Unit 17

Magnetic Properties of Materials

This unit online, with its interactives:
science-playground.com/s/12f17

Hold a fridge magnet against an aluminium pressure cooker and it slides off; hold it against the steel plate on the cooker's base, the plate that lets it work on an induction stove, and it clings. Hold it near a copper coin, a plastic comb or a drop of water and nothing seems to happen at all. Yet every one of these materials does answer a magnet, in its own way. In this unit you will see why.

Every atom holds tiny magnets: its electrons, each spinning and moving round the nucleus. How those tiny magnets respond to a field sorts all materials into three kinds: **diamagnetic**, pushed weakly out of a field; **paramagnetic**, pulled weakly in; and **ferromagnetic**, like iron, pulled in strongly, because its atomic magnets line up together in regions called domains. You will meet the quantities that describe a material in a field (H, I, B, μ and χ), the loop that B traces in iron as the field goes up and down, which decides what makes a good transformer core and what makes a good permanent magnet, and the Earth's own field.

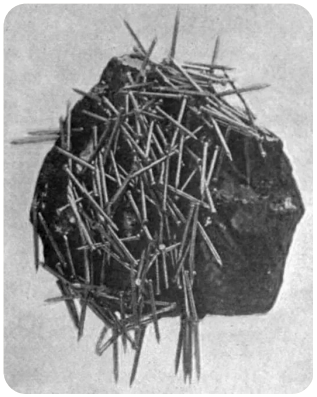


Figure 17.1 *Lodestone, the natural magnet: a piece of the iron ore magnetite (Fe_3O_4) holding small iron pins. People knew this stone for over two thousand years before they knew what made it a magnet.*
Photo: Fred Anzley Annet, Public domain

A STORY FROM SCIENCE

A mind that kept working

This unit opens with **Stephen Hawking** (1942–2018), one of the best-known physicists of our time. At 21 he learned that he had ALS (amyotrophic lateral sclerosis), a disease that slowly stops the nerves from working the muscles. He was not expected to live more than a few years. He lived for 55 more. Over time he lost the use of his legs, his hands and his voice, and in his last years he "spoke" through a computer that he worked with a single muscle in his cheek, choosing one word at a time.

His body failed, but his thinking did not. In 1974 he showed that black holes are not completely black: by the rules of quantum physics they must give off a faint glow, now called **Hawking radiation**. He held the professorship at Cambridge that Isaac Newton once held, and in 1988 he wrote *A Brief History of Time*, a book about the beginning of the universe for anyone to read, which sold more than ten million copies.

DID YOU KNOW?

Heat destroys a magnet

Every ferromagnetic material has a **Curie temperature**: above it, the material loses its strong magnetism and becomes paramagnetic. For iron it is about 1043 K (770 °C): heated past it, the jiggling of the atoms is strong enough to break up the lined-up regions (domains) that make iron magnetic. An iron nail heated bright red-hot, past 770 °C, is not attracted by a magnet; as it cools below 770 °C, it is again. (A dull red glow starts at about 550 °C, below the Curie temperature: a nail only just glowing is still attracted.)

17.1 History

People have known for over two thousand years that some stones attract iron, but what makes a magnet was understood only in the last two hundred.

Chinese legends tell of direction-finding devices as early as about 2600 BC, but there is no written evidence for them. Chinese writings from about the 4th century BC describe the lodestone attracting iron, and by the 11th century AD the Chinese scholar Shen Kuo described a magnetized needle that points north and south, and noticed that it points a little away from true north.

The name **magnet** is usually traced to **Magnesia**, where the iron ore **magnetite** (Fe_3O_4), the natural magnet or **lodestone**, was found: either the region of Magnesia in Greece or a city of the same name in Asia Minor (now Turkey). The Greeks knew of it by about 600 BC; the philosopher Thales is said to have thought the stone had a soul, since it could move iron. The **Magnetes**, the people who lived in Magnesia, gave their name to the region, so the second story of the word's origin, that it comes from a Greek tribe called the Magnetes, leads to the same place.

The Roman poet **Lucretius** (about 99–55 BC) described the magnet in his long poem *De Rerum Natura* ("On the Nature of Things"): a lodestone can hold a chain of iron rings, each hanging from the one above. Long before him, the Greek philosopher **Plato** had Socrates say: "There is a divinity moving you, like that contained in the stone which Euripides calls a magnet … This stone not only attracts iron rings, but also imparts to them a similar power of attracting other rings." The Roman writer **Pliny** (AD 23–79) told the legend of a shepherd named Magnes whose iron-nailed shoes stuck to the rock on which he walked.

The study of magnetism became a science with **Peter Peregrinus** (1269), who named the poles of a magnet and found that a broken magnet becomes two magnets; **William Gilbert** (1600), who showed that the Earth itself is a great magnet; **Hans Christian Oersted** (1820), who found that a current makes a magnetic field; and **André-Marie Ampère**, **Jean-Baptiste Biot** and **Félix Savart**, **Humphry Davy**, **William Wollaston** and **Michael Faraday**, who worked out the laws of electromagnetism in the years after.

Check 1

Which of these did William Gilbert show in 1600?

a that a current makes a magnetic field

b that the Earth behaves as a great magnet

c that a magnet has two poles that cannot be separated

d that a magnet loses its magnetism above a certain temperature

17.2 A few terms

To describe how a material behaves in a magnetic field, we need a few quantities: the field applied to it, how strongly it becomes magnetized, and the field that results.

A companion to your textbook, not a replacement for it: study from the book your school uses, and where the two differ, follow your teacher. Found a mistake? Please tell us.

Induced magnetism and the magnetizing field

When a piece of a magnetic substance, such as iron, is placed in a magnetic field, it becomes a magnet. The magnetism produced in it this way is called **induced magnetism**, and the process is called **magnetic induction**. (“Induced” means caused by the influence of something else, without direct contact.) The field that magnetizes the substance placed in it is called the **magnetizing field**.

This is why a magnet picks up an unmagnetized iron nail: the magnet’s field makes the nail a magnet, with its nearer end an opposite pole, and opposite poles attract. The nail can then pick up a pin, which becomes a magnet in turn, the chain of rings that Lucretius described.

Magnetic intensity H

The strength of the magnetizing field is called the **magnetic intensity** (or **magnetizing field strength**), H. It describes the field that the currents or magnets **apply** to a material, apart from the material’s own response. Its SI unit is the **ampere per meter** (A/m); in the older CGS system it is the **oersted** (1 Oe ≈ 79.6 A/m).

The easiest place to see H is inside a long solenoid of n turns per meter carrying a current I:

$$H = nI$$

whatever is inside the solenoid, air or iron. The current sets H; the material decides what B results. In air (or a vacuum), B and H are simply proportional:

$$B = \mu_0 H, \qquad \mu_0 = 4\pi \times 10^{-7}\ \text{T m/A}$$

In the older way of describing magnetism by poles, H at a point is defined as the force on a unit north pole placed there, in the direction a free north pole would move. Its direction at each point is along the magnetic line of force through that point, the line whose tangent everywhere gives the direction of the field (Unit 16).

> CAREFUL
>
> **H and B are different quantities**
>
> H, in A/m, is the field the currents apply; B, in T, is the field that results, and it includes the material’s own magnetism. In air the two differ only by the constant μ_0, so the number of lines of force per unit area, which some books use to define H, measures $B = \mu_0 H$ there. Inside iron, B can be thousands of times larger than $\mu_0 H$.

b. Two hysteresis loops, a and b, are shown in Figure 17.18.

i. Which best represents the hysteresis loop of soft iron? Give a reason for your answer.

ii. Which material, a or b, is more suitable for a transformer core, and which for a permanent magnet? Justify your answer.

iii. Name the physical quantity represented by the area of the hysteresis loop.

