in more miscellaneous tasks, mostly to do with controlling the rates of certain sorts of radioactive decay.

The weak nuclear force, despite its name, is ten billion billion billion times stronger than gravity, and the strong nuclear force is more powerful still – vastly so, in fact – but their influence extends to only the tiniest distances. The grip of the strong force reaches out only to about one-hundred-thousandth of the diameter of an atom. That's why the nuclei of atoms are so compacted and dense, and why elements with big, crowded nuclei tend to be so unstable: the strong force just can't hold on to all the protons.

The upshot of all this is that physics ended up with two bodies of laws – one for the world of the very small, one for the universe at large – leading quite separate lives. Einstein disliked that, too. He devoted the rest of his life to searching for a way to tie up these loose ends by finding a Grand Unified Theory, and always failed. From time to time he thought he had it, but it always unravelled on him in the end. As time passed he became increasingly marginalized and even a little pitied. Almost without exception, wrote Snow, 'his colleagues thought, and still think, that he wasted the second half of his life.'

Elsewhere, however, real progress was being made. By the mid-1940s scientists had reached a point where they understood the atom at an extremely profound level – as they all too effectively demonstrated in August 1945 by exploding a pair of atomic bombs over Japan.

By this point physicists could be excused for thinking that they had just about conquered the atom. In fact, everything in particle physics was about to get a whole lot more complicated. But before we take up that slightly exhausting story, we must bring another strand of our history up to date by considering an important and salutary tale of avarice, deceit, bad science, several needless deaths and the final determination of the age of the Earth.

10

GETTING THE LEAD OUT

In the late 1940s, a graduate student at the University of Chicago named Clair Patterson (who was, first name notwithstanding, an Iowa farm boy by origin) was using a new method of lead isotope measurement to try to get a definitive age for the Earth at last. Unfortunately, all his rock samples became contaminated – usually wildly so. Most contained something like two hundred times the levels of lead that would normally be expected to occur. Many years would pass before Patterson realized that the reason for this lay with a regrettable Ohio inventor named Thomas Midgley, Junior.

Midgley was an engineer by training and the world would no doubt have been a safer place if he had stayed so. Instead, he developed an interest in the industrial applications of chemistry. In 1921, while working for the General Motors Research Corporation in Dayton, Ohio, he investigated a compound called tetraethyl lead (also known, confusingly, as lead tetraethyl), and discovered that it significantly reduced the juddering condition known as engine knock.

Even though lead was widely known to be dangerous, by the early years of the twentieth century it could be found in all manner of consumer products. Food came in cans sealed with lead solder. Water was often stored in lead-lined tanks. Lead arsenate was sprayed onto fruit as a pesticide. Lead even came as part of the composition of toothpaste tubes. Hardly a product existed that didn't bring a little lead into consumers' lives. However, nothing gave it a greater and more lasting intimacy than its addition to motor fuel.

Lead is a neurotoxin. Get too much of it and you can irreparably damage the brain and central nervous system. Among the many symptoms associated with over-exposure are blindness, insomnia, kidney failure, hearing loss, cancer, palsies and convulsions. In its most acute form it produces abrupt and terrifying hallucinations, disturbing to victims and onlookers alike, which generally then give way to coma and death. You really don't want to get too much lead into your system.

On the other hand, lead was easy to extract and work, and almost embarrassingly profitable to produce industrially – and tetraethyl lead did indubitably stop engines from knocking. So in 1923 three of America's largest corporations, General Motors, Du Pont and Standard Oil of New Jersey, formed a joint enterprise called the Ethyl Gasoline Corporation (later shortened to simply Ethyl Corporation) with a view to making as much tetraethyl lead as the world was willing to buy, and that proved to be a very great deal. They called their additive 'ethyl' because it sounded friendlier and less toxic than 'lead', and introduced it for public consumption (in more ways than most people realized) on 1 February 1923.

