$$\mathbf{F} = qnA(\mathbf{v} \times \mathbf{B})$$

However, a unit length of the wire contains nA moving charges. So, assuming that each charge is subject to an equal force from the magnetic field (we have no reason to suppose otherwise), the force acting on an individual charge is

$$\mathbf{f} = q(\mathbf{v} \times \mathbf{B})$$

We can combine this with Eq. (169) to give the force acting on a charge q moving with velocity $\mathbf{v}$ in an electric field $\mathbf{E}$ and a magnetic field $\mathbf{B}$:

$$\mathbf{f} = q\left[\mathbf{E} + q(\mathbf{v} \times \mathbf{B})\right]$$

This is called the Lorentz force law, after the Dutch physicist Hendrik Antoon Lorentz who first formulated it. The electric force on a charged particle is parallel to the local electric field. The magnetic force, however, is perpendicular to both the local magnetic field and the particle's direction of motion. No magnetic force is exerted on a stationary charged particle.

2.2. Magnetic field intensity:

Magnetization M

When a substance is placed in an external magnetic field, the substance experiences a torque due to the field and aligns in the same direction as the field. The magnetization so produced in the substance is called Induced magnetization. It is denoted by symbol M. Magnetization in magnetic field is analogues to polarization of dielectric material in electrostatic field.

Magnetic field Intensity H

The magnetic field in "empty" space is denoted by the symbol B. It is calculated from Ampere's Law or Biot-Savart's Law and measured in teals. However, when the magnetic field passes through a magnetically responsive material, such as iron, the material itself contributes its internal magnetic field. Then a second quantity, H called as magnetic field intensity is used to characterize the strength of external field i.e. the magnetic field due to the external sources (electric current) only, excluding the contribution due to material's internal magnetic field. H is related to B through permeability μ as $B = \mu H$. Magnetic field Intensity H is also called as Magnetizing force or Auxiliary Magnetic field. H is also expressed in terms of M as follows

$$\text{curl}\, B = \mu_0 (J + J_M)$$

$$\text{curl}\, B = \mu_0 (J + \text{curl}\, M)$$

$$\text{curl}\left(\frac{B}{\mu_0} - M\right) = J$$

$(J \to J +$

$(J_M = \text{cur}$

$$H = \frac{B}{\mu_o} - M$$

$$B = \mu o(H + M)$$

H and M have the same units, amperes/meter.

Unit - II (Magnetostatic

2.3 Biot-Savart Law:

In 1819 Danish physicist Hans Christian Overstep observed that current through a wire caused a deflection in nearby magnetic needle. This indicates that magnetic field is associated with a current conductor. In 1820, Biot and Savart conducted many experiments to determine factors on which the magnetic field due to current. The results of the experiments are summarized as Biot-Savart law.

Construction:

Consider a conductor XY carrying a current I. AB=dl is a small element of the conductor. P is a point at a distance r from the midpoint O of AB.

According to Biot and Savart the magnetic induction dB at P due to the element of length dl is, Directly proportional to the current(I)

Directly proportional to the length of the element (dl).

Directly proportional to the sine of the angle between dl and the line joining element dl and the point $P(\sin\theta)$

Inversely proportional to the square of the distance of the point from the element

$\frac{dl}{4\pi R^2}$ $\times \vec{aR}$ $\rightarrow$ line current $(1/r^2)$

$I \times \vec{aR} \rightarrow$ surface cur

$$dB \alpha \frac{Idl\sin\theta}{r^2}$$

$$dB = k\frac{Idl\sin\theta}{r^2} \qquad k = \frac{\mu}{4\pi}$$

Where k is the constant of proportionality. The constant $k = \mu / 4\pi$. μ is the permeability of the medium.

$$\therefore dB = \frac{\mu}{4\pi} \frac{Idl \sin\theta}{r^2}$$

$\mu = \mu_0 \mu_r$ Where μ_r is the relative permeability of the medium and μ_0 is the permeability of free space. $\mu_0 = 4\pi \times 10^{-7}$ H/M For air $\mu_r = 1$.

So, in air medium,
$$dB = \frac{\mu_0}{4\pi} \frac{Idl \sin\theta}{r^2}$$

In vector form
$$\overline{dB} = \frac{\mu_0}{4\pi} \cdot \frac{I \ \overline{dl} \times \overline{r}}{r^3}$$

(Or)
$$\boxed{\overline{dB} = \frac{\mu_0}{4\pi} \cdot \frac{I \overline{dl} \times \hat{r}}{r^2}}.$$

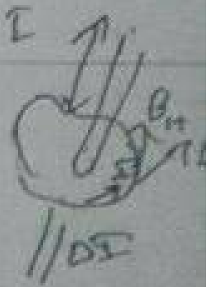
The direction of dB is perpendicular to the plane containing current element Idl and r and acts inwards. The unit of magnetic induction is Tesla (or) Weber / m2.

2. Ampere's Law

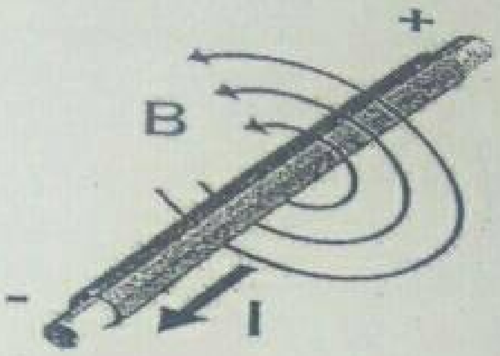
m.f space e.c ∝ e.c . Source

The magnetic field in space around an electric current is proportional to the electric current which serves as its source, just as the electric field in space is proportional to the charge which serves as its source. Ampere's Law states that for any closed loop path, the sum of the length elements times the magnetic field in the direction of the length element is equal to thepermeability times the electric current enclosed in the loop.

$$\sum B_{\|} \Delta l = \mu_0 I$$



In the electric case, the relation of field to source is quantified in Gauss's Lawwhich is a very powerful tool for calculating electric fields.



