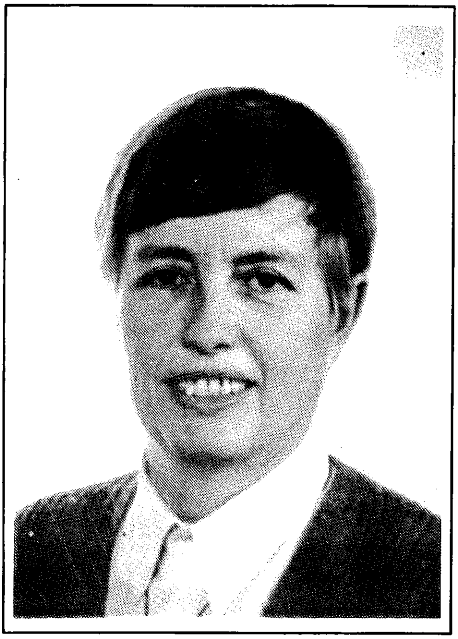

FROM POLE TO POLE: MAGNETIC INSTRUMENTS AND THEIR TIME

Christine Iserentant

I. Introduction

May I start this introduction by referring to the book From *Pole to Pole* by Sven Hedin (1865-1952)[1]. He was a great explorer, and I have borrowed the title of his book for this address.

"Once upon a time, there was a traveller who was forty-five years old. Twenty-five years ago he began his exploration of the world. At that time, he had just graduated and his knowledge was still rather basic...
However, a quarter of a century had passed... and he wondered how he could celebrate the twenty-fifth anniversary of this first journey...
Could there be a better way of celebrating than to turn his mind back to Asia, and to reminisce about everything he had seen and experienced. I invite everybody, present here today, to accompany me on a journey of recollection from one part of the world to the other, from Europe through Asia and back home. I will be your guide. I will lead you through the magnificent continent which filled twenty-five years of my life. And when we come back home and people ask us where we have been, then our answer will be: "From Pole to Pole".

II. From the Chinese to the European Pole: the magnetic compass

In the early history of modern science, the magnetic compass was considered one of the most important inventions of all times. The compass was crucial to shipping, more in particular for the naval powers in Western Europe. Even nowadays, it remains a crucial instrument for navigation. However, only few people know that the compass is of Chinese origin. Moreover, the invention had nothing to do with shipping.

In Europe as well as in China, legends were told about lodestone. And yet, only the Chinese were able to develop the science of magnetism. It originated in the "fengshui" or geomancy[2)], a particular form of fortune-telling, that departs from natural phenomena.

Geomancy was probably developed in the period of the Battling States, about the third century B.C. During and after the Han-dynasty this resulted in the actual creation of the compass (200 B.C. – 220 A.D.). The first practitioners of geomancy used a fortune-telling board consisting of two parts: a square plate that represented the Earth with a rotating disc attached. This disc represented the celestial sphere. Later, certainly in the first century A.D., people recognised that a complete celestial disc was not necessary. From now on, it was sufficient to use a spoon with its typical Chinese shape, representing the Beidou (the "northern spoon") : the seven clearest stars of the sign of the zodiac: the Big Bear (Ursa Major). In the course of the year, the 'tail' of the bear, matching the handle of the spoon, turns around the pole. In that way, the direction of the handle could indicate the seasons. Actually, this was a first step towards the development of dials.

Over the years, the Earth-plate was made out of bronze instead of wood. Thus, the spoon could turn around more easily. By using lodestone for manufacturing the spoon, people discovered the lodestone's natural tendency to direct itself according to a north-south axis.

Finally, the board of the fortune-telling device represented the Earth and the polished circle in the middle the sky. Chinese cyclical characters stood for the eight most important wind directions: north, north-east, east, etc. In addition, the smaller twenty-four points' graduations of the compass (every fifteen degrees) as well as the twenty-eight moonhouses – the base of the Chinese astronomy - were individually marked. As we have already mentioned, the handle of the spoon indicated south. This tradition lived on for many centuries in the use of the Chinese compass rose, whereas the European versions always indicated north.

The Chinese further investigated the properties of lodestone in a pure scientific way. This resulted in some sensational discoveries. Magnetic polarity was just one example.

Thus, they came to the conclusion that a magnet that floated on water was just as helpful as a spoon. This method was developed in the course of the second century B.C. The Chinese also made use of 'compasses' – if I may already use this word - made out of lodestone in the shape of a fish. Or, they placed the magnet in a wooden fish or turtle that floated on the water surface. Examples are also known of turtle-compasses with 'dry suspension'. Most noticeable is the fact that the floating type of compass remained very popular in China, whereas the dry type only became widely accepted as a consequence of the European maritime influence.

The various types of 'compasses' are described in the encyclopedia: "Guide through the forest of things" by Chen Yuanjing, compiled between 1100 – 1250 A.D.

