Elements of Technology

by Michael Droescher

There are many ways to look at the periodic table. When Mendeleev established the table, he arranged the elements according to atomic number and chemical properties. Here, we try a different look. We discuss the influence and links of elements on the development of cultures and technologies. Some of the elements have a direct impact on our life: carbon, nitrogen, hydrogen, oxygen and phosphorous are the main building blocks of our organism, besides small amounts of other elements. Many other elements, especially metals, are the base of the development of our social and technological world, due to the availability and/or innovative use of new or already known elements. We will have a look on the relevance and importance of these elements for the development of technologies over the last 10 millennia.

We learned in history class that early humans were using materials they found in the environment, as wood, stones, fibers, bones, etc. We call this time period the Stone Age. But about 10 000 years ago, new materials became available. Extracting metals from the earth, first copper and tin for bronze and then iron, were disruptive innovations and became the base of a dynamic growth of population and technologies. There was also gold in the form of nuggets found in nature, as there is evidence of gold in Egyptian history 5000 years ago. But in those days, gold was not relevant for technology; it was a symbol of wealth. It is said that the upper stones of pyramids in the middle dynasty in Egypt were covered with gold. Silver is also reported to be mined about 5000 years ago. Again, in those times, it was used for its value in coins or jewelry rather than as a material. Both gold and silver became important for technologies much later, as we will see below.

Let us begin in the Bronze Age. First, mankind learned to extract copper from copper ore and used copper directly. But tools and weapons made from copper were quite soft. Soon it was discovered that smelting copper together with tin or arsenic would yield better materials, what we call alloys. These materials are harder and stronger than the pure metal. Building a wide knowledge of mining various ores and learning to smelt these ores into metals and alloys gave rise to many new technologies. Also, increasing trade let to a strong interaction of cultures in South Europe, Asia Minor and North and Sub-Saharan Africa. Ingots of copper or tin are still found today in ancient trade shipwrecks on the ground of the Mediterranean Sea.

The first surviving iron artifacts, from the 4th millennium BC in Egypt, were made from meteoritic iron-nickel. One of the first smelted iron artifacts, a dagger, dates back to a tomb in Anatolia, dated about 2500 BC. It is not known where or when the smelting of iron ore began, but by the end of the 2nd millennium BC iron was being produced from iron ores from Sub-Saharan Africa to China [1]. The development of ferrous metallurgy technology would be a thick book of its own. Here, we will just mention that iron materials always contain carbon, which comes from the charcoal, today coke, used to reduce the ore. Cast iron has high carbon content. To produce steel, the carbon content has to be reduced. There was a long technology development from the first cast or pig iron to the modern thin steel sheet, used to build cars. For example, it takes many steps to forge a Japanese chef knife or a Saracen sword, both with a complicated structure of different layers of steel with different carbon content and structure.

Whereas bronze and iron were materials for tools, weapon or construction, we move on to the 15th century when we see a revolution in communication. Lead was already being used in many applications, such as plumbing. It melts quite low at 327°C and is easily formed. In the 1450s lead became the means for a revolution of communication when Gutenberg invented movable types. Before, books had been written by hand or printed by using printing plates cut from wood. Movable metal types, cast from an alloy of lead, tin and antimony, made the difference. Books and leaflets could be produced much cheaper and in larger numbers. This was clearly revolutionizing communication structures, and lead to the success of Martin Luther's reformation process some 60 years later.

Silver, before mainly used for coins and tableware and other household tools, played an important role in the next communication revolution, when photography was invented. In the process developed by Daquerre in the 1830s, silver was applied in the form of halides to capture the light. In the beginning, the exposure times of the glass plates took some minutes. Films were introduced in the late 19th century. I still remember my own square 8 x 8 cm black and white photos from the 1960s. Then, the film was taken out of the simple camera, put in a small light dense container and developed by a specialist nearby. A film had 12 to 20 exposures and required careful selection of subjects. As we all know, digital formats have taken photography. Today, we shoot hundreds of images on our smarthphones without such care in selecting a subject.

