II. Concept of fields

Prepared by Belgian BioElectroMagnetics Group (BBEMG)

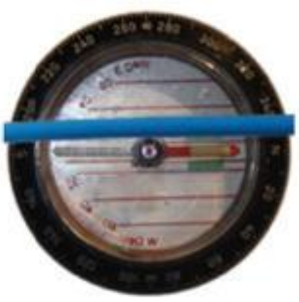
Note:
All the information on this page is available as Flash animation at the following address: http://www.bbemg.be/en/main-emf/electricity-fields/electric-and-magnetic-fields.html

Introduction

In physics, a field is part of space in which gravitational, magnetic, electrostatic, or any other force can be felt. (Source: Microsoft Encarta, 2009).

The electric and magnetic fields are distinct concepts that were developed to explain the effects of electricity at a distance.

In 1820, when Hans Christian Ørsted demonstrated that a compass needle is deflected when the compass is placed in the vicinity of the wire carrying a direct current, he opened the door to electromagnetism, this branch of physics which studies the interactions at a distance of electric and magnetic fields.



Without current in the wire, the red needle of the compass points to the North

The current flows from right to left.
The compass is disoriented!

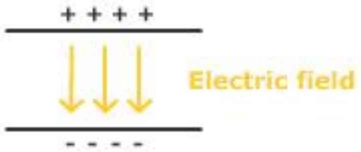
In this page, we will discuss the electric and magnetic fields. Later, we'll explore electromagnetism.

Electric field

The electric field is generated by the presence of electric charges. Let's take the example of the balloon charged with static electricity that our observant readers discovered in the "Basic electricity" section:

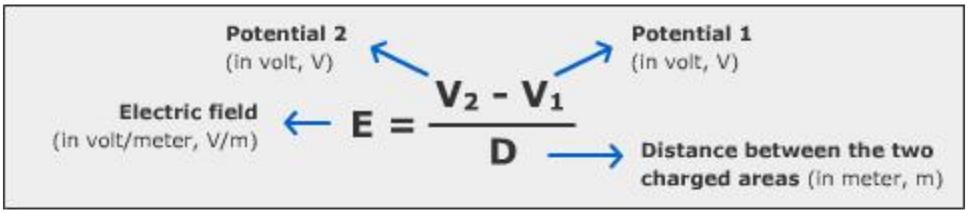
The balloon is negatively charged, and consequently, the ceiling positive charges converge towards it. There is air between the two, which is a bad conductor; the charges stay put.

The situation can be represented by the following diagram:



The electric field is oriented, by convention, from the positive potential area to the negative potential area.

The electric field intensity depends on the difference of potential between the two charged areas and on the distance separating them. An approximation of the electric field between two parallel flat surfaces is given by the following formula (assuming a uniform field in space):



There is a natural electric field at the surface of the Earth. It is generated by the difference of potential between the high atmosphere (the positively charged ionosphere) and the Earth (negatively charged).

Electric charges continuously leave the Earth surface towards the atmosphere. The thousands of electric (*) storms that occur every day at the four corners of the planet ensure, via lightning, the return of these charges to the ground in order to maintain a global equilibrium and keep life on Earth possible.

(*) Lightning is the luminous phenomenon that accompanies the electric discharge. It is caused by superheated gases on the path of the discharge. The colour of the lightning varies according to the conditions of the air: more or less humidity, presence of hail or of dust, etc.

Thunder is the noise due to the explosive expansion of the superheated air mass on the lightning's path.

Electric field in the 100 to 150 V/m range

Electric field that can reach 15 to 20 kV/m

Lightning is preferentially attracted by elevated and/or pointed objects because the electric field (and therefore the force applied to the charges) is more intense in their proximity than in the surrounding: it's the "point effect".

1. Causes of the point effect

The electric charges have a tendency to concentrate on the pointed parts of a conductor, typically a smaller area. Therefore, the intensity of the electrical forces is very high. The strong electric field that they generate causes the ionisation of the air and thus increases the conductivity of the air. For example, a pointed object like a lightning conductor doesn't actually attract lightning, but it makes more likely, during a storm, because of the point effect, the formation of discharges (e.g. St. Elmo's fires at the top of boat masts).

The point effect is also responsible for corona discharges, a phenomenon that takes place, among others, around overhead power lines in certain conditions.

The presence of small protuberances on the surface of conductors, such as a drop of water or snow flakes, or even an insect, cause large increases of the electric field. The corona effect varies drastically in function of the conditions of the external surface and of the atmosphere (Source : "Transport et distribution de l'énergie électrique" on the Université de Liège website).

2. Representation of the electric field

If our eyes were capable of visualising electric and magnetic fields, here is what we would see when looking at an unlit flashlight and a toaster: a static electric field around the flashlight and alternating at 50 Hz surrounding the toaster.