About the fourth century A.D., the Chinese found that iron needles could get magnetised by rubbing them against a lodestone. Such needles were attached to a silk thread and indicated north and south, just as the magnet itself would have done.

Such process of magnetisation was for the first time unambiguously mentioned in "Pen Chats on the banks of the pond of dreams", written around 1088 by astronomer, engineer and official Shen Kuo. In his work, he also refers to another, vital - Chinese - discovery, namely that of magnetic declination: the fact that north and south pole indicated by a compass do not exactly match the geographic, astronomical poles. The Chinese were acquainted with this phenomenon from about 1050 A.D., probably even a century earlier. In Europe, on the contrary, this phenomenon remained unknown till about the middle of the fifteenth century. Hence, the discovery of the magnetic declination, traditionally attributed to Columbus, was already known in China four centuries earlier.

All the discoveries mentioned above are much indebted to geomancy. In navigation, the magnetic needle was for the first time used in 960 A.D., at the time of the commencement of the Song-dynasty. Once the use of the compass became common practice in Chinese shipping, this knowledge reached the European continent within a century.

III. Europe had to re-discover the compass

Ancient Greece[3-5)]

Ancient Greece was familiar with the fact that, after friction, amber could attract small objects. On the other hand it was also well known that a certain mineral had the particular feature of attracting small pieces of iron. Such mineral was found in large quantities in Magnesia, a region east of Thessalia, Mid-Greece. The name 'magnet' is probably derived hereof. One of the first references to magnetism in Western history appears in the work 'De Rerum Naturae" by the Roman poet Lucretius, from the first century B.C. (? 98-55 B.C.)

The power to attract small parts of iron was the only distinguishing characteristic of lodestone, known at that time. However, over the centuries, beliefs about the lodestone power grew. In the thirteenth century Bartholomew the Englishman hailed its medicinal properties in his encyclopedia :

> *This kind of stone (the magnet) restores husbands to wives and increases elegance and charm in speech. Moreover, along with honey, it cures dropsy, spleen, fox mange, and burn. ... When placed on the head of a chaste woman (the magnet) causes its poisons to surround her immediately, (but) if she is an adultress she will instantly remove herself from bed for fear of an apparition.*

The Middle Ages (Petrus Peregrinus)[3-6)]

Petrus Peregrinus, also called Peter the Pilgrim, was a western pioneer in experimental physics, more particularly in the field of magnetism. He was born and raised in Méricourt, Picardy. Later, he was a member of the army of Charles I of Anjou, King of Sicily. In the army, he probably served as an engineer. During the siege of the city of Lucera, Petrus Peregrinus had enough time to write on his experiments on magnetism. We know this from the letter he wrote to one of the soldiers he became friends with. This "Epistola de Magnete" dated from August eight, 1269.

Apparently, Petrus had shaped a piece of lodestone into a sphere. In his letter, he described how he placed a magnetic needle on various parts of the ball and drew lines showing the direction of the needle. As a result, he obtained a number of lines, circling the ball. He found that the lines crossed in two points, directly opposed to each other on both ends of a diameter of the ball. He realised that the lines matched the meridians of the celestial sphere and corresponded to those of the Earth. He accordingly called these points poles. Moreover, he extended this concept to both ends of the magnetic 'needle'. In some simple experiments he also found that similar poles repel, whereas unlike magnetic poles attract each other. All of these experiments were performed outside the walls of the city of Lucera, the besieged city where people were starved for convincing them to another religion.

This epistola is very important as a historical document because of the fact that Peter the Pilgrim was one of the first European experimental scientists. In his Opus Magnus, the English Franciscan friar and famous philosopher, Roger Bacon (1214 –1294), refers to Peter the Pilgrim as such a scientific pioneer. Petrus Peregrinus was indeed one of the first, if not the first, to emphasize that "experience, rather than argument is the basis of certainty in science"6).

*William Gilbert*3-6)

Until the end of the sixteenth century, Peregrinus fell into oblivion. Actually, the history of the scientific study of electricity and magnetism dates from William Gilbert (1540-1603). Three hundred and thirty years had passed before someone else would take up the task of moving the subject of magnetism's mystery out of the realm of superstition into that of science. After that, it took another century for scientists to become aware of the reality of magnetism. In retrospect, we should also take into account that only then the concept of science –as we understand it nowadays came into being.

But, let us go back to China for a moment. Throughout the centuries, China was the cradle of many great inventions$^{8)}$. However, from the beginning of the seventeenth century onwards, the rise of modern science would cast a shadow on these early developments. Modern science differed in two main ways from all that preceded. First of all, mathematics was used to express theories and hypotheses on nature. And secondly, these were combined with accurate observations and experiments.

Scientific and technological developments in China never knew dark Middle Ages. In Europe on the contrary, after the essential scientific contribution in the era of Ancient Greece - until the second century A.D.-,scientific knowledge sank to a low. Only the Renaissance (1300 - 1600 A.D) would be able to rise Europe from that low point. In China, on the other hand, there was a steady rise in scientific evolution.