An electric current produces a magnetic field. It relates magnetic fields to electric currents that produce them. Using Ampere's law, one can determine the magnetic field associated with a given current or current associated with a given magnetic field, providing there is no time changing electric field present. In its historically original form, Ampere's circuital law relates the magnetic field to its electric current source. The law can be written in two forms, the "integral form" and the "differential form". The forms are equivalent, and related by the Kelvin-Stokes theorem. It can also be written in terms of either the B or H magnetic fields. Again, the two forms are equivalent (see the "proof" section below).

Ampere's circuital law is now known to be a correct law of physics in a magneto static situation: The system is static except possibly for continuous steady currents within closed loops. In all other cases the law is incorrect unless Maxwell's correction is included (see below).

Integral form

In SI units (cgs units are later), the "integral form" of the original Ampere's circuital law is aline integral of the magnetic field around some closed curve C (arbitrary but must be closed). The curve C in turn bounds both a surface S which the electric current passes through (again arbitrary but not closed—since no three-dimensional volume is enclosed by S), and encloses the current. The mathematical statement of the law is a relation between the total amounts of magnetic field around some path (line integral) due to the current which passes through that enclosed path (surface integral). It can be written in a number of forms.

In terms of total current, which includes both free and bound current, the line integral of the magnetic B-field (in teals, T) around closed curve C is proportional to the total current Ienc passing through a surface S (enclosed by C):

$$\oint_C \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 \iint_S \mathbf{J} \cdot d\mathbf{S} = \mu_0 I_{enc}$$

Where J is the total current density (in ampere per square meter, Am−2). -45-

Alternatively in terms of free current, the line integral of the magnetic H-field (in ampere per meter, Am−1) around closed curve C equals the free current If, enc through a surface S:

$$\oint_C \mathbf{H} \cdot d\boldsymbol{\ell} = \iint_S \mathbf{J}_f \cdot d\mathbf{S} = I_{f,enc}$$

Where Jf is the free current density only. Furthermore

$\oint_C$ Is the closed line integral around the closed curve C,

$\iint_S$ Denotes a 2d surface integral over S enclosed by C is the vector dot product,

Dℓ is an infinitesimal element (a differential) of the curve C (i.e. a vector with magnitude equal to the length of the infinitesimal line element, and direction given by the tangent to the curve C)

DS is the vector area of an infinitesimal element of surface S (that is, a vector with magnitude equal to the area of the infinitesimal surface element, and direction normal to surface S. The direction of the normal must correspond with the orientation of C by the right hand rule), see below for further explanation of the curve C and surface S.

The B and H fields are related by the constitutive equation

$$\mathbf{B} = \mu_0 \mathbf{H}$$

Where μ0 is the magnetic constant.

There are a number of ambiguities in the above definitions that require clarification and a choice of convention. First, three of these terms are associated with sign ambiguities: the line integral $\oint_C$ could go around the loop in either direction (clockwise or counterclockwise); the vector area dS could point in either of the two directions normal to the surface; and Ienc is the net current passing through the surface S, meaning the current passing through in one direction, minus

The current in the other direction—but either direction could be chosen as positive. These ambiguities are resolved by the right-hand rule: With the palm of the right-hand toward the area of integration, and the index-finger pointing along the direction of line-integration, the outstretched thumb points in the direction that must be chosen for the vector area dS. Also the current passing in the same direction as dS must be counted as positive. The right hand grip rule can also be used to determine the signs.

Second, there are infinitely many possible surfaces S that have the curve C as their border. (Imagine a soap film on a wire loop, which can be deformed by moving the wire). Which of those surfaces is to be chosen? If the loop does not lie in a single plane, for example, there is no one obvious choice. The answer is that it does not matter; it can be proven that any surface with boundary C can be chosen.

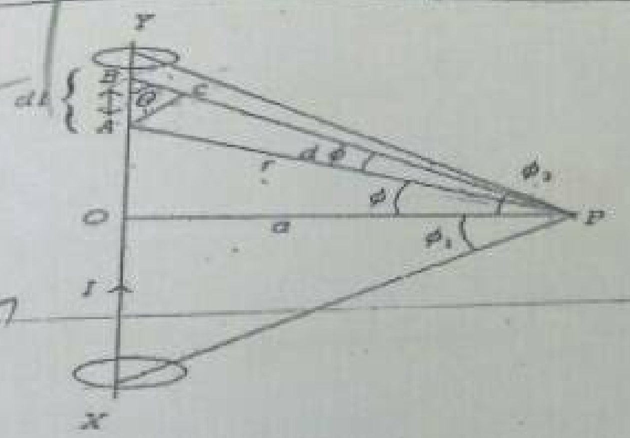
Differential form

By the Stokes' theorem, this equation can also be written in a "differential form". Again, this equation only applies in the case where the electric field is cons ant in time, meaning the currents are steady (time-independent, else the magnetic field would change with time); see below for the more general form. In SI units, the equation states for total current:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}, \quad \nabla \times \mathbf{H} = \mathbf{J}_f$$

where $\nabla\times$ is the curl operator.