Static electric field

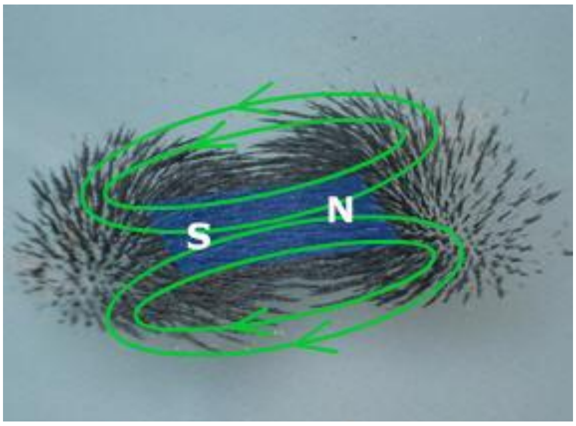
Electric field alternating at 50 Hz

Electric fields generated by alternating voltages are also alternating.

The darker areas represent zones of higher intensity of the field.

Magnetic field

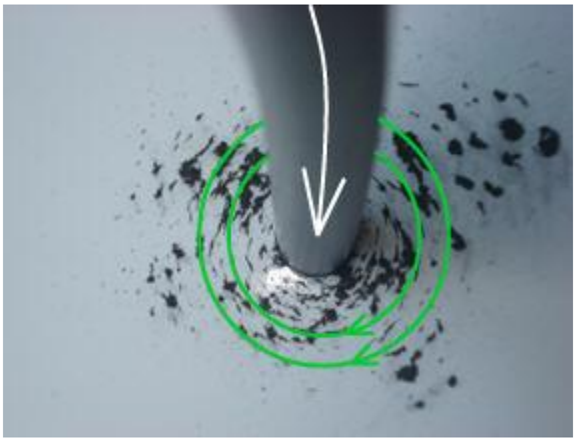
A magnetic field is produced by moving electric charges. This motion takes different forms according to the type of materials and their use:



A magnet is placed under the surface.

The iron filings align themselves along the field lines. By convention, the field lines leave the magnet at the North pole and enter at the South pole.

In a magnet, the magnetic field results from the movement of the electrons on themselves (called the spin).



The direction of the current is ‘down’. Here, a 30 A direct current.

The iron filings form circles around the wire along the magnetic field lines.

In a conducting material connected to a voltage source (direct in this case), the magnetic field is generated by the movement of the electrons (the electric current) in the conduction bands (see "Basic electricity").

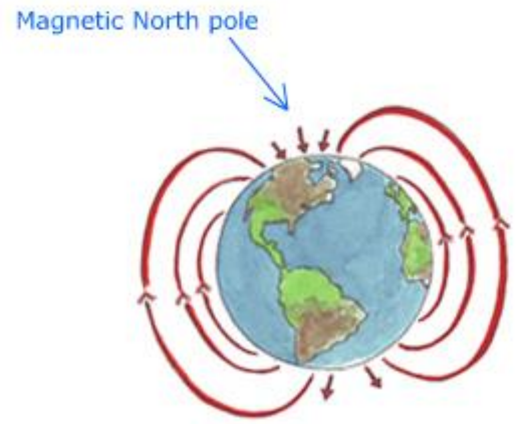
There is also a magnetic field around the earth. It can be detected by observing a compass needle. It is thought to be produced by movements of the molten magma in the earth's core.

Earth's magnetic field plays a critical role in the protection of the planet by deflecting cosmic radiation and solar winds particles.

This deflection takes place in the magnetosphere (the atmosphere layer above the ionosphere, more than 1000 km above earth's surface). Auroras borealis (at the North pole) and auroras australis (at the South pole) are caused by the collision of high energy particles and the magnetosphere.

1. Magnetic North pole – Geographic North pole

The magnetic North pole is defined as the location where the magnetic field lines are perpendicular to the surface of the earth. The geographic North pole, for its part, is defined by earth's rotation axis. The magnetic field axis is not aligned with earth's rotation axis, and as a result the magnetic North is actually about 1000 km away from the geographic North (for the moment).

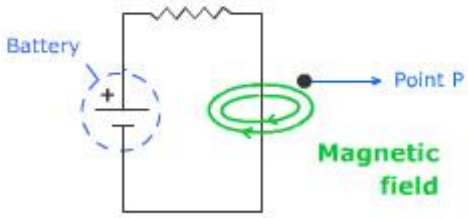


Earth's magnetic field intensity varies between 30 and 50 µT depending on where it is measured. It is a static field. A natural variable magnetic field can also be measured on earth's surface, the 50 Hz component of which is 10^{-6} µT.

