Magnetic properties of materials

An introduction for the designer of electrical wound components to the part played by materials within the magnetic field, and a summary of the related terminology.

About fonts: if the character in brackets here [×] does not look like a multiplication sign then try setting your browser to use the Unicode character set (view:character set menu on Netscape 4). Also this character [Φ] is the Greek letter 'phi' in modern browsers.

See also ...

[↑ Producing wound components] [Air coils] [Power loss in wound components] [The force produced by a magnetic field] [Faraday's law] [A guide to unit systems]

The scope of this page

An entire sub-branch of physics is devoted to the study of the effects produced within various materials by the application of a magnetic field. These web pages make no attempt to cover the subject fully, and if you wish to explore it in greater depth then you should consult a text such as Jiles. What can be said here is that if you are restricted to just one parameter to describe this complexity then permeability is the one to choose. Most inductor calculations make use of it, or one of its multitudinous variants.

Emphasis goes on the aspects of practical importance in the design of wound components.

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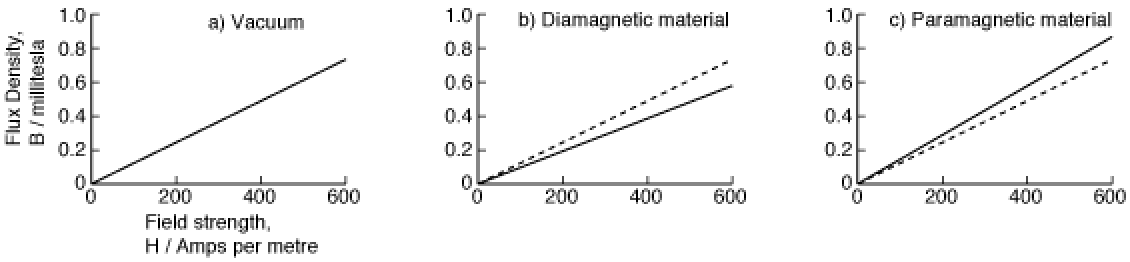
Magnetization Curves

Any discussion of the magnetic properties of a material is likely to include the type of graph known as a *magnetization* or *B-H curve*. Various methods are used to produce B-H curves, including one which you can easily replicate. Figure MPA shows how the B-H curve varies according to the type of material within the field.

Figure MPA: Magnetization in different materials



The 'curves' here are all straight lines and have magnetic field strength as the horizontal axis and the magnetic flux density as the vertical axis. Negative values of H aren't shown but the graphs are symmetrical about the vertical axis.

Fig. MPA a) is the curve in the absence of any material: a vacuum. The gradient of the curve is $4\pi.10^{-7}$ which corresponds to the fundamental physical constant μ_0. More on this later. Of greater interest is to see how placing a specimen of some material in the field affects this gradient. Manufacturers of a particular grade of ferrite material usually provide this curve because the shape reveals how the core material in any component made from it will respond to changes in applied field.

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Diamagnetic and paramagnetic materials

Imagine a hydrogen atom in which a nucleus with a single stationary and positively charged proton is orbited by a negatively charged electron. Can we view that electron in orbit as a sort of current loop? The answer is yes, and you might then think that hydrogen would have a strong magnetic moment. In fact ordinary hydrogen gas is only very weakly magnetic. Recall that each hydrogen atom is not isolated but is bonded to one other to form a molecule, giving the formula H_2 - because that has a lower chemical energy (for H by a whopping 218 kJ mol^{-1}) than two isolated atoms. It is not a coincidence that in these molecules the angular momentum of one electron is opposite in direction to that of its neighbour, leaving the molecule as a whole with little by way of magnetic moment. This behaviour is typical of many substances which are then said to lack a *permanent magnetic moment*.

