

MAGNETIC FIELD

Although the phenomenon of magnetism was known in antiquity, it was not well understood until the nineteenth century, when it was made comprehensible thanks to the work carried out by Maxwell.

Electromagnetism is at the heart of the creation of electric energy, radio, TV, computer engineering and information technology, so it certainly plays a crucial role in present day society.

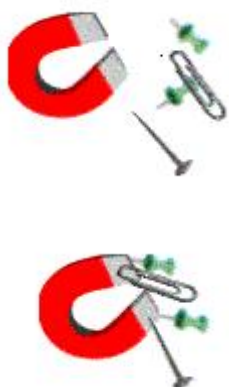
We will try to approach the subject in a simple way, without using complicated mathematics, to make some of its main properties comprehensible.

Click on next to see the objectives of this unit.

Objectives

- To remember the qualitative properties of magnetic phenomena studied in previous years.
- To understand the effects of the magnetic field on charged particles and currents and to understand some of the applications of these forces.
- To know how to measure the magnetic field produced in simple conditions and to understand natural magnetism.
- To understand the phenomenon of magnetic self-induction, its application to the creation of alternating current and its importance in relation to some components of alternating current circuits.

Natural magnets



We have often seen how a magnet, made of magnetite or some ferric alloy, attracts steel objects or other metals derived from iron. Substances that are strongly attracted by magnets are called **ferromagnetic**, those that are only slightly attracted (in such a way that the effect is imperceptible) are called **paramagnetic**, and those that are not affected at all or are faintly repelled by magnets are called **diamagnetic**.

We also know that each magnet has two areas where magnetism is more intense: the poles. Furthermore, the poles of different magnets interact strongly as you can see in the attached visual. The visual allows you to choose which poles you wish to place in front of each other. You can see how they interact by clicking on "release".

Click on next for a justification of the names of the poles: **north** and **south**.



The compass and the Earth as a magnet



We all understand **how a compass works. Wherever we are, it points northward.**

We also remember the explanation of this phenomenon:

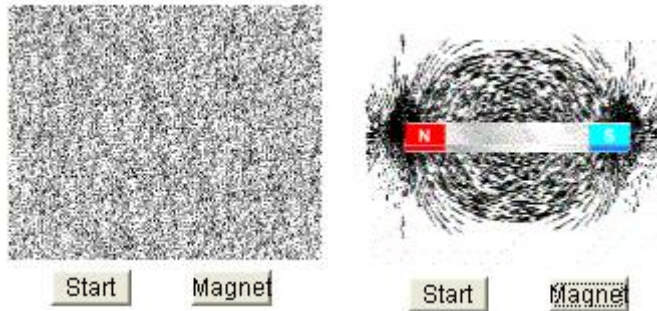
The Earth is a huge magnet with its poles near the geographical poles, and the compass is a small magnet with very little friction, so that it can move in the magnetic field of the Earth.

We will call the pole which points towards the geographical north pole, the north pole of the magnet, and we will call the pole that points towards the south, the south pole of the magnet. This means that the geographical north pole of the Earth is near the magnetic south pole of the Earth and viceversa.

In the following section you will find an illustration of the great planetary magnet.

Lines of force

The magnetic field is the only field where the lines of force that show the direction of the field can be made visible.

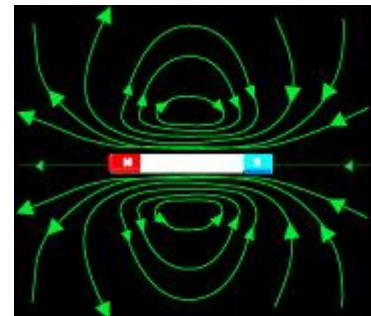


In the visual on the left you can see a surface covered with iron filings. If you click on the magnet control, you will see the lines of force because each iron particle turns into a small magnet and they all line up according to the lines of force.

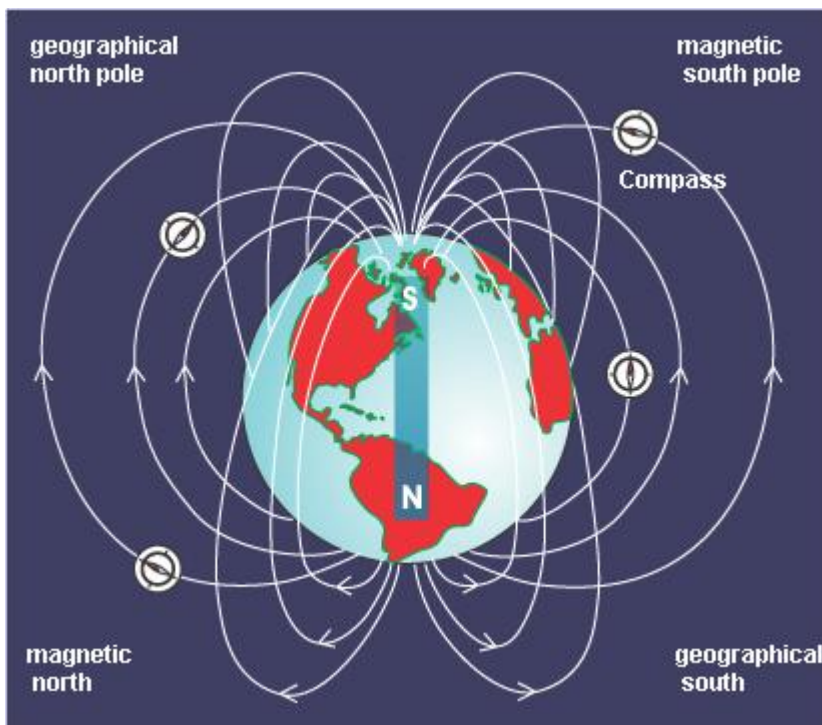
There is a convention that states that lines of force leave from the north pole of the magnet and enter the south pole, as we can see in the figure attached.

Inside the magnet, the lines of force are parallel, which means that the value of the field intensity is homogeneous.

Click on next to see the lines of force of the Earth.



The giant terrestrial magnet



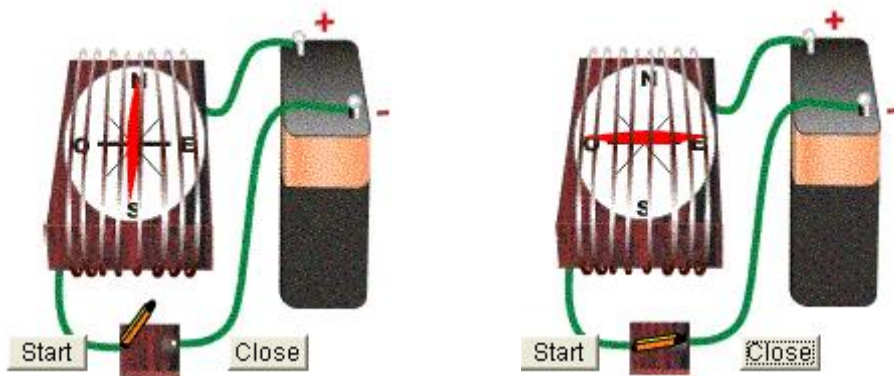
The inset shows the lines of force caused by the magnetic properties of the Earth.

Note how the lines leave the south pole (the magnetic north) and enter the north pole (the magnetic south).

Observe how compasses point north as a consequence.

It is important to note that the magnetic poles do not coincide with the geographic poles. From every point on the Earth, there is a difference of a few degrees between the direction in which a compass points and the direction of the geographical north pole. The difference is called **magnetic declination**. The magnetic declination changes slowly as time goes by. This means that the magnetic poles move. In fact, the polarity of the Earth, changes in irregular geological time periods.

Magnets and currents



While he was investigating the magnetic field, Ørsted carried out the experiment illustrated in the visual on the left. The compass initially points north, but closing the circuit changes its direction, and it points in a direction perpendicular to the current.

This experiment gave the same result no matter where one placed the compass.

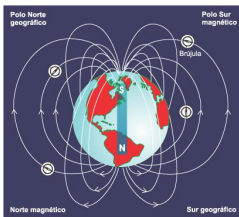
The only possible explanation was that the current created lines of force that were circular and concentric, with the current through their centre.

What do a magnetite magnet and a current have in common? We will answer this question later in this unit. For now, let us just note that, if electric currents, that is, charged particles in movement, create a magnetic field, then it is logical to assume that they will be affected by the magnetic fields created by other moving charges or magnets.

Conclusions about our introduction to magnetism

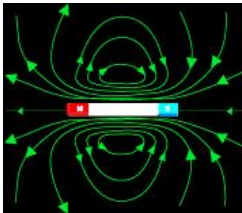


Magnets attract so-called ferromagnetic substances strongly, especially towards their **two poles**, paramagnetic substances are faintly attracted and diamagnetic substances are not attracted at all. The substances that are attracted act like magnets while they are in the field.

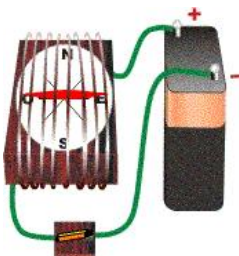


The behaviour of a compass proves that the Earth is a giant magnet with its magnetic poles close to the geographical poles.

The pole of a magnet that tends to point in the direction of the geographical north is called the **north pole of the magnet**, and the pole that points south is called the **south pole of the magnet**. **Magnets attract each other through opposite poles and they repel identical poles.**

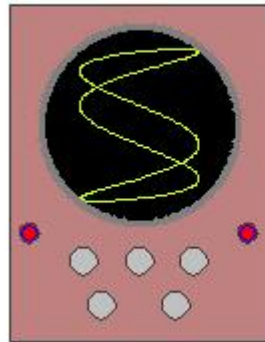


The magnetic field has the direction of the lines of force that leave the north pole of the magnet and enter its south pole. Inside the magnet, the lines of force are parallel and go from south to north. This means that the field inside the magnet is homogeneous.



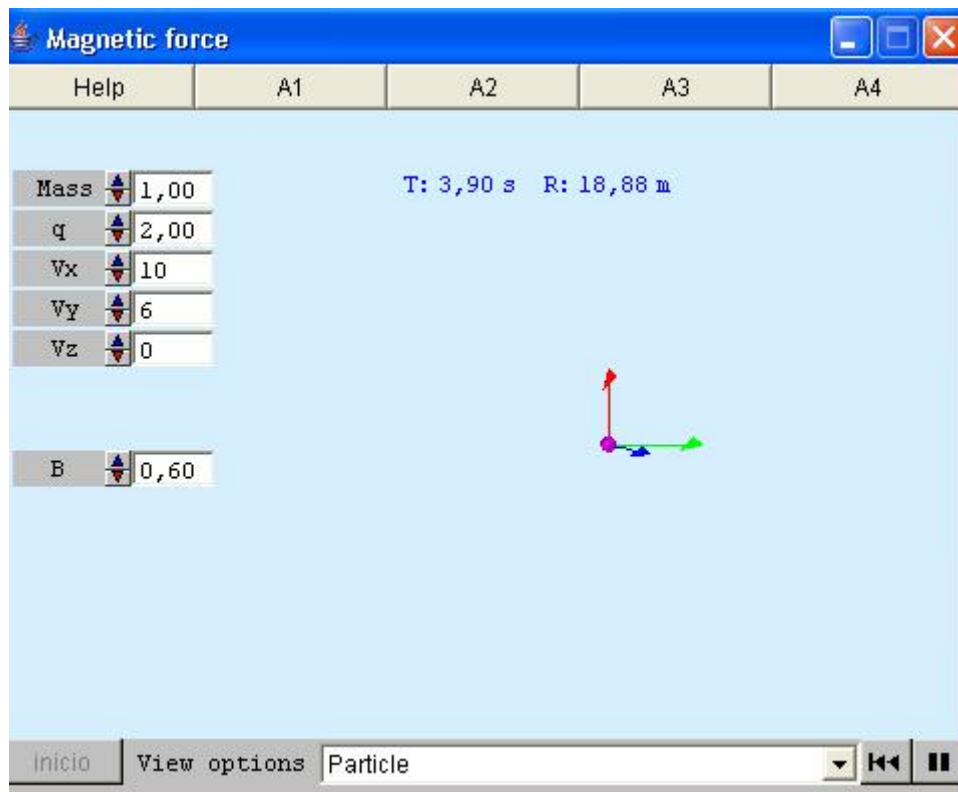
Örsted discovered that electric currents produce magnetic fields with lines of force that form concentric circles around the current. **Magnetic fields are created by particles in movement.**

The effects of the magnetic field on a charged particle



x wave	sinuso
frx	30,00
Ax	1,100
Ay	0,010
y wave	sinuso
fry	10,00
Vy	140,00
phase y	45,00

In the visual, you can see an oscilloscope, an instrument in which a beam of electrons is deflected by variable magnetic fields, according to the user's intention. Test the different possibilities (especially frx and fry) and then click on **Magnetic force** to study the effect of a magnetic force on a charged particle in detail. You can also use **Top view** and **Side view** to carry out the study with well known elementary particles.



