Chapter 1

Innovative materials, computational methods and their disruptive effects

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1.1. Materials that changed the world

The history of man and human societies has always been closely linked with technology and, consequently, with the materials which permitted technologies to be effective. This happened since very early times in our evolution and it is not by chance that the longer period, lasted about three million years, was named after stone, one of the most extensively and successfully exploited materials, together with perishable wood, bones, and skin. However, we consider here materials not existing in nature, but created by man, whose appearance had revolutionary effects on human societies and civilizations. Many technologies sprung from new materials such a long time ago that we now take them for granted, hardly realizing how disruptive their advent was. Some of them go back to the first technological revolution, thousand years ago.

1.1.1. Ancient disruptive materials

1.1.1.1. Ceramic

Despite sporadic early appearance and because of its fragility, pottery was unsuitable for the nomadic life of Paleolithic hunters-gatherers. The sedentary lifestyle of Neolithic farmers opened new possibilities. As early as late 8th millennium before common era (BCE), farmers living in some Neolithic villages in the Middle East, such as Tell Mureybet in present-day Syria, began moulding, drying and firing clay [1]. In this way, pottery started and ceramic waterproof containers such as vases, basins and jars could be made. Clues exist that pottery was derived from basketry, because early waterproof containers could be obtained by spreading clay on a basket and drying it. When firing was introduced, only clay was used, avoiding the time-consuming basket manufacturing. Regardless of this development, pottery constituted a new material for light and versatile containers, with notable advantages on basketry. It allowed not only a better conservation of a variety of foods, both solid and liquid, such as water and fruit juices, but also new ways of cooking vegetables such as cereals and legumes into of soups and broths, which became an important part of the diet of the Neolithic man. Alcoholic beverages were also a consequence:

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the earliest evidence of wine production by fermentation of grape juice was found in present-day Georgia and dates back to 6000 BCE. Pottery therefore changed the eating habits and induced an enrichment of the diet. It also had other social consequences: it gave birth to new artisans, potters, and thus to a social diversification.

Fig.1 about here

The potter's wheel, dating back to 4500 BCE, constituted the first use of rotary motion in productive work and turned out to be a revolutionary and fruitful concept over the time. Pottery had also another important impact. Good firing need promoted the construction of closed kilns, capable of the high temperatures needed to transform the chemical structure of clay into ceramics. Those kilns were instrumental in the development of furnaces and major technologies such as brick firing, metal smelting, and glassmaking, mortar production. Archaeologists qualify those new cultures with a specific name, as Pottery Neolithic. Under these points of view, we can hardly disregard ceramics as a disruptive material. And it is interesting to note that still now advanced ceramic materials play a crucial role in the development of futuristic technologies, e.g. thermal shields for space shuttles.

1.1.1.2. Brick

Bricks also were made from clay, shaped in simple forms, dried and eventually fired. They constituted a kind of artificial stone that was easy to obtain and that was actually the first use. It occurred with unfired bricks (called abode in America) in the Levant around 7500 BCE while fired ones appeared in present-day Iran around 3500 BCE. It hardly needs to be mentioned how many ancient and classical civilizations made a vast use of bricks in their buildings and monuments. And it really amazing that such a simple and old artefact still plays a paramount role in modern architecture and civil engineering.

1.1.1.3. Metals

Joroen van der Veer, former CEO of Royal Dutch Shell, claimed that "the Stone Age didn't end because they ran out of stones — but as a result of competition from the bronze tools which better met people's needs." In other words, the Neolithic come to an end when man started controlling metal smelting and the importance of metals was such that the new phases in human history are named after them.

1.1.1.4. Gold and Silver: early uses

Although small pieces of gold were used by Paleolithic men in Spain around 40 thousand years ago, early gold artifacts were cold formed from rare native nuggets ca. 5000 years before BCE. The discovery of gold nuggets is not surprising, because this metal is chemically unassailable from atmospheric agents and therefore does not turn into oxidized compounds (gold reacts only with mercury, cyanide and aqua regia). Thus, gold immediately revealed itself in its fascinating colour and lustre, which led to its first uses for ornamental purposes and soon its history intertwined with wealth and power [2]. Over time, a second form of finding was exploited, powder dispersed in alluvial deposits and in the sands of rivers from which it was filtered, initially with rudimentary sieves, such as a sheepskin, as told by one of the most ancient Greek myths, the journey of Jason to Colchis (a Caucasian region facing the Black Sea, in present-day Georgia) to take possession of the golden fleece (the golden skin of a goat). Indeed, Colchis is where the most ancient gold mine was found [3] and in that area the metal was worked since the 4th millennium BCE [4].

Unlike gold, silver combines with other elements into oxidized compounds, so that initially the pure native form was rarer than gold and silver was regarded more precious. But in the 4th millennium BCE, people of Middle East learned to extract silver from galena minerals (PbS), in which it is bound with lead. Once available in greater quantities, silver became less valuable.

Due to their low structural strength, gold and silver were unsuitable for technical uses in the antiquity and did not promoted the growth of metallurgy but were widely used ornamentally and as money. By the early 4th millennium BCE gold and silver were smelted in good kilns (melting points are 1063 °C and 960 °C, respectively) and their use spread. In the early 3rd millenium BCE, the Sumerians of Mesopotamia systematically melted gold, silver and their alloy electrum into precious objects and fine techniques were developed, such as filigree, inlay, granulation (tiny grains applied on a sheet) and cloisonné (pieces of enamel edged with thin gold edges). The skills of Sumerians goldsmiths are testified by splendid artifacts, dating back to the mid 3rd millennium BCE. In the same period, similar refined goldsmith techniques were used in the Caucasian Colchis and Svaneti.

1.1.1.5. Gold and silver: money

Barter, the first form of trade, was prone to constraints, which were overcome with money. Its earliest known form consisted of fixed amounts of barley, which began to be used by the Sumerians in the 30th century BC, at the time when writing was invented. While the latter allowed administrative activities to develop, the former promoted economic exchanges. In the beginning, it maintained an intrinsic value: a well-defined quantity of goods stored in the granaries.

A major turning point occurred in Mesopotamia in the middle of the third millennium BCE, when money began to be used which had no intrinsic functional value, but was easier to store, transport and exchange. It consisted of a predetermined quantity of silver: the 8.33 grams shekel. Pieces of gold, copper and lead were then also used, always of a predetermined weight. The use of money marked the transition to a monetary economy in which each object assumed the value corresponding to a certain quantity of gold or silver. Money could be used to sell and acquire goods and services and to defer over time these two aspects of a commercial exchange, unlike bartering. Money allowed giving an objective and comparable value to any goods. It made possible any kind of commercial mediation, facilitated the provision of services and allowed accumulating wealth in a lasting way.

Fig.2 about here

The next step came when weight and value of standardized pieces of precious metal were guaranteed by some higher authority by means of an imprinted effigy. Coinage was invented towards the end of the 7th century BCE by the Lydians, a people of western Anatolia who based their prosperity on artisanal production and trade [5]. Coins allowed more effective trade and gave new importance to gold and silver. Early Lydian coins (made of electrum) and shortly after Greek (silver) and Persian (gold) were minted in pieces of large denomination and high value. But later smaller coins were introduced, which promoted the small trade of agricultural products and handicrafts, allowing farmers and artisans to free themselves from a subsistence economy. On the other hand, coinage favoured usury and debt slavery.

However, the very true value of money is not so much the intrinsic value of the pieces of precious metal, but rather the value formally recognized by those who trade and can therefore take different forms. After all, money is anything having a shared value and it was invented many times in different places throughout history and other cultures have used different objects as money: beads, shells, written notes and now also intangible information recorded on the internet, like bitcoin. Its introduction did not require the invention by a technological genius, but rather the acceptance of a social convention, namely a mental revolution. The more people accept money, the more different goods one can buy and this produced a general acceptance. Thanks to this flexibility, money conquered merchants and producers, who very willingly became its faithful servants whatever their religious or political faiths. Indeed, "money is the most universal and most efficient system of mutual trust ever devised" [6]. Even today, peoples of the Earth speak different languages, obey different laws and worship different beings, but they all believe in the dollar and the euro, because money is absolutely tolerant, free from linguistic, legal, cultural, religious, race, age, gender and sexual discrimination. It is a trust system that can overcome any cultural barrier.

1.1.1.6. Copper

Early copper artifacts were cold formed from nuggets starting 8,700 BCE, earlier than similar gold objects. However, also these nuggets were rare and used to make voluptuary objects with no socio-economic impact. Copper came to a larger and socially important use when man learned to smelt ores such as malachite Cu2CO3(OH)3 around 4,500 BCE, starting the Copper Age (also called Chalcolithic, Eneolithic, Aeneolithic), that was a transitional period of coexistence of stone and copper manufacturing. Earliest evidence or copper smelting were found in Serbia dating back to 5000 BCE [7], followed by Anatolia (4200 BCE) and then Armenia, Mesopotamia (Sumer), Elam and Egypt (Sinai). Pure copper melts at 1083 °C, but malachite, the first smelted mineral, often contains impurities that lower the melting point, facilitating the process. The initial production may have been serendipitous, resulting from the accidental presence of copper ores in pottery kilns capable of reaching high temperatures, also thanks to beneficial ventilation. It is likely that the production of copper objects took place in two phases: first the ores were smelted to obtain pure metal and then this was remelted and poured into moulds. The artifacts were then brought to their final shape by beating and annealing. Early smelting and casting were tricky and resulted in rare and costly artifacts for elite uses, while for common uses traditional materials, whose processing techniques were widely known, continued to be used for a long time, such as stone tools, both chipped and polished. Such coexistence of an old technology and a new alternative appeared repeatedly throughout history. But even with in such conditions, copper smelting marked the beginning of the metal age and brought to an end the Neolithic and, more generally, the Stone Age.

Compared to stone, copper tools were less strong, less sharp and prone to losing their edge. However, casting of molten copper into carved stone forms, once established, provided tools more quickly and in greater quantities, so as to evade a growing demand, fed by agriculture and the demographic boom. Such needs were unknown to the Paleolithic or Mesolithic man, who for hundreds of thousands of years had obtained from stone technology the tools suited to his needs. Over time, hardening by beating was perfected, which produced an increase in the yield point (Brinell hardness could reach 130 HB compare to 85 HB of pure annealed copper) and the use of stone gradually reduced. By the beginning of the fourth millennium BCE, copper artifacts became more available and their use gradually diversified, bringing Middle Eastern civilizations into the Age of Metals [8]. The systematic production of metal artifacts required a number of mutually interdependent activities: mining, initially in the open air and later in tunnels, ore raise from deeper and deeper levels; ore transportation and smelting in high temperature furnaces; casting in moulds and forging, i.e. metal processing of metal softened by heat. These activities promoted a complementary technical evolution. Furnaces capable of smelting temperatures were needed which were fuelled with wood and charcoal from the third millennium (50 kilograms of charcoal were needed to smelt a kilogram of copper in those kilns). The kilns had to be equipped with bellows, consisting of simple bags made with animal skins, to blow oxygen-rich air so as to raise the fire temperature. Tools for working the artifacts were needed, such as pliers and pincers. The systematic practice of metallurgy led to a wider work specialization and therefore wider social diversification, but also to the need for new activities such as provisioning and subsistence of workers engaged in mining and metallurgical activities, which might be sited in isolated or remote areas. In this way metallurgy resulted in major socio-economic consequences. The development of civilizations became deeply intertwined with metallurgy, which was pursued even when mining imposed extreme danger and fatigue. Metals gradually became instrumental for the survival and supremacy of societies and their technology became indispensable: waiving metals would have implied regressing to the Stone Age.

1.1.1.7. Bronze

The transition from Copper Age to Bronze Age induced the systematic and extensive use of the latter alloy and posed an end to Neolithic cultures. The oldest bronze was arsenical. Artefacts were found in the Iranian plateau and date back to the 5th millennium BCE. Arsenical bronze alloy (typically 90% copper and 10% arsenic) was obtained accidentally by melting ores containing, in addition to copper, arsenic impurities. Around 3600 BC, the Sumerians cast deliberately this bronze by using proper proportions of different ores smelted together in closed kilns. They were followed by cultures of Anatolia (Turkey) around 3200 BCE. Compared to pure copper, arsenical bronze presented a lower melting point, better melt fluidity and greater hardness when solidified in artifacts. On the other hand, arsenic is a slow-action toxic element and, even without knowing the causes, ancient peoples were aware of that danger, as their mythologies attest: the Greeks and Romans attributed physical defects to their forging deities, Hephaestus and Vulcan [9].

Fig.3 about here

Throughout a long period of coexistence, tin gradually replaced arsenic in copper alloys. Apart from being not toxic, its advantages were the greater fluidity when melted - which facilitated pouring - and the greater hardness once solidified: the Brinell hardness could reach 120-150 HB (much higher than the 85 HB of pure annealed copper) [8]. Tin bronze allowed new civilizations to establish, which were named after it. Apart from jewels, it could be shaped into weapons, namely strategic artifacts for overcoming enemies, as well as agricultural and craft tools, namely artefacts ensuring economic prosperity. Long blades, very difficult to chip in stone, could be cast. Akkadian warriors led by Sargon the Great wielded such swords when they built the first empire in the 24th century BCE. As bronze objects took hold, the technology consolidated and costs reduced, making available a greater and greater variety of tools. Over time, the metal trade developed over longer and longer routes. Armies, farming and artisanship of many ancient civilizations and empires stood on bronze: Sumerian, Indus Valley, Yellow River – Chinese, Early European, Akkad, Minoan, Mycenaean, Amorites, Middle Kingdom Egyptian, Chimú, Inca, …

1.1.1.8. Iron

The very first iron artifacts were produced in Egypt and Sumer around 3500 BCE by cold forming with Neolithic techniques from rare meteoric monoliths (proven by the presence of nickel). Iron ores (siderite $FeCO_3$, hematite Fe_2O_3, limonite $FeO(OH)\cdot nH_2O$, …) are abundant in the Earth's crust but their smelting remained long elusive, because the high melting point of ca. 1550 °C remained inaccessible to ancient kilns, which were capable of 1100–1200 °C even if fed with charcoal. When intensive exploitation for bronze production led many tin mines in Anatolia to run out around 1500 BCE, people living in southern Caucasus started obtaining a partial melting of iron ores [10]. To those first smiths, iron appeared as an anomalous metal, given that, unlike the other known metals, it appeared unable to melt completely. By filling their kilns with alternating layers of ores and charcoal and burning the latter, they obtained a spongy and pasty mass called bloom. This had to be forged, with a long hammering process alternated with red-hot heating to keep it soft, and slag was gradually expelled in the process and the bloom was packed progressively into wrought iron (with a small carbon content less, less than 0.8%). Iron forging was slow and tiring but the longer it was, the better the iron obtained. It was also expensive because it required large quantities of wood. The good quality of the first Anatolian iron depended on the presence of titanium in the ores mined there. It was a fortuitous fact that favoured the success of the new technology.

