

[4] Another possible explanation is that because of the course structure and the active students' involvement, necessary for a course aiming at the development of problem solving skills, the homework has actually to be done in time for the next teaching session, while in other courses this may be left at the end of the semester.

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## Electric Art

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**Abstract.** Electric Art is a challenging and practical application of electricity and creativity. Participants will be presented with a cross-curricular application of Physics and Art that uses recycled materials. Art from the global scrap heap is the focus of this endeavor. Workshop includes goals, lesson plans and grading rubrics. Participants will receive a packet containing necessary materials for implementation. Project uses readily available materials.

The primary goal of the science component is to allow students to apply what they have learned about electricity and wiring to a hands-on project. After learning lab safety, how to wire a circuit and make a switch, they get to create an art piece that lights up, has an object that spins, or makes noises. The students will draw an accurate schematic diagram and be able to follow it to wire their art piece. They will apply their knowledge of how to strip wire, attach switches, motors, buzzers, and lights in parallel and series. Additionally, they will learn simple structural engineering techniques in order to create a sturdy and reliable final product.

The primary goal of the art component of this project is to encourage creativity by using only "found" objects to create esthetic and interesting art objects. The artworks must contain the required electrical circuitry. The students are introduced to "found art" through a series of prints of both global found art and contemporary artists who work with found objects. Through directed discussions, they learn about the process of seeing and transforming ordinary objects and trash, into meaningful and esthetic works of art. The second art component is the practice of using sketching to plan their artwork. They need to understand simple schematic drawing, i.e. aerial view, side view, details, etc., to do their planning.

**Keywords.** Electricity, Physics, Found Art.

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## From Electromagnetism to Electrodynamics: Ampère's Demonstration of the Interaction between Current Carrying Wires

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**Abstract.** We present Oersted's discovery of the torque exerted by a current carrying wire upon a nearby magnet and his interpretation of this experiment. This opened the field of electromagnetism, describing the interaction between current carrying wires and magnets. We discuss Ampère's alternative interpretation and his experiment showing a force between a magnet and a current carrying spiral. This led him to try an interaction between two current carrying spirals, without any magnet. He was successful with this trial and this is one of the most important experiments in the history of electricity. This led him to the result that current carrying parallel wires attract (repel) one another when the currents flow along the same direction (in opposite directions). This new field of research describing the interaction between current carrying wires was called electrodynamics by Ampère. We show how to perform Ampère's crucial experiment with simple and cheap materials.

**Keywords.** Ampère, Electro-dynamics, History of Physics, Low Cost Materials.

### 1. Introduction

Until the beginning of the nineteenth century there were some separate branches of physics including gravitation, electricity and magnetism. They were represented by inverse square central forces. The force of gravitation,  $F_g$ , was proportional to the product of the two masses,  $m_1$  and  $m_2$ , and inversely proportional to the square

of the distance  $r$  between them. We can express this proportionality as

$$F_g \propto \frac{m_1 m_2}{r^2}$$

This force was always attractive. The electrical force  $F_g$  was proportional to the product of the two charges,  $q_1$  and  $q_2$ , falling also as the square of the distance. We can express this as

$$F_e \propto \frac{q_1 q_2}{r^2}$$

This force was attractive if the two charges had opposite signs and repulsive if they had the same signs. The magnetic force  $F_m$  was proportional to the product of the two poles,  $p_1$  and  $p_2$ , falling also as  $r^2$ . We can express this as

$$F_m \propto \frac{p_1 p_2}{r^2}$$

This force was attractive if the two poles were of opposite types (a north and a south pole) and repulsive if they were of the same type (two north poles, or two south poles). Despite this mathematical similarity there were no known phenomena showing unambiguously a connection between these three branches of physics.

In 1800 Volta (1745-1827) invented the electric pile which allowed a source of constant current, [1]. This opened a new area of research and soon important new results were reported.