Note: By convention, the magnetic field lines exit the north pole of a magnet and enter at the south pole. However, on the above illustration, they enter at the North pole of the Earth. This is because the magnetic North pole of the Earth is actually the south pole of the equivalent magnet! The compass needle being a north pole, it is attracted to the south pole of our super magnet, Earth.

The orientation of the magnetic field lines depends on the configuration of the magnetic field source. Let's look at two examples:

a. Around a current carrying straight wire, the magnetic field lines are circular.

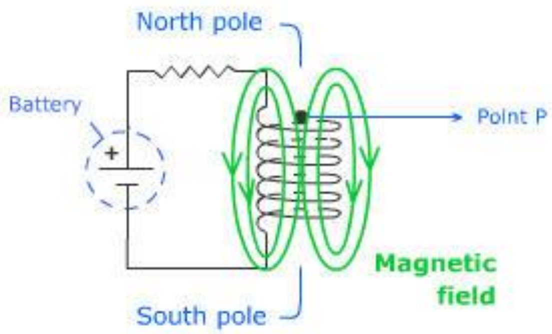


Around a straight wire :

$$H = \frac{I}{2 \pi r}$$

- **H**: **Magnetic field in a point P** (in ampere/meter, A/m)
- **I**: **Current intensity** (in ampere, A)
- **r**: **Distance between the wire and the point P** (in meter, m)

b. Around a coil that is carrying a current, the magnetic field lines look like those of a magnet.



By analogy, the coil is said to have a north pole where the lines exit and a south pole where they enter.

In a coil with N spires :

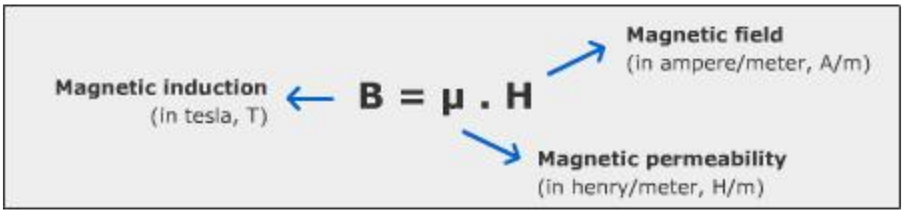
$$H = \frac{N \cdot I}{2 \cdot R}$$

- **H**: **Magnetic field in a point P** (in ampere/meter, A/m)
- **I**: **Current intensity** (in ampere, A)
- **R**: **Radius of the spires** (in meter, m)

The **magnetic field at a point P** depends on the current and on the distance to the conductor. It is denoted H and is measured in **ampere/metre (A/m)**.

The direction of the magnetic field lines can be determined by the "right hand grip rule": when the thumb points to the direction of the current (convention + towards –), the magnetic field orientation is that of the folded fingers.

The magnetic field H (in A/m) is frequently expressed by its **magnetic induction B (in tesla, T)**. In a given material, the magnetic field and the magnetic induction are linked by the following equation:



The magnetic permeability of a material is its ability to concentrate the magnetic flux lines and thus increase the magnetic induction. Therefore the magnetic induction depends on the medium where it is produced (see the site glossary under "Magnetic permeability").

The magnetic permeability of air is $4 \pi .10^{-7}$ H/m.

The magnetic permeability of a material (μ) is the product of the permeability of a vacuum (μ_0, expressed in henry/metre) and of the relative permeability (μ_r, dimensionless):

$$\mu=\mu_0 . \mu_r$$

- μ_0 is a universal constant, $4 \pi .10^{-7}$ H/m
- μ_r varies with the material. In air, vacuum, gases, copper, aluminium, the earth and some other materials, μr is very close to 1. These materials do not “channel” the magnetic field.

Therefore, in a vacuum or in air, a 1 A/m H-field is associated to a 1,26 µT B-field.

Note:

- The former unit of magnetic induction, the gauss (G), is still regularly used in some regions. The conversion is as follows: 10^{-4} T = 1 G or, to use values more commonly encountered in a 50/60 Hz environment: 0.1 µT = 1 mG.
- Later in this module we may often use “magnetic field” for B or B-field which is measured in µT.

2. Representation of the magnetic field

If our eyes were capable of visualising electric and magnetic fields, here is what we would see when looking at a flashlight and a toaster when they are turned on: static electric and magnetic fields around the flashlight and alternating at 50 Hz surrounding the toaster.

Static electric and magnetic fields

Electric and magnetic fields alternating at 50 Hz

Fields generated by alternating currents are also alternating.

The darker areas represent zones of higher intensity of the fields.