Help: You can choose the charge, mass and velocity of a particle that moves in the magnetic field.

You can also determine the value of the magnetic induction B (the field is homogenous).

If you have selected the particle view option, you will see the particle with the field vector (green), the velocity vector (blue) and the force (red).

The play button will allow you to watch the particle moving in the field.

If you select the trajectory view option, you will not be able to see the particle, but you will see its trajectory.

You can change your point of view by clicking and dragging the image in the visual.

A1: Give the B vector and the x component of the velocity vector different values. Can you see the force? Click on play and see what happens.

What if the x component of the velocity is negative?

What if the charge is negative?

Set the x component to zero and test different values on the y and z components, in such a way that the V vector is perpendicular to B .

You can change your point of view if you cannot see the vectors clearly.

What happens if you change the sign of the charge?

What if you change the value of the charge?

What happens when you change the mass?

Try to find a law in your textbook that justifies your observations.

A2: The vector of the magnetic field is called magnetic induction.

Its unit, the tesla, is the induction capable of exerting a given force on the unit charge when it is moving along a line perpendicular to the field.

Set $q=1$; $V_y=1$; $V_x=0$; $V_z=0$ and $B=1$. What force is exerted on the unit charge by a 1 tesla magnetic induction?

A3: Set B to 0.5, V_x and V_z to zero and V_y to 10, and click on play.

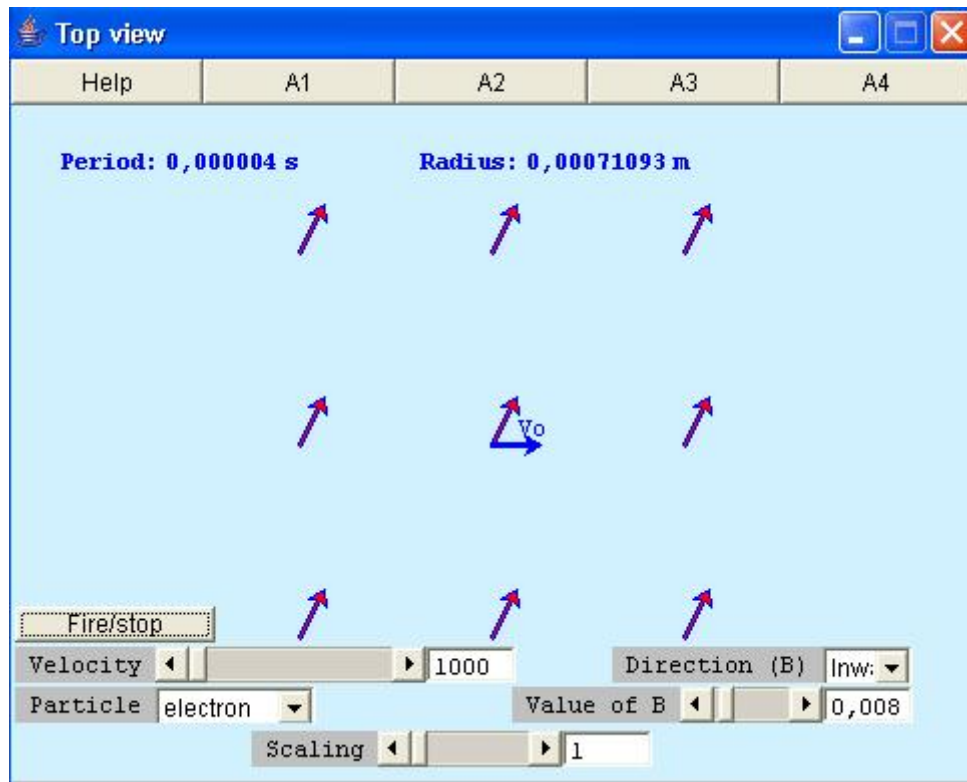
What is the trajectory of the particle? (Remember that you can always click and drag to change your point of view).

Change the values of the velocity, mass, charge and field until you manage to deduce a mathematical expression for the radius of the trajectory as a function of these parameters.

Search for a justification of these results in your textbook.

A4: Set the components of the velocity vector to non-zero values. Set the field to 1 tesla. Click on play. What is your explanation for what you observe?

Perhaps it will be easier to understand what you see with the trajectory view option.



Help: In this visual, a ray of particles shoots through a magnetic field perpendicular to its velocity.

We can change the type of particle and its speed. We can also determine the direction of the field vector B , perpendicular to the screen, and its modulus.

The scaling factor allows us to zoom in and out.

The fire/stop button alternates between the particles in movement and at rest.

A1: Click on fire. If you cannot see anything, zoom in.

See what would have happened if the ray had been a positron ray (a positron has the same mass as an electron but the opposite sign).

What can you deduce from this comparison.

Now try with a neutron. Can you explain this result?

A2: Now select a proton beam and note down the value of the radius and its period.

Do the same for the deuteron without changing the speed or the value of B .

If both particles have the same charge, what is the difference due to? Compare the results with those of an alpha particle.

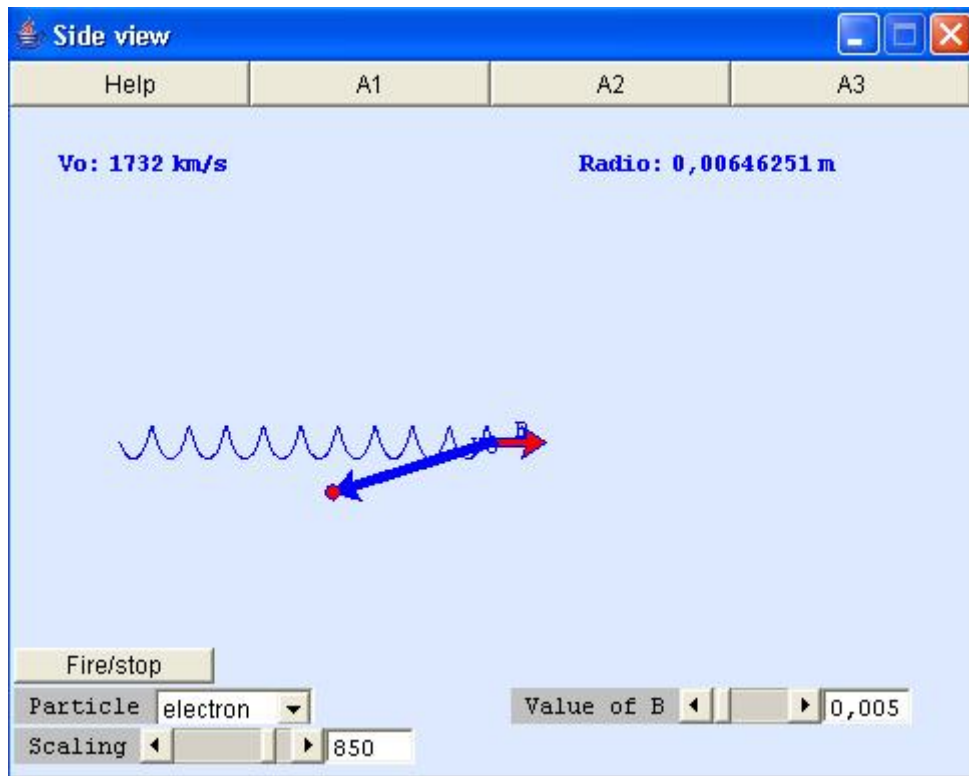
Can you explain this result?

A3: Select a particle, a proton, for example, and note down the values of the period and the radius of the trajectory for different values of the velocity. What can you deduce from your observations?

A4: Select a proton beam and check the effect of changing the direction of the magnetic field.

If you alter the modulus of B , how does this affect the trajectories?

Use the previous activities to deduce a couple of formulae to obtain the period and radius of the trajectory of a particle.



Help: In this visual, you can see the movement of a particle in a magnetic field that can form any angle with its speed.

You can use the particle control to select the type of particle.

A1: Click on fire to start with an electron. You can see the circular movement in perspective. Change the direction of its velocity. What happens to its trajectory? What happens when V_0 points along the same line as B ? How can you explain the shape of the trajectory?

Hint: consider the velocity as divided into two components, one in the direction of B and the other perpendicular to B .

A2: Now choose a positron and click on fire.

What is the difference compared to the electron?

If you take a proton, a deuteron or an alpha particle, you will have to change the scale. Why?

Why do different particles behave differently?

What happens if you choose a neutron? Why?

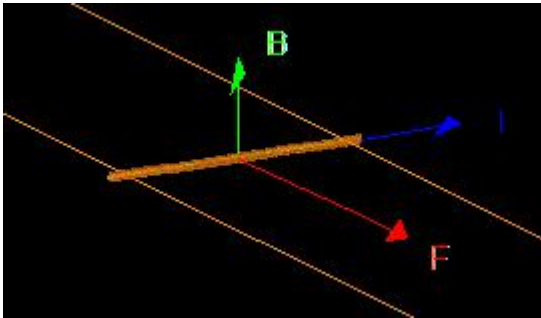
A3: Choose the proton and click on fire. What is the effect of altering the value of the field intensity?

Can you compensate for this effect by changing the velocity?

Now change the direction of the velocity. What is the effect of changing B now?

Observe the radius and the period of the circles.

The effects of the magnetic field on a straight cable



If the magnetic field affects charged particles in movement, then it must also affect a conductor through which a current is flowing. The charged particles moving through it will be pushed in some direction by the field. As they are confined inside the conductor, they will exert a measurable force on it.

In the visual **Field/Current**, you can observe the effect of the magnetic field on a straight cable. If the conductor is curved, or if the field is not homogeneous, then it is necessary to imagine the conductor is composed of an infinite number of small straight fragments of length dL and add up (integrate) the forces acting on each and every one of them.

Straight current:

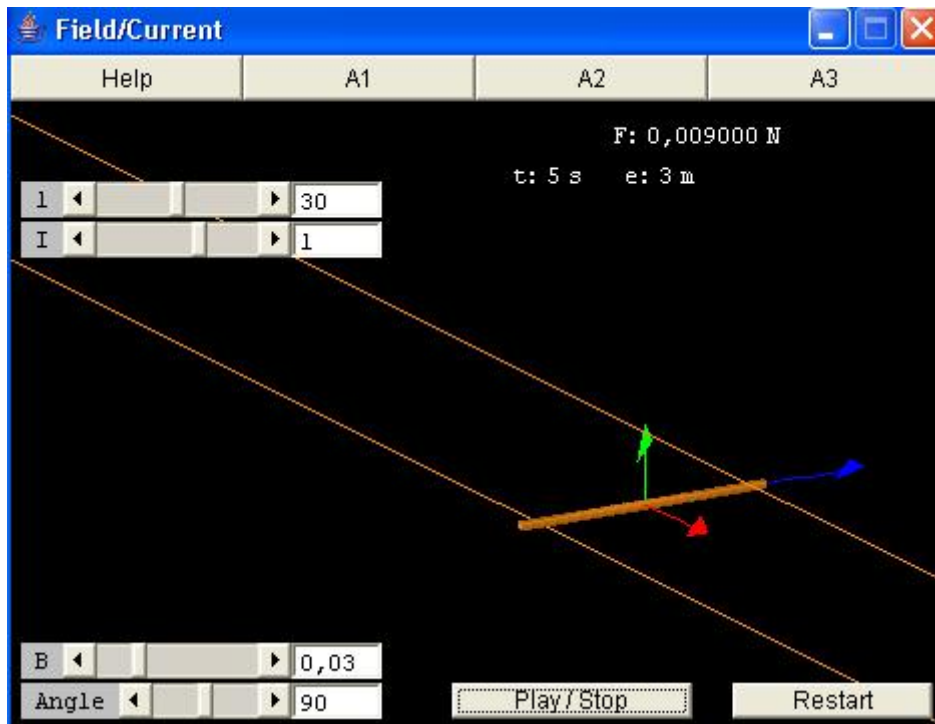
$$\vec{F} = I \cdot (\vec{L} \times \vec{B})$$

Curved current:

$$\vec{F} = \int I \cdot (d\vec{L} \times \vec{B})$$

The direction of the force is given by the left hand rule: if the index finger points in the direction of the field and the middle finger in the direction of the current, then the thumb will point in the direction of the force.