Almost at once production workers began to exhibit the staggered gait and confused faculties that mark the recently poisoned. Also almost at once, the Ethyl Corporation embarked on a policy of calm but unyielding denial that would serve it well for decades. As Sharon Bertsch McGrayne notes in her absorbing history of industrial chemistry, *Prometheans in the Lab*, when employees at one

plant developed irreversible delusions, a spokesman blandly informed reporters: 'These men probably went insane because they worked too hard.' Altogether, at least fifteen workers died in the early days of production of leaded gasoline, and untold numbers of others became ill, often violently so; the exact numbers are unknown because the company nearly always managed to hush up news of embarrassing leakages, spills and poisonings. At times, however, suppressing the news became impossible – most notably in 1924 when, in a matter of days, five production workers died and thirty-five more were turned into permanent staggering wrecks at a single ill-ventilated facility.

As rumours circulated about the dangers of the new product, ethyl's ebullient inventor, Thomas Midgley, decided to hold a demonstration for reporters to allay their concerns. As he chatted away about the company's commitment to safety, he poured tetraethyl lead over his hands, then held a beaker of it to his nose for sixty seconds, claiming all the while that he could repeat the procedure daily without harm. In fact, Midgley knew only too well the perils of lead poisoning: he had himself been made seriously ill from over-exposure a few months earlier and now, except when reassuring journalists, never went near the stuff if he could help it.

Buoyed by the success of leaded petrol, Midgley now turned to another technological problem of the age. Refrigerators in the 1920s were often appallingly risky because they used insidious and dangerous gases that sometimes seeped out. One leak from a refrigerator at a hospital in Cleveland, Ohio, in 1929 killed more than a hundred people. Midgley set out to create a gas that was stable, non-flammable, non-corrosive and safe to breathe. With an instinct for the regrettable that was almost uncanny, he invented chlorofluorocarbons, or CFCs.

Seldom has an industrial product been more swiftly or unfortunately embraced. CFCs went into production in the early 1930s and found a thousand applications in everything from car air-conditioners to deodorant sprays before it was noticed, half a century later, that they were devouring the ozone in the stratosphere. As you will be aware, this was not a good thing.

Ozone is a form of oxygen in which each molecule bears three atoms of oxygen instead of the normal two. It is a bit of a chemical oddity in that at ground level it is a pollutant, while way up in the stratosphere it is beneficial since it soaks up dangerous ultraviolet radiation. Beneficial ozone is not terribly abundant, however. If it were distributed evenly throughout the stratosphere, it would form a layer just 2 millimetres or so thick. That is why it is so easily disturbed.

Chlorofluorocarbons are also not very abundant – they constitute only about one part per billion of the atmosphere as a whole – but they are extravagantly destructive. A single kilogram of CFCs can capture and annihilate 70,000 kilograms of atmospheric ozone. CFCs also hang around for a long time – about a century on average – wreaking havoc all the while. And they are great heat sponges. A single CFC molecule is about ten thousand times more efficient at exacerbating greenhouse effects than a molecule of carbon dioxide – and carbon dioxide is of course no slouch itself as a greenhouse gas. In short, chlorofluorocarbons may ultimately prove to be just about the worst invention of the twentieth century.

Midgley never knew this because he died long before anyone realized how destructive CFCs were. His death was itself memorably unusual. After becoming crippled with polio, Midgley invented a contraption involving a series of motorized pulleys that automatically raised or turned him in bed. In 1944, he became entangled in the cords as the machine went into action and was strangled.

* * *

If you were interested in finding out the ages of things, the University of Chicago in the 1940s was the place to be. Willard Libby was in the process of inventing radiocarbon dating, allowing scientists to get an accurate reading of the age of bones and other organic remains, something they had never been able to do before. Up to this time, the oldest reliable dates went back no further than the First Dynasty in Egypt – about 3000 BC. No-one could confidently say, for instance, when the last ice sheets had retreated or at what time in the past the Cro-Magnon people had decorated the caves of Lascaux in France.

Libby's idea was so useful that he would be awarded a Nobel Prize for it in 1960. It was based on the realization that all living things have within them an isotope of carbon called carbon-14, which begins to decay at a measurable rate the instant they die. Carbon-14 has a half-life – that is, the time it takes for half of any sample to disappear – of about 5,600 years, so by working out how much of a given sample of carbon had decayed, Libby could get a good fix on the age of an object – though only up to a point. After eight half-lives, only 0.39 per cent of the original radioactive carbon remains, which is too little to make a reliable measurement, so radiocarbon dating works only for objects up to forty thousand or so years old.