Decrease of intensity with increasing distance

Both electric and magnetic fields decrease rapidly when moving away from the source. Depending on the source, the decrease may be more or less rapid:

- In the surroundings of an electrical cable (e.g. a cable from a high voltage powerline), the field intensity is inversely proportional to the distance (in our jargon, we use the notation 1/r).
- In the surroundings of domestic cables ("round-trip" conductors), the field intensity decreases with the square of the distance ($1/r^2$) and
- near a coil, as for example an industrial induction furnace, with the cube of the distance ($1/r^3$).

Electric alarm clocks, bedside lamps and most household appliances can be considered as sources from which magnetic field intensity decreases with the square of the distance. In concrete terms, this means that when the distance doubles, field intensity decreases by a factor of 4. For example, if the magnetic field intensity is 1 microTesla at 30 cm from an electric alarm clock, the intensity will become 0.25 µT at 60 cm, 0.0625 at 120 cm, and so on.

Further information regarding electric and magnetic fields values is available in the module “Fields in our environment”.

Example of an electric cord supplying a lamp with a 100 watts light bulb at 230 V:

a. Measuring the voltage between the two conductors in the cable (with a voltmeter), we obtain approximately 230 V (effective value, 50 Hz sinusoidal)
b. If the lamp is turned on, we can measure (with an ammeter) the current in the cable conductors (identical in both conductors, but in reverse directions):

$$P \text{ (in W)} = V \text{ (in V)}.\ I \text{ (in A)}$$

$$100 = 230\ .\ I$$

then I = 0.435 A (effective value, 50 Hz sinusoidal)

c. Calculation of the magnetic field near the electric cord:

Assuming a single conductor (effective value, 50 Hz sinusoidal):
approximately 0.8 µT at 10 cm

$$B = \mu_0 \frac{I}{2 \pi r} = 4 \pi 10^{-7} \frac{0,435}{2 \pi r} = 0,8\ \mu T$$

(Effective value, 50 Hz sinusoidal, at 10 cm)

With both conductors together (round-trip conductors): approximately 0.017 µT at 10 cm, that is 47 times less than in the fictitious single conductor.

$$B = \frac{\mu_0 I}{2 \pi r_1} - \frac{\mu_0 I}{2 \pi r_2} = \frac{\mu_0 I}{2 \pi} \left(\frac{r_2 - r_1}{r_2 . r_1} \right) \simeq \frac{\mu_0 I}{2 \pi} . \frac{r_2 - r_1}{r^2} = 0,017\ \mu T$$

insulating material: 2 mm

(Effective value, 50 Hz sinusoidal, at 10 cm)

We can derive the magnetic field values in function of the distance from the cables:

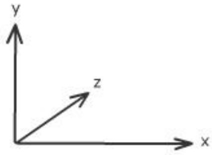
Distance from the cables (cm)	5	10	20	40	100
B-Field (µT)	0.068	0.017	0.0042	0.0011	0.00017

The magnetic field varies with the inverse of the square of the distance ($1/r^2$) as shown earlier. It would then require a load consuming more than 10 A to reach a B field higher than 0.4 µT at 10 cm from the cables and that value would decrease by a factor of 10 (which means 0.04 µT) at 31 cm from the cables.

Measurement methods

Various commercial instruments exist to measure electric and/or magnetic fields:

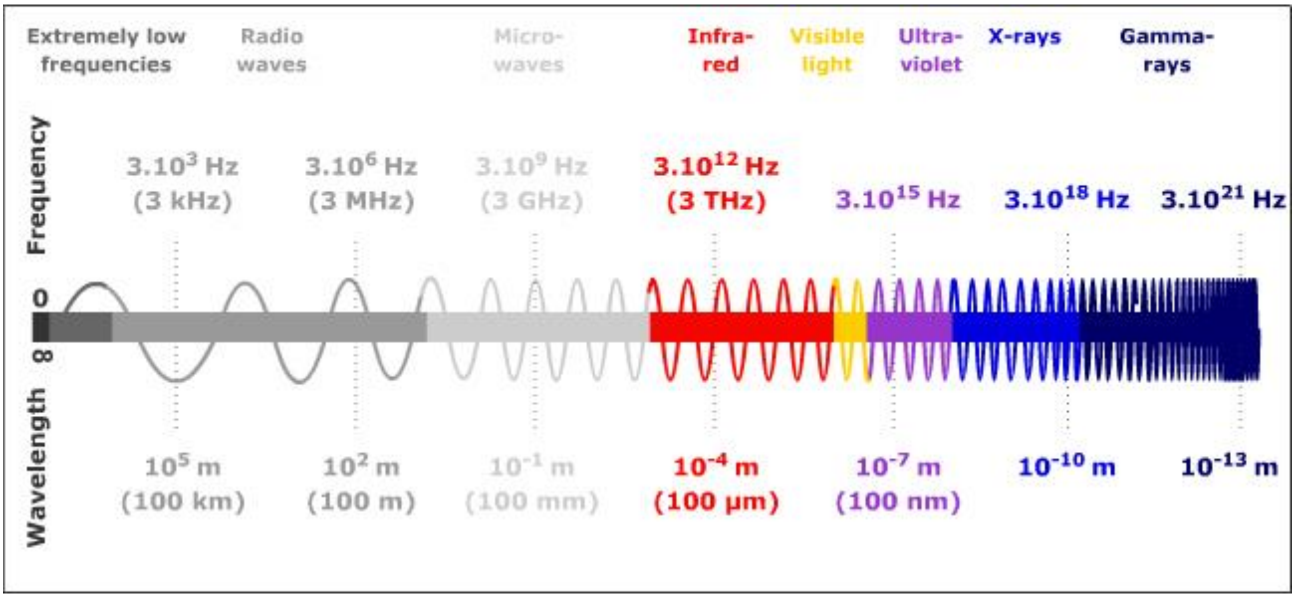
- Electric field measurements require some important precautions, as it is influenced by nearby objects as well as by the presence of the operator. One must take the measurement away from objects and people, at the end of an insulated long pole for example.
- Alternating magnetic B-fields (here 50 Hz) is measured by means of three orthogonal solenoids. The inducted voltage in each of the solenoids gives the 3 components (x, y, and z) of the field.