2.5 Magnetic Field Due To Straight Conductor, Circular, Infinite Sheet



Construction:

XY is an infinitely long straight conductor carrying a current I. P is a point at a distance 'a' from the conductor. AB is a small element of length dl. θ is the angle between the current element Idl and the line joining the element dl and the point P. So that the lines of magnetic induction are concentric circles around the wire. According to Biot-Savart law the magnetic induction at the point P due to the current element Idl is,

$$dB = \frac{\mu_0}{4\pi} \frac{Idl \sin\theta}{r^2} \longrightarrow (1)$$

Scanned with Fast Scan

AC is drawn perpendicular to BP from A

$$\angle OPA = \phi; \angle APB = d\phi$$

$$In \Delta ABC, \sin\theta = \frac{AC}{AB} = \frac{AC}{dl}$$

$$\therefore AC = dl \sin\theta \longrightarrow (2)$$

From $\Delta APC, AC = rd\phi \longrightarrow$ (3)

$$\left(d\phi = \frac{AC}{AP} = \frac{AC}{r}; AC = rd\phi\right)$$

From equations (2) & (3), $rd\phi = dl \sin\theta \longrightarrow$ (4)

Substituting equation (4) in equation (1),

$$dB = \frac{\mu_0}{4\pi} \cdot \frac{Ird\phi}{r^2}$$

$$= \frac{\mu_0}{4\pi} \cdot \frac{Id\phi}{r} \longrightarrow (5)$$

In $\Delta OPA, \cos\phi = \frac{a}{r}$

$$r = \frac{a}{\cos\phi} \longrightarrow (6)$$

Substituting equation (6) in equation (5)

$$dB = \frac{\mu_0}{4\pi} \cdot \frac{I}{a} \cos\phi \, d\phi$$

The total magnetic induction at P due to the conductor XY is,

$$B = \int_{-\phi_1}^{\phi_2} dB$$

$$= \int_{-\phi_1}^{\phi_2} \frac{\mu_0 I}{4\pi a} \cos\phi \, d\phi$$

$$= \frac{\mu_0 I}{4\pi a} (+\sin\phi)_{\phi_1}^{\phi_2}$$

$$= \frac{\mu_0 I}{4\pi a} \left[(+\sin\phi_2) - (-\sin\phi_1) \right]$$

$$= \frac{\mu_0 I}{4\pi a} \left[\sin\phi_2 + \sin\phi_1 \right]$$

For infinitely long conductor $\phi_1 = \phi_2 = 90°$. $B = \frac{\mu_0 I}{4\pi a} \cdot (2)$

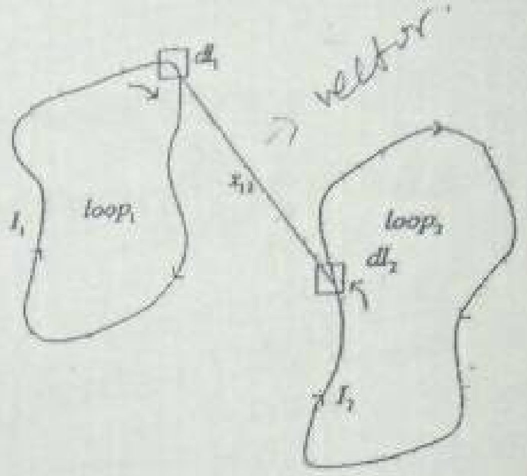
$$B = \frac{\mu_0 I}{2\pi a}$$

If the conductor is placed in a medium of permeability μ,

$$B = \frac{\mu I}{2\pi a} \longrightarrow (7)$$

Each of two long parallel, straight wires of distance 'a' carrying current I1, I2 experiences a force per unit length directly perpendicular to other wire and of magnitude. $\frac{dF}{dl} = \frac{\mu_0}{2\pi} \cdot \frac{I_1 I_2}{a}$

Magnetic Field Due To Circular Loop



We have already introduced the idea that a current element produces a magnetic induction. We phrase the force law as the force experienced by a current element I1dl1, in the presence of a magnetic induction B. The elemental force is

$$dF = I_1(dl_1 \times B)$$

If the external field B is due to a closed loop2 with current I2, then the total force which a closed current loop1 with current I1 experiences is,

$$F_{12} = \frac{\mu_0}{4\pi} I_1 I_2 \oint\oint \frac{dl_1 \times (dl_2 \times X_{12})}{|X_{12}|^3}$$

The line integrals are taken around the two loops. X12 is the vector distance from line element dl2 to dl1, as shown in fig. This is the mathematical statement of Ampere's observations about forces between current-carrying loops.

$$dl_1 \times (dl_2 \times X_{12})$$

$$a \times (b \times c) = (a \cdot c)b - (a \cdot b)c$$

$$= \frac{(dl_1 \cdot X_{12})}{|X_{12}|^3}(dl_2) - \frac{(dl_1 dl_2)}{|X_{12}|^3} X_{12}$$

$$= -(dl_1 \cdot dl_2) \cdot \frac{X_{12}}{|X_{12}|^3} + (dl_1 \cdot X_{12}) \cdot \frac{dl_2}{|X_{12}|^3}$$

The second term vanished because the paths are closed or extended to infinitely so it gives no contribution to the integral.

$$= \frac{dl_1 \times (dl_2 \times X_{12})}{|X_{12}|^3} - (dl_1 \cdot dl_2)\frac{X_{12}}{|X_{12}|^3}$$

The Ampere's law of force between current loops becomes,

$$F_{12} = \frac{-\mu_0}{4\pi} I_1 I_2 \oint\oint \frac{(dl_1 \cdot dl_2) X_{12}}{|X_{12}|^3}$$

