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Carbon Copy

On 25 April 1772, the French chemist Antoine Lavoisier set fire to a diamond. Several diamonds, actually, and on purpose.

Lavoisier and his colleagues, the chemist Pierre Macquer and the apothecary Louis Claude Cadet, burned those diamonds by putting them into a crucible, then placing the crucible in the furnace in Cadet's workshop. The experiment was, nominally, about determining whether air was necessary to burn a diamond, or if the gem could burn in a vacuum. The trio proceeded to put a plethora of other gems in the furnace, much to the shock and awe of members of their informal audience, such as Paris's eminent Duc de Croÿ, a fixture in popular intelligentsia circles of France, who had stopped by Cadet's shop that afternoon.

'I found the furnaces lit and everyone very busy. Monsieur Lavoisier, Farmer General and Academy member, and somebody else were trying to distill a diamond,' the Duc de Croÿ wrote, his shock and disbelief unmistakable. 'These experiments are putting lots of diamonds in the fire!'

These were not the first diamonds to be put 'in the fire', however. In 1694, Giuseppe Averani and Cipriano Targioni, two Florentine naturalists from the court of Cosimo III, used 'burning glasses' – large lenses of biconvex glass – to focus rays from the sun on to diamonds that were promptly converted into an ashy substance known as a calx. Isaac Newton incinerated diamonds as part of his various research experiments. And in 1760, the Austrian Emperor François I underwrote a wildly expensive experiment where 6,000 florins' worth of diamonds and rubies were enclosed in cone-shaped crucibles and stuck in a furnace for 24 hours.

‘The rubies had changed,’ the courts’ experimenters reported, ‘but the diamonds had completely disappeared, to the point that not the slightest trace was found.’

By the mid-eighteenth century, chemists throughout Europe were interested in observing, defining and documenting the physical properties of gems, minerals and elements. Diamonds were no exception and the work of these previous experimentalists provoked further curiosity. Lavoisier wanted to understand how the chemistry of combustion worked in diamonds – why the hardest mineral in the world could be changed from a shiny, brilliant gem into charcoal, and why this didn’t happen with other gemstones.

Five days after the Duc de Cröy’s visit, on 29 April 1772, Lavoisier reported his results from the tests on 21 diamonds to the Academy of Sciences, noting that there was a difference in a diamond’s ash when it was exposed to air and when it was not. But these results posed more questions than they answered. What was happening to those diamonds? Were they simply vaporised, as happens to water when it is heated? Were the diamonds actually combusting? Or were they simply breaking down into their most basic particles ‘so fine that they can no longer be perceived by our senses’? More experiments, Lavoisier concluded, were necessary. As were more diamonds.

And, on 8 August 1772, more experiments and more diamonds were what Lavoisier got. Instead of using a furnace, Lavoisier and his colleagues – Cadet, the natural philosopher Mathurin Jacques Brisson and the pharmacist Pierre François Mitouard – opted for a different experimental set-up.

Lavoisier ordered a large, six-wheeled wooden platform wagon with enough space for eight or nine scientists to work. He had two massive burning glasses – convex lenses – mounted on one end of the platform that could be

manipulated through a complex series of cogwheels and cranks to best capture the sun's rays as the sun moved across the sky throughout the day. The lenses were 2.4m (8ft) in diameter, jointed at the edges, and filled with 79.5 litres (140 pints) of alcohol as a way to make the lenses even thicker, intensifying and amplifying the sun's rays. (A 'liquor lens', per Lavoisier's notes.) Lavoisier outlined a programme of experiments and organised all the necessary materials.

'A group of assistants were in charge of adjusting and moving the machine while the four scientists, wearing wigs and dark glasses, proceed with the test, installed as if they were on the poop deck of a ship,' historian of science Jean-Pierre Poirier explains in his biography of Lavoisier. Because the experiment was set up on the vast south-facing terrace of the Jardin de l'Infante, which stretched between the royal palace and the banks of the Seine, 'Elegant women and the curious came to stroll there and observed the scene with amazement.'

Between 14 August and 13 October 1772, Lavoisier conducted 190 experiments on diamonds, metals and other minerals with this set-up. Then, between 14 March and 14 August 1773, he carried out an additional set of 19 experiments on diamonds – in glass jars – to be ignited by the sun's rays. (Unfortunately, the glass jars broke as a result of the incredibly high temperatures.) What Lavoisier and his colleagues were left with in every instance of their diamond experiments were piles of charcoal – in amounts that weighed the same as the diamonds that they had started with. Based on these experiments, as well as a number of others conducted over the next several years, Lavoisier concluded that the charcoal and diamonds were simply forms of the same material. When he published an updated list of chemical elements in 1789, he referred to this substance as carbon.

In the 1790s, the English chemist Smithson Tennant expanded Lavoisier's work with diamonds, and through his own sets of experiments, demonstrated that the gem is nearly pure carbon. (In his report to the Royal Society of London, Tennant noted that, 'Though [Lavoisier] observed the resemblance of charcoal to the diamond, yet he thought that nothing more could be reasonably deduced from their analogy, than that each of those substances belonged to the class of inflammable bodies.') Tennant converted identical weights of charcoal and diamond to exactly the same volume of carbon dioxide gas, establishing that charcoal and diamonds were chemically equivalent when they were both in solid form. 'As the nature of the diamond is so extremely singular,' Tennant reported to the Royal Society in 1797, 'that it consists entirely of charcoal, different from the usual state of that substance only by its crystallized form.'

Understanding what a natural diamond was made of was the first step towards thinking about how to reproduce it in a laboratory. The first reports of a 'man-made' diamond came just over 100 years after Lavoisier and Tennant demonstrated that diamonds were made of carbon. Their experiments opened the door to the possibility of transforming carbon – like its very common form of graphite – into diamonds. While forgers and fraudsters had been passing off fake diamonds for millennia, the idea that a diamond could be replicated – that it could be synthesised and still be 'real' – caught the imagination of many nineteenth- and early twentieth-century experimental scientists.

And thus begins the story of how to make a real, non-natural diamond.

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On 19 February 1880, Professor Mervyn Herbert Nevil Story-Maskelyne was working as Keeper of Minerals at the

British Museum, where he received a small package of nine crystalline specimens. (This Story-Maskelyne was the grandson of the royal astronomer with the same name, famous for devising a way to mark longitude while at sea.) James Ballantyne Hannay, a 25-year-old Scottish chemist who claimed that the pieces were diamonds that he had made himself, had sent the crystals to him.