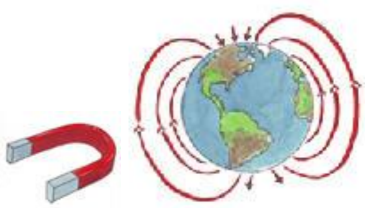
At very low frequencies, the magnetic field is not disturbed by the presence of objects or people, so its measurement doesn't require the same precautions than the electric field. It can easily be measured by a dosimeter worn on someone's belt for long term exposure situations.

Electromagnetic spectrum

So far, we concerned ourselves with static fields (magnets) and 50 Hz alternating fields generated by the power network. Among variable fields, 50 Hz fields are only a minute part of the electromagnetic waves spectrum: among others, visible light, radio waves, and X-rays are also part of that spectrum.



1. Static fields



- Frequency: 0 Hz
- Wavelength : infinite

Note:
Along with the static fields, there are also natural 50 Hz alternating fields around the Earth, though their intensity is extremely low (10^{-4} V/m, 10^{-6} µT)

2. Extremely low frequencies (ELF)

- Frequency from 3 Hz to 300 Hz
- Wavelength from 100,000 to 1000 km

The frequency of the transmission and distribution network is 50 Hz (or 60 Hz for example in the United States). It is therefore classified as extremely low frequency. It is also called power frequencies. The wavelength is respectively 6000 and 5000 km in 50 and 60 Hz.

3. Radio waves

- Frequencies from 0.3 to 3 kHz, wavelength from 1000 km to 100 km: voice data transmission, metallurgy, induction heating
- Frequencies from 3 to 30 kHz, wavelength from 100 km to 10 km: radiocommunications
- Frequencies from 30 to 300 kHz, wavelength from 10 to 1 km: long wave radio, induction ovens
- Frequencies from 0.3 to 3 MHz, wavelength from 1 km to 100 m: medium and short wave radio, medical diathermy
- Frequencies from 3 to 30 MHz, wavelength from 100 to 10 m: welding, bonding
- Frequencies from 30 to 300 MHz, wavelength from 10 to 1 m: television, FM radio

Source: Duchêne, A., & Joussot-Dubien, J. (2001)

4. Microwaves

- Frequencies from 0.3 to 3 GHz, wavelength from 1 to 0.1m: television, radar, mobile telephones, microwave ovens, magnetic hyperthermia
- Frequencies from 3 to 30 GHz, wavelength from 0.1 m to 0.01 m: radar, anti-intrusion alarms
- Frequencies from 30 GHz to 300 GHz, wavelength from 0.01 m to 1 mm: radar, satellite communication

Source: Duchêne, A., & Joussot-Dubien, J. (2001)

Microwave ovens operate at a 2450 MHz frequency to heat food. Mobile phones use a nearby frequency (900 MHz/1800 MHz), but at much less power.

5. Infrared

Frequencies from 0.3 THz to 385 THz, wavelength from 1 mm to 780 nm: heating, remote controls...

Source: Duchêne, A., & Joussot-Dubien, J. (2001)

As the name implies, their frequency range is just below the visible red frequency.

6. Visible light

Frequencies from 385 THz to 750 THz, wavelength from 780 nm to 400 nm: human vision, photosynthesis...

Source: Duchêne, A., & Joussot-Dubien, J. (2001)

The lowest frequencies radiations are red, the highest are blue and purple. This is the frequency range that can be seen by our eyes.