Curiously, just as the technique was becoming widespread, certain flaws within it became apparent. To begin with, it was discovered that one of the basic components of Libby's formula, known as the decay constant, was out by about 3 per cent. By this time, however, thousands of measurements had been taken throughout the world. Rather than restate every one, scientists decided to keep the inaccurate constant. 'Thus,' Tim Flannery notes, 'every raw radiocarbon date you read today is given as too young by around 3 per cent.' The problems didn't quite stop there. It was also quickly discovered that carbon-14 samples can be easily contaminated with carbon from other sources – a tiny scrap of vegetable matter, for instance, that has been collected with the sample and not noticed. For younger samples – those under twenty thousand years or so – slight contamination does not always matter so much, but for older samples it can be a serious problem because so few remaining atoms are being counted. In the first instance, to borrow from Flannery, it is like miscounting by a dollar when counting to a thousand; in the second it is more like miscounting by a dollar when you have only two dollars to count.

Libby's method was also based on the assumption that the amount of carbon-14 in the atmosphere, and the rate at which it has been absorbed by living things, has been consistent throughout history. In fact it hasn't been. We now know that the volume of atmospheric carbon-14 varies depending on how well or not the Earth's magnetism is deflecting cosmic rays, and that that can vary significantly over time. This means that some carbon-14 dates are more dubious than others. Among the more dubious are dates just around the time that people first came to the Americas, which is one of the reasons the matter is so perennially in dispute.

Finally, and perhaps a little unexpectedly, readings can be thrown out by seemingly unrelated external factors – such as the diets of those whose bones are being tested. One recent case involved the long-running debate over whether syphilis originated in the New World or the Old. Archaeologists in Hull found that monks in a monastery graveyard had suffered from syphilis, but the initial conclusion that the monks had done so before Columbus's voyage was cast into doubt by the realization that they had eaten a lot of fish, which could make their bones appear to be older than in fact they were. The monks may well have had syphilis, but how it got to them, and when, remain tantalizingly unresolved.

Because of the accumulated shortcomings of carbon-14, scientists devised other methods of dating ancient materials, among them thermoluminescence, which measures electrons trapped in clays, and electron spin resonance, which involves bombarding a sample with electromagnetic waves and measuring the vibrations of the electrons. But even the best of these could not date anything older than about two hundred thousand years, and they couldn't date inorganic materials like rocks at all, which is of course what you need to do if you wish to determine the age of your planet.

The problems of dating rocks were such that at one point almost everyone in the world had given up on them. Had it not been for a determined English professor named Arthur Holmes, the quest might well have fallen into abeyance altogether.

Holmes was heroic as much for the obstacles he overcame as for the results he achieved. By the 1920s, when he was in the prime of his career, geology had slipped out of fashion – physics was the new excitement of the age – and had become severely underfunded, particularly in Britain, its spiritual birthplace. At Durham University, Holmes was for many years the entire geology department. Often he had to borrow or patch together equipment in order to pursue his radiometric dating of rocks. At one point, his calculations were effectively held up for a year while he waited for the university to provide him with a simple adding machine. Occasionally, he had to drop out of academic life altogether to earn enough to support his family – for a time he ran a curio shop in Newcastle upon Tyne – and sometimes he could not even afford the £5 annual membership fee for the Geological Society.

The technique Holmes used in his work was theoretically straightforward and arose directly from the process first observed by Ernest Rutherford in 1904 by which some atoms decay from one element into another at a rate predictable enough that you can use them as clocks. If you know how long it takes for potassium-40 to become argon-40, and you measure the amounts of each in a sample, you can work out how old a material is. Holmes's contribution was to measure the decay rate of uranium into lead to calculate the age of rocks, and thus – he hoped – of the Earth.

But there were many technical difficulties to overcome. Holmes also needed – or at least would very much have appreciated – sophisticated gadgetry of a sort that could make very fine measurements from tiny samples, and, as we have seen, it was all he could do to get a simple adding machine. So it was quite an achievement when in 1946 he was able to announce with some confidence that the Earth was at least three billion years old and possibly rather more. Unfortunately, he now met yet another formidable impediment to acceptance: the conservativeness of his fellow scientists. Although happy to praise his methodology, many maintained that he had found not the age of the Earth but merely the age of the materials from which the Earth had been formed.

