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Literary
Agency

Author: Anja Røyne
Title: Human Elements -- the stuff our World is made of.
Original title: Menneskets grunnstoffer. Byggeklossene vi og verden er laget av.
Original publisher: Kagge Forlag
First published: 2018
Number of words: 60.000
English material available: two sample chapters.
Awards: Winner of Brage Prize 2018 for Best Norwegian Pop. Science Book.
Foreign rights: Stilton Literary Agency
Author's representative: Hans Petter Bakketeig, hanspetter@stilton.no, +47 47674759

ABOUT THE BOOK:

Where do the elements come from and could we use them up? Physicist Anja Røyne takes an original approach, writing a book about the building blocks fromwhich we humans – and the whole of the world – are made. By asking questions like “ could we run out of iron?” and “ is there enough sand?”, she leads the reader into discussions about the world’ s resources at both the micro and macro level, and about how the universe fits together. Røyne writes in clear language and demonstrates throughout a fearless ability to tackle the big questions that concern us all, which lifts the book up to an existential level; at the same time, she connects physics to the reader’ s everyday life.

The book starts and ends with outer space, where the elements originated and where we may perhaps be able to obtain resources sometime in the far future. Yet at the same time, the book is firmly anchored in our own planet, and its message is to explain how we need to protect the planet with its existing elements. In this way, physics becomes directly relevant to the reader, making this a book that elegantly links the tiniest particles with the biggest questions.

ABOUT THE AUTHOR:

Anja Røyne is a scientist and lecturer at the Institute of Physics, University of Oslo. She is a physicist with a background in solar energy, but has in the last 15 years researched geological and geo-chemical processes and is now researching how materials can be created with biotechnology. In addition she runs her own science blog, and often contributes in pop. science radio programmes on radio and in newspapers.

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THE IRON AGE ISN'T OVER

I lie still but my bed is moving. Tomorrow I'll be sitting in a meeting in Bergen. Tonight, like generations of people before me, I'm rocked to sleep by the sounds and motions of the train. Train journeys like this make me feel as if I'm part of a long history. Railways have transported people and cargo across landscapes and through cities since long before the days of cars and planes.

The trains and rails are both made of iron, the most important metal in our civilization. The first metals exploited by humans – gold, copper, and bronze, the latter an alloy of copper and tin – are too soft to replace tools made of stone and wood in most circumstances. However, the use of iron had a revolutionary impact on both warfare and agriculture. Just imagine the difference between tilling a field with a wooden plough and an iron one. Iron tools made it easy to work the soil, build roads, and chop and carve wood. This, together with iron weaponry such as arrowheads and swords, meant that the metal offered enormous advantages to those who mastered it before their neighbours.

IT'S NO GOOD BREATHING IF YOU DON'T HAVE IRON

Iron doesn't just play an important role in our society. It is also a crucial part of our body's own transport system. An adult human body contains around five grams of iron atoms – enough for a single medium-sized nail – and we use the iron in our body for a vital task.

I must breathe in order to live. All the cells in my body need oxygen. When I take a breath, I draw oxygen down into my lungs but I still need a way to transport it onward to all my cells. This is where the iron comes in. Unlike gold –

which prefers to retain its own electrons – iron is a generous soul, happy to give away a few of its electrons. This allows a close friendship to blossom between iron and oxygen, which is always eager to acquire extra electrons from other elements.

Where blood and air meet in my lungs, oxygen seizes the opportunity to attach itself to iron atoms that are bonded to molecules in my blood. This allows the oxygen to be transported further into my body through the circulatory system. Other molecules in my cells persuade iron and oxygen to part company again, and the solitary iron continues on its way through my veins to my heart, where it is pumped back to my lungs to fetch fresh oxygen. In the absence of iron, I can breathe as much as I like but I won't be able to use any of the oxygen I laboriously draw into my lungs. That is why I have to take iron tablets for weeks on end after donating half a litre of blood to the blood bank. My body has no trouble producing new blood cells but it cannot make iron on its own.

Once iron has given its electrons to oxygen, a lot of energy is needed to separate these two elements from one another again. It took a long time for humans to learn how to break this bond and return the electrons to the iron atom – a necessary step if it is to become a metal suitable for making weapons and tools.

INTO THE IRON AGE

When the Egyptian pharaoh Tutankhamun was buried 3,500 years ago, he took an iron dagger with him. For a long time, this and other extremely old iron artefacts found in Egypt and elsewhere posed a great mystery: the methods needed to produce the iron metal these objects were made from were not developed until roughly a thousand years later.

The solution to the mystery lies beyond our planet. The metal in Tutankhamun's tomb did not come from Earth.

In outer space there are numerous asteroids, large and small, composed of nickel-containing iron. Since they are not exposed to water or oxygen out there, the iron in the asteroid doesn't rust but retains a glossy, metallic sheen for all eternity. Now and again, some of these asteroids fall to Earth in the form of meteorites that can then be picked up off the ground and beaten into daggers and other artefacts. This was the very first iron metal we humans made use of. The likelihood is that all such early iron artefacts were made of meteorite iron.

There are vanishingly few places on Earth where iron atoms that occur in nature are not bonded to other elements but manifest themselves in the form of metal. One of them is Greenland, where iron-containing lava forced its way up through the Earth's crust long, long ago. On its upward journey, the lava pushed through a seam of coal – remnants of prehistoric plants consisting almost exclusively of the element carbon. One useful quality of carbon is that it is even keener to give away electrons than iron. As a result, when the bonded iron and oxygen atoms in the red-hot lava came into contact with the carbon in the coal, the carbon persuaded the iron atoms to take on its extra electrons. Carbon and oxygen poured out into the atmosphere in the form of carbon dioxide, while the iron was left in the ground as a vein of metal, ready for use by us humans.

And this is the key to producing metallic iron; the key human beings had to find before they could enter the Iron Age. We have plenty of iron all around us – the element accounts for roughly four per cent of the Earth's crust – but pretty much all of it is bonded to oxygen. Iron ore can be converted into iron metal by mixing it with coal and then heating it until the coal catches fire. This causes the carbon in the burning coal to react with the iron ore, give away its electrons and steal some oxygen – leaving the iron in metal form.