Professor Story-Maskelyne was an expert in gems, mineralogy and chemistry, having taught at Oxford for decades. After examination and a series of stringent tests, Story-Maskelyne authenticated the diamonds as real – albeit ‘man-made’ – and proceeded to report Hannay’s incredible achievements in *The Times*, as well as submitting a report to the scientific intelligentsia of the Royal Society of London.

James Ballantyne Hannay was a practising chemist and metallurgist. In his numerous experiments, he had observed that many substances (like silicon, aluminium and zinc) were insoluble in water at normal temperatures and would largely dissolve in water vapour at high temperatures. Hannay thought such a solvent might be found for carbon that would allow the structure of a chunk of carbon to rearrange itself from one form into another. In short, Hannay wanted to create a dissolving material in an appropriate solvent, and then figure out how to induce crystalline growth in a particular pattern – not unlike the process of making rock candy that uses a seed crystal to start the growing pattern. ‘I thought that if I could by increased temperature dissolve the nascent carbon in the metal I might obtain a diamond,’ Hannay reported to a meeting of the Royal Society in April 1880.

However, obtaining the diamonds that Hannay sent Story-Maskelyne wasn’t easy or straightforward, because designing and building an experimental set-up capable of reaching the high heat and pressure necessary was, in a

word, difficult. By September 1879, Hannay had started using wrought-iron tubes that were 50cm (20in) long and 1.5cm (1in) thick, with a 1.2cm (.5in) bore hole in the middle – each tube was roughly the size of a baton. The tubes acted as crucibles to isolate carbon, facilitating its transformation into a diamond. Hannay filled each two-thirds full of a ‘paraffin spirit’ and bone-oil mixture, adding 4g of lithium, and a pinch of lampblack for the carbon-base solvent. He heated the tubes to a ‘dull red-heat’ for 14 hours, then set them aside to cool.

Incidentally, finding a successful way to seal the tubes was not an insignificant part of Hannay’s experiments. The heat and pressure they were subjected to meant that they wouldn’t just stay screwed shut – they had to be crimped or welded. But when Hannay crimped end plugs – balls with an appropriate diameter – to the tubes, this inadvertently and invariably turned the tubes into miniature cannons. Once the pressure inside built up after hours in the furnace, the end of the tube would shoot out. ‘It was expected that the pressure would only serve to make the closing more secure, but, on heating, the iron yielded and the ball was driven out with a loud explosion,’ Hannay clinically noted in his report.

Nine out of ten times, the iron tubes exploded, destroying the furnaces and their contents, and essentially rendering Hannay’s workplace something akin to an active battlefield, repeatedly leaving his laboratory in shambles. ‘The experiments are, however, too few, and the evidence too vague, to draw any conclusions, as there are even very few negative experiments from which anything can be learned, most of the results being lost by explosion,’ he acknowledged.

Of the few tubes that survived Hannay’s ministrations, most of the carbon inside either ‘evaporated’ out completely or appeared ‘soft and scaly’, as he reported to the Royal Society. But a precious handful – three tubes out of

80 runs – had crystals inside that were hard and transparent. Under a microscope they looked like diamonds, and these hard, transparent, diamond-like specimens were what Hannay sent to Professor Story-Maskelyne in February 1880 and what Story-Maskelyne authenticated as real diamonds. It would seem that Hannay really had made the world's first genuine synthetic diamond.

Although Hannay's results resonated with some prominent scientists, like the Scottish chemist Sir Robert Robertson – the first scientist to establish two types of natural diamond – the scientific community politely but pointedly ignored Hannay, his claims and his diamonds, despite the backing of Robertson and Story-Maskelyne. (Fifty years before Hannay sent his diamonds to Story-Maskelyne, the British publication *Mechanics' Magazine: Museum, Register, Journal, and Gazette* printed a letter summarising a meeting of the French Academy of Sciences, where a gentleman named Monsieur Gannal claimed to have successfully 'converted pure carbon' into 'crystals possessing all of the properties of the diamond'. But that claim was never taken seriously.) Hannay died in 1931, having moved on from the project of making diamonds in his later years, but remained utterly convinced that he had succeeded.

Scientific and historical communities have never been exactly sure what to make of Hannay's crystals. For over 100 years, opinion has shifted backwards and forwards about whether the specimens that Hannay created were in fact diamonds and, if they were, whether Hannay actually created diamonds in his lab or if the specimens he sent to Story-Maskelyne were naturally produced diamonds that he attempted to pass off as his own handiwork. (In 1902, Hannay quietly refuted a suggestion made by the *Encyclopaedia Britannica* that his diamonds were simply carborundum or silicon carbide.) Throughout the twentieth

century, experts have examined the nine specimens that are still at the British Museum, testing them against increasingly sophisticated methodologies that have developed since Story-Maskelyne's original assessment of the stones.

More methods and more tests, however, have not made the Hannay story any more straightforward. The eminent crystallographer Professor Kathleen Lonsdale of University College London, who herself worked on the question of synthesising diamonds, examined Hannay's diamonds several times over many decades, eventually concluding that the gems were natural diamonds. Further examination of the diamonds in 1968 and 1975, using a series of tests that were capable of differentiating laboratory diamonds from naturally grown ones, concurred with Lonsdale's assessment that the diamonds were, indeed, diamonds, but that they were natural – Hannay hadn't made them.

All of these mid-twentieth-century reports charitably concluded that the natural diamonds had been 'contaminants' in Hannay's studies – natural seed diamonds that Hannay used to encourage crystal growth the way synthetic diamonds are made today, although Hannay never noted that he had used seed diamonds in his meticulous lab records. Some recent historians do not buy the contaminant theory and contend that Hannay was an out-and-out fraud, while others argue that Hannay's colleagues and workers seeded the tubes with natural diamonds in the hopes of staving off more dangerous experiments.

What is indisputable, however, is that the question of making a synthetic diamond certainly caught the public and scientific imaginations of the nineteenth century. While the scientific community might have, more or less, ignored Hannay's efforts when he first published his results, the question of whether a laboratory could reproduce a mineral made by nature was of utmost interest among experimentalists, as diamonds became better known as a

result of colonial mining and trade. This also neatly intersected with then-current research interests to do with materials science.