How can this be explained? One of the reasons was probably that Chinese bureaucracy recruited the brightest intellectuals of the country. In addition, there were also some other factors that help to explain this fact. The uninterrupted development of Chinese science and technology never resulted in a revision of the philosophical basis. There never was a drastic revolution that could outbalance the traditional ways of thinking. In China, the traditional order was preserved. Obviously, this was not the case on the European continent. In these parts, there was no continuous evolution in ways of thinking. After a long period of stagnation, intellectual concepts underwent a number of fundamental changes. This resulted e.g. in the Reformation: a profound reform of the traditional religious ways of thinking, which had the effect of a major Earthquake. Independent ways of thinking get a chance, and adventurous commercial enterprises expanded their activities. Daring explorative expeditions were undertaken and new commercial routes were set out.

Let us reflect now on William Gilbert. He was born in Colchester (England, Essex), studied medicine at Cambridge University and afterwards, he held the exercise of his duty in London. He became the personal physician of Queen Elisabeth I and was a contemporary of William Shakespeare. While he fulfilled his obligations at Court, Gilbert carried out the very important investigations that have earned for him the title of "Father of Magnetism". He elaborately wrote on this in his book: "De Magnete, Magneticisque corporibus et de magno magnete tellure", (On magnets, magnetic bodies and on the great magnet, the Earth) published in London in 1600(9). In general, this work is considered as being the first modern scientific treatise.

In his book, he illustrated how, on the basis of experiments, one could draw certain reliable conclusions concerning the characteristics of magnets and of the Earth. Indeed, he found that the Earth itself was a magnet and that the magnetic needle's characteristic of indicating the north-south direction was not caused by influences from the celestial sphere. His "Terrellae" (spheric magnets made from lodestone) displayed all magnetic effects of the Earth itself. A "versorium" (we call it now a magnetic needle) suspended above a "terrella", took a position which was known as inclination and declination (Fig. 1).

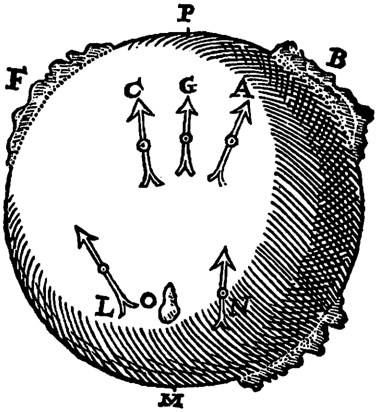

Fig. 1. One of W. Gilbert's irregular terrellae with versoria.

An instrument used to measure the inclination was first mentioned in a work published in 1581 by Robert Newman: "The Newe Attractive". A drawing of such a device is also found in the work of Gilbert. The experiments with terrellae had led Gilbert to the conclusion that lines which joined those places on Earth, where the inclination is the same, correspond to the lines of latitude. Gilbert also expressed the idea that a circle of inclination would be a more reliable means for navigation at sea than an ordinary compass. However, seamen soon detected that there could be substantial changes in inclination in places on the same latitude. Gilbert's prime idea was consequently abandoned.

The fact that a compass needle would not exactly indicate the north-south direction –as derived from astronomical observations- was already known a long time before Gilbert. The first marks of declination were found on sundials, produced in Nüremberg around 1450. The marks were used to orient the dials with a magnetic compass. A historically important corollary of the variability of declination was Christopher Columbus' discovery of America in 1492, partly by serendipity.

As he normally did on any great exploration, Columbus took along a good lodestone, which was carefully guarded, and a supply of spare compass needles. These would be remagnetized with the lodestone if they lost their ability to seek north. Columbus's ships headed westward according to the compass. However, this was not the geographic west. During their voyage they had –without knowing it- passed the point where the deviation of the magnetic pole was zero. This means that the magnetic pole and the geographical pole lay in the same direction. Once beyond this point, the magnetic north lies west of the geographical north instead of east, as it was the case in Spain at that time. This mistake caused his ships to sail further southward than would otherwise have been the case. This was important, because the sailors had made their captain Columbus to accept to head back to Spain if no land had been sighted within a certain time. If the ships would have sailed accurately westward, they would not have encountered land within that time, and Columbus would not have become famous.

The first numerical reference of declination is found from a measurement in Rome around 1510(10). In the following decades, similar measurements were carried out all over Europe. This is how the variability of declination was confirmed. The first map of declination was drawn in 1536 by the hand of Alonzo de Santo Cruz.

The fact that declination was place dependent strengthened the hopes of determining a position at sea by means of magnetic measurements. The knowledge of the world-wide variation of declination was of crucial importance for a naval power such as England. For two years –1698 till 1700- Edmund Halley (1656-1742) carried out declination measurements all over the North- and South-Atlantic Ocean. To do so, he made use of a specially designed and equipped ship, 'The Paramour', financed by the Royal Society, and later under the patronage of the king. The results of the expedition were published is 1701. The first isogonic map of the Atlantic Ocean was thus designed11).