When human beings first began to produce iron, this also led to an increase in demand for wood. When wood is heated in closed pits, without oxygen, the timber is converted into charcoal, which can be used in iron production. This often placed tremendous pressure on local forests, and deforestation was a common adverse side effect. These days we use coal to produce iron. Since we can mine it, we no longer need to cut down trees for this purpose. Coalmines have certainly done their bit to save many of the world's forests from ending up in charcoal pits. At the same time, though, the fossil carbon that is released into the atmosphere when we burn coal contributes to the warming of our planet. Every tonne of iron ore that is produced emits roughly half a tonne of carbon dioxide, formed by carbon from the coal and oxygen from the iron ore. Over the long term, this may pose an even greater threat to forests and ecosystems than the logging of earlier times.

SWEDISH IRON

Whereas the coal we need for iron production is provided by the forests of the past, the iron ore itself arose as a result of organisms that lived even further back in time. Almost all the iron ore we mine today comes from the rust-red layers of iron oxide that were built up on the ocean bed when photosynthesis started and the oceans rusted, roughly two and a half million years ago. Today, these deposits lie in horizontal layers close to the surface, and therefore lend themselves to opencast mining. The earth and stones that cover the iron ore are dug up and set aside so that enormous machines can break out the ore from large, bowl-shaped pits in the terrain – among the largest human-made structures produced here on Earth.

Since iron is such a common element, there are other iron ore deposits that were formed in different ways. One of the most important of these is in Scandinavia. You can get there by train from Oslo, travelling first to Stockholm and then heading north for just over 15 hours. Both the town of Kiruna and the railway that takes you there were established to enable the extraction of iron from the mountains of northern Sweden.

People had long been aware of the rich iron ore deposits in the area where Kiruna stands today. Yet this part of northern Sweden remained desolate until the very end of the 1800s because the high phosphorus content in the iron ore made it close to worthless on the world market. Once a method for eliminating phosphorus from iron ore was developed, however, Swedish ore became a sought-after raw commodity.

The Kiruna deposit was in a remote location and it could take several days to transport the ore by reindeer and sledge to the port at Luleå, innermost in the Bothnian Bay. During winter, the ice was often thick, so the ore had to be left lying in heaps on the land until the sea thawed, making it possible to transport the ore to other parts of Europe. In spring 1898, the Swedish parliament therefore resolved to build a railway that would link Kiruna to both Luleå and the Norwegian port of Narvik. This major investment would make it possible to deliver iron ore to the world market all year round. This development attracted thousands of Swedes, Norwegians and Finns keen to earn cash from mining work, railway construction or other trades that tend to spring up around this kind of enterprise, like crafts, spirit sales and prostitution. After a wretched start, Kiruna rapidly developed into a proper town with schools, a hospital and a fire station.

The railway was ready by 1902, and with that, Kiruna was established as an important source of iron ore for the whole of Europe. Germany was one of its biggest clients and Hitler was utterly reliant on this supply in the run-up the Second World War. More than half of the iron he needed to produce tanks, bombers and weapons for the German army came from Kiruna. The supply lines were secured once Germany occupied both Norway and Denmark on 9 April 1940, and shipments from Kiruna to Germany continued right up until they were halted by the Allies in 1944.

The iron in Kiruna comes from magma that forced its way into the Earth's crust at some point in the past. As the magma slowly cooled in the hollow space it had created for itself inside the rock, crystals of iron-containing minerals were formed, which sank down to the floor of the magma chamber. In this way, the iron was separated from the other elements in the magma. Today, the floor of the old magma chamber slopes sharply down into the rock. That is why Kiruna is one of the few large iron mines in the world where the ore is mined underground. Huge tunnels are bored deep down into the rock, into the veins of ore, before the rock above is blasted, causing the ore to fall down from the roof; it is broken in its fall, then collected in trucks and driven up to the surface. There, the iron-containing minerals are separated out and loaded onto railway wagons.

When the rock is mined and falls into the depths, cracks will inevitably form and spread upward towards the surface. The cracks beneath Kiruna have now extended so far that the town centre will subside into the fractured rock. The town can no longer remain where it currently stands. The church and other selected historic building will now be put on wheels and moved to firmer ground. There they will stand among newly built schools, shops and housing for all the people who will soon have to pack their removal boxes.

FROM ORE TO METAL

The trainloads of ore from Kiruna still travel to Narvik several times a day, every single day. In Narvik, the ore is reloaded onto ships, which transport it to ironworks all over the world. Today, China is the world's largest producer of iron metal, followed by Japan and India.

At the ironworks, the iron ore is heated up with the coal in gigantic smelting furnaces. The coal gives electrons to the iron and helps itself to oxygen. As the temperature in the furnace climbs, the minerals that won't be part of the finished metal melt. This liquid mass is called slag and can be either poured or scraped off the iron ore. By the end of this process, the ore has become a viscous, spongy lump of raw iron containing a great deal of carbon from the coal.

In earlier times, this was the iron that was used to make artefacts. The raw iron was hammered to remove as much as possible of the remaining slag. After that, the blacksmith could heat the iron until it was red-hot then use a hammer and anvil to forge weapons and tools. In Scandinavia, the Vikings produced lumps of raw iron like this in specially constructed furnaces on farms, usually using iron ore fetched from the bogs around the farm. The blacksmith had to know how to control the temperature, the air supply and the hammering of the iron in precisely the right way to achieve the best possible result.

It later transpired that the quality of the metal improved if the raw iron was smelted once more. Iron with high carbon content and other impurities remains in liquid form at a temperature low enough for the iron to be able to be poured into moulds. This is known as cast iron and is the cheapest iron metal produced today. We find it in the kitchen, in pots and frying pans, as well as in countless industrial machine parts.

Wrought iron, familiar to us from decorative black railings and chandeliers, is produced by smelting the raw iron, along with lime and other substances; this helps transfer as much of the remaining contamination as possible to the slag. As the iron becomes purer, its melting point also rises. When the iron can no longer be kept liquid in the furnace, it can be lifted out, hammered and forged. The Eiffel Tower, which was completed in 1889, is built of wrought iron.

SOUGHT-AFTER STEEL

The most sought-after iron metal has its own name and has become emblematic of strength. It sounds pretty impressive to have “arms and legs of steel” or “nerves of steel”. Steel is an iron metal with extremely low carbon content – no more than around one per cent. Steel production was extremely costly until the end of the 1800s, when a new technological development made it possible to produce steel on a large scale. Before this, steel was reserved for the most important artefacts, such as swords and elastic steel springs.

