Module P4.2 Introducing magnetism

Exit module

1 Opening items

1.1 Module introduction

One of the simplest ways to demonstrate magnetism is to dip a magnet into a box of paper clips — with care, you may succeed in picking up 20 or 30 clips. The objects around us divide broadly into two groups: those which are attracted by a magnet and those which are not. Those attracted by a magnet are made of *ferromagnetic* materials. In the case of the paper clips, the property of magnetic attraction is transferred by *magnetic induction* from the magnet to the nearest clips, which themselves then act as magnets and attract further clips.

In Section 2 of this module, you will see how interactions between magnets are described in terms of *magnetic poles* and *magnetic fields*. You will learn how to plot magnetic *field lines*, using either iron filings or a compass needle, how to interpret such plots, and how to sketch the field lines of magnets in new orientations and positions. This section of the module also includes a discussion of *magnetic dipoles* and *monopoles*, and ends with an overview of magnetic properties of materials.

Section 3 describes how magnetic fields can also be produced by electric currents, as shown by Hans Christian Oersted (1777–1851) in 1820. This section then discusses the magnetic fields produced by electric currents in certain well-defined circuit configurations, namely a long straight wire, a circular loop of wire, a *solenoid* and a *toroidal solenoid*. Using the *right-hand grip rule* and the *principle of superposition*, it shows how the field patterns from more complicated current configurations can be built up. The formulae for the magnetic field strengths produced by these basic current configurations are given, allowing the numerical calculation of these field strengths in various situations.

Study comment Having read the introduction you may feel that you are already familiar with the material covered by this module and that you do not need to study it. If so, try the *Fast track questions* given in Subsection 1.2. If not, proceed directly to *Ready to study?* in Subsection 1.3.

1.2 Fast track questions

Study comment Can you answer the following *Fast track questions*?. If you answer the questions successfully you need only glance through the module before looking at the *Module summary* (Subsection 5.1) and the *Achievements* listed in Subsection 5.2. If you are sure that you can meet each of these achievements, try the *Exit test* in Subsection 5.3. If you have difficulty with only one or two of the questions you should follow the guidance given in the answers and read the relevant parts of the module. However, *if you have difficulty with more than two of the Exit questions you are strongly advised to study the whole module*.

Question F1

The Earth's magnetic field is often described as being similar to that of a short bar magnet, placed near the centre of the Earth, with its south pole nearest the Earth's geographic North Pole.

(a) How do you explain this apparent ambiguity in the use of north and south?

(b) What evidence supports the statement that an equivalent field would be produced by a *short* bar magnet?

(c) In what region(s) of the Earth would you expect to find no vertical component to the Earth's field, i.e. a zero angle of dip?

Question F2

You are given three apparently identical iron rods, but are told that two of them are permanently magnetized. How would you distinguish which two are the magnets?

Question F3

Two concentric coils of wire are positioned with their planes perpendicular to one another. Coil A has 100 turns of radius 30 cm and carries a current of 1.5 A; coil B has 50 turns of radius 10 cm and a current of 0.9 A. Given that the magnitude of the field at the centre of a coil of N turns of radius R carrying a current I is given by $B = \mu_0 NI/(2R)$, where $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T\,m\,A^{-1}}$, find the magnitude of the resultant magnetic field at the centre of the coils.

Study comment Having seen the *Fast track questions* you may feel that it would be wiser to follow the normal route through the module and to proceed directly to *Ready to study?* in Subsection 1.3.

Alternatively, you may still be sufficiently comfortable with the material covered by the module to proceed directly to the *Closing items*.

1.3 Ready to study?

Study comment In order to study this module you will need little background knowledge of magnetism, beyond its occurrence. The module is not mathematically demanding because the formulae associated with magnetic fields are quoted and not proved. You will however need to be familiar with the following terms: *density*, *electric charge*, *electric current*, *energy*, *force*, *scalar*, *speed*, *temperature*, *vector*, *velocity* and *weight*. You will also need to be familiar with *vector notation*, including *magnitude of a vector*, and the idea of combining vectors in one and two dimensions, using the *triangle* or *parallelogram rules* and simple *trigonometry*. If you are uncertain about any of these terms then you can review them now by reference to the *Glossary*, which will also indicate where in *FLAP* they are developed. The following *Ready to study questions* will allow you to establish whether you need to review some of these topics before embarking on this module.

Question R1

Which of the following quantities are vectors and which are scalars: density, energy, force, speed, temperature, velocity and weight?

Question R2

When an electric current flows in a copper wire, what type of charged particle moves in the wire to constitute that current? In what way does this movement differ from the *conventional current* in the wire?

Question R3

A particle is subjected to two forces, each of the same magnitude F, acting simultaneously. Find the direction and magnitude of the resultant force in each of the following cases:

(a) both forces act in a northerly direction;

(b) one force acts in a northerly direction and the other in a southerly direction;

(c) one force acts in a northerly direction and the other in an easterly direction.

2 Magnets and magnetic fields

2.1 Magnetism in everyday life

Most of us are familiar with some simple applications of **magnets** and **magnetism** around the home which make use of the attractive force between small magnets and unmagnetized pieces of steel ☞. Magnetic cupboard catches (Figure 1) often consist of a small powerful horseshoe-shaped magnet attached to a door jamb, which exerts a strong retaining force on a steel plate attached to the door, when brought into contact. Many refrigerator doors are held closed by magnetic forces, though in this case the magnetized material, often a special ceramic powder, is dispersed in a rubber or plastic strip around the door opening and the steel of the door itself is attracted to the strip. Magnets are also to be found in television sets, electric motors, microwave ovens and loudspeakers.

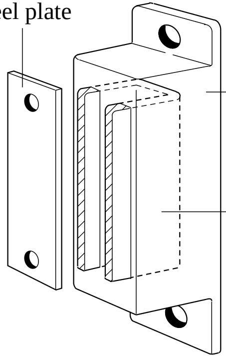


Figure 1 A magnetic cupboard catch.

A more ancient application of magnetism than any of the above examples can be seen in the compass. These small pivoted bar magnets have been used for navigation since the 11th century. The magnetic properties of certain minerals (e.g. magnetite or lodestone, containing the iron oxide Fe_2O_3), were known to the Greeks some 2300 years ago, and compass needles were once made by stroking (in one direction) a steel needle with a lodestone.

Magnetism may sometimes be seen in unexpected circumstances. Steel tools are sometimes found to have acquired magnetic properties, as shown by their ability to attract iron filings or small screws or nails — screwdrivers and cold chisels often exhibit this effect. ☞

2.2 Magnetic poles

The pattern of attraction of small iron or steel objects to a bar magnet shows that the strongest magnetic forces occur near the ends of the magnet. These regions are known as the **magnetic poles** of the magnet. The two poles of a magnet are not identical. A freely suspended bar magnet, or compass, will rotate to an approximately north–south line, but always the same pole points in the same direction. We therefore distinguish between the poles by calling the one that points north a **north pole** (usually written N-pole) and the other a **south pole** (S-pole). ☞

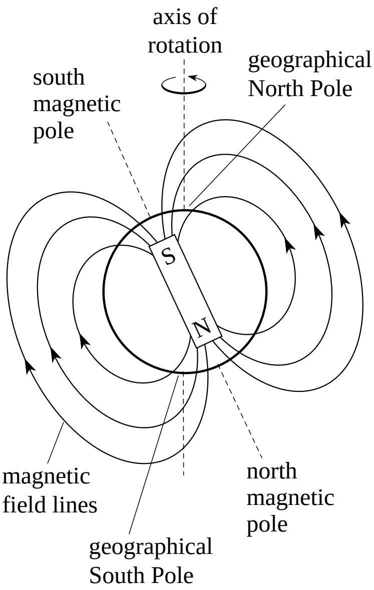


Figure 2 The Earth's magnetic and geographic poles and the Earth's magnetic field.

If the poles of two bar magnets are designated in this way, then observations of the interactions between pairs of magnets in various orientations lead to the elementary but very important rules that:

> *like poles* repel and *unlike poles* attract one another.
>
> Thus: a north pole repels another north pole
> a south pole repels another south pole
> a north pole attracts a south pole
> a south pole attracts a north pole

Since a compass needle adopts a particular orientation when no other magnets are near, the implication is that the Earth itself must have magnetic properties. As the north pole of a compass points approximately to the geographic north, the Earth must have a magnetic south pole near the geographic North Pole, as shown in Figure 2. (The *magnetic field lines* shown in Figure 2 will be discussed in Subsection 2.3.)