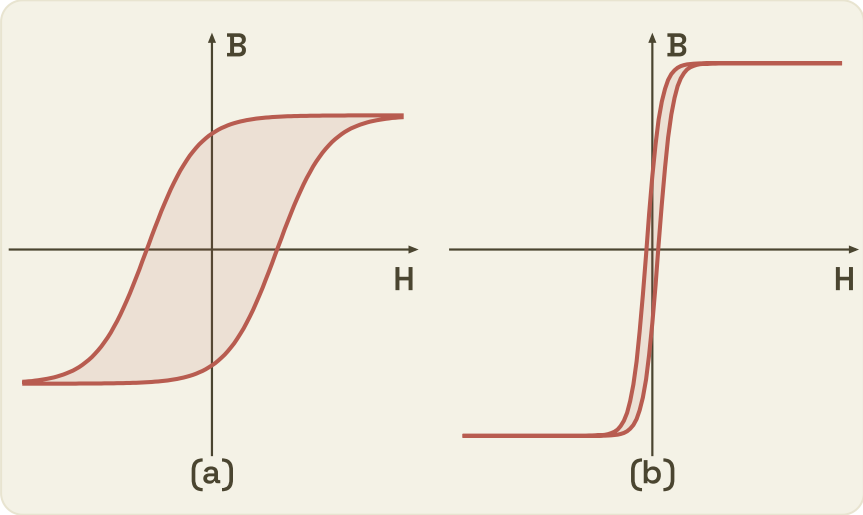


Figure 17.18 *For question 15: two hysteresis loops, a, wide, and b, narrow.*

16.

a. i. Define magnetic hysteresis. Sketch and label a typical hysteresis loop for a ferromagnetic material.

ii. Explain the significance of the following with reference to the hysteresis loop: 1. retentivity, 2. coercivity, 3. hysteresis loss.

iii. How are these properties used in choosing materials for permanent magnets and transformer cores?

b. i. Distinguish between diamagnetic, paramagnetic and ferromagnetic materials on the basis of 1. their magnetic susceptibility, 2. their behavior in an external magnetic field, 3. examples.

ii. Explain why ferromagnetic materials show hysteresis but diamagnetic and paramagnetic materials do not. Use the idea of magnetic domains in your explanation.

Pole strength

A magnet's north pole and its south pole are equally strong but opposite in kind. **Pole strength**, m, says how strong each pole is: a north pole has strength +m, a south pole −m. In SI, pole strength is measured in **ampere meters** (A m), and a pole of strength m in a field B feels a force F = mB. A magnet's poles always come in pairs: break a magnet and each piece has a north and a south pole.

Magnetic dipole moment

A bar magnet, with its north pole and its south pole a fixed distance apart, is a **magnetic dipole**. Its **magnetic dipole moment** M tells how strong the magnet is and which way it points: it is a vector pointing from the S pole to the N pole inside the magnet.

For a bar magnet, the dipole moment is the strength of either pole times the distance between the poles:

$$M = m \times 2l$$

where 2l is the **magnetic length**, the distance between the poles. The poles of a real bar magnet lie a little inside its ends, so its magnetic length is somewhat shorter than the bar (about 0.85 of it is a common figure). The unit of M is the **ampere meter squared** (A m^2).

For a current loop, as you saw in Unit 16, a flat loop of area A carrying a current I is a magnetic dipole too, with

$$M = IA$$

along the loop's normal (the way the right-hand grip rule gives from the current). For a coil of N turns, $M = NIA$. Both are in A m^2, the same unit: a current loop and a bar magnet are the same kind of thing as far as their fields are concerned.

A dipole in a uniform field

Put a bar magnet in a uniform field B, its moment M at an angle θ to the field (Figure 17.2 shows the moment). The N pole is pushed along the field with a force mB, and the S pole the opposite way with an equal force mB. The two forces are equal and opposite, so there is no net force, but they act along different lines: a **couple**. The perpendicular distance between their lines is 2l sin θ, so the torque is

$$\tau = mB \times 2l \sin\theta = (m \times 2l)B \sin\theta$$

$$\boxed{\tau = MB\sin\theta} \qquad \text{or, as vectors,} \quad \vec{\tau} = \vec{M} \times \vec{B}$$

This is the same law as for a coil in Unit 16. The torque turns the magnet towards the field: it is largest (MB) when the magnet is at right angles to the field and zero when

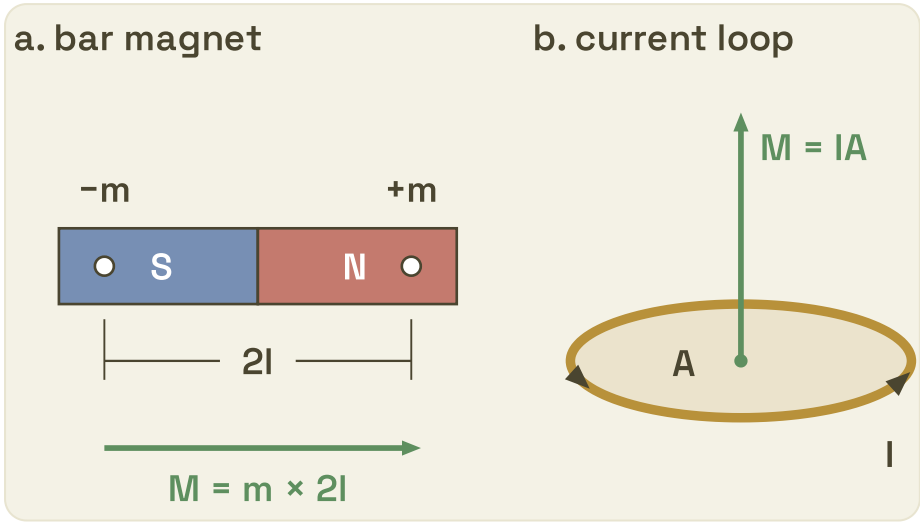


Figure 17.2 *Two magnetic dipoles. a. A bar magnet: poles of strength $-m$ and $+m$, a distance $2l$ apart, a little inside the ends; its moment $M = m \times 2l$ points from S to N. b. A flat loop of area A with a current I, anticlockwise seen from above: its moment $M = IA$ points up, along the loop's normal.*

WORKED EXAMPLE

Example 17.1: why 2l?

Why is the dipole moment of a bar magnet defined as M = m × 2l, and not as M = m × l?

Answer

A dipole moment is a pole strength times the **distance between the two poles**. Put the center of the magnet at the origin, with the magnet along an axis: the north pole is at +l and the south pole at −l, so the distance between the poles is

$$(+l) - (-l) = 2l$$

The letter l stands for **half** the magnetic length, measured from the center to either pole. So the moment is m × 2l. (Writing the length between the poles as 2l keeps the formulas for the field at a distance d from the center tidy: they contain $d^2 - l^2$ and $d^2 + l^2$.)

it lies along it. That is why a compass needle settles along the field.

Check 18

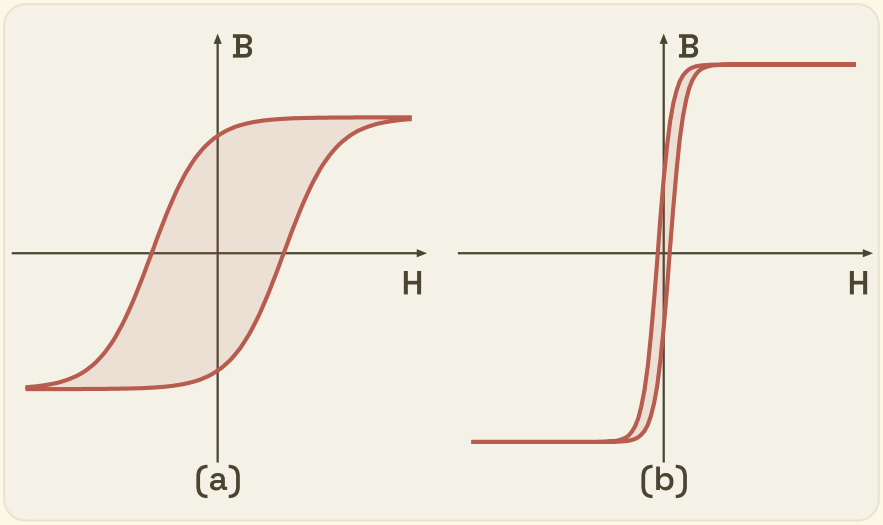


Figure 17.17 *For question 12: the hysteresis loops of two materials, a, wide, and b, narrow.*

12. The loops in the figure above belong to two materials. Magnets for electric generators, transformer cores and electromagnet cores are to be made from them. It is proper to use:

a. a for the generator's magnets, and b for the transformer cores and the electromagnet cores
b. b for the generator's magnets, and a for the transformer cores and the electromagnet cores
c. a for all three
d. b for all three

Answer these questions

13.
a. A ferromagnetic substance becomes paramagnetic above its Curie temperature. Explain why.
b. The magnetic intensity at a point is 1000 A/m. Find the magnetic induction in a material of magnetic susceptibility 1272 placed there.

14.
a. Define relative permeability and magnetic susceptibility.
b. Establish the relation between magnetic susceptibility and relative permeability.
c. What properties should a substance have to make a permanent magnet?

15.
a. Define retentivity and coercivity.

