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# Steel from space

In the palm of my hand lies a tiny piece of dark silvery metal, cold, smooth and surprisingly heavy for such a small thing. It must be iron, and iron of a special kind, judging from the pretty box in which I have received it. The accompanying handwritten card simply reads: 'Stainless from space!' And indeed there is not a spot of rust on it. I turn it over in my hand, round and round. Underneath I find a printed note from a crystal shop: 'Fragment of the Sikhote-Alin meteorite, with a chemical composition of ninety-three per cent iron and a small amount of nickel.' I go online and soon find abundant information on this shooting star, which hit eastern Siberia in 1947. A Russian postage stamp of the time shows thatched farmhouses under an immense sky cleaved by a ball of fire. This iron meteorite crashed to Earth with such force that the impact was felt tens of kilometres away. The meteorite exploded as it entered the atmosphere and tonnes of burning metal spread like shrapnel, turning a forested area into a crater landscape with bits of metal lodged in shattered trees more than a kilometre apart. The little fragment given to me as a present was found there. I am holding a bit of outer space.

For as long as we know, stones have fallen from clear skies as if by magic and although few are witnessed as they fall, two or three come down to Earth every day. For a long time, however, scientists dismissed this phenomenon as pure superstition, in fact the French Academy of Sciences decided by ballot that there was no such thing, and it was only after a meteorite exploded in broad daylight in 1803 and was witnessed by many people near the town

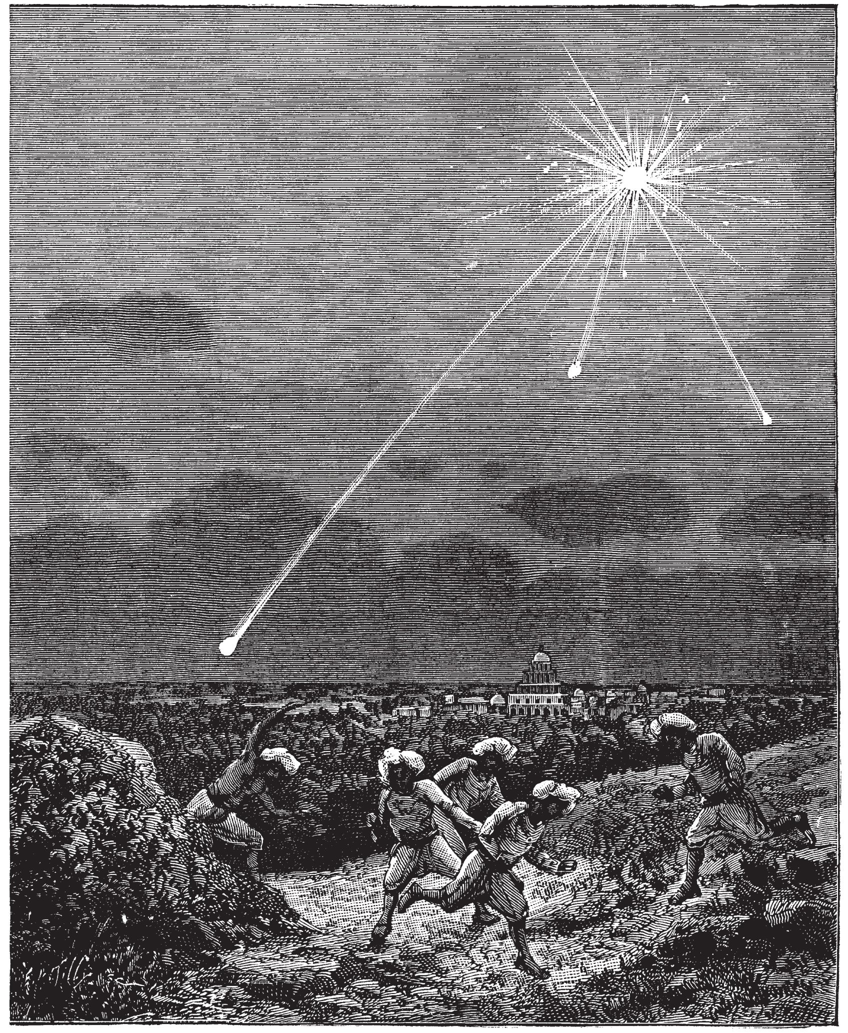

Soviet Union stamp

Fragment of Sikhote-Alin meteorite



of L'Aigle in Normandy that what had become a fervent dispute was finally settled. A detailed report of the event was presented to the Academy and the study of meteorites became a cornerstone of astronomy and geology.