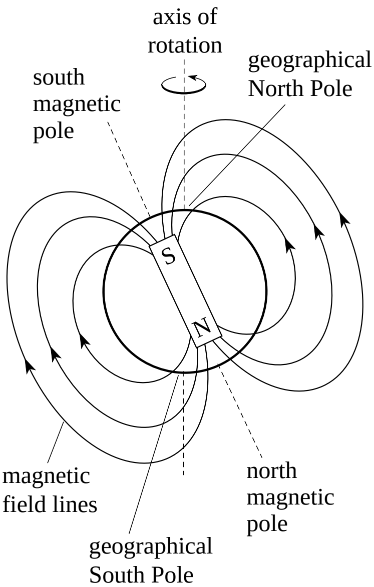


Figure 2 The Earth's magnetic and geographic poles and the Earth's magnetic field.

Note The Earth makes a complete revolution every 24 h about an axis through the geographic poles, which are identified by observing the apparent motion of stars. A star situated in line with the Earth's axis (e.g. the pole star) appears stationary, and other stars appear to move in circles around that point. The Earth's magnetic poles are close to, though not exactly coincident with, its geographic poles.

The concept of a magnetic pole is of great value in qualitative discussions of magnetic forces, but it is not particularly useful in quantitative work. The limitation arises from the fact that in practice it appears to be impossible to isolate either a north magnetic pole or a south magnetic pole. If, for instance, you cut a bar magnet in half, instead of obtaining two separate magnetic poles you will simply produce two small bar magnets, each with a north pole *and* a south pole (see Figure 3).

This continues to be the case no matter how finely you subdivide the original magnet. Even individual *atoms* or atomic constituents such as *electrons* and *protons* are magnetically similar to tiny bar magnets, not to isolated magnetic poles. Our inability to completely separate north and south poles contrasts sharply with the relative simplicity of separating positive and negative electric charges and means that magnetic phenomena have to be treated somewhat differently from the electrical phenomena with which they otherwise have a great deal in common.

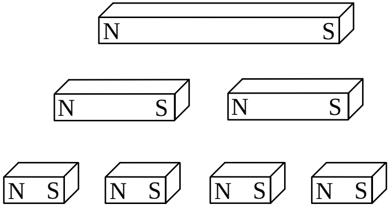


Figure 3 Cutting a bar magnet creates smaller bar magnets. It does not isolate individual north and south magnetic poles.

Before leaving the subject of magnetic poles its worth noting one further point, even though it relates to matters far beyond the scope of *FLAP*. At the present time many of the theories which aim to describe the nature of the fundamental constituents of all forms of matter, i.e. the ‘elementary particles’ of nature, do predict the existence of particles that have the magnetic properties of isolated poles. These hypothetical particles are referred to as **magnetic monopoles**. Such monopoles have never been convincingly detected, despite one or two claims to the contrary, and it is widely believed that even if they do exist they are so rare that they are never likely to be observed ☞. However, if magnetic monopoles do exist they are expected to exert forces on one another similar to those between isolated electric charges. In particular, if two stationary magnetic monopoles are separated by a distance r then the force that each experiences due to the other will have a magnitude given by

$$F = \frac{C}{r^2}$$

where C is a constant. This formula shows that the magnetic force between monopoles is expected to satisfy an *inverse square law* just like the electrostatic force between point charges ☞. Our inability to separate magnetic poles and to produce monopoles means that this formula is actually of much less use in the description of physical phenomena than its electrical counterpart (*Coulomb’s law*). It is this difference that accounts for a good deal of the mathematical complexity that arises in the description of magnetism.

2.3 Magnetic fields

The fact that magnets interact even when at a distance from one another is usually explained in terms of a **magnetic field**. The main purpose of this subsection is to introduce magnetic fields and to explain how they can be determined. You will also see how such fields can be represented mathematically and pictorially.

In physics the term *field* is generally used to denote a physical quantity to which a definite value may be ascribed at each point in some region of space at a given time. For example, the fact that a definite temperature can be associated with each point in the room you are now occupying means that there is a *temperature field* in the room. This is said to be a *scalar field* since its value at any point (at a particular time) is determined by a single scalar quantity — the temperature T at that point. We can denote this field by $T(x, y, z)$ where the Cartesian coordinates x, y, z can be used to identify any point in the room, and serve to emphasize that the temperature generally varies with position. The quite separate observation that a particle of mass m located at any point with position coordinates (x, y, z) experiences a downward force, $\boldsymbol{F}_{\rm grav}$ due to gravity can be explained saying that there is a *gravitational field* throughout the room. The gravitational field at any point (x, y, z) is conventionally defined as the gravitational force per unit mass that would act on a ‘test’ mass ☞ m at that point and is denoted by $\boldsymbol{g}(x, y, z)$, so we can write

$$\boldsymbol{g}(x,y,z) = \frac{\boldsymbol{F}_{\rm grav}(\text{on a mass } m \text{ at } (x,y,z))}{m}$$

Note that in this case the field is specified by a *vector* at every point — a quantity with magnitude and direction — and is therefore said to be a *vector field*. Our use of a bold symbol ($\boldsymbol{g}$) to represent the field indicates its vectorial nature. An *electric field* $\boldsymbol{E}(x, y, z)$ may be defined in much the same way, as the electrical force per unit charge that would act on a test charge placed at any point (x, y, z)

$$\boldsymbol{E}(x, y, z) = \frac{\boldsymbol{F}_{\text{el}}(\text{on a charge } q \text{ at } (x, y, z))}{q}$$

Now the magnetic field in some region of space must describe magnetic forces, so we might reasonably expect it be a vector field, just like the gravitational and electric fields. This is indeed the case and we usually denote the magnetic field at (x, y, z) by $\boldsymbol{B}(x, y, z)$. But in the absence of isolated magnetic poles (the magnetic equivalent of masses and charges) how are we to specify the magnitude and direction of this field?

Defining the direction of a magnetic field

It is relatively easy to define the direction of a magnetic field. There are a number of ways in which it might be done, but in view of what was said earlier the most obvious is to use a compass. We know that a compass needle tends to take on a specific alignment in the presence of a magnet, so we can define the direction of a magnetic field at any point as the direction indicated by the north pole of a compass needle placed at that point. This sounds like an eminently sensible way of defining the direction of a magnetic field, though we actually need to be think a little more about the details if we are to use it in a wide range of circumstances. For instance, if dealing with a magnetic field that changes direction over a small region of space (such as the magnetic field inside an electronic device) we would have to use a very tiny compass indeed, so we should really imagine that we are determining the direction with a vanishingly small compass that can effectively show us the direction of the field *at a point*. Moreover, we need to be aware that the magnetic field at a given location may point in any direction; it is not necessaily horizontal.

Consequently, if we use a compass needle to define the direction of the field we must either make sure that the needle is free to rotate in three dimensions, or we must use two needles (one rotating horizontally and the other vertically) to determine the three-dimensional orientation at any point. When dealing with the magnetic field of the Earth it has been traditional for centuries to use two needles. The angle between the Earth's magnetic field and the horizontal at any point is called the **angle of inclination** or the **angle of dip** and the device that uses a vertically rotating needle to measure that angle is called a *dip circle* or an *inclinometer* (Figure 4).

Of course, if you think that all this talk of vanishingly small compasses that are free to rotate in three dimensions is unnecessarily complicated you can just say that:

> The direction of a magnetic field at any point is the direction of the magnetic force that would act on an isolated north magnetic pole (if we had one) placed at that point.

But you shouldn't expect to determine the field direction by this method in practice.

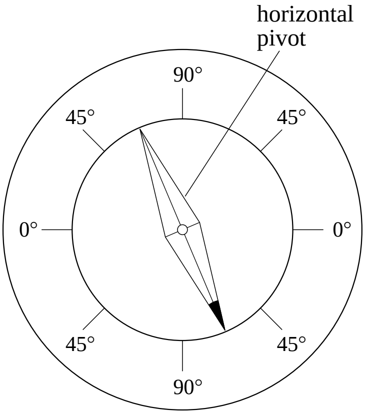


Figure 4 An inclinometer or dip circle, used for measuring the angle of the Earth's field with respect to the horizontal.

Defining the magnitude of a magnetic field

Defining the magnitude $B(x, y, z) = |\boldsymbol{B}(x, y, z)|$, of the magnetic field $\boldsymbol{B}(x, y, z)$ is a good deal more difficult than defining its direction ☞. Fortunately the intimate relationship between electricity and magnetism can aid us here. Once the direction of a magnetic field has been determined at some point, or better still in some small region, it is easy to place a wire at right angle to the field and to send an electric current through that wire. When this is done it is easy to show that the magnetic field exerts a force on the current carrying wire. The current in the wire is composed of moving charged particles, and the force that acts on the wire is one manifestation of the general observation that a magnetic field exerts a force on any moving charged particle, *provided the particle is not travelling parallel to the field*. The general relationship between the magnetic field $\boldsymbol{B}$ at a point, the velocity $\boldsymbol{v}$ of an electrically charged particle as it passes through that point, and the magnetic force $\boldsymbol{F}_{\rm mag}$ that acts on the particle is a little complicated so we will not discuss it here. We can say that in the special case when a particle of positive charge q passes through the point (x, y, z) with speed $v_\perp$ along a direction at right angles to the magnetic field at that point, it will be subjected to a force of magnitude

$$F_{\rm mag} = qv_\perp B(x, y, z)$$

where $B(x, y, z)$ is the magnitude of the magnetic field at the point (x, y, z).