In 1893, following Hannay's efforts, the French experimental chemist Ferdinand Frédéric Henri Moissan tried using his newly developed electric-arc furnace to transform graphite into diamonds. Moissan heated iron with sugar charcoal in a carbon crucible to 4000°C (7232°F) in the laboratory furnace, then plunged the white-hot crucible into cold water, solidifying the iron and thus exerting a very high pressure on the carbon. These experiments led Moissan to the discovery of 'moissanite', a silicon carbide, which he initially mistook for diamond, due to the mineral's hardness.

Moissan's experiments attempting to create diamonds were so well known that in 1904 his fellow Frenchman, Monsieur Henri Lemoine, exploited Moissan's celebrity, claiming to have been able to reproduce Moissan's laboratory diamonds and wanting to set up a laboratory-factory funded by wealthy investors. (Historical lore has it that Lemoine shocked his potential investors by performing a demonstration of a diamond-making experiment *au naturel* to prove to his audience that the technology to make diamonds was feasible and that he hadn't simply hidden natural diamonds in his clothes.) Over the next three years, Lemoine bilked investors out of 64,000 pounds sterling, an enormous sum of money. With the 1908 confession of a jeweller who admitted selling Lemoine a cache of small, uncut diamonds that matched the description of the gems Lemoine 'made' in his laboratory 'experiment', it quickly became clear that Lemoine's created gems were simply natural, river-washed diamonds from the Jagersfontein mine in South Africa. Lemoine was subsequently arrested, tried for fraud and found guilty. The scientific and historical juries are still out as to whether

what Moissan created were actually diamonds, since no one was able to reproduce his results.

In the ensuing decades of the early 1900s, several prominent scientists attempted to re-create both Hannay's and Moissan's experiments – including Sir Charles Algernon Parsons, inventor of the steam turbine. Many of these efforts produced small, diamond-like specimens. Parsons spent decades and a considerable chunk of his personal fortune in his quest, but in 1928 he renounced his claims, having become convinced that his synthesised gems were not, mineralogically, diamonds. The fervour that surrounded the manufacture of diamonds even crept into the budding world of nineteenth-century science fiction, when famous novelist H. G. Wells published a short story called 'The Diamond Maker' in 1894, based on Moissan's experiments. However intriguing these early attempts were, none of the experiments created reproducible results. And none yielded 'real' synthetic diamonds that were universally accepted by the scientific community.

'Some gemstone experts are apprehensive about synthetic gemstones,' chemist and mineralogist Kurt Nassau offered in the introduction to his 1980 book, *Gems Made By Man*, as tensions built in the gemmological world about how to make sense of non-natural diamonds. 'They regard them as intruders to be shunned.'

The suspicion of non-natural gems runs deep because for most of history, the only kinds of gem that didn't come from nature were fakes. Consequently, fake gems – fake diamonds – are nothing new. Like frauds and forgeries that we find in art, manuscripts, codices and fossils, fake gems find a plethora of ways to creep into the world of genuine things, and have done for millennia. Fakes serve as

a narrative foil to synthetic diamonds, and the relationship between synthetic, natural, fake and real is conflated and contorted. This is particularly true in the twenty-first century, when synthetic diamonds constantly come up against thousands of years of cultural mores that might see them as less than real.

In the first century AD, Roman author and natural philosopher Pliny the Elder took on the question of such fakes in the mineralogy section of his famous *Historia Naturalis*. Among the descriptions of various gems and minerals (where he reports that quartz is a form of ice produced by the congealing of water in the extreme cold), Pliny calls his reader's attention to the proliferation of fake gems – specifically, instances where fraudsters simply substituted cheap look-alikes for the genuine thing. He attributes the abundance of fakes to humanity's obsession with precious gems – his disdain is palpable: 'there is no other kind of fraud practiced, by which larger profits are made'. In order to combat the rampant gem deception across the Classical world, Pliny offers the first description of a scratch test to differentiate real diamonds from fakes – noting that real diamonds would scratch other minerals but not vice versa.

Most fake diamonds were attempts to pass off pieces of glass or quartz, with the hope that the buyer would be gullible enough to not notice a substitution. As very few diamonds were cut or faceted in ancient Rome, such substitutions were rather straightforward. Other fraudsters turned to alchemy as a clever way to dye stones to look like more expensive gems. The Stockholm Papyrus, for example, was a collection of alchemic recipes written in Greek in AD 200–300, which contained 71 how-tos for creating fake gems. It walked its readers through how to take selenite, topaz or moonstones and colour them to look like emeralds, rubies or beryls. (In going through those

Stockholm Papyrus alchemical recipes, reader, I was struck by the number that called for the use of ‘tortoise bile’.)

Yet these were all simply ways to approximate but never replicate nature. ‘For although art may imitate nature nevertheless is cannot reach the full perfection of nature,’ wrote Albertus Magnus, the thirteenth-century Dominican bishop and natural philosopher, in his *Book of Minerals*. Magnus was talking about glass – it could look exquisite and sparkle like a diamond, but only as an imitation. It was not natural. It could never be a ‘real’ gem.

Which brings us to the differences of intent between those creating and peddling fake diamonds, and what was going on with Moissan and Hannay’s experiments. Compound the differences of intent with the ever-shifting definition of imitation, and it’s no wonder that just what gets to count as a ‘real’ diamond is shaky. Synthetic gems are not merely imitations (simulation, a fake, a paste, a glass) of natural gemstones. To deserve – to earn, really – their designation as synthetic replicas they have to have the appearance, chemical composition, crystal structure, hardness and optical properties of a natural stone.

This is a huge change in the story of non-natural diamonds. In previous centuries, human-made diamonds were inherently frauds and hoaxes – fakes. With the attempts to transform one form of carbon into another – a piece of graphite into a diamond – the intent and context of the not-natural diamond changed. Was it possible, scientists asked themselves, to produce in their laboratories what nature had made millions of years ago, without the deception that had always surrounded fake diamonds?

So, when scientists began growing, manufacturing and synthesising diamonds, the research grew out of Lavoisier’s combustion experiments, rather than the fraudsters’ shilling glass imitations. (Lavoisier was very careful to position himself as a proper *chemist* – not an alchemist – to lend

more legitimacy to his research, distancing his work from the older discipline's reputation for fraud and deception.) The story of made diamonds is not the story of a fake becoming real, in the way Spanish Forger art pieces gained value in the art market. Synthetic diamonds were real diamonds to begin with, comparable and identical to natural diamonds on an elemental level. This shifted the story from fraud into one of scientific ingenuity – only the story of their origins separates the two.