IV. The Birth of Electromagnetism3-5)

W. Gilbert died in 1603. In the course of the seventeenth century only little progress was made, both in the field of electricity and magnetism. In the eighteenth century however, considerable progress was made in the study of charged bodies, the field of research now known as electrostatics. For a long time, the knowledge of electricity and magnetism has been restricted to a number of isolated facts. Only some two hundred years after Gilbert's death the link between electricity and magnetism would become clear.

Obviously, for the scientific study of any physical phenomenon, two conditions should be fulfilled. First a large quantity of material should be at hand on which experiments can be carried out. Secondly, measuring instruments were needed to give quantitative information on the phenomenon. What was needed here, were large quantities of electricity, strong magnets and instruments that could determine the various features of electricity and magnetism on a purely quantitative basis. Only then would experimentation begin in earnest.

A number of discoveries resulted in an almost endless list of new, practical applications. It was discovered by Peter van Musschenbroeck (1692-1761) that electricity can be stored in what we now call Leyden jars. The force between electrical charges could be measured by means of a torsion balance, designed by Charles-Augustin Coulomb (1736-1806). It was discov-

ered that larger *currents*, flowing electricity, could be generated by larger voltaic cells.
These discoveries brought along that some curious minds considered the use of voltaic cells for studying magnetic effects.

H.C. Oersted6)

Hans Christian Oersted (1777-1851), a Danish physicist, was strongly inspired by Immanuel Kant's unifying idea that physical experiences can be related to a unique force. In addition, Oersted was convinced that there had to be a link between electricity and magnetism. That was what he was looking for. Indeed, Oersted was the first to note that the orientation of a compass needle changed when, near to the compass, an electric current went through a wire. He revealed his findings of this key experiment in a four-page Latin publication: "Experimenta circa effectum conflictus electricia in acum magneticum" (Experiments concerning the effects of an eletrical conflict on a magnetic needle), July 21, 1820. The discovery of electromagnetism, the connection between electricity and magnetism, was a fact. Oersted had demonstrated that electricity could generate magnetism.

Soon enough, the implications became clear. Oersted's results operated as a fermentation process. Within a few months, numerous successes had been achieved. One of the pioneers was Andre-Marie Ampère (1775-1836).

A.M. Ampère6)

When Ampère became acquainted with Oersted's findings, he immediately started a thorough experimental study of this new phenomenon. For instance, he recorded that wires carrying currents exerted forces on each other (unit of current intensity: ampère). He also found that when a current was sent through a spiral wire (solenoid), this wire behaved as a magnet. One of his friends, François Arago (1786-1853) was the first to put an iron core inside the solenoid, which apparently increased the magnetic effect. The iron core behaved as a magnet every time the electric power was turned on. Ampère wondered if it were possible that the magnetism of the Earth originated in currents inside the Earth.

Undoubtedly Ampère's most important contribution lies in the fact that he was the first one to proclaim the idea that magnetism is caused by 'electricity in motion'.

*Galvanometers*12-16)

Oersted's discovery provided a means for the detection of a current by its magnetic effect. Instruments based on this principle are called galvanometers.

The Museum for the History of Science of the University of Gent houses a large number of these instruments. On their own, they offer scope for an interesting study.

The simplest type of galvanometer consists of a single wire coil, with a compass needle placed in the middle. The instrument is adjusted so that the plane of the coil is in the magnetic meridian. A weak current causes but a small deflection. The geomagnetic field attempts to keep the needle in its original position. Thus, it came down to increasing the sensitivity of the instruments. This could be obtained by raising the effect of the current, and by weakening the influence of the geomagnetic field.

By winding the wire several times round the magnet, the effect was multiplied by a large factor. The German J.S. Schweigger (1779-1857) was the first to actually realise such set-up. This construction was called a 'multiplicator'.

The second way to increase the sensitivity of the apparatus consisted of adding a second magnetic needle of about the same strength. This was done by Nobili in 1830. The needles were mounted in the same vertical plane, but with their similar poles turned in opposite directions, the so-called astatic system. In that way, the influence of the Earth was more or less neutralised.

On figure 2 the core of such a galvanometer is shown. We clearly see the multiplicator and the astatic system. Usually, a circular plate with graduation is placed underneath the upper needle. To increase the sensitivity of the instrument even more, a small mirror is attached to the thread. The mirror reflects a beam of light on a scale (mirror galvanometer).