Showing symmetry in the integration, apart from the necessary vector dependence on X12.If single current loop or a circular coil to magnetic induction is

$$B = \frac{\mu_0 nI}{2a} (at\ center)$$

If a current density $J(x)$ is in an external magnetic flux density $B(x)$. T elementary force law implies that the total force on the current distribution is,

$$F = \int J(x) \times B(x) d^3x.$$

d^3x is the volume element similarly, the total torque is,

$$N = \int X_{12} \times (J \times B) d^3x$$

Where d3x is the volume element $d^3x = dxdydz$

Magnetic Field of an Infinite Current Sheet

In this case symmetry and the infinite extent of the sheet insures that B will have no components toward or away from the sheet nor will be any components in the direction of the current. Thus B will be in the directions indicated in the figure. Ampere's law can be used easily here provided the line integral is evaluated along the rectangular path of the figure.

$$\int \mathbf{B}\cdot d\mathbf{s} = \mu_0 I,$$

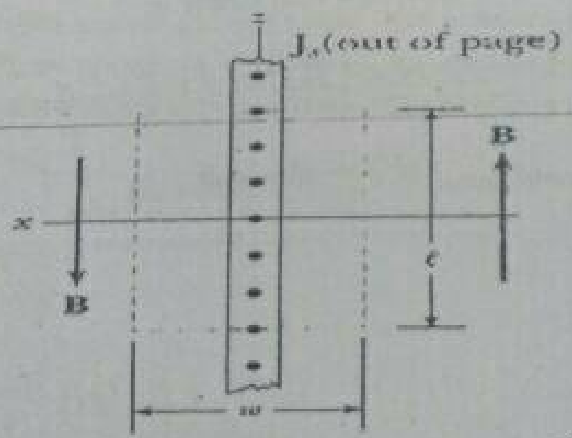
becomes, since the line integral is $\int \mathbf{B}\cdot d\mathbf{s} = 2lB$, and the current through the integration loop is $I = lJ_s$, where J_s is the current per unit length in the z-direction,

$$2lB = \mu_0 lJ_s,$$

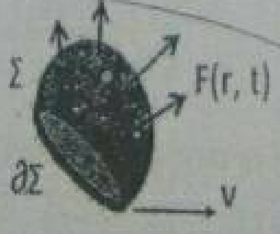
or

$$B = \mu_0 J_s/2$$

in the direction indicted. Note that B is independent of the distance from the current sheet. In a real situation, with a non-infinite sheet, the derived result is still close to being valid as long as the distance from the sheet is small compared the the extent of the sheet.



2.6 Magnetic Flux Density B In Free Space, Conductor



A vector field F (r, t) defined throughout space, and a surface Σ bounded by curve ∂Σ moving with velocity v over which the field is integrated.

While the magnetic flux through a closed surface is always zero, the magnetic flux through an open need not be zero and is an important quantity in electromagnetism. For example, a change in the magnetic flux passing through a loop of conductive wire will cause an electromotive (EMF). So, it will make an electric current, in the loop. The relationship is given by Faraday's law:

$$\mathcal{E} = \oint_{\partial\Sigma(t)} (\mathbf{E}(\mathbf{r},\ t) + \mathbf{v} \times \mathbf{B}(\mathbf{r},\ t)) \cdot d\ell = -\frac{d\Phi_m}{dt},$$

where $\mathcal{E}$ is the EMF,Φm is the flux through a surface with an opening bounded by a curve ∂Σ(t),∂Σ(t) is a closed contour that can change with time; the EMF is found around this contour, and the contour is a boundary of the surface over which Φm is found,dℓ is an infinitesimal vector element of the contour ∂Σ(t),v is the velocity of the segment dℓ,E is the electric field,B is the magnetic field.

The EMF is determined in this equation in two ways: first, as the work per unit charge done against the Lorentz force in moving a test charge around the (possibly moving) closed curve ∂Σ(t), and second, as the magnetic flux through the open surface Σ(t).

This equation is the principle behind an electrical generator.

The magnetic flux density B is similar to the electric flux density D. As $\vec{D} = \epsilon_0 \vec{E}$ in free space, the magnetic flux density B is related to the magnetic field intensity H according to

$$\vec{B} = \mu_0 \vec{H} \qquad (1.21)$$

Where, μ_0 is a constant known as the permeability of free space. The constant is in henrys/meter (H/m) and has the value of

$$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H/m} \qquad (1.22)$$

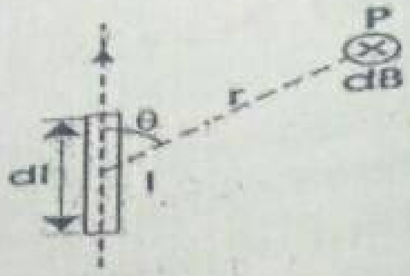
The precise definition of the magnetic field B, in terms of the magnetic force, is discussed later.

Magnetic flux crossing a unit area perpendicularly is defined as magnetic flux density.

Magnetic flux density due to a current carrying conductor

Whenever a current passes through a conductor, a magnetic field is appeared surrounding it. The direction of this magnetic field of current carrying conductor can be determined by Cork Screw Rule or Right Hand Rule. As per Biot Savart's law, the expression of magnetic flux density at a point P nearer to a conductor carrying a current 'I' is given as,

$$dB = \frac{\mu}{4\pi}\frac{I.dl.\sin\theta}{r^2}$$



Now in order to find the actual magnetic flux density B at the point P due to total length of the conductor, we have to integrate the expression of dB, in respect of dl.

$$B = \frac{\mu I}{4\pi}\int\frac{\sin\theta}{r^2}dl$$

The above expression is used to evaluate magnetic flux density B at any point due to infinitely long linear conductor and this comes as

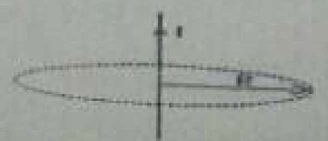
$$B = \frac{\mu I}{2\pi R}$$

Here, R is the radial distance from conductor to the point P.