Meteorites are pieces of debris from bodies in outer space, such as asteroids and comets, which have fallen apart. Iron meteorites come from the cores of such bodies. All the terrestrial planets of our solar system, Mercury, Venus, Earth and Mars, have a metallic core, consisting mostly of iron. Mars also owes its red colour to the oxidised iron in the soil and rocks on its surface and there is iron in the rings around Saturn. In science it is currently thought that most of the chemical elements that make up our planet, elements of which we ourselves are also composed, were born about thirteen billion years ago when our solar system came into being after what is often called



Meteorite fall, Chandpur, 1885

meteorite, weighing about twenty tonnes, was discovered in 1963 by the Danish engineer Vagn F. Buchwald. Known as the Agpalilik meteorite or the Man, it is now on display at the Natural History Museum in Copenhagen. While the Inuit probably could not have prevented the explorers from removing the blocks, by the 1890s they had found easier access to iron through trade, which was terrestrial iron.

Initially blacksmiths used locally found iron only. Later on, as trade routes developed, they were able to choose between different qualities which came to market from further away. Mining developed in accordance with expanding demand, the quantity and quality of local iron, and the availability of adequate tools to access deeper-lying iron deposits.

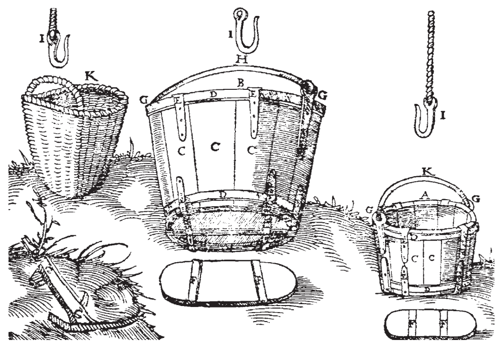
Mining was enveloped by a sense of mystery if not magic that has never completely been lost. Long ago, people believed that by reaching into the deeper

Entrance to a mine

Three mine shafts



Iron Age mining tools



Mining buckets

Pit pony at work

regions below their feet they were descending into the womb of Mother Earth, disturbing a natural order that was not really theirs to interfere with, where minerals grow in darkness, watched over by spirits who have to be appeased. Rituals were performed for divine protection and some awe is still felt when underground mining begins.

One might think that the core of our planet, since it consists mainly of iron, would be a perfect source for mining. In reality, at 2900 kilometres below the surface, the metal lies far too deep to be accessible in any controlled way and temperatures as hot as the surface of the sun would make working at that depth rather difficult.

Most iron mines are open pits, dug in a narrowing spiral shape from the surface of the earth. Even at open mines on mountainsides, such as at the ancient Erzberg ('Ore Mountain') in Styria, Austria, digging begins at the top. In the earliest days a mine often could not be dug deeper than about two metres because at lower levels ground water would threaten to drown the miners and make extraction impossible. Water was initially removed by hand in leather bags or buckets of wood, bronze or grass made waterproof with pitch, as were the iron-rich rocks themselves. The Romans figured out ways to hoist water out of the pits mechanically and generally improved mining, though they still sentenced criminals to work in these mines, a punishment named *damnatio ad metalla*. Wheels set in motion by men, animals or water power at ground level later made it possible to dig to greater depths and drag containers of minerals and ground water to the top on long chains. But digging deeper presents new problems: apart from the challenge of hauling up the heavy ores over a longer distance there is the increasing lack of oxygen and there are gases and tremors to take into account, particularly where explosives are used to dislodge the ores; there was, and in underground mines still is, an ever-present danger of collapse. Rats became an unexpected ally in underground mines; when rats came running, miners knew tremors or noxious fumes had been detected, which gave them a chance to escape. Other animals at work, though not in conditions one would accept today, were small horses, kept permanently underground, who helped transport the quarried material to the places where it could be hauled up. Fortunately these pit ponies have since been replaced by motorised solutions.

Pumps replaced early bellows to blow vital fresh air into the underground tunnels, initially driven by water wheels; drainage galleries were constructed; gradually all sorts of wheelbarrows and wagons were designed for underground transport and then early (wooden) rail tracks were laid and sophisticated lamps were devised to replace candles and reduce the risk of gas explosion. But it was not until the steam engine was introduced that the entire mining industry was effectively mechanised. From the 1890s electricity in turn began to replace steam-driven power.

sword Durandal (said to have been forged by Wayland) to stop it being captured by the attackers. I remember digging up what I thought was a dagger near our kitchen door, my secret treasure until I realised, years later, that it had only been a worn and rusted sharpening rod. Most of all I loved watching the blacksmith in the small coastal town of Veere where we spent our holidays. His workshop stood next to our house on the old market square and he was always busy catering to the local community of fishermen and farmers. He shod enormous horses in front of what seemed like a dark cave from which the loud clanging and hissing of hammers and bellows rang. Clouds of sparks lit up the gloom as sooty-faced but bright-eyed men moved back and forth between the open fireplace and their anvil, gripping pieces of glowing metal with tongs, hammer in hand.