Check 13

7. Magnetic lines of force:

a never intersect
b intersect at infinity
c intersect within the magnet
d intersect at a neutral point

Check 14

8. The temperature above which a ferromagnetic material becomes paramagnetic is called the:

a critical temperature
b inversion temperature
c Curie temperature
d Debye temperature

Check 15

9. What is the cause of the Earth's magnetic field?

a the motion of material inside the Earth
b the interaction of cosmic rays with currents in the Earth
c a magnetic dipole buried at the center of the Earth
d induction by the Sun

Check 16

10. A magnet of dipole moment 2 A m² is deflected through 30° from the magnetic meridian. The deflecting torque needed is ($B_H = 0.4 \times 10^{-4}$ T):

a 0.4×10^{-4} N m
b 0.4 N m
c 0.2×10^{-4} N m
d none of these

Check 17

11. The hysteresis loop of a ferromagnetic material becomes narrower when:

a the coercivity decreases
b the coercivity increases
c the saturation magnetization decreases
d the saturation magnetization increases

YOUR TURN

Test yourself 17.1: a compass needle

A compass needle has a magnetic moment of 0.05 A m². In Kathmandu the horizontal part of the Earth's field is about 35 μT. What torque turns the needle back when it is pushed 90° away from north?

Answer

$$\tau = MB\sin 90^\circ = 0.05 \times 35 \times 10^{-6} \times 1 = 1.75 \times 10^{-6}\ \text{N m}$$

About **1.8×10^{-6} N m**: a tiny torque, which is why a compass needle is light and balanced on a sharp point.

Intensity of magnetization I

A magnetized piece of material is full of tiny magnetic moments. The **intensity of magnetization**, I, measures how strongly it is magnetized: it is the **magnetic moment per unit volume**,

$$I = \frac{M}{V}$$

where M is the total magnetic moment developed in a specimen of volume V.

For a bar of cross-sectional area A and magnetic length 2l, with poles of strength m, the volume is V = A × 2l, so

$$I = \frac{m \times 2l}{A \times 2l} = \frac{m}{A}$$

So the intensity of magnetization is also the **pole strength per unit area of cross-section**. Its unit is (A m²)/m³ = **A/m**, the same as H's. (Many books write the magnetization as **M**; here M is the dipole moment, so the magnetization is I.)

CAREFUL

The unit of I

I is measured in A/m. Some older books give its unit as Wb/m² because they define the magnetization as μ_0 times ours; with the definition I = M/V used here, the unit is A/m.

WORKED EXAMPLE

Example 17.2: a bar magnet's magnetization

A bar magnet is 10 cm long with a cross-section of 2 cm × 1 cm, and its magnetic moment is 2.5 A m². Find a. the intensity of magnetization, and b. its pole strength, taking its magnetic length as 8.5 cm.

Answer

a. Volume $V = 0.10 \times 0.02 \times 0.01 = 2 \times 10^{-5}\ \text{m}^3$.

$$I = \frac{M}{V} = \frac{2.5}{2 \times 10^{-5}} = \mathbf{1.25 \times 10^{5}\ A/m}$$

b.

$$m = \frac{M}{2l} = \frac{2.5}{0.085} = \mathbf{29\ A\,m}$$

Magnetic induction B

Put a soft-iron bar in a uniform magnetizing field, as in Figure 17.3. The iron becomes a magnet at once: its left end, where the field enters, becomes an **S pole**, and its right end, where the field leaves, an **N pole**. The magnetized iron makes a field of its own, drawn in Figure 17.3a. Beyond its ends, in the regions A and B, the iron's own field points the same way as the magnetizing field and **strengthens** it. Beside it, in the regions C and D, the iron's field points the other way and **weakens** it. The resultant field (Figure 17.3b) is drawn into the iron: the lines bend inwards and crowd through it.

The lines of force inside a magnetic substance are called **lines of induction**. The **magnetic induction** B (the magnetic flux density of Unit 16) in the substance is the number of lines of induction crossing unit area at right angles. Its SI unit is the **tesla** (T), which is the weber per square meter; in the CGS system it is the **gauss** (G), the maxwell per square centimeter, and 1 T = 10^4 G.

The induction in the specimen has two sources:

i. the magnetizing field H, and

ii. the specimen's own magnetization I.

In SI units both are in A/m, and each contributes μ_0 times itself to B:

$$\boxed{B = \mu_0(H + I)}$$

Check 7

1. A permanent magnet is made from which of these substances?

a diamagnetic
b paramagnetic
c ferromagnetic
d soft iron

Check 8

2. At a certain place the horizontal component of the Earth's magnetic field is B_0 and the angle of dip is 45°. What is the total intensity of the field at that place?

a B_0
b $\sqrt{2}\,B_0$
c $2B_0$
d $B_0/\sqrt{2}$

Check 9

3. Where does the Earth's magnetic field have no horizontal component?

a at the magnetic equator
b at a magnetic pole
c at a latitude of 30°
d at a longitude of 60°

Check 10

4. A magnetic field can be detected because it:

a always exerts a force on a charged particle
b never exerts a force on a charged particle
c exerts a force on a charged particle moving along the field
d exerts a force on a charged particle moving at an angle to the field

Check 11

5. What happens to the susceptibility of a ferromagnetic substance when its temperature is increased?

a it increases
b it decreases
c it remains constant
d it can increase or decrease

Check 12

6. The magnetic susceptibility of a diamagnetic substance is:

a small and negative
b small and positive
c large and positive
d zero

IN SHORT

Summary

- Induced magnetism: a magnetic substance placed in a magnetizing field becomes a magnet. Magnetic intensity H (A/m) is the field the currents apply; in a long solenoid H = nI.
- Pole strength m (A m); dipole moment M = m × 2l for a bar magnet, M = NIA for a coil (A m²), pointing S to N. In a uniform field a dipole feels a torque $\tau = MB\sin\theta$.
- Intensity of magnetization I = M/V = m/A (A/m). Magnetic induction $B = \mu_0(H + I)$, in T (1 T = 10^4 G).
- Permeability $\mu = B/H$ (T m/A), relative permeability $\mu_r = \mu/\mu_0$, susceptibility $\chi = I/H$ (no unit): $\mu_r = 1 + \chi$.
- Diamagnetic: weakly repelled, χ small and negative, independent of T, $\mu r < 1$ (Cu, Bi, water; superconductors perfectly, $\chi = -1$). Paramagnetic: weakly attracted, χ small and positive, $\chi = C/T$ (Curie's law), $\mu r > 1$ (Al, Pt, O_2). Ferromagnetic: strongly attracted, χ and μr large, hysteresis, paramagnetic above the Curie temperature (Fe, Co, Ni).
- Domain theory: a ferromagnet is made of domains, each magnetized to saturation; a field grows the domains along it and then turns the rest; heat above the Curie temperature destroys them.
- Hysteresis: B lags behind H. Retentivity: B left at H = 0; coercivity: the reverse H that brings B to zero; the loop's area is the energy lost per unit volume per cycle.
- Soft iron (narrow loop, low coercivity, small loss) for transformer cores and electromagnets; steel and alnico (wide loop, high coercivity) for permanent magnets.
- The Earth's field comes from currents in its molten outer core. Declination, dip δ and $B_H = B\cos\delta$, $B_V = B\sin\delta$, $\tan\delta = B_V/B_H$.