## 2. Oersted's discovery of electromagnetism and his interpretation of his findings

In 1820 Oersted (1777-1851) obtained for the first time a clear phenomenon showing an interaction between a current carrying wire and a magnet. In particular he showed that a current carrying wire exerted a torque upon a nearby magnet, deflecting it from its natural orientation along a magnetic meridian. He wrote a short report in Latin, *Experimenta circa effectum conflictus electrici in acum magneticam*, and sent it to learned societies and scholars on July 21, 1820. Here we quote from the English translation, [2], which has the following title: Experiments on the Effect of a Current of Electricity on the Magnetic Needle. Instead of "current of electricity," Oersted utilized the expression "conflict of electricity." This appears

not only in the Latin title but also in his text, namely: "The opposite ends of the galvanic battery were joined by a metallic wire, which, for shortness sake, we shall call the *uniting conductor*, or the *uniting wire*. To the effect which takes place in this conductor and in the surrounding space, we shall give the name of the *conflict of electricity*."

Instead of adopting a more conventional view of a current as a stream of electric particles, Oersted thought that inside a current carrying wire there was a double flow of positive and negative electricity currents moving in opposite directions relative to the wire. This is evident from the explanation of his experiment, as we quote later on. These opposite charges would collide with one another and separate, all along a current carrying wire. This is the origin of the name *conflict* which he utilized.

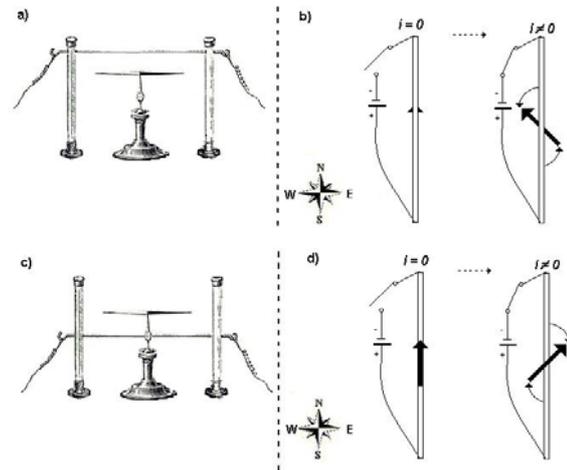


Figure 1. Deflection of a magnet in Oersted's experiment

The reason why he considered this conflict of electricity to happen not only inside the conductor but also in the "surrounding space," will become evident as a result of his fundamental finding, which he described as follows:

"Let the straight part of this wire be placed horizontally above the magnetic needle, properly suspended, and parallel to it. If necessary, the uniting wire is bent so as to assume a proper position for the experiment. Things being in this state, the needle will be moved, and the end of it next the negative side of the battery will go westward.

"If the distance of the uniting wire does not exceed three-quarters of an inch from the needle, the declination of the needle makes an angle of about 45°. If the distance is increased, the angle diminishes proportionally. The

declination likewise varies with the power of the battery. (...)

“If the uniting wire be placed in a horizontal plane under the magnetic needle, all the effects are the same as when it is above the needle, only they are in an opposite direction, for the pole of the magnetic needle next the negative end of the battery declines to the east.

“That these facts may be the more easily retained, we may use this formula – the pole above which the negative electricity enters is turned to the west, under which, to the east.”

This last sentence is illustrated in our Figure 1.

His interpretation of this fundamental discovery was expressed as follows:

“We may now make a few observations towards explaining these phenomena.

“The electric conflict acts only on the magnetic particles of matter. All non-magnetic bodies appear penetrable by the electric conflict, while magnetic bodies, or rather their magnetic particles, resist the passage of this conflict. Hence they can be moved by the impetus of the contending powers.

“It is sufficiently evident from the preceding facts that the electric conflict is not confined to the conductor, but dispersed pretty widely in the circumjacent space.

“From the preceding facts we may likewise infer that this conflict performs circles, for without this condition it seems impossible that the one part of the uniting wire, when placed below the magnetic pole, should drive it towards the east, and when placed above it towards the west, for it is the nature of a circle that the motions in opposite parts should have an opposite direction. Besides, a motion in circles, joined with a progressive motion, according to the length of the conductor, ought to form a conchoidal or spiral line, but this, unless I am mistaken, contributes nothing to explain the phenomena hitherto observed.

“All the effects on the north pole above-mentioned are easily understood by supposing that negative electricity moves in a spiral line bent towards the right, and propels the north pole, but does not act on the south pole. The effects on the south pole are explained in a similar manner, if we ascribe to positive electricity a contrary motion and power of acting on the south pole, but not upon the north. The agreement of this law with nature will be better seen by a repetition of the experiments than by a long explanation. The mode of judging of the experiments will be much facilitated if the course of the electricity currents in the uniting wire be pointed out by marks or figures.