Even though steel contains little carbon, it is still an alloy of iron and carbon. An alloy is a metal that combines two or more elements. The alloy can take on qualities completely different from those of its various constituent elements. It isn’t like mixing salt and sugar and ending up with something that tastes both salty and sweet. Strong steel is made of iron – which, in its pure form, is soft, malleable and ill-suited to tool-making – and carbon, familiar to us from the crumbling graphite in the pencils we write with. Steel is also combined with numerous other elements to give it special qualities. Small quantities of metals like vanadium and molybdenum make steel lighter and stronger, and you'll find it in monkey wrenches and plenty of other tools we keep in our sheds. Chrome produces steel that rusts less easily; along with nickel and manganese, it is a component in the stainless steel cutlery I use to eat my dinner.

If we want to grasp why a particular material behaves the way it does, we need to understand something about the way the atoms in the material fit together. If you put a piece of pure iron metal under a microscope with good magnification, you'll see that the metal consists of many small interconnected crystals without any gaps between them. Unfortunately you can't see individual atoms using a regular microscope but if you could, you would see that the iron atoms in each crystal are lined up in neat rows and columns.

If you try to bend a rod of pure iron metal with your bare hands, one row of atoms can simply slide past the next. As soon as you stop applying force to the metal, the atoms settle in their new position and remain there. The iron rod will not spring back into its original shape when you release it the way a steel spring would. The size of the crystals in the metal is the factor that determines how much pressure you must apply in order to make the rod bend. Wherever the crystals meet one another, the rows of atoms are at different angles, which slightly hinders the sliding movement of the rows of atoms. That is why it is easier to bend an iron rod whose crystals are large rather than small.

In the liquid metal in the smelting furnace, carbon and iron atoms become thoroughly intermingled. When the melt cools, it will initially produce crystals of pure iron. The iron is separated out from the liquid metal whereas the carbon is not, increasing the quantity of carbon in the melt. This will continue until the temperature in the furnace has become so low that the remaining mixture of iron and carbon cannot retain its liquid form either. Then a new substance, iron carbide, is formed, which consists of one-quarter carbon atoms and three-quarters iron atoms. The spaces between the iron crystals are filled with layer upon layer of iron carbide, interspersed with pure iron. The finished, solid metal is a mixture of pure iron crystals, which are ductile, and the layered carbon-containing material, which is strong.

This combination of strength and ductility is what makes steel such a sought-after material. Thanks to its ductility an overloaded steel bridge will not collapse without warning. Instead, it will buckle slightly and be roughly as strong afterwards. One of the most important areas of application for steel today is for reinforcement of concrete structures. Concrete can bear a great deal of weight, but cracks easily if it is bent or stretched. When concrete is reinforced with steel, the steel rods inside the concrete resist the forces that are bending or stretching the structure, while the concrete bears the heavy load that would have made the steel rods alone buckle and give way.

THE PROBLEM OF RUST

Steel solves many issues for us, but does not solve them once and for all. The use of iron implies a constant battle against the forces of nature. When we produce iron metal from iron ore, we use a lot of energy to force the iron atoms into a state they don't actually want to be in.

We have all seen how the shiny metal of a car's bodywork or a cycle frame becomes flecked with red porous material after a while. This is rust, which is produced when the iron atoms get a chance to give away some of their electrons to oxygen again. It is iron's favoured form here on the surface of the Earth. That's why our society spends a great deal of money and energy combating the formation of rust – or corrosion – and repairing the damage that is done when corrosion is unavoidable.

Even though iron and oxygen generally want to exchange electrons with one another, they need water in order for the reaction to happen. That is why the first, and often the simplest, defence against rust is to prevent the iron surface from coming into contact with water. The wrought iron of the Eiffel Tower is painted regularly to ensure that all the surfaces receive a fresh coat of paint every seventh year. This is how the tower has remained intact since it was built well over a hundred years ago.

Painting is simple but not always practical. Nobody wants to have paint on the cutlery they eat dinner with because the paint would peel off and get mixed up in their food. Instead, we use stainless steel, an alloy of iron and chrome, in which a reaction between the steel and the oxygen in the atmosphere causes a dense film of impenetrable material to form on the outside of the metal. This film prevents the oxygen from reacting with the iron further in. Like the film, the rust on ordinary non-stainless steel also forms on the surface, but in this case, it forms a porous layer that falls off easily in large flakes so that the reaction won't be prevented from continuing inwards.

It is much more expensive to produce stainless steel than ordinary steel. That is why stainless steel is not used to build large structures like ships, bridges or oil platforms. It may also be impossible to protect metal structures that stand wholly or partially in water with paint. On ships, pieces of zinc or magnesium are generally placed on the outside of the steel hull so that these metals will rust instead of the iron. They are known as sacrificial anodes and will work as long as they consist of metals that are even keener to give away some of their electrons than iron.

Sometimes it's easiest to accept that things will rust. Unpainted steel piles must be made extra thick so that they won't collapse even if part of the surface rusts away. It is calculated that four millimetres will rust away over the course of a century in humid soil or as much as thirty millimetres per century in seawater or areas of sea spray.

Our infrastructure is built with loss in mind. Rusting steel is washed away by rainstorms. Paint gets worn and is washed or blown off. Sacrificial anodes made of zinc, aluminium and magnesium dissolve and vanish into the sea. We also lose iron when it becomes worn. A blunt knife blade must be sharpened. When that happens, a thin layer of material is removed. The sharp teeth on the cogs of a bicycle also become rounder with use. The material that used to be in the teeth now lies by the roadside in the form of dust and will in time be washed into the rivers and, eventually, out to sea.

Even so, steel artefacts are made to last – and do so. Stainless steel cutlery can last for at least a hundred years, while bridges, railway tracks and sky scrapers may remain in use for fifty to one hundred and fifty years. We therefore have a large and increasing store of iron in our society, which can be recycled and reused in new structures.

COULD WE RUN OUT OF IRON?

Iron is the world's cheapest and most widely used metal. 1,640 million tonnes of steel were produced worldwide In 2016. That is 22 times more than our production of the next most common metal, aluminium. Over the past one 170 years iron production has risen between five and ten per cent per year. We use iron and steel to make buildings, bridges, railway tracks, ships, trains, buses, cars, pylons and hydropower stations. Iron is the most important ingredient in the most important parts of our infrastructure. We are Iron Age people, you and I.