The first wrought iron had mechanical characteristics lower than the best bronzes of the time and was impossible to be worked in sharp weapons. But around 1350 BCE, cementation was invented. It consisted in steeping forging iron into the charcoal embers, thus causing the absorption of carbon in the outer layer, so that the melting point was locally lowered to 1300–1400 °C and a pasty iron was obtained that was easier to work, although not totally melted. Most importantly, cementation transformed the surface layer into a steel alloy (iron-carbon) of increased hardness (Brinell hardness up to 200 HB), while the bulk remained elastic and not brittle. A good cemented iron was harder than the best bronzes.

Initially considered a precious metal for ornaments, Homer gives such a description in the Iliad, iron slowly became the metal of choice for superior swords and daggers and the strength of the stroke from such iron weapons was limited only by the force of the arm. Forging and cementing techniques were first developed by the Hittites, who dominated the Caucasian region. When the Hittites of Muwatalli faced the Egyptians of Ramses II in the battle of Kadesh in 1286 BCE, they had iron weapons. When iron spread to other cultures after the 10th century BCE, it was the castes of blacksmiths who kept its working secrets. In fact, iron metallurgy was for a long time kept an esoteric art of divine origin: in the Greek and Roman pantheons Hephaestus and Vulcan were forging gods.

Iron became the strategic material of new powerful empires: Assyrians, Chaldeans, Greeks, Macedonians, Romans, Chinese, Maurya, Byzantines, Arabs, … not to mention Phoenicians, Etruscans, Celts and others. From the 3rd century BCE, high quality steel, ideal for weapons, was obtained in the Western World by means of a time-consuming process in which layered sheets with alternating high and low carbon content were pounded and folded on themselves several times. A similar and even more sophisticated layered steel was obtained by Japanese smiths starting in the 6th century CE to manufacture samurai katanas and tachis and a couple of centuries later by the Arab smiths in the Damascus steel. The Chinese were the first to use coal in advanced furnaces to fully melt iron ores into pig iron, which could be poured into moulds in the 5th century BCE. Less than two centuries later, they started decarburizing pig iron to obtain steel [11]. Around the 3rd century BCE, smiths in the Mauryan India were also able of melting steel, the so called wootz steel, in crucibles. Despite the great importance of iron and steel in the Western World, Europeans could melt pig iron for the first time only around the 12th century CE. The production of iron soared when firearms spread, in the Far East from the 14th century and in Europe to a much larger extent from the 15th century, reaching an estimated 100,000 tons in 1540 and starting a new phase in the Age of Iron. It was on those iron firearms that the European nations founded their colonial empires extended all over the Earth in the following centuries.

1.1.1.9. Concrete

Very early hardened granular materials were used by the Assyrians, Egyptians and Greeks. But it was the Romans who developed a superior concrete and mastered its use, starting in the early 2nd century BCE. It consisted of a mixture of crushed stone and liquid mortar made of lime (obtained by cooking limestone) and pozzolan (a sand rich in silica). These latter two substances, once mixed with water, reacted allowing the mortar to harden quickly even in the absence of air, resulting in a high-strength binder. Since Roman concrete was capable to solidify in water, it made possible the construction of artificial piers, greatly increasing the possibilities offered by the relatively few safe natural dockings, which promoted Rome's maritime expansion. By pouring liquid concrete into properly shaped shuttering, it was possible to obtain quickly and easily an artificial stone of any form. Arches, vaults and domes made of concrete widespread into unpreceded buildings which gave life to the Roman Architectural Revolution. Buildings like the Colosseum (80 CE) and the Pantheon (135 CE) were made of concrete [12]. The latter's dome, spanning over 43 meters in diameter, was built in concrete with differentiated compositions, stronger at the bottom and lighter at the top, where crushed pumice was used. Its size remained unparalleled for 13 centuries and is still the world's largest unreinforced concrete dome. The recipe of concrete went lost after the fall of the western Roman Empire and other 13 centuries passed before John Smeaton reinvented a similar material, in 1756, which was perfected with the Portland cement of Joseph Aspdin in 1824.

Fig.4 about here

1.1.1.10. Blown glass

Early glass was likely produced in Egypt, around the mid 3rd millennium BCE. It is supposed that this occurred by chance with the accidental fusion of natron (hydrated sodium carbonate, available in the beds of dried lakes) and silica (silicon oxide, forming sand) at the high temperature reached in metallurgic or ceramic kilns. That early glass was opaque and coloured and, due to the difficult production, it was for a long time considered a kind of artificial precious stone and small glass beads were set in jewels [13]. Only a millennium later glass-coated vases and entire glass vases were produced by forming molten glass on clay casts. Two further millennia later, around 20 BCE, glass blowing was developed in Phenicia, which had been conquered by Roman general Pompey in 64 BCE. The technique relied on improved ovens, capable of reaching temperatures of complete melting, which made the glass blowable and transparent. Blowing simplified and greatly speeded up the production of artifacts, causing the cost to drop. Glassmakers learned to select silicates in order to control the colour of the glass and it was possible to produce colourless glass, by using manganese oxide. Glass became in fact a new material, in terms of cost, appearance, workability and final uses. When glassmakers migrated to Rome, attracted by the rich city markets, glass started spreading in the West. The first stained-glass windows were used in public buildings and palaces in the 1st century CE and by the end of the century blown glass spread throughout the empire. Glass objects became common for everyday objects, alternatively to pottery, at such a breadth that its diffusion is indicated as Glass Revolution in Ancient Rome [14].

Fig.5 about here

Some centuries later blown transparent glass could be shaped in the form of lenses. At the turn of the first millennium CE, Arab scholars such as Abū al-Haytham (latinized as Alhazen) used them to explore refraction, setting the basis of modern optics. Around 1290, eyeglasses were invented in northern Italy and soon produced in Venice, with a major social impact because they allowed the extension of the productive life of elder people. At the turn of the 16th century, such lenses were combined into telescopes and microscopes, which opened the door to modern optical astronomy, starting with the seminal observations by Galileo Galileo of 1609, and to microbiology, two pillars of the Scientific Revolution [15].

1.1.1.11. Silk and porcelain

Two other ancient materials which were devised in China are worth citing, although they did not have major technological applications. The earliest silk finds were produced by the Yangshao culture of Henan, China, around 3630 BCE. The production of excellent quality silk was made possible by the domestication of the Bombyx mori worm, so that intact cocoons and long and regular burrs were obtained. The spinning and weaving of the almost invisible filament in such ancient times constituted an extraordinary technical achievement by itself. The value of Chinese silk was such as to motivate very lucrative long-distance trades to the Near East beginning in the 11th century BCE.

The network of routes which started being established in the 1st century BCE, later extended toward the Roman Empire, became famous as the Silk Road [16]. In the 1st–2nd century CE, under the Han dynasty, the first true porcelain was produced from kaolin and firing at 1400 °C, resulting in a translucent ceramic with an amazing vitrified enamel finish. Those Chinese handicrafts, highly valued on the international markets, contributed expanding the Silk Road. And those century-long trades brought an extraordinary exchange of ideas, culture and knowledge between civilizations far each other, deeply influencing the history of man. Only in the 6th century CE silk manufacturing was started in the Byzantine Empire, therefrom expanding to Western Europe. And only in 1710 European porcelain could be manufactured in Meissen, Saxony.

1.1.2. Materials of the Industrial Revolution

1.1.2.1. Cast iron and steam engine

Iron and steel entered a new era during the industrial revolution. The first European high-quality melted steel was obtained by clockmaker Benjamin Huntsman in England in 1740. He used a calibrated mixture of soft iron and cast iron and that he placed in a clay crucible to avert any contact with the burning coal. The furnace reached 1600 °C, at which the mixture melted completely and the two components mixed. The crucible size contained about 15 kg of iron and the process lasted about three hours, so that the steel obtained was very expensive, although of excellent quality, castable or forgeable.

The production of large quantities of iron and steel was achieved along a different path. In 1709, Abraham Darby began using coke, a pre-treated coal with reduced sulphur content, in his iron furnaces to obtain cast iron of better quality. In addition, the coke resilience to crashing allowed larger quantities to be stacked in higher and bigger blast furnaces, where larger ore loads could be smelt at reduced costs [17]. In those blast furnaces that cheap and of good cast iron reached the melting point and could therefore be cast into moulds. It was a of paramount importance for Newcomen's steam engines. Coke was used systematically from 1735, allowing English iron industry to soar. But that iron remained too fragile for hammering, due to residual sulphur and phosphorus content. In 1748 Abraham Darby II succeeded in producing forgeable cast iron by a careful selection of ores with low phosphorus content and the production of iron by means of coke achieved full success. Although higher quality steel still had to be bought in Sweden and Russia, British imports dropped and English iron began to be exported. Much better guns could be cast with Darby's iron, which constituted one of the strategic oversea advantages, together with navy, in establishing the British Empire.

Fig.6 about here

Steel puddling consisted of mixing pasty cast iron, to allow carbon in the melt iron to oxidize at the air and ultimately to reduce the carbon content, resulting in wrought iron or even fair quality steel. The procedure was expensive, because slow and only small charges could be worked at a time. Puddling gained momentum in England about 1768 thanks to Henry Cort, who also adopted the rolling mill for the direct production of steel ingots from wrought iron in 1783, a process 15 times faster than hammering, that had already been introduced in Sweden by Christopher Polhem in 1745 [18]. In 1784, Cort introduced puddling in reverberation furnaces, which allowed to obtain a fairly cheap steel. This was another achievement of strategic importance for Great Britain because it allowed to satisfy the high demand for steel coming from soaring productive sectors, notably steam engines, which until then were made with costly steel imported from Sweden and Russia. Thanks to Cort's iron making technology and to the growing industrial demand, English steel production soared from 200 tons in 1740 to 80,000 in 1840. James Watt relied on that kind of iron in building his steam engines. In the same period, Sweden and Russia gradually lost their leadership in iron and steel making in Europe.

The Bessemer converter, that was introduced in 1855 and perfected 1875, and the Martin-Siemens blast furnace of 1864 constituted new iron breakthroughs. In the former process, the melted cast iron poured into the converter was blown with air from the bottom so that atmospheric oxygen reacted with the carbon contained in the iron removing it, while the exothermal reaction heated the melt up to at 1600 °C and burned other impurities. In this way, carbon content was reduced from above 4% to below 1.5% and cast iron loads up to 25 tons were converted into good steel without additional fuel in just 20 minutes [19]. It was a quick and inexpensive process that made the cost of steel production to fall by seven times. In the latter process, fuel gas produced from low quality coke in an external generator was fired in the furnace that heated up to 1650 °C, reducing the carbon content and other impurities. The process was suitable for all types of ferrous ores and also for scrap. It was therefore inexpensive both in fuel and raw materials. Bessemer and Siemens-Martin steels fed a new phase in the industrial revolution. From 1862 Bessemer steel was used in railway tracks 15 times more durable than wrought iron. Good steel was instrumental to steam engines, locomotives, steamers, electrical machines, bridges, skyscrapers and monuments. And to more powerful heavy artillery. Wrought iron had a major part, too, notably in the structure of the Statue of Liberty of 1886 and the Eifel Tower of 1889, both designed by Gustave Eiffel.

The increase in production was impressive. British steel, which in 1870 was 220,000 tons of which 5,000 by Bessemer converter, in 1900 had risen to 4.9 million tons, of which 1.75 were Bessemer and the rest Martin-Siemens. The most sensational progress was achieved in the United States and Germany. In 1900, compared with a world production of 28 million tons, US production was 10 million tons, two thirds of which were produced with the Bessemer converter, while German production was 8 million tons. World production of Bessemer steel peaked in 1913 with 10.5 million tons (56%), compared to 7.3 (39%) for Martin-Siemens steel. A new Iron Age was spreading into the 20th century. Or maybe it was a new phase in a single Iron Age lasting over millennia and changing its face century after century, while supporting man in his achievements and social evolution.

1.1.2.2. Special steels

Special steels are alloys of steel with metals such as chromium, nickel, tungsten, molybdenum, manganese and vanadium, which had been discovered mostly during the 18th century and became more and more available in the following. Those additions yield better mechanical, thermal, electromagnetic, and/or chemical properties, at a point that special steels had a deep impact in the development of advanced products and processes and on the overall iron industry.

Chromium and nickel steels were first obtained in laboratory by Michael Faraday in 1819. Nickel steel was then made in 1824 by the Swiss metallurgist Johann Conrad Fischer in his steel mill, but industrial production begun only after 1888, particularly by the Schneider steel mills, in France, in different composition: high resistance (1%–3.5% nickel) and self-hardening (4%–5% nickel). Franz Köller of the Reichraming steel mills in Austria began working tungsten steel in 1855, becoming the first special steel to be industrially produced. The American Julius Baur patented a method of producing chromium steel in 1865, which was brought to commercialization also in France in 1877. The British metallurgist Robert Forester Mushet mastered special steel. He obtained tungsten-manganese steel, also called Mushet special steel (or RMS, 7% tungsten, 2.5% manganese and 2% carbon) in 1868, which was capable of self-hardening in air. This was the first steel for tools, which could cut common steel at an amazing speed, specifically it was twice faster and five to six times more durable than carbon steel. Mushet ceded the rights to a Sheffield steel mill, which spread it around the world. In 1889, by varying the tungsten contents and replacing manganese with chromium (18% tungsten, 4% chromium), high-speed steel (HSS) was obtained. To exploit these special alloys to the best of their possibilities, new operating machines were developed capable of producing cutting speeds up to about 7.5 meters per minute, under operator control.