Rearranging this equation (and providing a little more explanation) we can define the magnitude of the magnetic field at the point (x, y, z) by

$$B(x,y,z) = \frac{F_{\rm mag}(\text{on } q \text{ as it moves through the point } (x,y,z))}{qv_\perp} \qquad (1)$$

Since the magnetic force magnitude $F_{\rm mag}$ may be measured in newton (N), the charge q in coulomb (C) and the perpendicular speed $v_\perp$ in metre per second ($\rm m\,s^{-1}$), it follows that the magnetic field strength can be measured in units of $\rm N\,s\,C^{-1}\,m^{-1}$. This is a sufficiently important combination of units that it is given its own SI name and symbol.

The SI unit of magnetic field strength is the **tesla** (T), where $1\,{\rm T} = 1\,{\rm N\,s\,C^{-1}\,m^{-1}}$.

It is worth noting that the tesla is large unit by everyday standards. The magnitude of the Earth's magnetic field over much of its surface is around $10^{-5}\,$T, and a typical bar magnet might produce a field of magnitude $10^{-2}\,$T within a centimetre or two of its pole pieces.

✦ A proton (charge $e = 1.60 \times 10^{-19}$ C) travels with speed 4.00×10^6 m s^{-1} through a point at which there is an intense magnetic field of magnitude 2.50 T. Assuming that the proton is moving at right angles to the field at the point in question, what is the magnitude of the instantaneous magnetic force on the proton?

Representing a magnetic field

It is often necessary to represent magnetic fields on diagrams. This may be done by using **magnetic field lines**. These are directed lines (i.e. lines with arrows on them) that have the following properties:

- The lines are drawn so that at any point the magnetic field is tangential to the lines. ☞
- The direction of the field line at any point indicates the direction of the magnetic field at that point (i.e. the direction that the north pole of a compass would point, or an isolated north pole would tend to move).
- The density of the field lines in any region is proportional to the magnitude of the magnetic field in that region.

In practice the last of these conditions is quite hard to satisfy, especially if you are trying to represent a three-dimensional field (such as that of the Earth) on a flat piece of paper (as in Figure 2). For that reason most field line representations of magnetic fields are at best approximate.

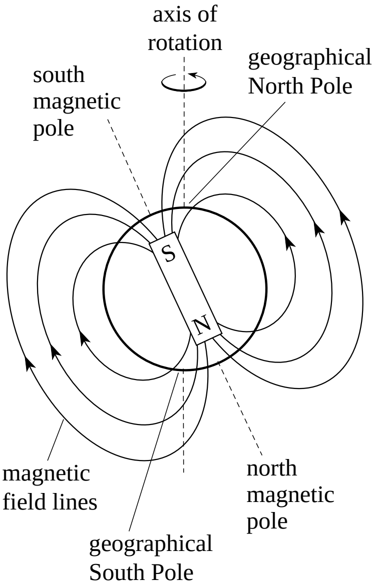


Figure 2 The Earth's magnetic and geographic poles and the Earth's magnetic field.

With this in mind, look at Figure 5 which shows the magnetic field of a bar magnet. Since the bar magnet essentially consists of two opposite magnetic poles of equal strength separated by a fixed distance it is sometimes described as a **magnetic dipole**, and the field that it produces is said to be a *dipolar field*. Figure 5 makes no attempt to show the three-dimensional nature of the field; it is restricted to the plane of the page. Furthermore it is only an approximate representation of the field; the field lines near the mid-point of the magnet have been drawn with roughly equal separations, indicating that the field is of uniform magnitude in that region whereas in reality the magnitude of the field would actually decrease as the distance from the magnet increased. Nonetheless, the diagram gives a clear (and correct) impression that the field of the dipole is the vector sum of the fields from the poles at either end of the magnet.

In plotting the field of a magnet, as in Figure 5, we would not normally attempt to nullify the Earth's field. The observed field would therefore be the resultant vector sum of the fields of the Earth and the magnet. However, provided we restrict the plot to points close to the magnet, where the magnet's field is much larger than the Earth's field, then it would be a fairly accurate representation of the magnet's field.

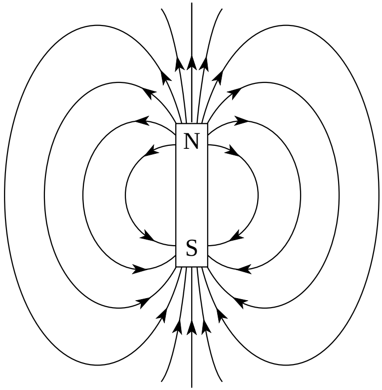


Figure 5 The magnetic field of an isolated bar magnet represented (approximately) by magnetic field lines.

✦ As we plot the field at points which are further away from the magnet, what happens to the relative magnitudes of the fields of the Earth and of the magnet?

Just how the bar magnet's field and the Earth's field merge will depend on the orientation of the magnet. Figures 6a and 6b show extended plots when the magnet has its N-pole pointing south and east, respectively. Note that there are regions where the fields of the Earth and the magnet are almost equal and opposite, so the resultant field is very weak and the field lines correspondingly far apart.

There is one further important feature of field line plots: field lines will never be found to cross each other because that would imply that a compass placed at the cross-over point would have to point in two directions at once!

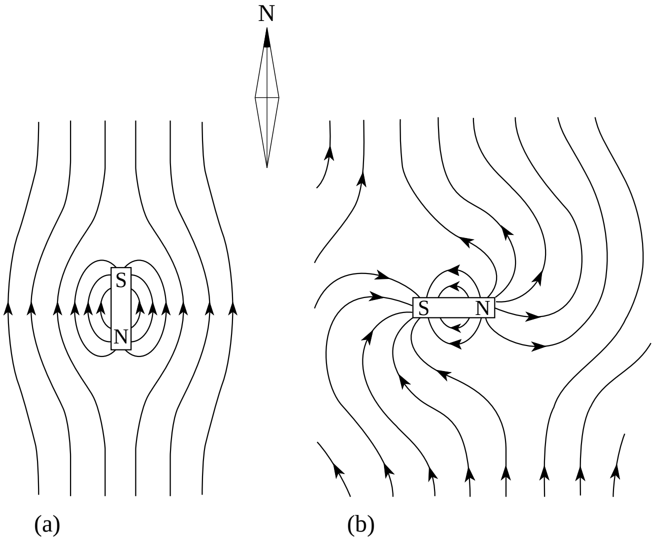
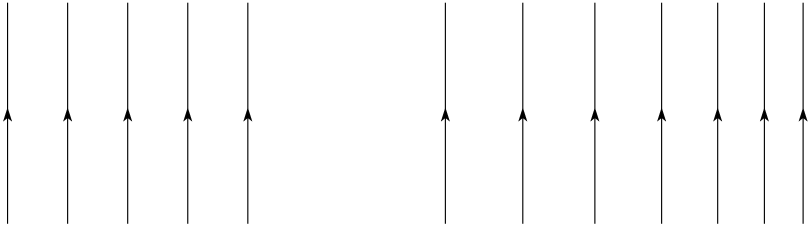


Figure 6 Field plot of a bar magnet with N-pole pointing (a) south and (b) east.

Another method of finding the shape of the field pattern near a magnet is to cover the magnet with a horizontal sheet of paper and to sprinkle fine iron filings evenly over the paper. ☞ When the paper is tapped gently, the filings tend to congregate in the regions of high field and also to show some line structure in the pattern. This similarity between the lines of filings and field line patterns can be very misleading as it may be interpreted as meaning that the magnetic field exists only along these lines, and that at points in between the lines there is no field. In fact, using a compass, we can follow a field line anywhere we like in the vicinity of a magnet (provided our starting point is not one at which the the field is zero) because the field is continuous from point to point. The apparently significant lines of filings are quite fortuitous and arise through the existence of a few, perhaps larger, filings which are more reluctant to move when the paper is tapped, and so provide a centre to which other filings are attracted.

❖ (a) If Figures 7a and 7b represent the magnetic field lines in some region of space, describe the corresponding magnetic fields.

(b) If Figures 7a and 7b represent patterns of iron filings, rather than field lines, what can you now say about the magnetic field.



(a) (b)

Figure 7 Examples of different magnetic fields.