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To that end, the first non-natural diamonds were made in General Electric's laboratories in December 1954.

Ever since Lavoisier and Tennent's experiments, scientists and engineers had known that they needed to subject carbon to enormous amounts of heat and pressure in order to transform it into a diamond, but just how to pull this off required no small amount of trial and error. As demonstrated in the experiments of Hannay, Moissan and even Parsons, creating immense amounts of pressure is difficult, if not downright dangerous. But, their early experimental designs weren't necessarily flawed – they just needed different technologies and manufacturing to be able to create those pressures in the lab. The answer came from the American Nobel-winning physicist Percy Bridgman, who worked with the development of a vertical hydraulic piston that pressed into a cylinder, which created 4,200 atmospheres of pressure through a complex anvil system. For years, Bridgman's laboratory at Harvard had holes in the walls where the canister – affectionately known as 'The Bomb' – blew out and embedded materials in the walls. Bridgman, it was reported, superstitiously never had the holes repaired.

By the 1940s, the General Electric Research Laboratory in Schenectady, New York, had become the centre of

synthetic diamond research, bringing together researchers from chemistry, physics and industrial engineering. (Schenectady had a long tradition of supporting speculative research projects even if they weren't directly related to the production of electrical equipment.) The team was made up of Francis Bund, Herbert Strong, Howard Tracy Hall (generally H. Tracy Hall or Tracy Hall in popular literature), Robert Wentorf and James Cheney, and was managed by Anthony Nerad. The project was code-named 'Project Superpressure' and everyone was sworn to secrecy. Drawing on Bridgman's work, Superpressure used several different apparatuses in its experiments. For years, the team devoted extraordinary time, effort and resources to making synthetic diamonds – and, more importantly, to learning how to manufacture them in a way that was replicable. As the years went by, the management at General Electric began to worry that manufacturing diamonds would turn out to be gimmicky at best and a total monetary sinkhole at worst. By December 1954, the team needed concrete, tangible results – diamonds – to justify its work.

On the evening of 8 December 1954, Herbert Strong began Experiment 151, setting the pressure cone apparatus at an estimated 50,000 atmospheres, cranking the temperature up to 1250°C (2282°F), and depositing a carbon and iron mixture with two small natural diamonds to seed diamond crystal growth. It was not unlike the methods used by Hannay decades earlier, only Strong was clearly using seed crystals. (Research in the Soviet Union used seed diamonds as part of the effort to grow diamonds, as near as General Electric could tell.) Most of Strong's earlier experiment runs had been short, a couple hours at most. But this time he decided to let Experiment 151 mimic nature – which took millions of years to produce diamonds – and, at least, to extend the time of the experiment and let it run overnight.

On the morning of 9 December, the two seed crystals tumbled out freely, unchanged in the crucible. A blob of

the iron-carbon mixture had melted into one end of the tube and Strong sent the blob to the metallurgy division to be polished. A bit miffed, metallurgy sent back a message on 15 December, informing Strong that they were unable to polish his sample because it was destroying the polishing wheel. Whatever was in the blob was strong and hard – hard enough to gouge metallurgy's equipment – and only a diamond could be that tough. Strong recounts, 'The entire group gathered around to inspect the hard point. Initially there was a moment of stunned silence. Could it possibly be diamond? Finally, Hall spoke the verdict: "It must be diamond!"' Subsequent X-ray analysis confirmed that the diamonds in question were, in fact, laboratory made.

On 16 December 1954, Hall performed a similar experiment by himself, using an older bit of technology, a high-pressure press called a belt. He added two diamond seed crystals to iron sulphide and placed everything in a cylindrical graphite heater. Carefully following the belt protocol he had designed after months of working with the apparatus, he placed thin disks of tantalum metal between the sample and the belt anvils to facilitate current to heat the sample. Everything was cooked at 1600°C (2912°F) under 100,000 atmospheres of pressure. The entire experiment took 38 minutes.

'I broke open a sample cell after removing it from the Belt. It cleaved near that tantalum disk,' Hall said of his discovery, after seeing flashes of light from octahedral crystals that were stuck to the disk. 'Instantly, my hands began to tremble. My heart beat wildly. My knees weakened and no longer gave support. Indescribable emotion overcame me and I had to find a place to sit down!' In Hall's mind, there was no doubt about the results. 'I knew that diamonds had finally been made by man.'

Suddenly, after years of research and in the space of a mere week, General Electric had two possible ways to manufacture

diamonds. In the weeks that followed the question wasn't so much whether researchers could make diamonds. The question was whether they could make them again according to either Strong's or Hall's experiment designs. Which method was better?

Researchers spent weeks trying to duplicate Strong's results and never could. (Strong contended that the heat had fluctuated significantly during the night of Experiment 151 and that fluctuation played a role in the run's success – serendipity as its finest.) Hall, working with Robert Wentorf, verified his original results rather decisively. Over the next two weeks the two of them successfully made diamonds 20 times, using Hall's 400-ton press and belt system. On 31 December 1953, General Electric had physicist Hugh Woodbury independently confirm Hall's diamond-making methodology.

Like many discoveries in the history of science, pinpointing exactly who ought to be credited with a discovery – and who history has credited – is a bit tricky, and the story of who manufactured the first synthetic diamond and when is no exception. In a series of publications, Strong has highlighted the work that the group did, pointing to the complicated nature of the problem and emphasising that the work was beyond what one man could claim to do.

Hall, on the other hand, felt ostracised from the team. (As a practising member of The Church of Jesus Christ of Latter-day Saints, he claimed to have been on the receiving end of religious prejudice during his tenure at General Electric.) He also felt underappreciated by the company: General Electric increased his salary from \$10,000 to a mere \$11,000 between 1953 to 1954, and paid him a \$10 savings bond, despite making millions from his work. (This was somewhat typical for a Cold War research laboratory. Corporate scientists signed over the rights of their intellectual property to their parent companies and often received small

bonuses like this one in connection with any patents that resulted from their work.) Hall left General Electric in mid-1955 to take a faculty research position at Brigham Young University, and authored several patents related to the manufacture of synthetic, laboratory-grown diamonds. He also started the company MegaDiamond, which eventually became General Electric's biggest domestic competitor in the diamond-making business. Both Hall and Strong have claims to be 'the first' to create diamonds, although most tellings of the story credit Hall because of the replicability of his experiments.