Steel with a manganese content of few percent was known as a brittle and useless alloy, but in 1882 the English metallurgist Sir Robert Hadfield increased the content to an unusual 12%–14% and treated the alloy with 1000 °C heating and rapid cooling, obtaining a manganese steel that exhibited high hardness and wear resistance. It was used to manufacture objects such as grinders, safes, engine components (shafts, rods, gears, …) and railway parts. It was later partially replaced by nickel-chromium steel (typically 3.7% nickel, 0.8% chromium and 0.2% carbon), but is still widely used. In 1886 Hadfield patented silicon steel, that was intended for mechanical uses, e.g. springs. However, after 1900, it was discovered that silicon contents up to 6% increased the electrical resistivity (therefore reducing eddy electric currents and related Joule losses) and also narrowed the hysteresis loops (therefore reducing hysteresis losses and related losses), which made it ideal for iron cores and armatures of transformers, motors, and generators. Silicon steel sheets at 3%–4% began to be used in rotating and static electrical machines in 1902, initially in Great Britain and Germany. Scientific investigations on the metallographic properties of this alloy, e.g. anisotropy, were started in the 1930s.

Mechanical engineer Frederick Winslow Taylor and entrepreneur Maunsel White of the Bethlehem Iron Company, Pennsylvania, achieved a major development in 1898, when they perfected a high temperature quenching treatment that made steel alloys (in particular, tungsten-chromium) capable of maintaining their hardness at higher temperatures. Tools made of such high-speed steel (HSS) could cut standard steel at speeds of 18 meters per minute, which grew to 30 meters per minute by 1910, and at much greater cutting depths than previous tool steels. In the early years of the 20th century, vanadium steel was developed which presented high ultimate tensile strength and fatigue limit and found wide use in the rising automotive industry (gears, crankshafts, axles, ...), but also in tools and in other critical components. Molybdenum in content of 3%–4% was added to steel for tool steel, permanent magnets and also for heavy artillery and tank armours during World War I.

In 1912, Brenno Strauss and Eduar Maurer, two engineers of the German Krupp company, patented austenitic stainless steel, an iron alloy with chromium and nickel. A year later, a martensitic stainless steel was obtained by Harry Brearley in Great Britain, who was working on new special steels for firearms in Sheffield. It had an unusually high chromium content (>10%). In the same period stainless steels were also developed by Max Mauermann in Austria, by Léon Guillet in France and by Elwood Haynes in the United States. These steels proved able to resist erosion better than any other iron alloy and with other additional elements acquired different and often unprecedented properties, further expanding the use of iron.

Alnico, an iron alloy with aluminium (Al), nickel (Ni) and cobalt (Co) that was developed by T. Mishima in Japan in 1931, exhibited excellent magnet properties, having double coercivity than other magnetic alloys of the time. Nickel-chromium steels were developed for high temperature uses. One of them is Nimonic 80 alloy, which was developed in Great Britain in 1941 and was soon used in aeronautical gas turbine blades, which operated at 800 °C.

1.1.2.3. Electrolytic copper, communications and power transmission

In the 19th century, the traditional methods of refining copper with fire, improved over the millennia, were still suitable for producing good copper for domestic tools, burners of steam engines and for wrapping ship hulls, but not for the electrical conductors of dynamos, electric rotary machines and electric lines. Refining with fire provided a copper containing small quantities of arsenic, nickel and iron, which altogether amounted to not more than 0.1%, but were enough to reduce the electrical conductivity to 50%–70% respect to pure copper. Electrolytic refining was introduced shortly after the mid-century, in particular with a patent of James Balleny Elkington of 1865, who first industrialized it in Wales around 1885. The first American electrolytic copper refinery was established near New York in 1892. Copper electrolysis was produced by passing an electric current between two copper electrodes placed in a copper sulphate bath. Most impurities deposited on the bottom of the electrolytic bath as a mud from which precious metals often contained in copper ores, namely gold, silver, platinum, rhodium and iridium, were recovered. The process needed cheap electricity, that was generated by magnetoelectric machines capable of high electrical powers at low costs, which had come available after 1871. In this way, a synergy established: powerful electric generators allowed electrolytic refining of copper of unpreceded purity and conductivity and this copper was instrumental in the manufacturing of more powerful and efficient electrical machines, as well as in the construction of long electric lines for telegraph, telephone and power. At the turn of the century, copper with impurities of a few fractions per thousand was produced. In 1914 the International Annealed Copper Standard (IACS) was established that stated a conductivity of 58 MS/m for pure copper: it was obtained by leaving a very small content of oxygen (0.03%–0.05%) to capture residual traces of impurities, preventing these from affecting the conductivity of the copper.

American Telephone and Telegraph Company (AT&T) was founded in 1885, to develop long-distance lines. In 1899 it absorbed the mother company Bell Telephone Company and soon assumed a monopolistic position in the United States, remaining for many years the largest telephone company in the world. By using also electrolytic copper conductors of large cross-section, by 1887-89 it had laid several telephone lines that extended up to 700 kilometres. A 2,100-kilometer line was also built between Boston and Milwaukee, but it performed very poorly because efficient amplifiers were still missing. In the following decades, electrolytic copper was pivotal in the expansion of telegraph and telephone lines, submarine cables, as well as power lines, which extended to longer and longer distances, from the 11-km 10-kV 4-MW of the Deptford-London line of 1889, to the 180-km 110-kV of the

Stanislaus River–San Francisco line of 1908, to the 1000-km 1200-kV 6-GW of the Kasachstan-Tambow line of 1976 [20].

1.1.2.4. Electrolytic aluminium and airplanes

Aluminium has a much more recent story than copper and iron. It was first isolated in 1825 by Danish physicist Hans Christian Ørsted and two years later by German chemist Friedrich Wöhler. The first industrial production method was developed in 1854 by French chemist Henri Étienne Sainte-Claire Deville and consisted in obtaining alumina (aluminium oxide) from bauxite using caustic soda and then in obtaining aluminium through reduction by liquid sodium. The process was very expensive, so much so that the final aluminium cost more than gold and was only used to produce precious objects. It remained like that even when American chemist Hamilton Young Castner found a cheaper way of obtaining sodium, in 1888, and caustic soda, in 1890 [21].

When electromechanical generators capable of producing cheap electricity became available, after 1871, the method of producing aluminium by electrolytic reduction of alumina became practicable. The process was identified in 1886 by two men independently, Charles Martin Hall in America and Paul Louis-Toussaint Héroult in France, who were united by a singular twist of fate, in fact not only did they achieved their remarkable invention in the same year, but also were born and died in the same years, 1863 and 1914 [22]. Their method, called Hall-Hérault, made use of cryolite and alumina. It required high electrical currents at low voltage and 18–20 MWh of electrical energy allowed producing one ton of aluminium, which was enormously cheaper than the previous one, provided cheap electricity was supplied. Suddenly aluminium became an economic metal available for large-scale industrial exploitation, which promoted the great electrochemical industry. The Héroult cells began to be used in Neuhausen, Switzerland, in 1887 exploiting electrical hydropower produced at the local Rhine waterfall and the country remained the world's leading producer for several years. Hall formed the Pittsburgh Reduction Company in America in 1888, which exploited the low-cost hydropower of Niagara Falls. In 1907 this company became Aluminum Company of America (ALCOA), still an industrial giant. This companies made widely available a metal of incomparable lightness (its density is 2,700 kg m–3 compared to 7,874 kg m–3 of iron and 8,920 kg m–3 of copper), high electrical conductivity and high corrosion resistance. Aluminium and its improved alloys (duralumin, Y alloy, Aldrey, …) developed in the following century found important industrial uses and, notably, had a paramount importance in the expansion of the aeronautical industry, since early aluminium plane appeared during World War One, e.g., the Yunkers J.1 of 1918.

Starting from aluminium, the German chemist and industrialist Hans Goldschmidt invented the aluminothermic reduction process in 1895, which exploited the heat of the exothermic oxidation reaction of metallic aluminium with ferric oxide to produce cheaply metals such as chromium, manganese, molybdenum and tungsten (melting point 3422 °C) which were needed in high quality steel alloys and otherwise were hardly accessible. After a few years, thermite welding, that exploits the great heat of the aluminothermic reduction, was developed and alumina began to be used as an abrasive material for industrial grinding, thanks to its hardness, and as a refractory, thanks to the high melting point.

1.1.2.5. Tungsten, ribbon glass and the incandescent lamps

An attractive use for tungsten was the filament of incandescent lamps, because its high fusion point (3422 °C) promised much higher working temperatures and ultimately much more efficient lighting than carbon filament bulbs. But this use was elusive, because tungsten is brittle and non-malleable so that it refused drawing in very thin filaments [14]. A process for manufacturing tungsten filaments was first patented by Hungarian Sándor Just and Croatian Franjo Hanaman in 1904, who succeeded in drawing the metal. Tungsten bulbs were marketed that same year by a Hungarian company. William Coolidge, a researcher at the General Electric (GE) Research Laboratory, achieved independently a similar result in 1907. The high operational temperature allowed tungsten bulbs to reach a luminous efficacy of 8 lumen/watt, compared to 3.5 lumen/watt of carbon types. By exploiting the Coolidge process, GE produced bulbs which ensured an important energy saving and marked the definitive sunset of gas lighting. In 1913, Coolidge used his invention to perfect the tungsten hot cathode X-ray tube, which could be powered at lower voltages than cold cathode type and found wide use in medical diagnostics. A further major improvement in light bulbs was introduced in 1913 by Irving Langmuir, another research fellow at GE Research Laboratory, who devised the gas-filled incandescent lamp, using nitrogen first and argon later, which reached 12 lumen/watt and lasted longer than vacuum bulbs[2] [23]. Another major advancement of incandescent bulbs consisted in the ribbon machine developed by the American Corning Glass Works around 1926 to produce glass bulbs without welding very cheaply and on a large scale, at a rate of 300 pieces per minute (later tripled). The success of the technology was such that by 1970 all bulbs produced in the world came out of only 15 machines of this type. It was again GE to patent a practical tungsten lamp filled with halogen gas (iodine) in 1959, capable of 19–35 lumen/watt. Thanks to these technological advancements, incandescent bulbs achieved a huge success all throughout the 20th century. Their decline started in the new century, when LED lamps became available, capable of up to 170 lumen/watt. The EU and several other countries begun phasing-out them in 2009.

Fig.7 about here

1.1.2.6. Pure semiconductors and solid-state electronics

In the late 1940s an event occurred which had paramount consequences in the following decades, arriving to revolutionize information and electricity

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[2] Langmuir (1881–1957) had earned his doctorate in Göttingen, Germany, working with Nobel laureate Walther Nernst. Perfecting in Europe was quite common among talented American researchers of the time. After providing huge profits to the company with the gas-filled bulb, he was left free to develop his own research interests at GE, which was a happy choice, because his scientific creativity became prodigious. He pioneered the chemistry of surfaces, for which he was awarded the Nobel Prize in Chemistry in 1932, the first to an industrial chemist. He defined the chemical valence, introduced the concepts of covalence and ionic bonds, pioneered studies on ionized gases and introduced the term "plasma", now a central topic in nuclear fusion research. He invented the atomic hydrogen welding (AHW, capable of temperatures up to 4000 °C) and the thermionic probe (Langmuir probe). He studied methods of removing ice from aircraft wings and more … He registered 63 patents.

technologies. The electronics of thermionic valves, born in 1904-6, had allowed sensational developments in communications with radio, long-distance telephony, radar and television in the timespan of four decades, and very recently had paved the way to early fast digital computers, whose full potential was still substantially unexplored [24]. But thermionic valves were fraught with severe limitations: they were bulky, expensive, suffered relatively short lifetime and limited reliability and consumed a lot of power to heat the emitting filaments. Alternative solutions had long been explored, but with to practical success.

Fig.8 about here

In December 1947, two research fellows at Bell Labs, theoretical physicist John Bardeen and experimental physicist Walter H. Brattain, created a small device consisting of a semiconductor (germanium) base equipped with two gold-tipped electrical contacts, the emitter and the collector, that was capable to amplify an electrical signal and which they called *transistor* (from transfer resistor) [25]. A month later the group leader William B. Shockley built the first doped germanium junction transistor, building on previous research by others. Due to the strong antagonism between Shockley on the one side and Bardeen and Brattain on the other, the two devices were developed independently and all three inventors were awarded the 1956 Nobel Prize in Physics[3]. They anticipated by two months Herbert Mataré and Heinrich Welker, two German physicists who had been engaged in radar research during the war and who were working at a French company controlled by Westinghouse. These two physicists independently invented the contact tip transistor on a germanium crystal, which they called *transistron*. Western Electric put into production the germanium contact tip transistor in 1951 and Mataré founded Intermetall in Düsseldorf, to market it in 1952.

Obtaining very pure semiconductor was vital for the transistor reproducibly and for taking it to a commercial success. This hard challenge was won by Shockley, Gordon Teal and Morgan Sparks at Bell Labs in 1950, resorting to a process for producing single crystals that Polish chemist Jan Czochralski had invented by chance in 1916. Two laboratories independently developed the method for mass production of Shockley's junction transistors in 1952. In 1954 Morris Tanenbaum, also at Bell Labs, made the first silicon transistor and the same year Tael, who had passed to Texas Instruments, produced a silicon transistor that was immediately marketed by that company. Thanks to these developments, the transistor began gaining success from the mid-1950s, particularly in the United States, where it could rely on significant financial support from the US Department of Defense, which aimed at its potential military applications. As Nathan Rosenberg wrote: "The semiconductor industry represents perhaps the most relevant success story of the entire postwar period for the United States, in terms of government policies aimed at stimulating technical progress, as well as the growth of production and occupation"[26]. By the mid 1905s, the era of solid-state electronics had begun. The

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[3] Bardeen received a second Nobel Prize in Physics in 1972, with Cooper and Schrieffer, for the CBS theory of superconductivity. He remains the only person to have received two Nobel prizes in physics. Besides him, only three people have obtained two Nobel Prizes: Maria Sklodowska Curie, biochemist Frederick Sanger and chemist Linus Pauling.

transistor would become in a few decades the workhorse of almost all modern electronics, for signal conditioning, information processing and power applications, being capable of both signal modulation and of two-state switching. Its importance derives from the capability to be mass produced in highly automated processes at extremely low cost, which, together with its flexibility and reliability, have made it as ubiquitous as few other products.

