Block 15 — Magnets, their Effects and Fieldline Images

Student Group

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Block 15 — Magnets and their Effects

Learning objectives

> After this 90-minute block, you
>
> 1. know that forces act between magnetic poles and know the direction of the forces.
> 2. know that a magnetic field is formed around a current-carrying conductor.
> 3. be able to sketch the field lines of the magnetic field. Know the direction of the field and where the field is densest.

Preparation at Home

Well, again

- read through the present chapter and write down anything you did not understand.
- Also here, there are some clips for more clarification under 'Embedded resources' (check the text above/below, sometimes only part of the clip is interesting).

For checking your understanding please do the following exercises:

- …

90-minute plan

1. Warm-up (x min):
    1. ….
2. Core concepts & derivations (x min):
    1. …
3. Practice (x min): …
4. Wrap-up (x min): Summary box; common pitfalls checklist.

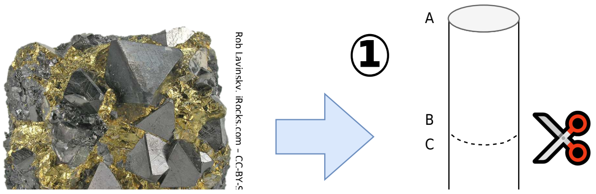
Conceptual overview

> 1. …

Core content

Effects around Permanent Magnets

Fig. 1: First approximation to magnetism



First, permanent magnets made of magnetic magnetite ($\rm Fe_{3} O_{4}$) were found in Greece in the region around Magnesia. Besides the iron materials, other elements also show a similar “strong and permanent magnetic force effect”, which is also called ferromagnetism after iron: Cobalt and nickel, as well as many of their alloys, also exhibit such an effect. Chapter 3.5 Matter in the magnetic field describes the subdivision of magnetic materials in detail.

Here now the “magnetic force effect” is to be looked at more near. For this purpose, a few thought experiments are carried out with a magnetic iron stone figure 1.

1. From the iron ore should now first be separated a handy elongated part. If one is lucky, the given iron ore is already magnetic by itself. This case will be considered in the following. The

elongated piece is now to be cut into two small pieces.

2. As soon as the two pieces are removed from each other, one notices that the two pieces attract each other again directly at the cut surface.
3. If one of the two parts is turned (the upper part in the picture below), a repulsive force acts on the two parts.

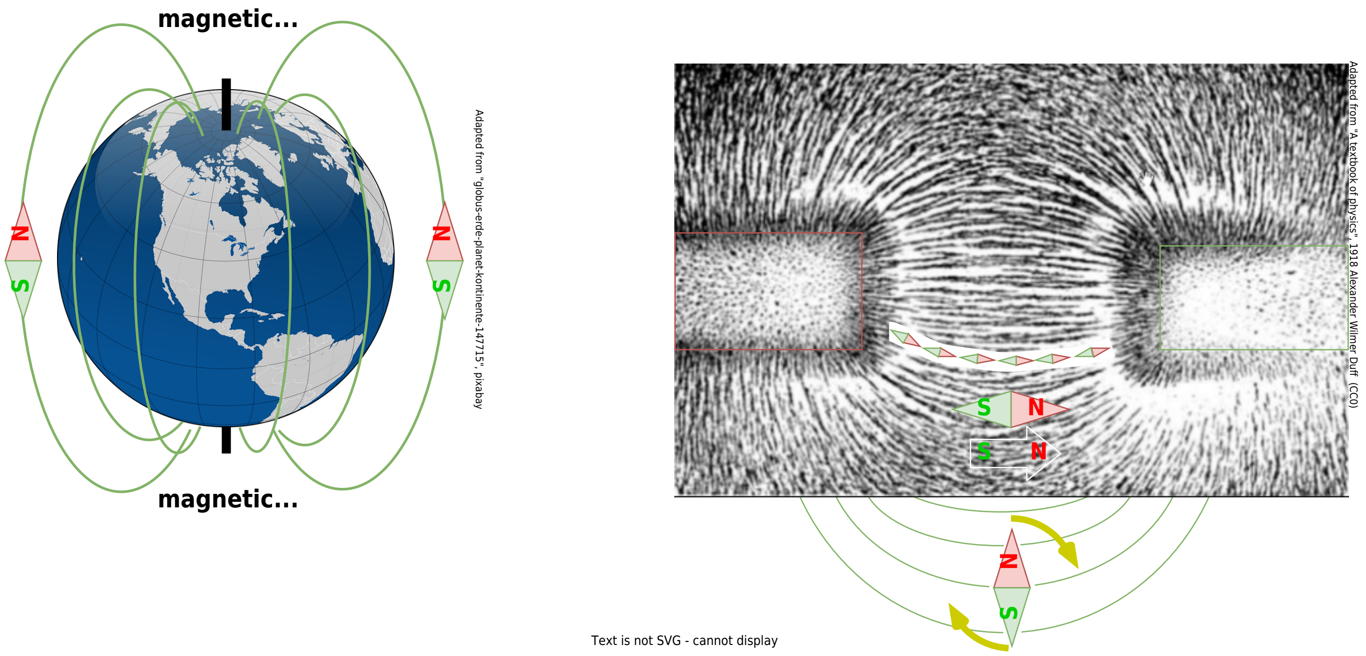
So, it seems that there is a directed force around each of the two parts. If you dig a little deeper you will find that this force is focused on one part of the outer surface.

