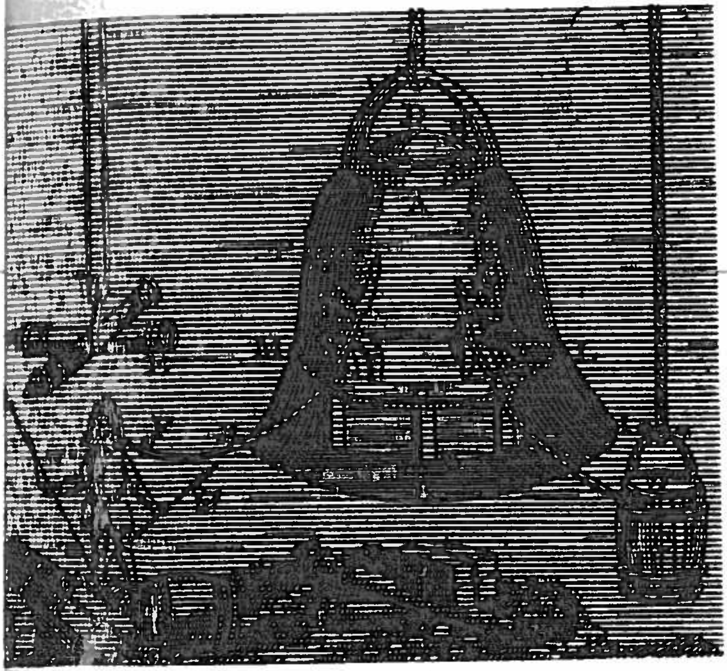

Above left: **The first commercially successful diving bell, illustrated here in 1787, which Edmond Halley invented to allow shipwrecks in shallow waters to be explored more easily.**

Above right: **The English astronomer Edmond Halley, namesake of the Earth's most famous comet, whose lesser-known achievements included inventing weather maps and writing extensively about opium.**

and the great and stately Sir Christopher Wren, who was actually an astronomer first and an 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 40 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 travelled to Cambridge and boldly called upon the university's Lucasian Professor of Mathematics, Isaac Newton, in the hope that he could help.

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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.

Sir Isaac Newton, whose scientific genius produced his universal law of gravitation, but who equally was not above bizarre experiments that included jamming a long needle between his eyeball and socket to see what would happen.

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

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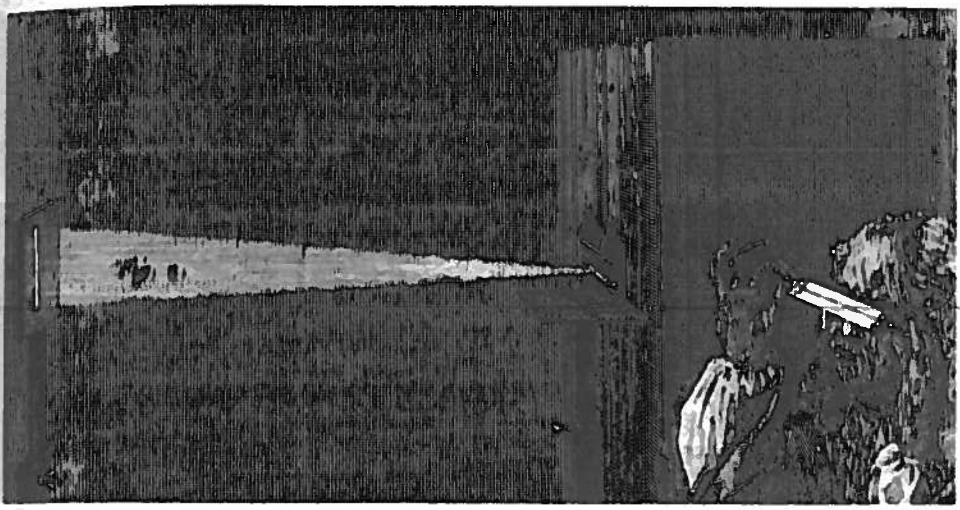


Experimenting with the concept of light: Newton's findings would lay the foundations for the science of spectroscopy, although it would be three decades before he enlightened anyone to this discovery.

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 get up 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 Dr. Halley came to visit at Cambridge [and] after they had some time together the Dr. asked him what he thought the curve would be that would be described by the Planets supposing the force of attraction towards 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.

> Sr. 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 Dr. Halley asked him for his calculation without farther delay. Sr. 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. The appearance of the *Principia* was one of those moments. It made Newton instantly famous. For the rest of his life he would be draped with plaudits and honours, 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.

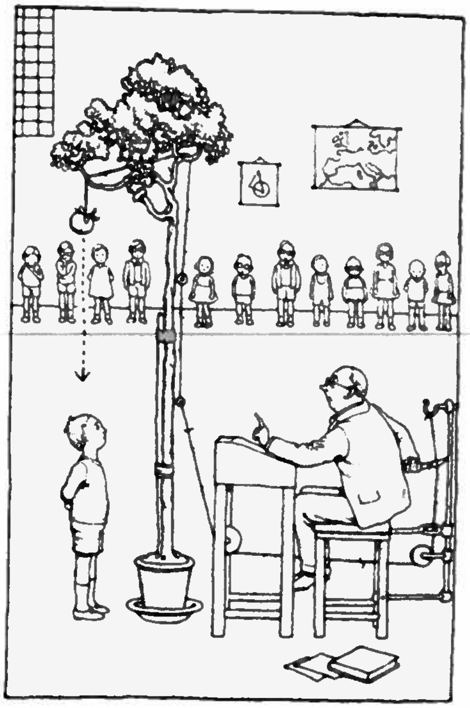
At the *Principia*'s heart were Newton's three laws of motion (which state, very baldly, that a thing moves in the direction in which it is pushed; that it will keep moving in a straight line until some other force acts to slow or deflect it; and that every action has an opposite and equal reaction) 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—towards 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

> A couple of brief multiplications, a simple division and, bingo, you know your gravitational position wherever you go.