The idea of a single device containing multiple electronic components was conceived and patented in 1949 by Werner Jacobi at Siemens & Halske, although with no practical developments. In the summer of 1958, Jack S. Kilby, a new employee at Texas Instruments, found himself working alone in the laboratory while his colleagues were on vacation. Taking advantage of the temporary freedom, he thought of building a transistor, three resistors and a capacitor onto a single germanium substrate of a few square centimetres. This was the first integrated circuit [27]. The following year, Robert Noyce at Fairchild Semiconductor created the planar version, easier to made and therefore suitable for low-cost large-scale production. The integrated circuit was another epochal breakthrough with a series of fundamental benefits:

- avoided circuit assembly and related working time, cost and error risk,
- drastically reduced the circuit sizes,
- drastically reduced supplying powers,
- paved the way for the circuit miniaturization,
- paved the way for new economic empires, of companies which could master the technology quicker.

The road to miniaturization had been envisaged by Richard Feynman in his prophetic lecture “There’s Plenty of Room at the Bottom”, held at Caltech (Pasadena, California) in December 1959. In the late 1960s computers had took the path and were in full expansion, thanks to integrated circuit technology and powerful machines were produced by big companies with IBM above all.

But some talented young people were at work to explore new frontiers. One of them was Federico Faggin, who had joined Fairchild Semiconductors in 1968 where he had designed the first digital integrated circuit based on metal-oxid-semiconductor (MOS) silicon gate technology (SGT). It allowed producing higher density integrated circuits (the so-called Large Scale of Integration, LSI), thus making possible semiconductor memories, in place of previous magnetic core ones [28]. In the same year, Robert Noyce and Gordon Moore left Fairchild Semiconductor and, supported by two venture capitalists, founded Intel Corporation (from INTegrated ELectronics), which had to become the world's largest manufacturer of integrated circuits in a few years. Faggin soon joined them to contribute in a more ambitious project, a new integrated circuit with a high number of miniaturized components, that had been designed by Marcian Edward "Ted" Hoff Jr., with contributions from Stanley Mazor (another past-Fairchild) and Masatoshi Shima of the Japanese company Busicom that had commissioned the device to use it in a new electronic calculator.

Fig.9 about here

Faggin devised the technology to implement the circuit and in less than a year made *Intel 4004*, the first microprocessor, or chip. It consisted of a silicon substrate of 13 mm2 housing a miniaturized digital programmable circuit of 2300 transistors that operated as a 4-bit logic unit with a clock speed of 108 kHz. It was a real central processing unit (cpu) enormously cheaper, smaller, more reliable and also more powerful than early electronic computers (e.g. ENIAC, 1945). Faggin showed that 4004 could be used for different applications, convincing Noyce to renegotiate the exclusivity with Busicom so as to freely market the chip in 1971, paving the way for a new era in computer science. He designed the 8008 at Intel, the first 8-bit cpu and then, the 4040 and 8080 models in 1974, the latter resulting in a huge success. Faggin left Intel in 1974 and co-founded Zilog, where he created Z80 in 1976, one of the most successful microprocessors ever and a direct competitor of the Intel 8080. After leaving Zilog in 1980, Faggin co-founded Cygnet Technology in 1982. In 1986 he was one of the founders of Synaptic, with Carver Mead, which he headed until 1999. Synaptic developed neural networks, which combine the capabilities of biological brains and electronic brains, starting with I-1000, the first neuronal chip capable of recognize handwriting, and created cutting-edge solutions in human-machine interfaces (touch-pad, touch-screen, ecc.).

On a close inspection, we can recognize that semiconductor technology, with its enormous impact, is largely due to a few people, who worked in close connection each other, a condition that had already happened in the past in other innovative technological sectors like modern metallic mechanics in England at the turn of the 18th century. In this case, the progenitor is William Shockley, who initiated this revolution when he created the research group at Bell Labs that built the first transistors in 1947–48. After bringing semiconductor technology to the San Francisco Peninsula, Shockley hired Moore and Noyce in his Shockley Laboratory in 1956. Both left one year later, as part of the "traitorous eight", to found Fairchild Semiconductors, where Noyce developed the first integrated circuit, independently of Kilby. After founding Intel in 1968, Moore and Noyce hired Hoff and Faggin, who created the microprocessor. All the latter contributed to creating innovative start-up companies, from which a part of the innovation continues to spring today. In this case also, those researchers formed a highly innovative school of excellence aggregated in a spontaneous way where knowledge spread apart of formal education. They formed a network of high-tech semiconductor companies, all located in the same limited area that began to be called Silicon Valley in 1971. Today it hosts many other companies, large and small, which operate also in different sectors, but always with a strong vocation for technological innovation. Silicon Valley is considered the Olympus of microelectronics and information technology, and of other engineering sectors. Several billion transistors are manufactured every year as single devices but especially inside integrated circuits (ICs, microchips, VLSI, …) with an estimated ca. 60 million per year for inhabitant of the Earth. The transistor has conquered areas traditionally dominated by other technologies: it is often easier and more convenient to use a microcontroller (a type of IC) and write a program into it to perform a control task, rather than to perform the same function with a mechanical controller.

1.1.2.7. Plastics

Only few lines are reserved here to the very large family of artificial materials based on polymers. Cellulose was the first raw material used to this aim, with increasing success along the 19th century. The process for pulping wood fibres was invented in in 1844, to produce cheap cellulose paper that was instrumental in popularizing press and books, and ultimately in mass alphabetization. Nitrocellulose, the first modern explosive, was invented by chance in 1846 starting a new era in these materials which had many major effects in peaceful activities and warfare. Celluloid was perfected in 1870, resulting in the first successful synthetic material. Viscose was also obtained from cellulose in 1884 and 1892 and was the first synthetic fibre, also marketed as artificial silk and Rayon. Cellophane, a very innovative wrapping material also suitable for insulation in electrical devices, was developed in 1908. Bakelite was an artificial material obtained instead from phenol and formaldehyde in 1907. Notably, it was the first one thermosetting (allowing easy shaping before hardening) and exhibiting extremely high electrical resistivity, good mechanical strength and heat resilience, for which it encountered a very wide use in electrical devices, but also in common-use objects.

However, the vast majority of industrial synthetic materials introduced in the 20th century were developed from coal first and hydrocarbons then, typically after very expensive research programs developed by huge companies. The most important among them were polyvinyl chloride (PVC, 1926), polyester (PS, 1930), neoprene (1931), polyethylene (PE, 1933), polyamide (PA, 1934), polymethyl methacrylate (PMMA, 1936), polyurethane (PUR, 1937–1942), polytetrafluoroethylene (PTFE, 1938), polycarbonate (PC, 1953), polypropylene (PP, 1955). These plastics often present exceptional properties and low costs resulting in huge industrial success and production amounting at tens of millions of tons per year, with 68 Mton/year of PP at the top. Undoubtedly, synthetic materials have a paramount importance in our everyday life, as we can realize just looking at an endless number of objects around us. Just to mention one, the Lego brick, which much stimulated our creativity and filled are playtime when we were children, are made of acrylonitrile butadiene styrene (ABS). The reverse of the coin is that, due to their durability, these materials have become major responsible for global pollution and plastic waste disposal only recently has emerged in all its dramatic importance, calling for wiser uses and quick global recycling policies. Ocean accumulations fed by rivers are an awful evidence: the Great Pacific Garbage Patch (GPGP), discovered in 1988, is estimated to extend over 1.6 million square kilometres.

1.1.2.8. The emergence of composite materials

Composite materials have a long history and bricks made from mud and straws are possibly the most ancient, having been documented in Egyptian frescos ca. 3,000 BCE. Concrete is another ancient composite, that, after being used by the other civilizations, was mastered by the Romans, as we have already seen. Composite bows made of horn and wood were in use in Eurasia during the Bronze Age and were later adopted by other civilizations, including the Roman Empire. The light and powerful short composite bow made with wood and organic fibres was developed in Central Asia in the 5th century CE and centuries later became the weapon of choice of Mongol mounted conquerors. Although thin layers of wood orthogonally glued were used by ancient Egyptians and Greeks, modern plywood was described only in a 1797 patent and was produced some fifty years later. However, few composites materials appeared overall before the industrial revolution, due to the limited number of raw materials which were available to be combined together. Reinforced concrete, that was introduced in France between 1850 and 1892, combined the tensile strength of cheap steel then available with the formability into complex shapes of concrete, opening new frontiers to architecture, civil engineering and art of constructions which spread during the following century. In recent years, several types of engineering wood have been developed, which are manufactured by binding or fixing strands, particles, fibres, veneers or boards of wood with advanced adhesives or other methods of fixation. They are used in a variety of technical and architectural applications, including buildings, covers, watercraft and furniture. Laminates are another family of composite materials, which include mallite, formica, plastic coated paper, arborite, micarta, etc. and are used in a vast number of applications.

Fig.10 about here

As regard mechanical applications, only in the 20th century, a major leap forward occurred starting with fibre reinforced plastic made with fibreglass and bakelite at Owens Corning Company in 1935. A more suitable impregnating resin was used by du Pont in 1936. Progress in fibre-reinforced plastics, made of a polymer matrix, occurred in the 1940s and they have evolved later into advanced composites. Fibre-reinforced plastic made with glass fibre (often called fibreglass) is relatively cheap, stronger by weight than many metals, chemically inert and electrically insulating, which make it suitable for a wide number of applications. Carbon fibre reinforced polymer is more expensive, but extremely light, stiff and strong, resulting in a material of choice in applications like aerospace, watercraft, automotive, civil engineering and sport equipment. In more recent years a number of different composites have been developed, including shape-memory polymer, high strain composites, metal matrix composites, ceramics matric composites, organic matrix/ceramic aggregates, sandwich-structured composites. In this evolution, the concept of metamaterial has emerged, namely a material that has a combination of properties not present in naturally materials. To do so, metamaterials consist of assemblies of several components made of composite materials. Typically, these materials are shaped in repeating patterns, having dimensions smaller than the wavelengths of the events they are designed to manage. It is this structure than provide a metamaterial with its smart properties, rather than the materials (metals, plastics, …) it is made from. Chapter 3 of this book provides a presentation of the possibilities offered by to 3D printing in producing numerically identified optimal shapes.

The optimized design of composite materials and metamaterials has attracted computational studies to which this most of this book is devoted [29]. In this way, composite materials head to became more and more performing compared to bulk materials. And even smarter, being capable of combining different functions, from sensing to actuation, from computation to communication [30].

1.2. Computing machines and computers

1.2.1. Ancient mechanical computing

The previous section on silicon and microprocessors introduces us to electronic computers. It is the case now to consider when computing tools where first used. This occurred with the abacus, far into antiquity and by different civilizations. The oldest known was used in the Akkadian Empire ca. 2200 BCE to compute sums and differences. The Egyptian used it in the 7th century BCE, the Chinese about the same time and the Greek a little later. Some remained in use until recent times in some cultures, allowing skilled user to execute complex computation at a sensational speed, e.g. the soroban, the Japanese evolution of the Chinses *suanpan*, introduced in the 14^{th} century CE. The *yupana* was a system of knots on strings used in the pre-Colombian Inca Empire.

Fig.11 about here

The Antikythera mechanism is an extraordinary device dated ca. 80 BCE that was recovered from a Roman shipwreck in 1902 [31]. It was a three-quadrant astronomical calculator capable of determining the position of the 5 known planets, the phases of the moon, the equinoxes, the months and days of the week, thanks to a complex kinematic system consisting of at least 30 gears including an epicycloidal one and a differential gear with ratio 235: 19, so as to reproduce Metonic cycle for which the moon that makes 235 sidereal revolutions every 19 tropical years. It witnesses the level reached by Roman-Greek mechanics that later went forgotten.

1.2.2. Mechanical calculators

In modern Europe, progress in computing machines was brought by the Scientific Revolution, starting with the sector, or proportional compass, that was shaped as a graduated calliper and was built in many models by several mathematicians, including Fabrizio Mordente, James Hood and Galileo Galilei. It anticipated the slide ruler, that was developed by William Oughtred in 1622 building on other's achievements, notably Napier's logarithms and bones. By resorting to clock technology, German Wilhelm Schickard built he first mechanical calculator of the modern world in 1624. It could perform the four arithmetical operations and was aimed at assisting Schickard's friend Johannes Kepler in his astronomical calculations, but went destroyed before delivery, in a fire during the Thirty Years War, and went forgotten for centuries.

Blaise Pascal was one of the most influential mathematicians, physicists and philosophers of the century, a follower of Galileo's theories and a great supporter of the existence of the void. At the aim of facilitating his father in the work as a tax collector, Pascal conceived a mechanical calculator at the age of nineteen in 1642. This device, that was based on cogwheels and came known as the Pascaline, could perform additions and subtractions [32]. It took Pascal three years of work to build it, and it was then replicated in some twenty units. Although not very efficient due to mechanical shortcomings, it gained popularity, spreading the idea of mechanical calculation and motivating other people to build similar machines, e.g. Tito Livio Burattini. Gottfried Wilhelm Leibniz was a prominent diplomat, philosopher, jurist and mathematician. From 1675 he developed infinitesimal calculus independently of Newton and in 1679 he studied binary arithmetic as pure theoretical speculation. Inspired by Pascal's machine, he undertook the construction of the Stepped Reckoner at the age of 25 in 1671. This was a calculator capable of performing all four arithmetical operations, thanks to the Leibniz wheel, a drum with stepped gears that he had invented. The machine was completed only in 1694, 23 years later. Again, Leibniz's invention motivated the construction of similar calculators, e.g. by Giovanni Poleni in 1709, who used an alternative mechanism to the Leibniz wheel.

These replications must not surprise, because they were the effect of the spread of scientific information nurtured by the promoted by the Scientific Revolution.

Fig.12 about here

Building on Leibniz's device, the Frenchman Charles Xavier Thomas de Colmar made and patented a mechanical calculator named the *arithmometer* in 1820. De Colmar presented it at the Great Exhibition of Crystal Palace in 1851 and then successfully industrialized it. It was improved repeatedly and was produced in several thousand units by 1915: it was the first successful and widely used calculator.