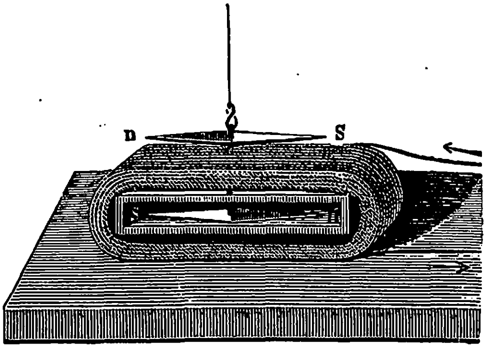

Fig.2. The core of a galvanometer with multiplicator and astatic system

In the instruments mentioned above, the coil (multiplicator) took up a fixed position. Later, the coil itself could spin : hence the name moving coil galvanometer. The subsequent volt- and ampère-meters were based on the same principle. One of the first, and definitely the most famous moving coil galvanometer was the meter designed by the engineer M. Deprez (1843-1918) and professor A. d'Arsonval (1851-1940). Their first model contained a large, vertically installed horseshoe magnet. Attached to a thread, a small coil is suspended inside the magnetic field. When the electric current flows through the circuit, the coil will turn, in accordance with the laws of electromagnetism. However, it will also be impeded by the torsion of the thread. Usually, the apparatus was placed underneath a bell-glass. Later, a number of other improvements resulted in very sensitive and accurate instruments.

Galvanometers helped to save the live of thousands of frogs. Indeed, before the invention of the galvanometer, galvanic electricity was detected by means of the contraction of frog's legs.

Telegraphy[17]

Electromagnetism was first applied in the field of telegraphy. Ampère suggested already in 1820 that a magnetic needle placed on a very remote point of a circuit could be used to transfer signals. He proposed to set 30 needles into motion by means of 2x 30 wires. In 1828, the Frenchman de Saint-Amand suggested however to use only one needle and to code the alphabet via the number of deviations of the needle. His proposal was ignored.

In 1832 the German physicists Karl Friedrich Gauss (1777-1855) and Wilhelm Weber (1804-1891) were the first to create an efficient telegraphic line about 2.5 km long, between the astronomy observatory in Göttingen (Gauss) and Weber's physics laboratory. The line was used to exchange data through a mirror galvanometer. They soon realised that the system was a useful tool to exchange coded messages.

Telegraphy was given incentives from various areas. The introduction of telegraphy was heaven-sent for the railways as both efficiency and safety increased. Adolphe Quetelet (1796-1874) (a teacher and good friend of Joseph Plateau (1801-1883)) contributed to the introduction of telegraphy in Belgium. Belgium's first electric telegraph service was installed along the railway line Brussels-Antwerp. On 9 September 1846 this connection was open to the public and people could go and see the working of the instrument if they were willing to pay 1 franc per person.

It was only in 1845 that the 1-needle-telegraph was introduced. Such a type of telegraph was in fact a large galvanometer with an astatic needle-pair, such as the one designed by Nobili, but it was positioned vertically. A positive current made the needle deflect to the right, a negative current to the left (cf. the Frenchman's idea in 1828). Later on, people switched to Morse (left = point, right = stripe). It might be interesting to know that the last bastion of commercial radiotelegraphy in Morse, namely connecting ships and coastal stations, came to an end on 31 January 1999.

V. The Discovery of Electromagnetic Induction - M. Faraday(3-7)18)

Experiments thus proved the link between magnetism and electricity in motion. Briton Michael Faraday (1791-1867) made headway with his law of induction in 1831. He stated that a changing magnetic field generated an electric current in a circuit. In a way, this boils down to the opposite of Oersted's observation.

Michael Faraday is one of the fairy tales of science: originally he was an apprentice-bookbinder, but he became one of the greatest scientific researchers and he received nearly all the important scientific awards of that period.

Faraday never received any formal education. His school education was basic. He couldn't fully grasp the mathematics in Ampère's papers. But he had an intuitive feeling for the processes of nature. Furthermore, he was also extremely talented in choosing the right experiments. The blacksmith's son had marvellous hands and nature was a challenge to him. He was a scientific Casanova.

Faraday's life was science. His leading characteristic was reliance on facts derived from experiments. "Without experiments, I am nothing." he wrote. Experimenting was in fact the only thing in which he excelled. But he had one tremendous advantage: his observations were not hampered by biased ideas about the results. Actually, electromagnetic induction had already been observed by Ampère nine years earlier, but to Ampère the effect, although noted, was simply ignored. It was not what he was looking for and he failed to recognize its significance.

Fortunately, Faraday provided us with a detailed report of his research. The descriptions are of particular interest, as they were written at the time of the experiments. To a certain extent, this allows us to grasp his working strategies and to comprehend how he came to his conclusions.

Giving a short overview of Faraday's scientific research is a hopeless task. Faraday started to work for Sir Humphry Davy, a great chemist, thanks to his interest in chemistry. Apart from his electrochemical experiments, three of his physical results would influence history dramatically.