Help: A conductor with a variable length can move without friction along two conducting rails.

You can set the intensity of the current through the moving conductor and its direction (understanding the direction as the movement of positive charges). The negative sign means movement towards the left.

The blue vector indicates the direction of the current.

You can also choose the value of the homogeneous induction B and the angle it forms with the mobile conductor. The green vector indicates the direction of this vector.

The program calculates the force (red vector) and the movement of the conductor when you click on play.

To calculate the movement of the conductor, we have assumed that it weighs 100 gr/m.

A1: Set the intensity of the current to a positive value. 5 A, for example.

What is the relation between the vectors that indicate the direction of the current, the field and the force?

What if we change the direction of the current?

A2: Note down the force for different values of the field intensity. What is the relation between the the force and the current?

Repeat the experiment, but this time change only the value of the length to determine the relation between the length of the conductor and the force.

Now try to find out the relation between the force and B .

To find out the relation between the angle and the force, you will need to calculate a data table for the sine of the angle (one entry for every 30° , for example) and then relate these values to those of the force.

Try to summarize your conclusions in a mathematical law taking into account your previous observations.

A3: Once you have set the intensity of the current to a value different from zero, click on play and then stop the animation every 5 seconds to note down the distance covered by the conductor.

What type of movement can you observe? Explain why it is moving this way.

The effects of the magnetic field on a loop



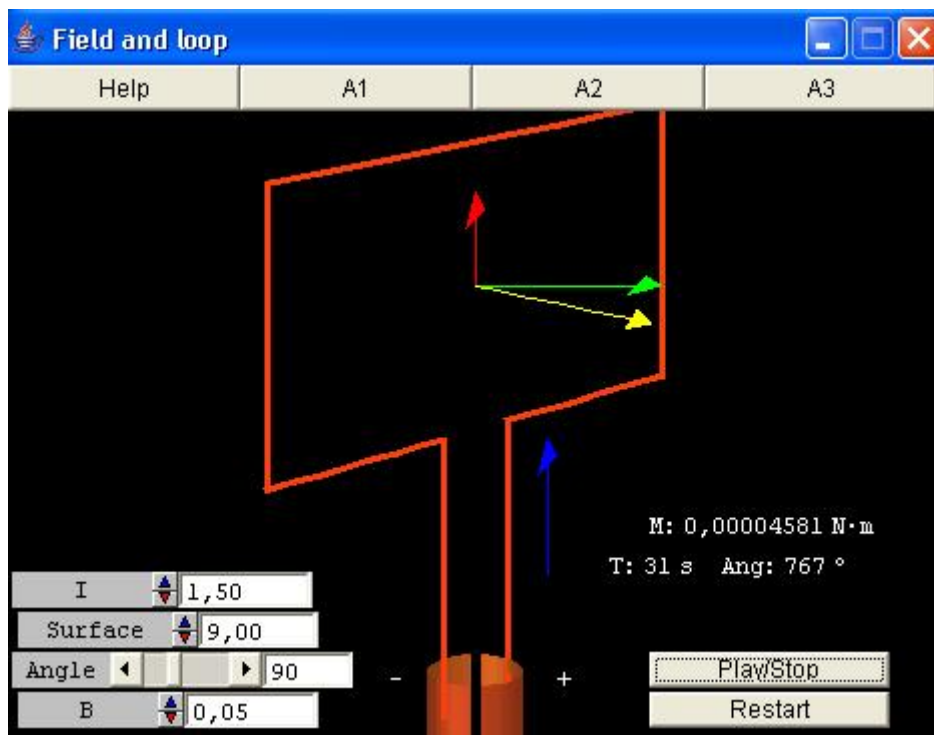
One of the most interesting applications of electromagnetism is the production of mechanical energy with electric motors like the one in the illustration on the left.

We all know that, inside these motors, one or more coils spin in a magnetic field when a current circulates through them.

Why is this so?. Let us study the simplest case in order to understand why.

In this case, a single loop is moving in the magnetic field. You can easily understand that the field would produce the same effect on a coil (multiplying by the number of loops).

Click on **Field and loop** to carry out the experiment.



Help: The visual represents a rectangular loop of current (with the direction of the current indicated by the blue arrow). You can change the size of the rectangle. You can also change the value of the magnetic field B and the initial angle between the surface vector (yellow) and the field vector (green).

The effect of the magnetic field on the loop is a pair of forces which produce a torque (red vector).

The program tells us the value of this torque.

The Play/Stop control allows you to start the visual and watch the loop move.

The Restart control restores the initial values of the experiment.

A1: Set the value of the current to 1 A. Watch the three vectors.

Justify the direction of the surface vector (note the direction of the current). If you cannot see the angles between vectors clearly, increase the initial angle.

What is the angle between the torque vector and the surface and magnetic induction vectors? Why do you think this is so?

A2: If you only change the value of the current, how does the torque change?

What if you only change the surface of the rectangle?

What if you change the value of B?

You can also study the variation of the torque with the angle by comparing the values of the torque to the values of the sine of the angles.

Try to express your conclusions in a mathematical formula.

A3: Set the value of the intensity of the current to 1 A and the value of B to 0.1 T.

Click on play and note down the angle after 5, 10, 15 and 20 seconds.

What kind of movement is taking place? Would you say that the acceleration is uniform?

Repeat the experiment changing the initial angle to 0°. What happens when you click on play now? Why?

When is the torque greater?

Conclusions about the effects of the magnetic field

A charged particle q with velocity \mathbf{V} moving in a magnetic field \mathbf{B} will feel a force \mathbf{F} given by the formula on the right.

$$\vec{F} = q \cdot \vec{V} \times \vec{B}$$

Under the influence of such a force, the particle will move along a circular trajectory (if \mathbf{V} is perpendicular to \mathbf{B}), or along a helix (if \mathbf{V} and \mathbf{B} form an oblique angle).

The unit of magnetic induction (tesla) will exert a force of one newton on a unit charge moving at a speed of 1 m/s in a direction perpendicular to the field.

A straight wire of length L through which a current I is flowing is affected by the field \mathbf{B} in accordance with the expression on the right.

Straight current:

$$\vec{F} = I \cdot (\vec{L} \times \vec{B})$$

If the cable is curved or the field \mathbf{B} is not homogeneous, it is necessary to integrate the effect of the field on an infinite number of small elements $d\mathbf{L}$, as you can see in the formula on the right.

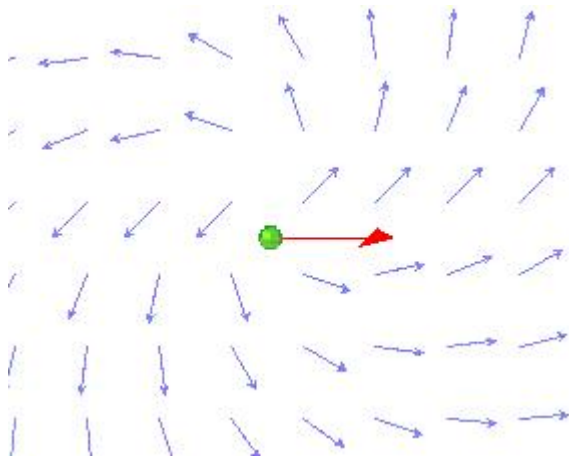
Curved current:

$$\vec{F} = \int I \cdot (d\vec{L} \times \vec{B})$$

A current flowing through a loop which encloses a surface S , would feel a torque M given by the expression on the right. A similar effect would take place on a coil, but the torque would be greater, as it would be proportional to the number of loops.

$$\vec{M} = I \cdot \vec{S} \times \vec{B}$$

The field created by a charged particle



We already know (as a consequence of Öersted's experiment) that electric currents produce magnetic fields because an electric current affects the behaviour of a compass.

The smallest electric current that we can imagine is the current produced by a single charged particle. That is why the following visual studies the field created by a particle in movement: **Field/Particle**

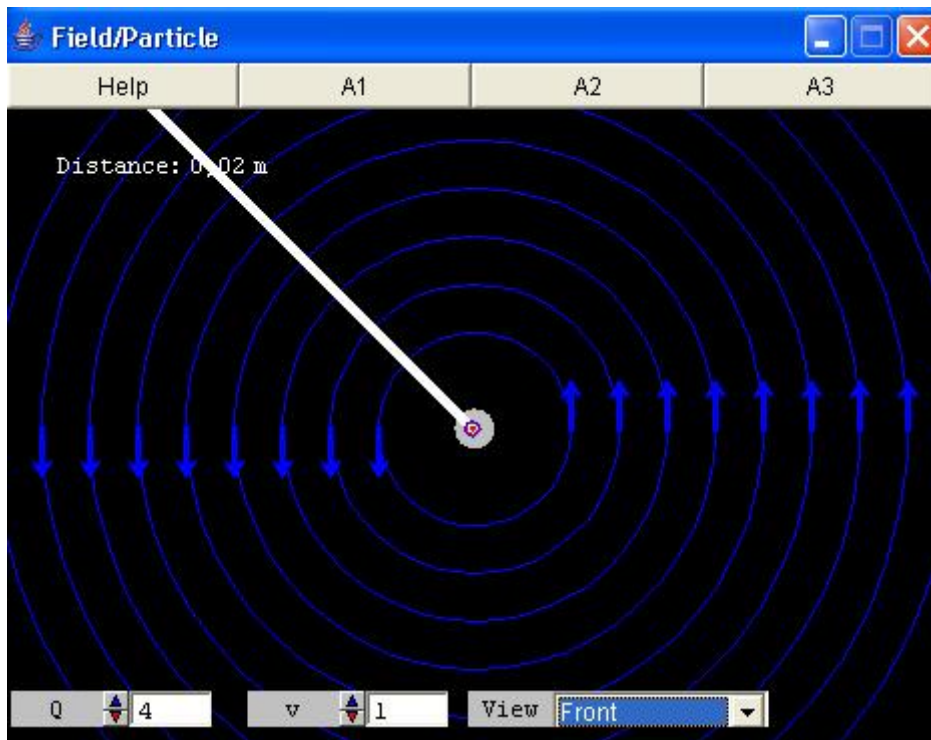
Note that, in this visual, you will observe the field from two different points of view, because the magnetic field created by a particle is asymmetrical.

Hopefully, the visual and your textbook will help you understand the following expression:

$$\vec{B} = \frac{\mu_0 \cdot q \cdot \vec{V} \times \vec{R}}{4 \cdot \pi \cdot R^3}$$

The formula expresses the fact that the particle with charge q and velocity V creates a field B at a point which is defined by the vector R from the position of the particle.

The constant μ_0 is known as the magnetic permeability of free space or the magnetic constant.



Help: This visual represents the magnetic field created by a charged particle in movement from two different points of view.

The front view shows the lines of force in the plane perpendicular to the trajectory of the particle at the point where the particle is.

You can also see the induction vector and its value by dragging the red dot to any point on the visual.

The side view shows the trajectory and velocity of the particle and allows you to measure the intensity of the field created along a line perpendicular to your field of vision.

A1: In the front view, the particle is moving towards the observer.

If you give the speed a positive value, you will see the lines of force appear. What happens if you change the sign of the charge?

Drag the red dot along a line of force. What is the relation between the induction vector and the line of force?

A2: For fixed values of Q and v , observe the change in the value of B with the distance r . Try to discover a mathematical expression that describes your observations.