The American inventor Frank Stephen Baldwin devised an alternative mechanism to the Leibniz wheel, based on two coaxial wheels for each digit, and used it in a mechanical calculator built in 1873. A similar device was brought to success by the Swedish instrument maker Willgodt Theophil Odhner in 1875 which was superior to de Colmar's calculator and was also called *arithmometer*. By 1918, when production ceased, Odhner's calculator, had been made in about 23,000 units. After patent expired in 1907, it was replicated in several clones. Other successful mechanical calculators of the time were the *Brunsviga*, built in Braunschweig, Germany, from 1892, and the *Saxonia*, built from 1895. In 1887 the Swiss Otto Steiger (1858-1923) built a different type of mechanical calculator, called *Millionaire*, which performed multiplications by automating the method of Napier's bones and could divide and extract the square root.

Other mechanical calculators were the hand-cranked Burroughs *adder*, built in the United States in 1886 by William Seward Burroughs I, and the *comptometer*, a keyboard adder built in the United States by Dorr Eugene Felt at the age twenty, which was put into production in 1887. The keyboard drive was easily motorized and the first model powered by an electric motor appeared in 1906. Mechanical calculators were widely used in the 20th century, until the advent of electronic calculators and programmable computers.

1.2.3. Mechanical and electromechanical computers

Charles Babbage was the visionary mathematician who first conceived a programmable computer. In 19th century, logarithm tables were needed in several scientific and technical computations and were hand-calculated based on polynomial expansions. But these calculations, performed manually by people called computers, were prone to frequent errors. Together with friend astronomer John Herschel, Babbage envisaged a mechanical alternative in 1822. Babbage knew that a polynomial of a suitable degree n can properly approximate any differentiable function, according to Taylor's theorem, and that a polynomial $p^n(x)$ of degree n presents equal n-order differences at constant increments of x. He devised a mechanical calculator, that was and capable of calculating automatically differences up to the sixth order of twenty-digit numbers, to exploit that principle. He called it the *Difference Engine*. Supported by a substantial government funding of 1,700 pounds, Babbage undertook the construction of the 25,000-part machine, initially assisted by Joseph Clement, one of the finest British mechanical engineers of the day. For 14 years, with a stop of five, Babbage worked on the grandiose project, without bringing it to completion, despite the government funding had risen to £17,000 in the while, a colossal amount, as much as the cost of two warships.

Babbage resumed the project in 1847–48 with the *Difference Engine No. 2*, which also was never completed, but which was built in 1989–91 at the Science Museum, London, based on the original design and resorting to the mechanical technology of the time, thus demonstrating that Babbage's idea was feasible. The machine can provide results to an accuracy of 31 digits. Starting from 1832 Babbage to conceive a much more advanced machine, called the *Analytical Engine*, which could be programmed to perform automatically any desired algorithm. Babbage devoted himself to this project from 1837 and, although working for the rest of his life, he never completed it. It had to be a programmable computer based on mechanical technology. The program was provided through punched cards borrowed from the Jacquard loom of 1804 and was placed in the store (today we call it memory) capable of 1000 numbers of 50 digits. The mill (now we say central processing unit) performed the four operations, the square root, comparison operations, sequential control, loops, and conditional branching. Lady Ada Byron, daughter of the poet and countess of Lovelace, and a fine mathematician, wrote for the *Analytical Engine* an algorithm capable of calculating Bernoulli numbers. This is now considered the first computer program and Lady Lovelace the first programmer [33].

The Swedish lawyer and inventor Per Georg Scheutz and his son Edvard took up Babbage's idea of the Difference Engine in 1843 and arrived to build an operating model that was presented at the 1855 Paris World Exhibition and was sold to British Government in 1859. A second model, built in 1860, was sold to the United States Government for use in the Albany Astronomical Observatory (New York). The Scheutzs published the first mathematical tables elaborated by means of a machine.

There is a couple of reasons for citing the tabulating machine built by Herman Hollerith in 1889, that successfully automatized the US Census operations of 1890. One is that it was the first device that used electricity for data processing. In fact, it used electric contacts through the holes of Jaquard-like punched cards, which closed an electric circuit to increment a counter, recording information. The other reason is that the Tabulating Machine Company that Hollerith founded in 1896 to exploit his invention eventually evolved into the International Business Machine (IBM) in 1924.

The idea of a computer capable of executing complex calculations re-emerged in the 1930s in two different concepts, the analog computer and the digital computer. Both were initially pursued with mechanical and then electromechanical technology. In the first includes the *differential analyzer* built by Vannevar Bush and coworkers starting in 1928, that consisted of wheel-and-disc mechanisms and could solve systems of differential equations with 18 unknowns, a mathematical problem inaccessible by hand [34]. It gained good success, being replicated in several units. The electromechanical digital computer was first conceived in America by George Stibitz, who, after a first simple prototype made at home with spare parts (the Model K, from kitchen) of 1937, built the Complex Number Computer (later renamed Model I Relay Calculator) with Samuel Williams at Bel Labs in 1940. This was a programmable binary electromechanical computer made of 3,000 relays and 800 kilometres of connections. It could compute complex algebra algorithms with conditional branching. On the occasion of a demonstrative test, it was used in the first telematic link, over a distance of 360 kilometres. Howard Hathaway Aiken, a reputed mathematician at Harvard University inspired by Babbage's Analytical

Engine, built ASCC (Automatic Sequence Controlled Calculator) between 1937 and 1944, with financial and technical support by IBM. This remarkable electromechanical digital computer, later renamed Harvard Mark I, was conceptually similar to Babbage's machine, though less ambitious, being able to memorize 72 numbers of 23 digits plus the sign. And it was programmable, indeed the first American memorized-program machine. This 16-meter long 4.5-ton calculator consisted of 765,000 electrical and mechanical components and 800 km of electrical connections. Data input resorted to IBM punched cards and the program was loaded onto a punched paper ribbon. It could tackle any mathematical-scientific problem, at the speed of a multiplication in 6 seconds and a division in 15.3. During the war it was used by the U.S. Navy to perform cumbersome ballistic calculations and by John von Neumann within the Manhattan project.

Unaware of American projects, Konrad Zuse took the same path in Germany, to cope with the calculations he had to face in aeronautical designs. He constructed a programmable binary mechanical computer, later known as *Z1*, which was completed in 1938 [35]. It had keyboard data input, a processing unit, a memory unit and a punched-card control unit. In 1940, he built a second machine, *Z2*, of the electromechanical type, because based on relays thus resulting more efficient than Z1. Zuse completed a third machine in 1941. *Z3* was a more advanced model that worked in floating point and was Turing-complete, although Zuse ignored Alan Turing's computational theories. Indeed, *Z3* was the first fully operational programmable computer. After that these machines went destroyed by bombing during the War, Zuse started building a more advanced model in 1942, *Z4*, which was completed after the war and sold to ETH, the Zurich Polytechnic, in 1950, becoming the first operative computer to be marketed. Zuse's machines were conceptually superior to contemporary American electromechanical machines and much more compact.

1.2.4. Wartime electronic computers

Electromechanical computers built on two-state relays were naturally suited for handling digital logics and Boolean algebra, as Claude Shannon had theoretically proved in his famous MIT master thesis *A Symbolic Analysis of Relay and Switching Circuits* published in 1938 [36]. At that time, most specialists did not believe that electronic valves were a viable option. But John Vincent Atanasoff, a young physics professor at Iowa University, toyed with the idea in 1936. He started building a binary computer assisted by fresh engineer Clifford Berry and the machine was partially completed when Atanasoff was called into active military service in 1942. Later called ABC (Atanasoff-Berry-Computer), it was the first computer in the world resorting to electronics, since it used 300 vacuum valves as fast switches and a memory of 1,600 capacitors, capable of thirty 50-bit numbers, but had also electromechanical parts and rotating drums hosting the capacitors. Data entry resorted to punched cards, and the machine operated in binary digital logics. it was designed to compute systems of linear partial differential equations (PDEs), up to 29 and the solution took 15 days. Consequently, it was not general-purpose programmable.

Coding and codebreaking had a major part in World War Two. In this framework, Alan Turing and co-workers at the Government Code and Cypher School at Bletchley Park, UK, had built a complex electromechanical deciphering machine, called Bombe. When Nazi codes became more complex, code breaking with such machines resulted too long. Tommy Flowers, an electrical engineer at Bletchley Park, thought of a computer made only of electronic switches, understanding that they were much faster than relays and sufficiently reliable in that use. A design team led by Flowers and mathematicians Alan Turing and Max Newman was formed, who completed Colossus in December 1943. Specifically designed for codebreaking, it was the first fully electronic computer, consisting of 1,500 valves. Consequently, it was much faster than electromechanical machines [37]. In June 1944 a more powerful version was completed, Colossus Mark 2. Given their strategic importance, these machines were kept under military secrecy for many years after the war. They were declassified only in the 1970s, their designers having been long deprived of public recognition.

Aware of Atanasoff's work on ABC, Physicist John William Mauchly and engineer John Presper Eckert of the University of Pennsylvania's Moore School of Electrical Engineering conceived a fully electronic programmable computer in 1941. In view of its potential to quickly compute complex ballistic calculations for the U.S. Army, it was funded and classified under military secret. The construction of ENIAC (Electronic Numerical Integrator And Computer) begun in 1943 and ended in 1946. This 30-ton machine occupied 200 square meters, consisted of 18,000 vacuum valves and 70,000 resistors and consumed 250 kW of electrical power. It operated in decimal digital logic and had a memory of only 20 numbers of 10 digits, much less than Aiken's Harvard Mark I. But it was the first fully electronic general-purpose programmable computer and, performing an algebraic operation in 10–4 seconds, it was 100 to 1000 times faster than electromechanical machines. In thirty seconds, it could perform a ballistic calculation which took twenty hours with traditional methods. But it was not very rational: programming was done by manually acting on connections and switches, which took a long time and was prone to errors. It found large use in postwar activities for over ten years, particularly in science and statistics and within the hydrogen bomb project.

Fig.13 about here

After developing a deep analysis of ENIAC shortcomings with Mauchly and Eckert, John von Neumann wrote the *First draft of a report on the EDVAC* in 1945, where he proposed a conceptual scheme consisting in a single memory for data and program, to be used in EDVAC, the next project of Mauchly and Eckert [38]. This concept, that had actually already been used by Babage, Zuse and Aiken, constitutes what became known as the Von Neumann architecture and is now adopted in all computers. Incidentally, the premature distribution of the *First Draft* later nullified the patent claims of EDVAC by Mauchly and Eckert.

1.2.5. Generations of electronic computers

In the early postwar period, existing technical background merged with von Neumann architecture to give life to the first generation of programmable digital electronic computers, both in Great Britain and in the United States.

Building on Aiken's Harvard Mark I experience, IBM started the SSEC (Selective Sequence Electronic Calculator) project in 1944 and completed it in February 1948. This was a gigantic machine that conformed the principles of

Babbage's analytical engine and von Neumann architecture, then a consultant to the company. Being both electromechanical and electronic, it was not very fast, but it was the first computer that performed both accounting-commercial and scientific calculations. It was used only for demonstration and advertising purposes: it remained on display in Manhattan, to exhibit the technological capabilities of IBM, which thus gave a clear signal of its interest in the rising information technology.

The first stored program digital (binary) electronic computer was SSEM (Small-Scale Experimental Machine), also called Baby. This was a small demonstrative machine completed in 1948 at Victoria University in Manchester by a group led by Frederic C. Williams and Tom Kilburn. It had an original memory device, the Williams tube, which was a special cathode ray tube. Baby was not intended for operational use, but served to demonstrate the feasibility of the concept, after that the Manchester Mark 1 was built, which was operational in June 1949. Alan Turing worked on its software. The Ferranti company built its commercial version, Ferranti Mark 1, and put it on sale in February 1951, thus becoming the first commercial electronic computer[4]. The Williams tube enjoyed some success for a few years, being adopted in computers built also in California, Sweden and the Soviet Union.

The first operational stored program (i.e. with von Neumann architecture) digital electronic computer was EDSAC (Electronic Delay Storage Automatic Calculator), which was built by the group of Maurice Wilkes at the University of Cambridge and started operation in May 1949, before Manchester Mark 1. EDSAC had a memory of 512 words (used for data and instructions) of 34 bits each, made with a delay line technology, just devised by Eckert. It consisted of tubes filled with mercury and with a transducer at one end that converted an electrical impulse (representing a bit) into a sound. This took some time to travel along the tube at the speed of sound and at the other end it was converted into an electrical impulse by a second transducer. By continuously entering the lines, data remained stored. EDSAC used groups of subroutines and routines which were assembled to make programming work easier. The idea proved fruitful and the use of assemblers spread. The same technology was used for the 384-word 32-bit memory of Pilot Model ACE (Automatic Calculating Engine), which was built at the British National Physical Laboratory under the lead of Alan Turing and became operational in May 1950. It had a very rational design, that used 1,000 vacuum tubes only.

After completing ENIAC, Mauchly and Eckert left the EDVAC project at the University of Pennsylvania and founded the Eckert – Mauchly Computer Corporation (EMCC) in 1947, to commercially exploit their know-how. They built BINAC (Binary Automatic Computer) for Northrop Aircraft Company and delivered it in 1949, but this machine never became operational. Due to financial difficulties, the company was absorbed in 1950 by Remington Rand, then a producer of office machines. In 1951 EMCC built UNIVAC I, an electronic computer with von Neumann architecture, for which Eckert created the delay line memory (first adopted in EDSAC). For data input and output UNIVAC I used magnetic tapes, borrowed from sound recording technology, which ensured much shorter access times than punched cards, a bottleneck two to three thousand times slower than electronic processing. The first UNIVAC I was placed on the market in March 1951

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4 After that Zuse had sold Z4 to the ETH, Zurich, in 1950.

and entered service in June (after Ferranti Mark 1). The fifth UNIVAC I was used by CBS in the exit polls of the 1952 presidential election and predicted Eisenhower's victory with a sensational accuracy. In 1955 Remington Rand merged with Sperry Corporation to become Sperry Rand, which in the 1960s was a major IBM main competitor.

Jay Forrester, a professor at MIT, envisaged of making the electronic computing capabilities available on a video output, in order to obtain real-time virtual simulator for training US Air Force pilots, a valuable device in the growing Cold War condition. Whirlwind was operative in 1951, used a cathode ray tube as a monitor and 6,000 thermionic valves. It had a 1,000-word 16-bit RAM (Random Access Memory) of the dielectric type, to ensure very fast access times, but this memory was not satisfactory so that the more performing magnetic memory was developed in 1953. It used matrices of 1024 small toroidal magnetic cores placed at each intersection of a double grid of 32×32 wires capable of magnetizing the cores in two opposite directions, thus storing a bit, and to read the state of magnetization. With these cutting-edge solutions, Whirlwind became the progenitor of the computers used by the SAGE defence system of the US Air Force and of the commercial computers of the 1960s.