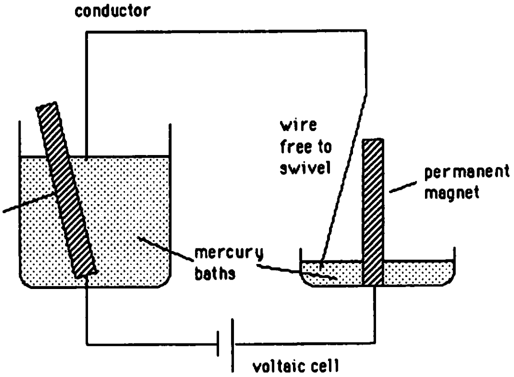

Fig.3. A sketch showing the apparatus Faraday used to demonstrate the mechanical effects of electric currents

First, in 1821 Faraday discovered that an electric current could generate mechanical action. This experiment is schematically shown on figure 3 : when a current flows in the circuit, the suspended magnet at the left rotates around the wire firmly fixed in the bowl of mercury. Simultaneously, the current carrying wire at the right rotates about the permanent magnet anchored in another bowl of mercury. This concept formed the basis for the present electric motor.

This type of engine developed rather quickly. In 1839, a boat was propelled along the river Neva at a rate of 4 km/h by means of an electric motor. In this initial period, the current for the motors was produced by batteries or voltaic cells, sometimes up to seventy units. The construction of powerful motors required high electromotive forces to feed the electromagnets. As long as no better power source than an ordinary chemical cell was developed, this remained impossible. The cost played a role as well. The price of electrical power was about 60 times higher than the power produced by steam engines. However, the construction of more efficient dynamos –

Ampère laid the basis for this – soon resulted in the production of cheaper electricity.

Indeed, on 17 October 1831, Faraday concluded that the mechanical motion of a magnet in the vicinity of a closed circuit could generate an electric current, but only during the time the magnet was moving. Eleven days later he inverted the procedure. Instead of moving a magnet trough a coil of wire, he arranged that a conductor in the form of a copper disc should be made to turn between the poles of a magnet. For this purpose he used the great horse-shoe magnet that is still to be seen at the house of the Royal Society. Between the axis and the rim of the disc a current was induced when the disc was turning. So the dynamo was born: mechanical energy of motion could be converted into electrical energy. Faraday then built the first primitive electric generator. The Belgian Zénobe Gramme (1826-1901) constructed the first serviceable dynamo in 1871(17).

Also in 1831, Faraday made a third crucial discovery which had a great influence on history: he showed that electric current could be induced in a circuit by changing the current in a nearby circuit. This observation announced the birth of the transformer and the induction coil. At the same time and independently from Faraday, the American scientist Joseph Henry (1791-1878) also discovered this effect, but he published his findings only later. Thanks to the induction coil, a very high electromotive force could be generated, starting from current provided by a couple of voltaic cells. Men finally had a useful high-tension generator and this meant farewell to all friction machines. The German instrument maker Heinrich Ruhmkorff (1803-1877) designed the first efficient instrument(17). Ruhmkorff's coil played a crucial role in many areas: in the medical world, for the study of electric discharges in rarefied gases (especially X-rays) and also in telecommunication. Even today the coil of Ruhmkorff generates the spark required to ignite the mixture of gases in an internal combustion engine.

To round off this chapter on Faraday, it might be interesting to point out again that – in contrast to what was generally accepted till then – *time* was a factor which had to be taken into account when explaining physical phenomena, as induction required varying currents and varying fields.

VI. All electromagnetic phenomena explained - J.C. Maxwell[3-6]

The Scot James Clerck Maxwell (1831- 1879) crowned the work in 1873. His four fundamental, mathematical laws describe all electromagnetic phenomena and form the foundation for the physics of the 20th century. In his "Treatise on Electricity and Magnetism"[19], he came to the astonishing conclusion that – to use Faraday's terminology -electric and magnetic forces travel with the speed of light. This involved that light had to be an electromagnetic phenomenon. This conclusion meant a fantastic breakthrough. After centuries of research, magnetism, electricity and light turned out to be connected. Moreover, Maxwell postulated the existence of electromagnetic waves of the same nature as light waves. Heinrich Rudolf Hertz (1847 –1894) proved the authenticity by means of experiments, which introduced the foundation for wireless telecommunication.

The quest for an explanation of the fascinating force exhibited by the lodestone culminated in the discovery that an electrical current created magnetic fields. A logical step was to consider circular currents to be responsible for magnetism in the world of atoms and molecules in order to explain the properties of lodestone and permanent magnets : in the beginning of the 20th century, the atomic theory of matter supported this hypothesis.

VII. Final journeys

As final journeys, I would like to dilate on the importance of magnetism in daily life and in some other fields of science, apart from the applications already mentioned.

Magnetic recording[20]

In 1998, magnetic recording celebrated its hundredth anniversary. Initially magnetic recording developed slowly, even though its technology is omnipresent today. The underlying physics were unknown, applications were slow to emerge, and business and politics stifled development.