When a molecule is subjected to a magnetic field those electrons in orbit planes at a right angle to the field will change their momentum (very slightly). This is predicted by Faraday's Law which tells us that as the field is increased there will be a an induced E-field which the electrons (being charged particles) will experience as a force. This means that the individual magnetic moments no longer cancel completely and the molecule then acquires an *induced magnetic moment*. This behaviour, whereby the induced moment is opposite to the applied field, is present in all materials and is called *diamagnetism*. Hydrogen, ammonia, bismuth, copper, graphite and other *diamagnetic substances*, are **repelled** by a nearby magnet (although the effect is extremely feeble). Think of it as a manifestation of Lenz's law. Diamagnetic materials are those whose atoms have only *paired electrons*.

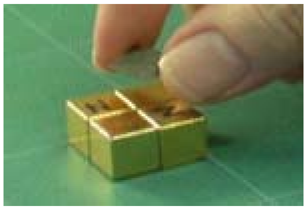
In other molecules, however, such as oxygen, where there are unpaired electrons, the cancellation of magnetic moments belonging to the electrons is incomplete. An O_2 molecule has a net or *permanent magnetic moment* even in the absence of an externally applied field. If an external magnetic field is applied then the electron orbits are still altered in the same manner as the diamagnets but the permanent moment is usually a more powerful influence. The 'poles' of the molecule tend to line up parallel with the field and reinforce it. Such molecules, with permanent magnetic moments are called *paramagnetic*.

Although paramagnetic substances like oxygen, tin, aluminium and copper sulphate are attracted to a magnet the effect is almost as feeble as diamagnetism. The reason is that the permanent moments are continually knocked out of alignment with the field by thermal vibration, at room temperatures anyway (liquid oxygen at -183 °C can be pulled about by a strong magnet).

Particular materials where the magnetic moment of each atom can be made to favour one direction are said to be *magnetizable*. The extent to which this happens is called the *magnetization*. Fig. MPA b) above is the magnetization curve for diamagnetic materials. In diamagnetic substances the flux grows slightly more slowly with the field than it does in a vacuum. The decrease in gradient is greatly exaggerated in the figure - in practice the drop is usually less than one part in 6,000.

Fig. MPA c) is the curve for paramagnetic materials. Flux growth in this case is again linear (at moderate values of H) but slightly faster than in a vacuum. Again, the increase for most substances is very slight.

Although neither diamagnetic nor paramagnetic materials are technologically important (geophysical surveying is one exception), they are much studied by physicists, and the terminology of magnetics is enriched thereby. A short QuickTime movie (388 KB) demonstrates diamagnetism.



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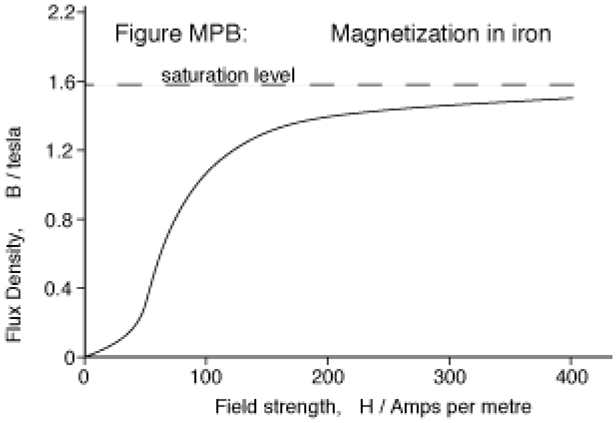
Ferromagnetic materials



The most important class of magnetic materials is the *ferromagnets*: iron, nickel, cobalt and manganese, or their compounds (and a few more exotic ones as well). The magnetization curve looks very different to that of a diamagnetic or paramagnetic material. We might note in passing that although pure manganese is not ferromagnetic the name of that element shares a common root with magnetism: the Greek *mágnes lithos* - "stone from Magnesia" (now Manisa in Turkey).

Figure MPB above shows a typical curve for iron. It's important to realize that the magnetization curves for ferromagnetic materials are all strongly dependant upon purity, heat treatment and other factors. However, two features of this curve are immediately apparent: it really is curved rather than straight (as with non-ferromagnets) and also that the vertical scale is now in teslas (rather than milliteslas as with Figure MPA).