Try to find out how B depends on the values q and v for a given point.

Find a mathematical law in your textbook that justifies your observations.

A3: Set the charge and the speed to a given value. Select the side view.

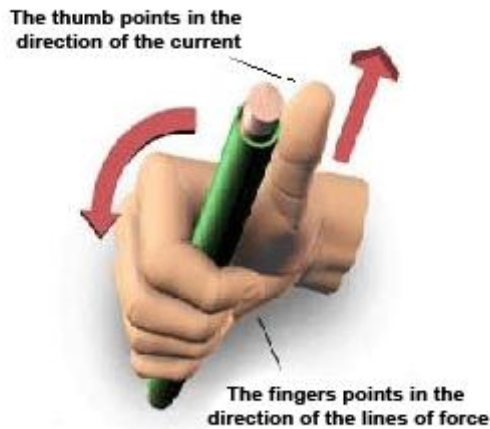
Observe the value of B for points situated at the same distance from the charge, but at different angles.

What can you deduce from your observations?

Search your textbook for a theoretical justification of these observations.

The field created by a rectilinear current

A rectilinear electric current of an indefinite length creates a magnetic field around itself.



You can study the main features of this type of field in the following visual: **Field/Current**. The visual will help you understand that the value of the magnetic induction is equal to

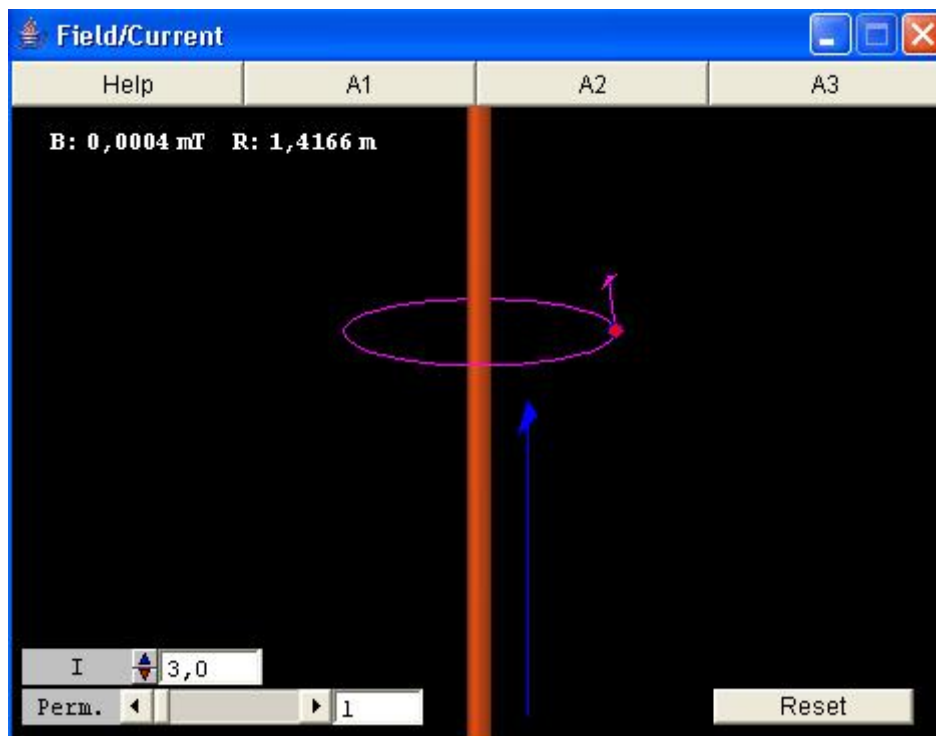
$$B = \frac{\mu \cdot I}{2 \cdot \pi \cdot r}$$

where I is the intensity of the current and r is the distance from the current to the point at which we are measuring the field B .

The magnetic constant μ (magnetic permeability) depends on the medium.

This expression does not give the direction of the field vector, but you can use the right-hand rule illustrated above to figure it out.

The visual **Between currents** studies the effect of the magnetic field created by one current on another current.



Help: This visual represents the magnetic field created by an indefinite rectilinear current.

You may set the value of the intensity of the current (negative values for currents moving towards the bottom of the visual).

You can also set the permeability relative to the permeability of free space.

Drag the red dot to different points to see the value of the field at these points.

Click on any point of the visual to see the field and the lines of force there.

The reset button takes the visual back to the initial point of view.

A1: Set the current to 1 A and drag the red dot to different points of the screen. You will see a curve and a vector. What is the curve like? What is its position in relation to the conductor?

You can rotate the point of view by dragging the conductor.

What happens if you change the sign of the current?

Try to find a mnemonic device to help you remember what you have just discovered.

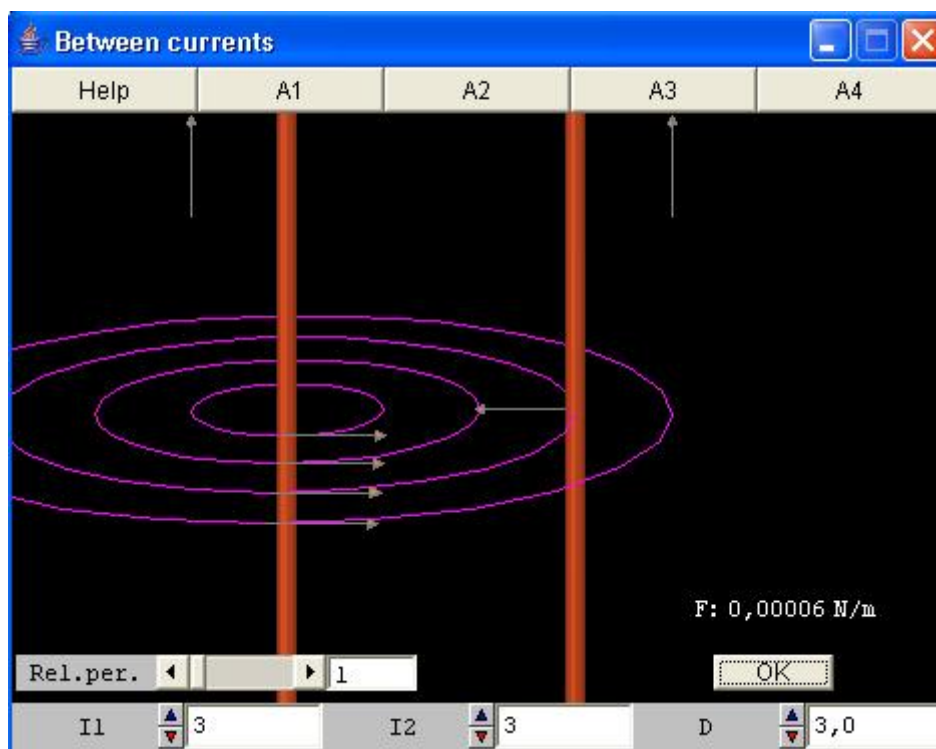
A2: The intensity of the field at a given point varies when you change the intensity of the current. How does the value of B vary?

For a fixed value of the current, try to find out how B varies with the distance. How does B vary now?

Now try to figure out how B changes when you change the magnetic permeability.

A3: You have probably noticed that, once you know the intensity of the current and the permeability of the medium, you only need to find out the distance to the conductor to determine the value of B. Being above or below this point, or being behind or in front of the current is immaterial, as long as the distance to the current is the same. Why?

What would happen towards the edges of the conductor if the length was not indefinite?



Help: This visual allows you to choose the intensity of the current flowing through two conductors. Negative values mean the current is pointing towards the bottom of the visual.

You can also set the distance between the two cables and the relative magnetic permeability of the medium between them. If the value is equal to 1, the medium is free space.

The OK button shows the lines of force created by one of the currents and the force exerted on the other cable per unit length.

You will see another vector on the second cable which shows the direction of the force.

A1: Set I_1 to a positive value and click on OK.

You will see some of the lines of force created by this conductor and some arrows that point in the direction of the lines of force. What happens if the current is flowing in the opposite direction?

A2: Set I_1 and I_2 to positive values. Click on OK. In which direction is the force exerted?

Change the values of I_1 and I_2 . What is the relation between the force and the intensities of the currents?

Alter the distance between the conductors. How does this influence the observed force?

What happens when the intensities have opposite signs? How do the results differ?

A3: Give I_1 and I_2 values different from zero and click on OK.

Increase the value of the relative permeability. You will now see a medium between the two conductors.

What is the influence of the medium on the force measured?

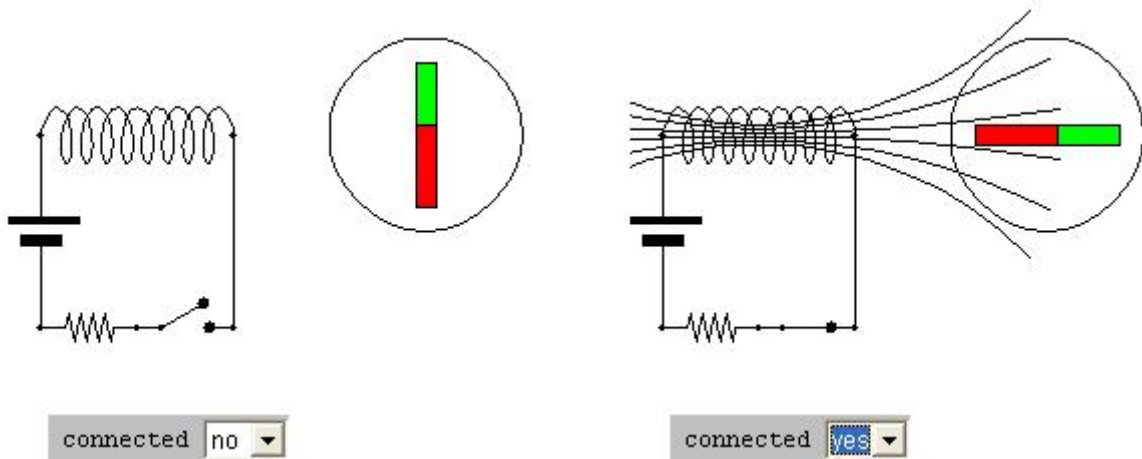
How would you synthesise your conclusions about this activity and the previous one in a single mathematical formula?

A4: Set I_1 and I_2 to 1 A and the value of the relative permeability to 1. Then choose a distance of 1 cm.

What is the force between the two conductors? Calculate the value of this force for a distance of 1 m.

Try to come up with a definition of the unit of current, the ampere, taking into account the force you have just calculated.

The field created by an electromagnetic coil

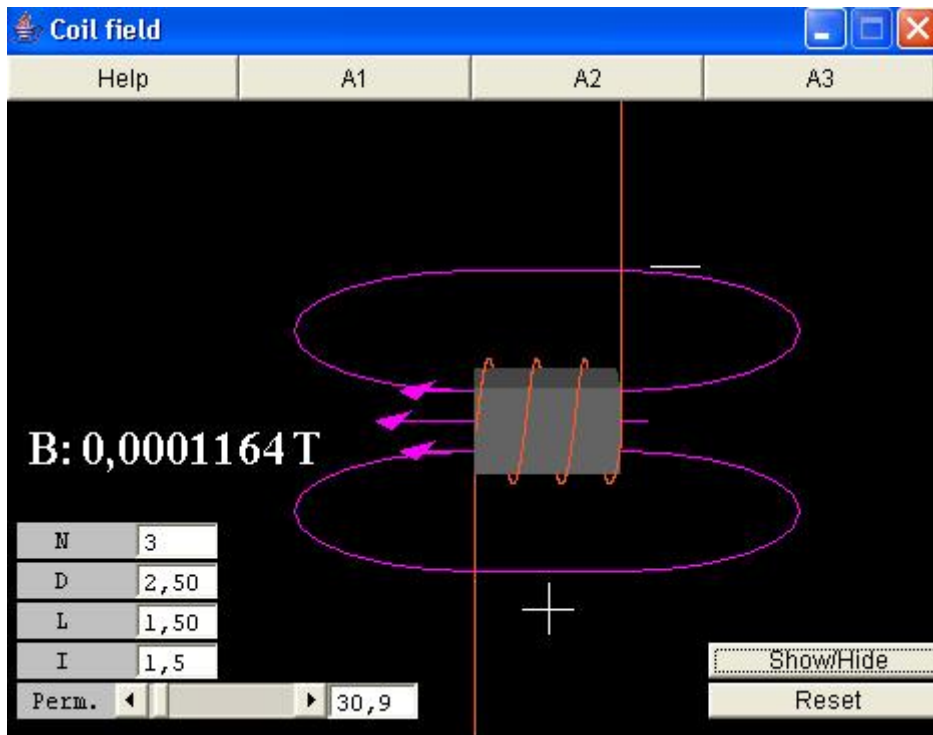


In the visual, you can see a circuit with a coil or solenoid near a compass. When you close the circuit the coil behaves like an electromagnet and it attracts the magnet in the compass towards one of its poles.

