But what happened when a thing in motion—light, above all—encountered an obstacle such as gravity? It was a question that would occupy his thoughts for most of the next decade and lead to the publication in early 1917 of a paper entitled “Cosmological Considerations on the General Theory of Relativity.” The special theory of relativity of 1905 was a profound and important piece of work, of course, but as C. P. Snow once observed, if Einstein hadn’t thought of it when he did someone else would have, probably within five years; it was an idea waiting to happen. But the general theory was something else altogether. “Without it,” wrote Snow in 1979, “it is likely that we should still be waiting for the theory today.”

With his pipe, genially self-effacing manner, and electrified hair, Einstein was too splendid a figure to remain permanently obscure, and in 1919, the war over, the world suddenly discovered him. Almost at once his theories of relativity developed a reputation for being impossible for an ordinary person to grasp. Matters were not helped, as David Bodanis points out in his superb book $E=mc^2$, when the New York Times decided to do a story, and—for reasons that can never fail to excite wonder—sent the paper’s golfing correspondent, one Henry Crouch, to conduct the interview.

Crouch was hopelessly out of his depth, and got nearly everything wrong. Among the more lasting errors in his report was the assertion that Einstein had found a publisher daring enough to publish a book that only twelve men “in all the world could comprehend.” There was no such book, no such publisher, no such circle of learned men, but the notion stuck anyway. Soon the number of people who could grasp relativity had been reduced even further in the popular imagination—and the scientific establishment, it must be said, did little to disturb the myth.

When a journalist asked the British astronomer Sir Arthur Eddington if it was true that he was one of only three people in the world who could understand Einstein’s relativity theories, Eddington considered deeply for a moment and replied: “I am trying to think who the third person is.” In fact, the problem with relativity wasn’t that it involved a lot of differential equations, Lorentz transformations, and other complicated mathematics (though it did—even Einstein needed help with some of it), but that it was just so thoroughly nonintuitive.

In essence what relativity says is that space and time are not absolute, but relative to both the observer and to the thing being observed, and the faster one moves the more pronounced these effects become. We can never accelerate ourselves to the speed of light, and the harder we try (and faster we go) the more distorted we will become, relative to an outside observer.

Almost at once popularizers of science tried to come up with ways to make these concepts accessible to a general audience. One of the more successful attempts—commercially at least—was The ABC of Relativity by the mathematician and philosopher Bertrand Russell. In it, Russell employed an image that has been used many times since. He asked the reader to envision a train one hundred yards long moving at 60 percent of the speed of light. To someone standing on a platform watching it pass, the train would appear to be only eighty yards long and everything on it would be similarly compressed. If we could hear the passengers on the train speak, their voices would sound slurred and sluggish, like a record played at too slow a speed, and their movements would appear similarly ponderous. Even the clocks on the train would seem to be running at only four-fifths of their normal speed.

However—and here's the thing—people on the train would have no sense of these distortions. To them, everything on the train would seem quite normal. It would be we on the platform who looked weirdly compressed and slowed down. It is all to do, you see, with your position relative to the moving object.

This effect actually happens every time you move. Fly across the United States, and you will step from the plane a quinzillionth of a second, or something, younger than those you left behind. Even in walking across the room you will very slightly alter your own experience of time and space. It has been calculated that a baseball thrown at a hundred miles an hour will pick up 0.000000000002 grams of mass on its way to home plate. So the effects of relativity are real and have been measured. The problem is that such changes are much too small to make the tiniest detectable difference to us. But for other things in the universe—light, gravity, the universe itself—these are matters of consequence.

So if the ideas of relativity seem weird, it is only because we don't experience these sorts of interactions in normal life. However, to turn to Bodanis again, we all commonly encounter other kinds of relativity—for instance with regard to sound. If you are in a park and someone is playing annoying music, you know that if you move to a more distant spot the music will seem quieter. That's not because the musicis quieter, of course, but simply that your position relative to it has changed. To something too small or sluggish to duplicate this experience—a snail, say—the idea that a boom box could seem to two observers to produce two different volumes of music simultaneously might seem incredible.

The most challenging and nonintuitive of all the concepts in the general theory of relativity is the idea that time is part of space. Our instinct is to regard time as eternal, absolute, immutable—nothing can disturb its steady tick. In fact, according to Einstein, time is variable and ever changing. It even has shape. It is bound up—"inextricably interconnected," in Stephen Hawking's expression—with the three dimensions of space in a curious dimension known as spacetime.