7. UV rays

Frequencies from 750 to 3000 THz, wavelength from 400 nm to 100 nm: tanning bed, water sterilisation

Ultra-violet frequencies are just above those of the visible purple. We can't see them, but we certainly feel their effects (sun burns).

Source: Duchêne, A., & Joussot-Dubien, J. (2001)

At these wavelengths, the transmitted energy is very high. High doses can be hazardous: melanomas...

8. X rays

Frequencies up to 3000 THz, wavelength shorter than 100 nm: medical imaging, radiography.

X rays carry even more energy than UV rays. They can penetrate soft tissues, but are stopped by bones, hence their application in radiology.

9. Gamma rays and cosmic rays

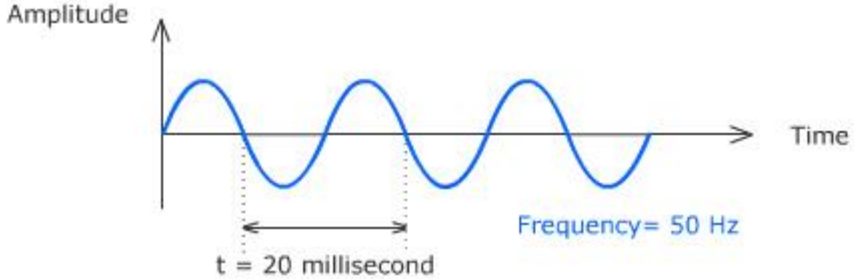
Gamma rays and cosmic rays are the most energetic of all.

The level of exposure to cosmic radiation increases with altitude, as there is less atmosphere to protect us; air travel is the source of most of our exposure.

Frequency and wavelength

The electromagnetic spectrum covers a very wide range of frequencies (in Hz) and wavelengths (in m).

The frequency is the number of cycles per second. The unit of frequency is the hertz (Hz). The alternating current power supply of most electrical appliances is at a 50 Hz frequency. The fields it produces are also alternating at 50 Hz. **The wavelength** is the distance travelled between two consecutive cycles of the wave.



Frequency and wavelength are related: the higher the frequency, the shorter the wavelength. The speed of propagation of electromagnetic waves is the speed of light in vacuum, air, and other gases, that is a speed of about 300,000,000 m/s.

Therefore, at a 50 Hz frequency for example, the wave travels 6000 km in one second.

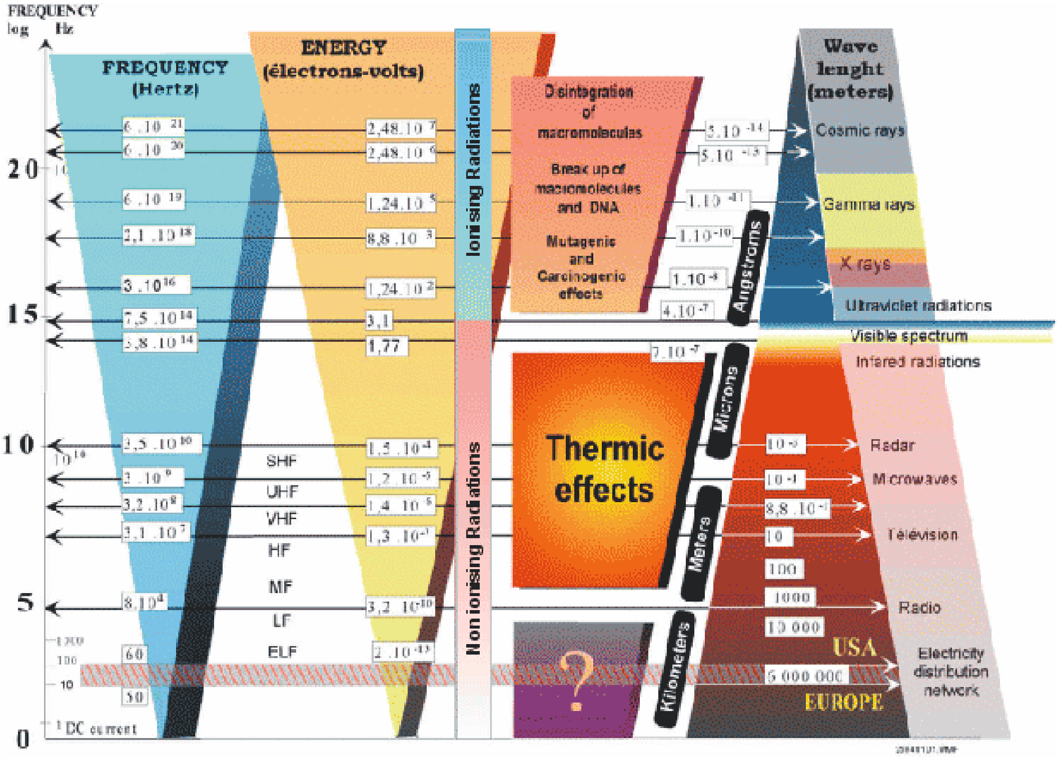
$$\text{Wavelenght} = \frac{\text{Speed of light}}{\text{Frequency}} = \frac{300\ 000\ 000}{50} = 6\ 000\ 000 \text{ m or } 6000 \text{ km}$$

Waves can also differ in their shape. We have so far described sinusoidal (*) waves, but there are square waves, pulse waves, etc.