Exercise

Choose the correct option

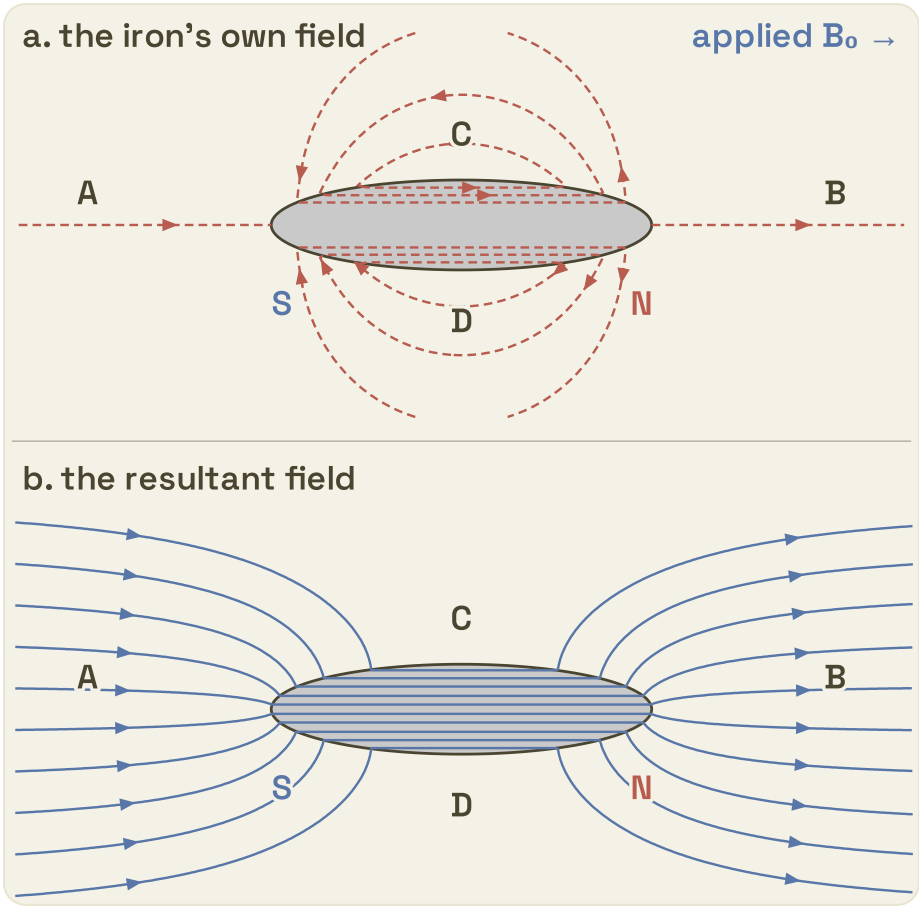


Figure 17.3 *A long piece of soft iron in a uniform field to the right, worked out exactly for iron of relative permeability 1000. a. The iron's own field once it is magnetized (dashed): out of its N end, round, and into its S end. At A and B it points along the applied field, at C and D against it. b. The resultant: lines evenly spaced far away crowd through the iron, about five times closer together inside, so the field is stronger at A and B and weaker at C and D.*

Magnetic permeability μ

Magnetic permeability measures how easily a material lets a magnetic field form in it: how much induction B results from a given magnetizing field H. It is defined as the ratio of the magnetic induction to the magnetizing field:

$$\mu = \frac{B}{H}$$

Its unit is T/(A/m) = **T m/A** (the same as the henry per meter, H/m). The higher a material's permeability, the more B a given H produces in it: iron, of high permeabil-

ity, gathers the field lines into itself, as in Figure 17.3b. In a vacuum, $\mu = \mu_0 = 4\pi \times 10^{-7}$ T m/A.

Relative permeability μr

The **relative permeability** of a material is the ratio of its permeability to that of a vacuum:

$$\mu_r = \frac{\mu}{\mu_0}$$

It has no unit. It tells how many times larger B is in the material than it would be in a vacuum for the same H. For air, μr is 1.0000004; for soft iron, it is in the thousands.

Magnetic susceptibility χ

Magnetic susceptibility measures how easily a material becomes magnetized in a field. It is the ratio of the intensity of magnetization to the magnetizing field:

$$\chi = \frac{I}{H}$$

Since I and H are both in A/m, χ has **no unit**. It is negative for a material magnetized against the field, positive for one magnetized along it.

Relation between μr and χ

The relative permeability and the susceptibility are two ways of saying the same thing.

Step 1. Start from B. $B = \mu_0(H + I)$.

Step 2. Write I in terms of H. From $\chi = I/H$, $I = \chi H$, so

$$B = \mu_0(H + \chi H) = \mu_0 H(1 + \chi)$$

Step 3. Divide by H. $\frac{B}{H} = \mu_0(1 + \chi)$, and B/H is the permeability μ:

$$\mu = \mu_0(1 + \chi)$$

Step 4. Divide by μ_0. $\mu/\mu_0 = \mu_r$, so

$$\boxed{\mu_r = 1 + \chi}$$

A material with χ slightly below zero has μr slightly below 1; one with a large χ has a large μr.

WORKED EXAMPLE

Example 17.8: turning a magnet in the Earth's field

A magnet of dipole moment 2 A m² is turned through 30° from the magnetic meridian. What torque is needed to hold it there, where $B_H = 0.4 \times 10^{-4}$ T?

Answer

The horizontal component pulls the magnet back towards the meridian with a torque

$\tau = MB_H \sin\theta = 2 \times 0.4 \times 10^{-4} \times \sin 30^\circ = 2 \times 0.4 \times 10^{-4} \times 0.5 = \mathbf{0.4 \times 10}$

and the deflecting torque must be equal and opposite.

DID YOU KNOW?

Maps that need a date

The Earth's field changes from year to year, so a map that gives the declination also gives its year and how fast it changes. Scientists publish a new model of the whole field every five years (the International Geomagnetic Reference Field); the values for Kathmandu in this unit come from it.

Check 6

At a place where the angle of dip is 60°, the horizontal component of the Earth's field is 20 μT. The total field is:

a 10 μT
b 17.3 μT
c 34.6 μT
d 40 μT

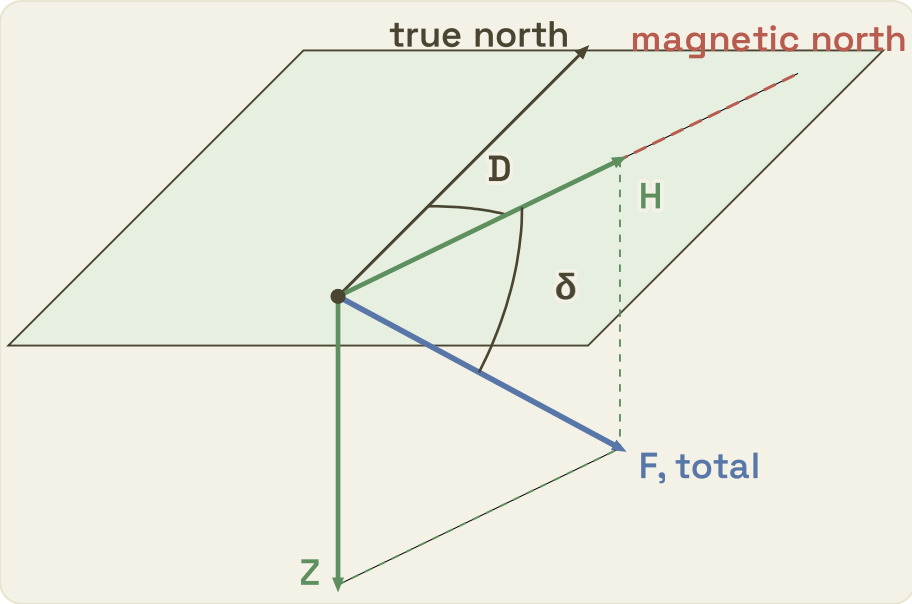


Figure 17.16 *The elements of the Earth's field at a place. On the horizontal ground, the magnetic meridian makes the declination D with true north. The total field F dips at the angle δ below the horizontal; its horizontal part H (B_H in the text) lies along the magnetic meridian and its vertical part Z (B_V) points straight down. Drawn with D = 25° and δ = 40°, so that the angles can be seen.*

WORKED EXAMPLE

Example 17.7: the field at Kathmandu

In Kathmandu in 2026, the Earth's total field is about 49.2 μT and the angle of dip about 44.4°. Find the horizontal and vertical components.

Answer

$$B_H = B\cos\delta = 49.2 \times \cos 44.4^\circ = 49.2 \times 0.714 = \mathbf{35.1\ \mu T}$$

$$B_V = B\sin\delta = 49.2 \times \sin 44.4^\circ = 49.2 \times 0.700 = \mathbf{34.4\ \mu T}$$

The two are almost equal, since the dip is close to 45°. (The declination at Kathmandu is less than half a degree east: a compass there points almost exactly to true north.)

WORKED EXAMPLE

Example 17.3: from B and H

The magnetic field B and the magnetic intensity H in a material are 2 T and 950 A/m. Find its relative permeability μr and its susceptibility χ. ($\mu_0 = 4\pi \times 10^{-7}$ T m/A)

Answer

B = 2 T, H = 950 A/m.

$$B = \mu_0(1+\chi)H \quad \Rightarrow \quad 1+\chi = \frac{B}{\mu_0 H} = \frac{2}{4\pi \times 10^{-7} \times 950} = \frac{2}{1.194 \times 10^{-3}} =$$

So $\chi = 1675 - 1 = \mathbf{1674}$, and $\mu_r = 1 + \chi = \mathbf{1675}$. A material with χ this large is ferromagnetic.

WORKED EXAMPLE

Example 17.4: an iron core in a solenoid

A long solenoid has 1000 turns per meter and carries a current of 2 A. Its core is iron of relative permeability 500. Find a. H in the core, b. B in the core, c. the intensity of magnetization of the iron.