How can we tell which of the poles is north and which is south in the electromagnet that has just been created?

How can you make the magnetic field more intense? You will be able to answer all these questions after you have studied the following visual: **Coil field**.

Through some "experiments", you have studied the electromagnetic field created by straight cables and coils. In both cases we could have used Ampère's law, which is also applicable to many other cases. You can study Ampère's law in **Ampere**, and try to deduce the value of B theoretically.



Help: This visual calculates the value of the magnetic field inside and near the poles of a straight solenoid or coil.

It also shows some of the lines of force of the field (use the Show/Hide control).

If the magnetic permeability increases you will see a core inside which corresponds to a medium with the right permeability.

You can change your point of view by dragging the coil with your mouse.

The reset control takes you back to the initial point of view.

A1: Increase the value of L until you reach the maximum and set the intensity of the current to a positive value.

Note that the lines of force inside the solenoid remain parallel (use the Show/Hide control).

What is the relation between this fact and the intensity of the field?

Where is the field stronger, inside or outside the solenoid?

Rotate the coil to the side where the lines of force leave the solenoid. Which of the two poles are you looking at? Can you tell if the current is flowing clockwise or anticlockwise from this point of view?

Rotate the solenoid until you can see the other pole and answer the same questions.

A2: Change the value of I and observe the variation in B. What is the relation between I and B?

What if you change the number of loops?

What if you alter the diameter of the coil?

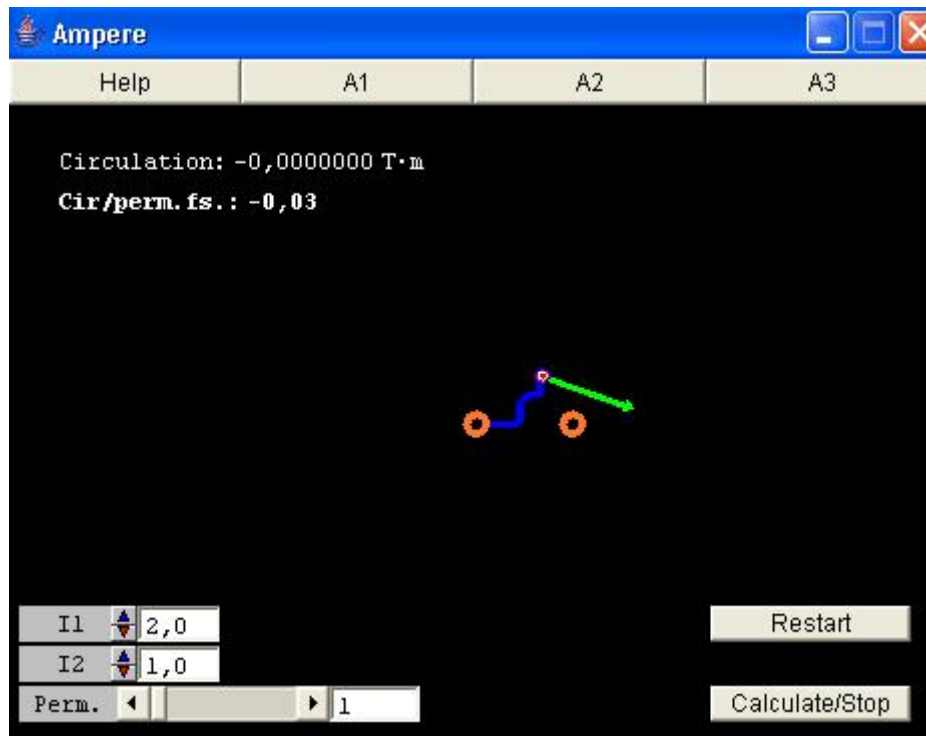
What if you change the length of the coil?

Try to come up with a mathematical law which expresses your conclusions.

A3: Change the magnetic permeability. Diamagnetic media have a permeability which is similar to (or smaller than) the permeability of free space. Paramagnetic media (most metals) have a permeability which is dozens of times greater than the permeability of free space. Ferromagnetic media (iron and alloys of iron) have a magnetic permeability which is hundreds and even thousands of times greater than that of free space.

How does the field depend on the permeability? What type of substance would you use as a core for an electromagnet?

Insert the relation between the permeability and B in the law that you deduced in the previous exercise.



Help: In the visual you can see the section of one or two conductors (depending on whether their intensities are different from zero).

If the intensity of the current is positive the current flows into the screen (this is indicated by a black dot on the conductor), otherwise the current flows towards the observer (this is indicated by a blue dot on the conductor).

If you drag the red dot with your mouse, you will see a green vector that indicates the direction of the magnetic induction (but it does not show its value).

Click on Calculate/Stop to sum up all the terms $b \cdot dl$ that correspond to the displacement of the red dot. The smaller the displacement of the dot (if you move the mouse without leaving gaps along the way) the better the results will be in terms of precision.

The screen will show the total circulation and the result of dividing this circulation by the permeability of free space.

Click on restart to restore initial values.

A1: Set I1 and I2 to any value, 1 and 2 A, for example.

Click on Calculate/Stop and drag the red dot along any closed trajectory which does not enclose the two conductors. Repeat the experiment a few times with different values of I1 and I2. What is the approximate value of the circulation in every case?

A2: Set I1 to 2 A and I2 to 0. Click on Calculate/Stop and drag the red dot along a trajectory that encloses a conductor. What happens to the value of Cir/perm. fs.? What if you set I1 to a negative value? How about the case when I1 and I2 are set to positive values? What if you set I1 to a positive value and you set I2 to the same value, but with a negative sign. Try to deduce a general law for the circulation of B along a closed trajectory.

A3: Set the permeability to a large value (500, for example) and give I_1 and I_2 the values 1 and 0.

Calculate the circulation along a closed trajectory that encloses the conductor.

Compare your results with those of the previous activity.

Now use values different from zero for both intensities of current. Modify the law you obtained in the previous activity to include your most recent discoveries.

Assuming you have carried out the activities correctly, you will have deduced Ampère's law.

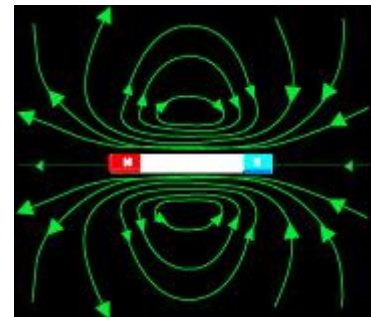
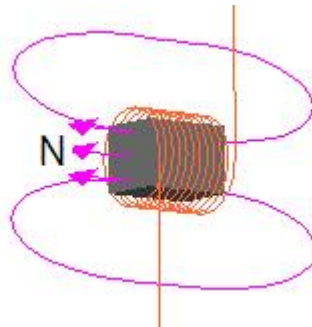
An explanation of natural magnetism



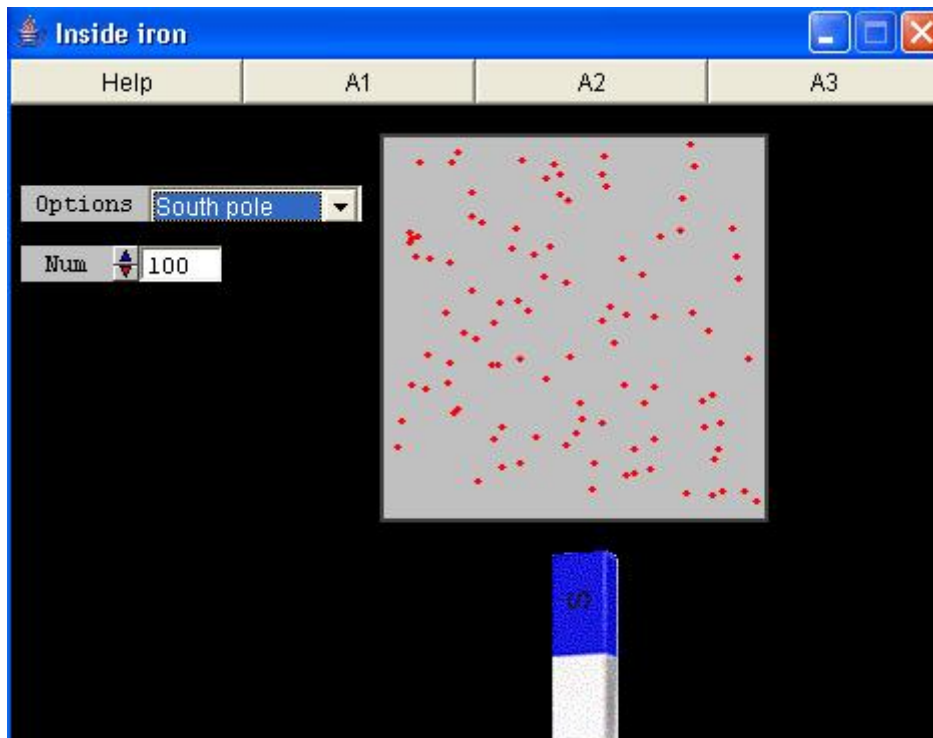
At the beginning of the unit, you were asked about the relation between the magnetic field created by a natural magnet and the magnetic field created by an electric current.

Having studied the magnetic field created by an electromagnetic coil, you have seen the similarity between the field created by a coil and the field created by a natural magnet.

In both cases, the polarity and the lines of force are similar.



Click on [Inside iron](#) to understand the cause of this similarity.



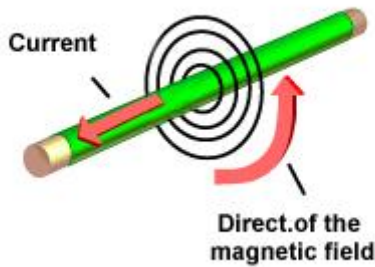
Help: The visual represents a cloud of electrons inside a block of iron.
 You may choose the number of electrons shown (using the Num. parameter).
 You can also choose whether to place one of the poles of a magnet near the block.
 Otherwise, the magnetic field is nil near the block.

A1: When you activate the visual, you can see the electrons in a block of iron. Can you identify a fixed trajectory followed by all the electrons? If it is difficult to tell, you can decrease the number of electrons (use the Num. control)
 Search your Physics and Chemistry textbook (first year of post-compulsory secondary education) for a justification of this cloud-like behaviour (check the chapter on the chemical bond).

A2: Use the options control to place a magnet near the block of iron. What is the effect on the trajectories of the electrons?

A3: Place a magnet near the iron. Compare the movement of the electrons to the movement of the current through a Solenoid.
 Can you explain why the metal will behave like a magnet?
 Where will its north pole be? What about the south pole?
 In some alloys of iron, the effect persists even when the natural magnet has been removed, in such a way that the metal becomes a permanent magnet. If you wish to find out more about the subject look up the word hysteresis in a good encyclopaedia.

Conclusions about the creation of magnetic fields

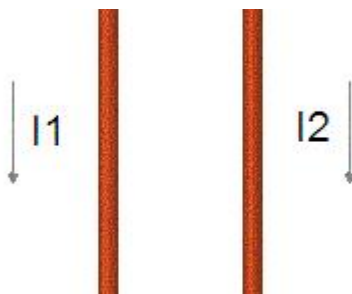


A rectilinear current or a moving charge create lines of force around themselves as shown in the figure on the left.