“I shall merely add to the above that I have demonstrated in a book published five years ago that heat and light consist of the conflict of the electricity currents. From the observations now stated, we may conclude that a circular motion likewise occurs in these effects. This I think will contribute very much to illustrate the phenomena to which the appellation of polarization of light has been given.”

### **3. Ampère's interpretation of Oersted's experiment**

Oersted's experiment was presented and repeated at the French Academy of Sciences by Arago (1786-1853). Ampère (1775-1836) was fascinated by it and devoted himself to this subject during the following months. He did not accept Oersted's interpretation that something was circulating around the wire. Ampère preferred to interpret this experiment as indicating a direct interaction between currents. To this end he supposed that any magnet was composed of electric currents following closed curves perpendicular to its axis. In order to explain the magnetic properties of the Earth he also supposed that it had internal currents flowing from east to west in a direction perpendicular to the magnetic meridian.

He expressed his opposition to Oersted's interpretation in his main work, *On the Mathematical Theory of Electrodynamical Phenomena, experimentally Deduced*, published in 1826. Here we quote from the partial English translation of this work, [3, pp. 155-157].

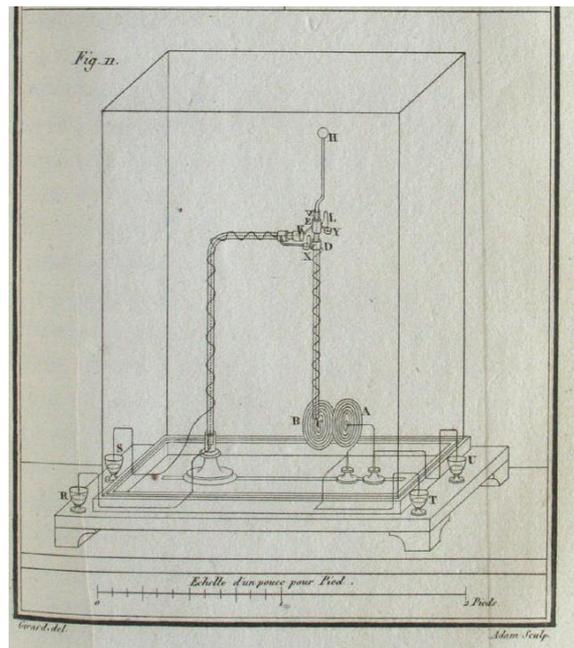
“The new era in the history of science marked by the works of Newton, is not only the age of man's most important discovery in the causes of natural phenomena, it is also the age in which the human spirit has opened a new highway into the sciences which have natural phenomena as their object of study.

“Until Newton, the causes of natural phenomena had been sought almost exclusively in the impulsion of an unknown fluid which entrained particles of materials in the same direction as its own particles, wherever rotational motion occurred, and a vortex in the same direction was imagined.

“Newton taught us that motion of this kind, like all motions in nature, must be reducible by calculation to forces acting between two material particles along the straight line between them such that the action of one upon the other is equal and opposite to that which the latter has upon the former and, consequently, assuming the two particles to be permanently associated, that no motion whatsoever can result from their interaction. (...)

"It does not appear that this approach, the only one which can lead to results which are free of all hypothesis, is preferred by physicists in the rest of Europe like it is by Frenchmen, the famous scientist who first saw the poles of a magnet transported by the action of a conductor in directions perpendicular to those of the wire, concluded that electrical matter revolved about it and pushed the poles along with it, just as Descartes made the 'matter of the vortices' revolve in the direction of planetary revolution. Guided by Newtonian philosophy, I have reduced the phenomenon observed by M. Oersted, as has been done for all similar natural phenomena, to forces acting along a straight line joining the two particles between which the actions are exerted, and if I have established that the same arrangement, or the same movement of electricity, which exists in the conductor is present also round the particles of the magnets, it is certainly not to explain their action by impulsion as with a vortex, but to calculate, according to my formula, the resultant forces acting between the particles of a magnet, and those of a conductor, or of another magnet, along the lines joining the particles in pairs which are considered to be interacting, and to show that the results of the calculation are completely verified by (1) the experiments of M. Pouillet and my own into the precise determination of the conditions which must exist for a moving conductor to remain in equilibrium when acted upon, whether by another conductor, or by a magnet, and (2) by the agreement between these results and the laws which Coulomb and M. Biot have deduced by their experiments, the former relating to the interaction of two magnets, and the latter to the interaction between a magnet and a conductor."