Answer

a. $H = nI = 1000 \times 2 = \mathbf{2000\ A/m}$, set by the current alone.

b. $B = \mu_0\mu_r H = 4\pi \times 10^{-7} \times 500 \times 2000 = \mathbf{1.26\ T}$. Without the iron it would be $\mu_0 H = 2.5 \times 10^{-3}$ T: the iron multiplies the field 500 times.

c. $\chi = \mu_r - 1 = 499$, so $I = \chi H = 499 \times 2000 = \mathbf{1.0 \times 10^6\ A/m}$. Almost all of B comes from the iron's magnetization, not from the current.

Check 2

The intensity of magnetization of a material is 300 A/m in a magnetizing field of 6×10^5 A/m. Its susceptibility is:

a 5×10^{-4}
b 2×10^3
c 1.8×10^8
d 5×10^{-4} A/m

17.3 Classification of magnetic substances

Every material responds to a magnetic field, though most so weakly that only a strong magnet shows it. By the way they respond, substances fall into three groups: **diamagnetic**, **paramagnetic** and **ferromagnetic**.

The difference starts inside the atom. Each electron is a tiny magnet, from its spin and from its motion round the nucleus. In most atoms the electrons are in pairs whose tiny magnets cancel; an atom with unpaired electrons has a magnetic moment of its own.

Diamagnetic substances

Diamagnetic substances are those which, placed in a magnetic field, are **weakly repelled** by it: they are feebly magnetized in the direction **opposite** to the magnetizing field. Copper, zinc, bismuth, antimony, mercury, silver, gold, water and most organic materials are diamagnetic.

Diamagnetism happens in **every** atom. When a field is applied, it changes the motion of the electrons round the nucleus a little, and by the same rule as Lenz's law (Unit 18) the change makes a magnetic moment that **opposes** the field. In atoms whose electrons are all paired, this is the only response, so the substance is pushed weakly away from a strong field.

Their properties:

i. A rod of a diamagnetic substance hung between the poles of a strong magnet settles **at right angles** to the field (Figure 17.5a).

ii. They are magnetized in the direction **opposite** to the applied field.

iii. They are **weakly repelled** by a magnet: they move from the stronger to the weaker part of a field.

iv. Their susceptibility is **small and negative**, about -10^{-5} (bismuth's, one of the largest, is about -1.7×10^{-4}), and it does **not depend on temperature**.

v. Their relative permeability is **slightly less than 1**.

vi. They show **no hysteresis**: the magnetization disappears as soon as the field is removed.

vii. **Superconductors** are perfect diamagnets: $\chi = -1$ and $\mu r = 0$. They push a magnetic field out of themselves entirely (the **Meissner effect**, Figure 17.4a), strongly enough to float above a magnet.

viii. Examples: bismuth, antimony, copper, mercury, silver, zinc, gold and water.

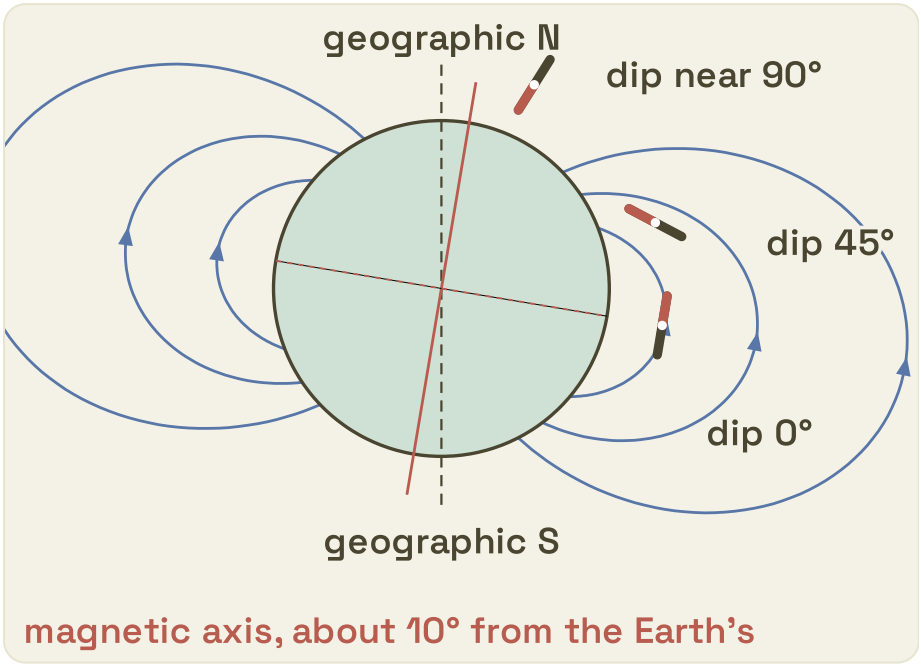


Figure 17.15 *The Earth's field, like that of a magnet at its center whose axis (red) is tilted about 10° from the Earth's axis (dashed). The lines leave the southern hemisphere and enter the northern. Dip needles (north end red) lie level at the magnetic equator, dip about 45° at a magnetic latitude like Nepal's, and stand almost upright near the magnetic pole.*

- **Dip (or inclination) δ**: the angle the total field makes with the horizontal, in the magnetic meridian. A needle free to turn in a vertical plane (a **dip needle**) shows it. The dip is 0° at the **magnetic equator** and 90° at the **magnetic poles**.
- **Horizontal component B_H**: the part of the field along the ground, in the magnetic meridian. It is what turns an ordinary compass.

If the total field is B, its horizontal and vertical parts are

$$B_H = B\cos\delta, \qquad B_V = B\sin\delta$$

so that

$$\boxed{B = \sqrt{B_H^2 + B_V^2}}, \qquad \boxed{\tan\delta = \frac{B_V}{B_H}}$$

At a magnetic pole, $\delta = 90°$, so $B_H = B\cos 90° = 0$: a compass there has no horizontal field to turn it, and points nowhere in particular. At the magnetic equator, $\delta = 0$ and the field is all horizontal.

CAREFUL

Retentivity is not the only test

A good permanent magnet needs a **high coercivity** above all, so that stray fields and knocks do not demagnetize it. Soft iron can keep a large B after a field is removed from a closed ring of it, but its coercivity is so small that a tiny reverse field, or a knock, removes it.

Check 5

A material is wanted for the core of a transformer. Its hysteresis loop should be:

a wide, with a large area
b narrow, with a small area
c narrow, with a large coercivity
d any shape, if the retentivity is large

17.6 The Earth's magnetic field

A compass works because the Earth is a magnet, as Gilbert showed in 1600. The exercise below asks about it, so here is what you need.

The Earth as a magnet

Near the Earth's surface, its field is much like that of a huge bar magnet at its center, tilted about 10° from the Earth's axis (Figure 17.15). The field lines leave the southern hemisphere and enter the northern one: near the **geographic North Pole** there is a magnetic **S pole**, which is why the north pole of a compass needle is drawn there.

There is no magnet inside the Earth: the center is far hotter than iron's Curie temperature. The field is made by **electric currents in the Earth's outer core**, a layer of molten iron 2,900 km down, kept moving by heat flowing out of the core and stirred by the Earth's rotation. This self-sustaining process is called the **geodynamo**. It changes slowly: the magnetic poles wander tens of kilometers a year, and over millions of years the field has reversed many times, the last time about 780,000 years ago.

Declination, dip and the horizontal component

At any place, three quantities describe the Earth's field, its **elements** (Figure 17.16):

- **Declination D**: the angle between the **geographic meridian** (the north–south line through true north) and the **magnetic meridian** (the vertical plane in which a freely turning compass needle settles). It is how far a compass points away from true north.

