

Block 15 — Magnets, their Effects and Fieldline Images

Student Group

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Block 15 — Magnets, their Effects and Fieldline Images

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 (Fe_3O_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.

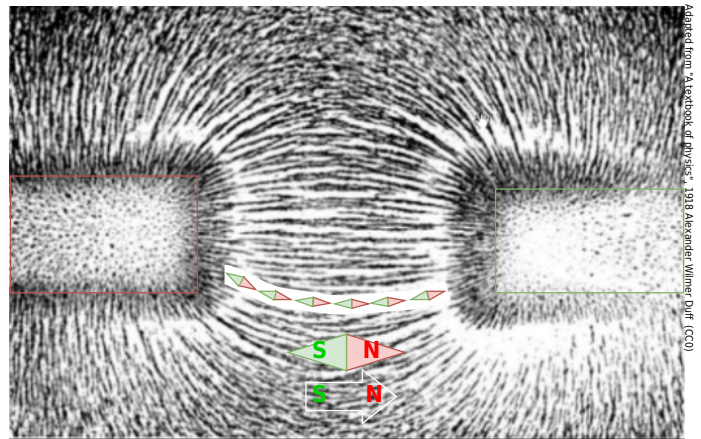
Of course, you already know magnets and also know that there are poles. The considered thought experiment shall clarify, how one could have proceeded at an unknown appearance. In further thought experiments, such magnet iron stones can also be cut into other directions and the forces analyzed.

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, see [figure 2](#) leftside.
6. Magnetic poles are not isolatable. Even the smallest fraction of a magnet shows either no magnetism or both north and south poles.

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](#) rightside. Also here there is a force effect and a torque, which aligns the iron filings. The visible field seems to form field lines here.

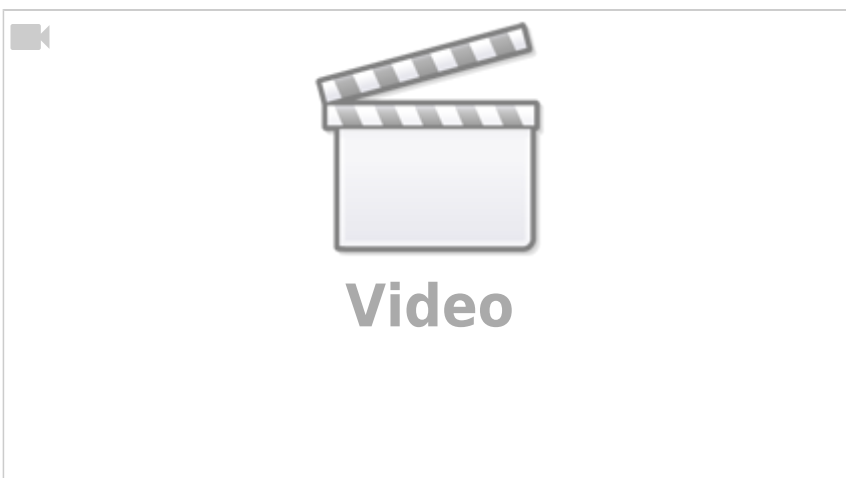
Fig. 2: Magnetic field becomes visible through iron filings



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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”).



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 best to use a cylindrical coordinate system. Then the magnetic field \vec{H} is given as $\begin{aligned} \vec{H} &= \left(\begin{matrix} H_r \\ H_\varphi \\ H_\theta \end{matrix} \right) = \left(\begin{matrix} 0 \\ H_\varphi \\ 0 \end{matrix} \right) \end{aligned}$ The radial and axial part is zero - the field is curling around the wire.

For the azimuthal magnetic field strength around a single conductor is defined as: $H_\varphi = \frac{I}{2 \pi r}$ $\quad \quad \quad | \quad \quad \quad \text{applies only to the long, straight conductor}$

l is here the length of a coaxial magnetic fieldline.