The modulus of the field created by a rectilinear current of an indefinite length is given by the following formula:

$$B = \frac{\mu \cdot I}{2 \cdot \pi \cdot r}$$

where I is the intensity of the current and r is the distance to the point at which the intensity is equal to B , μ is the magnetic permeability of the medium.

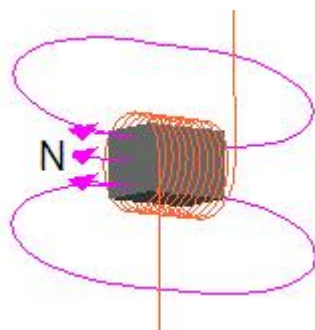


Two parallel rectilinear currents interact in such a way that they attract each other if they are flowing in the same direction and they repel each other if they are flowing in opposite directions. The value of this force per unit length is:

$$F/l = \frac{\mu \cdot I_1 \cdot I_2}{2 \cdot \pi \cdot r}$$

where r is the distance between the conductors, I_1 and I_2 are the corresponding intensities of the current and μ is the magnetic permeability of the medium.

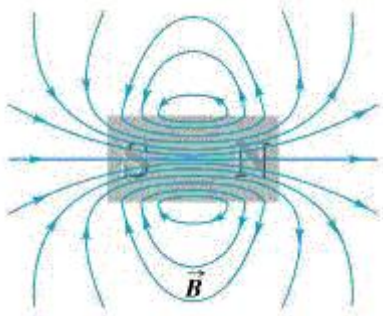
More conclusions about the creation of magnetic fields



Coils create a magnetic field with the following intensity:

$$B = \frac{\mu \cdot n \cdot I}{l}$$

where l is the length of the coil and n is the number of loops. You can tell between the poles by noting that if you look at the north pole, the current circulates counterclockwise.



A natural magnet behaves like a coil because a significant percentage of the electrons revolve in a preferred direction.

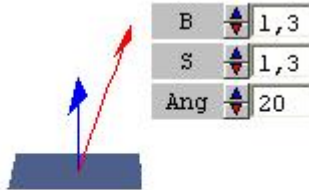
The field of a natural magnet affects the electrons in other materials containing iron in such a way that the electrons in the other material change their trajectories. If the electrons go back to their chaotic trajectories when the natural magnet is removed, then the magnetization is **temporal**, otherwise it is **permanent**.

$$\oint \vec{B} \cdot d\vec{l} = \mu \cdot \sum I$$

Ampère proved that if we divide a trajectory up into an infinite number of elements and integrate the scalar products of the induction **B** and each element of the trajectory **dl**, then the result is proportional to the sum of the intensities of current that flow through the surface limited by the closed trajectory. This law has been very helpful in the theoretical analysis of many magnetic fields.

Ampère proved that if we divide a trajectory up into an infinite number of elements and integrate the scalar products of the induction **B** and each element of the trajectory **dl**, then the result is proportional to the sum

Magnetic flux



$$\begin{aligned} \Phi &= 1,3 \cdot 1,3 \cdot \cos(20,0) \\ \Phi &= 1,58 \text{ T} \cdot \text{m}^2 \end{aligned}$$

The mathematical concept of magnetic flux is helpful when you deal with induced currents. It is time, therefore, to include its definition here.

The magnetic flux through a surface is equal to the following scalar product:

$$\Phi = \vec{B} \cdot \Delta \vec{S}$$

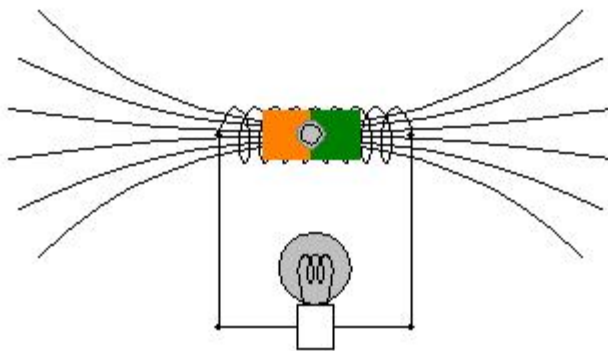
where **B** is the magnetic induction and **ΔS** is the surface vector. In the above visual, you can study the variation of flux with each of the variables involved.

When the field is not homogeneous, or the surface is curved, it is necessary to imagine the surface divided into small elements **dS** and sum (integrate) the flux

through each of these elements. Here is a general expression for the value of the flux through an arbitrary surface:

$$\Phi = \int \vec{B} \cdot d\vec{S}$$

The laws of Faraday and Lenz



The visual on the left shows Faraday's experiment in a qualitative way: you can see a magnet, with its lines of force, and a circuit formed by a coil and a light bulb, without a power supply.

If we move the magnet through the coil or away from it (dragging the dot in the middle) the bulb will light up.

It is the **variation of the magnetic flux** through the coil that generates a current through the light bulb.

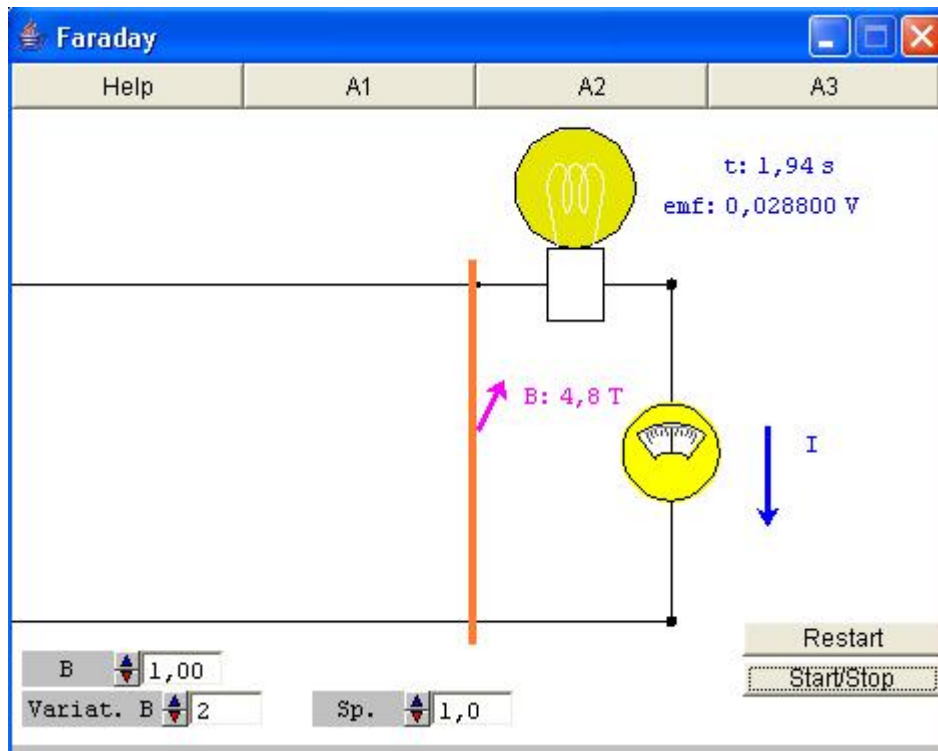
This current is known as an **induced current**.

You can study the production of induced currents in more detail by clicking on **Faraday**. In this visual, you will be able to study the induced current in a simple circuit when the surface of the circuit is changed and when the field intensity is altered. You will also learn the laws of Faraday and Lenz, which can be summarised in the following expression:

$$\text{emf} = - \frac{d\Phi}{dt}$$

where emf is the induced electromotive force.

In the section on alternating current you will find how an induced current is produced when the angle between the field vector and the surface of the circuit changes.



Help: This visual represents the current induced by the variation of the intensity of the homogeneous field B (perpendicular to the surface of the circuit) or by the variation of the surface of the circuit as a metal rod moves along.

You can control the initial value of B and its rate of change with time. You may also set the speed of the displacement of the only element of the circuit that can move: the orange rod.

Once you click on Start/Stop, the program will simulate the passing of time and the electromotive force produced.

The arrow labeled B shows the direction of the field vector. The arrow labeled I shows the direction of the induced current.

The restart control takes you back to the initial conditions of the visual.

A1: Set the rate of change of B to a positive value and click on Start/Stop.

Test different positive values of this rate of change. What is the effect of this variation in time?

Observe the direction of the induced current. Try to determine the direction of the current induced by this current as it flows through the circuit.

Now test negative values of the rate of change of B . What is the direction of the induced current now? What about the magnetic field produced in the circuit?

A2: Set the value of the speed of the rod to a positive number and click on Start/Stop.

Will the surface of the circuit increase or decrease? What current is induced? What is the direction of this current? Try to determine the direction of the magnetic field produced by this current.

Test different positive values of the speed. What is the relation between the induced current and the speed of the rod?

Now test different negative values of the speed. Can you tell the difference?

A3: Once you have noted down the results of the previous activities, search your textbook for the laws of Faraday and Lenz and try to justify your results using these laws.

Self-induction



A very simple way of producing induced currents in a circuit is to change the intensity of the current that flows through it, as this generates a variable magnetic field. This phenomenon takes place when you switch on an electric device. The phenomenon is much stronger if there is a coil in the circuit, as in the figure on the left.

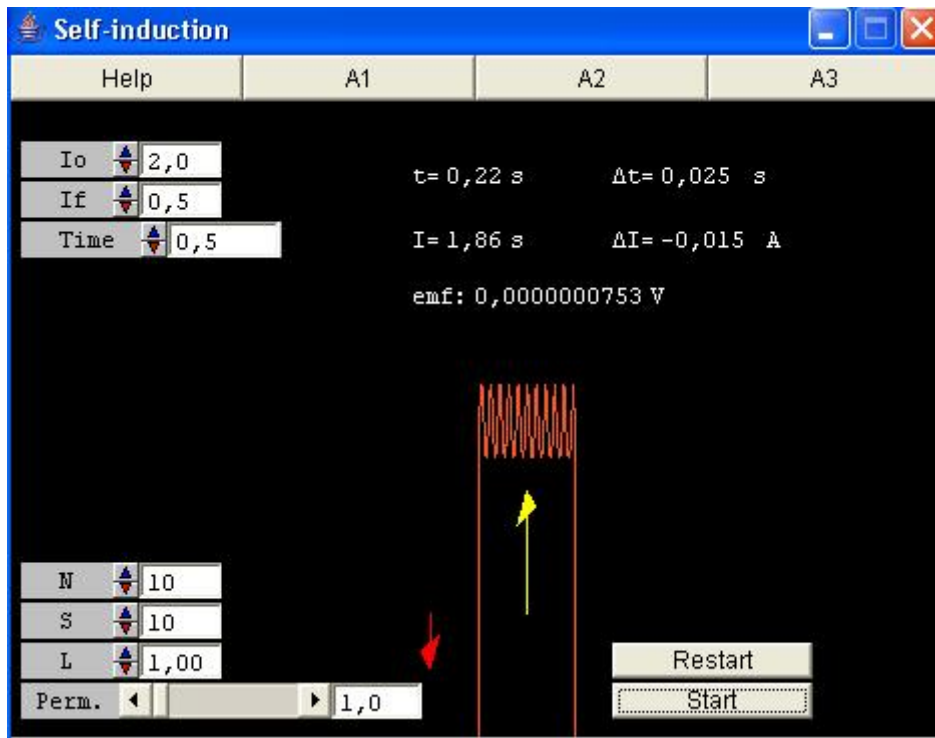
You can study the phenomenon of self-induction of a coil in the following visual **self-induction**, where you will be able to see how it depends on some of the properties of the circuit, as the law of Henry states:

$$\text{emf} = - L \cdot \frac{di}{dt}$$

emf is the self-induced electromotive force, di/dt is the variation of the intensity of current with time and L is the self-inductance or inductance of the coil, which is a property of the coil and is measured in henries. Its value is equal to:

$$L = \frac{\mu \cdot n^2 \cdot S}{l}$$

where μ is the magnetic permeability of the medium, n is the number of loops and l is the length of the coil.



Help: This visual represents the current induced in a coil by a variable electric current in the same coil.

You can change the initial and final values of the variable current and change the time it takes to go from one to another.

You can also change other properties of the coil, like the number of loops, the surface enclosed by each of them, the length of the coil and the magnetic permeability of the core (1 corresponds to a vacuum).