Spacetime is usually explained by asking you to imagine something flat but pliant—a mattress, say, or a sheet of stretched rubber—on which is resting a heavy round object, such as an iron ball. The weight of the iron ball causes the material on which it is sitting to stretch and sag slightly. This is roughly analogous to the effect that a massive object such as the Sun (the iron ball) has on spacetime (the material): it stretches and curves and warps it. Now if you roll a smaller ball across the sheet, it tries to go in a straight line as required by Newton's laws of motion, but as it nears the massive object and the slope of the sagging fabric, it rolls downward, ineluctably drawn to the more massive object. This is gravity—a product of the bending of spacetime.

Every object that has mass creates a little depression in the fabric of the cosmos. Thus the universe, as Dennis Overbye has put it, is "the ultimate sagging mattress." Gravity on this view is no longer so much a thing as an outcome—"not a 'force' but a byproduct of the warping of spacetime," in the words of the physicist Michio Kaku, who goes on: "In some sense, gravity does not exist; what moves the planets and stars is the distortion of space and time."

Of course the sagging mattress analogy can take us only so far because it doesn't incorporate the effect of time. But then our brains can take us only so far because it is so nearly impossible to envision a dimension comprising three parts space to one part time, all interwoven like the threads in a plaid fabric. At all events, I think we can agree that this was an awfully big thought for a young man staring out the window of a patent office in the capital of Switzerland.

Among much else, Einstein's general theory of relativity suggested that the universe must be either expanding or contracting. But Einstein was not a cosmologist, and he accepted the prevailing wisdom that the universe was fixed and eternal. More or less reflexively, he dropped into his equations something called the cosmological constant, which arbitrarily counterbalanced the effects of gravity, serving as a kind of mathematical pause button. Books on the history of science always forgive Einstein this lapse, but it was actually a fairly appalling piece of science and he knew it. He called it "the biggest blunder of my life."

Coincidentally, at about the time that Einstein was affixing a cosmological constant to his theory, at the Lowell Observatory in Arizona, an astronomer with the cheerily intergalactic name of Vesto Slipher (who was in fact from Indiana) was taking spectrographic readings of distant stars and discovering that they appeared to be moving away from us. The universe wasn't static. The stars Slipher looked at showed unmistakable signs of a Doppler shift[5]—the same mechanism behind that distinctive stretched-out yee-yummm sound cars make as they flash past on a racetrack. The phenomenon also applies to light, and in the case of receding galaxies it is known as a red shift (because light moving away from us shifts toward the red end of the spectrum; approaching light shifts to blue).

Slipher was the first to notice this effect with light and to realize its potential importance for understanding the motions of the cosmos. Unfortunately no one much noticed him. The Lowell Observatory, as you will recall, was a bit of an oddity thanks to Percival Lowell's obsession with Martian canals, which in the 1910s made it, in every sense, an outpost of astronomical endeavor. Slipher was unaware of Einstein's theory of relativity, and the world was equally unaware of Slipher. So his finding had no impact.

Glory instead would pass to a large mass of ego named Edwin Hubble. Hubble was born in 1889, ten years after Einstein, in a small Missouri town on the edge of the Ozarks and grew up there and in Wheaton, Illinois, a suburb of Chicago. His father was a successful insurance executive, so life was always comfortable, and Edwin enjoyed a wealth of physical endowments, too. He was a strong and gifted athlete, charming, smart, and immensely good-looking—"handsome almost to a fault," in the description of William H. Cropper, "an

---

[5] Named for Johann Christian Doppler, an Austrian physicist, who first noticed the effect in 1842. Briefly, what happens is that as a moving object approaches a stationary one its sound waves become bunched up as they cram up against whatever device is receiving them (your ears, say), just as you would expect of anything that is being pushed from behind toward an immobile object. This bunching is perceived by the listener as a kind of pinched and elevated sound (the yee). As the sound source passes, the sound waves spread out and lengthen, causing the pitch to drop abruptly (the yummm).

Adonis" in the words of another admirer. According to his own accounts, he also managed to fit into his life more or less constant acts of valor—rescuing drowning swimmers, leading frightened men to safety across the battlefields of France, embarrassing world-champion boxers with knockdown punches in exhibition bouts. It all seemed too good to be true. It was. For all his gifts, Hubble was also an inveterate liar.