The Great Tamerlane

The Spirit of Iron was often felt to be dangerous if not angry and became linked with diverse personifications of Mars, the Roman god of war, and with gods of fire such as the Greek Hephaestus, who forged arms and armour for his fellow gods in his palace on Mount Olympus: Poseidon's trident, Artemis' bow and arrows of moonlight, Apollo's bow and sun ray arrows, Hades' helmet of darkness. Hephaestus' Roman counterpart Vulcan made thunderbolts for his father Jupiter in his workshop under the Etna volcano. In the Slavic tradition he is Svarog, the god of heavenly fire who created the sun and who uses his blacksmith's tongs to capture the dragon Zmey.

Fear of these mythical ironworkers was heightened by their physical oddities: in the Icelandic *Edda* it is dwarves who forge Thor's hammer; both Hephaestus and Wayland are crippled; Hephaestus's giant assistants are the

The cyclops Polyphemus

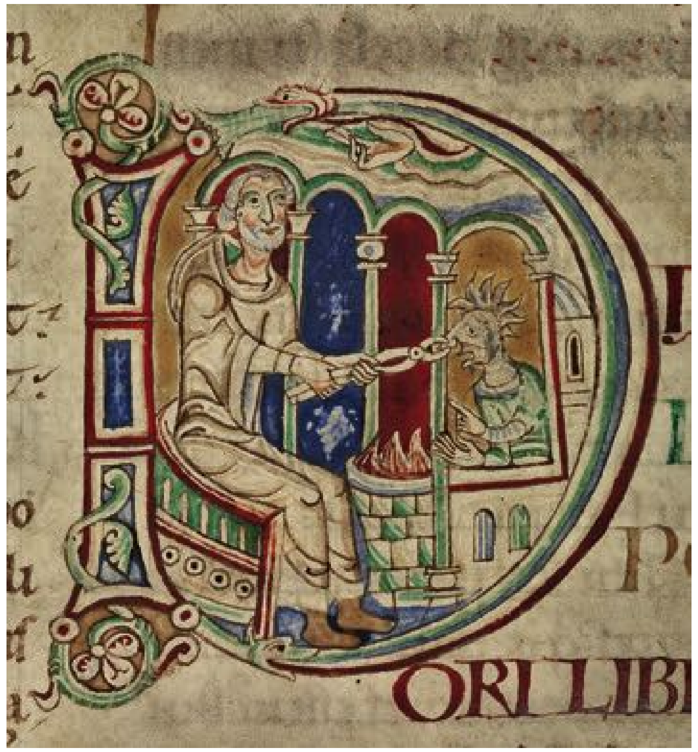
Ilmarinen makes a new wife



terrifying one-eyed Cyclops. The Japanese Shinto god of smiths, Ama-Tsu-Mara[2], has only one eye, and in Morocco there were said to be pygmy smiths whose cloaks were decorated with a single eye.

[2] Ama-Tsu-Mara made a mirror to bring Amaterasu, the goddess of the sun, out of her cave. The Japanese imperial insignia, all made of iron, include such a mirror.

Blacksmiths were often associated with evil, figures who had sold their souls to the Devil, but sometimes they were benign, like Saint Dunstan, who recognised the Devil in a beautiful girl and caught its nose in his blacksmith's tongs. In Japan the legendary swordsmith Masamune's sword could cut all that was evil and heal what was pure and all over the world iron, particularly in the shape of knives, could be used to ward off demons. In some cultures any piece of iron is considered a safeguard against evil spirits, but horseshoes seem to be considered auspicious pretty much everywhere. One often finds them mounted above a front door, ends up or down depending on local tradition. In medieval France a bride would receive an iron ring made from a horseshoe nail for happiness; in Irish folklore a crooked horseshoe nail is hung about a child's neck to protect it; an Indian friend of mine wears an iron bangle made from a stallion's horseshoe; old horseshoes can even be ordered online in attractive gift-packaging. The smith's tools, meanwhile, were sometimes thought of as animate objects, characters that were able to create the most magical items of all: other tools.



St Dunstan and the Devil

Swordsmith Munechika with fox spirit Inari the ‘pilgrim’s tread process’, as the most crucial part of the procedure involves a gradual two-steps-forwards, one-step-back movement that resembles the movements of pilgrims in the Echternach Dancing Procession. Hot ‘pilger-rolled’ tubes have a fairly large diameter. Smaller diameters can be achieved through cold pilger-rolling; this is how the Mannesmanns became contributors to the bicycle boom.

Bending a tube is very tricky and techniques for bending are closely guarded secrets. I once saw large, thick tubes for a gas pipeline being shaped to beautiful curves, but I was strictly forbidden from taking photographs while this was done. The tubes were heated by induction and then coerced super slowly. The overall resistance of the tube is of course not allowed to weaken in the bends.