Now if we integrate B around a path of radius R enclosing the current carrying conductor, we get

$$\oint B.dl = \frac{\mu I}{2\pi R}\oint dl = \frac{\mu I}{2\pi R}2\pi R = \mu I$$

$$or \oint H.dl = I \; Since\; H = \frac{B}{\mu}$$



Ampere's Law

This equation shows that the integral of H around a closed path is equal to the current enclosed by the path. This is nothing but Ampere's law. If the path of

The corresponding magnetic field is equal to

$$\bar{B}_{dipole} = \bar{\nabla}\times\bar{A}_{dipole} = \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\mu_0}{4\pi}\frac{m\sin\theta}{r^2}\right)\hat{r} - \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\mu_0}{4\pi}\frac{m\sin\theta}{r^2}\right)\hat{\theta} =$$

$$= \frac{\mu_0}{4\pi}\frac{m}{r^3}\left\{2\cos\theta\,\hat{r} + \sin\theta\,\hat{\theta}\right\}$$

The shape of the field generated by a magnetic dipole is identical to the shape of the field generated byan electric dipole.

2.10. The Boundary Conditions of B

In Chapter 2 we studied the boundary conditions of the electric field and concluded that the electric field suffers a discontinuity at a surface charge. Similarly, the magnetic field suffers a discontinuity at a surface current.

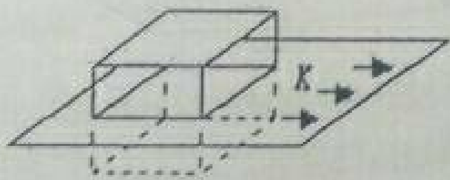


Figure 5.7. Boundary conditions for $\bar{B}$.

Consider the surface current $\bar{K}$ (see Figure 5.7). The surface integral of $\bar{B}$ over a wafer thin pillbox is equal to

$$\int_{Surface} \bar{B}\bullet d\bar{a} = B_{\perp,above}A - B_{\perp,below}A$$

Where A is the area of the top and bottom of the pill box. The surface integral of $\bar{B}$ can be rewritten using the divergence theorem:

$$\int_{Surface} \bar{B}\bullet d\bar{a} = \int_{Volume}\left(\bar{\nabla}\bullet\bar{B}\right)d\tau = 0$$

Since $\bar{\nabla}\bullet\bar{B}=0$ for any magnetic field $\bar{B}$. Therefore, the perpendicular component of the magnetic field is continuous at a surface current:

$$B_{\perp,above} = B_{\perp,below}$$

The line integral of $\bar{B}$ around the loop shown in Figure 5.8 (in the limit $\varepsilon \to 0$) is equal to

$$\oint_{Loop} \bar{B} \bullet d\bar{l} = B_{1,above} L - B_{1,below} L$$

According to Ampere's law the line integral of $\bar{B}$ around this loop is equal to

$$\oint_{Loop} \bar{B} \bullet d\bar{l} = \mu_0 I_{encl} = \mu_0 K L$$

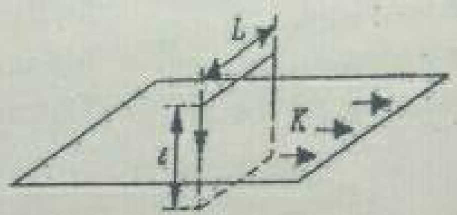


Figure 5.8. Boundary conditions for $\bar{B}$.

Therefore, the boundary condition for the component of $\bar{B}$, parallel to the surface and perpendicular to the current, is equal to

$$B_{1,above} - B_{1,below} = \mu_0 K$$

The boundary conditions for $\bar{B}$ can be combined into one equation:

$$\bar{B}_{above} - \bar{B}_{below} = \mu_0 (\bar{K} \times \hat{n})$$

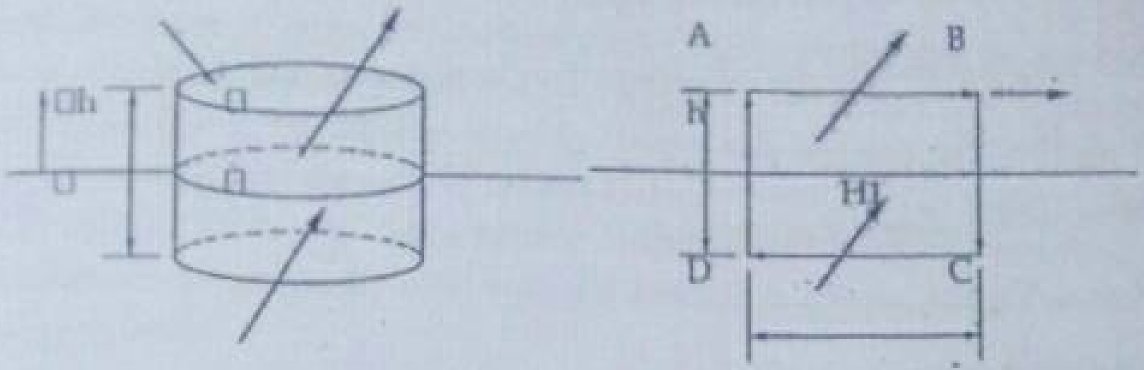
Where $\hat{n}$ is a unit vector perpendicular to the surface and the surface current and pointing "upward". The vector potential $\bar{A}$ is continuous at a surface current, but its normal derivative is not:

$$\frac{\partial \bar{A}_{above}}{\partial n} - \frac{\partial \bar{A}_{below}}{\partial n} = -\mu_0 \bar{K}$$