Today, magnets store much of the world's information: data on computer discs, videos and tapes for leisure activities, messages on telephone answering machines, and data on credit cards. All such media store words, numbers, images and sounds as invisible patterns of north and south poles.

During the last decades, magnetic memories and audio taping have played an influential role in society and political life. Some famous U.S. presidents might confirm.

It was at the end of the 19th century that people started using magnetic material to record and reproduce the human voice. In 1898 the Danish engineer Valdemar Poulsen patented an apparatus, the so called telegraphone. He demonstrated the principle by means of a steel piano wire stretched across the laboratory. Poulsen spoke into a telephone mouthpiece connected to an electromagnet sliding along the wire. The device converted his words into electric signals of diverse intensities which in turn were sent to the magnet. The varying magnetic field was then imprinted along the steel wire. By replacing the mounthpiece by a receiver and by sliding again the electromagnet along the wire, the apparatus functioned in the opposite way. Poulsen improved his invention by e.g. wrapping up the steel wire around a cylinder. In the beginning people were rather sceptical about Poulsen's telegraphone. In the U.S.A., an office specialised in patents disapproved of the telegraphone, because the apparatus conflicted with "all common laws on magnetism". Apparently not all laws on magnetism were commonly known at that time, because Poulsen's invention functioned properly. However, in 1900 the telegraphone became a tremendous success during the exhibition in Paris. One of the visitors was the emperor of Austria, Franz Joseph, who recorded a message which still exists and which is the oldest magnetic recording.

What hampered the development of this invention for such a long time, half a century to be more precise? The answer is plain, namely a combination of business interests and technical factors. An example: the American Telephone & Telegraph Company was opposed to the telegraphone because they were convinced that they would lose 1/3 of their business interests if the customers would realise that their conversations might be recorded. A kind of remark that sounds familiar.

There were of course also technical problems which obstructed the sophistication of the apparatus. But there was more. Of the few telegraphones which had been sold in the U.S.A, several of them had been installed in two transatlantic wireless stations on the East coast which were then operated by German companies. It was also known that the German Navy had purchased telegraphones for its submarines. Consequently, at the outbreak of the first World War, the two transmitting stations were suspected to pass on military information to German submarines in the Atlantic Ocean. This might have been at the origin of the torpedoing of the British liner Lusitania near the Irish coast, because Germans used the telegraphone for high-speed transmissions.

In Europe, magnetic recording fared much better. An intermediate stage in the development was e.g. the Blattnerphone which was already in use by the BBC in 1931. It was a huge machine: height: 1.5m, width: 1.5m, depth: 0.5m and weight: approximately 1 ton. The recording-medium was a steel ribbon, approximately 3 mm wide, which passed the record and reproduction heads at a speed of 1m/s. A tape of 1.5 km was needed for a recording of half an hour. Two men were required to insert the reels.

In certain countries this type of apparatus remained in use until 1945. The exceptional length of the heavy steel tapes clearly impeded further development. Fortunately, Fritz Pfeumer, an Austrian chemist, improved the system in 1927: he invented a paper tape coated with magnetic particles in powder form. We are all familiar with the modern product which has been derived from this principle.

Let us reflect once more on the scientific world. Many phenomena in which magnetism plays a role can be discussed. Some of these issues are dealt with below.

The drift of the continents[21)22)]

One example is the drift of the continents. The German climatologist Alfred Wegener (1880 –1930) formulated his first theory on the basis of biological and geological arguments. This theory, alike any other, had its opponents and advocates. Once, all continents were believed to have formed one block (Pangea). This supercontinent was ripped into pieces, and the pieces would have drifted away as rafts on the Earth's crust. But where did these immense forces, necessary for the movement of the continents, originate?

From the moment geologists and physicists started to cooperate, a better insight in this matter could be obtained. In the 50s, a palaeo-magnetic research indicated that ancient magnetic poles witnessed from various continents diverged with age, which indeed illustrated the relative movement of the continents. However, the question remained: how?

During the second World War, the American Navy had developed aeromagnetic measurement techniques for detecting submarines. The techniques were later converted into marine magnetometers which were towed at the rear of a ship. Around 1955 these modern proton precession magnetometers were dragged along the bottom of the sea (accuracy: $0.5\gamma = 0.5\ 10^{-9}$ Tesla!). The results were astonishing. Magnetic anomalies formed zebra-like parallel ribbon patterns, parallel to the ridges. They were soon correlated with reversals of the sense of the magnetic field of the Earth. The sea-floor spreading theory was born, heralding plate tectonics, the most profound revolution in Earth Sciences (fig.4).