General Electric published the results of its laboratory-grown (or 'man-made' or synthetic in the parlance of the mid-twentieth century) diamonds on 15 February 1955. Reporters were invited to check the laboratory-made diamond dust under a microscope, and the research team was under strict instructions to keep mum about details of its work. Between February and March 1955, newspapers across the country blurbed General Electric's success, but were short on technical details for their readers. Most of those quoted in articles were jewellery experts, who dismissed these diamonds as any sort of financial challenge to the diamond market at that point. In the following months, General Electric held several more press events (one, for example, in May 1955, was at the Sheraton Hotel in Rochester, New York), which talked up not only the engineering prowess of its synthesised diamonds, but also how the project would be a 'boon to US industry'.

Superpressure's research didn't stop with press releases. Just because General Electric had a reliable method of producing diamonds, the logic went, it didn't mean that there wasn't plenty to explore in the world of synthetic diamonds. General Electric also wasn't so naïve as to think that others weren't pursuing the same goal. In fact, more than a decade earlier, in the early 1940s, Sweden's major

electrical company, ASEA, had begun its attempts under the direction of the Swedish scientist and inventor Baltzar von Platen. ASEA ran extravagant experiments, and despite a series of complications not unlike those that General Electric faced, actually produced synthetic diamonds (diamond grit, technically, similar to the dust that General Electric showed reporters in that first press conference) in 1953, before team Superpressure produced theirs.

However, ASEA never published anything about its project. 'The most maddening, inexplicable aspect of ASEA's diamond-making victory was their absolute, absurd silence,' Robert Hazen laments in his book *The Diamond Makers*. 'After hundreds of years of concerted effort in which brilliant scientist after brilliant scientist had failed ... ASEA had triumphed.' In fact, it wasn't until two years later, after the Americans at General Electric had announced their own success, that ASEA deigned to make a brief statement about its experiments, publishing the work in 1960. In subsequent decades ASEA scientists explained that they felt that publishing in 1953 would have been premature, and that they wanted to have something more substantive when they did publish – they also claimed that they had no idea that other scientists were working on the same question.

Back in America, however, the race was on to patent the technologies and to corner the manufacturing market for synthetic diamonds. The US Army's Electronics Research and Development Laboratory at Fort Monmouth, New Jersey, became interested in pursuing the research question, in large part because diamonds had so many industrial applications, as did a research group at the University of Michigan. When scientists from the US Army met with General Electric researchers, all of the company's equipment was covered with paper drapes for secrecy.

In 1957, General Electric began selling industrial-grade diamonds, and in 1959 the team published the details of its discovery in *Nature* and filed a globally recognised patent for its ‘Man-Made’ diamonds, as rumours swirled that South African and Soviet labs were close to producing diamonds. In February 1960, Hall published a detailed description of a similar belt apparatus to General Electric’s and filed his own patent, followed by two more over the ensuing years. The process of making a synthetic, laboratory-grown diamond was beginning to enter the competitive intersection of science and industry, and within a year historical estimates suggest that more than two dozen research groups had successfully synthesised diamonds.

Consequently, questions about how to make the laboratory process better, faster, cheaper and more reliable began to creep into the research, now that the proof of the concept was thoroughly demonstrated. The key to better diamond synthesis, Superpressure found, was to reach temperature and pressure conditions that were conducive to forming a diamond at the same time that the metal mixture was in a liquid state. Liquid metal – as hypothesised and used seven decades earlier by Hannay and Moissan – was necessary to dissolve the carbon source, in order to provide a steady supply of carbon atoms and to catalyse diamond growth. The high-pressure/high-temperature experiments produced a lot of other successes, in addition to actual diamonds, by creating new substances. The team began to look for new milestones.

And the team wasn’t without a sense of humour. In December 1955, Robert Wentorf went to the local food co-op in Niskayuna, New York, bought his favourite type of crunchy peanut butter and brought it back to the diamond lab at General Electric. With a certain theatrical flair, he scooped out a spoonful of the crunchy peanut butter and ran it through the Superpressure’s experiment protocols,

transforming it into tiny crystals of diamond – thus demonstrating that a carbon base of any sort could be turned into a diamond, given enough heat and pressure.

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In nature, diamonds start out as carbon-containing fluids, hundreds of kilometres below the Earth's surface, typically involving the breakdown of carbon dioxide or methane. While some diamonds – microdiamonds or nanodiamonds – form when a meteor hits the Earth, the majority of diamonds form deep inside the Earth's mantle, under immense heat and pressure, until they are transformed into diamonds that are carried to the crust.

The growth pattern of diamonds indicates that they grow slowly and are anywhere from three billion to a few hundred million years old. Although diamonds take eons to form, they reach the surface rather quickly – some scientific estimates put diamonds' travel time at months or even hours. Most diamonds come to the surface through a specific type of molten rock, called kimberlite, which works its way up from the mantle through vertical fractures in the Earth's surface. The kimberlite-magma pipeline is what we know as a diamond vein or diamond mine. Creating diamonds in a laboratory shortcuts millions, if not billions, of years of geologic time.

The 1960s saw the rise of jewellery-quality non-natural diamonds, both in size and in clarity, as the team at General Electric started producing diamonds that were at least a carat in size, at the rate of about one carat per week. Photos from the late 1960s to the early 1970s show researchers and General Electric executives posing with large, discernibly cut diamonds. These diamonds, the pictures subtly suggest, are 'real' diamonds – they are cut gems just waiting for their jewellery settings. Creating this sort of narrative

around the synthetic diamonds translated their real-ness to sceptical audiences. The diamonds *looked* like gems, ergo they *were* gems, in a way that synthesising grit for industrial tools wasn't. In 1968, General Electric transferred the diamond project to Worthington, Ohio, where it remains today, known as the 'GE Specialty Materials Department'. By the late twentieth century, Sumitomo Electric Industries Ltd in Japan, De Beers Industrial Diamond Division (Pty) Ltd in South Africa, General Electric in the United States and Russian researchers in Novosibirsk were all creating diamonds that were going to either industrial or jewellery markets.