Figure MPB is a *normal magnetization curve* because it starts from an unmagnetized sample and shows how the flux density increases as the field strength is increased. You can identify four distinct regions in most such curves. These can be explained in terms of changes to the material's magnetic 'domains':

1. Close to the origin a slow rise due to 'reversible growth'.
2. A longer, fairly straight, stretch representing 'irreversible growth'.
3. A slower rise representing 'rotation'.
4. An almost flat region corresponding to paramagnetic behaviour and then μ_0 - the core can't handle any more flux growth and has *saturated*.

At an atomic level ferromagnetism is explained by a tendency for neighbouring atomic magnetic moments to become locked in parallel with their neighbours. This is only possible at temperatures below the *curie point*, above which thermal disordering causes a sharp drop in permeability and degeneration into paramagnetism. Ferromagnetism is distinguished from paramagnetism by more than just permeability because it also has the important properties of remnance and coercivity.

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Ferrimagnetic materials

Almost every item of electronic equipment produced today contains some *ferrimagnetic* material: loudspeakers, motors, deflection yokes, interference suppressors, antenna rods, proximity sensors, recording heads, transformers and inductors are frequently based on *ferrites*. The market is vast.

What properties make *ferrimagnets* so ubiquitous? They possess permeability to rival most ferromagnets but their eddy current losses are far lower because of the material's greater electrical resistivity. Also it is practicable (if not straightforward) to fabricate different shapes by pressing or extruding - both low cost techniques.

What is the composition of ferrimagnetic materials? They are, in general, oxides of iron combined with one or more of the transition metals such as manganese, nickel or zinc, e.g. $MnFe_2O_4$. Permanent ferrimagnets often include barium. The raw material is turned into a powder which is then fired in a kiln or *sintered* to produce a dark gray, hard, brittle ceramic material having a cubic crystalline structure.

At an atomic level the magnetic properties depend upon interaction between the electrons associated with the metal ions. Neighbouring atomic magnetic moments become locked in **anti**-parallel with their neighbours (which contrasts with the ferromagnets). However, the magnetic moments in one direction are weaker than the moments in the opposite direction leading to an overall magnetic moment.

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Saturation

Saturation is a limitation occurring in inductors having a ferromagnetic or ferrimagnetic core. Initially, as current is increased the flux increases in proportion to it (see figure MPB). At some point, however, further increases in current lead to progressively smaller increases in flux. Eventually, the core can make no further contribution to flux growth and any increase thereafter is limited to that provided by μ_0 - perhaps three orders of magnitude smaller. Iron saturates at about 1.6 T while ferrites will normally saturate between about 200 mT and 500 mT.

It is usually essential to avoid reaching saturation since it is accompanied by a drop in inductance. In many circuits the rate at which current in the coil increases is inversely proportional to inductance ($I = V * T / L$). Any drop in inductance therefore causes the current to rise faster, increasing the field strength and so the core is driven even further into saturation.

Core manufacturers normally specify the saturation flux density for the particular material used. You can also measure saturation using a simple circuit. There are two methods by which you can calculate flux if you know the number of turns and either -

1. The current, the length of the magnetic path and the B-H characteristics of the material.
2. The voltage waveform on a winding and the cross sectional area of the core - see Faraday's Law.

Although saturation is mostly a risk in high power circuits it is still a possibility in 'small signal' applications having many turns on an ungapped core and a DC bias (such as the collector current of a transistor).

If you find that saturation is likely then you might -

- Run the inductor at a lower current
- Use a larger core
- Alter the number of turns
- Use a core with a lower permeability
- Use a core with an air gap

or some combination thereof - but you'll need to re-calculate the design in any case.

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Materials classification

Table MPJ categorizes (in a simplified fashion) each class assigned to a material according to its behaviour in a field.

Table MPJ: Materials classified by their magnetic properties.