(*) In 50 Hz, power plant alternators produce a sinusoidal current, hence perfectly sinusoidal fields at their origin. However, after transmission and utilisation, the sine curves deteriorate somewhat and harmonics superimpose themselves. Harmonics are waves the frequency of which is a multiple of the original 50 Hz or 60 Hz frequency. The fields that are generated at that point are no longer perfectly sinusoidal.

Electromagnetic waves are a form of energy. The amount of energy carried by a wave depends on its frequency (or its wavelength). **Radiations whose frequency is**:

a. **Higher than 10^{15} Hz** contain enough energy to break chemical bonds and ionise molecules. They are said to be ionising radiations: cosmic rays, gamma rays and X rays. In the human body, the ionisation energy level for water is between 12 and 35 eV (electron-volt). For a radiation to have such high energy, the frequency must be higher than 3.10^{15} Hz, that is approximately that of UV radiation.



Source: ISSep, 2001

b. **Lower than 10^{15} Hz** are not sufficiently energetic to break chemical bonds. They are said to be non-ionising: most UV radiation, visible light, radio frequencies and low and extremely low frequencies. UV rays are at the threshold of ionisation.

Note: Non-ionising radiations still carry quite a bit of energy: it is that energy that heats your lunch in a microwave oven or that gives you that sun burn instead of the nice tan you were looking for...

Different frequencies radiations are produced by different processes. But this would take us far afield in this module. For further information, you may want to click on the icon.

Fields and waves

At the beginning of this module, we introduced electric and magnetic fields separately. Later, we spoke of the electromagnetic waves spectrum. Why?

In fact, time-varying fields are, when sufficiently far from the source, waves that spread at the speed of light. However, the transmitters of these waves have for output either a mostly electric or mostly magnetic field depending on their geometry and their operating principle. These fields are labelled near electric or near magnetic fields; strictly speaking, there is no propagation.

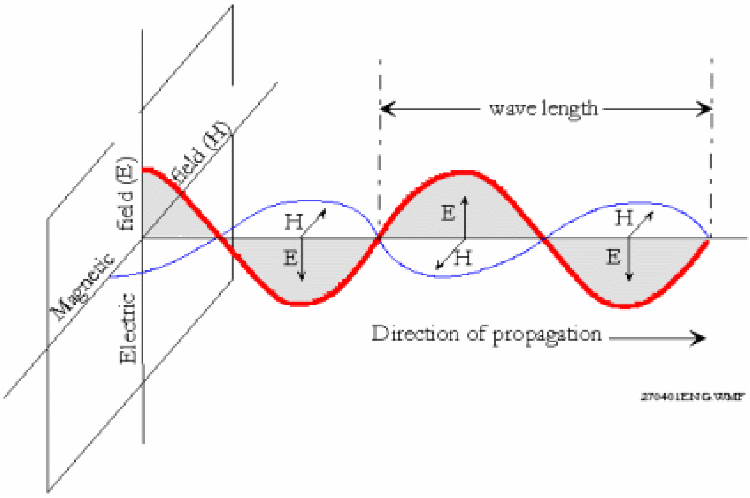
Further away from the source, time-varying fields evolve: the magnetic field progressively increases in relation with the electric field (or vice versa), so that at a “long” distance from the transmitter (*), the electric and magnetic components become intertwined and propagate as a wave, perpendicular to each other and perpendicular to the direction of propagation. We are now in the domain of far electromagnetic fields.

(*) The “long” distance that is mentioned above depends on the frequency of the wave:

For a mobile phone antenna at 900 MHz, the "long distance" corresponds to a few centimeters, while for a short wave radio emitter at 10 MHz, the "long distance" corresponds to about a hundred meters.

At 50 Hz, the “long” distance corresponds to several thousand kilometers. Since the amplitude of the field at such a distance is negligible, it can usually be neglected. In practice, at 50 Hz, we can thus usually assume that we are in the "near field", and we can consider the electric and the magnetic fields separately.

Only a static field can remain purely electric or purely magnetic.