In order to test his ideas Ampère first tried to model a magnet pole by means of a metallic spiral, [4, pp. 235-246]. He placed the plane of this spiral along a vertical plane, with its axis coinciding with the north-south direction of a bar magnet suspended horizontally. The spiral was suspended from above in such a way that it could move or oscillate along the horizontal direction. When there was no current flowing along the spiral, there was no perceptible interaction between it and the nearby magnet. He then connected the spiral to a battery. When a constant current was flowing along the spiral it was attracted or repelled by the magnet, depending upon the direction of the current. In this way he could reproduce qualitatively the attraction and repulsion between two bar magnets depending upon their facing poles, but now with one of the magnets replaced by a current carrying spiral.



**Figure 2. Ampère's crucial experiment showing for the first time the interaction between two current carrying circuits**

In order to test his ideas Ampère first tried to model a magnet pole by means of a metallic spiral, [4, pp. 235-246]. He placed the plane of this spiral along a vertical plane, with its axis coinciding with the north-south direction of a bar magnet suspended horizontally. The spiral was suspended from above in such a way that it could move or oscillate along the horizontal direction. When there was no current flowing along the spiral, there was no perceptible interaction between it and the nearby magnet. He then connected the spiral to a battery. When a constant current was flowing along the spiral it was attracted or repelled by the magnet, depending upon the direction of the current. In this way he could reproduce qualitatively the attraction and repulsion between two bar magnets depending upon their facing poles, but now with one of the magnets replaced by a current carrying spiral.

Then it came a crucial moment. Ampère now replaced the magnet by another spiral. The two spirals were in parallel vertical planes facing one another, with collinear axes. There was no visible interaction between them when no current was flowing. When there was a constant current flowing along both spirals they attracted or repelled one another, depending upon the directions of the currents. It was in this way that he concluded for the first time that two parallel straight wires should attract (repel) one another if their currents were flowing along the same direction (in opposite directions), an arrangement

which he presented in his first published paper about this subject, [5]. It is worth while quoting in full this crucial experiment of Ampère, performed and described in 1820, [6, pp. 152-154]:

“Now, if electric currents are the cause of the directive action of the earth, then electric currents could also cause the action of one magnet on another magnet, it therefore follows that a magnet could be regarded as an assembly of electric currents in planes perpendicular to its axis, their direction being such that the austral pole of the magnet, pointing north, is to the right of these currents since it is always to the left of a current placed outside the magnet, and which faces it in a parallel direction, or rather that these currents establish themselves first in the magnet along the shortest closed curves, whether from left to right, or from right to left, and the line perpendicular to the planes of these currents then becomes the axis of the magnet and its extremities make the two poles. Thus, at each pole the electric currents of which the magnet is composed are directed along closed concentric curves, I simulated this arrangement as much as possible by bending a conducting wire in a spiral: this spiral was made from brass wire terminating in two straight portions enclosed in glass tubes so as to eliminate contact and attach them to the two extremities of the battery.

“Depending on the direction of the current, such a spiral is greatly attracted or repelled by the pole of a magnet which is presented with its axis perpendicular to the plane of the spiral, according as the current of the spiral and of the magnet flow in the same or opposite directions. In replacing the magnet by another spiral with its current in the same direction, the same attractions and repulsions occur, it is in this way that I discovered that two electric currents attract each other when they flow in the same direction and repel each other in the other case.”