Class	χ dependant on B?	Dependant on temperature?	Hysteresis?	Example	χ
Diamagnetic	No	No	No	water	-9.0×10^{-6}
Paramagnetic	No	Yes	No	Aluminium	2.2×10^{-5}
Ferromagnetic	Yes	Yes	Yes	Iron	3000
Antiferromagnetic	Yes	Yes	Yes	Terbium	9.51E-02
Ferrimagnetic	Yes	Yes	Yes	$MnZn(Fe_2O_4)_2$	2500

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Permeability

Permeability in the SI

Quantity name	permeability alias absolute permeability
Quantity symbol	μ
Unit name	henrys per metre
Unit symbols	$H\ m^{-1}$
Base units	$kg\ m\ s^{-2}\ A^{-2}$

Duality with the Electric World

Quantity	**Unit**	**Formula**
Permeability	henrys per metre	$\mu = L/d$
Permittivity	farads per metre	$\varepsilon = C/d$

Although, as suggested above, magnetic permeability is related in physical terms most closely to electric permittivity, it is probably easier to think of permeability as representing 'conductivity for magnetic flux'; just as those materials with high electrical conductivity let electric current through easily so materials with high permeabilities allow magnetic flux through more easily than others. Materials with high permeabilities include iron and the other ferromagnetic materials. Most plastics, wood, non ferrous metals, air and other fluids have permeabilities very much lower: μ_0.

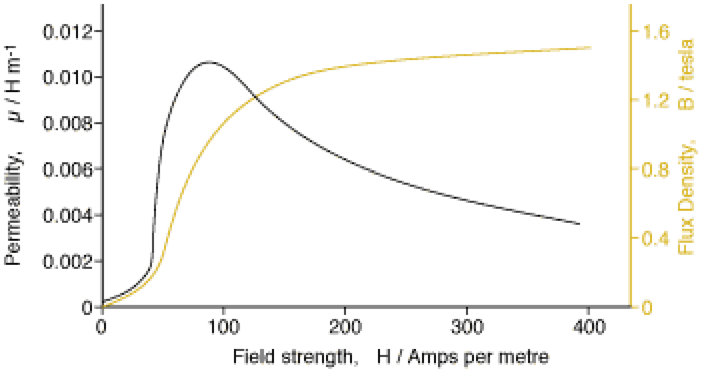
Just as electrical conductivity is defined as the ratio of the current density to the electric field strength, so the magnetic permeability, μ, of a particular material is defined as the ratio of flux density to magnetic field strength -

$$\mu = B / H$$

Equation MPD

This information is most easily obtained from the magnetization curve. Figure MPC shows the permeability (in black) derived from the magnetization curve (in colour) using equation MPD. Note carefully that permeability so defined is **not** the same as the slope of a tangent to the B-H curve except at the peak (around 80 A m^{-1} in this case). The latter is called *differential permeability*, $\mu' = dB/dH$.

Figure MPC: Permeability of iron



In ferromagnetic materials the hysteresis phenomenon means that if the field strength is increasing then the flux density is less than when the field strength is decreasing. This means that the permeability must also be lower during 'charge up' than it is during 'relaxation', even for the same value of H. In the extreme case of a permanent magnet the permeability within it will be negative. There is an analogy here with electric cells, since they may be said to have 'negative resistance'.

If you use a core with a high value of permeability then fewer turns will be required to produce a coil with a given value of inductance. You can understand why by remembering that inductance is the ratio of flux to current. For a given core B is proportional to flux and H is proportional to the current so that inductance is also proportional to μ: the ratio of B to H.

Unlike electrical conductivity, permeability is often a highly non-linear quantity. Most coil design formulæ, however, **pretend** that μ is a linear quantity. If you were working at a peak value of H of 100 A m^{-1}, for example, then you might take an average value for μ of about 0.006 H m^{-1}. This is all very approximate, but you must accept inaccuracy if you insist on treating a non-linear quantity as though it was actually linear.

This form of permeability, where μ is written without a subscript, is known in SI parlance as *absolute permeability*. It is seldom quoted in engineering texts. Instead a variant is used called *relative permeability* described next.

$$\mu = \mu_0 \times \mu_r$$ Equation MPG

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Relative permeability

Relative permeability

Quantity name	Relative permeability
Quantity symbol	μ_r
Unit symbols	dimensionless

Relative permeability is a very frequently used parameter. It is a variation upon 'straight' or absolute permeability, μ, but is more useful to you because it makes clearer how the presence of a particular material affects the relationship between flux density and field strength. The term 'relative' arises because this permeability is defined in relation to the permeability of a vacuum, μ_0

$$\mu_r = \mu / \mu_0$$ Equation MPE

For example, if you use a material for which $\mu_r = 3$ then you know that the flux density will be three times as great as it would be if we just applied the same field strength to a vacuum. This is simply a more user friendly way of saying that $\mu = 3.77\times10^{-6}$ H m^{-1}. Note that because μ_r is a dimensionless ratio that there are no units associated with it.