Long billets of steel, heated like baguettes in an oven, may be drawn to steel wire. From a length of ten metres I saw them grow to lengths of ten kilometres while their original fifteen-centimetre diameter was reduced to five millimetres. Speeding up through a long series of continuous presses, the wire emerged from a four-hundred-metre production line at three hundred and fifty kilometres an hour, clanging into loops and coils at the end of the line like armfuls of bracelets. My hands nearly melted as I photographed them, as did my camera. After hot-drawing, wire may be cold-drawn to smaller gauges via an age-old method: pulled through successive dies, its passage eased with soap. The calm atmosphere in which this is done feels remarkably artisanal. In essence it is the same technique jewellers apply to gold and silver wire.

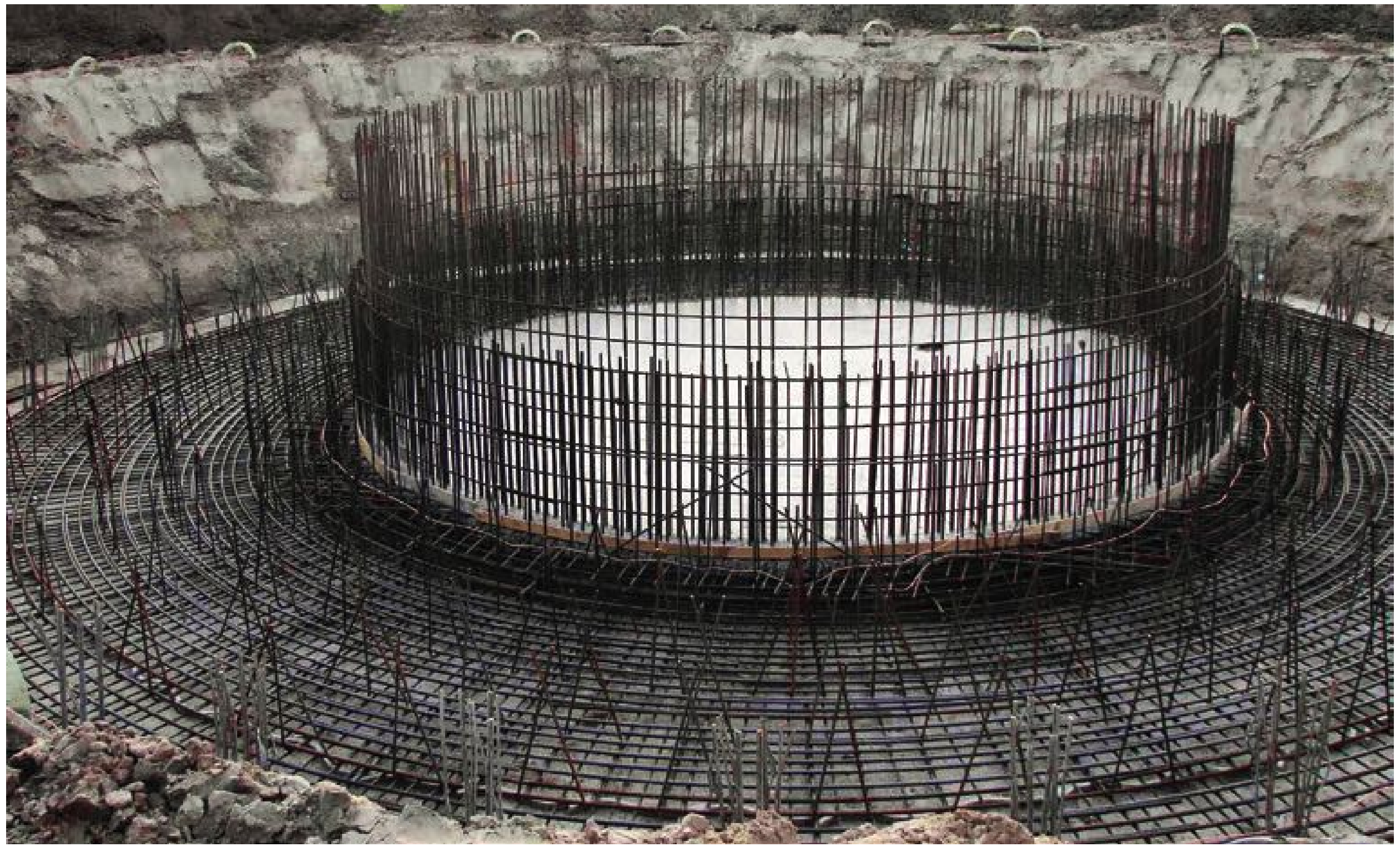
Wind turbine assembly

Internal welding of a wind turbine tower



Steel wire may be spun into cables, weaved to chicken wire, shaped into chains, nails[4], needles, paperclips… It is even the starting material for ball bearings and roller bearings, on which it could be said the world turns; bearings are found in everything from the dentist’s drill to giant digging machines, easing their movements and saving heaps of energy. Much of the world’s steel wire is invisible, in the shape of reinforcing steel for concrete structures. Concrete is a much-beloved building material, but while it can take a lot of compression, it is no good in tension. To resist being pulled apart, it needs steel, so we reinforce it with cables or mats of steel wire that are specially made to be pulled taut before or after concrete-casting. Almost a hundred per cent of ‘re-bar’ is made out of recycled steel and a surprising amount of rebar armatures are made to measure. Proper mixing and pouring of concrete is crucial. If it is poured well, concrete will form a strong bond with steel, an entity that expands and contracts in nearly perfect rapport, and it will passivate any oxidation of the steel. Poured less well and in the wrong proportion to steel, concrete will develop cracks and allow humidity and oxygen to affect the metal. It is then that the structure becomes dangerous and, seemingly out of nowhere, may collapse.