What if we ran out of iron? The consequences would be catastrophic. In some circumstances, it is true, we could replace iron with other materials. Sometimes other metals work better than iron because we need something that is lighter, like aluminium, more conductive, like copper, or that can be implanted into a human body without rusting to bits, like titanium. In other situations, we can replace iron with non-metallic materials. A bridge can be made of wood instead of steel. Ships can be made of fibreglass and plastic. Knives can be made of ceramic materials. But even if we produce as much as we can of all the rest, we will never come close to being able to replace all the iron with other materials while maintaining the society we have today.

It is difficult to say for certain how much of the different elements it will be possible to extract in the future. The most reliable figures we have for this are known as reserves. These are based on the overviews that all mining companies are obliged to give the authorities, documenting how much they will be able to extract from their mines.

Sometimes we'll hear on the news that we have only five years' worth of a certain element left, or twenty years of another. You obtain these sorts of figures by adding up all the documented reserves for a given element and dividing this sum by the amount being extracted each year right now. The resulting number tells us how many years it will be before we have used up the reserves of this element. Published iron reserves currently stand at 83 billion tonnes, and 2.9 billion tons are being extracted from the mines every year. This means that, if we continue to extract as much as today, we will have used up the reserves within 28 years. And if we continue to increase production, they will run out even sooner. If this were the reality of the matter, we would be in a very tricky position. But it isn't. In fact, this "lifetime" for the iron reserves has been pretty constant for a long time. 50 years ago, we also had several decades of reserves left. The same goes for the other metals. For the whole of the period from 1980 to 2011, we had 30 years of copper left and 60 years of nickel, even though production of both metals doubled in that time.

There is a very simple explanation for this: the reserves tell us how much the mining companies know for certain they will be able to extract from a given area. They tell us nothing about the deposits we have not yet discovered. Since the reserves are part of the mining companies' valuations, a costly process of geological investigation, test drilling, verification and certification is required in order for the deposits to be classified as reserves. It is important for the mining companies to be able to document sufficient reserves to justify the investment needed to start up or continue extraction, but they don't actually need any more than that. This is why there is no point documenting reserves for many centuries of future use, although it might be obvious that they exist.

If technological development leads to a new and major area of application for an element or if war breaks out in one of the key producing countries, reserves shrink in relation to production and the calculated lifetime shortens. This is a sign that the element may come to be in short supply and that prices will rise. Faced with the prospect of higher prices, mining companies will opt to use more resources to locate and classify new reserves. So what initially looks like an imminent halt in supply actually leads to new finds and higher reserves.

When the prices rise, deposits that are already known of may be moved over to the reserves category. This is because reserves only denote the deposits that can be extracted at an economic profit. When prices are higher, the mining companies can afford to dig deeper, break more rock and use more expensive and sophisticated sorting methods.

Technological advances can also create new reserves. The iron ore from Kiruna was long seen as unusable because of its high phosphorus content. A new method for extracting phosphorus from raw iron transformed Kiruna from a wilderness to a town with a key position in the political life of Europe. In future, the entry of robots into the mining operations will make it possible to dig deeper and sort more efficiently. In this way, the reserves will continue to grow in the future.

It is in the nature of reserves that they will grow when we need them to. Some use this as an argument that we will never actually experience scarcity of resources: we can always find more, or invent methods for extracting more. But that can't be quite right either. Everything that is moved over into the little box called reserves was already in the box referred to as known resources. This contains all the deposits we have already found but have not yet classified as reserves because they are too far off the beaten track, or are located in a country that is at war, or a country that does not allow extraction for environmental reasons or because the geology means that extraction is not profitable in the current market using current technology.

The last box is for unknown resources. This contains everything we have not yet discovered because we have not mapped every cubic metre of the Earth's crust.

Every time we discover a new deposit, it is moved from the unknown to the known box. After that, it may be moved again into the reserves box. Every time the reserves grow, the resources are reduced by an equivalent amount. They may be unknown but they are not infinite. And when the resources box is empty, there will be nothing left to extract.

Scientists who have tried to estimate total iron resources have ended up with a figure somewhere between 230 and 360 billion tonnes. Of these, eighty-two billion are classified as reserves. In addition, between 30 and 70 billion tonnes have already been extracted and are now either in our society or have been lost to rust or wear and tear.

We have been using iron for more than 3,000 years, but have only extracted maybe a tenth of all the iron available. However, this does not mean that we can carry on as we are for tens of millennia: we extracted most of that iron in the past century. The relationship between today's iron production and the total resources indicates roughly 250 more years of production.

Since the figures for unknown resources are so uncertain, we could just as easily assume that they are actually four times greater, implying that we have enough iron for another thousand years. Or ten times greater. In that case we would not be at the end of the Iron Age in a thousand years' time but only halfway through it. The problem is that scarcity of a resource does not arise when the Earth's crust is emptied. We will experience a shortage of iron the instant our society can no longer afford to extract it.

OUT OF THE IRON AGE?

How long will we be able to afford iron? This is a difficult and important question. If the number of human beings on the planet continues to rise, iron usage will probably increase too. If more people get more money, there will also be higher demand. A population decline and harder times may lead to reduced demand. New technology may create new markets or eliminate previously large markets, thereby causing demand to rise or fall.

Among all the known and unknown resources, some deposits are high grade. The concentration of iron is high, so that there is no need to blast, move, crush, sort and store excessively large amounts of stone in order to acquire the iron we need. Once the best deposits are used up, we are forced to start work on those with a lower concentration. Consequently, for every tonne of iron we remove from the planet's store, we are forced to expend increasing amounts of energy and money on extracting the next tonne. This may cause iron to become more expensive, making it more difficult for us all to buy iron tools and increasing the cost of building and maintaining the infrastructure we are so dependent on.