Question T1

Sketch the magnetic field plots for a bar magnet in the Earth's field with its N-pole pointing (a) north, and (b) west. ❏ ☞

Question T2

Sketch magnetic field plots for the magnets shown in Figure 8. (Assume that the Earth's contribution can be ignored.) ❏

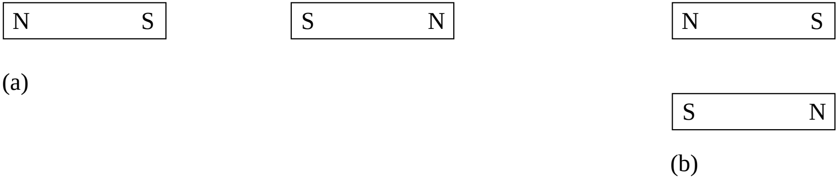


Figure 8 See Question T2.

2.4 Magnetic materials

As was described earlier, a very simple test of the magnetic properties of different materials is to see if they are attracted by a magnet. This test provides an easy and immediate classification into materials which are strongly attracted and those which are not. The former group has been found to consist primarily of five elements — iron (Fe), cobalt (Co), nickel (Ni), gadolinium (Gd) and dysprosium (Dy) — and some associated *alloys*. These are known as **ferromagnetic** materials, taking their name from iron, the most common member of the group. Materials which are apparently unaffected by a magnet do in fact have weak magnetic properties, some are actually repelled by a magnet, but such effects are seen only with very sensitive apparatus and we will not discuss them further.

If we place a bar magnet near to a rod of pure iron, then the rod and the magnet are attracted to one another. When, however, the bar magnet is removed, the iron retains (almost) none of its magnetic properties. We say that these magnetic properties are *induced* in the iron rod by the bar magnet, that is to say that the magnet's field causes the rod to change temporarily into a magnet. Further observation shows that the force between the magnet and the rod is always one of attraction, from which we deduce that the induced pole at the near end of the rod is always of the opposite polarity to the adjacent end of the magnet. This process of **magnetic induction** can be extended. If we put the rod in contact with the magnet, it acts like an extension of the magnet and it, in turn, can attract a further rod and so on, but with the strength of the attractive forces becoming weaker, as we go further from the magnet. This is a familiar result — a permanent magnet can lift a chain of nails or pins (Figure 9), but when the magnet is forcibly removed from the first nail or pin, the rest fall. The induced magnetism is only temporary, and disappears when the inducing field is removed.

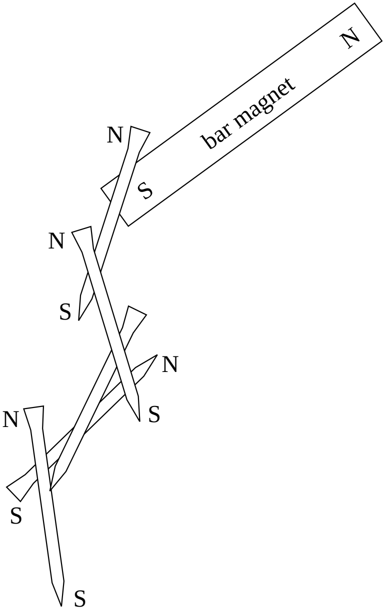


Figure 9 Magnetic induction enables a magnet to lift a chain of nails.

Materials, such as pure iron, which depend (almost entirely) on the presence of another magnet for their magnetism are described as **magnetically soft**. In contrast, steels are examples of alloys made by adding other elements (typically carbon) to iron. These materials are harder to magnetize, but once they are magnetized they do not easily become demagnetized. Such materials are said to be **magnetically hard** and are the materials from which **permanent magnets** are made. The study of **permanent magnetism** is an area of great technological importance, but one with unexpected results. For example, the simple addition of small amounts of copper (a non-ferromagnetic material) to carbon steel produces magnets of much greater strength.

Another group of magnetic materials, known as **ferrites**, are brittle ceramics made by sintering oxides ☞ of iron and barium (Ba). Granules of these ceramics can also be bonded with plastics or rubber to give flexible magnets (such as refrigerator seals) and are also used to make magnetic audio and video tapes, or floppy disks for computers. Information is recorded on tapes or disks by magnetizing their ferromagnetic grains through the application of a localized external magnetic field that is generated by, and is proportional to the strength of, the signal being recorded. The stored information can be erased with a strong magnetic field, allowing the tape or disk to be reused.

Scientific studies of the magnetic properties of materials are far more sophisticated than this brief discussion might indicate. Research into the magnetic properties of materials has been, and continues to be, one of the most active areas of physics. International conferences entirely devoted to magnetism are held on a regular basis and there is a very large annual output of books and scientific papers dealing with magnetic materials.

With the understanding of atomic structure and quantum mechanics has come an appreciation that ferromagnetism and permanent magnetism have their origins almost entirely in the intrinsic properties of the electrons (**electron spin magnetism**) which make up their constituent atoms. ☞

Question T3

Should the materials used in the storage of information be magnetically soft or magnetically hard? ❏

3 Magnetic fields produced by electric currents: electromagnetism

3.1 Introduction to electromagnetism

In 1820, a Danish philosopher and scientist, Hans Christian Oersted, performed the first experiment to show an interaction between an electric current and a compass needle. This association of magnetic fields and currents provided the basis for a new branch of physical science — **electromagnetism**. Electromagnetism is a major topic within physics and in this module we are able only to give the briefest of introductions to it. ☞

Oersted showed that a current in a wire could, in certain circumstances, cause the deflection of a compass needle placed nearby. The greatest deflection was produced with the wire in a horizontal plane parallel to the undeflected needle and either above or below it. Oersted also found the important result that reversing the current reversed the direction of the deflection. Subsequent experiments soon extended Oersted's results. For example, as you will see later in this section, the field of a bar magnet can be reproduced using current in a coil. ☞ Although permanent magnetism was discovered before electromagnetism, permanent magnetism could not be understood until quantum mechanics arrived and it was the understanding of electromagnetism which allowed progress in classical physics to be made, culminating in an understanding of light as an electromagnetic phenomenon. We will follow the early stages of this course of development in this module.

3.2 The magnetic field of a long straight current

A further simple experiment leads to an explanation of Oersted's results. If you pass a vertical current carrying wire through a horizontal card on which you place a compass, then you can plot the magnetic field produced by the current. The field lines are found to be closed loops about the wire. With a sufficiently large current these loops are circles concentric with the wire, as shown in Figure 10. ☞

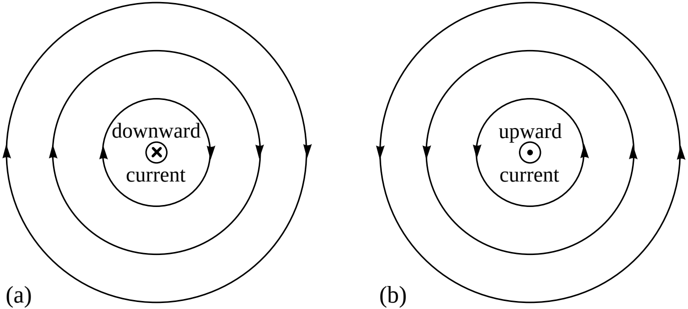


Figure 10 Circular magnetic field lines produced by a current in a long straight wire with the current pointing (a) downwards, and (b) upwards. ☞

Iron filings may also be used to show the field pattern, but this needs currents of some tens of amps (or several adjacent wires, each carrying more moderate currents in the same direction).

The direction of the field lines depends on the direction of the current. If the direction of current is reversed, then the direction of the field lines is also reversed, as is shown in Figure 10.

Fortunately, there is an easy way to remember the field directions. Just close the palm of your *right* hand with thumb extended and point your thumb in the direction of the current shown in either diagram of Figure 10.

In each case you will find that your fingers curl around your thumb in exactly the same way that the magnetic field lines curl around the current. This simple way of remembering the direction of the magnetic field is illustrated in Figure 11 and is known as the **right-hand grip rule**.

We can now use the right-hand grip rule to explain why Oersted obtained a compass deflection in some positions relative to the wire and not in others.

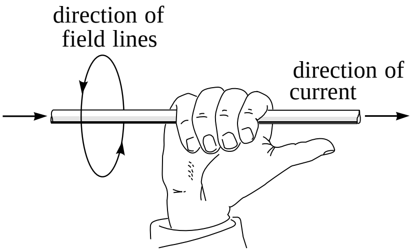
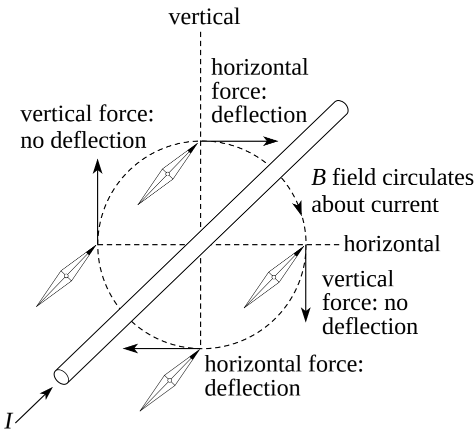


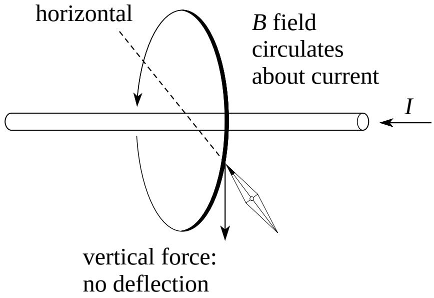
Figure 11 The right-hand grip rule. The fingers curl about the pointing thumb in the same sense as the field lines curl about the current.