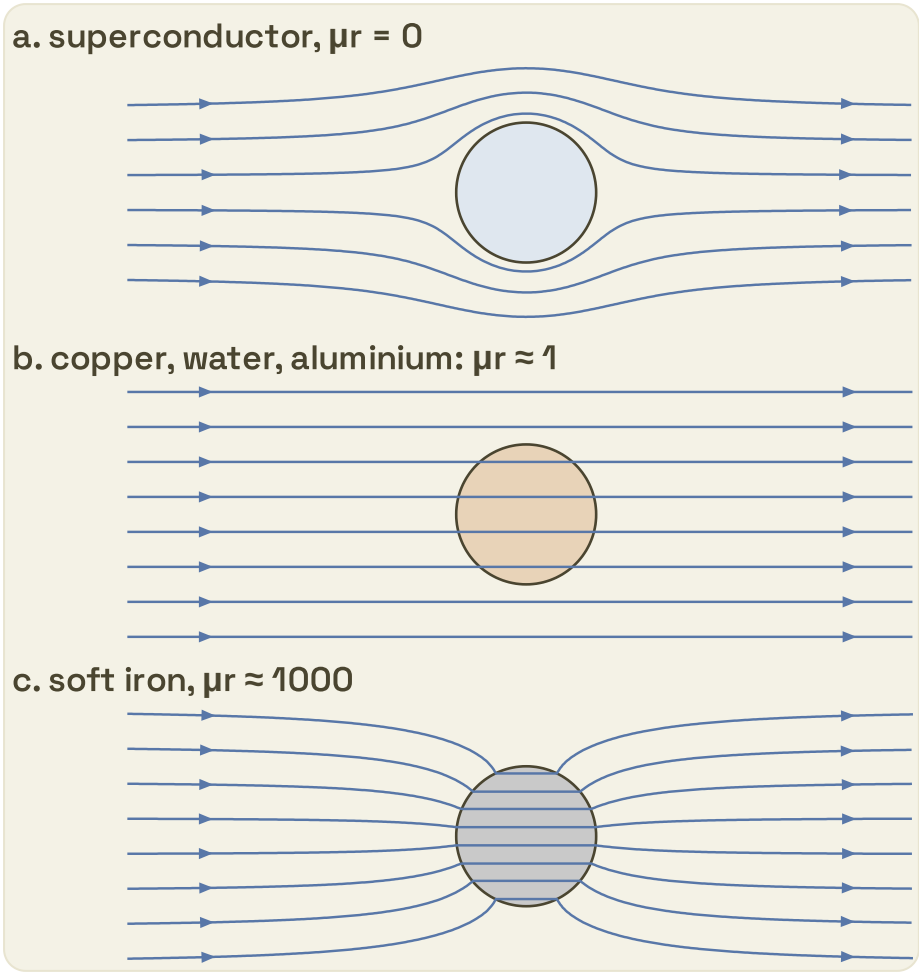


Figure 17.4 *Round rods of three materials, seen end on, in a uniform field to the right, worked out exactly. a. A superconductor (μr = 0): the field is pushed out entirely and the lines go round it. b. Copper, water or aluminium, diamagnetic or paramagnetic: μr differs from 1 by less than one part in a thousand, so the lines are unchanged as far as the eye can see. c. Soft iron (μr ≈ 1000): the lines crowd into it, twice as close together inside.*

Paramagnetic substances

Paramagnetic substances are those which, placed in a magnetic field, are **weakly attracted** by it: they are feebly magnetized in the **direction** of the magnetizing field. Aluminium, platinum, sodium, potassium, magnesium and oxygen are paramagnetic.

Their atoms have unpaired electrons, so each atom is a tiny permanent magnet. With no field, heat keeps these tiny magnets pointing every way, and they cancel. A field

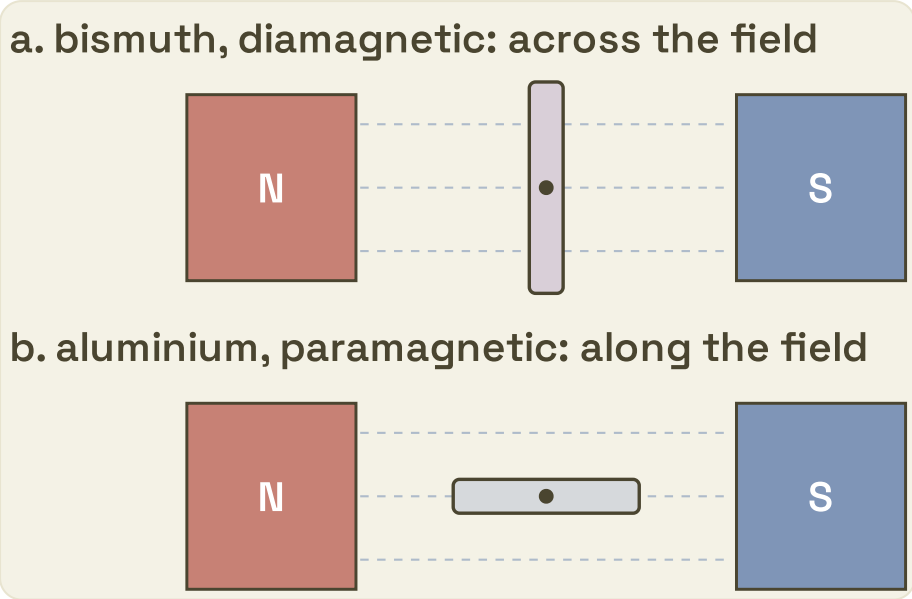


Figure 17.5 *A short rod hung by a thread between the poles of a strong magnet, seen from above. a. Bismuth, diamagnetic: it settles across the field. b. Aluminium, paramagnetic: it settles along the field, from pole to pole.*

turns them a little towards itself, against the jiggling of the atoms, so the substance is magnetized weakly along the field (and its own diamagnetism, much weaker, is outweighed).



Figure 17.6 *A live frog floating inside a 16 T magnet at Radboud University in Nijmegen (1997). The frog, mostly water, is diamagnetic: in so strong a field the push on it balances its weight. The frog was unharmed.*

Photo: Lijnis Nelemans, CC BY-SA 3.0

Their properties:

i. A rod of a paramagnetic substance hung between the poles of a magnet settles **along** the field (Figure 17.5b).

ii. They are magnetized **along** the field.

iii. They are **weakly attracted** by a magnet: they move from the weaker to the stronger part of a field. A paramagnetic liquid in a U-tube rises in the limb placed between the poles (Figure 17.8).

iv. Their relative permeability is **slightly greater than 1**.

v. Their susceptibility is **small and positive**, about 10^{-5} to 10^{-3} (aluminium's is about 2×10^{-5}, platinum's about 2.6×10^{-4}).

vi. They show **no hysteresis**.

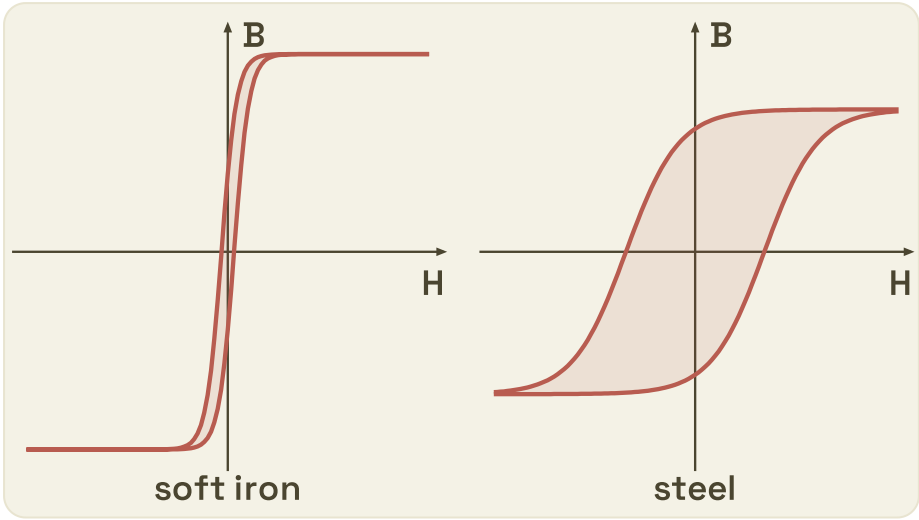


Figure 17.14 *Hysteresis loops of soft iron and steel, drawn to the same scale. Soft iron: tall and narrow, with a small coercivity and a small area. Steel: shorter and wide, with a large coercivity and a large area.*

% silicon) and mumetal (a nickel–iron alloy) also have narrow loops; silicon steel is used for most transformer cores.

- **Steel** (and other **hard** magnetic materials): a **shorter, wide** loop with a **large area**. It has a **high coercivity** and a fairly high retentivity, so once magnetized it is very hard to demagnetize. Its large hysteresis loss does not matter for a permanent magnet, which is never taken round its loop. Ideal for **permanent magnets**: cobalt steel, chromium steel, tungsten steel and **alnico** (iron with aluminium, nickel and cobalt, and a little copper). Today's strongest permanent magnets are **neodymium magnets** (an alloy of neodymium, iron and boron, made since the 1980s), in earphones, phone speakers, electric-car motors and wind turbines.