It was just at this time that Harrison Brown of the University of Chicago developed a new method for counting lead isotopes in igneous rocks (which is to say those that were created through heating, as opposed to the laying down of sediments). Realizing that the work would be exceedingly tedious, he assigned it to young Clair Patterson as his dissertation project. Famously, he promised Patterson that determining the age of the Earth with his new method would be 'duck soup'. In fact, it would take years.

Patterson began work on the project in 1948. Compared with Thomas Midgley's colourful contributions to the march of progress, Patterson's discovery of the age of the Earth feels more than a touch anti-climactic. For seven

years, first at the University of Chicago and then at the California Institute of Technology (where he moved in 1952), he worked in a sterile lab, making very precise measurements of the lead/uranium ratios in carefully selected samples of old rock.

The problem with measuring the age of the Earth was that you needed rocks that were extremely ancient, containing lead- and uranium-bearing crystals that were about as old as the planet itself – anything much younger would obviously give you misleadingly youthful dates – but really ancient rocks are only rarely found on Earth. In the late 1940s no-one altogether understood why this should be. Indeed, and rather extraordinarily, we would be well into the space age before anyone could plausibly account for where all the Earth's old rocks went. (The answer was plate tectonics, which we shall of course get to.) Patterson, meanwhile, was left to try to make sense of things with very limited materials. Eventually, and ingeniously, it occurred to him that he could circumvent the rock shortage by using rocks from beyond Earth. He turned to meteorites.

The assumption he made – rather a large one, but correct as it turned out – was that many meteorites are essentially left-over building materials from the early days of the solar system, and thus have managed to preserve a more or less pristine interior chemistry. Measure the age of these wandering rocks and you would have the age also (near enough) of the Earth.

As always, however, nothing was quite as straightforward as such a breezy description makes it sound. Meteorites are not abundant and meteoritic samples not especially easy to get hold of. Moreover, Brown's measurement technique proved finicky in the extreme and needed much refinement. Above all, there was the problem that Patterson's samples were continuously and unaccountably contaminated with large doses of atmospheric lead whenever they were exposed to air. It was this that eventually led him to create a sterile laboratory – the world's first, according to at least one account.

It took Patterson seven years of patient work just to find and measure suitable samples for final testing. In the spring of 1953 he took his specimens to the Argonne National Laboratory in Illinois, where he was granted time on a late-model mass spectrograph, a machine capable of detecting and measuring the minute quantities of uranium and lead locked up in ancient crystals. When at last he had his results, Patterson was so excited that he drove straight to his boyhood home in Iowa and had his mother check him into a hospital because he thought he was having a heart attack.

Soon afterwards, at a meeting in Wisconsin, Patterson announced a definitive age for the Earth of 4,550 million years (plus or minus 70 million years) – 'a figure that stands unchanged 50 years later', as McGrayne admiringly notes. After two hundred years of attempts, the Earth finally had an age.

Almost at once, Patterson turned his attention to the question of all that lead in the atmosphere. He was astounded to find that what little was known about the effects of lead on humans was almost invariably wrong or misleading – and not surprisingly, since for forty years every study of lead's effects had been funded exclusively by manufacturers of lead additives.

In one such study, a doctor who had no specialized training in chemical pathology undertook a five-year programme in which volunteers were asked to breathe in or swallow lead in elevated quantities. Then their urine and faeces were tested. Unfortunately, as the doctor appears not to have known, lead is not excreted as a waste product. Rather, it accumulates in the bones and blood – that's what makes it so dangerous – and neither bone nor blood was

tested. In consequence, lead was given a clean bill of health.

Patterson quickly established that we had a lot of lead in the atmosphere – still do, in fact, since lead never goes away – and that about 90 per cent of it appeared to come from car exhaust pipes; but he couldn't prove it. What he needed was a way to compare lead levels in the atmosphere now with the levels that existed before 1923, when tetraethyl lead began to be commercially produced. It occurred to him that ice cores could provide the answer.