✦ In which of the following situations will there be a deflection of the compass? (a) When the undeflected compass lies in a horizontal plane, directly above or below the horizontal wire, with the compass needle initially pointing parallel to the wire. (b) When the undeflected compass is initially pointing towards the wire, in the horizontal plane containing the wire.

Figure 12
(a) Here the wire is in the horizontal plane and the current is S to N. The field it produces at the sides is vertical and the compass cannot respond but the field above and below is horizontal and the compass will be deflected, either to the W or to the E.
(return to answer)



(a)



(b)

(b) With the current from W to E, the compass to one side of the wire experiences a vertical force and cannot respond. A compass placed below the wire has an additional force aligning it N–S. (return to answer)

As well as its direction, we generally also want to know the strength of a magnetic field. At a perpendicular radial distance r from a long straight wire, the magnitude of the magnetic field vector (or the magnetic field strength), for which we use the symbol $B(r)$, is proportional to the current I in the wire and inversely proportional to the distance r. ☞ This relationship is normally expressed as:

Magnetic field strength at a distance r from a *long straight wire* is:

$$B(r) = \frac{\mu_0 I}{2\pi r} \qquad (2)$$

where μ_0 (pronounced mew-nought) is a constant, called the **permeability of free space**, I is the current and r is the perpendicular distance of the point from the wire.

First, notice that the form of Equation 2 is physically reasonable. It shows that if the current is increased, so is the strength of the field that it produces at a fixed distance from the wire. Also, for a given current, the field gets weaker as the distance from the wire increases. Equation 2 has a very simple form because the field produced by this current is *highly symmetrical* — the field strength at any point is determined by the perpendicular distance from the wire.

If you imagine a set of coaxial cylinders drawn around the wire, as shown in Figure 13, the field strength is the same at all points on the surface of any one cylinder, but is different for each cylinder.

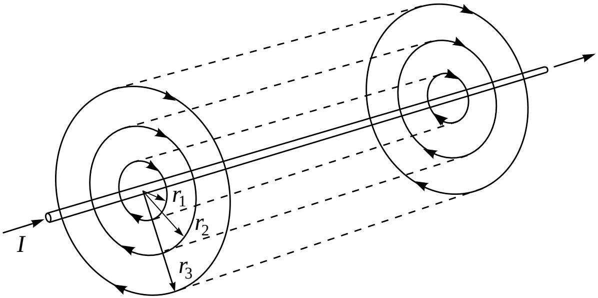


Figure 13 The field strength is the same at any point on the surface of a cylinder which is coaxial with the wire. It is different for each cylinder.

Second, notice that Equation 2

$$B(r) = \frac{\mu_0 I}{2\pi r} \qquad \text{(Eqn 2)}$$

is *not* a vector equation — it shows the *magnitude* of the field but not its direction. A magnetic field is a vector field and we could write a more complicated vector equation which would fully describe both its magnitude and direction. We will, instead, rely on the right-hand grip rule to tell us the field direction in this simple situation.

As noted earlier the SI unit of the field strength $B(r)$ is the tesla (abbreviated to T) and the SI unit of current is the ampere (A). With distances in metres Equation 2 then establishes the dimensions of the constant μ_0 as $\mathrm{T\,m\,A^{-1}}$. ☞

The ampere itself is defined in terms of the force between two current carrying conductors and when this force is expressed in newtons, the numerical value for μ_0 in SI units is fixed (i.e. no measurement of it is required) at $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T\,m\,A^{-1}}$. Thus the choice of the name for μ_0 is unfortunate, since μ_0 does not describe some property of free space (i.e. of a vacuum) but is simply a constant which is defined to allow SI units to be used consistently in the equations.

Question T4

Figure 14 shows three points close to a wire carrying a current of 12 A. For each of the points a, b and c, calculate the local magnetic field strength, and state whether the magnetic field points into or out of the plane of the paper. ❑

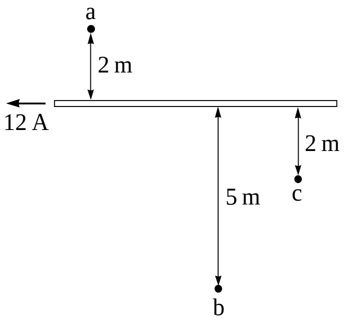


Figure 14 See Question T4.

Question T5

A horizontal straight wire carries a current of 1 A. At what distance is the magnetic field strength equal to that of the horizontal component of the Earth's field (i.e. 20 μT) ☞ . If a compass is placed at this distance above the wire, in the arrangement shown in Figure 15, through what angle will the compass needle rotate? ❏

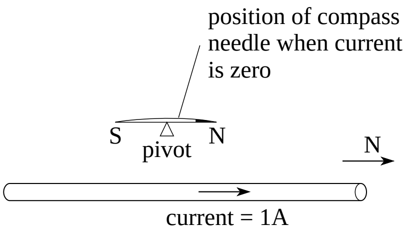


Figure 15 See Question T5.

Finally, we note one further point concerning the magnetic fields produced by current in straight wires. If we have a bundle of straight wires, all close together and each carrying a current in the same direction, then the total magnetic field produced at some point by the bundle will be the vector sum of the fields produced by the individual currents. This is an example of the **principle of superposition** — which is an extension of a familiar result concerning forces. If several forces act on a body at the same time, then the resultant force is the vector sum of those forces taken one at a time. If the forces are produced by the magnetic fields of several different currents, then the resultant force can be found by adding the forces due to the separate currents — in other words, the resultant magnetic field is the vector sum of the individual magnetic fields due to the separate currents.

For a bundle of wires each carrying a current, the resultant field will be approximately the same as if we had the same total current flowing in a single wire. We say ‘approximately’ because the wires in the bundle will not all be in precisely the same position as the single wire: the larger the distance from the bundle, the more accurate this approximation will be.

3.3 The magnetic field of a current in a circular loop

If we know the shape of the magnetic field due to a long straight wire carrying a steady current, it is fairly easy to build up pictures of the sort of magnetic fields that are produced by other configurations of current carrying wires.

Imagine taking the long straight wire illustrated in Figure 11, and bending it into a circle.

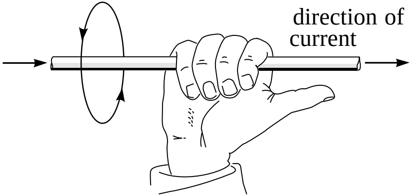


Figure 11 The right-hand grip rule. The fingers curl about the pointing thumb in the same sense as the field lines curl about the current.

At any particular point on the wire, the field lines will be concentric circles about the wire, at least to the extent that the influence of other parts of the wire can be ignored, as shown in Figure 16a. Of course, in the real world, the points on the wire cannot be considered in complete isolation and the pattern of field lines sketched in Figure 16a is therefore only an approximation.

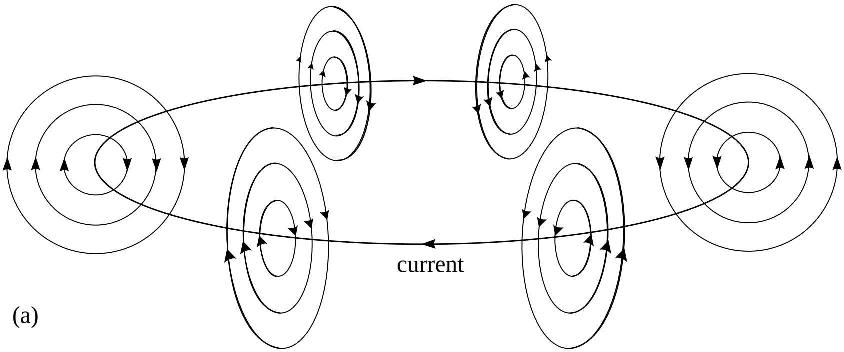


Figure 16a Magnetic field components produced by small elements of a circular loop of wire.