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

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) **c**urrent 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**lectron 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 | <p>Fig. 5: Electrostatic field lines</p>  <p>Text is not SVG - cannot display</p> | <p>Fig. 6: Magnetostatic field lines</p>  <p>Text is not SVG - cannot display</p> |
| 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 <u>no</u> sources and sinks |
| field type | vortex-free source field | source-free vortex field |

Superposition of the magnetostatic Field

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).

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.

Below, 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?

Complex Geometry: toroidal Coil

Fig. ##: Magnetic field in a toroidal coil

A toroidal coil has a donut-like setup. This can be seen in [figure ##](#). For reasons of symmetry, it shall get clear that the field lines form concentric circles. The magnetic field in a toroidal coil is often considered as homogenous.

In the following chapters the magnetic field will also be divided into a “causer field” (a field caused by magnets/currents) and an “acting field” (a field acting on a magnet/current).
 Since the H -field focuses on the causing current (I) and does not give us a force depending on the value of second magnet/current, it is the **causer field**.

Common pitfalls

- ...

Exercises

Task 3.2.1 Magnetic Field Strength around a horizontal straight Conductor

What is the magnetic field strength H at a point P on a straight conductor which is inside the cross section. The conductor has a constant section r_2 and the conductor axis is z -axis. The radius of the conductor is $r_L = 4 \text{ mm}$.

Path

```

\begin{align*} H(3 \text{ mm}) &= \frac{100 \text{ A}}{2\pi \cdot 0.1 \text{ m}} \quad \rightarrow H(3 \text{ mm}) \\ &= \frac{100}{2\pi \cdot 0.1} \text{ A/m} \end{align*}
    
```

The H -field is given as $H(r) = \frac{I_0}{2\pi r}$

But now I is not I_0 anymore, but only a fraction, so ΔI . I_0 is evenly distributed over the cross section A of the conductor. The cross sectional area is given as $A = \pi r_2^2$ of the closed path around the area.

- Here, the relevant current is **not** the given one. There is only a fraction of the current flowing through the part of the conductor inside the area.

The H -field is given as the current I through an area divided by the “specific” length Δl of the closed path around the area. This shall give you the formula (when not in already known)

Therefore, the relevant current is $I(r) = \frac{\Delta I}{2\pi r_2} \cdot \pi r_2^2 = \frac{I_0}{2\pi r_2} \cdot \pi r^2$

```

\begin{align*} H(r) &= \frac{I(r)}{2\pi r} = \frac{\frac{I_0}{2\pi r_2} \cdot \pi r^2}{2\pi r} \\ &= \frac{I_0}{4\pi} \cdot \frac{r^2}{r_2^2} \cdot \frac{1}{r} = \frac{1}{4\pi} \cdot I_0 \cdot \frac{r}{r_2^2} \end{align*}
    
```

Task 3.2.2 Superposition

Now the current arrangement of the conductors is reversed. To which value does the magnetic field strength $H(P)$ change?

Path

```

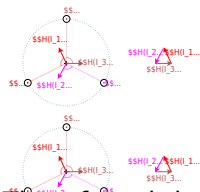
\begin{align*} H &= \frac{100 \text{ A}}{2\pi \cdot 0.1 \text{ m}} - \frac{100 \text{ A}}{2\pi \cdot 0.1 \text{ m}} \\ &= 0 \text{ A/m} \end{align*}
    
```

The field of the single conductor is given as $H(I) = \frac{I}{2\pi r}$

- Now, the formula for a single wire has to be used to calculate the field of a single

- Once again, we can try to sketch the distribution of the field vectors.
- Find the resulting field of the circle with field H_3 if it has to be superimposed.
- By its symmetry of the result of question 1, the angles of the field vectors are much stronger and result in H_3 has to be compared to the field of the reversed one.

Fig. 2: Conductor Arrangement



Therefore, it is visible, that the resulting field is twice the value of $H(I_3)$:
 The vectors of $H(I_1)$ plus $H(I_2)$ had in the task 1 just the length of $H(I_3)$.