These machines, based on valves and different types of memories, constituted the first generation of electronic digital computers which met the demand of a new rising market. The second generation used transistors, ferrite core memories and high-level languages. The first of them was a demonstrative machine made by Tom Kilburn at Victoria University of Manchester in 1953 using germanium point-contact transistors, but also vacuum valves. TRADIC (TRansistorized Airborne DIgital Computer), the first American transistorized computer, was made at Bell Labs in 1954, using 800 transistors and vacuum valves. It was used aboard military aircrafts. The first fully transistorized models, in 1955-58, were CADET of Atomic Energy Research Establishment of Harwell TX-0 built at MIT, Mailüfterl, created at the Vienna Polytechnic with the support of Philips company, Japanese ETL Mark III and Canadian Defense Research Telecommunications Establishment Computer.

The first fully transistorized commercial computer, Metrovick 950, was produced in 1956 by Metropolitan-Vickers in the UK. Shortly thereafter, other companies came out with their transistorized models: IBM with model 7070 sold at US$813,000 in 1958 and model 7090 sold at US$2.9 million in 1959; Sperry Rand with UNIVAC Solid State in 1958; Siemens & Halske with model 2002 in 1959; Digital Equipment Corporation (DEC)[5] with PDP-1 that priced "only" US$120,000 in 1959; Olivetti with Elea 9003 in 1959. Generally speaking, these machines were 10 times cheaper, faster, more powerful and more reliable, and 100 times smaller and less consuming than vacuum valve models. The computer market grew very rapidly and 26 companies in the United States, 7 in Great Britain, 3 in Germany, 2 in Holland, 1 in France and 1 in Italy were competing by 1960. The technological and commercial policies of some US companies were so effective that they achieved a dominant position in the international market. IBM, although not the most technologically innovative, was able to increase its market share more than others, reaching 70% in 1960.

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[5] DEC was a MIT spinoff created in 1957 to exploit the TX-0 know-how.

The third generation appeared around 1964 featuring integrated circuits, semiconductor memories (which were a kind of integrated circuits) and operating systems. Multitasking and time sharing became common in these computers, which prevented long waiting queues and allowed real time operation at video terminals. The most significant products were American. IBM announced the 360 system, a family of differently sized machines, in 1964. A model with a computing speed of 500 KIPS (kilo instructions per second) and a power of 256 kB (kilo bytes) priced US$111,000. DEC marketed PDP-8 in 1965, with a computing speed of 300 KIPS and a power of 6 kB, which cost US$16,000. It was the first successful minicomputer, sold in 50,000 units. Typically, these machines were 100 times faster and cheaper, 1000 times smaller, more powerful and more reliable and 1000 times less consuming than vacuum valve models of the first generation.

1.2.6. Supercomputers

Supercomputers are extremely powerful machines aiming at extreme performance. The first was Atlas, built at the University of Manchester in 1962 and capable of 1000 KIPS. The guru of these machines was Seymour Cray, who built CDC 6600 at Control Data Corporation (CDC) in 1964, performing 2 MB RAM and 10 MHz clock rate, that priced US$7 million. Cray founded Cray Research Inc. in 1972 and produced Cray-1 in 1976, which used 200,000 integrated circuits and an innovative architecture to achieve performance then fantastic: 80 MHz clock rate, 8 MB RAM, 80 MFLOPS (millions of floating-point operations per second) speed and 303 MB secondary storage. It was sold at US$8.8 million and was very successful.

Fig.14 about here

Microprocessor, starting with Intel 4004, revolutionized the computer world, allowing personal computer to be built and extreme powers to be increasingly achieved. Compared to Cray 1 of 1976, an iPhone 11 of 2019 is capable of 2.66 GHz, 4 GB RAM, 512 GB secondary storage and prices some hundred dollars. On the other hand, supercomputers have established new records. Today, Fujitsu Fugaku, that started operation at Kobe, Japan, in 2020, boast a speed of 415.5 PLFOPS (millions of billions of FOPS). It outperformed IBM Summit of Oak Ridge National Laboratory that is capable of 148.6 PLFOPS and was put into service in 2018. The growth in computing power has revolutionized the exploitation of accurate mathematical models in science and engineering, and subtle numerical methods which allow implement very detailed models of the real world. In this way, supercomputers have a disrupting impact in scientific research and technological development, allowing extremely intensive computations in various fields, including quantum mechanics, weather forecasting, climate research, oil and gas exploration, molecular material modelling, physical and engineering simulations and cryptanalysis.

1.2.7. Software

The first high-level programming language, *Plankalkül*, was developed by Konrad Zuse for Z4 in 1943–45. With the emergence of von Neumann's architecture, the need for similar programming languages quickly emerged also in Great Britain and the United States. The first British was *Autocode*, developed for Manchester Mark 1 in 1952. In America, the first person to deal extensively with high-level programming languages was Grace Hopper, a former programmer of Aiken's Harvard Mark I [39]. Hopper joined Eckert-Mauchly Computer Corporation (MECC) in 1949 to work on UNIVAC I, developing *A-0*, the first American compiler, in 1951. Building on *A-0*, she directed the development of *MATH-MATIC* in 1955–1958 and *FLOW-MATIC* in 1955–1959, which were the first compiler-based languages intended for scientific and business computing, respectively.

In 1954–1957, John Backus of IBM developed *FORTRAN* (Formula Translator) for scientific computing. Continuously improved, it is still widely used more than sixty years after its birth. A similar success has LISP, a family of languages created by John McCarthy at MIT in 1958, which has been and is used preferentially in applications of Artificial Intelligence, a term coined by McCarthy.

ALGOL (ALGOrithmic Language), the first version of which was written by the Dutch Edsger W. Dijkstra in 1958, was a family of languages written on rules established and shared by American and European researchers. It was an important step towards the creation of an international computer language. In 1959, Hopper promoted the creation of a working group formed by companies and research institutions to create *COBOL* (COmmon Business-Oriented Language), based largely on *FLOW-MATIC*. It was conceived specifically for accounting and business calculation and was also the first capable of running on different computers, albeit in different versions, called dialects.

Operating systems, capable of managing hardware and of providing basic functions, appeared in the 1960s, particularly with the IBM 360 series machines, and allowed computers to perform multiple functions and instructions simultaneously. In 1972, Kenneth Lane Thompson of Bell Labs developed the first version of the UNIX cross-platform operating system, which quickly became an industry standard, suitable for heterogeneous applications such as Computer Aided Design (CAD), numerical control machine systems and numerical simulations. In 1991, Finnish Linus Torvalds released Linux, the kernel of open-source Unix-like operating systems, which are now provided by the GNU Project. In 1994, a group of researchers led by Canadian James Arthur Gosling produced JAVA, the programming language for multi-platform networked applications. While progress in software remains parallel to that of hardware, programming languages and operating systems have greatly simplified the writing of computer programs, reducing development time and errors and simplifying debugging.

1.3. Numerical methods

1.3.1. Numerical methods in antiquity

Numerical approximation is as old as mathematics. Babylonian mathematicians of the 18th–17th centuries BCE could compute the square root of two with an accuracy at the 6th digit. An iterative method for computing square roots was conceived by Archytas of Tarentum, a Greek stateman, mathematician and philosopher living in Magna Graecia in the 4th century BCE and the great Archimedes of Syracuse, also in Magna Graecia, computed π at the third digit in 3rd century BCE. Liu Hui, a Chinese mathematician living in the same century, explored iterative processes and

Chinese mathematicians of the 2nd century CE used the elimination method to solve systems of three linear equations (what became much later known as Gauss elimination).

Fig.15 about here

Zu Chongzhi, another Chinese mathematician living in the 5th century CE, computed π at the seventh digit, a precision that remained long unparalleled. After than early forms of linear interpolation were used by Babylon astronomers and by Hipparchus of Rhodes, both in the Hellenistic period, second order interpolation was first used in China by astronomer Liù Zhuó around 600 CE and third order interpolation was used again in China around 1280 CE. In the same period Chinese mathematician Zhū Shìjié explored early finite-difference computation. In India, second order interpolation was proposed ca. 625 CE by Brahmagupta, who also introduced zero, negative numbers and their algebra in the decimal positional numbers, thus giving a fundamental contribution to the Hindu-Arabic numeral system. Parabolic interpolation schemes were used by Persian mathematicians al-Bīrūnī in the 11th century [40].

1.3.2. Numerical methods in the early modern period

Persian mathematician al-Kashī was able of going further, computing π at the sixteenth digit in the 15th century. Many others improved this computation later, notably with Austrian astronomer Christoph Grienberger reaching 38 digits in 1630 by means of a polygonal approximation, that still remains a record for manual computation. The Euler number e was discovered by Jacob Bernoulli in 1683, and was later computed with increasing precision, starting with Roger Cotes who reached 13 digits in 1714, Leonhard Euler with 23 digits in 1748, John von Neumann with 2010 digits on the ENIAC in 1949 and Steve Wozniak with 116000 digits on Apple II in 1978, to cite a few.

Isaac Newton described the eponymous iterative method for finding the root of a real-valued function, $f(x)=0$, in 1669 and proposed an early form of polynomial interpolation and the minimal resistance problem, namely an early approach to the calculus of variations, in his *Prinicipia Mathematica* of 1687. In Europe, an early polynomial interpolation formula was proposed also by British Edward Waring in 1779 and the same result was published by Italian-French Joseph-Lois Lagrange in 1795 to whom it is now usually attributed. It is also a corollary of a formula published by Leonhard Euler in 1783, who also proposed the eponymous single step method in 1768–1780. This is a first-order numerical procedure for solving ordinary differential equations (ODEs) with a given initial value occurring in problems of celestial mechanics [41], and was later encountered in modelling chemical reaction rate, electrical circuits, … In addition, Euler first formalized and named the calculus of variations in 1756, building on previous results by Lagrange [42].

1.3.3. Numerical methods in the modern period

In the 19th century, advancement in the interpolation theory were proposed mainly by Augustin-Louis Cauchy and Charles Hermite in France and by Carl W. Borchardt and Leopold Kronecker in Germany. Late in the century and in the beginning of the next, approximation theory was developed, with major contributions by Germans Karl Weierstrass, Carl Runge and George Faber, French Charles Méray and Hungarian Lipót Fejér. In the first part of the 19th century several physical phenomena developing in continuum media were formulated in mathematical models consisting of partial differential equations (PDEs) of elliptic form (e.g. Poisson equation), parabolic form (e.g. diffusion equations, Fourier heat conduction equation, Navier–Stokes equations for fluid-dynamics) and hyperbolic form (e.g. wave equations, Maxwell electromagnetic wave equation). The solution of PDE systems called for new numerical tools.

Carl Friedrich Gauss was likely the first to propose an iterative method for a solving system of linear equations, now known as Gauss elimination, between 1798 and 1810. It consists in a sequence of operations to modify the matrix of coefficients until a lower triangular matrix is obtained. The theory of system of linear equations progressed greatly in the 19th century, starting with German mathematician Hermann Grassmann, and then progressing with the work by British and French scholars such as James Joseph Sylvester, who introduced the term matrix, Arthur Cayley, Augustin-Louis Cauchy, and William Rowan Hamilton, who took the matrix and determinant concepts to maturity. The Gauss-Jordan elimination is an improvement with contribution by German geodesist Wilhelm Jordan. The Gauss-Seidel method and the Jacobi methods are also iterative schemes for solving systems of linear equations, the former being due to improvements by Phillipp Gustav von Seidel (and inappropriately attributed also to Gauss) and the latter was proposed by Carl Gustav Jacobi within celestial mechanics investigation [43]. All these German mathematicians were active in the 19th century. At the mid of that century, Ada Lovelace, inspired by Babbage's Analytical Engine, conceived the algorithm for computing Bernoulli's numbers, as already mentioned. During the 19th century, important progress occurred also in the calculus of variations for the search of maxima and minima of functionals [44].

Building on Euler single-step method, British astronomer John Couch Adams and coworkers developed multi-step methods for solving ODEs in the 19th century. Similar work was done by German mathematicians Carl Runge and Martin Kutta, who developed the eponymous family of implicit and explicit iterative schemes for the approximate solution of ODEs encountered in studying aerodynamics around 1901.

1.3.4. Numerical methods in the 20th century

The early decades of the 20th century saw new steps ahead toward the establishment of numerical analysis. Important progresses were made on series convergence. In 1909, the Swiss physicist Walther Ritz developed the variational method for solving partial differential equations (PDEs) related to acoustic and elasticity, that consisted in converting the differential problem into the solution of a matrix equation and anticipating the finite element method. The method is now credited (unproperly) also to John W. Strutt (Lord Rayleigh). In 1915, Russian engineer Boris Galërkin published an article in which he proposed an approximate method for converting a differential equation to a discrete problem by using weak formulations of the original problem, which later became seminal to the development of discretization approaches such as finite element methods and spectral element methods.

Applied mathematics boomed in America from the 1930s, mainly due to two events. On the one hand, from the late 1930s analog computers and then digital ones became operative which provided much more computing power than previous tools. On the other hand, refugees escaping Nazi Germany and controlled countries stated arriving from the 1930s. One of them was Richard Courant, who gave a major contribution to wartime mathematical investigations. Generally speaking, a revolution occurred in numerical analysis in the 1940s, as a consequence of the participation of large numbers of mathematicians in war efforts (especially in USA, Germany and USSR), such as the Manhattan Project that aimed at constructing the atomic bomb and the development of the electronic computers, with their superior computing speed, as we have already noted.

An early development in linear programming (i.e. optimization in linear system) was proposed by Soviet economist Leonid Kantorovich in 1939 for reducing costs in the army and increasing losses imposed on the enemy. Similar work was developed by Dutch-American economist Tjalling Koopmans, for which the two shared the 1975 Nobel prize in economics. In 1947, American mathematician George Dantzig and John von Neumann proposed the simplex method to tackle linear programming problems, particularly in finding the best assignment of 70 people to 70 jobs. The Monte Carlo method resorts to randomness to solve complex deterministic problems and Italian-American physicist Enrico Fermi first experimented it in studying neutron diffusion, without publishing [45]. Polish-American physicist and mathematician Stanislaw Ulam used the Monte Carlo method in the late 1940s to solve hydrodynamic problems encountered while working on the hydrogen bomb. John von Neumann contributed further developing the method and implementing it in ENIAC.