Many authors simply say "permeability" and leave you to infer that they mean relative permeability. In the CGS system of units these are one and the same thing really. If a figure greater than 1.0 is quoted then you can be almost certain it is μ_r.

Approximate maximum permeabilities

Material	**μ/(H m^{-1})**	**μ_r**	**Application**
Ferrite U 60	1.00E-05	8	UHF chokes
Ferrite M33	9.42E-04	750	Resonant circuit RM cores
Nickel (99% pure)	7.54E-04	600	-
Ferrite N41	3.77E-03	3000	Power circuits
Iron (99.8% pure)	6.28E-03	5000	-
Ferrite T38	1.26E-02	10000	Broadband transformers
Silicon GO steel	5.03E-02	40000	Dynamos, mains transformers
supermalloy	1.26	1000000	Recording heads

Note that, unlike μ_0, μ_r is not constant and changes with flux density. Also, if the temperature is increased from, say, 20 to 80 centigrade then a typical ferrite can suffer a 25% drop in permeability. This is a big problem in high-Q tuned circuits.

Another factor, with steel cores especially, is the microstructure, in particular *grain orientation*. Silicon steel sheet is often made by cold rolling to orient the grains along the laminations (rather than allowing them to lie randomly) giving increased μ. We call such material *anisotropic*.

Before you pull any value of μ from a data sheet ask yourself if it is appropriate for your material under the actual conditions under which you use it. Finally, if you do not know the permeability of your core then build a simple circuit to measure it.

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Variant forms of permeability and related quantities

Initial permeability

Initial permeability

Quantity name	initial permeability
Quantity symbol	μ_i
Unit symbols	dimensionless *

Initial permeability describes the relative permeability of a material at low values of B (below 0.1T).

The maximum value for μ in a material is frequently a factor of between 2 and 5 or more above its initial value.

Low flux has the advantage that every ferrite can be measured at that density without risk of saturation. This consistency means that comparison between different ferrites is easy. Also, if you measure the inductance with a normal component bridge then you are doing so with respect to the initial permeability.

* Although initial permeability is usually relative to μ_0, you may see μ_i as an absolute permeability.

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Effective permeability

Effective permeability

Quantity name	Effective permeability
Quantity symbol	μ_e
Unit symbols	dimensionless *

Effective permeability is seen in some data sheets for cores which have air gaps. Coil calculations are easier because you can simply ignore the gap by pretending that you are using a material whose permeability is lower than the material you actually have.

* Effective permeability is usually *relative* to μ_0.

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Permeability of a vacuum in the SI

Permeability of a vacuum

Quantity name	Permeability of a vacuum alias Permeability of free space, magnetic space constant, magnetic constant
Quantity symbol	

	μ_0
Unit name	henrys per metre
Unit symbols	$H\ m^{-1}$
Base units	$kg\ m\ s^{-2}\ A^{-2}$

The permeability of a vacuum has a finite value - about 1.257×10^{-6} $H\ m^{-1}$ - and in the SI system (unlike the cgs system) is denoted by the symbol μ_0. Note that this value is constant with field strength and temperature. Contrast this with the situation in ferromagnetic materials where μ is strongly dependant upon both. Also, for practical purposes, most non-ferromagnetic substances (such as wood, plastic, glass, bone, copper aluminium, air and water) have a permeability almost equal to μ_0; that is, their relative permeability is 1.0.