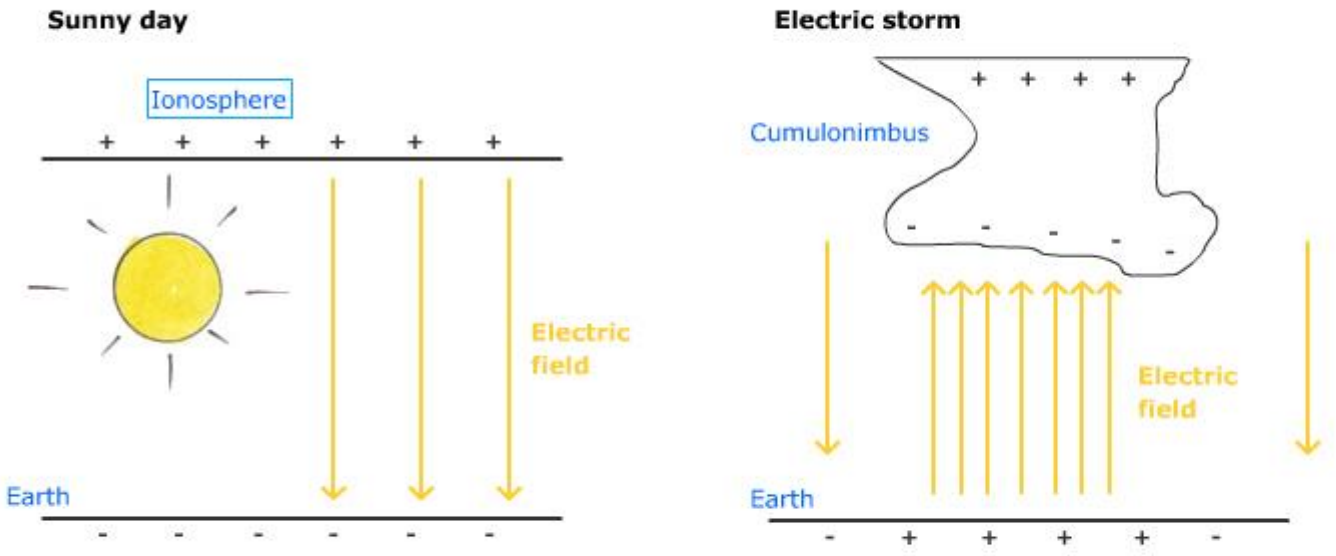


Quiz (Flash)

To access the Quiz, click on the link:
http://www.bbemg.be/en/main-emf/electricity-fields/electric-and-magnetic-fields.html

Appendices

1. Characteristics of Earth's electric field



Electric storms are associated with a particular type of cloud: the cumulonimbus, the top of which can be culminating at 12 000 metres or more above earth's surface. Negative charges accumulate at the bottom of the cumulonimbus, positive charges at the top (*).

(*) *How do the charges get segregated between the top and the bottom of the cloud?*

This question is not quite resolved: some researchers think that the separation of the charges is due to friction between water drops and ice crystals when air moves inside the cloud. Others look for an explanation involving the different states of the water (vapour, liquid, and ice).

The presence of negative charges at the bottom of the cloud leads to an accumulation of positive charges on the ground. The electric field between the base of the cloud and the ground reverses itself and becomes stronger.

The phenomenon known as lightning is highly susceptible to the very intense electric field. Lightning takes place in three steps: (1) creation of an ionised channel by a downward stepped leader (it makes it way down by steps of tens of metres) starting at the base of the cloud, (2) when this leader gets close enough to the ground, an upwards streamer (similar to a leader, but made of positive charges) starts from the ground, (3) leader and streamer connect, forming a conducting channel between earth and the cloud. The electric current through that channel is the major discharge, that we call the lightning strike.

2. Sources of electromagnetic waves

Electromagnetic radiation can be produced by various processes:

- The first process involves electrons transitioning from one given energy level to a lower energy level. The energy difference is converted to light. These transitions can take place inside atoms, molecules, or solids. For example, in a fluorescent tube, light is produced by electronic transitions in the atoms of the gas that fills the tube (actually, they first produce UV radiation that causes the phosphorescent material coating the tube to emit visible light). In an LED (light emitting diode), which is an electroluminescent semiconductor, the light is produced by electronic transitions in the semiconductor material, essentially between the conduction and valence bands.
- A second process is the acceleration (or deceleration) of charged particles. This process is the operating principle of a radio or Wifi transmitter: a variable current travels through the antenna, which means that a variable acceleration is imparted to the charges that are the current.
- Last, very high energy electromagnetic waves (including gamma rays) are produced by energy transitions inside the atom nucleus, by interaction of subatomic particles, or by the annihilation of matter by antimatter. Such waves are observed in high energy colliders (such the CERN in Geneva), in the sun, and in deep space.