This was more than a little odd, for Hubble's life was filled from an early age with a level of distinction that was at times almost ludicrously golden. At a single high school track meet in 1906, he won the pole vault, shot put, discus, hammer throw, standing high jump, and running high jump, and was on the winning mile-relay team—that is seven first places in one meet—and came in third in the broad jump. In the same year, he set a state record for the high jump in Illinois.

As a scholar he was equally proficient, and had no trouble gaining admission to study physics and astronomy at the University of Chicago (where, coincidentally, the head of the department was now Albert Michelson). There he was selected to be one of the first Rhodes scholars at Oxford. Three years of English life evidently turned his head, for he returned to Wheaton in 1913 wearing an Inverness cape, smoking a pipe, and talking with a peculiarly orotund accent—not quite British but not quite not—that would remain with him for life. Though he later claimed to have passed most of the second decade of the century practicing law in Kentucky, in fact he worked as a high school teacher and basketball coach in New Albany, Indiana, before belatedly attaining his doctorate and passing briefly through the Army. (He arrived in France one month before the Armistice and almost certainly never heard a shot fired in anger.)

In 1919, now aged thirty, he moved to California and took up a position at the Mount Wilson Observatory near Los Angeles. Swiftly, and more than a little unexpectedly, he became the most outstanding astronomer of the twentieth century.

It is worth pausing for a moment to consider just how little was known of the cosmos at this time. Astronomers today believe there are perhaps 140 billion galaxies in the visible universe. That's a huge number, much bigger than merely saying it would lead you to suppose. If galaxies were frozen peas, it would be enough to fill a large auditorium—the old Boston Garden, say, or the Royal Albert Hall. (An astrophysicist named Bruce Gregory has actually computed this.) In 1919, when Hubble first put his head to the eyepiece, the number of these galaxies that were known to us was exactly one: the Milky Way. Everything else was thought to be either part of the Milky Way itself or one of many distant, peripheral puffs of gas. Hubble quickly demonstrated how wrong that belief was.

Over the next decade, Hubble tackled two of the most fundamental questions of the universe: how old is it, and how big? To answer both it is necessary to know two things—how far away certain galaxies are and how fast they are flying away from us (what is known as their recessional velocity). The red shift gives the speed at which galaxies are retiring, but doesn't tell us how far away they are to begin with. For that you need what are known as "standard candles"—stars whose brightness can be reliably calculated and used as benchmarks to measure the brightness (and hence relative distance) of other stars.

Hubble's luck was to come along soon after an ingenious woman named Henrietta Swan Leavitt had figured out a way to do so. Leavitt worked at the Harvard College Observatory as a computer, as they were known. Computers spent their lives studying photographic plates of stars and making computations—hence the name. It was little more than drudgery by another name, but it was as close as women could get to real astronomy at Harvard—or indeed pretty much anywhere—in those days. The system, however unfair, did have certain unexpected benefits: it meant that half the finest minds available were directed to work that would otherwise have attracted little reflective attention, and it ensured that women ended up with an appreciation of the fine structure of the cosmos that often eluded their male counterparts.

One Harvard computer, Annie Jump Cannon, used her repetitive acquaintance with the stars to devise a system of stellar classifications so practical that it is still in use today. Leavitt's contribution was even more profound. She noticed that a type of star known as a Cepheid variable (after the constellation Cepheus, where it first was identified) pulsated with a regular rhythm—a kind of stellar heartbeat. Cepheids are quite rare, but at least one of them is well known to most of us. Polaris, the Pole Star, is a Cepheid.

We now know that Cepheids throb as they do because they are elderly stars that have moved past their "main sequence phase," in the parlance of astronomers, and become red giants. The chemistry of red giants is a little weighty for our purposes here (it requires an appreciation for the properties of singly ionized helium atoms, among quite a lot else), but put simply it means that they burn their remaining fuel in a way that produces a very rhythmic, very reliable brightening and dimming. Leavitt's genius was to realize that by comparing the relative magnitudes of Cepheids at different points in the sky you could work out where they were in relation to each other. They could be used as "standard candles"—a term she coined and still in universal use. The method provided only relative distances, not absolute distances, but even so it was the first time that anyone had come up with a usable way to measure the large-scale universe.

(Just to put these insights into perspective, it is perhaps worth noting that at the time Leavitt and Cannon were inferring fundamental properties of the cosmos from dim smudges on photographic plates, the Harvard astronomer William H. Pickering, who could of course peer into a first-class telescope as often as he wanted, was developing his seminal theory that dark patches on the Moon were caused by swarms of seasonally migrating insects.)