A red vector indicates the direction of the incoming current and a yellow vector indicates the induced current.

Click on start to set the visual in motion. Restart takes you back to the initial values.

A1: Set $I_0=0$ A, $I_f=5$ A and the time to 0.1.

Click on start.

Observe that the visual takes small time steps and shows the corresponding variations of the intensity.

Divide the increase in the intensity by the increase in t and write it down beside the emf produced.

Repeat the process for different values of I_f . What is the relation between the quotients and the increase in intensity and emf?

Now set $I_0=5$ A and $I_f=0$. What differences can you observe?

Can you find a law for the direction of the induced current?

A2: Set $I_0=0$ A and $I_f=5$ A. Set the time to 0.1 s.

Increase the number of loops to 10 and click on start.

What is the influence of the number of loops on the emf? Try out other values of n to see if you can find a law of proportionality or some other kind of law.

Use the same process to try to find out the influence of the parameters S and L and the relative permeability of the nucleus.

Can you write a mathematical formula that takes all these influences into account?

A3: Search for the law that describes the phenomenon you have just studied in your textbook. What is the inductance? What is its relation with the previous activities?

Conclusions about induced currents

The concept of magnetic flux

The magnetic flux through a surface is the scalar product of the surface and induction vectors, or, if the product is variable along the surface, the flux is equal to the following integral

Falta

Induced currents

When the magnetic flux through a circuit changes, the circuit produces an electric current called induced current.

The laws of Faraday and Lenz

According to the law of Faraday, the current induced in a circuit has an emf equal to

$$\text{emf} = - \frac{d\Phi}{dt}$$

where the sign means that the induced emf generates a flux that tends to compensate the flux that generated the current (this is the law of Lenz)

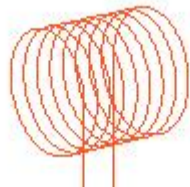
Self-induction

When a variable current flows through a coil, it generates an induced current:

$$\text{emf} = - L \cdot \frac{di}{dt}$$

where L is the self-inductance of inductance, which is measured in henries.

The generation of alternating currents



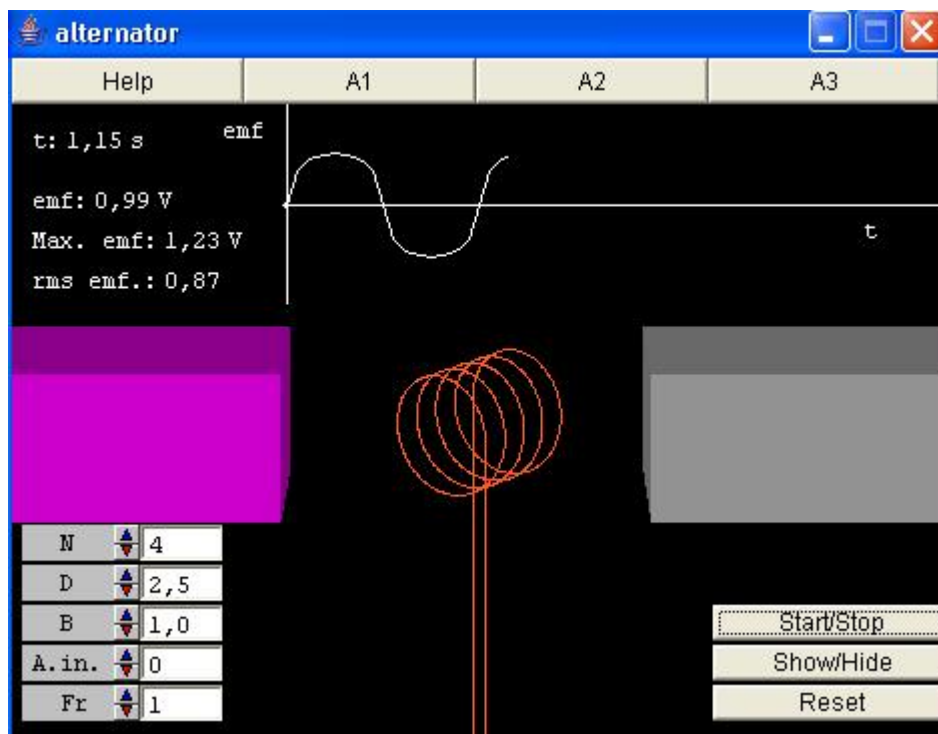
Another way of varying the magnetic flux through a circuit is to make it rotate in a magnetic field.

In the visual **alternator** you can examine this phenomenon by making a coil rotate within a magnetic field.

You will discover that this produces a variable electric current known as alternating current, which is equal to:

$emf = E_m \cdot \sin(2\pi \cdot f \cdot t + \varphi)$, where f is the frequency of the rotation of the coil, φ is the initial phase angle (the initial angular position of the coil) and E_m is the maximum value of the electromotive force, which is given by the following formula:

$E_m = n \cdot B \cdot S \cdot \omega$ where $\omega = 2\pi \cdot f$, n is the number of loops, B is the magnetic induction and S is the surface enclosed by each loop.



Help: The visual shows a graph of the current induced when a coil rotates uniformly in a homogeneous magnetic field.

You can set the number of loops in the coil and their diameter, and the value of the field B , the initial phase angle of the coil and the frequency of its rotation.

The Start/Stop control sets the coil in motion and stops it if it is pressed again.
The visual shows the value of the induced electromotive force as time goes by, its maximum value and its root mean square value.
The Show/Hide control toggles the visibility of the magnetic field and surface vectors.
The Restart button resets the visual.

A1: Click on Start and observe the current produced. How is this possible if B and S have not changed?

Click on Show/Hide to better understand this point. Do the B and S vectors always form the same angle?

Observe the graph and the values on the left. Why is this current known as alternating current?

What mathematical function looks like the graph you are observing?

A2: Change the value of N and observe the variation in the maximum emf. What is the relation between the two?

What if you change the number of loops or the magnetic field?

What if you change the frequency?

Observe the fact that the alteration of the initial angle does not seem to affect the variation of the maximum emf. What affects this parameter?

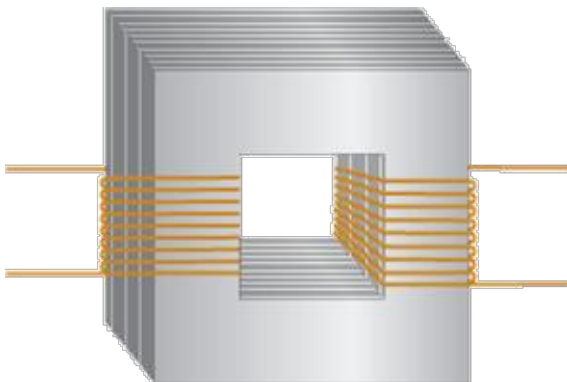
Try to deduce a mathematical formula from your observations in order to calculate the emf. Use your textbook to give a theoretical justification of the formula.

A3: The root mean square value of the electromotive force is the equivalent electromotive force that would be produced by a direct current that acted on a resistance during the same time interval.

Change the values of the parameters to determine the relation between the root mean square emf and the maximum emf.

Search for a theoretical justification of this relation in your textbook.

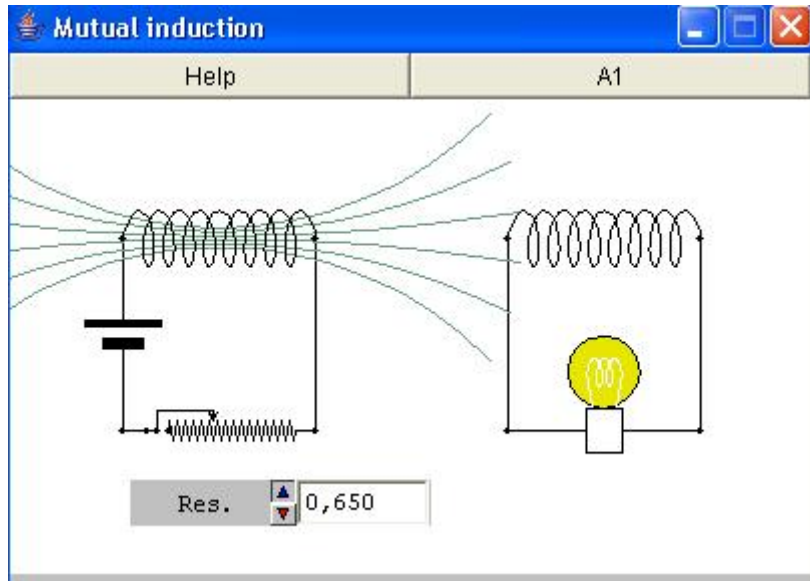
The properties of circuits of alternating current



Alternating current allows the manipulation of electricity in ways that would be difficult to achieve with direct current. The figure attached is a drawing of a transformer, which is capable of altering the electromotive force of a generator. To understand how it works, let us first examine the following visual **Mutual induction** to find out how one circuit can affect another.

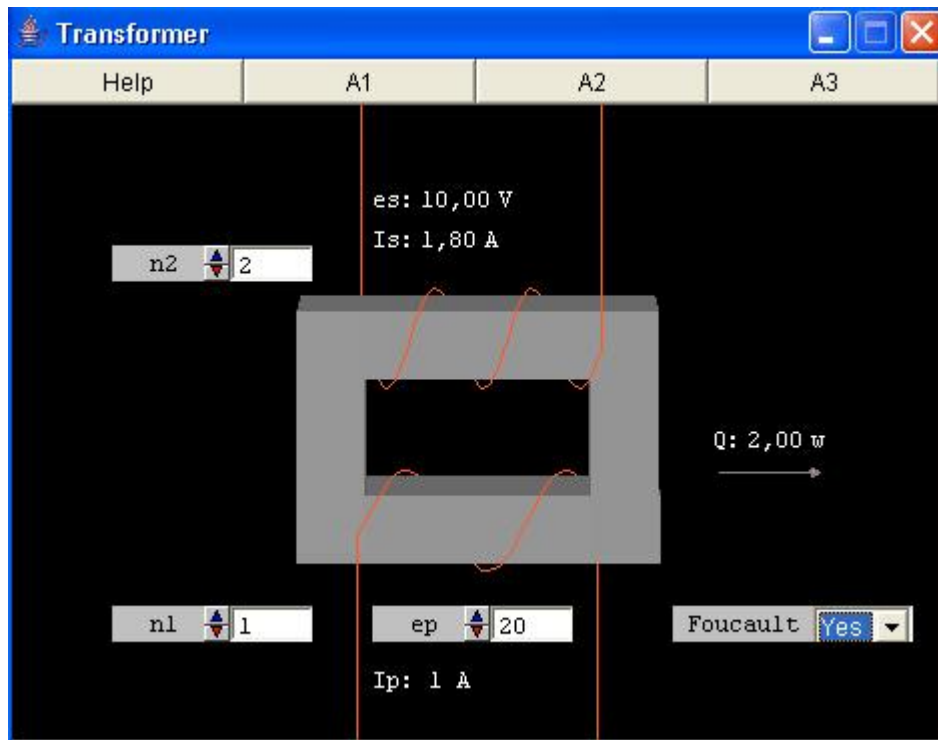
Then click on **Transformer** to find out about the laws of transformers.

In addition to this effect, alternating current also behaves differently from direct current in coils and capacitors. The study of these effects is undertaken at higher levels, but we can see some of the main features in the visual **RLC Circuit**, which includes a resistance, a coil and a capacitor.



Help: The visual represents a circuit of direct current with a generator, a coil and a variable resistance.
Next to this circuit, there is another one with a light bulb and a coil (without a power source).
You can change the value of the resistance in the first circuit (and, with it, the intensity of the current)

A1: What happens when you change the value of the resistance in the first circuit?
Why?



Help: This visual represents a transformer with a ferromagnetic core shared between two coils, which are called primary and secondary winding.

The primary current is equal to 1 A (an arbitrary value). You can set the electromotive force.

You can also set the number of loops in the primary and secondary windings, and whether the visual takes into account the currents induced in the core by the transformer (Foucault currents).

A1: Set the number of loops in the primary winding to 4.