In Fig. MPZ you see, in cross section, two long, straight conductors spaced one metre apart in a vacuum. Both carry one ampere. The field strength due to the current in conductor A at a distance of one metre may be found, using Ampère's Law -

$$H = I / d = 1 / (2\pi) \quad A\ m^{-1}$$

Equation MPI

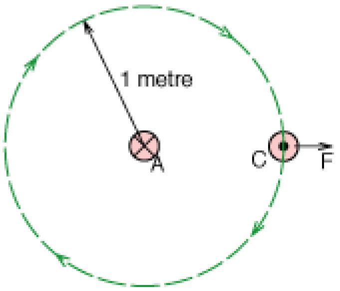

Fig. MPZ -
Two parallel conductors

where I is the current in conductor A and d is the path length around the circular field line. We know, from the definition of the ampere, that the force on conductor C is 2×10^{-7} newtons per metre of its length. However, flux density, B, is also defined in terms of the force F, in newtons, exerted on a conductor of unit length and carrying unit current -

$$B = F / I = 2\times10^{-7} / 1 \quad \text{tesla}$$

Equation MPO

Since we now know both B and H at a distance of 1 metre from A we calculate the permeability of a vacuum as -

$$\mu_0 = B / H = 2\times10^{-7} / (1 / (2\pi)) = 4\pi10^{-7} \quad H\ m^{-1}$$

Equation MPF

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Susceptibility

Susceptibility (magnetic) in the SI

Quantity name	Susceptibility alias bulk susceptibility or volumetric susceptibility

Quantity symbol	χ, χ_v
Unit symbols	dimensionless

Duality with the Electric World

Quantity	Unit	Formula
magnetic susceptibility	1	$\chi_{mg} = \mu_r - 1$
electric susceptibility	1	$\chi_{el} = \varepsilon - 1$

Although susceptibility is seldom directly important to the designer of wound components it is used in most textbooks which explain the theory of magnetism. When you work with non-ferromagnetic substances the permeability is so close to μ_0 that characterizing them by μ is inconvenient. Instead use the magnetic susceptibility, χ - via the permeability

$$\chi = \mu_r - 1$$

Equation MPS

In paramagnetic and diamagnetic materials the susceptibility is given by

$$\chi = M / H$$

Equation MPH

Susceptibilities of some other substances are given in table MPS where the paramagnetic substances have positive susceptibilities and the diamagnetic substances have negative susceptibilities. The susceptibility of a vacuum is then zero.

Table MPS: Magnetic susceptibilities

Material	**χ_v / 10^{-5}**
Aluminium	+2.2
Ammonia	-1.06
Bismuth	-16.7
Copper	-0.92
Hydrogen	-0.00022
Oxygen	+0.19
Silicon	-0.37
Water	-0.90

Susceptibility is a strong contender for the title of 'most confusing quantity in all science'. There are five reasons for this:

1. The counterpart to permeability in electrostatics has a distinct name: permittivity. Unfortunately, the counterpart to susceptibility in electrostatics has the same name. However, the electrostatic susceptibility should be given the symbol χ_e. *Susceptance* has nothing to do with susceptibility.
2. There are variant forms of susceptibility, the main two of which are listed below. Authors do not always explicitly state which variant is being used and, worse still, there is incomplete agreement about the names and symbols of each variant. The symbol χ_m is somewhat overloaded: **m**agnetic susceptibility, **m**ass susceptibility, or **m**olar susceptibility? Take your pick.
3. Most reference books, and many instruments, still present susceptibility figures in CGS units. Often, the units are not made explicit and you are left to deduce them from the context or the values themselves. The procedures for converting to SI are not obvious.
4. Some quite prestigious publications incorrectly abbreviate the units to 'per gram' or 'per kilogram'. :-(

5. Measurement of susceptibility is notoriously difficult. The slightest whiff of contamination by iron in the sample will send the experimental results off into the twilight. Published figures frequently show differences of 5%; and 50% is not rare.

The international symbol for susceptibility of the ordinary ('volumetric') kind is simply χ without any subscript. ISO suggests χ_m to distinguish **m**agnetic susceptibility from electric susceptibility but this may risk confusion with mass or molar susceptibility. Some writers have used χ_v to indicate volumetric susceptibility. Although electromagnetism is already up to its ears in subscript soup, this seems a good solution.