Combining Leavitt's cosmic yardstick with Vesto Slipher's handy red shifts, Edwin Hubble now began to measure selected points in space with a fresh eye. In 1923 he showed that a puff of distant gossamer in the Andromeda constellation known as M31 wasn't a gas cloud at all but a blaze of stars, a galaxy in its own right, a hundred thousand light-years across and at least nine hundred thousand light-years away. The universe was vaster—vastly vaster—than anyone had ever supposed. In 1924 he produced a landmark paper, "Cepheids in Spiral Nebulae" (nebulae,from the Latin for "clouds," was his word for galaxies), showing that the universe consisted not just of the Milky Way but of lots of independent galaxies—"island universes"—many of them bigger than the Milky Way and much more distant.

This finding alone would have ensured Hubble's reputation, but he now turned to the question of working out just how much vaster the universe was, and made an even more striking discovery. Hubble began to measure the spectra of distant galaxies—the business that Slipher had begun in Arizona. Using Mount Wilson's new hundred-inch Hooker telescope and some clever inferences, he worked out that all the galaxies in the sky (except for our own local cluster) are moving away from us. Moreover, their speed and distance were neatly proportional: the further away the galaxy, the faster it was moving.

This was truly startling. The universe was expanding, swiftly and evenly in all directions. It didn't take a huge amount of imagination to read backwards from this and realize that it must therefore have started from some central point. Far from being the stable, fixed, eternal void that everyone had always assumed, this was a universe that had a beginning. It might therefore also have an end.

The wonder, as Stephen Hawking has noted, is that no one had hit on the idea of the expanding universe before. A static universe, as should have been obvious to Newton and every thinking astronomer since, would collapse in upon itself. There was also the problem that if stars had been burning indefinitely in a static universe they'd have made the whole intolerably hot—certainly much too hot for the likes of us. An expanding universe resolved much of this at a stroke.

Hubble was a much better observer than a thinker and didn't immediately appreciate the full implications of what he had found. Partly this was because he was woefully ignorant of Einstein's General Theory of Relativity. This was quite remarkable because, for one thing, Einstein and his theory were world famous by now. Moreover, in 1929 Albert Michelson—now in his twilight years but still one of the world's most alert and esteemed scientists—accepted a position at Mount Wilson to measure the velocity of light with his trusty interferometer, and must surely have at least mentioned to him the applicability of Einstein's theory to his own findings.

At all events, Hubble failed to make theoretical hay when the chance was there. Instead, it was left to a Belgian priest-scholar (with a Ph.D. from MIT) named Georges Lemaître to bring together the two strands in his own "fireworks theory," which suggested that the universe began as a geometrical point, a "primeval atom," which burst into glory and had been moving apart ever since. It was an idea that very neatly anticipated the modern conception of the Big Bang but was so far ahead of its time that Lemaître seldom gets more than the sentence or two that we have given him here. The world would need additional decades, and the inadvertent discovery of cosmic background radiation by Penzias and Wilson at their hissing antenna in New Jersey, before the Big Bang would begin to move from interesting idea to established theory.

Neither Hubble nor Einstein would be much of a part of that big story. Though no one would have guessed it at the time, both men had done about as much as they were ever going to do.

In 1936 Hubble produced a popular book called The Realm of the Nebulae, which explained in flattering style his own considerable achievements. Here at last he showed that he had acquainted himself with Einstein's theory—up to a point anyway: he gave it four pages out of about two hundred.

Hubble died of a heart attack in 1953. One last small oddity awaited him. For reasons cloaked in mystery, his wife declined to have a funeral and never revealed what she did with his body. Half a century later the whereabouts of the century's greatest astronomer remain unknown. For a memorial you must look to the sky and the Hubble Space Telescope, launched in 1990 and named in his honor.

Chapter 8: Einstein's Universe

Discussion Questions

1. What is the luminiferous ether? How does it relate to experiments about determining the speed of light?

2. Some writers classify Max Planck as the first quantum physicist. Provide evidence to support this classification.

3. Describe the meaning of $E=mc^2$.

4. Einstein reported that he seldom had a good idea. Do you agree with this? What do you think is Einstein's classification of a "good idea"? What is your classification of a good scientific idea?

5. In what ways are Einstein's relativity theories nonintuitive?

6. How does a train traveling at 60 percent of the speed of light illustrate Einstein's theory of special relativity?

7. How is spacetime like a sheet of stretched rubber?

8. Describe the contributions of Henrietta Swan Leavitt and Annie Jump Cannon to our understanding of the universe.