[4] Since the nineteenth century we have made nails from steel wire, instead of forging them from wrought iron.



Rebar foundations of a wind turbine

Cast iron, Père-Lachaise cemetery

be quick to understand, this is to do with their microstructures. The atomic structure of pure iron is closely packed and does not react easily with oxygen. An average steel, depending on its composition and heat treatment, will have an atomic structure that makes it much more prone to reaction with oxygen.

Rust can be a warning, but very often it gives no warning, because it can do its destructive work out of sight. A small hole in a protective coating can allow larger damage to grow underneath. "Under every tiny hole there is always a big one," as an old friend said to me; a passionate restorer of classic cars, he hates rust, but considers it par for the course in a job he loves. Sometimes rust is welcome: golfers like a bit of rust on the unplated steel of certain wedges as it adds roughness and increases spin. In the eighteenth century the wooden breakwaters along the coast of Holland were covered with iron nails to generate a layer of rust that warded off a particularly destructive mollusc. Many artists love the look of rust and most art made of iron and steel plays with rust's effects. But rust is rarely considered a friend. The cost of metallic corrosion is considerable so, pretty though rust can be, we cannot afford to be romantic about it and developing effective, durable solutions is serious business.

Not all methods to protect iron and steel against rust do the same thing and not all are suitable for (or affordable in) all situations. Solutions are therefore often used in combination. They frequently tackle other forms of corrosion at the same time, too. Our forefathers' most immediate solution was oil. When I see old-fashioned oil cans I always think of Tin Man in 'The Wizard

A rusted nut and bolt

Part of a mining flight-bar



[2] Unless the concrete cracks and air and water creep in. Rust's expansion will then force the concrete further apart.

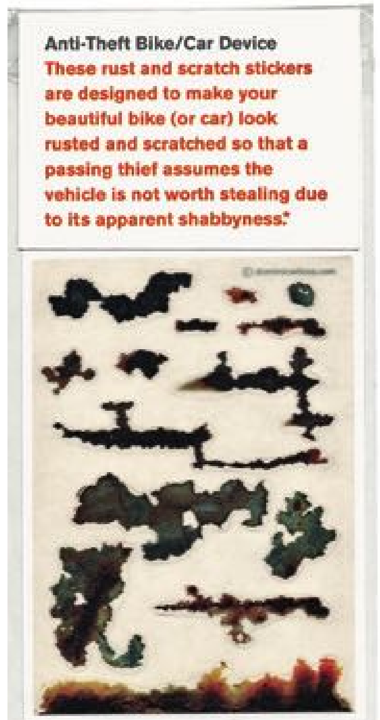
[3] Wonderfully, it is possible to keep out water with water-based paints.


Big Rusty golf club

of Oz', so relieved when Dorothy oils his joints after he "rusted silent" in the rain. Oil can penetrate into the surface layer and isolate the metal from oxygen and moisture. The iron parts of the Menai bridge, built in 1826 between the island of Anglesey and the Welsh mainland, were not 'boiled in wine', as the White Knight in Lewis Carroll has it, but soaked in linseed oil before they were put into place. Greasing an entire tanker, crane or skyscraper, however, gets a little impractical and there are more durable as well as less slippery options to choose from.

Nowadays we combat corrosion mainly through paints and coatings, via the composition of metal, and by controlling corrosion as a form of protection itself. Some environments provide their own anti-rust treatments: dredging pipes, for example, are never painted because nature sands them all the time, chafing off whatever rust develops; neither is reinforcing steel, which typically has a layer of rust on it when it is installed on a building site, but placed in the alkaline environment of the concrete it will form a passivating film.[2]

When the first steel ships and structures were built, before the days of steel tests and alloying, a coat of paint was the only way to ensure long-term preservation. Once the nature of rust began to be understood, protective paints for metals began to be developed for specific conditions and as metallurgy became a science, coatings became a science too. In the early days painters prepared their own mixtures at home, with oils, tars and hand-ground pigments, often applied simply with rags. When people started coking coal, the by-product coal tar became the basis for many paints. Nowadays we use more environmentally friendly resins with lower levels of volatile solvents or, in water-based paints, no solvents at all.[3] We also investigate biomimicry as a means to combat corrosion from organisms in environmentally friendly




Anti-theft stickers

A rusted Bugatti

# A new mine

Recycling may sound like a relatively new, 'green' activity, but people have reused iron fastidiously throughout history. For a long time, iron and steel were such hard work to produce and so valuable that anything made out of them was used and repurposed endlessly. Only when it was beyond repair was it put back into the furnace. In nineteenth-century America, nails were still expensive enough for abandoned houses to be burnt down expressly so the nails could be recovered. Roman doctors kept iron scrap to provide them with rust that they used for medicinal purposes. Textile dyers use scrap to create a kind of dark soup to colour cloth such as the Indian *reta*.