So the material is chosen by its loop:

Use	It needs	Material
permanent magnet	high retentivity, high coercivity (a wide loop)	steel, alnico, neodymium–iron–boron
electromagnet	high permeability, low retentivity, low coercivity	soft iron
transformer core	high permeability, low coercivity, small loop area	silicon steel, soft iron

Retentivity, coercivity and the loop's area

- **Retentivity** (Ob): the magnetic induction left in the material when the magnetizing field is reduced to zero. It tells how much magnetism the material keeps.
- **Coercivity** (Oc): the reverse magnetizing field needed to bring the magnetic induction to zero. It tells how hard it is to demagnetize the material.
- **Hysteresis loss**: in every cycle, the material is magnetized one way, demagnetized and magnetized the other way, and the domain walls jumping past flaws waste energy as heat. The **energy spent per unit volume in one complete cycle is equal to the area of the hysteresis loop**:

$$\text{energy lost per unit volume per cycle} = \oint H\,dB$$

On a B–H graph, the area has the unit $(\text{A/m}) \times \text{T} = \text{J/m}^3$. A transformer core is taken round its loop 50 times a second by the mains, so its loss each second is 50 times the loop's area times the core's volume.

WORKED EXAMPLE

Example 17.6: heat from a transformer core

The hysteresis loop of a transformer core has an area of 250 J/m³. The core's volume is 2000 cm³, and the mains frequency is 50 Hz. How much power is lost as heat in the core by hysteresis?

Answer

Volume $V = 2000\ \text{cm}^3 = 2 \times 10^{-3}\ \text{m}^3$. Energy lost in one cycle = area × volume = $250 \times 2 \times 10^{-3} = 0.5$ J. With 50 cycles a second:

$$P = 0.5 \times 50 = \mathbf{25\ W}$$

This heat is one reason a working transformer is warm; a core of hard steel, whose loop can be dozens of times larger, would waste far more.

Soft and hard magnetic materials

The shape of the hysteresis loop depends on the material (Figure 17.14).

- **Soft iron** (and other **soft** magnetic materials): a **tall, narrow** loop with a **small area**. It reaches a high B in a small H (high permeability), is easily demagnetized (low coercivity), and wastes little energy in each cycle. Ideal for **transformer cores**, **generator and motor cores** and **electromagnets**, which must be magnetized and demagnetized quickly and often. Silicon steel (iron with about 3

vii. Examples: aluminium, platinum, sodium, potassium, magnesium and oxygen.

viii. Their susceptibility is **inversely proportional to the absolute temperature**:

$$\chi \propto \frac{1}{T} \qquad \text{or} \qquad \boxed{\chi = \frac{C}{T}}$$

where C is a constant for the substance, its **Curie constant**. This is **Curie's law**, found by Pierre Curie in 1895. The hotter the substance, the harder its atoms jiggle and the less a field can line up their tiny magnets.

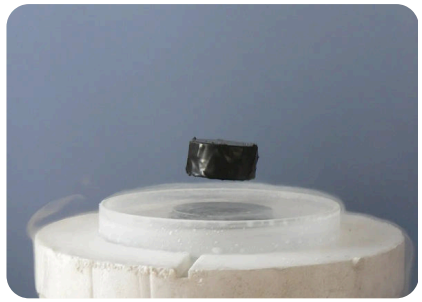


Figure 17.7 *A magnet floating over a superconductor cooled with liquid nitrogen: the superconductor pushes the magnet's field out of itself (the Meissner effect).*
Photo: Mai-Linh Doan, CC BY-SA 3.0

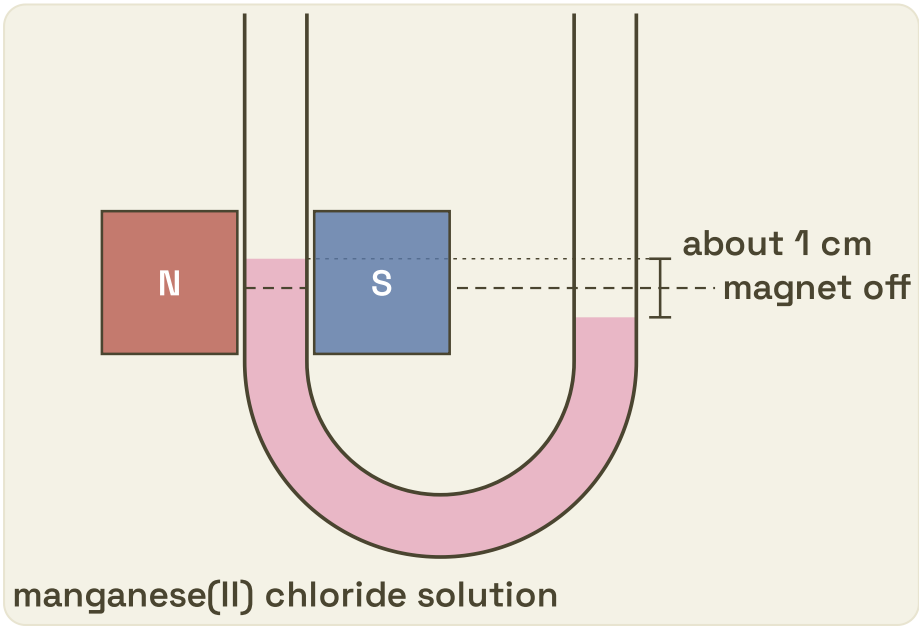


Figure 17.8 *Quincke's method: a paramagnetic solution of manganese(II) chloride in a U-tube, one limb between the poles of an electromagnet. With the field on (about 1 T), the liquid in the field stands about 1 cm higher than in the other limb, drawn to scale; the dashed line is the level with the magnet off. Water, diamagnetic, falls instead, but by less than half a millimeter in the same field.*

Ferromagnetic substances

Ferromagnetic substances are those which are **strongly attracted** by a magnet: they are strongly magnetized in the direction of the magnetizing field. Iron, cobalt,

nickel, gadolinium and their alloys, such as steel, are ferromagnetic.

Their properties:

i. A rod of a ferromagnetic substance hung near a magnet turns quickly and settles **along** the field.

ii. They are **strongly** magnetized along the field.

iii. They are **strongly attracted** by a magnet.

iv. Their susceptibility **decreases as the temperature rises**. Above the Curie temperature T_C the substance is paramagnetic, with $\chi = C/(T - T_C)$, the **Curie–Weiss law**.

v. Their relative permeability is **much larger than 1**: hundreds to many thousands.

vi. Their susceptibility is **large and positive**.

vii. They show **hysteresis** (Section 17.5).

viii. Examples: iron, cobalt, nickel and gadolinium.

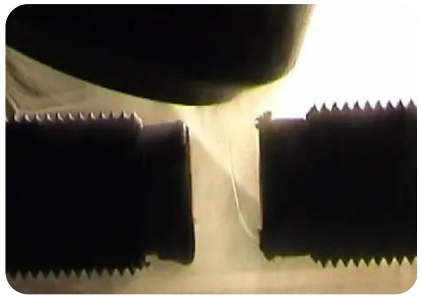


Figure 17.9 *Liquid oxygen poured past the poles of a strong magnet: the stream is pulled into the field. Oxygen molecules have unpaired electrons, so oxygen is paramagnetic.*
Photo: Pieter Kuiper, Public domain



Figure 17.10 *Pierre Curie (1859–1906), who found how the magnetism of materials depends on temperature (1895). He later shared the 1903 Nobel Prize in Physics with Marie Curie and Henri Becquerel for their work on radioactivity.*
Photo: Nobel Foundation, Public domain

ii.

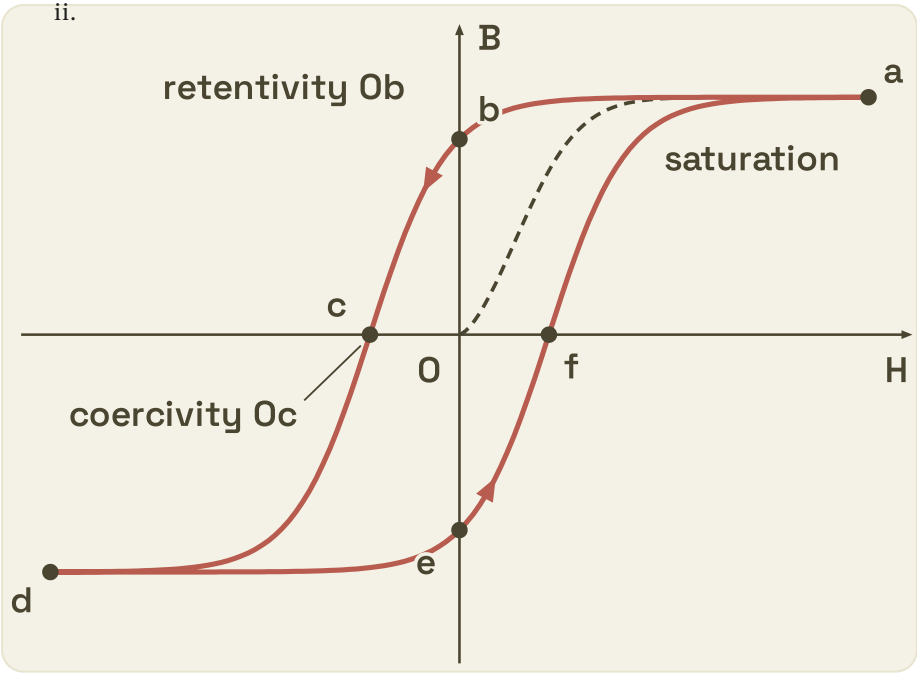


Figure 17.13 *The hysteresis loop of a ferromagnetic material: B against H. The dashed curve Oa is the first magnetization, to saturation at a. Then B follows $a \to b \to c \to d \to e \to f \to a$ as H goes down to zero, reverses, and comes back: Ob is the retentivity, Oc the coercivity.*