Figure 2 presents Ampère's apparatus to show this effect. It might at first appear that Ampère's experiment with the two spirals was a necessary consequence of Oersted's discovery. That this was not the case was shown by Arago and Ampère, [7, pp. 23 and 195-196]. They pointed out that a magnet exerts forces upon a piece of soft iron but two pieces of soft iron are without effect upon each other. Only experiments could decide if two current carrying conductors would or not exert forces upon each other. The experiment with the two current carrying spirals was performed by Ampère in September 1820, thus confirming his expectation. It opened up a new area of physics, namely, the interaction between current carrying wires without the presence of any magnet. Oersted's discovery, describing the interactions between a current

carrying wire and a magnet, was called sometimes as an *electromagnetic* phenomenon. In order to distinguish the new class of phenomena from those analogous to Oersted's discovery, Ampère created two new names, *electrostatics* and *electrodynamics*. To the first class we should include the attractions and repulsions of charges at rest, while the second class should include specially the attractions and repulsions between current carrying wires, [8] and [9, p. 78]:

“The name *electro-magnetic*, given to the phenomena produced by the conducting wires of Volta's pile, could only conveniently describe these phenomena at the time in which there were only known between these phenomena those which Mr. Oersted discovered between an electric current and a magnet. I believe that I should utilize the denomination *electro-dynamic*, to join in a single common name all these phenomena, and specially to designate the phenomena which I observed between two voltaic conductors. It expresses the characteristic property of these phenomena, namely, to be produced by electricity in motion, while the electrical attractions and repulsions known for a very long time are the *electro-static* phenomena produced by the unequal distribution of electricity at rest upon the bodies in which these phenomena are observed.”

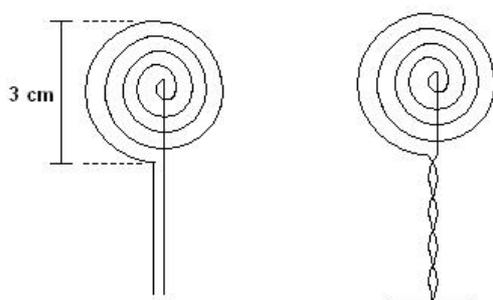
In the following Section we show how reproduce Ampère's crucial experiment with low cost material.

#### 4. Reproducing Ampère's crucial experiment with low-cost materials

In order to perform experiments analogous to those of Ampère we need essentially the following material: two small cylindrical magnets, 4 D size batteries (alkaline 1.5 V piles), two metallic spirals, two switches and connecting wires. At least one of the magnets should be suspended by a string, like a pendulum, with its north-south axis horizontal. Two batteries connected in series will be the power supply for the current to flow in each spiral. The circuit connecting the extremities of the batteries to each spiral can be made of common copper wire or aluminum strips fixed over a wood board 20 cm × 20 cm. Each circuit should have a switch which will be normally open to prevent the quick loss of energy from the batteries.

The most unusual part of the apparatus is the spiral. We made it with AWG 26 insulated copper wire, easily available from electric shops. We fixed loosely a nail upon a wood board, so that we could remove it easily with our hands when necessary. Each spiral utilized approximately 2

m of wire. We fixed one of its extremities at the board with a tape distant 15 cm from the nail. The wire was wound around the nail making a plane spiral. Each spiral consisted of some 30 turns, with the largest turn having a diameter of around 3 cm. After the last turn there remained an extra 15 cm of wire at the other extremity, Figure 3. We removed the nail from the board and fixed the spiral in a planar shape with some glue. To this end we also utilized three radial extra wires leaving from the center of the spiral, reaching the largest turn, returning to the center of the spiral at its other side and making an angle of  $120^\circ$  between them. We wound the two extremities of the spiral containing 15 cm of straight wire in such a way that it remained only 2 cm of each side. We put these extremities on fire to remove the electrical insulation. In its final shape the spiral would be in a vertical plane, with the wound wires descending vertically from the center of the spiral and the two bare extremities pointing laterally to the left and to the right into the same plane of the spiral, Figure 3.