Fairly recently, scientists looked at all these mechanisms in conjunction to try and reach some conclusions about the kind of developments we can expect in the extraction and use of iron over the next four hundred years. They started by estimating that total iron resources stand at 340 billion tonnes, and that the global population will fall drastically towards the year 2400 (this is linked to the future outlook they discovered for other elements, including phosphorus, which we'll come back to later). According to the results, the extraction of iron from mines will continue to grow up until the middle of the current century and decline thereafter because it becomes ever more expensive and more energy intensive. The rising price of iron ore will also affect the price of scrap iron, so that more iron will be delivered for recycling. Towards the end of the century, most of the iron on the market will be produced from scrap, whereas its share today stands at less than a third. Some way into the twenty-second century, the mining industry will be as good as finished. At the same time corrosion, and wear and tear mean that iron will continue to be lost as before. We cannot limit these losses by producing more stainless steel, because that would lead to shortages in the metals used to make this alloy – chrome, manganese and nickel – long before iron became a scarce commodity. The amount of iron in human ownership will increase from around 50 billion tonnes today to nearly a 160 billion tonnes by the middle of the 2100s; in 2400, however, where the scenario ends, human beings will be left with just 30 billion tonnes.

We should never accept a single study as the absolute truth, especially when we are trying to predict events so far into the future. But on the basis that nothing lasts forever, it seems reasonable to assume that our descendants will be obliged to exit the Iron Age at some point.

Iron is critically important for our civilization. For Hitler, the iron from Kiruna was so important that he occupied Norway and Denmark to secure supplies. It isn't especially pleasant to imagine what other states or powerful figures might be willing to do the day that iron ceases to be cheap and easily available to all. Just as the Stone Age did not end because we ran out of stone, we must hope that our descendants develop new and better infrastructure that is already in place before steel becomes a luxury product again.

POTASSIUM, NITROGEN AND PHOSPHORUS – THE ELEMENTS THAT GIVE US FOOD

It may seem obvious that we use the elements on our planet to build the objects we surround ourselves with. But maybe we give less thought to the fact that we need elements from rock, water and air to build ourselves. We do this by extracting these elements and transforming them into chemical fertilizers so that they can become a part of plants, and then a part of us when we eat the plants or eat animals that have eaten these plants. The most common chemical fertilizer on the market is known as NPK, after the atomic symbols of the elements it is vital for plants to have: nitrogen (N), phosphorus (P) and potassium (K).

Most of the other elements we use in our civilization – iron for tools, copper for electric cables and gold as a means of payment – can be substituted with others if necessary. The situation in food production is different. Without nitrogen, potassium and phosphorus, we cannot exist.

JOURNEY TO THE DEAD SEA

In autumn 2016 I travelled to Israel for the first time. The occasion was a meeting of a European research project in which Israel was a partner. In order to bring the scientists together in a place where we could work closely for a week without being disturbed by the bustle of a town or a university environment, our Israeli partners decided the meeting should be held at a hotel by the Dead Sea.

Since I'd never been to the region before, I took a peek on Google Maps before we left to see where we would be. The area looks odd. The Dead Sea is divided in two by a strip of land, so that there is one lake to the north and another to the south. The northern part looks like a regular lake, surrounded by the desert. But the lake to the south looks like nothing I've ever seen before. It is divided into areas separated by straight lines, roughly like small fields. The water between these lines is coloured in shades that range from turquoise to dark blue, moving from north to south on the Israeli portion of the lake. In addition the border between Israel and Jordan, which runs through the middle of the Dead Sea, is marked with a thick strip of land. I was very curious to find out what these patterns meant.

After a couple of days playing tourist in Tel Aviv, I set out on the bus journey to the Dead Sea, which took us through a dry, flat desert until we reached the edge of a cliff. From here, the road ran steeply down towards a lake that looked like a blue and turquoise patchwork, just the way it had in the image. It was still a long way below when we passed the sign telling us that we were at sea level. When we finally reached the base of the valley, we passed an industrial facility with huge tanks, conveyor belts, tubes and pipes. The straight lines in the lake turned out to be long earthen dikes where huge machines drove backwards and forwards between the patches of blue-green water.

It is true that the southern part of the Dead Sea is different from the northern end. The whole thing was once a single, connected lake, whose surface level of around four hundred meters below sea level was maintained by the fact that just as much water ran continuously into the lake as evaporated out of it. This situation changed in the 1960s and 1970s when first Israel and then Jordan and Syria built pumping stations and syphoned off water that had hitherto run into the Dead Sea, transporting it by pipeline for use in agriculture and in cities.

Today, the surface of the Dead Sea is more than 40 metres lower than it was before the pumping stations were built. In recent years, the water level has fallen roughly one metre a year. The northern and southern sections of the lake have become completely separated from one another at a point where there was previously just a headland.

The southern part of the lake, which is generally only a few metres deep, has been converted into an enormous mineral extraction facility. Natural evaporation means that the water in the Dead Sea is already much saltier than that of any other ocean or lake on Earth. When the water is transferred to shallow ponds, evaporation speeds up – just as laundry dries more quickly if you hang it up than if you leave it lying in a soggy heap. Evaporation can only occur on the surface of water, where the sun heats it and makes it vanish into the atmosphere in the form of water vapour. As the water continuously dwindles, the salt dissolved in it starts to precipitate in the form of crystals. The first to form are potassium chloride, ordinary table salt, and calcium chloride, which is often used to de-ice roads. These crystals sink and form a salt crust at the bottom of the pond. The water is then pumped onward to the next evaporation pond where crystals of the sought-after mineral carnallite form, and are then scraped up and transported to a processing facility on the shore of the lake. Carnallite is valuable because it contains potassium, which is used in chemical fertilizer because plants need it to live, as do we human beings.

NUTRITION ON THE BRAIN

Potassium is an element that dissolves easily in water. It does this by giving away an electron, which it is keen to get rid of, to other atoms in the water. This allows potassium to float around with its positive charge, surrounded by a friendly bunch of water molecules. In our body, potassium is involved in the electrical signals that are sent between our neural pathways. When I looked out over the Dead Sea, the light that hit my eye set in motion a reaction in which minuscule gates in my optic nerve allowed potassium to flow in and out of the nerve cells. This impulse was reproduced all the way along the optic nerve and up into my brain, where similar potassium signals were sent through my brain cells at lightning speed, storing the image of the Dead Sea in my memory.

Since potassium is water-soluble, we are constantly losing certain amounts of it from our bodies when we sweat, pee or cry. The only way we can replace the potassium in our body is by eating plants that contain it, or animals that have eaten plants containing it. Potassium finds its way into the plants through their roots when they absorb the water that lies between the particles of the soil where they are growing. If this water contains no potassium, the plants will not be able to grow properly either.