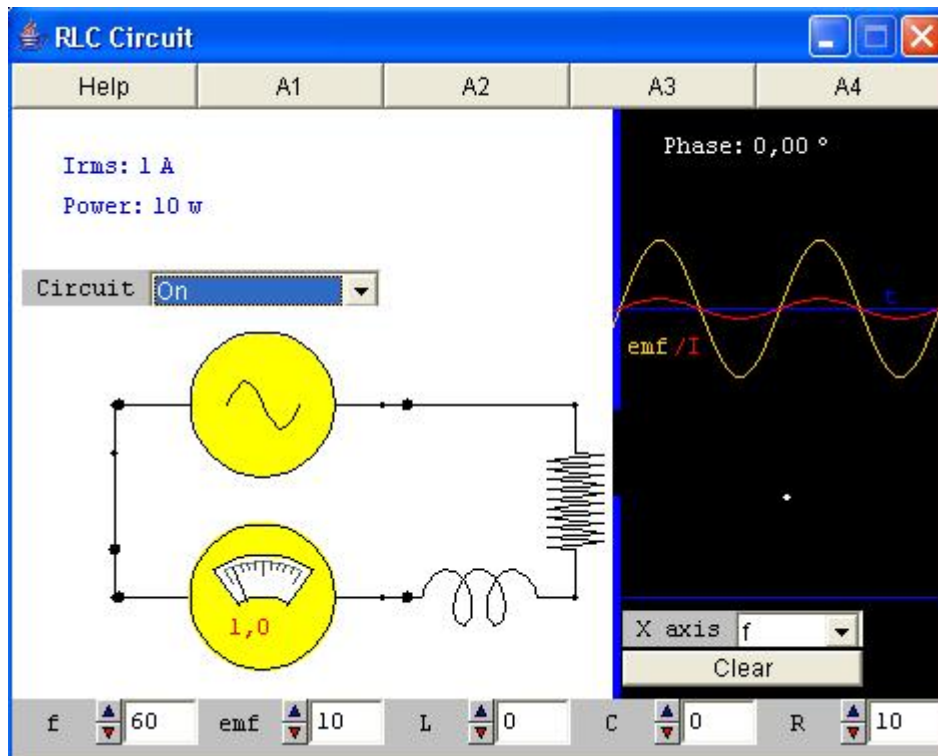
Change the number of loops in the secondary winding in such a way that it is:

- Four times greater than in the primary winding.
- Half the number in the primary winding.

Try to deduce the expression that relates the number of loops to the corresponding emf.

A2: Note that it is not the same thing to say that we are multiplying the emf as to say that we are multiplying the energy. Observe the variation of the intensity of current in the secondary winding when you increase its emf. Calculate the product emf x intensity for each coil. What physical magnitude is conserved?

A3: In real transformers, the windings produce induced currents (Foucault currents). Use the drop-down menu to activate the Foucault option. What happens to the intensity in the secondary winding? What does the new term Q mean?



Help: This visual represents a circuit with an alternator, a switch, an ammeter, a coil, a resistance and a capacitor (the capacitor is shown only when the value of C is different from zero)

You can turn the circuit on and off and set the values of the root mean square electromotive force, the frequency of the alternating current, the inductance of the coil, the capacity of the capacitor and the resistance.

At the top of the visual you can see the value of the root mean square intensity and the power consumed.

The graph at the top right corner shows the variation of the electromotive force and the intensity as time goes by. You can also see the phase angle between both values.

The lower graph shows the power consumed versus a parameter that you can choose from the drop down menu. You should turn the circuit off before you change this parameter.

The scale in this graph is logarithmic because it must cover a wide range of values.

A1: Set $L=0$ y $C=0$ and turn the circuit on. Note that the root mean square emf and the root mean square intensity behave in the way predicted by Ohm's law for circuits of direct current.

What is the value of the phase angle between emf and I? What if you change the value of R?

Choose R as the parameter for the lower graph. How does the power change with R?

Turn the circuit on and select the emf as the parameter for the graph. Turn the circuit on again and examine all the possible values of the emf.

What is the relation between the emf and the power? Can you see any dependence among the values of the emf the intensity and the power?

A2: Set R to 1, C to 0 and L to the value 10. Turn the circuit on.

What happens to the phase angle between the emf and I? What is the value of the phase angle when the resistance tends towards zero?

Divide the emf by the root mean square intensity. The result is not just equal to the resistance, there is an added value.

Choose L as the parameter for the lower graph.

Test all possible values of L. What is the effect on the power? What is the effect on the root mean square intensity?

Turn the circuit off. Choose f as the parameter and change the value of the frequency. How does the power change now?

You can see that the effect of the coil depends on L and on the frequency. This effect is called inductance.

A3: Set $L=0$, $R=1$ and $C=20$. Turn the circuit on. Choose the capacity C as the parameter for the lower graph.

What happens to the phase angle between the emf and I? What value does it tend towards when the resistance tends towards zero?

Divide the emf by the root mean square I. The result is not equal to the resistance, as there seems to be an added value.

Test all the possible values of C. What is the effect on the power? What about the effect on the root mean square intensity?

Turn the circuit off and select f as the parameter. Change the value of the frequency.

What variation can you observe in the power?

You can see that the effect on the condenser depends on C and on the frequency.

This effect is known as capacity.

A4: Set $f=60$, and $L=0$, $C=80$ y $R=10$. Choose L as the parameter for the lower graph.

Turn the circuit on and change the value of L until the phase angle between I and emf is as close to 0° as possible.

Compare the intensity and the power in this case with the values of these magnitudes for $L=0$ and $C=0$.

What is the combined effect of the capacity and the inductance?

This effect is known as resonance and it is very useful. For example, it can be used in the tuning of a radio station. Why?

To find out why, choose values of L and C that will cause resonance. Choose f as the frequency and test all the possible values of the frequency.

What is the effect on the power when we move away from resonance?

Similarly, a radio searches for resonance to listen to the frequency of the radio station.

Conclusions about alternating current

Alternating current is produced when a coil rotates in a homogeneous

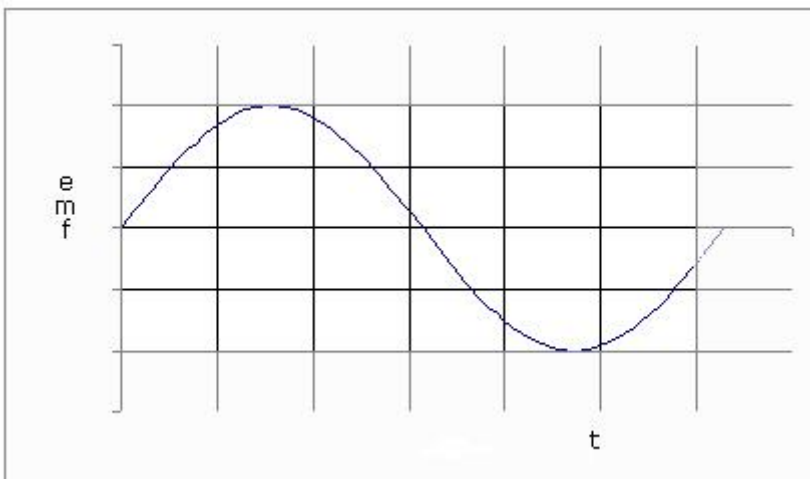
magnetic field.

An emf is produced that varies sinusoidally with time, according to the following formula:

$$\text{emf} = E_m \cdot \sin(2 \cdot \pi \cdot f \cdot t + \phi)$$

where the maximum electromotive force is equal to: $E_m = n \cdot B \cdot S \cdot \omega$ ($\omega = 2 \cdot \pi \cdot f$, and f is the frequency of the rotating coil).

The root mean square electromotive force of an



alternator is equal to the emf of a generator of direct current that produces the same effect on a resistance as the alternator. Its value is given by the following formula:

$$\text{root mean square emf} = \frac{E_m}{\sqrt{2}}$$

A transformer is a device formed by two coils that share a common metallic core. This device allows us to transform the emf according to the formula $e_1 \cdot n_1 = e_2 \cdot n_2$ in such a way that by altering the number of loops n_2 of the secondary winding, we are able to obtain an emf different from that of the primary winding. The intensity of current is inversely proportional to the emf. Furthermore, there are energy losses due to currents induced in the core (Foucault currents).

The presence of capacitors and coils in a circuit of alternating current produces a phase difference in the intensity of current in relation to the emf, in addition to a variation in the resistance of the circuit that depends on the frequency of the current.

Evaluation

- Can you remember the qualitative properties of the magnetic phenomena that you studied in previous years?
- Do you understand the effects of the magnetic fields on charged particles and currents? Can you explain some of the practical uses of these forces?
- Can you measure the magnetic field under simple conditions? Do you understand the phenomenon of natural magnetism?
- Do you know what magnetic induction is? Can you explain how it can be applied to the production of alternating current? Could you describe some of the main properties of alternating current?

You can test your knowledge with the following three tests:

Evaluation >>>

Test your comprehension of the concepts in the unit

Fill in the blank spaces

Magnetic fields are created by particles in , never by particles at .

The of a particle in a magnetic field does not increase because its speed remains constant.

A straight current creates a magnetic which is directly proportional to its and to the distance to the point under consideration.

We call a current induced by the variation of the an induced current. This variation can be due to changes in the magnetic , changes in the surface of the or changes in the formed by the magnetic induction vector and the surface vector.

Some peculiarities of the magnetic field

Match the beginning of each sentence with the correct ending.

Magnetic forces

The lines of force of the magnetic field

Induced currents produce magnetic fluxes

Gadgets such as transformers

The magnetic poles of an electromagnet

Are determined by the direction of the current.

Do no work on charged particles in motion.

Which oppose the variations that cause them.

Are perpendicular to the force they cause.

Do not work with direct current.

Magnetic field (exercises)

1. The number of loops in the primary winding of a transformer is five times the number of loops in the secondary winding. If the intensity of the current in the primary winding is 2 A, what is the value of the current in the secondary winding? (consider the Foucault currents as negligible).
Check the results with the visual

- A. 0.4 A
- B. 0.1 A
- C. 2 A
- D. 10 A

2. What intensity of current must flow through a conductor of infinite length for there to be a magnetic induction of 0.001 T at a distance of 0.5 m in a vacuum?
Check your results with the following visual

- A. 5 A
- B. 0.15 A
- C. 0.5 A
- D. 2.5 A

3. A 5 cm long solenoid with a 2 cm^2 cross-section has 100 loops wrapped around a core with a magnetic permeability of 1000. What intensity of current will create a magnetic field of 1 T? Check your results with the following visual

- A. 3 A
- B. 1 A
- C. 4 A
- D. 2 A

4. A circuit of alternating current with an root mean square emf of 10 V contains a 10 ohm resistance, a 0.004 henrie coil and a 20 microfarad capacitor. Calculate the frequency which produces resonance. Check your results with this visual

- A. 685 Hz
- B. 1120 Hz
- C. 0 Hz
- D. 560 Hz

5. What is the speed at which the trajectory of an electron under the influence of a magnetic field of 0.001 T would have a radius of 1 cm? You can check your result with this visual

- A. 1760
- B. 1200
- C. 525
- D. 564

6. What is the value of the torque exerted by a 0.1 T magnetic field on a 30 cm^2 loop with a current of 2 A, if the field vector and the surface vector form an angle of 60 degrees.
You can check your results with the visual

- A. 1.2 tentousandths of a N·m
- B. 1.3 N·m
- C. 35 N·m
- D. 3.5 hundrethds of a N·m

7. The friction experienced by a 30 cm long conducting rod with a mass of 30 grams and with a current of 1 A flowing through it is negligible. If it is under the influence of a magnetic field of intensity equal to 0.02 T perpendicular to its direction, what distance will it cover in 8 seconds? You can check your results with the following visual

- A. 6 m
- B. 0, it remains at rest.
- C. 4.25 m
- D. 1 m

8. A square circuit with a surface of 2 dm^2 is inside a magnetic field perpendicular to its surface. If the magnetic induction decreases in 0.5 seconds from 1 T to 0 T, calculate the induced efm.
Check your results with the following visual

- A. 0 V
- B. 3.5 V
- C. 0.32 V
- D. 1.4 V