Increasing H further, B increases until it reaches **saturation** at a: all the domains point along the field, and B hardly changes any more.

iii. Now decrease H. B decreases too, but it does not come back along aO: at H = 0, B is not zero but Ob. The material keeps some magnetism. This is called the **retentivity** (or **remanence**, or **residual magnetism**), Ob.

iv. Reverse H and increase it the other way. B decreases further, and at c (H = −Oc) the material is fully demagnetized, B = 0. The reverse field needed to bring B to zero, Oc, is called the **coercivity** (or **coercive force**).

v. Increasing the reverse field saturates the material the other way, at d. Bringing H back to zero leaves B = −Oe at e; a field Of the first way brings B to zero at f, and B returns to saturation at a. The closed curve **abcdefa** is the **hysteresis loop**.

The point O is never reached again unless the material is demagnetized, for example by an alternating field that dies away slowly. B always lags behind H: on the way down it is higher than on the way up.

Metal	Curie temperature
gadolinium	about 20 °C (293 K)
nickel	about 360 °C
iron	770 °C (1043 K)
cobalt	about 1120 °C

DID YOU KNOW?

A metal that changes with the weather

Gadolinium's Curie temperature is about 20 °C, near room temperature. On a cold morning in Kathmandu a piece of gadolinium is ferromagnetic and a magnet grabs it; warmed in the hand on a hot day, it loses its strong magnetism and becomes paramagnetic.

Check 4

In an unmagnetized iron nail, the domains:

a do not exist until a field is applied
b are each unmagnetized
c are each magnetized, but point in different directions and cancel
d all point the same way

17.5 Magnetic hysteresis

Magnetize a piece of iron, then switch the field off. Does the iron go back to how it was? Not quite: it remembers.

Hysteresis means "lagging behind". The lagging of the magnetic induction B behind the magnetizing field H, when H is changed, is called **magnetic hysteresis**.

The hysteresis loop

Take an unmagnetized ferromagnetic specimen (an iron ring wound with a coil, for instance) and change H, by changing the current, through a full cycle while measuring B. Figure 17.13 shows the graph of B against H.

i. As H is increased from zero, B increases, along the curve Oa, at first slowly, then fast as the domains grow, then slowly again.

WORKED EXAMPLE

Example 17.5: Curie's law

The susceptibility of a paramagnetic salt is 2.8×10^{-4} at 27 °C. Find its susceptibility at −73 °C.

Answer

By Curie's law, $\chi T = C$ is constant. Use absolute temperatures: $T_1 = 27 + 273 = 300$ K, $T_2 = -73 + 273 = 200$ K.

$$\chi_2 = \chi_1 \frac{T_1}{T_2} = 2.8 \times 10^{-4} \times \frac{300}{200} = \mathbf{4.2 \times 10^{-4}}$$

Cooled, the salt is magnetized more easily.

	Diamagnetic	Paramagnetic	Ferromagnetic
In a field	weakly repelled	weakly attracted	strongly attracted
Magnetized	against the field, feebly	along the field, feebly	along the field, strongly
Susceptibility χ	small, negative (about -10^{-5})	small, positive (10^{-5} to 10^{-3})	large, positive (hundreds to thousands)
Relative permeability μr	slightly less than 1	slightly more than 1	much more than 1
χ and temperature	does not depend on it	$\chi = C/T$ (Curie's law)	falls as T rises; paramagnetic above T_C
Hysteresis	no	no	yes
Examples	Bi, Cu, Ag, Hg, water	Al, Pt, Na, O_2	Fe, Co, Ni, Gd

CAREFUL

Which susceptibility depends on temperature?

A **paramagnetic** substance's susceptibility depends on temperature (Curie's law); a **diamagnetic** substance's does not. Mixing the two up is a common slip.

Check 3

A substance has a relative permeability of 0.99998. It is:

a diamagnetic
b paramagnetic
c ferromagnetic
d a superconductor

17.4 Ferromagnetism on the basis of domain theory

Why is iron so different from aluminium? In both, the atoms are tiny magnets. In iron, cobalt and nickel, neighboring atomic magnets act on each other so strongly (by an effect of quantum physics called the **exchange interaction**) that they line up with one another of their own accord, even with no field around.

The **domain theory** explains ferromagnetism this way:

- A ferromagnetic material is divided into small regions called **domains**, each perhaps a hundredth to a tenth of a millimeter across but holding many trillions of atoms. In each domain, all the atomic magnetic moments are lined up: each domain is magnetized to saturation, a strong little magnet.
- With **no external field**, the domains point in different directions (Figure 17.11a). Their moments cancel, and the piece as a whole is not a magnet.
- In a **weak field**, the walls between domains move: the domains whose moments point along the field (or nearly along it) **grow**, at the expense of the others (Figure 17.11b). The piece becomes magnetized along the field.
- In a **strong field**, the remaining domains turn until all the moments point along the field (Figure 17.11c). The piece is magnetized as much as it can be: **saturated**.
- When the material is heated, its atoms jiggle harder and the lining up breaks down; at the **Curie temperature** the domains are gone and the material becomes **paramagnetic**.

The domains explain what the other two groups lack. Moving a domain wall is not perfectly smooth: the walls catch on impurities and flaws in the crystal and jump past them. So when the field is removed, the walls do not all go back: some magnetization **remains**. That is the origin of hysteresis, the subject of the next section, and the reason a steel needle can become a permanent magnet.

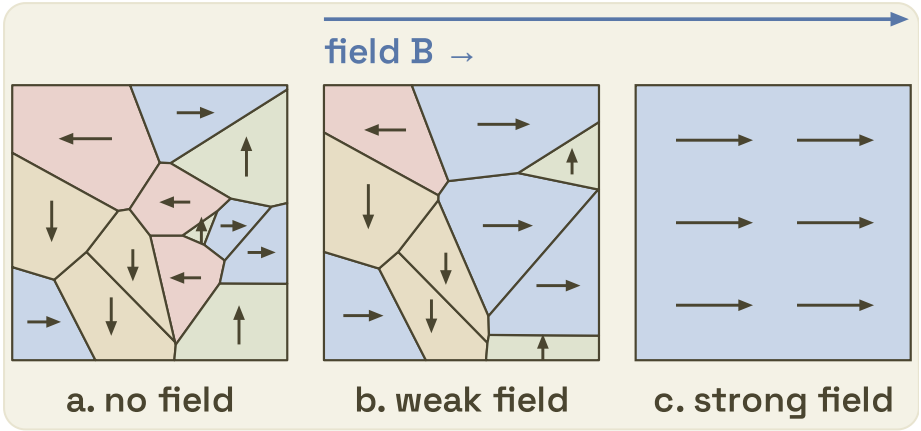


Figure 17.11 *The domains of a small piece of iron. In this flat drawing each points one of four ways (in iron the atomic magnets line up along the edges of its cubic crystal, six ways in all). a. No field: the domains point every way and cancel. b. A weak field to the right: the walls have moved, so the domains pointing right have grown and those pointing left have shrunk. c. A strong field: one domain, all along the field, saturated.*

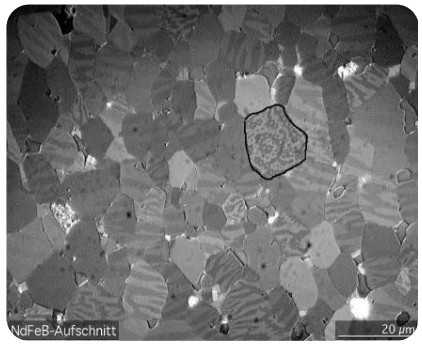


Figure 17.12 *The domains of a neodymium magnet, made visible under a microscope (by the Kerr effect, which turns the polarization of light by different amounts in domains magnetized different ways). Each grain, a few hundredths of a millimeter across, holds several stripe-shaped domains.*

Photo: Gorchy, CC BY-SA 3.0