*Intense magnetic fields*23-25)

To have an idea of the order of magnitude of the magnetic field intensity, it is worth noting that the strength of the Earth magnetic field amounts to $0.5\ 10^{-4}$T. This field occupies an intermediate position between galactic fields, which extend over vast distances but amount to only a few thousandths of the Earth magnetic field, and fields in the vicinity of atomic nuclei, which occupy tiny volumes of space but may exceed 100T. Magnetic fields generated in the laboratory have surpassed atomic fields in both intensity and volume. The need for very intense magnetic fields to serve as extreme research environments is shared by almost all the major divisions of physics : high-energy physics, plasma physics, solid-state physics, geophysics and even biophysics.

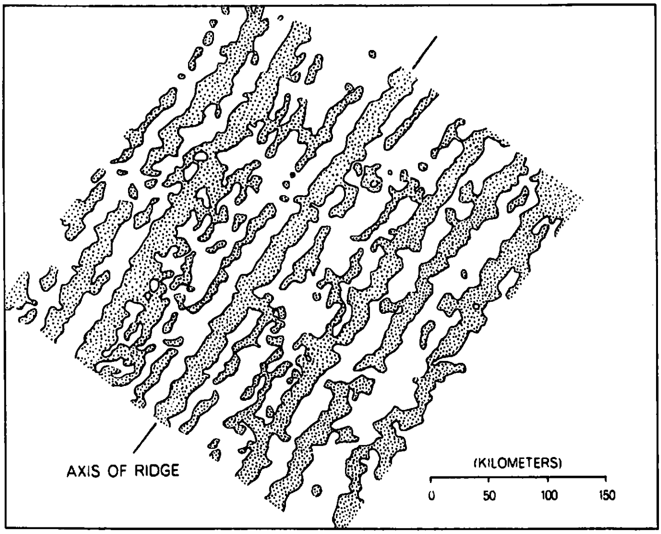

Fig.4. Example of anomaly pattern discovered in ocean floors, particularly along mid-ocean ridges. The pattern is strikingly symmetrical. The parallel bands in which the Earth's field is stronger (stippled) or weaker (white) than the regional average are oriented along the ridge's axis. The magnetic bands are produced by bands of rock with "normal" and "reversed" magnetism.

Several giant electromagnets were built around the first World War, one of which is the well-known magnet of Bellevue, France, weighing 120 tons and built in 1927. The windings around the iron core are 1.90 m in diameter. The generation of a field of 5T within a volume of 20 cm^3 consumed a power of 100 kW. For all practical purposed 3T represents however the limit of magnetic field intensity for such type of magnets.

Fields exceeding 3 T however are more expediently generated in iron-free solenoids. This involves enormous currents, thousands of ampères, which confronts scientists with a first main problem, namely heat. The generation of intense magnetic fields is the only process customarily performed at zero efficiency : nearly all of the energy dissipated in a magnet coil is removed as heat. A second problem is the mechanical force exerted by a magnetic field on an electric current. This force is the magnetic equivalent of pressure. At 25 T the pressure reaches the yield strength of copper, with the result that an ordinary copper coil, no matter how well constrained, will begin to flow like a liquid. The National Magnet Laboratory at MIT (Massachusetts Institute of Technology) managed to produce the most intense continuous magnetic field in this way with a 25 T solenoid. The magnet contains 3 tons of copper and has an outside diameter of approximately 1 m. At full power it consumes 16 million watts of electricity and 7500 l water per minute!

Superconductive magnets, which are available now at reasonable prices, solved the problems of the enormous power and need for cooling.

Magnetic fields in space[4)]

Magnetism was also fundamental to our understanding of astronomic phenomena. Everything we know about the remote universe was derived from a study of electromagnetic waves, such as light, X-rays, radio-waves, ultraviolet and infrared radiation. The discovery of magnetism in astronomical objects is based on an effect observed by Pieter Zeeman (1865 – 1943) in 1896. An effect which has been named after him. Today there are a dozen of telescopes in the world that do nothing else but measure the Zeeman splitting of light from the sun, in order to measure magnetic fields in and around sun-spots. These reveal that the sun's basic field amounts to the double of the field of the Earth, that it runs north-south and that it reverses its direction every 22 years. The magnetic fields in sun-spots can be 1000 times stronger. Pairs of spots appear to act as the north and south poles of huge magnets hundreds of times the size of the Earth. The fields in pairs of sun-spots also change their relative polarity with the eleven-year sun-spot cycle. Magnetic stars are known, with fields ranging from 10^{-2} T to 3,5 T. Magnetic fields are also present between stars. Magnetism in space influences there various physical processes, ranging from the genesis of stars to the evolution of galaxies. Their origin remains mysterious.

VIII. Conclusion

In conclusion I would like to stress that our present knowledge in magnetism is the product of several generations. Knowledge certainly is a living and growing phenomenon. We can only grasp a living organism if we are acquainted with its inheritance and upbringing. No one can acquire a valuable scientific knowledge while ignoring how ideas have been achieved. Wolfgang Goethe (1749 – 1832) befittingly wrote: " The history of science is science in its own."...27)

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