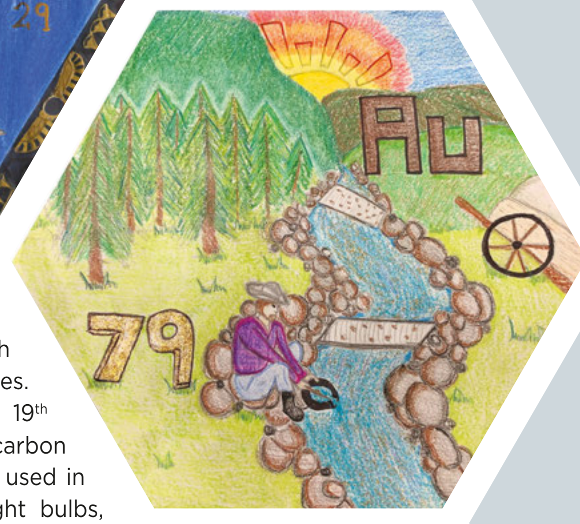
Let us go back into the 18th century and look at the industrial revolution induced by the invention of the

steam engine. Without access to materials like modern steel and cast iron, Thomas Watt would not have invented this important tool. And perhaps England would have more forest today, as most of the wood available at the time was turned into charcoal to smelt iron ore. Later, coke from coal was used as reducing agent. Steel was always needed in large quantities. A new means of transportation to fuel the economy, the railway, was invented. In the German and French words for railway, *Eisenbahn* and *chemin de fer*, the importance of iron for the development of the infrastructure is still present.

The next revolution focused on warfare and agriculture. Nitrogen, in the form of N_2, is the most abundant uncombined element. Nitrates are used in explosives and more importantly, ammonia in fertilizer. Until 110 years ago, nitrates were only available from deposits and ammonia from electrolysis. Only when Haber and Bosch developed a new synthesis process for ammonia in 1909 could large scale production be started. This first helped Germany in World War I to overcome the blockade of saltpeter from Chile, but much more importantly fueled the agricultural revolution by providing synthetic fertilizer in previously unknown capacities and volumes.

Carbon, now in the form of organic materials, is the topic of the next industrial revolution, synthetic organic materials. Today most of the fossil carbon, about 90 % of the coal, gas and oil extracted from earth, ends up as CO_2 from combustion processes. Only about 10 % of the fossil resources are used to produce synthetic organic materials, which have to a large extent replaced natural materials like wood or wool. In the beginning of the 20th century coal was the raw material base. After World War II, raw oil became the fuel of the new and fast growing global economy. Today, natural gas and renewable raw materials are gaining increasing importance as feedstock. Synthetic organic materials, as plastics, thermosets, coatings, foams, synthetic textiles, make upmost of the materials we use. And we use large volumes. About 335 million metric tons of plastics are produced annually [2].

Elemental carbon in the form of diamond was always used as jewelry. Synthetic diamonds became available with high pressure synthesis technologies and are used as polishing material, being the hardest material of all.



Graphite has many uses, such as electrodes. In the late 19th century carbon fibers were used in the first light bulbs, soon to be replaced by tungsten, which was much less prone to breaking. Today, carbon fibers are the base of lightweight materials, such as for the construction of airplanes or the cockpit of Formula 1 racecars. Recently, two-dimensional elemental carbon structures, graphenes, have been developed into new materials with a hope for application in electronics.

The next revolution was based on sand, or silicon dioxide, the source of purest silicon. Silicon is a semiconductor material, it conducts electron holes and electrons. Thus, it became the workhorse of electronic structures. Processes had to be developed to produce 99.9999999 % pure silicon with a mono-crystalline structure. From these crystals wafers are cut on which the integrated circuits are modeled. I remember my first transistor radio from 1966 and write this article on a laptop produced in 2018. In this timespan the number of microprocessors in an integrated circuit has grown from a few to over 20 billion. Digitalization, the buss word of today, started in the 1950s and has changed our life and communication, much as the printing press with movable letters did 500 years ago.