Area A

B2

H2 10

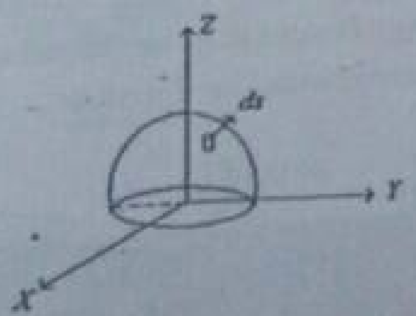


Consider a Gaussian pill-box at the interface between two different media, arranged as in the figure above. The net enclosed (free) magnetic charge density is zero so as the height of the pill-box □h tends to zero so the integral form of Gauss's law tells us that

2.11. Magnetic Vector Potential:

The magnetic flux density is always solenoid because its divergence is zero. A vector whose divergence is zero can be expressed in terms of the curl of another vector quantity as $\vec{B} = \nabla \times \bar{A}$ $\longrightarrow$ (1)

Where $\bar{A}$ is called the magnetic vector potential, and is expressed in Weber per meter (Web/m). Quite often, we find it expedient to work with the magnetic vector potential $\bar{A}$ and then obtain $\vec{B}$ using (1).To obtain an expression for $\bar{A}$, and then obtain $\vec{B}$, we begin our discussion with the Biot-Savart law for the $\vec{B}$ field. The magnetic flux density at any point p(x, y, z) produced by a current-carrying conductor is,



$$\vec{B} = \frac{\mu_o I}{4\pi}\int_c \frac{d\vec{l}\,' \times \vec{R}}{R^3}$$

The scalar potential is another useful quantity in describing the magnetic field, especially for permanent magnets.

In a simply connected domain where there is no free current,

$$\nabla \times \mathbf{H} = 0,$$

Hence we can define magnetic scalar potential ψ as

$$\mathbf{H} = -\nabla\psi.$$

Using the definition of H:

$$\nabla \cdot \mathbf{B} = \mu_0 \nabla \cdot (\mathbf{H} + \mathbf{M}) = 0,$$

it follows that

$$\nabla^2\psi = -\nabla \cdot \mathbf{H} = \nabla \cdot \mathbf{M}.$$

Here $\nabla \cdot \mathbf{M}$ acts as the source for magnetic field, much like $\nabla \cdot \mathbf{P}$ acts as the source for electric field. So analogously to bound electric charge, the quantity

$$\rho_m = -\nabla \cdot \mathbf{M}$$

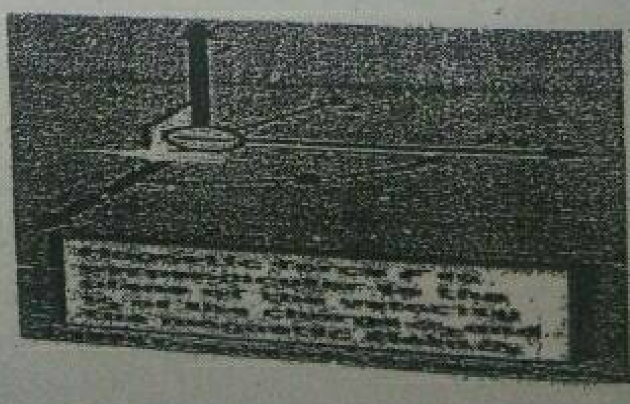
is called the bound magnetic charge.

If there is free current, one may subtract the contribution of free current per Biot-Savart law from total magnetic field and solve the remainder with the scalar potential method.

2.2. Magnetic Force

Attraction or repulsion that arises between electrically charged particles because of their motion; the basic force responsible for the action of electric motors and the attraction of magnets for iron. Electric forces exist among stationary electric charges; both electric and magnetic forces exist among moving electric charges. The magnetic force between two moving charges may be described as the effect exerted upon either charge by a magnetic field created by the other.

...ay Law!
...ell equations
transformation



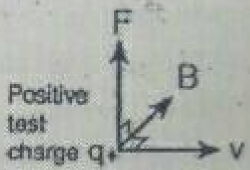
From this point of view, the magnetic force F on the second particle is proportional to its charge q2, the magnitude of its velocity v2, the magnitude of the magnetic field B1 produced by the first moving charge, and the sine of the angle theta, θ, between the path of the second particle and the direction of the magnetic field; that is, $F = q2B1v2 \sin\theta$. The force is zero if the second charge is travelling in the direction of the magnetic field and is greatest if it travels at right angles to the magnetic field.

The magnetic force on a moving charge is exerted in a direction at a right angle to the plane formed by the direction of its velocity and the direction of the surrounding magnetic field.

The magnetic field B is defined from the Lorentz Force Law, and specifically from the magnetic force on a moving charge:

Lorentz

$$\boxed{\vec{F} = q\vec{v} \times \vec{B}}$$



$\delta F_m = I\,\delta L \times B$

$F_m = \Sigma \delta F_m$

$= \Sigma I \delta L$

$= I l B \sin\theta$

$= I l B \hat{n}$

The implications of this expression include:

1. The force is perpendicular to both the velocity v of the charge q and the magnetic field B.

2. The magnitude of the force is $F = qvB \sin\theta$ where θ is the angle < 180 degrees between the velocity and the magnetic field. This implies that the magnetic force on a stationary charge or a charge moving parallel to the magnetic field is zero.