Three long straight conductors are arranged in a vacuum to lie at the vertices of an equilateral triangle (see figure 8). The radius of the circumcircle is $r = 2 \text{ cm}$; the current is given by $I = 2 \text{ A}$.

1. What is the magnetic field strength $H(\text{P})$ at the center of the equilateral triangle?

Path

- The formula for a single wire can calculate the field of a single conductor.
- For the resulting field, the single wire fields have to be superimposed.
- Since it is symmetric the resulting field has to be neutral.

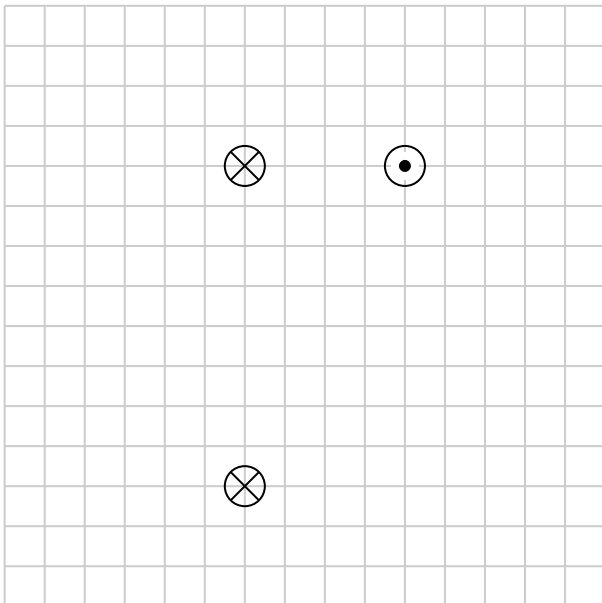
Exercise E2 Magnetic Field Lines

(written test, approx. 4 % of a 120-minute written test, SS2021)

Several parallel conductors are projecting out of the plane.

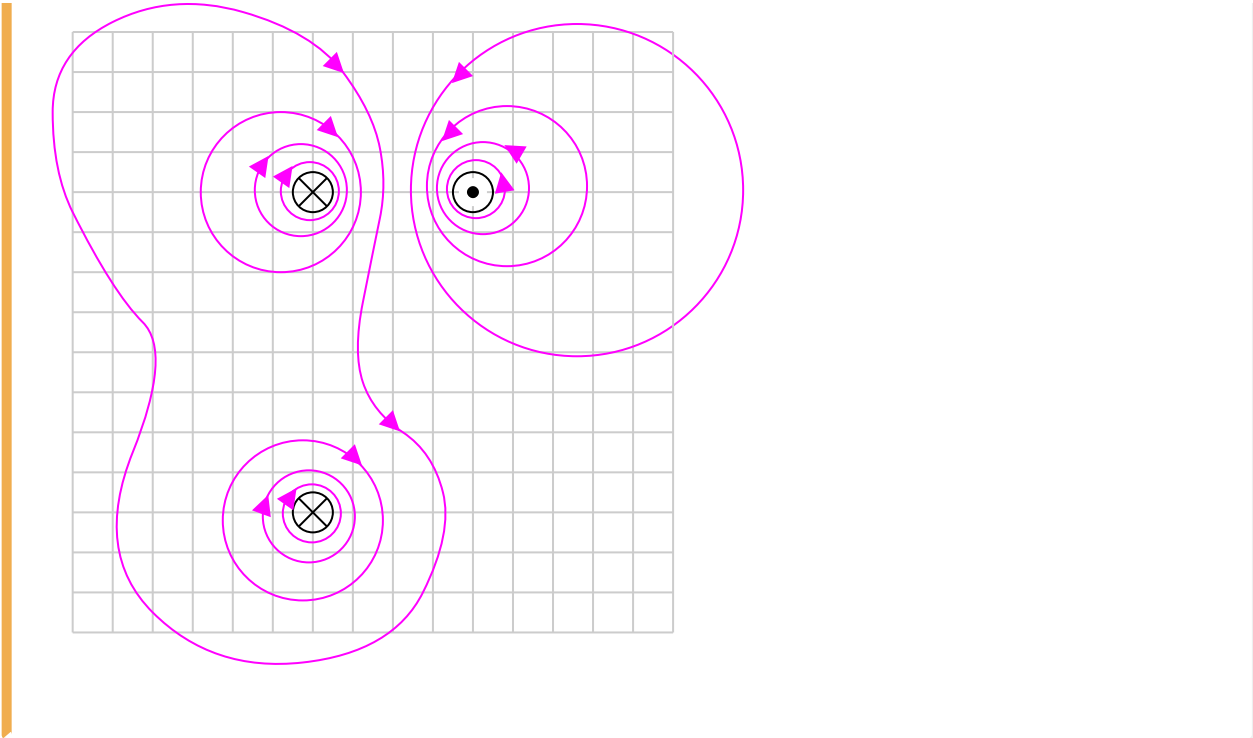
The same current I flows through all the conductors in different directions (see image below).