While the mid-twentieth century laboratory diamond research pushed towards new goals, all of the experiments and manufacturing depended on the technique of creating diamonds using high pressure and high temperature – what is known in the industry as HPHT diamond manufacture. (Even in the twenty-first century, HPHT is used to make most synthetic diamonds.) But in the late twentieth century, a new generation of diamond makers hypothesised that diamond layers could form from hot, vaporised carbon atoms at low pressure. This sort of method would, potentially, allow industries to manufacture synthetic diamonds on a much larger scale.

This new method, called chemical vapour deposition (CVD), was a recycling of experiments from the 1950s, but with the technology and engineering of the late twentieth century. In 1952, William Eversole of the US-based Union Carbide Corporation demonstrated that it was possible to grow diamonds at lower pressures if one started with a carbon-containing gas. Basically, CVD works by forming a gas of single, isolated carbon atoms from a hydrocarbon mix (heating carbon atoms to an incredibly high temperature), then encouraging the atoms to cool into a crystalline lattice structure, forming a film, much like how

layers are formed on a 3D printer. Researchers began successfully creating greyish diamonds through CVD in the late 1980s to the early 1990s.

This method enabled more diamonds to be made over a larger variety of substrates and at lower temperatures and pressures. CVD for diamonds overlapped quite a bit with CVD research in semiconductors and wafers. The most common material used in semiconductors is silicone – silicone oxide – and the explosion of semiconductors for electronic chips and integrated circuits saw an industry refine and hone the technology necessary to be able to successfully use CVD techniques. Advances in CVD diamonds continue today, and although HPHT is still used for the manufacture of the majority of diamonds, CVD is quickly catching up.

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The story of a natural diamond begins, of course, millions if not billions of years ago and deep within the Earth. Even once a diamond comes to the Earth's crust, it's still a long way from becoming the gem that sparkles in its setting, or even, for that matter, from becoming the diamond grit for industrial uses. In order for a diamond to become, well, a diamond, it undergoes intense cultural forces that morph it into the object that we know it as today. Diamonds are just as much the result of their history as their chemistry and geology.

For millennia, humans have manipulated diamonds – for jewellery, yes, but also for technology. In late Neolithic China some 4,500 years ago, for example, when craftspeople polished ceremonial burial axes made of the extremely hard mineral corundum, they used diamonds to obtain the exceptionally smooth finish. For thousands of years, peoples and cultures have exploited the hardness of diamonds in a

variety of forms – from tipped tools to industrial grit – taking advantage of the mineral's physical properties. While Pliny the Elder described both the natural and cultural elements of diamonds (as well as the proliferation of fakes) in *Natural History*, cultural meaning beyond strict financial valuation varied greatly throughout human history over the last two millennia. The Middle Ages and the early Renaissance saw a plethora of meanings attached to the mineral. The eleventh-century poet Marbodius of Brittany, for example, suggested that diamonds were magic stones of great power that could be used to drive away nocturnal spectres, and he recommended wearing diamonds set in gold on one's left arm. In the twelfth century, Saint Hildegard claimed that the diamond allowed its wearers to ward off Satan, thus resisting his power day and night.

With the publication of his book *Travels* in 1360, the English writer and knight Sir John Mandeville proposed that diamonds could prove guilt or innocence when one was accused of a crime – if the accused was guilty, the diamond would dim and if innocent, it would sparkle and shine even more than it did before. (Mandeville also hypothesised that 'A diamond is synthesized when two larger ones, one male and one female, come together, in the hills where the gold is. And the diamond grows larger in the dew of a May morning.') For several centuries, diamond dust was considered to be a deadly poison – Florentine sculptor and goldsmith Benvenuto Cellini was convinced he was being poisoned by diamond dust when he was imprisoned on false charges in 1538. In the world of sixteenth-century natural philosophy, Italian Gerolamo Cardano claimed that diamonds make their wearers unhappy by preying frequently on the mind – not unlike the irritation of the sun being constantly in one's eyes. Since the stone was hard and transparent it was often ascribed moral characteristics, like invincibility and purity, which would rub off on to its wearer.

Throughout their history, natural diamonds have been material as well as metaphor, a duality of nature and culture that continues to shape what we think of as a real, authentic diamond even today. However, the cultural cachet of diamonds accelerated exponentially over the last 130 years due to De Beers and its diamond legacy. Indeed, it is impossible to talk about the cultural invention of diamonds – synthetic or natural – without talking about De Beers.

Until the late nineteenth century, diamonds were found primarily in India and Brazil. Historical estimates suggest that for centuries the entire production of gem diamonds could be measured by only a few pounds per year. When huge diamond mines were discovered in northern South Africa in the 1870s, near the Orange River, diamonds were ‘being scooped out by the ton’. The British financiers who had backed the South African mines were concerned about what the influx of gems would mean – as the market at this time depended entirely on the gems’ scarcity – and became convinced that if all of the mined diamonds went to market, diamonds would become semi-precious stones at best. Major investors moved to consolidate their diamond-mining investments to control production and ‘perpetuate the illusion of scarcity’ that shaped the diamond market.

And thus, in 1888, De Beers Consolidated Mines, Ltd. incorporated in South Africa. (De Beers’s first president was Cecil Rhodes, an ardent and unapologetic British imperialist. Rhodes would go on to oversee the establishment of Rhodesia – now Zimbabwe and Zambia – in the 1890s, and was very invested in attempts to connect British colonies in Africa by rail.) From the beginning of their history, South African diamonds were inexorably intertwined with the history of empire, power, colonialism and capitalism in South Africa. And early experimentalists like Hannay would have been aware of the market for diamonds

as their research overlapped so much with the influx of diamonds from colonies like South Africa.

In relatively short order, De Beers was everywhere in the diamond business. In London, it was known as the Diamond Tradition Company; in continental Europe it was the CSO (Central Selling Organization, which was an arm of the Diamond Trading Company); a few decades later, in Israel, it was known as 'The Syndicate'. At the height of its power, in the mid-twentieth century, De Beers either directly owned or controlled all the diamond mines in southern Africa (disguising its South African origins with subsidiary names like Diamond Development Corporation and Mining Services, Inc.), and owned diamond-trading companies in Britain, Portugal, Israel, Belgium, the Netherlands and Switzerland. In addition to the mines, De Beers controlled what gems went to what dealers. When Marilyn Monroe sang 'Diamonds Are a Girl's Best Friend' in the 1953 diamond-crazed film *Gentlemen Prefer Blondes*, De Beers had a complete monopoly on the diamond trade, controlling all mines and all sales of diamonds, and also had the financial and political resources to pre-emptively buy out any new diamond discoveries in just about any part of the world. There were no negotiations.