When plants and animals die and end up lying on the ground they are decomposed by living organisms, large and small. This causes the nutrients contained in the dead material to be absorbed by the roots of living plants. In this way, potassium can circulate from one living being to another forever. But if we look at a single contained area – for example a forest – this is not quite true. There is no avoiding the fact that some of the nutrients will disappear from the forest. An animal may eat plants inside the forest but die outside it. Leaves from the trees may blow away in the wind. Soil and the remains of plants and animals may be carried out to sea by streams and rivers, along with the nutrients they contain.

Over a long period of time, this loss of potassium from the forest can cause life there to dwindle. Fortunately, there is another source of potassium, which is the rock on which the forest grows. The bedrock contains many of the nutrients necessary to life. Perhaps this very rock was once an ocean bed scattered with the microscopic remnants of another forest long, long ago. When the rock becomes weathered, it breaks up, allowing fungi and bacteria to work on the surface of the ever-shrinking mineral particles to release the nutrients needed to sustain life on the surface. Loss is unavoidable, but as long as the losses do not exceed the supply of nutrients provided by the weathering of the rock, life in the area can actually continue for all eternity.

Where we humans pursue agriculture, however, the situation is different. The whole point of cultivating grain in fields is to enable the plants to absorb energy from the sun, carbon from the atmosphere and nutrients from the soil, and then to transport this from the field to the places where humans live. In cultivated soil, the release of nutrients through weathering of the bedrock occurs too slowly to replace the substances that we remove from the soil. We can return nutrients to the field by composting the remains of plants and fertilizing the fields with animal dung. Even so, it is difficult to return enough to make up for the amounts we remove when we produce our food.

What we can do to maintain the soil's capacity to produce food is to help nature by making nutrients from air, water and rock available to the plants. This is what we call chemical fertilizer. By taking control over how this nutrition is added to the soil, we humans have liberated ourselves from a fundamental limitation that applies to all other creatures on Earth. But is this a permanent solution? Could we run out of any of these elements?

POTASSIUM FROM WATER

Potassium is all around us. It is dissolved in all the water on the face of the earth, even rainwater. Salty seawater contains much more potassium than rainwater and freshwater in rivers and lakes. Nonetheless, the concentration of potassium in the sea is too low to make it profitable to extract it directly. In order to produce chemical fertilizers, we need especially concentrated sources of potassium.

These days, potassium is extracted from areas where seawater has been evaporating for thousands and millions of years. Most of these deposits lie beneath the ground in the form of thick veins of salt – the remains of former salt lakes. If the veins of salt lie close to the surface, they can be dug up, as in other mining operations. However, many of the deposits lie deep underground and if the machines have to mine more than a kilometre beneath the Earth's crust, mining operations become extremely costly. Since potassium is so easily dissolved in water, this problem is solved by pumping water down into the deep veins of salt. When the water returns to the surface, it is carrying salts that can then be precipitated in evaporation ponds. After that, the extraction takes place as in the Dead Sea. On satellite images, these sorts of potassium mines look like industrial facilities surrounded by blue and turquoise ponds – beautiful, but dead. Canada is the world's largest potassium producer followed by Russia, Belarus and China. Only five per cent of the potassium that is obtained is used for purposes other than fertilizer production.

Although the reserves provided in geological reports indicate that there is only enough potassium for around a hundred years based on current consumption, estimated resources are large enough to ensure that it will be possible to produce potassium for several thousand more years. Most of it is at great depths. The challenge in future is not finding enough potassium, but having enough energy and water available to be able to extract the existing supplies.

Those of us who live in Norway are used to having a surplus of clean water. We are lucky. In large parts of the world, water is a scarce resource. By the Dead Sea, I saw how the flowers, trees and lawns around the tourist hotels obtained their water from a network of pipes that used industrial wastewater: one hole for every flower and big signs with skulls on to warn thirsty tourists against taking a swig.

We need clean water for drinking and food production but also to produce chemical fertilizer, and extract metals and other raw materials from the earth. Nature produces clean water for us in two ways. One is that the sun causes water to evaporate from the sea – or from the evaporation ponds in the potassium mines. The water vapour is transported inland on air currents, falls as rain and the water gathers in streams and rivers, ready for use. Nature also has its own filter for cleaning dirty water. When water runs through the soil, bacteria and other microorganisms break down the substances dissolved in the water. Other substances adhere to the surface of sand or clay the water runs past.

Today we do not just use the water nature cleans for us every day; we also use water that was cleaned thousands of years ago and stored deep down in the earth in the form of groundwater. Several of these ancient sources are running dry because replenishment with rainwater from the surface takes too long to make up for the amounts we are removing. In certain places, natural sources of clean water are so scarce that people have switched to desalinating seawater – but this expends a lot of energy. Our needs for water, energy and chemical fertilizer are tightly interlinked.

NITROGEN FROM AIR

The first element in NPK fertilizer, nitrogen, accounts for around 3.2 per cent of our body weight. Nitrogen plays a key role in the large molecules that build up our skin, hair, muscle fibre, tendons and cartilage. It is also incorporated into the molecules that control all the chemical processes in our body. Without nitrogen it is impossible to make a functioning human body.

Most of the air we breathe in consists of nitrogen, so you might think we would always have enough of this substance. The problem is that the nitrogen gas in the atmosphere consists of two nitrogen atoms that are strongly bonded together. We just breathe nitrogen in and straight out again because our body cannot split the nitrogen atoms apart and make use of them. That is why we have to obtain the nitrogen we need from the food we eat.

Luckily for life on Earth, there are bacteria capable of breaking the bond in the nitrogen molecules. These bacteria bond the liberated nitrogen atoms with three atoms of either hydrogen or oxygen, and when these compounds are dissolved in water, they can be absorbed and used by plants. Some plants, like clover, allow just such a bacteria to live in special nodules on their roots. Here, the clover ensures that the bacteria are safe and well and in return, the plant receives a stable supply of nitrogen for its own growth. When the clover plant dies, the nitrogen that was stored in the plant can be used by the other plants growing nearby.