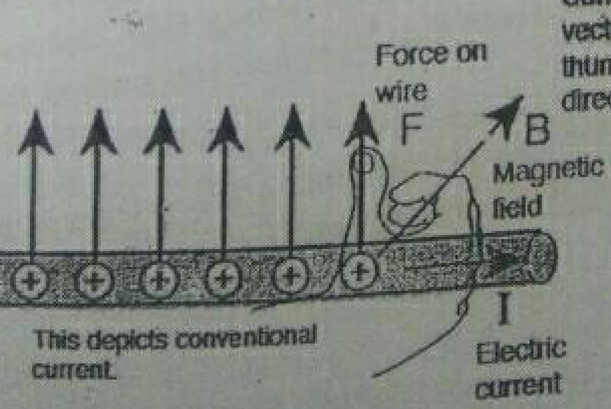
$\delta F_m = I \delta L$

3. The direction of the force is given by the right hand rule. The force relationship above is in the form of a vector product.

$J = nqv$

$I = J \cdot A = nq$

$\delta F_m = (nqvA)$



Curl fingers as if rotating vector I into vector B. The thumb is then in the direction of the force F

$$\vec{F} = \vec{I}L \times \vec{B}$$

Force on straight wire of length L

$J = nqv = I l B$

$= I \delta L$

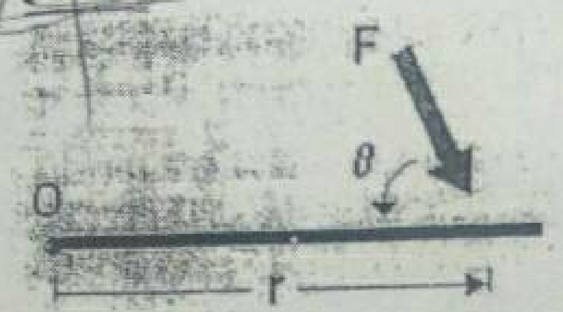
$\delta F_m = I \delta L \times B$

δF_m

When the magnetic force relationship is applied to a current-carrying wire, the right hand rule may be used to determine the direction of force on the wire.

From the force relationship above it can be deduced that the units of magnetic field are Newton seconds /(Coulomb meter) or Newton's per Ampere meter. This unit is named the Tesla. It is a large unit, and the smaller unit Gauss is used for small fields like the Earth's magnetic field. A Tesla is 10,000 Gauss. The Earth's magnetic field at the surface is on the order of half a Gauss.

2.13 TORQUE

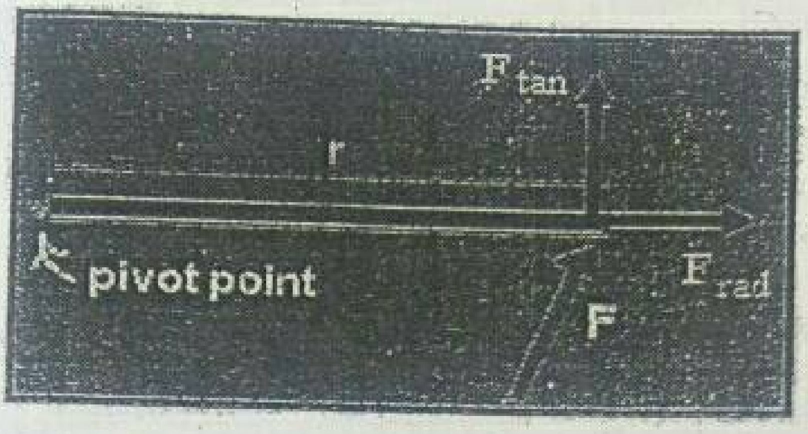


Torque is defined as

$$\tau = r \times F = r F \sin(\theta).$$

In other words, torque is the cross product between the distance vector (the distance from the pivot point to the point where force is applied) and the force vector, 'a' being the angle between r and F. Using the right hand rule, we can find the direction of the torque vector. If we put our fingers in the direction of r, and curl them to the direction of F, then the thumb points in the direction of the torque vector. Imagine pushing a door to open it. The force of your push (F) causes the door to rotate about its hinges (the pivot point, O). How hard you need to push depends on the distance you are from the hinges (r) (and several other things, but let's ignore them now). The closer you are to the hinges (i.e. the smaller r is), the harder it is to push. This is what happens when you try to push open a door on the wrong side. The torque you created on the door is smaller than it would have been had you pushed the correct side (away from its hinges).

Note that the force applied, F, and the moment arm, r, are independent of the object. Furthermore, a force applied at the pivot point will cause no torque since the moment arm would be zero (r = 0).



Another way of expressing the above equation is that torque is the product of the magnitude of the force and the perpendicular distance from the force to the axis of rotation (i.e. the pivot point). Let the force acting on an object be broken up into its tangential (Ftan) and radial (Frad) components (see Figure 2). (Note that the tangential component is perpendicular to the moment arm, while the radial component isparallel to the moment arm.) The radial component of the force has no contribution to the torque because it passes through the pivot point. So, it is only the tangential component of the force which affects torque (since it is perpendicular to the line between the point of action of the force and the pivot point).

There may be more than one force acting on an object, and each of these forces may act on different point on the object. Then, each force will cause a torque. The net torque is the sum of the individual torques. Rotational Equilibrium is analogous to translational equilibrium, where the sum of the forces are equal to zero. In rotational equilibrium, the sum of the torques is equal to zero. In other words, there is no net torque on the object.

$$\sum \tau = 0$$

Note that the SI units of torque is a Newton-meter, which is also a way of expressing a Joule (the unit for energy). However, torque is not energy. So, to avoid confusion, we will use the units N.m, and not J. The distinction arises because energy is a scalar quantity, whereas torque is a vector.

2.14.Inductance

When induction occurs in an electrical circuit and affects the flow of electricity it is called inductance. Self-inductance, or simply inductance, is the property of a circuit whereby a change in current causes a change in voltage in the same circuit. When one circuit induces current flow in a second nearby circuit, it is known as mutual inductance. The image to the right shows an example of mutual-inductance. When an AC current is flowing through a piece of wire in a circuit, an electromagnetic field is produced that is constantly growing and shrinking and changing direction due to the constantly changing current in the wire.