American Claude Shannon published the sampling theorem in his celebrated paper on information theory of 1948 [46], that actually had been previously presented in the Soviet Union by Vladimir Kotelnikov and outlined earlier by Herbert Raabe in 1939. Someya introduced the theorem independently in Japan in 1949. Spline interpolation was introduced by Romanian-American Isaac J. Schoenberg in 1946 and consists in fitting low-degree polynomials to small subsets of the values instead of fitting a single, high-degree polynomial to all of the values at once. While Shannon sampling theorem has major applications in communication and signal engineering, splines are largely used in approximation, interpolation, numerical analysis, and other branches of mathematics. In addition, splines are largely used in computer-aided geometrical modelling and geometric design, computer graphics, medical imaging and other computer applications.

John Crank and Phyllis Nicolson proposed the eponymous method in 1947 [47], which is a finite difference method for solving parabolic partial differential equations (PDEs) such as the heat equation. It is of the second order and implicit in time, that can be written as an implicit Runge-Kutta method, resulting numerically stable and often unconditionally stable, e.g. in the case of diffusion equations. A procedure for checking the stability of finite difference schemes was then applied to PDEs, resorting to Fourier decomposition, was developed at Los Alamaos National Laboratory and then rigorously formalized by John von Newmann and coauthors [48].

A milestone in modern numerical linear algebra consisted of the study by John von Neumann and American mathematician Herman H. Goldstine on roundoff error analysis of matrix factorization and inversion methods, where the concept of condition number k(A) of a symmetric positive defined (SPD) matrix with respect to inversion was introduced [49]. Alan Turing developed a similar analysis for Gaussian Elimination in 1948.

The Institute for Numerical Analysis, established on the UCLA campus in 1947, had a pivotal role in the development of the discipline, because INA attracted a stream of internationally recognized applied mathematicians, promoting their fruitful cooperation [50]. They included George Forsythe, Isaac Schoenberg, Olga Taussky-Todd, John Todd, Magnus Hestenes, and Eduard Stiefel. Among them was also Hungarian mathematician Cornelius Lanczos, who conceived the eponymous algorithm in 1950 to find the most useful eigenvalues and eigenvectors of a Hermitian matrix [51].

1.3.5. Computerized numerical methods

Numerical methods soared after 1950, when electronic computers started providing full benefits of their power. American mathematician David M. Young pioneered the theory of stationary iterative methods in the 1950s, now used in the numerical solution of large sparse linear systems of partial differential equations (PDEs), notably leading to the development of the methods of successive over-relaxation (SOR) in computer applications, a variant of the Gauss-Seidel method, and later of the symmetric successive over-relaxation (SSOR) method by Young and Stanley Phillips Frankel.

Cornelius Lanczos and, independently, American Magnus Hestenes and Swiss Eduard Stiefel conceived the conjugate gradient (CG) method around 1950–1952. Stiefel implemented it in Zuse's Z4, at the Institute of Applied Mathematics of ETH, Zurich [52]. The method resulted suitable for system of linear equations with symmetric positive-definite (SPD) matrixes, working well in the case of sparse systems. It resulted also suitable for unconstrained optimization problems. In the 1970s it became well known that conjugacy-based methods work very well for PDEs, especially of the elliptic type, such as the Laplace equation $\Delta u=0$ and the Poisson equation $\Delta u=f$.

In 1953, Greek-American mathematician Nicholas Metropolis and others proposed a Monte Carlo method named Metropolis-Hastings algorithm to generate sample states of a thermodynamic system [53]. From this algorithm, the simulated annealing method was eventually derived, that is a stochastic approach to search the global optimum of an optimization problem.

In the 1950s and 1960s stable and efficient numerical methods for linear systems and eigenvalue calculations were developed by several authors in the US (e.g. Wallace Givens at Aragonne NL and Alston Householder at Oak Ridge NL), in UK (e.g. James Wilkinson at National Physical Laboratory and John Francis at National Research Development Corporation – NRDC –), in Switzerland (Heinz Rutishauser at ETH, Alexander Ostrowski at University of Basel) and in the USSR (Vera Kublanovskaya, at Steklov Mathematical Institute).

Francis and Kublanovskaya proposed independently the QR algorithm for computing eigenvalues and eigenvectors in 1961. In the US, David Young, Richard Varga, and Gene Golub provided contributions to iterative methods, while Golub and William (Velvel) Kahan, and others, developed stable algorithms for singular value decomposition (SVD)-based least-squares and pseudoinverse calculations [54].

Several authors proposed non-iterative methods for solving the Poisson equation on regular grids in the 1960s and 1970s. In particular these investigations were carried out by Oscar Buneman and Golub at Stanford University while working on plasma physics. They are related to cyclic reduction and to the Fast Fourier Transform (FFT), that gained consensus after its generalization by Americans James W. Cooley and John W. Tuckey in 1965 [55]. Non-iterative methods found application also in petroleum engineering.

In more recent years, namely in the 1970s, 1980s and 1990s, other sectors of numerical analysis gained increasing attention from several researchers, including nonsymmetric linear systems, preconditioning, multilevel algorithms, and large-scale eigenvalues solvers gained increasing interest from several researchers. The emergence of parallel computing promoted investigations on domain decomposition.

Among many books on numerical analysis, the canonical text remains the comprehensive treatise edited by Milton Abramowitz and Irene Stegun for the US National Bureau of Standards (NBS) in 1964 [56]. Much more is available today in digital form.

1.4. Numerical optimization

1.4.1. Deterministic optimization

We have seen that algorithms for finding a minimum of a function were first formulated by Newton and Gauss and that linear programming for solving optimization problems was introduced by Leonid Kantorovich in the Soviet Union in 1939 [57]. Advancements came in the US in 1947, with the simplex method by George Bernard Dantzig [58] and the theory of duality by John von Neumann. Several other deterministic techniques for dealing with optimization problems were developed in the following years, e.g.: the Levenberg–Marquardt algorithm (LMA, 1963), convex programming (CP, 1970), nonlinear optimization (NLO, 1979), gradient methods (GM), and support vector machines (SVM, 1995). All of these methods are very effective and fast for specific problems, but suffer from some drawbacks too, because they can deal better with unconstrained problems, are sensitive to noise, and prone to remain trapped in local minima.

1.4.2. Stochastic optimization

Stochastic optimization methods, which are the most common of the so-called metaheuristic family of techniques, are convenient options to cope with the above issues. They are iterative, can deal with non-differentiable problems and typically work with populations of candidate solutions. They use random variables which can be introduced in different positions within the algorithm, resulting in different formulations, and which can be trimmed to achieve the best performance. Stochastic optimization methods are simple and effective tools capable of achieving good performance in almost all cases [59]. They exhibit noise robustness and can escape from local optima/minima to seek the global optimum/minimum, so that very good solutions can be obtained for most problems. On the other hand, stochastic methods are computationally expensive in terms of CPU size and processing time. But are also usually intrinsically suitable for parallel computation, which make them profitable in high performance computers. The first of these methods was the evolutionary algorithms (EA) first proposed by Nils Aall Barricelli in the 1950s [60].

Evolution-inspired optimization strategies gained momentum after the mid-1970s, notably with Genetic Algorithms (GA, 1970), Artificial Immune System (AIS, 1986), Differential Evolution (DE, 1995). Different forms of foraging algorithms, another group of biologically inspired methods, appeared later, such a Particle Swarm Optimization (PSO, 1995) [61], Artificial Bee Colony (ABC, 2005), Seeker Optimization Algorithm (SOA, 2006). In the same span of years, methods simulating natural and artificial concepts were also proposed. Just to name a few, we can cite Simulated Annealing (SA, 1983), Tabu Search (1986), Taguchi Method (1998), Harmony Search (HS, 2001), P System Based Optimization (PSBO, 2002). A larger number of derived formulations have germinated from the ingenuity of researchers, who dubbed them with fantasy names taken from the inspiring concepts and applied them in different fields of optimization. An uncomplete list is Ant Colony Optimization (ACO), Bacterial Foraging Optimization Algorithms (BFOA), Cross-entropy Method (CE), Evolution Strategies (ES), Parallel Tempering (PT), Probability Collectives (PC), Quantum Annealing (QA), Random Search (RS), Reactive Search Optimization (RSO), Stochastic Hill Climbing (SHC), Stochastic Tunneling (STUN). Thus, a large number of stochastic optimization algorithms are now available, among which those best fitted to a specific task can be selected and adapted.

Chapter 2 of this book provides a keen presentation of recent advances in numerical methods for design optimisation in which the possibilities offered by 3D printing and metamaterials are exploited.

1.5. Numerical models for continuum models

The computational power of computers, immensely superior to human capacity, opened new doors to the numerical analysis of continuum problems formulated in terms of steady-state and time-variable ODEs or PDEs.

1.5.1. FDMs for ODEs and PDEs (1920s)

Finite difference methods (FDMs) discretize differential equation by approximating derivative with finite differences, so that they can convert a possibly nonlinear system of ODEs or PDEs into a system of linear equations that can be solved by matrix algebra techniques. A FDM was first proposed by English mathematician Lewis F. Richardson to solve PDEs related to stresses in a masonry dam in 1910 [62]. It was re-proposed by A. Thom in the 1920s under the title “the method of square” to solve nonlinear hydrodynamic differential equations [63]. It was then used by Richardson to solve PDEs in weather forecasting in the 1922. German mathematicians Richard Courant, Kurt Otto Friedrichs and Hans Lewy worked on FDMs for solving PDEs and defined the eponymous convergence condition for explicit time-integration schemes in 1928 [64]. All three moved to America in the

1930s, eventually becoming American citizens and much contributing to the rise of numerical analysis in that part of the world.

FDM gained momentum in the 1950s, to convert ODEs and PDEs, possibly non-linear, into systems of linear equations to be solved with matrix algebra methods. Major progress occurred in FDMs for PDEs in the 1950s, particularly with the equivalence theorem of Hungarian-American Peter Lax, the alternating direction implicit (ADI) iterative method for solving elliptic and parabolic PDEs and splitting-up methods. Notable contributions to ADI came from Donald W. Peaceman and H. H. Rachford Jr., Garret Birkhoff, Richard Varga and David Young, and Jim Douglas in USA and by Nikolai Nikolaevich Yanenko and others in USSR.

Together with the successive over-relaxation (SOR) method, ADIs became the methods of choice for the numerical solution of discretized PDEs during much of the 1950s and 1960s. Only in the 1970s the Conjugate Gradient (CG) method emerged, especially after the development of incomplete Cholesky factorization, which was used a preconditioner for CG. Pivotal contributions came from John Reid in UK, Koos Meijerink and Henk van der Vorst in the Netherlands and Paul Concus, Gene Golub, and Dianne O'Leary in the US [65]. Thanks to ease of implementation, developed numerical methods and computational power of present-day computers, FDM algorithms are still widely used in the solution of a large variety of physics and engineering problems.

1.5.2. FEM for PDEs (1940s)

The finite element method (FEM) is the most widely used method for solving systems of PDEs modeling continuum physics and engineering problem, including structural analysis, heat transfer, fluid flow, mass transport, electromagnetic field and coupled problems. A FEM subdivides the analysis domain into small parts called finite elements. This is achieved by a space discretization based on the construction of a mesh consisting of a finite number of points. The unknown functions are then approximated over the mesh and the resulting simple approximated equations that hold in the finite elements are assembled into a larger system of equations that models the entire problem. The FEM then uses variational methods, or other reduction methods, to approximate a solution by minimizing an associated error function. A system of linear equations is obtained that can be solved by matrix algebra techniques.

Early work leading to the development of FEM for structural problems was carried out by different authors, notably Greek Johann Argyris, Chinese Feng Kang at Steklov Institute in Moskow, and Russian-Canadian Alexander Hrennikoff [66]. A seminal work on variational methods was published by Richard Courant in 1943 [67]. FEM gained major impetus with the spread of electronic computers in the 1960s, mainly thanks to contributions from Argyris at University of Stuttgart, Polish-British Olgierd Zienkiewicz at Swansea University, French Philippe G. Ciarlet at University of Paris 6 and American Richard Gallagher at Cornell University. The spread of the method was helped by the public release of the NASTRAN (NASA STRucture ANalysis) code in 1968, that was developed for NASA under federal funding to enforce the use of a single generic software program by all research centres involved in aerospace programs. Its success was such that it was inducted into the U.S. Space Foundation's Space Technology Hall of Fame in 1988. The SAP code, developed by the Ray Clough and Edward Wilson group at

Berkeley University in 1970, was also made widely available for free. Updated into SAP IV by Jurgen Bethe, it became one of the best performing structural analysis code of the time. FEM than spread to numerical modelling in several other fields.

1.5.3. Other methods (1960s)

The finite volume method (FVM), first introduced in early 1960s, is an alternative method for representing PDEs in the form of systems of algebraic equations to be solved with matrix algebra methods. In the FVM, volume integrals containing divergence terms are converted to surface integrals through the surfaces of each finite volume, based on the divergence theorem. Then the condition that the flux entering a given volume is identical to that leaving the adjacent volume is applied. The FVM evaluates exact expressions for the average value of the solution over some volume and uses them to construct approximations of the solution within cells. The method is used in many fluid dynamics and electromagnetics packages.

The Boundary Element Method (BEM) was introduced in the 1970s to solve linear PDEs formulated in integral form. BEMs provide approximate solutions of boundary value problems which are exact solutions of the differential equations inside the domain and are parametrized by a finite set of parameters on the boundary. They are used in fluid mechanics, acoustics and electromagnetics.

Meshfree methods, introduced in 1977, do not require connections between nodes of the simulation domain, i.e. a mesh, and are formulated in terms of interaction of each node with all its neighbours. As a consequence, extensive properties such as mass or kinetic energy are assigned to the single nodes. Meshfree methods enable the simulation of some otherwise difficult types of problems, including Lagrangian simulations, in which the nodes can move according to a velocity field.