Nitrogen is an element that thrives in gaseous form, so it is easily lost when dead plants and animals decompose. Sometimes we smell ammonia in outhouses and cowsheds. Ammonia consists of nitrogen and hydrogen, and can form when organic material decomposes. This flow of nitrogen out into the atmosphere makes it particularly important for there to be organisms in the soil that can do the job of drawing nitrogen back out of the atmosphere again.

The only natural process that makes the nitrogen in the atmosphere available to plants without involving microorganisms is lightning. When lightning strikes, so much energy is released that the nitrogen and the oxygen in the air can react with one another, forming new molecules. Early in the 1900s, Norwegian physicist Kristian Birkeland and engineer Sam Eyde discovered that they could replicate this process by using electricity to make artificial lightning in the laboratory. This was the first time anybody had managed to outsmart biological processes and produce nitrogen fertilizer directly from the atmosphere. The Birkeland-Eyde process, as it became known, laid the foundations for Norsk Hydro's production of chemical fertilizer using energy produced by the power stations in Notodden and Rjukan.

Norsk Hydro's production of chemical fertilizer was, in many ways, a revolution and helped pave the way for the enormous increase in global food production of the 1900s. Even so, it was replaced fairly rapidly by the cheaper Haber-Bosch process, which is based on natural gas, i.e. gas from fossil sources.

In the Haber-Bosch process, natural gas provides both the energy needed to break the strong bond between the nitrogen atoms, and hydrogen atoms for the liberated nitrogen to bind itself to. Totally pure carbon dioxide is produced as a by-product and is sold both to the oil industry and water purification facilities. Oslo's gardeners became aware of this when a period of extra low production of nitrogen fertilizer in Europe obliged the municipality to order them to switch off their water sprinklers at the height of the dry summer of 2018.

More than half of the nitrogen absorbed by the plants we cultivate in our agricultural practice around the world comes from chemical fertilizer. We now rely on nitrogen produced by industrial methods to build our bodies. How long can we go on like this?

If all current known reserves of natural gas were used solely to produce chemical fertilizer, this would give us enough nitrogen fertilizer for around a thousand years before the gas ran out. It is almost certain that actual amounts of natural gas exceed today's known reserves. At the same time, though, it is unrealistic to imagine that natural gas won't be used for purposes other than fertilizer production. When the deposits of fossil oil and gas decrease and become more expensive, natural gas will become a sought-after raw material for a whole range of chemical processes. We will therefore be obliged to produce nitrogen fertilizer from something other than natural gas, even before a millennium has passed.

Already today, scientists are hard at work on alternative production methods. One strategy is to use solar energy both to separate the nitrogen atoms and produce hydrogen that can react with the nitrogen. Others are working to develop the old Birkeland-Eyde process and make it more energy efficient.

Perhaps it will be a matter of just a few years before smallholders can produce their own nitrogen fertilizer using solar cells on their roofs.

When bacteria capture nitrogen, they do so by producing organic molecules that make the nitrogen gas react with hydrogen, without requiring much energy. In a sense, the molecules coax the atoms into position. Now that we humans are starting to acquire good tools for editing the genes of both bacteria and plants, we may have the chance to alter agricultural plants in such a way that they will become capable either of capturing nitrogen from the air by themselves, or entering into a new collaboration with specially adapted bacteria the way clover plants do. These genetically modified plants would, in principle, enable us to cultivate all the food we need without having to use nitrogen fertilizer. The issue of nitrogen for food production is a technical challenge with a range of possible solutions. We will not run out of nitrogen.

Phosphorus from rock

The last of the vital elements, phosphorus, is not found in the atmosphere. We won’t find much of it in water either, because it has a tedious tendency to cling to mineral surfaces and is happier in solid form than dissolved in water. This means we need to turn to solid stone and rock to harvest phosphorus.

Phosphorus accounts for roughly one per cent of an adult human’s body weight, most of it in the skeleton. But even in organisms without a bone structure, phosphorus plays a crucial role. The recipe for my body, who I am, is written in every single one of my cells in chemical script. The chemical alphabet consists of just four letters and these letters constitute the rungs in a long molecule that resembles a twisted ladder. The phosphorus atoms are what hold the rungs in the ladder together. Without phosphorus, no DNA – and therefore no life either.

Sources of phosphorus like human urine and bone meal from domestic animals have been used worldwide as fertilizer for several centuries, but from the mid-1800s, farmers started to use phosphorus from geological deposits too. The first lucrative source was bird droppings, known as guano, which can be found in vast quantities on certain islands where sea birds have nested for thousands of years. These deposits of "fossilized" bird dung were extracted on a massive scale, but since they were limited, it wasn't long before more phosphorus was being produced from phosphorus-containing rock than from guano.

Since the 1960s, more of the phosphorus applied to our fields has come from geological sources than from the dung of domestic animals and the remains of plants, and more than three times as much geological phosphorus is currently being applied than is recycled in these biological processes. If we were to stop producing phosphorus from rock today, we would be obliged to cut food production to a quarter of the current level. Geological phosphorus is even used in organic farming, although generally in the form of ground rock. For conventional agriculture, the rock often undergoes a series of chemical processes to make the phosphorus as accessible as possible to the plants.

A handful of countries dominate when it comes to current phosphorus extraction. The largest and most important producers are Morocco, the US and China. Morocco alone controls more than two-thirds of the world's known phosphorus reserves. A large proportion of these are located in the disputed area of West Sahara, which would hold the world's second-largest phosphorus reserves if it achieved independence from Morocco. Many are concerned that Morocco could gain a near-monopoly in phosphorus in the future, which would give it a major say in global food production.

On certain parts of the ocean bed, there are sediments so rich in phosphorus that it may be profitable to extract them. Large deposits of this kind exist, for example, off the coasts of New Zealand and Namibia. In order to obtain phosphorus from the ocean bed, the uppermost layer of sediments must be sucked up in a boat, where the phosphorus-containing particles are separated out before the rest of the material is pumped back down to the ocean bed. This will destroy life on the ocean bed during the period in which the extraction takes place. And although advocates of the process think that life will return fairly quickly afterwards, uncertainty about how damaging this could be to marine life has so far prevented the start-up of any such projects.

Documented reserves of phosphorus are large enough to last more than 300 years based on current consumption levels. However, phosphorus consumption is increasing and is expected to continue to rise in line with population growth over the coming years. Several scientists warn that the world will face a dramatic scarcity of phosphorus for food production in less than 100 years, and that it is only a matter of decades before we will start noticing this in the form of global increases in food prices. Others think we will be able to continue extracting phosphorus for more than 1100 years based on current usage if we take into account the deposits that have not yet been mapped.