Of course, you already know magnets and also know that there are poles. The considered thought experiment shall clarify, how one could have proceeded at an unknown appearance. In further thought experiments, such magnet iron stones can also be cut into other directions and the forces analyzed.

The result here is:

1. There are two poles. These are called the north pole and the south pole. The north pole is colored red, and the south pole is green.
2. Poles with the same name repel each other. Unequal poles attract each other. This is similar to the electric field (opposite charges attract).
3. So magnets experience a force in the vicinity of other magnets.
4. A compass is a small rotating “sample” magnet and is also called a magnetic needle. This sample magnet can thus represent the effect of a magnet. This is also similar to the sample charge of the electric field.
5. The naming of the magnetic poles was done by the part of the compass which points to the geographic north pole. The reason for this is that the magnetic south pole is found at the geographic north pole.
6. Magnetic poles are not isolatable. Even the smallest fraction of a magnet shows either no magnetism or both north and south poles.

Fig. 2: Magnetic field becomes visible through iron filings



Adapted from "globus-erde-planet-kontinente-147715", pixabay

Adapted from "A textbook of physics", 1918 Alexander Wilmer Duff (CC0)

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Interestingly, even non-magnetized, ferromagnetic materials experience a force effect in the magnetic field. A nail - which is not a magnet itself - is attracted by a permanent magnet. This even happens independently of the magnetic pole. This also explains the visualization about iron filings (= small ferromagnetic parts), see figure 2. Also here there is a force effect and a torque, which aligns the iron filings. The visible field seems to form field lines here.

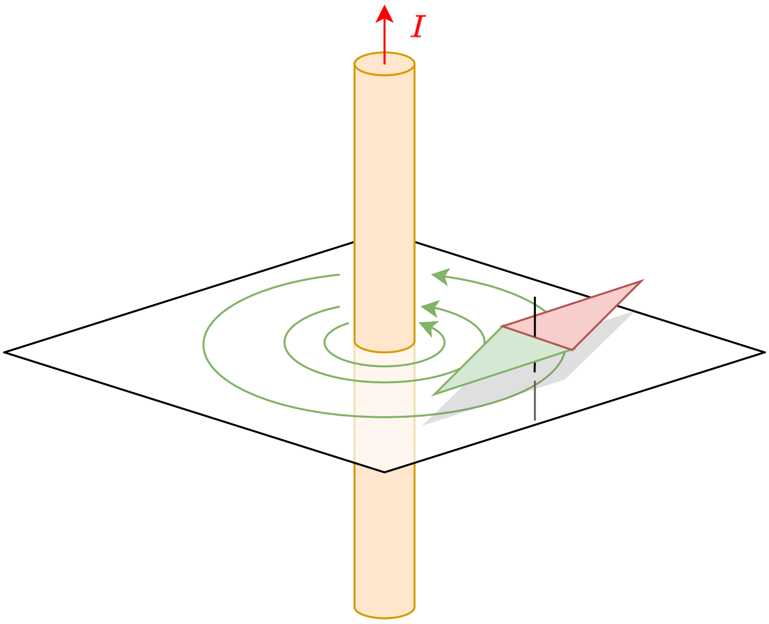
Notice:

- Field line images can be visualized by iron filings. Conceptually, these can be understood as a string of sample magnets.
- The **direction of the magnetic field** defined via the sample magnet: The north pole of the sample magnet points in the direction of the magnetic field.
- The **amount of magnetic field** is given by the torque experienced by a sample magnet oriented perpendicular to the field.
- Field lines seem to repel each other (“perpendicular push”). e.g. visible when the field exits the permanent magnet.
- Field lines attempt to travel as short a path as possible (“longitudinal pull”).

Video

Effects around Current-carrying Wires

Fig. 3: Magnetic field around a current-carrying conductor



In 1820, Christian Ørsted discovered by chance during a lecture that current-carrying conductors also affect a compass. This experiment is illustrated in figure 3. A long, straight conductor with a circular cross-section has current I flowing through it. Due to symmetry considerations, the field line pattern must be radially symmetric concerning the conductor axis. In an experiment with a magnetic needle, it can be shown that the field lines form concentric circles.

Ørsted found out, that the torque on the compass is

- proportional to the current I
- inversely proportional to the distance r to the cable (= the radius)

The direction of the field here is coaxial circular around the wire.
For a detailed definition it is bes to use a cylintrical coordinate system. Then the magnetic field $\vec{H}$ is given as \begin{align*} \vec{H} = \left(\begin{matrix} H_r \\ H_\varphi \\ H_\theta \end{matrix} \right) = \left(\begin{matrix} 0 \\ H_\varphi \\ 0 \end{matrix} \right) \\ \end{align*} The radial and axial part is zero - the field is curling around the wire.

For the azimutal magnetic field strength around a single conductor is defined as: \begin{align*} \boxed{H_\varphi ={I\over{l}} = {{I}\over{2 \cdot \pi \cdot r}}} \quad \quad | \quad \text{applies only to the long, straight conductor} \end{align*}

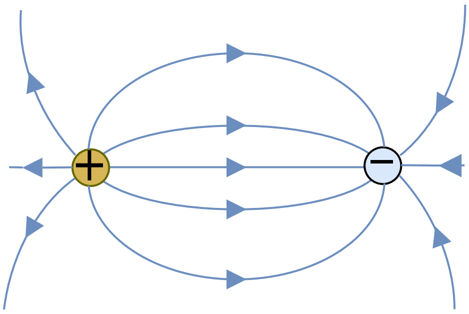
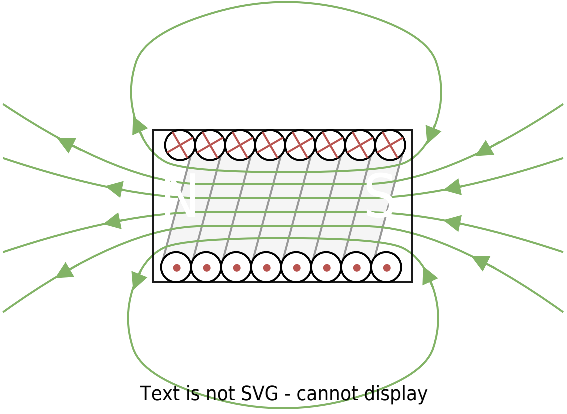
l is here the length of a coaxial magnetic fieldline.
For the unit of the magnetic field strength H we get $[H] = {{[I]}\over{[l]}}= \rm 1~{{A}\over{m}}$