Typewriter on a scrap heap

There are countless interesting stories about iron recycling in history, but one that seems to have escaped the history books is that of a 'horseshoe war', told by the grandson of one of the parties involved. In 1895 an ambitious Dutch scrap dealer had the brilliant idea of selling worn horseshoes for ballast on empty ships destined for China, whence they would return filled with porcelain for the European market. The Dutch still used great numbers of heavy horses to work the land and pull carts. Some had to be reshod as often as once a week. Frisian beer brewers' horses were the heaviest and their shoes were more than twice the size of an average horseshoe. Nicely compacted on cobbled roads, they proved very popular with Chinese metalsmiths, so popular that a German competitor soon arrived on the scene, claiming that German draught horses were even heavier and German horseshoes therefore gave even more bang for the buck. In the end the Dutch won the 'war' by showing the Chinese buyers a photograph of some massive horses at work in their home country, which the German competitor could not top. This will not have stopped the Chinese from buying German horseshoes, but meant they fetched a lower price.

'Junkman'

The scrap market



My own earliest memory of iron scrap is the cry of "*Máárchand d' ferraille!*" as the scrap merchant pushed his handcart through the streets of Brussels, where the 1960s were years of extensive demolition, grand houses being torn down to make space for offices to accommodate the rapidly growing European Community. The scrapper's cries echoing down our street somehow impressed me far more than all the wrecking balls and hammers. Sadly he was soon replaced by a man in a car who drove slowly by the dustbins lined up on the pavement, loading anything metallic, from old saucepans to broken lawnmowers, into the open boot.

Thanks to the open-hearth furnace and later EAFs, industrial quantities of scrap steel have been melted down and worked into good new steel since the last decades of the nineteenth century. Thus, long before working from recycled steel alone had become possible, scrap became a commodity and the collection and preparation of scrap for recycling became an industry in its own right. Some countries did not have the capacity to produce as much steel as they needed from iron alone and took to importing scrap. Scrap exports from Europe to the United States, for example, went from 38,500 tonnes to over 380,000 tonnes in the space of three years in the 1880s, boom time for the American railways, and went on until the U.S. produced enough steel to become self-sufficient, around 1900.[1] There is a famous expression in the steel-recycling industry, quoted to me with a wink by the chairman of an international recyclers' organisation: "My wife irons and I steal!"

[1] Railway tracks themselves are among the most coveted scrap in the business. Like heavy horses compress horseshoes, the passage of countless trains means a railway element gives you nicely concentrated steel for your money.

Bicycle-dredging

The wrecking-ball

# A body of iron

"But dear lady, that isn't the same iron!" So said a shocked workman in a sandblasting yard when I told him about this book. It may by now take a little stretch of the imagination, but the iron we take from the earth and are able to transmute into ever finer steel, whose innermost properties we are growing to understand on an ever-deeper level, is exactly the same iron we have in our blood.

We cannot live without iron. All vertebrates and some invertebrates need iron to bind and transport oxygen from our lungs to our cells and to collect carbon dioxide from them, taking this back to our lungs for release when we breathe out. Most of our body's iron is contained in red blood cells, bound into haemoglobin, the transport protein that fills about a third of our red blood cells. If you don't have enough iron in your body you cannot make enough haemoglobin and as a result you are likely to feel tired and weak as your cells are insufficiently energised by oxygen. Iron (and oxygen) can also be bound into myoglobin in our muscle cells. Both haemoglobin and myoglobin owe their colour to iron. Some invertebrates like crabs and squids use copper as we do iron and as a result their blood is blue-green, the colour of oxidised copper.

We absorb and dispose of iron through our digestive system, but how we assimilate it depends on what we eat. We absorb iron more easily from meat and fish, for example, than from fruit and vegetables, because iron from animal foods is 'heme', i.e. derived from haemoglobin. Heme iron is divalent iron, $Fe^{2+}$ (also referred to as 'ferrous'). Iron from plants is trivalent iron, $Fe^{3+}$ (referred to as 'ferric'), and must first be converted to $Fe^{2+}$ before it can be absorbed by our body. Certain plants are of course richer in iron than others. Popeye guzzled all those cans of spinach, but he might have been even stronger if he had chosen tofu or beans instead. We also need acids such as vitamin C to aid iron absorption. A protein called ferroportin transports the iron from the cells of our gut into our bloodstream and another protein called hepcidin (from Greek *hepar* for the liver, where it is produced, and Latin *caedere*, 'to kill') regulates the amount of iron in circulation by stopping ferroportin from exporting iron when necessary. Wonderfully, our cells reuse the iron we absorb from food numerous times. Red blood cells have a limited life span and when their time comes these cells are eliminated by other cells called macrophages (Greek for 'big eaters'), but not before the latter have saved the iron, which they pass on to new red blood cells when these are grown in the bone marrow. Our friend ferroportin is again responsible for getting the iron from the macrophages into the new red blood cells. Small miracles happen every day.