But, De Beers needed people to want to buy diamonds – and up until the nineteenth century only the very wealthy and aristocratic bought and wore them. 'The diamond invention is far more than a monopoly for fixing diamond prices,' journalist Edward Epstein argued in his 1982 investigative expose for *The Atlantic*, 'it is a mechanism for converting tiny crystals of carbon into universally recognized tokens of wealth, power, and romance.' De Beers hit on the idea of marketing diamonds as symbols of courtship and married life of the aspiring emerging post-Second World War middle class by promising customers that 'A Diamond Is Forever'. The slogan rolled out in 1947.

In the space of a mere two decades, De Beers convinced diamond-buying markets across the world that diamond engagement rings were the tangible symbol of affluence and success, disrupting hundreds of years of local cultural engagement customs. Until 1959, for example, diamonds were not permitted to be imported into post-war Japan. When De Beers began its diamond engagement ring campaign in 1968, less than 5 per cent of Japanese women who were getting married were given a diamond engagement ring – by 1972 that number had risen to 27 per cent, and by 1981 some 60 per cent of Japanese engaged women wore diamond rings. It took De Beers a mere 13 years to completely change the material culture of engagement in Japan. To ensure that people would not want to resell diamonds – to keep De Beers in the selling seat of the diamond market – De Beers found incredibly clever ways to imbue the gems with sentimental meaning. And year and year, decade after decade, the price of diamonds increased irrespective of the surrounding economic conditions.

In 1950, however, a threat to the De Beers diamond empire emerged. Scientists at De Beers knew that engineers and scientists in the United States (and the Soviet Union) were working on lab-grown, industrial-grade diamonds in labs like those of General Electric, and concluded that gem-grade diamonds would be next. The research lab took its concerns to Sir Ernest Oppenheimer (then the president of De Beers) to convince him that De Beers needed to seriously pursue the question of synthesising diamonds, as any outside patent would interrupt the company's monopoly. Oppenheimer dismissed the scientists and declined to fund the research, blithely declaring, 'Only God can make a diamond.'

Four years later, God apparently had no problem with General Electric cracking diamond-making technology. After General Electric's February 1955 press release, shares

of De Beers stock plummeted. 'The diamond's price is strictly controlled by a European cartel,' *The Evening Independent* of Massillon, Ohio, reported in 18 February 1955. 'With General Electric now able to produce synthetic diamonds for industrial use – even if at a much higher price so far from that of a natural diamond – the time could come when the cartel's monopoly was challenged.' Investors were alarmed that nascent though the market was, it was only a matter of time before laboratory-grown diamonds outstripped the market for natural ones. Even more concerning was the possibility that these laboratory diamonds were outside De Beers's carefully controlled diamond ecosystem. In March 1955, Oppenheimer reversed his position and ordered De Beers's research lab to begin a programme to create diamonds.

The De Beers team began developing the high-pressure presses and catalysts necessary to produce diamonds, under the direction of Dutch-born physicist Dr J. H. Custers. But General Electric had a huge head start on De Beers, as the press and catalyst technologies took years to fine-tune. (De Beers's scientists reported that their lab was often 'rocked by explosions' and the walls were 'covered with smouldering carbon'.) De Beers began negotiations with ASEA in Sweden to buy laboratory equipment, and the US government came down with a tight embargo on publishing any details from General Electric's experiments, in order to freeze out any diamond-making research advances in the Soviet Union during the Cold War. It would be years before General Electric was permitted to even take out patents. By then, Tracy Hall had filed his own patents, having 'reinvented' the pressure belt to ensure that his company, MegaDiamond, wasn't in violation of General Electric's holdings.

After a period of trial and error, De Beers's scientists hit on the same conical press design that General Electric had

used. Three years later, in 1958, the lab synthesised its first diamond from graphite. Custers declared 'Eureka' in his laboratory notebook.

Yet the results of the 1958 experiment were unrepeatable, a frustration that General Electric would have been well familiar with. It wasn't until 8 September 1959 that De Beers hit its stride with a method that resulted in success 60 per cent of the time – a few more tweaks, De Beers's logic went, and it would begin to look towards the possibility of taking out a world patent. At this point, General Electric's industrial diamonds were keeping pace with the price of De Beers's natural industrial-grade diamonds at \$3 per carat, and the company knew that it had to act fast. General Electric pressured (as it were) the Eisenhower administration to lift the embargo, to enable it to file the patent for laboratory-grown diamonds before De Beers.

In mid-September 1959, General Electric filed its patents, cornering diamond manufacture before the South African team. After an extremely messy patent-rights trial in the early 1960s that lasted six years and consumed millions of dollars – where De Beers claimed that General Electric was in patent violation – the South African court ruled in General Electric's favour, and De Beers signed a licensing agreement to make laboratory-grown diamonds using General Electric's process and technology.

By the mid-1960s, lab-grown diamonds were pouring out of South Africa, the United States and the Soviet Union, and by 1970, more than half the diamonds produced in the world came from laboratories. Unlike the market for gem-grade diamonds – which De Beers tightly controlled and which continued to rise – the price for industrial-grade diamonds dropped sharply, buoyed up only because the world's consumption of industrial diamonds had actually quadrupled between 1955 and 1970 due to new uses for

diamond abrasives. 'The decision a decade ago by De Beers to go into synthetic diamond production was obviously a highly emotional matter, akin to mounting an attack on one's own children,' the *Detroit Free Press* reported decades earlier, on 27 October 1969. 'But it had to come and De Beers decided it was better to be on the inside than the outside.'

When General Electric announced its one-carat, gem-grade diamond mark in 1970, De Beers reacted calmly, despite the fact that it had decided against trying to synthesise gem-grade diamonds, a decision it now regretted. It would seem that it was impossible to differentiate cut and polished General Electric diamonds from natural ones, even using a jeweller's loupe, crushing De Beers's carefully curated cultural invention of a diamond's significance. The only discernible difference, in fact, between General Electric diamonds and natural ones was that lab-grown diamonds tended to phosphoresce under an ultraviolet lamp. General Electric opted not to seriously pursue manufacturing gem-grade diamonds, citing concerns that if it did so the entire diamond market would collapse. In a 1970s' exposé about the diamond industry, a senior General Electric executive went on record with, 'We would be destroyed by the success of our invention. The more diamonds that we made, the cheaper they would become. Then the mystique would be gone, and the price would drop to next to nothing.'