Notice:

Fig. 4: Right hand rule

- If the technical direction of the current is considered, the magnetic field lines surround the current in the sense of a right-hand screw. (“right screw rule”)
- This rule can also be remembered in another way: If the thumb of the **r**ight hand points in the (technical) cu**rr**ent direction, the fingers of the hand surround the conductor like the magnetic field lines. Likewise, if the thumb of the **l**eft hand points in the E**l**ectron flow direction, the fingers of the hand surround the conductor like the magnetic field lines.

Comparison of Electrostatics and Magnetostatics

Property	**Electrostatic**	**Magnetostatic**
Field line images	Fig. 5: Electrostatic field lines  Text is not SVG - cannot display	Fig. 6: Magnetostatic field lines  Text is not SVG - cannot display
sample for the field	positive sample charge	compass
field lines	- start on a positive charge - end on a negative charge	- have no start and no end - are closed
field line ends	there are sources and sinks	there are no sources and sinks
field type	vortex-free **source field**	source-free **vortex field**

Superposition of the magnetostatic Field

Before the magnetic field strength will be considered in more detail, the simulation and superposition of the magnetic field will be discussed in more detail here.

Magnetostatic fields can be superposed, just like electrostatic fields. This allows the fields of several current-carrying lines to be combined into a single one. This trick is used in the following chapter to examine the magnetic field in more detail.

On the right side, the magnetic field of a single current-carrying conductor is shown. This was already derived in the previous chapter by symmetry considerations. The representation in the simulation can be simplified a bit here to see the conditions more clearly: Currently, the field lines are displayed in 3D, which is done by selecting `Display: Field Lines` and `No Slicing`. If you change the selection to `Show Z Slice` instead of `No Slicing`, you can switch to a 2D display. In this display, small compass needles can also show the magnetic field. To do this, select `Display: Field Vectors` instead of `Display: Field Lines`. In addition, a “magnetic sample”, i.e. a moving compass, can be found at the mouse pointer in the 2D display.

If there is another current-carrying conductor near the first conductor, the fields overlap. In the simulation below, the current of both conductors is directed in the same direction. The field between the conductors overlaps just enough to weaken. This can also be deduced by previous knowledge if just the middle point between both conductors is considered: There, for the left conductor the right-hand rule results in a vector directed towards the observer. For the right conductor, it results in a vector that is directed away from the observer. These just cancel each other out. Further outward field lines go around both conductors. The North and south poles here are not fixed localized toward the outside.

If, on the other hand, the current in the second conductor is directed in the opposite direction to the current in the first conductor, the picture changes: Here there is a reinforcing superposition between the two conductors. Using the nomenclature from the previous chapter, it is also possible to assign north and south poles locally. Towards the outside, one pole appears to be located in front of the two conductors and another one behind.

in both simulations, the distances between the conductors can also be changed using the `Line Separation` slider. What do you notice in each case when the two lines are brought close together?

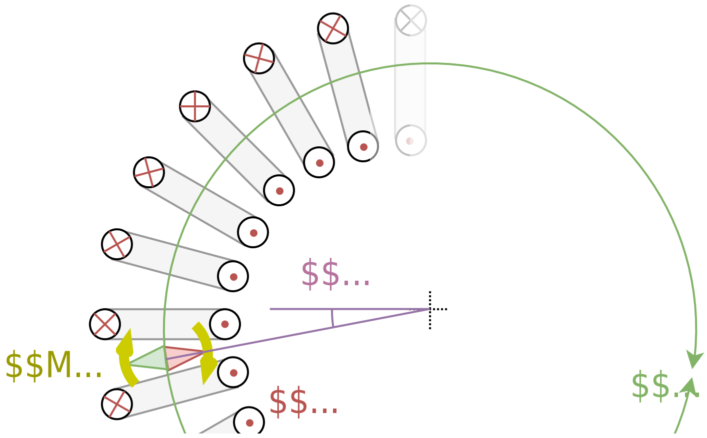
Magnetic Field Strength part 1: toroidal Coil