Table MPN: Variant forms of susceptibility

Name	Equation	Symbol	SI Units
bulk susceptibility	M / H	χ, χ_v or κ	dimensionless
mass susceptibility	χ_v / ρ	χ_ρ	$m^3\ kg^{-1}$
molar susceptibility or molar mass susceptibility	$\chi_v \times W_a / \rho$	χ_M	$m^3\ mol^{-1}$

where ρ is the density of the substance in kg m^{-3} and W_a is the molar mass in kg mol^{-1}.

To appreciate the difference for each variant think of it as being a separate way to get the total magnetic moment for a magnetic field strength of one amp per metre. With bulk susceptibility you start from a known volume, with mass susceptibility you start from a known mass and from molar susceptibility you start from a known number of moles. Depending upon your application one form will be more convenient than another. Physicists like molar susceptibility because their calculations derive from atomic properties. Geologists like mass susceptibility because they know the weight of their sample.

⚠ The definition of susceptibility given here accords with the Sommerfeld SI variant. In the Kennelly variant χ has a different definition.

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Mass susceptibility

Magnetic susceptibility by mass in the SI

Quantity name	Magnetic mass susceptibility alias specific susceptibility
Quantity symbol	χ_ρ
Unit symbols	$m^3\ kg^{-1}$

Magnetic mass susceptibility is simply

$$\chi_\rho = \chi_v / \rho \quad \mathrm{m^3\ kg^{-1}}$$

Equation MPT

where χ_v is the ordinary ('volumetric') susceptibility and ρ is the density of the material in kg per cubic metre. Unfortunately some tables of mass susceptibility, even in prestigious publications, abbreviate the units to 'susceptibility per gram' or 'susceptibility per kilogram' which is, at best, a source of confusion. Take care to distinguish χ_ρ from χ_M or *molar* susceptibility; that is a different quantity.

Table MPM: Magnetic mass susceptibilities

Material	**χ_ρ / (10^{-8} m^3 kg^{-1})**
Aluminium	+0.82
Ammonia	-1.38
Bismuth	-1.70
Copper	-0.107
Hydrogen	-2.49
Oxygen	+133.6
Silicon	-0.16
Water	-0.90

So, if you know the mass of your material sample you need only multiply by χ_ρ to find its magnetic moment when the field strength is one amp per metre.

⚠ This definition of susceptibility accords with the Sommerfeld SI variant. In the Kennelly variant χ has a different definition.

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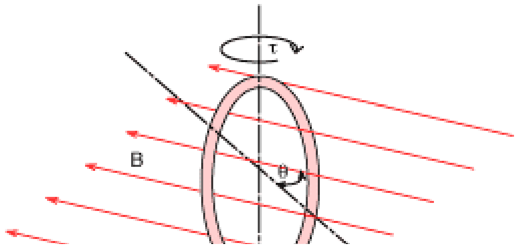
Terminology for intrinsic fields within materials -

Magnetic moment

Magnetic moment in the SI

Quantity name	magnetic moment alias magnetic dipole moment or electromagnetic moment
Quantity symbol	m
Unit name	ampere metre squared
Unit symbols	A m^2

Fig. MPM: The concept of magnetic moment.



The concept of magnetic moment is the starting point when discussing the behaviour of magnetic materials within a field. If you place a bar magnet in a field then it will experience a torque or *moment* tending to align its axis in the direction of the field. A compass needle behaves the same. This torque increases with the strength of the poles and their distance apart. So the value of magnetic moment tells you, in effect, 'how big a magnet' you have.

It is also well known that a current carrying loop in a field also experiences a torque (electric motors rely on this effect). Here the torque, τ, increases with the current, i, and the area of the loop, A. θ is the angle made between the axis of the loop normal to its plane and the field direction.

$$\tau = B \times i \times A \times \sin\theta$$

Equation MPU

The unit of τ is the newton metre. This puzzling quantity appears to have the dimensions of force times distance ... which is energy. Hmmm.