When people suffer from iron deficiency, the most common form of anaemia, they are often given supplements, although these are moderately effective at best. As children my sisters and I were made to take iron pills and I well remember their strange blackening effect on our stools. More fun was the discovery of a brilliant sketch by the French actor Bourvil, slurring his words as he sang the praises of ferruginous water to combat alcoholism. His recommendations seem to have fallen on deaf ears in southern Europe, where wine remains the beverage of choice because, as they say in Tuscany, *bere acqua fa la ruggine*, drinking water makes you rusty. Their ancestors

**In the nineteenth century mineral springs became fashionable locations for family holidays. In Europe, the iron-rich waters of Bohemia were especially popular. While guests 'took the waters' and socialised around their smart hotels they also left small mementoes in the springs, which were soon coated with a velvety layer of rust.**

Rust-covered bear from Carlsbad


Carlsbad springs



'Taking the waters' at Marienbad

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Iron rods, Beauvais cathedral. Photo Philippe Dillmann.

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Window, Amiens Cathedral. Photo Pauline van Lynden.

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Wrought-ironwork on the Sainte-Anne door, *c.* 1200. Notre-Dame, Paris. Subes, Raymond, La Ferronnerie d'Art, Paris, Librairie d'Art R. Ducher, 1928.

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Door ring on the Portail de la Vierge, Notre-Dame de Paris, 1210–1220 Photo: Myrabella. Via Wikimedia Commons.

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Iron folding key, inscribed 'Karolus Rex', France, 14-15th century. Musée Le Secq des Tournelles, France. © C. Lancien - Réunion des Musées métropolitains Rouen Normandie.

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Chest, 17th century, France or Germany. Musée Le Secq des Tournelles, France. Inv. LS 2005.13.1. © C. Lancien, C. Loisel - Réunion des Musées métropolitains Rouen Normandie.

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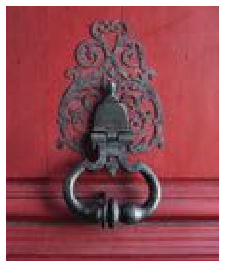
Wrought-iron weather vanes at Séailles, France. Photo Pauline van Lynden.



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Iron door knocker, St Germain-en-Laye, France. Photo Pauline van Lynden.

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A View of the Upper works at Coalbrookdale. Francis Vivares after Thomas Smith of Derby, 1758. Courtesy of and Copyright of the Ironbridge Gorge Museum Trust - the Sir Arthur Elton Collection.

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Iron Works, Colebrook Dale. R. Bowyer, from a drawing by P.I. de Loutherbourg, 1805. Courtesy of and Copyright of the Ironbridge Gorge Museum Trust - the Sir Arthur Elton Collection.

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Iron Bridge near Coalbrookdale. William Williams, 1780. Courtesy of and Copyright of the Ironbridge Gorge Museum Trust - the Sir Arthur Elton Collection.

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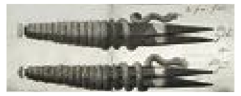
Carving knife and fork, steel and green-coloured staghorn with silver rivets, Solingen, 18th century. Courtesy Deutsches Klingenmuseum, Germany.



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Files from Remscheid, from a Mannesmann catalogue dated *c.* 1800. Wessel, Horst A. A. Mannesmann. 1796-2014. Von der Feile zum hochpräzisen Maschinenelement, Remscheid, Bergischer Verlag, 2014. Courtesy of the author.

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Crucible steelworks, Sheffield. J.S. Tulley & Co., Photographers, for Thos. Firth & Sons, Sheffield. England, *c.* 1880.

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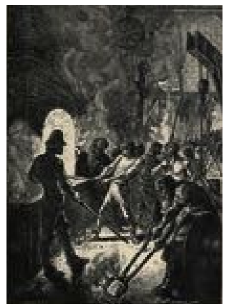
Stahlstadt. Léon Benett. From Verne, Jules, Les Cinq Cents Millions de la Bégum, Paris, Pierre-Jules Hetzel, 1879.



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Puddlers in Stahlstadt. Léon Benett. From Verne, Jules, Les Cinq Cents Millions de la Bégum, Paris, Pierre-Jules Hetzel, 1879.

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Puddling furnaces at Le Creusot, 1899. Courtesy Ecomusée, Le Creusot, France. © CUCM, document Ecomusée. Inv. 2391-4.