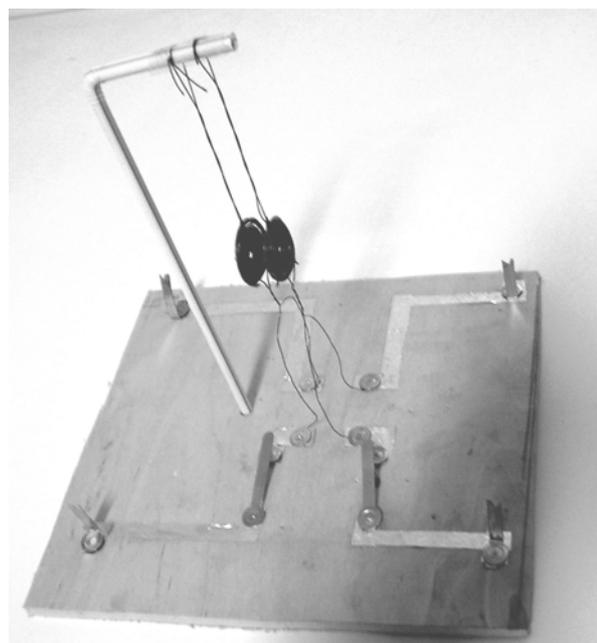
**Figure 3. A typical spiral utilizes 2 m of wire, has 30 turns with largest diameter of 3 cm and two legs of 15 cm. The legs are wound together except at their extremities, which are uninsulated and bent to opposite sides**

The photos illustrating this procedure are presented in Figure 4.

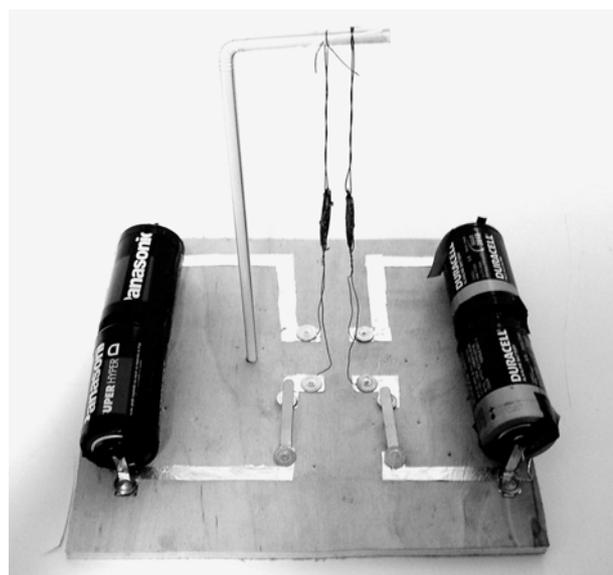


**Figure 4. Procedure to make the spiral and its final shape**

We hung each spiral in a vertical plane utilizing a string connected to a higher support in such a loose way that the spiral could oscillate around this support like a pendulum. Finally we connected the two batteries in series with a switch and with the two bare extremities of the spiral. The photos of two of these circuits facing one another with and without batteries are presented in Figures 5 and 6.



**Figure 5. Final apparatus without batteries**



**Figure 6. Final apparatus with batteries**

## 5. Experiments

With this apparatus it is possible to illustrate easily three classes of phenomena, namely, magnetic, electromagnetic and electrodynamic.

A magnetic phenomenon is characterized by the interaction of two magnets. This can be shown by hanging one cylindrical magnet like a pendulum with its north-south axis along a horizontal direction. We hold another cylindrical magnet in our hand with its north-south axis collinear with the first magnet. By presenting it to the pendular magnet it is easy to see this last magnet being attracted or repelled by the magnet in our hand depending upon the facing poles, Figure 7.

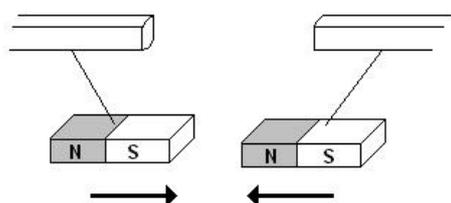


Figure 7. Two collinear magnets attracting one another

An electromagnetic phenomenon is characterized by an interaction between a current carrying wire and a magnet. This can be illustrated with our apparatus by mounting one spiral circuit with batteries and switch. We hold a cylindrical magnet in our hand with its north-south axis collinear with the spiral axis. When the switch is open there is no interaction between them. By closing the switch a constant current flows along the spiral. In this case it can be observed its attraction or repulsion by the magnet depending upon the direction of the current and upon which pole is closest to the spiral, Figure 8. An attraction in one configuration can be transformed into a repulsion by reversing the orientation of the pair of batteries, or by reversing the polarity of the magnet. By reversing both there will remain an attraction between the magnet and the spiral. The main difference between this experience of Ampère and that of Oersted is that now we are observing attractions and repulsions between the magnet and the current carrying spiral, while in Oersted's experiment he observed a deflection of a magnetic due to a torque exerted by a nearby current carrying wire.