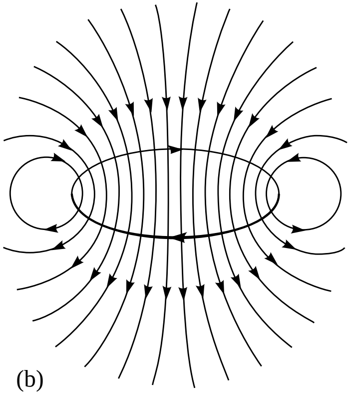
To obtain a more accurate result, it is necessary to add vectorially all the small magnetic field components created by the various small sections of the wire. The mathematics of such a sum is beyond the scope of this module, but the rough shape of the field pattern is clear from Figure 16b. For example, in the centre of the loop the fields due to each individual part of the wire reinforce one another, with all the field lines pointing downwards through the middle of the loop.

When the vector addition of all the field contributions is performed to give the total field strength, then the magnetic field strength *at the centre* of the loop is found to be given by:

Magnetic field strength at the *centre* of a *circular loop* is:

$$B_{\rm loop} = \frac{\mu_0 I}{2R} \tag{3}$$

where I is the current and R is the radius of the loop.



(b)

Figure 16b An accurate representation of a cross section of the field through a circular loop; the full field pattern comes from the rotation of the figure around the vertical axis of symmetry of the loop.

Even without deriving this equation,

$$B_{\text{loop}} = \frac{\mu_0 I}{2R} \tag{Eqn 3}$$

it is easy to see that its form is physically plausible: the larger the current, the stronger the magnetic field that results. Also, for a given current, the bigger the loop (i.e. the further away the centre is from the wire), the weaker the field will be at the centre of the loop.

❖ Check that the units on the right-hand side of Equation 3 do reduce to tesla.

Question T6

The wire in Figure 16b consists of a single loop. How would you expect the field pattern and the strength of the field at the centre to change if the single loop were replaced by a compact coil of N turns, all having the same radius as the single turn? State any assumptions you make. ❏

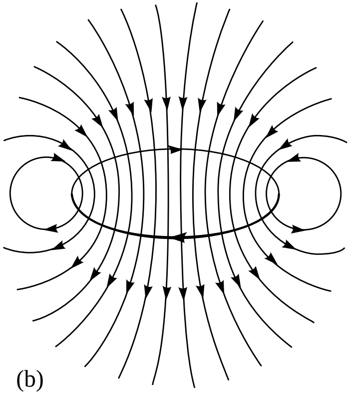


Figure 16b An accurate representation of a cross section of the field through a circular loop; the full field pattern comes from the rotation of the figure around the vertical axis of symmetry of the loop.

3.4 The magnetic field of a solenoid

Suppose we take a single loop of wire (as in Figure 16b), and place a second loop parallel to the first and a short distance away, as in Figure 17a. If the currents in the two loops circulate in the same sense, as shown, then the two loops produce similar fields at their centres. The fields are in the same direction and combine in the region of their centres to produce a continuous field, as in Figure 17b.

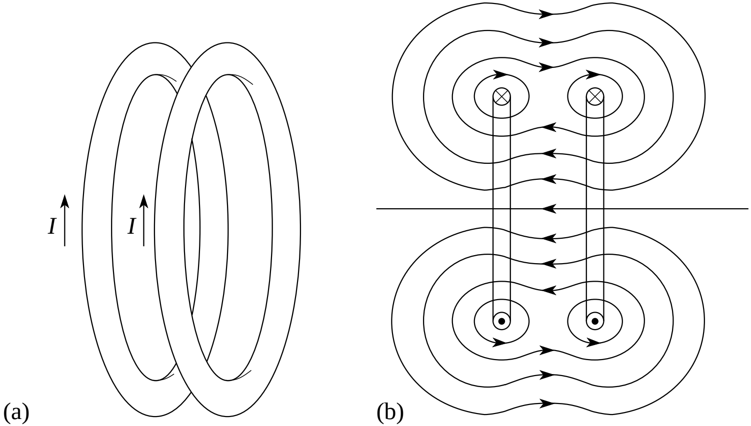
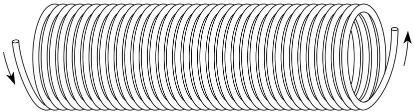


Figure 17 (a) Two similar circular current loops. (b) Bringing the loops together produces an extended region of uniform central field.

We now extend our two loops of wire into a whole series of loops, arranged sequentially and pushed close together. If each loop is connected to the adjacent loops, so that they form a single continuous coil, as illustrated in Figure 18a, then the coil so formed is called a **solenoid** and its shape is that of a **helix**.



(a)

Figure 18a A solenoid.

The resulting pattern of field lines is shown in Figure 18b for a loosely wound solenoid

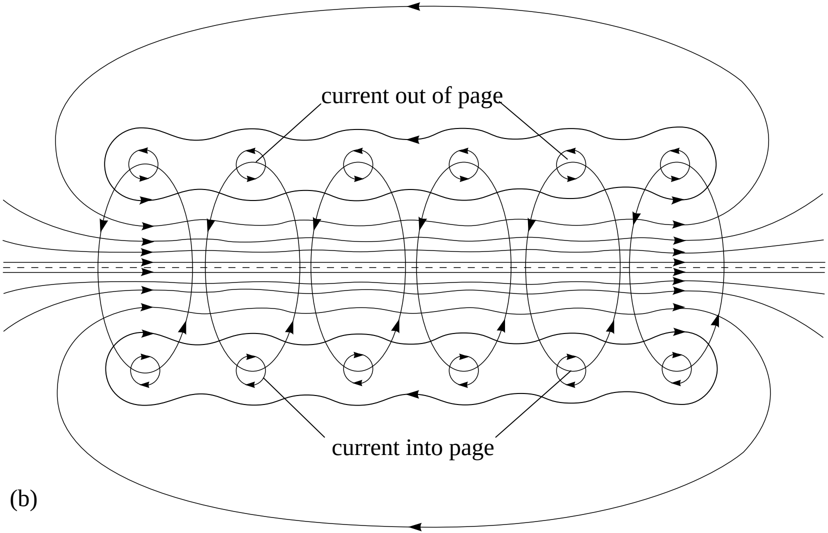


Figure 18b The field from a loosely wound solenoid.

and in Figure 18c for a tightly wound solenoid.

✥ Where else in this module have you previously seen a field like that shown in Figure 18c?

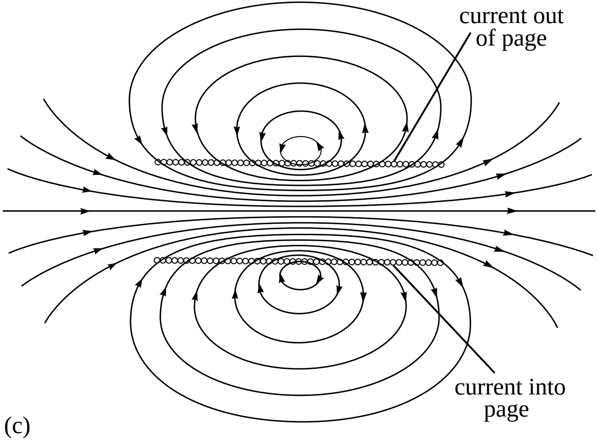


Figure 18c (a) A solenoid. (b) The field from a loosely wound solenoid. (c) The field from a tightly wound solenoid.

Calculations which are beyond the range of this discussion show that the magnetic field *at any point* inside an infinitely long solenoid is directed parallel to the axis of the solenoid and has a strength given by:

Magnetic field strength at *any point* within an *infinitely long solenoid* is:

$$B_{\text{solenoid}} = \frac{\mu_0 NI}{L} \tag{4}$$

where N is the number of turns in a length L of the solenoid.

Question T7

(a) How would you interpret the quantity (N/L) in Equation 4? (b) Suggest why we have said that Equation 4 applies to an *infinitely long* solenoid. (c) No real solenoid can be infinitely long, so how might this situation be approximated in practical situations? (d) Is the form of Equation 4 physically reasonable? ❏

We have said that Equation 4 applies to *any* point within the solenoid.

$$B_{\text{solenoid}} = \frac{\mu_0 NI}{L} \qquad \text{(Eqn 4)}$$

This is very different from Equation 3,

$$B_{\text{loop}} = \frac{\mu_0 I}{2R} \qquad \text{(Eqn 3)}$$

which gives the field at the *centre* of a loop and not at any other point. Provided we do not approach the ends of the solenoid, the field within it is uniform — the field has the same strength at points immediately adjacent to the wires as it has in the centre. If an experiment requires some object to be placed in a uniform magnetic field, then one way of achieving this is to place the object inside a long solenoid, keeping it away from the ends where we would expect some decrease in the field.

Perhaps at this point we should take a little time to consider the use of words like *long* and *short*; Question T7 has already asked you to think about this. Words of this type are only meaningful if we are told, or can infer, some yardstick for comparison. When we say that a solenoid is long and no other object is mentioned, then our only item of comparison is another dimension of the solenoid — the radius (or diameter). So, a long solenoid has a length much greater than its diameter, and a short solenoid is one which has a length less than its diameter. A *very* short solenoid is simply called a coil, particularly if later turns are wound on top of earlier turns; an 'ideal' coil would have zero length.