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 everywhere regarded with such profound esteem.



Heath Robinson's "The Soundness of Newton's Laws."

The *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 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 kilometres an hour*—that it took a while for all their implications to seep in. But one revelation became almost immediately controversial.

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* How fast you are spinning depends on where you are. The speed of the Earth's spin varies from something over 1,600 kilometres an hour at the equator to zero at the poles. In London the speed is 998 kilometres an hour.

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 of meridian 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 planet were based on the assumption that it 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 travelled to Bermuda with a diving bell modelled 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 dismayingly large margins. Norwood, whose first love was trigonometry and thus angles, decided to bring a little mathematical rigour 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

This was not good news for those people whose measurements of the planet were based on the assumption that it was a perfect sphere, which was everyone.

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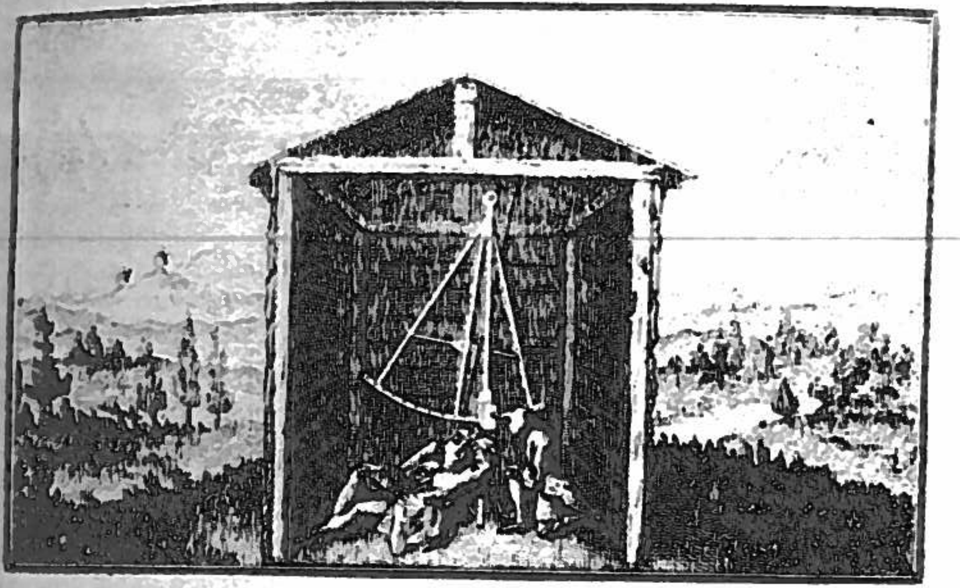
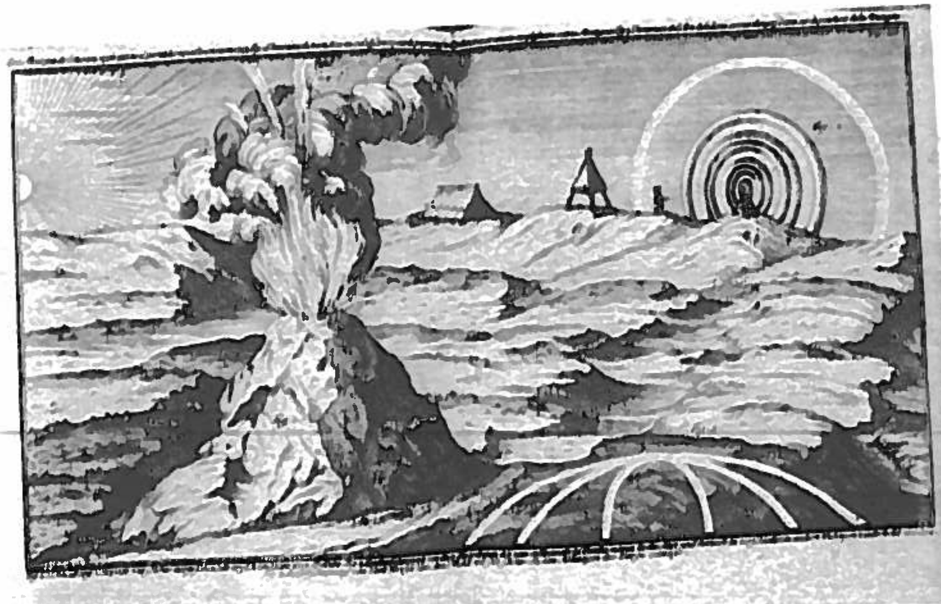


The father and son team of Giovanni and Jacques Cassini shown here used some of the complicated equipment devised by Jean Picard to measure the distance round the Earth. Their results conflicted awkwardly with those of Isaac Newton.

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 kilometres 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, where he became a successful planter and devoted 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 witchcraft trials came to Bermuda and Norwood spent his final years in severe unease that his papers on trigonometry, with



An illustration based on a drawing by members of La Condamine's expedition showing the eruption of Mount Cotopaxi. After nine years of hardship in the Andes, the group discovered that another French team, working in Scandinavia, had made the correct calculation of the Earth's circumference ahead of them.

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 kilometres 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

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