This changing magnetic field will induce electrical current in another wire or circuit that is brought close to the wire in the primary circuit. The current in the second wire will also be AC and in fact will look very similar to the current flowing in the first wire. An electrical transformer uses inductance to change the voltage of electricity into a more useful level. In nondestructive testing, inductance is used to generate eddy currents in the test piece.

It should be noted that since it is the changing magnetic field that is responsible for inductance, it is only present in AC circuits. High frequency AC will result in greater inductive reactance since the magnetic field is changing more rapidly.

2.15. Energy Density

the amount of energy stored in a given system or region of space per unit volume or mass, though the latter is more accurately termed specific energy. Often only the useful or extractable energy is measured, which is to say that chemically inaccessible energy such as rest mass energy is ignored. Energy per unit volume has the same physical units as pressure, and in many circumstances is a synonym: for example, the energy density of a magnetic field may be expressed as (and behaves as) a physical pressure,

the energy required to compress a compressed gas a little more may be determined by multiplying the difference between the gas pressure and the external pressure by the change in volume. In short, pressure is a measure of the enthalpy per unit volume of a system. A pressure gradient has a potential to perform work on the surroundings by converting enthalpy until equilibrium is reached. Energy can be stored in many different types of material, and there are several types of reactions that release energy. In order of the typical magnitude of the energy released, these types of reactions are: nuclear, chemical, electrochemical, and electrical.

Chemical reactions are used by animals to derive energy from food, and by automobiles to derive energy from gasoline. Electrochemical reactions are used by most mobile devices such as laptop computers and mobile phones to release the energy from batteries.

Energy Densities Of Common Energy Storage Materials

The following is a list of the combustion energy densities of commonly used or well-known energy storage materials; it doesn't include uncommon or experimental materials. Note that this list does not consider the mass of reactants commonly available such as the oxygen required for combustion.

The following unit conversions may be helpful when considering the data in the table: 1 MJ ≈ 0.28 kWh ≈ 0.37 HPh.

6. Magnetic circuit

Magnetic circuit is made up of one or more closed loop paths containing a magnetic flux. The flux is usually generated by permanent magnets or electromagnets and confined to the path by magnetic cores consisting of ferromagnetic materials like iron, although there may be air gaps or other materials in the path. Magnetic circuits are employed to efficiently channel magnetic fields in many devices such as electric motors, generators, transformers, relays, lifting electromagnets, SQUIDs, galvanometers, and magnetic recording heads.

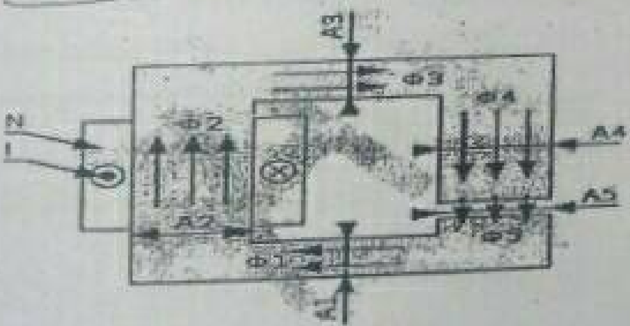
The concept of a "magnetic circuit" exploits a one-to-one correspondence between the equations of the magnetic field in an unsaturated ferromagnetic material to that of an electrical circuit. Using this concept the magnetic fields of complex devices such as transformers can be quickly solved using the methods and techniques developed for electrical circuits.

Some examples of magnetic circuits are:

horseshoe magnet with iron keeper (low-reluctance circuit)

horseshoe magnet with no keeper (high-reluctance circuit)

electric motor (variable-reluctance circuit)



$R_T = R_1 + R_2 +$

Magnetic circuits obey other laws that are similar to electrical circuit laws. For example, the total reluctance $\mathcal{R}_T$ of reluctances in series is:

$$\mathcal{R}_T = \mathcal{R}_1 + \mathcal{R}_2 + \cdots$$

This also follows from Ampere's law and is analogous to Kirchhoff's voltage law for adding resistances in series. Also, the sum of magnetic fluxes $\Phi_1, \Phi_2, \ldots$ into any node is always zero:

$$\Phi_1 + \Phi_2 + \cdots = 0.$$

This follows from Gauss's law and is analogous to Kirchhoff's current law for analyzing electrical circuits.Together, the three laws above form a complete system for analysing magnetic circuits, in a manner similar to electric circuits. Comparing the two types of circuits shows that:The equivalent to resistance R is the reluctance $\mathcal{R}_m$ The equivalent to current I is the magnetic flux Φ The equivalent to voltage V is the magneto motive Force F Magnetic circuits can be solved for the flux in each branch by application of the magnetic equivalent of Kirchhoff's Voltage Law (KVL) for pure source/resistance circuits. Specifically,

whereas KVL states that the voltage excitation applied to a loop is equal to the sum of the voltage drops (resistance times current) around the loop, the magnetic analogue states that the magneto motive force (achieved from ampere-turn excitation) is equal to the sum of MMF drops (product of flux and reluctance) across the rest of the loop. (If there are multiple loops, the current in each branch can be solved through a matrix equation—much as a matrix solution for mesh circuit branch currents is obtained in loop analysis—after which the individual branch currents are obtained by adding and/or subtracting the constituent loop currents as indicated by the adopted sign convention and loop orientations.) Per Ampere's law, the excitation is the product of the current and the number of complete loops made and is measured in ampere-turns. Stated more generally:

$$F = NI = \oint \vec{H} \cdot d\vec{l}.$$

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