Electronic devices need a surface to use easily. Up to the 1960s computers were programmed and fed with data from punched cards. We had to punch and carry hundreds or even thousands of cards to the computer center of the University of Mainz in 1970. In the 1970s computers were fed information via a keyboard. Today we use touch screens. Here, the metal indium comes into the focus. It was first used to produce flat screen television sets, where thin layers of

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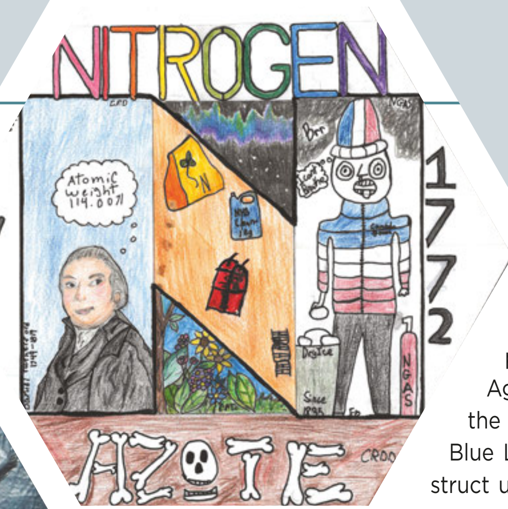

liquid crystal materials are switched in an electric field, built up between the pixel structure in the back and a transparent and electric conducting indium tin oxide layer in front. Today touch screens are everywhere in our life, from household appliances to our cars and all hand-held communication tools.

This brings us back to gold, which continues to be a sign of wealth and power for 10 000 years in the form of coins, ingots and jewelry. As gold is a very good conductor material, it is employed in the electronic structures of our smartphone, laptops, or any other electronic device, together with a large number of other elements. Have a look on the video of Arjan Dijkstra and Colin Wilkins of the University of Plymouth in the U.K. They used a blender to reveal what our smartphones are made of. The experiment was designed to highlight the rare mineral resources used in our everyday electronic devices. They discovered that the phone used in the tests contained 33 g of iron, 13 g of silicon and 7 g of chromium. It also contained other important elements, including 900 mg of tungsten, 90 mg of silver, 70 mg of cobalt, and 36 mg of gold [3].

Modern technologies always make use of a large variety of ingredients. For Li-ion batteries, besides lithium, which is extracted from salt lakes in countries like Bolivia or Chile, cobalt is an important element. Here, the political stability of the source of the ore in the Democratic Republic of the Congo and Zambia is of some concern.

light emitting diodes, which have by now taken the lead in lighting applications around the world. Again, new materials opened the route to wider application. Blue LEDs were difficult to construct until gallium nitride crystals were made available. As electric mobility and the investments in windmills grow, the need for permanent magnets is also growing rapidly. Neodymium magnets are the strongest permanent magnets known. A list of the application of the various rare earth elements in modern technology would fill another paper. Here, we can conclude, that modern technologies need half of the elements in the periodic table. And, although not all so-called rare earth elements are really rare, we must be very careful with our resources.

This is also true for the smallest noble gas. Helium is, after hydrogen, the second most abundant element in the observable universe. However, helium gas escapes into space when released to our atmosphere. Helium is needed to cool down many appliances, for example the superconducting magnets in magnetic resonance imaging scanners.

We have to acknowledge that most of our resources are limited. For the first time in history we might run out of some of the elements necessary to keep our technologies alive. Therefore, we should make sure that all elements and materials which are brought into the technical sphere will not disappear in landfills or other depots after application and use, but should be recycled and brought back into the value cycle.

References

1. en.m.wikipedia.org, Ferrous metallurgy, retrieved 2019-05-14
2. www.plasticseurope.org, newsroom: the Facts 2017, retrieved 2019-05-14
3. https://youtu.be/bhuWmcDT05Q, What’s in a smartphone, University of Plymouth, published 2019-03-16, retrieved 2019-05-20

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