Fig. ##: Magnetic field in a toroidal coil

So far the magnetic field was defined quite pragmatically by the effect on a compass. For a deeper analysis of the magnetic field, the field is now to be considered again - as with the electric field - from two directions. The magnetic field will also be considered a “causer field” (a field caused by magnets) and an “acting field” (a field acting on a magnet). This chapter will first discuss the acting magnetic field. For this, it is convenient to consider the effects inside a toroidal coil (= donut-like setup). This can be seen in figure ##. For reasons of symmetry, it is also clear here that the field lines form concentric circles.

In an experiment, a magnetic needle inside the toroidal coil is now to be aligned perpendicular to the field lines. Then, the magnetic field will generate a torque M which tries to align the magnetic needle in the field direction.

Fig. ##: Toroidal Coil



It now follows:

1. $M = {\rm const.} \neq f(\varphi)$: For the same distance from the axis of symmetry, the torque M is independent of the angle ϕ.
2. $M \sim I$: The stronger the current flowing through a winding, the stronger the effect, i.e. the stronger the torque.
3. $M \sim N$: The greater the number N of windings, the stronger the torque M.
4. $M \sim {1 \over l}$: The smaller the average coil circumference l the greater the torque. The average coil circumference l is equal to the **mean magnetic path length** (=average field line length).

To summarize: \begin{align*} M \sim {{I \cdot N}\over{l}} \end{align*}

The **magnetic field strength** H inside the toroidal coil is given as: \begin{align*} \boxed{H ={{I \cdot N}\over{l}}} \quad \quad | \quad \text{applies to toroidal coil only} \end{align*}

For the unit of the magnetic field strength H we get $[H] = {{[I]}\over{[l]}}= \rm 1~{{A}\over{m}}$

Magnetic Field Strength part 2: straight conductor

The previous derivation from the toroidal coil is now used to derive the field strength around a long, straight conductor. For a single conductor the part $N \cdot I$ of the formula can be reduced to $ N \cdot I = 1 \cdot I = I$ since there is only one conductor. For the toroidal coil, the magnetic field strength was given by this current(s) divided by the (average) field line length. Because of the (same rotational) symmetry, this is also true for the single conductor. Also here the field line length has to be taken into account.

The length of a field line around the conductor is given by the distance r of the field line from the conductor: $l = l(r) = 2 \cdot \pi \cdot r$.
For the magnetic field strength of the single conductor we then get: \begin{align*} \boxed{H ={I\over{l}} = {{I}\over{2 \cdot \pi \cdot r}}} \quad \quad | \quad \text{applies only to the long, straight conductor} \end{align*}

Fig. ##: magnetic Field Lines around a Conductor

In the electric field, the field line density was a measure of the strength of the field. This is also used for the magnetic field. Looking at the simulations in Falstad (e.g. figure ##) with this understanding, one notices an inconsistency: contrary to the relationship just given, the field line density in the Falstad simulation **not** indicates the strength of the field. A realistic simulation is shown in figure 7 for comparison, which makes the difference clear: the field is stronger near the conductor. Thus the field line density must also be stronger there.

Fig. 7: correct Picture of Magnetic Field Lines around a Conductor

Attention:

- The density of the field lines is a measure of the field strength.
- The simulation in Falstad cannot represent this in this way. Here the field strength is coded by the color intensity (dark green = low field strength, light green to white = high field strength).

Common pitfalls

- …

Exercises

Worked examples

…

Embedded resources

The following video gives a similar introduction

Superposition of magnetic fields

> The online book 'University Physics II' is strongly recommended as a reference for this and the following chapter - especially the following chapters: 11. Magnetic Forces and Fields (only 11.1 - 11.3 and 11.5)