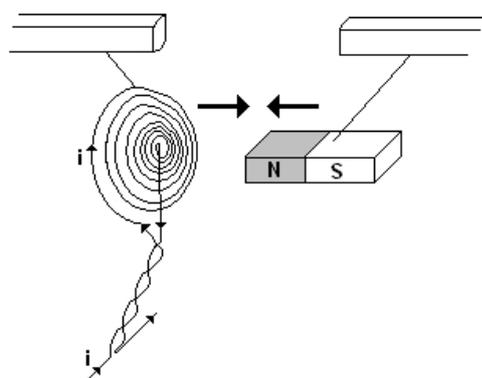


Figure 8. A spiral with its plane orthogonal to the north-south axis of a magnet, with its axis collinear with that of the magnet. There is an attraction between the magnet and the spiral depending upon the direction of the current in the spiral and the orientation of the poles of the magnet. The closing circuit of the spiral is not shown

An electrodynamic phenomenon is characterized by an interaction between two current carrying wires. This is illustrated with our apparatus in Figure 6. When one or two switches are open no interaction is observed between the spirals. When both switches are closed there is a visible attraction or repulsion between both spirals depending upon the directions of the currents, Figure 9. An attraction in one configuration can be reversed to a repulsion by changing the direction of only one current (this can be easily achieved by reversing the orientation of one pair of batteries). On the other hand, an attraction will remain by reversing the orientation of both pairs of batteries. In this way it is easily verified that currents flowing along the same direction attract one another while currents flowing in opposite directions repel one another.

Two batteries connected in series produce a voltage of 3 V between their terminals. With an amperimeter we measured the typical current in our circuit, of the order of 1.3 A. This means that the total resistance of each circuit had a value of some 2.3  $\Omega$ . With these small currents we could easily observe two spirals which were initially separated by 1 cm attract one another and remain in touch after that. The advantage of this didactic apparatus is evident when we compare it with a real reproduction of Ampère's original experiment, [10]. In this case it was only possible to see two straight wires touching one another for high currents of the order of 30 amperes.

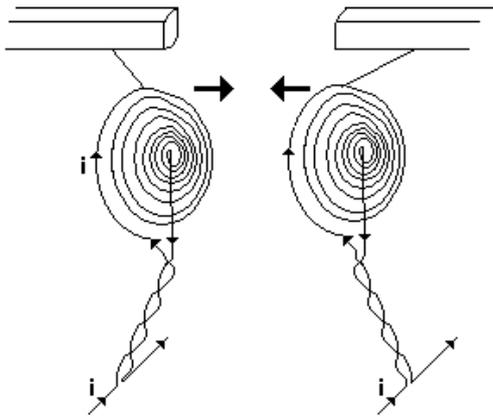


Figure 9. Two spirals with their planes parallel to one another and collinear axes. There is an attraction between them when both currents flow along the same directions

## 6. Acknowledgements

JPMCC wishes to thank Funcamp-Unicamp for financial support.

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## The Educational Role of Play at the Teaching of Physics

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**Abstract.** Whether you consider it as an activity, or as an object in the form of a toy, playing vindicates a great importance in the harmonious development of the child's physics and an important role in the understanding of the rules of nature. It is by means of the magic world of playing that basic rules and principles of Physics find a way to give logical answers to questions about life. Under certain circumstances, play can turn into a wonderful teaching aid and a dynamic tool in the teaching of Physics, provided that the teacher uses it correctly in the classroom. Almost all the topics of Physics can be taught experimentally or theoretically throughout "playing", whether it means the use of toys, or an activity with the participation of the students. Watches with salted water instead of battery, solar helicopters, leaking bottles carrying water, lamps which switch on without electricity, balls carried away without any support, under water fire, plays with static electricity are only some of the experiments with ...playful mood which can contribute to the understanding of the laws of Physics as well as to the development of positive feelings towards the Physics' lessons. In order to use in its greater extent this teaching method, the teacher has to take into consideration some parameters. The lecture refers to the pedagogic and didactic dimension of play in Physics. In addition, it is out to show the way (throughout selected references such as photos and short