For the solutions of PDE-based continuum problems, several other numerical methods have created, such as the control volume finite element method (1983) and the finite volume element method (1990). The extended finite element method (XFEM) is an improved version of the FEM, developed by Ted Belytschko in 1999 for applications in computational mechanics. It is suitable to model the propagation of various discontinuities either strong (cracks) and weak (material interfaces), by adopting advantages of meshfree methods while alleviating their negative sides.

1.5.4. Key developments in computational electromagnetics

The beginning of computational methods for electromagnetics can be traced back to a seminal treatise by Richard V. Southwell of 1946 [68]. Early development regarded mainly FDMs applied to static linear problems and eddy current problems, in which the computational domains were discretized with structured meshes and lower order approximation was used [69]. More sophisticated schemes were proposed in the 1960s, notably by Alan Winslow, who used discretization scheme based on unstructured grids, obtained with an automatic generator, and variational algorithms. At later investigations, this approach resulted equivalent to a FEM formulation.

Straightforward applications of FEMs to electromagnetics emerged in the 1970s, starting with works on rotary electrical machines by Peter P. Silvester and

Madabushi V. K. Chari [70] and then widespread to deal generalized time-dependent 3-D problems. In the same period, integral formulations were developed into the moment method (MM), later generalized to non-linear 3-D problems. BEM formulations based on the Green's integral theorems were also introduced.

Successful improvements of FEMs consisted in the incomplete Cholesky CG (ICCG) used as a pre-conditioner for dealing with large sparse matrices and Delaunay triangular meshing that was soon generalized to 3-D tetrahedral elements. Kelvin transformation allowed managing open boundary FEM problems, while Whitney forms were demonstrated to be an effective approach for computational electromagnetics (CEM). Other advanced approaches were introduced to increase the computation efficiency.

Algorithms for electromagnetic force computation, a major effect in magnetic problems, appeared since the 1980s, when advanced modelling of magnetic hysteresis and anisotropy was introduced, too. More recently material modelling was extended to soft magnetic composite and high temperature superconductors, which both have the potential of a disruptive impact on electric devices.

A number of methods have been introduced to overcome the low effectiveness of FEMs in high frequency problems. One of them is the finite difference in time domain (FDTD), proposed by Yee in 1966, which uses two staggered grids in space and time for each electric and magnetic for the electric and the magnetic fields, can deal with nonlinear materials and results effective in such high frequency problems. Other effective approaches are the method of moments (MoM) that has been successfully applied to antenna applications, and the transmission line matrix (TLM) first published by P. B. Johns and R. L. Beurle in 1971, that has emerged as a powerful method for wave propagation.

As regards alternative formulations, the finite integral method (FIM) proposed by Thomas Weiland in 1i977 replaces field components with their integrals over lines and surfaces belonging to two interlacing meshes and discretization is applied to the constitutive relations. Notably, it can be used effectively across the frequency spectrum. The cell method (CM) results in a very similar approach while maintaining multi-dimensional attributes of physical quantities, which are disregarded in FDM, FEM, BEM and FVM. It is also used in solid mechanics, fluid mechanics and continuum mechanics and is a promising tool for modelling heterogeneous materials.

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Figures

Fig. 1 – Kamares-style pottery of the old palatial period (2100-1700 BCE) at the Archaeological Museum of Herakleion. (Wolfgang Sauber in Wikimedia Commons) Impermeable containers of any form allowed the safe conservation of grains and beverages, with a deep impact on dietary habits.

https://en.wikipedia.org/wiki/File:AMI_-_Kamaresvase_1.jpg

Fig. 2 – Early Lydian coins, in electro, late 7th century BC. (Wikimedia Commons) Coins, consisting of standardized pieces of precious metals with an identifying effigy, had a profound impact on societies, greatly facilitating trades.

https://en.wikipedia.org/wiki/File:KINGS_of_LYDIA._Alyattes._Circa_620-10-564-53_BC.jpg

Fig. 3 – Bronze sword from Lugdunum at the Gallo-Roman Museum of Lyon-Fourvière, Lyon, France. (Rama in Wikimedia Commons) Weapons like this could only be manufactured with metals and shaped warfare until the invention of firearms

https://en.wikipedia.org/wiki/File:Bronze_swords-MGR_Lyon-IMG_9732-1.jpg

Fig. 4 – Interior of the Pantheon dome spanning 43 meters in diameter, with the oculus, the central hole having both a technical function (avoided closing the dome at the top) and an aesthetic purpose, 135 CE. (ArnoldDekker at Wikimedia Commons) Built in differentiated concrete, the dome remained unparalleled for more than 13 centuries.

https://commons.wikimedia.org/wiki/File:PantheonOculus.jpg

Fig. 5 – Blu blown glass vase and a glass terrine depicted in a fresco both from Pompeii, 79 CE. (Wikimedia Commons) Blowing transformed glass into a cheap material, well suited for countless uses.

https://commons.wikimedia.org/wiki/File:Brocca_in_vetro_blu,_da_pompei.JPG

https://commons.wikimedia.org/wiki/File:Glasschale,_Villa_Boscoreale.jpg

Fig. 6 – Cast iron bridge on the Severn at Ironbridge, England, erected by iron industrialists Abraham Darby III, John Wilkinson and others, 1781. (Wikimedia Commons) It was the first large iron structure ever built and demonstrated the potentials of cast iron obtained in large quantities and at relatively low cost with coke and puddling.

https://commons.wikimedia.org/wiki/File:Ironbridge002.JPG

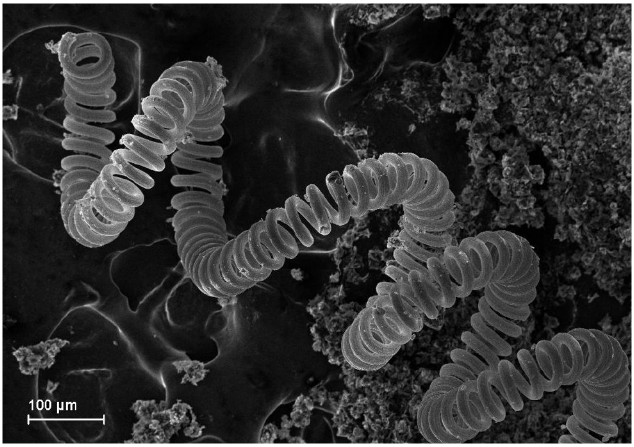

Fig. 7 – SEM image of a tungsten filament in an incandescent light bulb. (Дагесян Саркис Арменакович in Wikimedia Commons) Electric lighting the first mass use of electricity, a revolutionary technology spreading in the 20th century.

https://en.wikipedia.org/wiki/File:Tungsten_filament.JPG

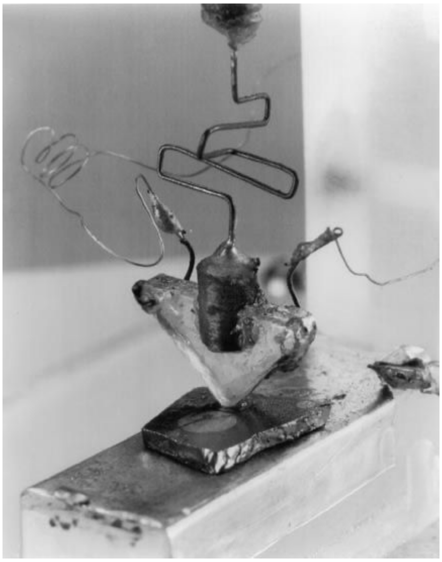

Fig. 8 – A replica of the first working transistor, of the point-contact type, built by John Bardeen and Walter H. Brattain in December 1947 (radiomarconi) It stated the age of pervasive solid-state electronics.

http://www.radiomarconi.com/marconi/transistor/index.html

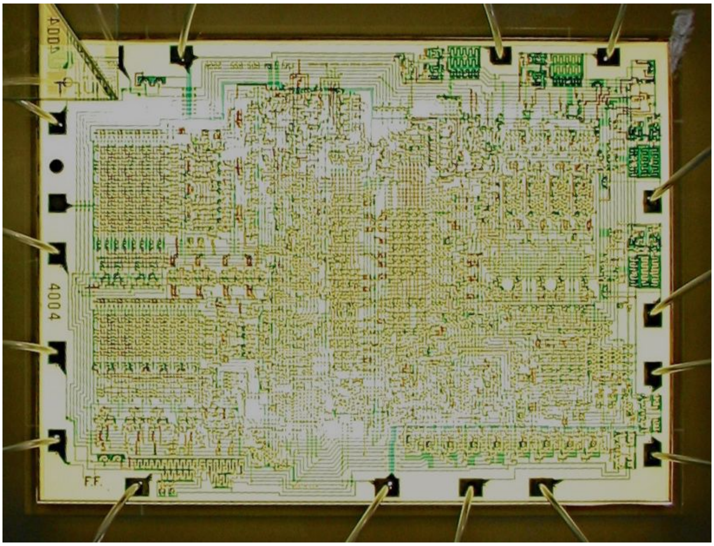

Fig. 9 – A microscope view of the Intel 4004 with the signature F.F. of inventor Federico Faggin in the bottom left corner, 1971 (Intel Free Press in Wikimedia Commons) It was a first chip, starting the revolution of microprocessor the astonishing rise of ICT in a matter of 30 years.

https://en.wikipedia.org/wiki/File:Legendary_Chip_Designer_Betting_on_Human_Mind.jpg

Fig. 10 – The Airbus A350, released in 2013, makes large use of composite materials in its structure and fuselage (Eric Salard in Wikimedia Commons)

https://en.wikipedia.org/wiki/File:F-WWCF_A350_LBG_SIAE_2015_(18953559366).jpg

Fig. 11 – The Antikythera mechanism, dated ca. 80 BCE. Fragment A–Front; the largest gear, ca. 13 centimetres in diameter, is visible in the front. (Wikimedia Commons). It was an ancient complex time-computing machine with very sophisticated gears.

https://en.wikipedia.org/wiki/File:NAMA_Machine_d%27Anticyth%C3%A8re_1.jpg

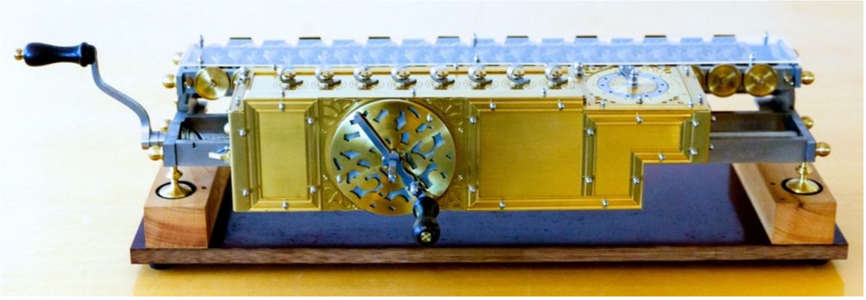

Fig. 12 – Replica of Leibniz's stepped reckoner at the Deutsches Museum. (Eremeev at Wikimedia Copmmons) The original calculator was built between 1671 and 1694 and was capable of performing the 4 operations, thanks to the Leibniz wheel.

https://commons.wikimedia.org/wiki/File:Rechenmaschine_von_Leibniz_(Nachbau)_05.jpg

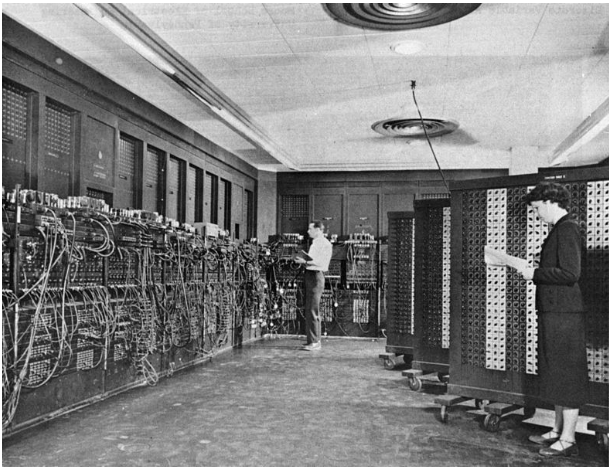

Fig. 13 – ENIAC, the first fully programmable general-purpose electronic computer, completed by Mauchly and Eckert at the University of Pennsylvania in 1946 (Wikimedia Commons).

https://en.wikipedia.org/wiki/File:Eniac.jpg

Fig. 14 – The Summit supercomputer, in operation at the Oak Ridge NL, US, was the fastest supercomputer in the world as of November 2018. (Carlos Jones/ORNL at Wikimedia Commons) With a measured power efficiency of 14.668 GFlops/watt it was also the 3rd most energy efficient in the world. Since 2020 it has been surpassed by Japanese Fujitsu Fugaku, capable of 415,5 PLFOPS.

https://en.wikipedia.org/wiki/File:Summit_(supercomputer).jpg

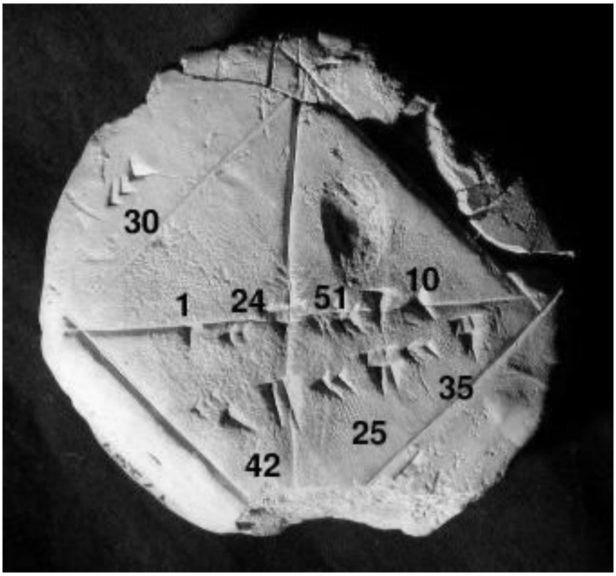

Fig. 15 – A Babylonian clay tablet with cuneiform writings of the approximation of the square root of 2, corresponding to 1.41421296, with an accuracy at the 6th digit, ca. 1800–1600 BCE (Bill Casselman at Wikimedia Commons)

https://en.wikipedia.org/wiki/File:Ybc7289-bw.jpg