It is clear that we cannot apply the expression for the field in a long solenoid to an ideal coil: if we were to put the length as zero in the denominator of Equation 4

$$B_{\rm solenoid} = \frac{\mu_0 NI}{L} \qquad \text{(Eqn 4)}$$

we would obtain an infinite field strength. The correct approach here is to regard the ideal coil as a *multi-turn* loop, and to multiply the right-hand side of Equation 3

$$B_{\rm loop} = \frac{\mu_0 I}{2R} \qquad \text{(Eqn 3)}$$

by the number of turns in the coil. The magnetic field strength at points inside a solenoid of 'moderate' length (taken to mean one for which the length is comparable to the diameter) is given by an expression which is much more complicated than either Equation 3 or 4 and which will not be discussed here.

Question T8

A very long cylindrical solenoid of radius 0.1 m and 500 turns per metre carries a current of 4 A. Calculate the magnetic field strength at a point halfway between the axis of the solenoid and the windings. ❏

Question T9

The cylindrical solenoid shown in Figure 19 is of length 1 m and radius 0.1 m. It consists of 1000 turns of wire carrying a current of 1 A. A separate circular conducting loop, electrically insulated from the solenoid and carrying a current of 700 A has been wound around the middle of the solenoid so that it rests on top of the solenoid's central loop. What is the magnetic field strength at the centre of the solenoid if the current in the separate loop flows (a) in the same direction and (b) in the opposite direction to the current in the solenoid? (c) If the current in the solenoid always flows in the direction shown in Figure 19, what is the direction of the magnetic field at the centre of the solenoid for each of the cases described in (a) and (b)? ❏

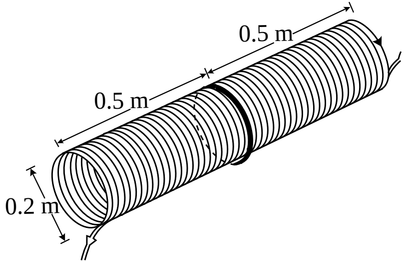


Figure 19 See Question T9.

We will consider one further current configuration. Suppose we take a long solenoid and curl it up so that the solenoid itself forms a single circular loop. This doughnut shape, shown in Figure 20a, is called a **toroid** or a **torus** and a coil wrapped around it is a **toroidal solenoid**. The magnetic field strength at a point which is within the coils of a toroidal solenoid (as shown in Figure 20b) and at a radial distance r from the centre of the toroid is:

Magnetic field strength at *a point* within a *very long toroidal solenoid* is:

$$B_{\text{toroid}}(r) = \frac{\mu_0 NI}{2\pi r} \tag{5}$$

where r is measured from the centre of the torus and N is the total number of turns on the solenoid. Figure 20b shows a very long toroidal solenoid, with the toroidal radius R_T which is much larger than the coil turns radius R_C.

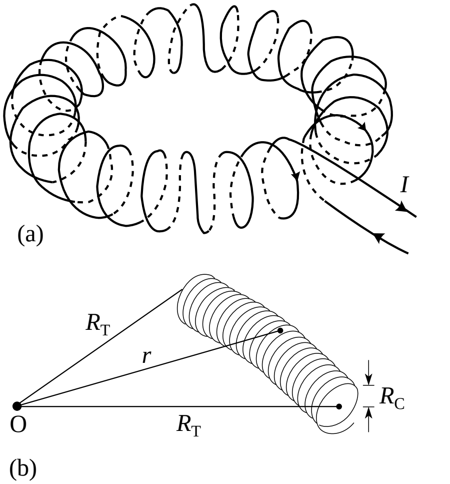


Figure 20 (a) A toroidal solenoid. (b) A section of a toroidal solenoid, having radius R_T which is much larger than the coil turns radius R_C.

Again, it is not appropriate here to prove Equation 5

$$B_{\text{toroid}}(r) = \frac{\mu_0 NI}{2\pi r} \qquad \text{(Eqn 5)}$$

but we can see that it is consistent with Equation 4

$$B_{\text{solenoid}} = \frac{\mu_0 NI}{L} \qquad \text{(Eqn 4)}$$

for the case where $R_{\rm T} >> R_{\rm C}$. In such a case $r \approx R_{\rm T}$ and $L = 2\pi R_{\rm T} \approx 2\pi r$ and Equation 5 becomes the same as Equation 4. This might be expected for a toroidal solenoid of sufficiently large toroidal radius since an enlarged view of a small section of such a solenoid would appear to be almost straight and very long. We should not be surprised by this result for, after all, a toroidal solenoid is just a solenoid which has been made to join up with itself and might be thought of as having infinite length because it has no ends! Because the solenoid has no ends, the field does not 'escape' from the turns, and so the field outside an ideal uniformly-wound toroidal solenoid is zero.

Question T10

A toroidal solenoid with 200 turns has a radius of 10 cm, measured from the toroid centre to the centre of the solenoid turns, the latter having a radius of 2 cm. What are the maximum and minimum values of the magnetic field inside the coils when a current of 1.5 A flows through the wires? (You may treat this solenoid as long.) ❑

3.5 Summary of results for the fields produced by currents

Now we will summarize all the expressions for the magnitudes of the magnetic fields generated by simple current geometries.

Field strength at a radial distance r from a long straight wire

$$B(r) = \frac{\mu_0 I}{2\pi r} \qquad \text{(Eqn 2)}$$

Field strength at the centre of a current loop of radius R

$$B_{\rm loop} = \frac{\mu_0 I}{2R} \qquad \text{(Eqn 3)}$$

Field strength inside a long solenoid of N turns in a length L, far from the ends

$$B_{\rm solenoid} = \frac{\mu_0 NI}{L} \qquad \text{(Eqn 4)}$$

Field strength within the turns of a long toroidal solenoid of N turns at a distance r from the toroid centre

$$B_{\rm toroid}(r) = \frac{\mu_0 NI}{2\pi r} \qquad \text{(Eqn 5)}$$

To this collection, we will add one further useful result, stated without proof:

> If we have a current carrying circuit of wire which includes a straight section, then there will be no contribution from that section to the magnetic field at any point along the projection of the axis of the straight section.

While we are not able to prove this final quoted result now we can make it reasonable by the following argument. Movement of electric charge constitutes a current and it is this current which gives rise to magnetic fields. Imagine an observer positioned in line with a current flowing towards or away from the observer. The charge flow has no velocity component across the line of sight and the observer will therefore be unaware of the motion of the charge and will observe no magnetic field.

The boxed results above, together with the principle of superposition, allow us to deduce the magnetic field produced by various configurations of current, provided they can be related to the simple situations discussed above. We will end this subsection by giving an example of this technique.

Example 1 A wire loop, carrying a current I, has the shape shown by the solid lines in Figure 21. Find an expression for the magnetic field at the point P.

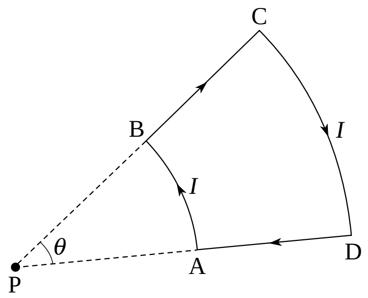


Figure 21 A circuit composed of straight and circular sections.

Solution From Figure 21, we see that there are two straight sections of wire (DA and BC) in which the current is directed towards and away from the point P. The currents in these sections produce no magnetic field at P. The two circular segments AB and CD both subtend the same angle θ at P. We can take the logical step of saying that if a full turn of a circular loop produces a certain value of field at the centre of the loop, then the fraction $\theta/2\pi$ of the loop produces that fraction of the field ☞. The fields from the two current segments will oppose one another (as the currents are in opposite directions), and that of the nearer segment, AB, will be the stronger so that the resultant field will be pointing out of the page at P. From Equation 3,

$$B_{\rm loop} = \frac{\mu_0 I}{2R} \qquad \text{(Eqn 3)}$$

its magnitude B is found to be given by

$$B_{\rm net} = \frac{\theta}{2\pi}\left(\frac{\mu_0 I}{2R_1} - \frac{\mu_0 I}{2R_2}\right) = \frac{\mu_0 I\theta}{4\pi}\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

where R_1 is the radius of arc AB and R_2 is the radius of arc CD. ❏

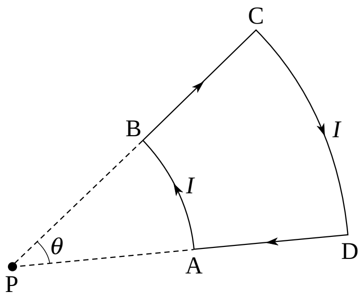


Figure 21 A circuit composed of straight and circular sections.