Sketch at least 10 field lines of the magnetic field strength \vec{H} in such a way that the different properties of the field lines (e.g. direction and density) can be seen.



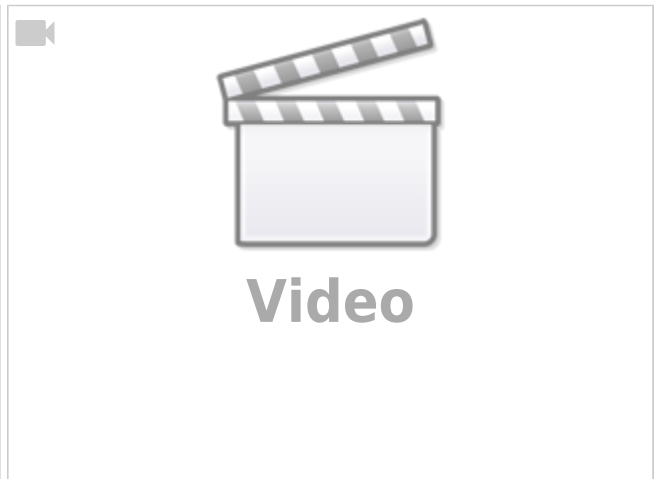
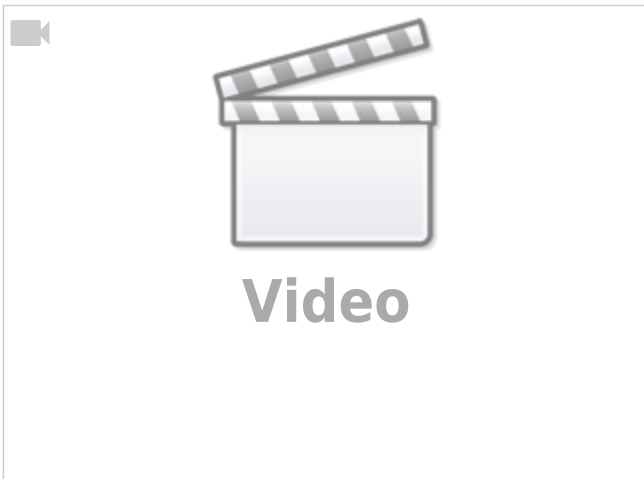
Result

- high density of field lines near the conductors
- direction of the field lines given by the right-hand rule
- magnetic field has closed field lines
- resulting field given by superposition of field lines

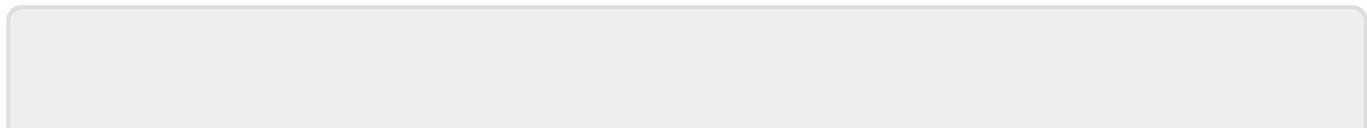


Embedded resources

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)



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