It was known that snowfall in places like Greenland accumulates into discrete annual layers (because seasonal temperature differences produce slight changes in coloration from winter to summer). By counting back through these layers and measuring the amount of lead in each, he could work out global atmospheric lead concentrations at any time for hundreds, or even thousands, of years. The notion became the foundation of ice core studies, on which much modern climatological work is based.

What Patterson found was that before 1923 there was almost no lead in the atmosphere, and that since that time lead levels had climbed steadily and dangerously. He now made it his life's quest to get lead taken out of petrol. To that end, he became a constant and often vocal critic of the lead industry and its interests.

It would prove to be a hellish campaign. Ethyl was a powerful global corporation with many friends in high places. (Among its directors have been Supreme Court Justice Lewis Powell and Gilbert Grosvenor of the National Geographic Society.) Patterson suddenly found research funding withdrawn or difficult to acquire. The American Petroleum Institute cancelled a research contract with him, as did the United States Public Health Service, a supposedly neutral government body.

As Patterson increasingly became a liability to his institution, the Caltech trustees were repeatedly pressed by lead industry officials to shut him up or let him go. According to Jamie Lincoln Kitman, writing in *The Nation* in 2000, Ethyl executives allegedly offered to endow a chair at Caltech 'if Patterson was sent packing'. Absurdly, he was excluded from a 1971 National Research Council panel appointed to investigate the dangers of atmospheric lead poisoning, even though he was by then unquestionably America's leading expert on atmospheric lead.

To his great credit, Patterson never wavered. Eventually his efforts led to the introduction of the Clean Air Act of 1970 and finally to the removal from sale of all leaded petrol in the United States in 1986. Almost immediately lead levels in the blood of Americans fell by 80 per cent. But because lead is for ever, Americans alive today each have about 625 times more lead in their blood than people did a century ago. The amount of lead in the atmosphere also continues to grow, quite legally, by about a hundred thousand tonnes a year, mostly from mining, smelting and industrial activities. The United States also banned lead in indoor paint, '44 years after most of Europe', as McGrayne notes. Remarkably, considering its startling toxicity, lead solder was not removed from American food containers until 1993.

As for the Ethyl Corporation, it's still going strong, though GM, Standard Oil and Du Pont no longer have stakes in the company. (They sold out to a company called Albemarle Paper in 1962.) According to McGrayne, as late as February 2001 Ethyl continued to contend 'that research has failed to show that leaded gasoline poses a threat to human health or the environment'. On its website, a history of the company makes no mention of lead – or indeed of Thomas Midgley – but simply refers to the original product as containing 'a certain combination of chemicals'.

Ethyl no longer makes leaded petrol, although, according to its 2001 company accounts, tetraethyl lead (or TEL as it calls it) still accounted for $25.1 million sales in 2000 (out of

overall sales of $795 million), up from $24.1 million in 1999, but down from $117 million in 1998. The company stated in its report its determination to 'maximize the cash generated by TEL as its usage continues to phase down around the world'. Ethyl markets TEL worldwide through an agreement with Associated Octel Ltd of England.

As for the other scourge left to us by Thomas Midgley, chlorofluorocarbons, they were banned in 1974 in the United States, but they are tenacious little devils and any that were loosed into the atmosphere before then (in deodorants or hairsprays, for instance) will almost certainly be around and devouring ozone long after you and I have shuffled off. Worse, we are still introducing huge amounts of CFCs into the atmosphere every year. According to Wayne Biddle, over 27 million kilograms of the stuff, worth $1.5 billion, still finds its way onto the market every year. So who is making it? We are – that is to say, many large corporations are still making it at their plants overseas. It will not be banned in third world countries until 2010.

Clair Patterson died in 1995. He didn't win a Nobel Prize for his work. Geologists never do. Nor, more puzzlingly, did he gain any fame or even much attention from half a century of consistent and increasingly selfless achievement. A good case could be made that he was the most influential geologist of the twentieth century. Yet who has ever heard of Clair Patterson? Most geology textbooks don't mention him. Two recent popular books on the history of the dating of the Earth actually manage to misspell his name. In early 2001, a reviewer of one of these books in the journal *Nature* made the additional, rather astounding error of thinking Patterson was a woman.

At all events, thanks to the work of Clair Patterson, by 1953 the Earth at last had an age everyone could agree on. The only problem now was that it was older than the universe that contained it.