The quantity i × A is defined as the magnetic moment, m. This gives

$$\tau = B \times m \times \sin\theta$$

Equation MPL

Particular materials where the magnetic moment of each atom can be made to favour one direction are said to be *magnetizable*. The extent to which this happens is called the *magnetization*. Magnetic moment is a vector quantity which has both direction and magnitude. This is important because although the atoms in most materials may have magnetic moments they are not easily brought into alignment in one direction, so the moments cancel each other, leading to weak magnetization.

The Earth has a magnetic moment of 8×10^{22} A m^2. A single electron has a magnetic moment due to its orbit around the nucleus which is a multiple of 9.27×10^{-24} A m^2 (known as the *Bohr magneton*, μ_B).

We have, then, two ways of looking at the basis of magnetism: one is the idea of a pair of opposing poles and the other is current circulation. Each viewpoint has some advantages over the other; and this gave science a hard time deciding which to prefer. The reason this is worth mentioning is that different definitions arose for several quantities in magnetics. Both models, however, function more as convenient mathematical abstractions rather than literal descriptions of the physical origins of magnetism.

⚠ The definition given above accords with the Sommerfeld variant of the SI system of units. In the Kennelly variant m is in weber metres.

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Magnetization

Magnetization in the SI

Quantity name	Magnetization
Quantity symbol	M
Unit name	ampere per metre
Unit symbols	$A\ m^{-1}$

Magnetic fields are caused by the movement of charge, normally electrons. This movement may take place in a wire carrying current. The wire then develops a surrounding magnetic field which is given the symbol, H.

In a bar magnet you may not think that there need be any current but the magnetic field here is also due to moving charge: the electrons circling around the nuclei of the iron atoms or simply spinning about their own axis. Atoms like this are said to possess a magnetic moment. The average field strength due to these moments at any particular point is called *magnetization* and given the symbol M.

In most materials the moments are oriented almost at random - which leads to weak magnetization and 'non-magnetic' properties. In iron the moments readily align themselves along an applied field so inducing a large value of M and the familiar characteristics in the presence of a field.

Magnetization is defined -

$$M = m / V \quad A\ m^{-1}$$ Equation MPV

where m is the total vector sum for the magnetic moments of all the atoms in a given volume V (in m^3) of the material. We can then say -

$$B = \mu_0 (H + M) \quad \text{teslas}$$ Sommerfeld field equation

This equation is of theoretical importance because it highlights a closeness between H and M. The H field is related to 'free currents': for example those flowing from a battery along a piece of wire. M, on the other hand, is related to the 'bound' ('Ampèrian') currents of electron orbitals within magnetized materials.

In practice, with ferromagnetic materials, M tends to be a very complex function of H - including values of H in the past. As a designer of wound components you therefore pretend instead that $B = \mu H$ ... and hope for the best!

Magnetization occurs not just in materials having permanent magnetic moments but also in any *magnetizable* material in a field which can *induce* a magnetic moment in its constituent atoms. In the special case of paramagnetic and diamagnetic materials this magnetization is given by

$$M = \chi H \quad A\ m^{-1}$$ Equation MPZ

⚠ The definition given above accords with the Sommerfeld variant of the SI system of units. The Kennelly variant M is in tesla.

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Intensity of magnetization

Intensity of magnetization in the SI

Quantity name	Intensity of magnetization alias Magnetic polarization
Quantity symbol	I
Unit name	tesla
Unit symbol	T

Intensity of magnetization functions in the Kennelly variant of the SI as an alternative to the Sommerfeld variant for magnetization, M.

$$I = \mu_0 M \quad \text{teslas}$$ Equation MPX

We can then say -

$$B = \mu_0 H + I \quad \text{teslas}$$ Kennelly field equation

Note the units of I: teslas, not amps per metre as in the Sommerfeld magnetization. So don't confuse intensity of magnetization with magnetization.

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Magnetic polarization

Magnetic polarization in the SI

Quantity name	Magnetic polarization alias Intensity of magnetization
Quantity symbol	J
Unit name	tesla
Unit symbols	T

Magnetic polarization is a synonym for intensity of magnetization in the Kennelly variant of the SI

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