By 1996, it was clear that between CVD technology and the increased production of jewellery-quality diamonds, synthetic diamonds were here to stay in the luxury market. To carefully maintain the divide between natural and synthetic diamonds, De Beers developed technologies that could differentiate lab diamonds from natural ones. Two of these – the DiamondSure and the DiamondView – were able to detect the presence of an optical absorption line,

found in the majority of natural diamonds but not in laboratory ones.

These technologies clearly established an ethos that, yes, laboratory-grown diamonds were ‘real’ diamonds, as both were the same mineral. However, it reinforced De Beers’s narrative that it was important, necessary and prudent to divide diamonds between natural and non-natural, and that De Beers’s technology provided a way of maintaining that divide under the auspices of technology. If a diamond was to be forever, it simply wouldn’t do to have science make it appear at will in a laboratory.

Diamonds have changed a great deal since the 1950s. For one thing, De Beers no longer holds a monopoly on the diamond market, natural or otherwise. After decades of price fixing and issues of legal trust, De Beers now only sells approximately 35 per cent of the world’s diamonds. (In 2004, De Beers pleaded guilty to the 1994 US-brought charges of collusion with General Electric to fix the price of industrial diamonds, and paid a US \$10 million fine. General Electric was acquitted of all charges.) But more than legal issues, De Beers experienced pushback from its customers. Having spent the majority of the twentieth century cajoling, manipulating and persuading customers that a diamond engagement ring was a cultural necessity of middle-class success, customers pushed back.

In 1999, a campaign led by Global Witness highlighted the role that diamonds play in international conflicts, and in March 2000 the famous ‘Fowler Report’ detailed the extent to which European and African governments and financial companies violated UN protocols, leading to an undeniable link between the illicit diamond trade and armed conflict in developing countries.

Known as conflict diamonds, war diamonds or red diamonds, these diamonds are mined in war zones and their proceeds are used to fund a plethora of unsavoury activities, such as insurgency, arms dealing and terrorism. They are extracted using underpaid labour in unsustainable mining practices in countries like the Democratic Republic of the Congo, Angola, Sierra Leone and the Ivory Coast. (Although illegal and unethical diamond mining practices are not limited to Africa.) De Beers stopped buying diamonds from conflict-zone areas in 1999, and by 2000 guaranteed that all of its diamonds were conflict free. In 2000, the Kimberly Process Certification was established to prevent conflict diamonds from entering the raw diamond market, although the efficacy of the Kimberly Process has been challenged.

The cost of conflict diamonds catapulted to public consciousness with the release of the film *Blood Diamond*, starring Leonardo DiCaprio, in 2006, along with a number of books, investigative journalism and high-profile publicity. Was it ethical, many consumers began to ask themselves, to own a diamond if it meant contributing to the trade in conflict diamonds? Laboratory-grown diamonds offer consumers an ethical alternative. Indeed, in 2015, DiCaprio (as well as other backers) invested in Diamond Foundry, a start-up company in Santa Clara, California, that grows gem-grade diamonds, publicising its jewellery as an ethical alternative to natural diamonds, conflict free or not. 'I'm proud to invest in Diamond Foundry, Inc. – cultivating real diamonds in America without the human and environmental toll of mining,' DiCaprio states on the Foundry's website.

De Beers countered with a campaign in 2016 that proclaimed 'Real is Rare', targeting millennial buyers – a less than subtle counterpunch, implying that laboratory diamonds were neither, since they could simply be conjured out of a lab. A friend of mine who got engaged while I was writing this

chapter opted to propose with a laboratory-grown diamond. I asked him why he chose a lab diamond over a natural one. 'Laboratory diamonds have significantly lower environmental and social impact, which my girlfriend finds important. I decided that if I am to buy a diamond, then I'm not going to buy one that comes with an artificially high price,' he explained decisively. 'Besides, as a physicist, I liked the idea that the lab diamond was a better carbon crystal lattice.'

Customers and start-ups are finding even more unique ways to incorporate laboratory diamonds into everyday life. The same versatility of the carbon that allowed General Electric's Superpressure group to pull the crunchy-peanut-butter-to-diamond stunt allows twenty-first-century companies the opportunity to offer 'memorial gems', where cremated ashes of a loved one are transformed into a diamond. Companies like the start-up Eterneva in Austin, Texas, promise that a memorial diamond will be, 'an heirloom to be passed down through the generations'. When I interviewed the spokesperson for Eterneva, it was clear that the company sees itself as part of people's grieving process, and as a positive alternative to celebrate and cherish the life of a loved one. Memorial diamonds, much like non-natural diamond engagement rings, offer consumers an option of choosing how the cultural mores of diamonds can be rewritten, even after millennia.

Natural diamonds undergo a cultural transformation from mineral to gem – a narrative that imbues them with value and meaning. The story of diamonds in the twenty-first century is a story of capitalism – but unlike the capitalism of twentieth-century De Beers, contemporary consumers demand diamonds with different cultural values and ethics. It would seem that those ethics are coalescing more and more around non-natural diamonds – so much so, in fact, that in May 2018, De Beers announced that it

was launching 'Lightbox', a line of lab-grown diamonds targeting the Sweet Sixteen necklace market, offering the less than natural diamond as a starter diamond for the 'real' one later on. Headlines the week of the launch proclaimed, 'A diamond is forever – and forever now costs \$200 from De Beers.' Laboratory-grown diamonds have their own parallel process of social and technological transformations.

When General Electric demonstrated that it could create diamonds – and when its results were independently verified – the implications of laboratory-manufactured diamonds had concrete, tangible effects for the diamond industry. In the ensuing decades, synthetic diamonds moved from a hypothetical question of science and engineering into the tangible, with concrete implications for contemporary diamond markets. Today, diamond sellers are working to translate the material reality of lab diamonds into the appropriate metaphor and cultural mores for twenty-first-century consumers.

The twentieth century made laboratory-grown diamonds a reality. It's up to the twenty-first century to make them as authentic as natural ones – to make them the Real Thing.