3.6 The electromagnet

Several times in this module we have referred to the fact that a magnet can be made using electric currents. In the sense that a coil or solenoid carrying a current produces a magnetic field, these devices behave as magnets. We can dramatically increase the magnetic strength of such a device by wrapping the coil or solenoid around a core of ferromagnetic material, such as iron. Such a device is said to be an **electromagnet**.

In an electromagnet the current produces a magnetic field and this in turn induces strong magnetism in the ferromagnetic material within the coil or solenoid. This induced magnetism then enhances considerably the magnetic forces from the coil or solenoid alone. If the ferromagnetic material is magnetically soft then when the current ceases so too does the magnetism, although a small amount may remain in the ferromagnetic material to the extent that it is not fully soft. The flexibility of the electromagnet, as opposed to a permanent magnet, is that its strength is variable and controllable. Electromagnets have very widespread applications, ranging from tiny earphones to huge cranes for lifting magnetic materials. If the ferromagnetic material within a coil is magnetically hard then the material may become permanently magnetized. ☞

4 Closing items

4.1 Module summary

1 There are many examples of everyday applications of magnetism, including the use of the magnetic compass in navigation.

2 The centres of magnetic force in a bar magnet are located near the ends of the magnet and are known as the *poles* of the magnet. A freely-suspended bar magnet aligns itself north–south, and its poles are known as the *north* and *south poles*. Two unlike poles attract each other and two poles of the same polarity repel each other.

3 At any point (x, y, z) the magnetic field $\boldsymbol{B}(x, y, z)$ relates the magnetic force $\boldsymbol{F}_{\rm mag}$ on a moving charged particle to the charge q of the particle and its velocity $\boldsymbol{v}$. The *direction* of the field at any point indicates the direction in which an isolated north magnetic pole placed at that point would tend to move (or the direction in which the north pole of a freely suspended compass needle would point). The *magnitude* of the field at any point may be determined by measuring the magnitude $F_{\rm mag}$ of the magnetic force that would act on a particle of charge q as it moves through the point (x, y, z), in a direction at right angles to the magnetic field, with a speed $v_\perp$

$$B(x,y,z) = \frac{F_{\rm mag}\big(\text{on } q \text{ as it moves through } (x,y,z)\big)}{|q|\,v_\perp} \qquad \text{(Eqn 1)}$$

The SI unit of magnetic field is the tesla (T) where $1\,\mathrm{T} = 1\,\mathrm{N\,s\,C^{-1}\,m^{-1}}$.

4 An elementary description of the Earth's magnetic field is that it is similar to the field of a bar magnet, oriented such that its magnetic south pole points towards the Earth's geographic North Pole.

5 A magnetic field may be depicted by *field lines*. Such lines are drawn so that the field is tangential to the field line at any point and has the same direction as the field line at that point. The density of the field lines in any region is proportional to the magnitude of the magnetic field in that region. (In practice this last requirement is sometimes ignored, for the sake of simplicity.) Plots of the field patterns of various orientations and arrangements of magnets can be obtained using a compass needle.

6 Magnetic poles are invariably found in pairs of opposite polarity. An isolated pair of poles of equal strength but opposite polarity, separated by a small distance, is known as a *magnetic dipole*. There is no evidence for the existence of isolated *magnetic monopoles*.

7 Materials can be simply classified into two groups: those attracted by a magnet and those not attracted by a magnet. Materials in the first group (*ferromagnetic* materials) can be further classified as *magnetically hard* or *magnetically soft*. *Permanent magnets* are made from magnetically hard materials.

8 Oersted's experiments on the deflection of a compass needle by electric currents were the first to demonstrate the connection between electric currents and magnetic fields. The lines of the magnetic field produced by a current in a straight wire are concentric circles about the current, hence explaining Oersted's results. The *right-hand grip rule* gives the direction of the magnetic field produced by a current in a straight wire.

9 Formulae are available which give the strength of the magnetic fields produced in certain specified locations in the vicinity of currents in: a straight wire, a circular loop and a multi-turn coil, a long *solenoid* and a long *toroidal solenoid*

Field strength at a radial distance r from a long straight wire

$$B(r) = \frac{\mu_0 I}{2\pi r} \qquad \text{(Eqn 2)}$$

Field strength at the centre of a current loop of radius R

$$B_{\text{loop}} = \frac{\mu_0 I}{2R} \qquad \text{(Eqn 3)}$$

Field strength inside a long solenoid of N turns in a length L, far from the ends

$$B_{\text{solenoid}} = \frac{\mu_0 NI}{L} \qquad \text{(Eqn 4)}$$

Field strength within the turns of a long toroidal solenoid of N turns at a distance r from the toroid centre

$$B_{\text{toroid}}(r) = \frac{\mu_0 NI}{2\pi r} \qquad \text{(Eqn 5)}$$

10 It is the electrons within the constituent atoms of materials which generate their magnetic properties.

11 *Electromagnets* are made by winding a coil or a solenoid around a core of magnetically soft ferromagnetic material.

4.2 Achievements

Having completed this module, you should be able to:

A1 Define the terms that are emboldened and flagged in the margins of the module.

A2 Describe and sketch the form of the Earth's magnetic field, and explain the use of an inclinometer to measure the angle of inclination or dip.

A3 Describe the interactions which arise between like and unlike poles.

A4 Describe how the magnitude and direction of a magnetic field can be determined at any point, and explain how information about magnetic fields can be obtained using a compass. Describe how field lines may be used to indicate the strength and direction of a magnetic field. Describe and illustrate the form of the field patterns produced by bar magnets in various orientations.

A5 Describe the broad categorization into magnetic and non-magnetic materials and the division of magnetic materials into hard and soft; describe further categorizations, including that of ferrites.

A6 Describe Oersted's experiments, concerning the deflection of a compass needle near an electric current, and explain the results in terms of the magnetic field produced by a current in a long straight wire.

A7 Describe and draw the field pattern produced by a current in a straight wire; state and use the right-hand grip rule to determine the field direction at a point near the wire.

A8 Use the field pattern of a straight wire to predict patterns for other simple wire configurations and, in particular, to reproduce patterns associated with loops, coils, solenoids and toroids.

A9 Recognize and use formulae which give the magnetic field strength at certain locations near the wire configurations in *Achievements* A7 and A8 and justify that these formulae are physically plausible.

A10 Use the principle of superposition to calculate resultant field strengths in regions where there is more than one source of magnetic field.

Study comment You may now wish to take the *Exit test* for this module which tests these Achievements. If you prefer to study the module further before taking this test then return to the *Module contents* to review some of the topics.

4.3 Exit test

Study comment Having completed this module, you should be able to answer the following questions each of which tests one or more of the Achievements.

Question E1

(*A2*) How does the angle of inclination or dip vary as the point of observation moves over the Earth's surface from the magnetic pole in the southern hemisphere to that in the northern hemisphere? Over what parts of the Earth's surface would you expect to find zero angle of dip?

Question E2

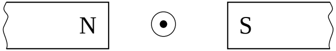


Figure 22 See Question E2.

(*A3*, *A4* and *A7*) Figure 22 shows a wire carrying a current out of the plane of the paper, placed between the poles of two bar magnets. (a) State whether the two bar magnets are attracting or repelling each other. (b) Sketch the resultant magnetic field pattern due to the bar magnets and the current.

Question E3

(*A6* and *A7*) Electrical apparatus is often connected to a power supply using a live and a return wire, carrying the current, and an earth wire, carrying no current, bound together in a single three-core cable. What effect does this arrangement have on the magnetic fields generated by the currents in the two current carrying wires? (*Hint*: You are not required to include the earth wire in your discussion.)

Question E4

(*A6* and *A9*) A long straight wire carries a current of 8 A. Calculate the strength of the magnetic field produced at distances of 5, 10, 20 and 50 mm from the wire. Sketch a graph to show how field strength varies with radial distance from the wire.

Question E5

(*A9* and *A10*) A wire of length L carries a current I. Compare the strengths of the central magnetic fields produced when this length of wire is formed into (a) a single circular loop, (b) a circular coil of n turns. (c) If more of this same wire were available, how many turns of the loop in (a) would be required to produce the field obtained in (b)?

Question E6

(*A8*, *A9* and *A10*) A large even number of long straight parallel wires, each carrying the same current in the same sense, are arranged symmetrically at equal spacings around the circumference of a cylinder parallel to the axis of the cylinder. Describe the magnetic field generated by these currents (a) in the regions inside and (b) outside the cylinder.

Study comment This is the final *Exit test* question. When you have completed the *Exit test* go back to Subsection 1.2 and try the *Fast track questions* if you have not already done so.

If you have completed **both** the *Fast track questions* and the *Exit test*, then you have finished the module and may leave it here.