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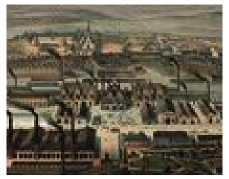
The steam hammer, forge and steelworks of Saint-Chamond. Fortuné Layraud, 1889. Courtesy Ecomusée, Le Creusot, France. © CUCM, document Ecomusée. Inv. 2587-4.



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Vue d'ensemble de la ville du Creusot. After Pierre Trémaux. Reproduction D. Busseuil. Courtesy Ecomusée, Le Creusot, France. © CUCM, document Ecomusée. Inv. 2092-5.

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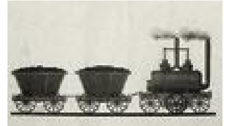
The ironworks at Seraing near Liège. E. Toovey. From Belgique Industrielle, Brussels, 1852. Reproduction D. Busseuil. Courtesy Ecomusée, Le Creusot, France. © CUCM, document Ecomusée. Inv. 3165-1.





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One of George Stephenson's first trains at the Hetton colliery, England, *c.* 1822. Courtesy Spoorwegmuseum, The Netherlands.

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Elephant attack on a train. G. Dupré. From De Hollandsche Illustratie, vol. 12, 1876. Courtesy Spoorwegmuseum, The Netherlands.

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The Opening of the Liverpool & Manchester Railway, September 15th, 1830, with the Moorish arch at the Edge Hill as it appeared on that day. Drawn & Engraved by I. Shaw Jr, published 1831. Courtesy Spoorweg-museum, The Netherlands.

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The SS Great Eastern before launch. Photo Robert Howlett, 1857. Victoria and Albert Museum, United Kingdom. Inv. PH.258-1979.

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Vaisseau à vapeur The "Great Eastern". Louis Le Breton, year unknown. Courtesy Chasse-Marée, Douarnenez, France.

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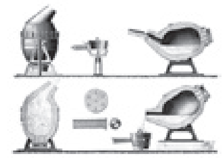
The Bessemer process. Possibly from A People's History of England, 1878. Author and artist unknown. © Getty Images.



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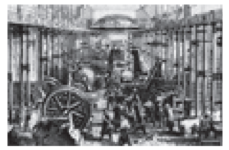
A diagram of the Bessemer converter. Artist unknown. Allegedly from an 1867 British publication. Via Wikimedia Commons.



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The machine factory of Richard Hartmann in Chemnitz, Saxony, Germany. Unknown artist, 1868. Scan by Norbert Kaiser. Via Wikimedia Commons.

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Open converter doors at HKM, Duisburg. Photo Pauline van Lynden.

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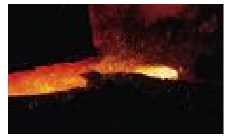
After steel tap at the Nedstaal Electric Arc Furnace, Alblasserdam. Photo Pauline van Lynden.



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Tapping of a blast furnace, HKM, Duisburg. Photo Pauline van Lynden.

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Solidifying steel slag. Photo Pauline van Lynden.

p. 95
Tapping of a steel ladle. Photo Pauline van Lynden.

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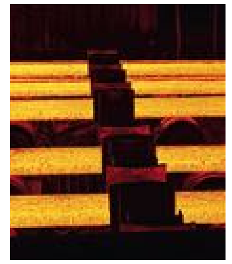
Lifting a billet from the reheating furnace, Vallourec Düsseldorf-Reisholz. Photo Pauline van Lynden.



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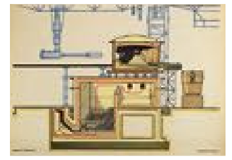
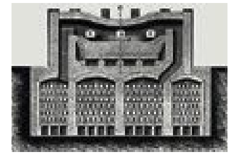
Continuous casting at HKM, Duisburg. Photo Pauline van Lynden.

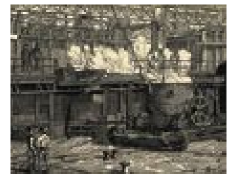
p. 98
Open-hearth furnace (Siemens-Martin-Ofen). Part of a school poster. Erna Graupner Verlag, Leipzig, *c.* 1960.



p. 98
Section of an open-hearth furnace. Part of a school poster. Erna Graupner Verlag, Leipzig, *c.* 1960.



p. 99
Horno Martin-Siemens (sección longitudinal). From Enciclopedia Universal Ilustrada Europeo-Americana. Madrid, Espasa-Calpe, 1910.



p. 99
Établissements Schneider - Fours à acier Martin Siemens. From Bonnefont, Gaston, Souvenirs d'un vieil ingénieur au Creusot, Paris, Félix Juven, 1905. Courtesy Ecomusée, Le Creusot, France. © CUCM, document Ecomusée. Inv. 2192-2

p. 100
Palais de l'Industrie, coupe transversale. Max Berthelin, 1854. Ink and watercolour. © RMN-Grand Palais (Musée d'Orsay)/Hervé Lewandowski. Inv. RF 37305.

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