Only 20 per cent of the phosphorus extracted in the world's mines finds its way into the food we eat. The rest is lost under way. Some of it is already lost at the mine; some vanishes in the chemical treatment of the phosphorus rock, and during the transport and distribution of fertilizer. Some gets lost when crops fail as a result of plant diseases or bad weather, or are destroyed by fire. A third of the phosphorus that actually ends up in human food is never eaten. Since the phosphorus we apply to our fields will always adhere to the particles that form the soil, the greatest loss of phosphorus – around half of the total we extract – will, in any event, be caused by soil loss.

The cultivable soil on our planet has been accumulating since the very first living organisms emerged from the sea. In order for topsoil to form, the rock on which it is lying must be broken up and weathered, freeing the nutrients. Small and large organisms in the soil, such as bacteria, fungi and earthworms, ensure that the nutrient from the rock blends with organic material from dead plants and animals. In all, nature takes around 100 years to produce a centimetre-thick layer of topsoil.

Erosion can cause this precious soil to disappear from our agricultural areas and out into the sea. On a newly ploughed field, soil particles lie unprotected against wind and rain. A severe rainstorm can turn the rivers brown with lost topsoil. After droughts, the wind can bear the topsoil away from fields in enormous clouds of dust. This is what happened to the cultivated American prairie during the massive catastrophe known as “The Dust Bowl” in the 1930s, in which tens of thousands of families were forced to leave their homes and farms. In this region, as much as half of the topsoil may have been lost since Europeans first began to farm there. The falling water level around the Dead Sea is causing fertile soil to be washed down the slopes every time there is a rainstorm.

Today, the world's topsoil is vanishing between ten and a hundred times faster than new soil is being produced through natural processes. Good strategies exist for limiting the erosion of agricultural regions – like ploughing less or using plants that cover as much of the soil as possible. Even so, we must expect climate change to lead to more storms and floods, which will increase erosion. If the loss of topsoil continues at the current rate, we will face serious difficulties cultivating enough food for the world's population in the future, regardless of the scale of any the phosphorus deposits we may find.

A day will come when it will become too expensive to obtain phosphorus from geological sources and apply it to our fields. In order for our existence to continue in future we must reach a point where we are not losing more phosphorus than nature provides us with through the weathering of the bedrock – implying a large reduction from current levels of phosphorus loss, which are six times higher than natural supply. We can optimize agriculture to obtain as much phosphorus as possible from our surroundings, for example by allowing domestic animals to graze on non-cultivable fields, thereby bringing phosphorus "home to the farm". Nonetheless, this will only compensate for roughly a third of today's losses.

If everybody is to have enough food in future, we must either reduce the Earth's population substantially – not an especially pleasant outlook – or reduce our dependence on geological phosphorus before it is too late. We can do this by eating less meat, preventing soil erosion, halting climate change and recycling phosphorus at all links of the chain – from the mine via the manure cellar on the farm and the food waste in our kitchens to the sewage from our homes. Perhaps in future we must have specialized toilets with an extra hole at the front that separates urine from faeces – like the kind that have already been introduced in some Swedish municipalities. Preventing the urine and faeces from intermingling is a step that makes the path from sewage to fertilizer notably smoother.

NUTRITION GONE ASTRAY

The reason we have to apply fertilizer to our fields in order to grow the food we eat today is that we remove more nutrients from the fields than we return to them through biological processes. But elements do not go away. The nitrogen, phosphorus and potassium in the food we eat become part of our body for a while and are then eliminated through urine and faeces. Nutrients are also found in parts of plants and animals that do not become food.

Today, only a small proportion of this nutrition is returned to the fields it came from. The transport costs are too high and there is a risk that dangerous diseases could spread if human and animal faeces are used for fertilizer. Instead the nutrients end up where they shouldn't be. In rivers, lakes and seas, large amounts of nitrogen and phosphorus are causing enormous algae growth; the algae use up the oxygen in the water, suffocating fish that live deeper down. If we manage to develop good methods for harvesting the nutrients and returning them to our fields without spreading infection, we can continue to produce food in the fields and simultaneously ensure that our seas and lakes are in better condition to produce the fish we want to eat.

The ecosystems in seas and lakes aren't just suffering from our nutrient-rich waste. They also receive large quantities of the chemical fertilizer that is spread on the fields. When farmers apply more than the roots can absorb, the surplus runs out into streams and rivers. It is difficult to know exactly what levels of nutrients the plants need at any given time. Fortunately, this is an area that is seeing technological advance. Computers can analyse images taken by drones to find out whether the plants are lacking anything. And then the farmers can use computer-controlled agricultural machinery to apply the amount of fertilizer needed – and no more – in the correct place.

THE FUTURE OF THE DEAD SEA

The Dead Sea is a remarkable place.

At the northern end of the lake, the surface has sunk several metres since the large spa hotels were built. Now, the tourists are driven down to the shore in small buses. The roads between the hotels require constant repair because the rainwater that sweeps through what used to be a salt lake bed washes the salt away with it, leaving hollows that collapse into gaping craters on the surface.

The guests in the hotels at the southern end have to walk up a staircase to get from the pool area to the beach. Construction work is constantly underway. All the salt that is left in the evaporation ponds once the valuable minerals have been extracted is causing the bed of the lake to rise by around twenty centimetres a year. The water no longer flows from north to south. It is pumped up.

In a way, I think it is heart-breaking to see this poisonous dead sea, where the scrawny bushes and rubbish that line its shores are slowly being coated in a thick layer of salt. On the other hand, there is something majestic about this sight. We humans have taken control of this entire ecosystem, this entire lake, and we use it to produce what we need most of all: the food that gives us the building blocks of life. Without chemical fertilizer there would not be as many of us humans on earth as there are today. It's as simple as that. And without the population explosion the world has seen in recent years, maybe we wouldn't have the technology and research we have today. I would never have travelled to Israel to meet researchers from all over the world. Potassium from the Dead Sea or from a mine in Canada would never have flowed in and out of the gates in my optic nerve to give me the image of the Israeli desert. Perhaps I wouldn't even have existed.